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SINKHOLES, HYDROGEOLOGY, AND GROUND-WATER QUALITY IN NORTHEAST IOWA

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Iowa Department of Environmental Quality
from the:

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EXECUTIVE SUMMARY

Northeastern Iowa is considered to have Iowa's most abundant supplies of good quality ground water. The most widely accessible aquifers (water-producing geologic units) are comprised of carbonate (limestone or dolomite) rocks. Unfortunately, these carbonate aquifers are much more susceptible to contamination from sources at the land surface than other types of aquifers. This is because the ground water flows through openings in the rock, enlarged by chemical solution, which range in size from microscopic fractures to large caves. When these larger openings extend to the land surface, they form depressions, called sinkholes. The open sinkholes provide a direct conduit for surface waters, and contaminants which they may carry, to run directly into the underground cavities in the carbonate rocks, and join the ground-water system. Where sinkholes are abundant they form distinct landforms, collectively called karst topography.

Documented, local occurrences of serious ground-water contamination in the karst areas have raised the concern of whether or not regional ground-water contamination is occurring. If so, are regional or local control measures necessary to alleviate the problem? These are vital questions because water-quality problems may impact public health as well as the region's economic well-being.

To address these issues a systematic analysis was undertaken for the karst regions and the carbonate aquifers in 22 counties in northeast Iowa. Pertinent geologic, hydrologic and water quality data were compiled, and analyzed, including over 14,000 water analysis records provided by the University Hygienic Laboratory (UHL). The distribution of over 12,700 sinkholes was mapped. "Soil-materials" cover the bedrock to depths varying from 0 to 500 feet, but the sinkholes are only found in certain areas where the "soil-materials" are less than 30 feet thick. There are three main areas of sinkhole concentrations: one in the area of exposure of the Galena aquifer, in southwestern Allamakee County, and adjacent areas; and two areas in the Silurian-Devonian aquifer, in southern Clayton County and adjacent areas, and adjacent to the Cedar River, mainly in Floyd and Mitchell Counties.

Results of the geological studies were used to subdivide the area into three geologic regions: Karst--areas with significant concentrations of sinkholes; Shallow Bedrock--areas with less than 50 feet of "soil" covering the bedrock, but with few sinkholes; and Deep Bedrock--areas with more than 50 feet of "soil" covering the bedrock.

Ground water in the Karst and Shallow Bedrock areas exhibits significantly higher concentrations of nitrate than in the Deep Bedrock areas, particularly to depths of 150 feet. The greatest differences occur in the 50-99 foot depth range, where the median nitrate concentration in the Karst regions (34 mg/l) is 1.8 times greater than in the Shallow Bedrock regions (19 mg/l) and nearly 6 times greater than in the Deep Bedrock regions (6 mg/l). Below 100 feet the Karst and Shallow Bedrock areas show similar levels of nitrate. This is attributed to the direct inflow of nitrate in surface waters into sinkholes in Karst regions, combined with signficant diffuse recharge of nitrate to the aquifer in both the Karst and Shallow Bedrock regions. For perspective, the median nitrate values from all areas are below the 45 mg/l drinking water standard. For the study area, 18% of all samples exceed 45 mg/l. Within the different geologic settings, 25% of analyses from the Karst areas, 19% in the Shallow Bedrock, and 15% in the Deep Bedrock areas exceeded 45 mg/l. Much of the excessive nitrate contamination is localized to individual wells, but nitrate levels are clearly elevated regionally as well.

The source of the nitrates is clearly man's activity; natural background levels of nitrate are generally less than detectable. Little data is available regarding other widely used chemicals. What data there is indicate that pesticides, albeit in low concentrations, are entering the ground water in these areas. The fate of these chemicals in the ground-water system is unclear, as are the possible health effects of these low concentrations.

The physical setting in both the Karst and Shallow-Bedrock regions present potential hazards for ground-water contamination. Any management strategies developed for protection of these water resources must consider both of these settings, which in total constitute about 6,800 square miles of land overlying important bedrock aquifers.

The relationship between the sinkholes and the ground-water flow system in the carbonate aquifers suggests that the bulk of these surface contaminants in the Karst regions should be contained within the shallow portion of the flow system. This may, in part, explain why significant nitrate contamination is confined to relatively shallow depths (less than 150 feet). However, because of the lack of detailed data about the aquifers, an alternative which must be considered is that the deeper portions of the aquifer show less contamination because there has not been enough time for the nitrates to diffuse this deep.

Further research is needed on the nature of bacterial contamination of ground water in the Karst areas. Analysis of bacterial data indicates that bacterial contamination of rural water supplies requires attention. Thirty-five percent of all analyses from UHL for the study area do not meet health standards. This contamination appears to be primarily related to problems in individual rural domestic water systems, but in Karst regions may be increased by the influx of surface waters.

The magnitude of chemical and bacterial contamination of an individual well is also related to problems of poor well construction, maintenance and/or well placement. Contamination of a well from surface sources may also introduce contaminants into the aquifer.

Shallow wells, less than 50 feet deep, statistically show high nitrate values regardless of their geologic setting. Shallow wells throughout Iowa, regardless of the aquifer involved, are susceptible to contamination by nitrates, and indeed are exhibiting significantly high levels of nitrate contamination.

Ground water in the Karst areas is readily susceptible to contamination from hazardous substances which locally may be discharged at the surface. On the regional level, nitrates, bacteria and pesticides are the three general contaminants of concern for public health. Both point and non-point sources can be identified. Land use patterns and other studies suggest that non-point sources, primarily infiltration, tile drainage, and water and sediment runoff from agricultural lands are the most significant. Point sources, however, should be eliminated where possible. There are existing rules and regulations to control these point sources, but many of these rules are difficult or impossible to enforce. Non-point source problems are particularly difficult to resolve, and given the complex interaction of climate and farming practices some delivery of these contaminants into the ground water in the Karst areas is unavoidable. Possible control measures or best management practices (BMP's) must take into account these complex variables, as well as the needs of particular farm operations, and the nature and extent of existing tile drainage.

Before any effective management scheme can be developed, further research must address the details of the delivery and fate of these contaminants in the ground-water system, locally and regionally. Also, there is a pressing need for a water-quality monitoring network to provide a base of information on Iowa's water resources. This should include improvements in present water-quality data collection schemes.

The development of a management plan and BMP's to protect ground-water quality in these carbonate aquifers will require the integrated cooperation of many agencies and people. Implementation of any effective measures will require an effective program of public education.

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INTRODUCTION

Northeastern Iowa is generally considered to have Iowa's most abundant supplies of good quality ground water. Yet in recent decades public officials and private citizens have expressed concern for the continued quality of their public and private well-or ground-water supplies. This concern stems from many local cases of contaminated water and reports from well drillers having increased difficulty in finishing wells with high-quality water. These problems arise because many of the most important water-bearing bedrock units, or aquifers in the region are comprised of limestone or dolomite, collectively referred to as carbonate rocks. Such carbonate rocks comprise the Silurian-Devonian aquifer, a thick, widespread source of ground water, as well as the Galena aquifer, a more restricted aquifer in northeast Iowa. Because these aquifers are found at relatively shallow depths and they generally provide reliable quantities of water they afford the most economically accessible sources of ground water in the region. The Silurian-Devonian aquifer especially, is a major source of public as well as private water supplies throughout eastern Iowa.

Carbonate aquifers exhibit some properties which can also create unique problems. Aquifers in Iowa can be separated into two groups: those composed of the carbonate rocks, and those composed of clastic rocks, such as a sandstone. In clastic rocks the aquifer's permeability, the property which allows water movement, is a primary feature. The water moves through the small, interconnected pores between the grains which comprise the rock. In contrast most carbonate rocks are well cemented and their primary, intergranular permeability is generally quite low. The features which allow significant water movement through carbonate rocks are secondary features such as joints and fractures. In humid environments, carbonate rocks are subject to chemical solution by infiltrating soil and ground water. As the water moves it dissolves the adjacent rock. Fractures, joints, and other secondary openings are enlarged, and over time the ground water moves through a series of interconnected openings which range from microscopic fractures to large caves and caverns. The flow of water in these larger openings, such as through cave passages, is like open channel or pipe flow and contrasts sharply with the slower, intergranular flow in a sandstone aquifer. This rapid flow is one of the problems in carbonate aquifers: the open channel flow does not provide the natural filtering effect that occurs with intergranular ground-water flow.

Another consequence of the solution of the carbonate rocks is the development of unique land-surface features, collectively referred to as karst topography. One of the more conspicuous and important features is the sinkhole. Sinkholes form as a consequence of the rock solution and collapse. Soil materials and rock may wash or collapse into enlarged vertical joints or conduits. Subsurface caverns reduce the support for the overlying rocks and soil materials which may then collapse into the cavern. At the surface, sinkholes appear as conical depressions. As depressions the sinkholes will obviously collect surface drainage. Occasionally they will intercept entire streams to form "blind valleys." These are valleys where a stream disappears by discharging into the sinkhole. This is one of the major problems with sinkhole regions. The sinkholes provide a direct conduit for surface water to run directly into the undergound cavities in the limestone, and join the ground-water system. These surface waters, and the contaminants they may carry, can reach the ground water in a wholly unfiltered and undiluted state. As a consequence, carbonate aquifers are highly susceptible to contamination by surface runoff from agricultural or industrial land, effluent from sewage or waste disposal or surface spills of various kinds. Because sinkholes are depressions and they naturally both collect and dispose of surface runoff, they have often been used as discharge points for drainage tiles and even septic systems. Furthermore, sinkholes provide a common and convenient, though potentially dangerous, place to dispose of solid waste materials. Observations and case studies in Iowa have shown local occurrences where everything from solid refuse, to old chemical containers, car bodies, creamery wastes, and even dead animals have been dumped into sinkholes. Out-of-site is not necessarily out-of-mind in these instances, because this dumping has sometimes seriously contaminated local water supplies.

These localized cases have naturally raised the question of whether regional contamination of these aquifers is occurring? If so, it could threaten Iowa with long-term water-quality problems and could impact public health as well as local economies. If this is happening, are widespread control measures necessary to alleviate this contamination? To answer such questions, more fundamental issues must be addressed first: Where are the karst areas? What are their relationships to the ground-water flow system? Is there any evidence for regional degradation of ground-water quality?

Until this study there has been no systematic analysis of Iowa's karst areas or the potential regional water-quality problems that might be associated with them. This contract was entered into to provide such basic information. This report marks the completion of the first phase of this study, under Grant Number M007055-81 from the Iowa Department of Environmental Quality (DEQ) to the Iowa Geological Survey (IGS).

Nearly the entire IGS staff was involved in this study, as well as 6 university graduate students, hired under the grant. This team of workers analyzed the karst regions of northeast Iowa, their hydrogeologic setting, and their impact on ground-water quality. This study was focused on 22 counties in northeast Iowa, as shown in figure 1. The findings of this study will describe and discuss: 1. the distribution of karst features, particularly sinkholes; 2. the geologic factors affecting sinkhole distribution; 3. an evaluation of the karst's relationship to the ground-water system; 4. an assessment of the principal hazard areas, where there is a high potential for ground-water contamination from surface activites; 5. a compilation and evaluation of all pertinent, extant ground-water quality data, in relation to geologic and other environmental controls which effect the water quality; 6. the evidence for local and regional water-quality degradation; 7. an assessment of the ground-water flow systems in the carbonate aquifers and how this relates to the water quality considerations; 8. an evaluation of potential and likely sources of ground-water contamination in the karst regions, and a discussion of various control measures affecting these sources. The report concludes with recommendations for further study necessary to refine our understanding of the carbonate aquifers and the extent of ground-water contamination, and an assessment of some control measures which could be evaluated.

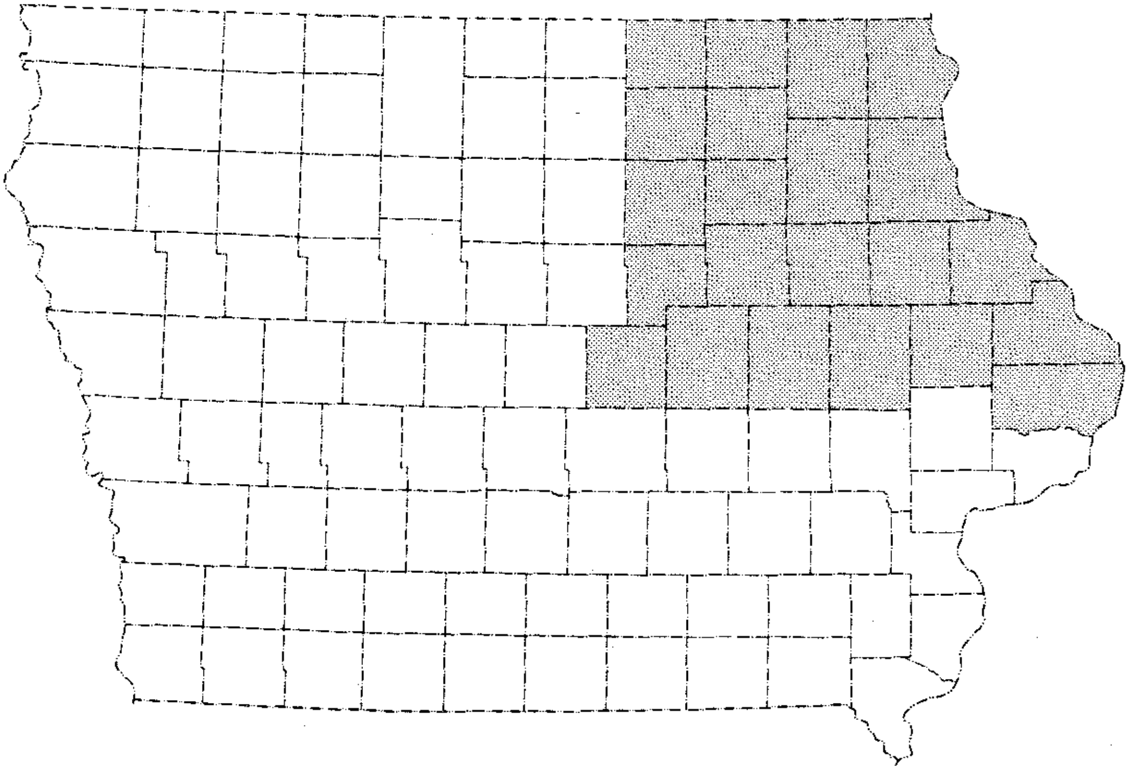

Figure 1. Location of 22 county study area in northeast Iowa.

DISTRIBUTION OF SINKHOLES IN NORTHEAST IOWA

Sinkhole Mapping

A primary task of this study was to identify and map the sinkholes in the karst terrain of northeast Iowa. Sinkholes are the most obvious surface expression of the well developed karst areas and also are the principal avenues which allow surface water into the carbonate ground-water system. The mapped locations of the sinkoles are shown on Plate 1. Their distribution is summarized on figure 2. Over 12,700 sinkholes were identified and mapped in the region. The primary sources of information for mapping the sinkholes were: 1. published and unpublished modern soil surveys; 2. published reports involving field surveys; 3. unpublished field surveys by IGS personnel; 4. photo-interpretation of IGS color-infrared aerial photography (scale 1:80,000); and 5. unpublished master's theses.

The most accurate sources of information about sinkhole locations are those reports which involved actual field surveys. In this category the soil surveys provided the most complete and accurate coverage of the area. References to the soil surveys used are given in Appendix 1. Only the soil surveys in categories 1 and 2 in Appendix 1 could be used for the sinkhole mapping. All

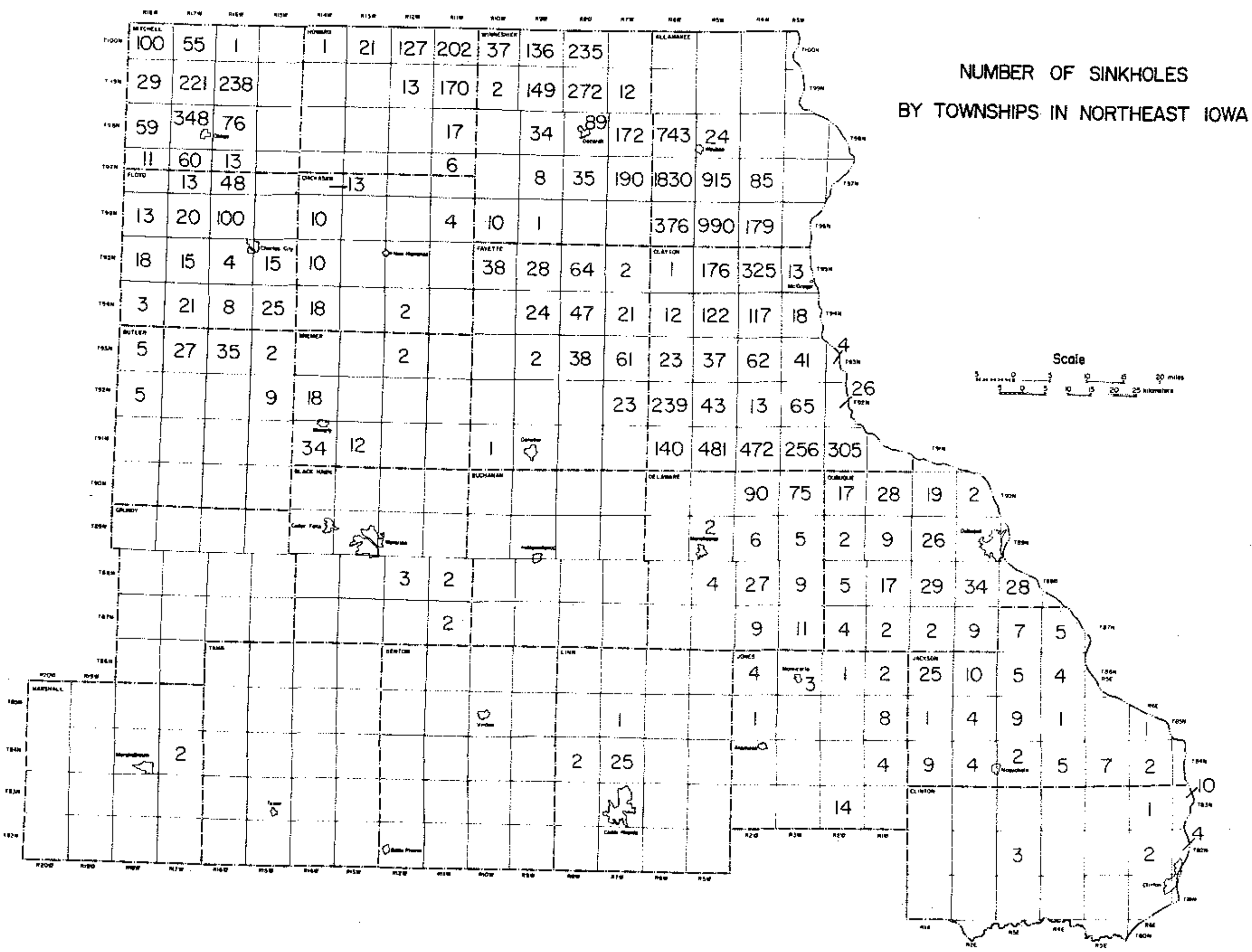

Figure 2. Summary of the distribution of sinkholes mapped in this study. Numbers indicate the number of sinkholes in the township.

of 17 counties, and portions of 2 additional counties (Delaware and Dubuque) are covered by completed modern soil survey maps. On these soil maps sinkholes are shown as either a mapping unit, or as a special spot symbol (map symbol within a soil mapping unit delineation), or with a symbol which simply indicates an unclassified closed depression.

The soil surveys are field surveys, and because of the scale (1:15,840), and detail of mapping, locations are quite accurate. Limited field checking indicated that in some instances, two adjacent, small sinkholes might be shown by one map symbol. Still, however, the locations, distributions, and relative abundance are quite accurate.

In the most critical counties in the study area special maps were compiled, or special symbols were used by the soil scientists to indicate the location of sinkholes. These areas include Allamakee, Clayton, Fayette, Mitchell, and

Winneshiek Counties. However, in the remaining counties, sinkholes were shown by a map symbol used to denote any form of closed depression. In these counties further work and interpretations had to be made, particularly in the low-relief areas in the central and western part of the study area (Blackhawk and Bremer Counties, for example). In these areas other forms of closed depressions commonly occur related to wind-blown sand and silt deposits ("blowouts"), on stream terraces, and in some places on the low-relief eroded glacial deposits. Each of these depressions was reviewed using the soil maps, topographic maps, aerial photographs, and other geologic data. Most of the depressions were easily classified. Many of the non-sinkholes would occur associated with eolian deposits in areas where the bedrock was deep below the land surface (100 feet or more). Most of the sinkholes occurred in areas of near surface bedrock and often clearly had the morphology of sinkholes on the aerial photographs. Obviously, there were some situations in between where depressions occurred in sediments where bedrock was at a relatively shallow depth (10 to 25 feet), but not exposed. These areas were interpreted conservatively, and checked against all sources of information, particularly field surveys. Some were field checked. Only the most probable depressions were classed as sinkholes. Plate 1 shows a two-fold classification in pertinent areas to distinguish between sinkholes and interpreted "probable" sinkholes.

In Chickasaw, Floyd, Jackson, Jones, and portions of Delaware and Dubuque Counties, no modern soil survey information was available. In these areas, photo-interpretation of the color-infrared photography was used to map the sinkholes. In portions of this area unpublished field surveys were also available as a guide and a check on the photo-interpretation. In some areas interpretation was very difficult, and the interpretations were conservatively edited, using all the other available information. Limited areas were field checked as well. On Plate 1 the photo-interpreted sinkholes are also divided into two groups based on the confidence of the interpretations.

As noted, published reports (Heitmann, 1980; Tjostem, et al., 1977; Steinhilber, et al., 1961) also provided information for limited areas. Two unpublished master's theses provided field survey data for portions of Clayton and Delaware Counties (Hansel, 1976) and a portion of Allamakee County (Iles, 1977). Another unpublished thesis (Ramp, 1977) presented information on sinkhole distribution throughout northeast Iowa from interpretation of aerial photography. However, in comparing this work (Ramp, 1977) with other field survey work many discrepencies were noted. Consequently, this work was not used for comparison.

These reports, cited above, and the other unpublished IGS field surveys were principally used as a check on the sinkhole distributions as mapped from soil surveys and air photos. For consistency, only the sinkholes derived from the modern soil surveys or the interpretation of the IGS color-infrared aerial photography, used in this study, or IGS field studies, are shown on Plate 1 (and figure 1). As noted, over 12,700 sinkholes were identified and mapped in this study. Comparison of the sinkholes mapped in this study with the other field surveys described above indicate that these numbers are conservative, but that the relative distributions are accurate. The absolute number of sinkholes is not particularly critical anyway. Any map showing the sinkholes is only an inventory at that point in time, because new sinkholes are continually forming. During the course of this study, three new sinkholes are known to have formed.

Geologic Distribution of Sinkholes

The sinkholes are also shown on Plate 2 in relation to the bedrock geologic units in northeast Iowa. Solutional karst features occur principally in the thicker, relatively pure carbonate rock sequences especially the limestone sequences. The highest concentrations of sinkholes occur in: 1. the Silurian age rocks, particularly along the topographic escarpment (the Niagaran escarpment) formed by these rocks, in southern Clayton and eastern Fayette County; 2. the Galena Group rocks, of Ordovician age, in southwestern Allamakee, and portions of Clayton and Winneshiek Counties; and 3. the outcrop area of Middle Devonian rocks (principally the Cedar Valley Limestone) adjacent to the Cedar River in Mitchell, Floyd, Chickasaw, and Bremer Counties. All of these sinkhole regions are in important carbonate aquifers: the Galena aquifer has been historically important locally in northeast Iowa; the Silurian-Devonian aquifer is one of the major sources of ground-water supplies thoughout eastern Iowa. The importance of the Galena has declined in recent years because of the water-quality problems this study is addressing.

A few sinkholes and karst features also occur in other bedrock units, such as the Mississippian age rocks in Marshall County and in the upper Devonian rocks of the Shell Rock and Lime Creek Formations in Butler and Floyd County. Sinkholes are also shown in the mapped area of the Maquoketa Formation. Although the Maquoketa is dominantly a shale, these sinkholes which appear (in Clayton, Allamakee, and Winneshiek Counties) occur in areas where the Maquoketa is thin, and intervals of carbonate rocks are present in the lower portion of the formation. It is not known however, whether these sinkholes are actual solutional features in the Maquoketa, or whether they result from stoping (collapse) into solutional cavities in the underlying Galena Group rocks. Published and unpublished dye-tracing studies, as well as studies of ground-water contaminant travel paths demonstrate that these sinkholes and their subsurface conduits are connected through the Maquoketa rocks into the underlying Galena Group. A few sinkholes are also shown in the Cambro-Ordovician age rocks. In this area some sinkholes, caves, and karst springs are found in the Prairie du Chien Group dolomites (see also Plate 3).

The known distribution of karst features throughout Iowa is shown on Plate 3. Outside of the northeast Iowa study area there are a few additional karst regions. Numerous sinkholes occur in the Mississippian age Burlington Limestone around the town of Burlington in southeast Iowa. Some minor karst features are also known in Mississippian rocks in the Humboldt County area in north-central Iowa. A well-developed karst surface is formed on the Ft. Dodge Gypsum beds in north-central Iowa also (Plate 3). This karst is essentially inactive now, and the karst surface is filled in by Pre-Illinoian and late-Wisconsinan glacial deposits.

Geometry of Sinkholes

The sinkholes vary in size, shape, and depth from very small (a few feet in diameter), shallow (one foot in depth), incipient depressions, to quite large (a few hundred feet in long dimension, and several tens of feet deep) coalescing sinkholes. The shapes of the sinkholes are variable. Some are very elongate and appear as long linear fissures, occurring along joints which have been widened by solution. However, numerous measurements (Iles, 1977; and this study) indicate that in general the sinkholes tend to be circular to just slightly elongate. In the Silurian and Galena karst areas the mean diameter of the sinkholes is about 70 feet (21 m) and the mean depth about 12 feet (3.7 m). In the Devonian karst of Floyd County sinkholes tend to be slightly smaller, with a mean diameter of about 60 feet (18 m) and mean depth of 8 feet (2.4 m).

A more important characteristic of the sinkholes is their drainage area. Unfortunately, this is highly variable and impossible to characterize from existing maps. Many sinks occurring on hill sides will drain little more than the immediate area around the depression of the sink. Larger sinkholes take the drainage from areas of 50 to 500 acres. Still other sinks occur in stream beds and effectively have very large drainage areas. Some of these "swallow holes" which occur in stream beds are quite small (one to two feet in diameter), and are not obvious as sinkholes, but may divert substantial amounts of surface water into the subsurface.

FACTORS AFFECTING THE SINKHOLE DISTRIBUTION

Many factors affect the formation and distribution of sinkholes in northeast Iowa. Most important are the lithology and structure of the karst-forming rocks, erosional relief, and the thickness of Quaternary age "soil" materials covering the bedrock.

Lithology and Structure

As noted previously, karst features, including sinkholes, are best developed in relatively pure carbonate rock sequences (see Thrailkill, 1968; White, 1977). In northeast Iowa, for example, the intensity of karst development and the frequency of sinkholes appears to increase as some of the karst-forming rock units change from dolomite to limestone. Particular stratigraphic units also control the development of karst features. For example, Bounk, (1982) has shown that many of the major cave systems in the Silurian rocks are formed in the *Cyclocrinites* beds. Where such stratigraphic controls exist, the depth below landsurface of prominent karst-forming beds may affect sinkhole formation and density. Such stratigraphic controls, in areas of relatively flat-lying strata, such as northeast Iowa, promote the development of extensive, complex karst drainage systems or conduits (White, 1977).

Rock structures, such as joints or fractures, and bedding planes also affect karst development and sinkholes. As noted previously, solution takes place along such openings in the carbonate rocks to form the karst features. The structures influence the detailed pattern of conduit systems and generally determine the location of zones of high permeability in carbonate rocks (White, 1977). Many studies have demonstrated that caves and conduits are controlled by, and form along linear joint and fracture traces (Powell, 1977; Wermund, et al., 1978) and that fracture density is an excellent indicator of increased zones of permeability and porosity in ground-water supply exploration (Parizek, 1976). In many areas in the karst of northeast Iowa sinkholes occur in linear groups, paralleling the trends of fracture-controlled solution featues in the subsurface. Bounk (1982) has demonstrated that the orientaton of many caves in Silurian rocks is controlled by the relationship between jointing and hydraulic gradient. Major conduits, or caves, were formed along those joints which were aligned in the direction of the hydraulic gradient that existed at the time the caves were formed.

Erosional Relief

Erosional relief may play two roles in the development of karst features. First, the relief in an area will affect the hydraulic gradient, and second, it may, in appropriate settings, promote the development of "mechanical" karst.

The age of development of the erosional relief will also affect karst development. The amount of time available since the carbonate rocks have been in the appropriate hydrologic setting will obviously affect the maturity or extent of karst development. Further, greater relief in an area may increase the hydraulic gradient, thus increasing the rate of water movement and concurrent solutional processes. Differences in age, or length of karst-forming time, may explain why some areas (e.g. -Buchanan County) of shallow limestone do not exhibit sinkholes, whereas other areas in the same rocks do.

Mechanically induced karst has been postulated by Hansel (1976) to explain certain aspects of the karst features along the escarpment of the Silurian rocks in southern Clayton and northern Delaware Counties. Along the escarpment stream erosion has exposed the Ordovician age shales of the Maquoketa Formation which underlies the Silurian carbonate rocks. The upper portion of the Maquoketa is a thick sequence of rather plastic clay-shales. When exposed these shales become unstable. The stream erosion which has cut valleys into the Maquoketa has also removed the lateral support or confinement on these plastic clay-shales. As a result the shale may deform laterally from the stress exerted by the mass of the overlying rocks and from the (latent) lateral earth pressures within shales related to their consolidation history. This lateral deformation removes some support from the overlying Silurian carbonate rocks resulting in tension fracturing or failure in the Silurian rocks. This is generally expressed as widening and/or movement along existing vertical joints and fractures. This mechanical action further increases the permeability of these joints, promoting more active or rapid solutional action. Mechanical slippage of large blocks of the Silurian rocks may also form surface features (depressions - or sinkholes) which enhance diversion of surface drainage into the rocks, further promoting solutional karst development. This theory (Hansel, 1976) helps to explain the much greater density of sinkholes found immediately adjacent to the Silurian escarpment, than is found elsewhere in the Silurian rocks.

Depth to Bedrock; Thickness of Quaternary Soil Materials Over Bedrock

One of the factors affecting the distribution of sinkholes is the thickness of the Quaternary sediments or "soil" materials (loess, till, alluvium, etc.) over the bedrock surface. The thickness of sediments also affects the rate and amount of surface water infiltration into the bedrock system.

The data on the thickness of sediments over bedrock, or conversely the depth to bedrock, was compiled for the study area and is presented in two maps (Plates 4 and 5). The depth to bedrock varies from zero, in areas of bedrock exposure, to more than 400 feet in buried bedrock valleys (figure 3). Plate 4 shows the distribution of bedrock outcrops for the study area. This map was principally prepared from the detailed information in the modern soil survey reports (Appendix 1; categories 1 and 2). Where this information was not available the mapping was done from older soil survey reports (Appendix 1; category 3) and IGS field records. The map depicts where bedrock is exposed or has a mantle of soil less than 5 feet (1.5 m) in thickness. No regional map of bedrock outcrops, with this detail has ever been prepared before in Iowa.

Plate 5 shows the thickness of Quaternary soil materials over bedrock, or conversely the depth to bedrock. The contour lines delineate areas of equal depth to bedrock from the landsurface. The contour interval is not uniform (i.e., contours are at values of 25, 50, 100, 200 feet, etc.) because more detail was desired in the areas where bedrock is near the landsurface. The control for this map was provided from the outcrop map (Plate 4) and also from data from nearly 4,000 well borings, outcrop, and quarry records on file at IGS.

The mapped sinkholes occur in areas where there is a relatively thin mantle of Quaternary sediments. Analysis of Plates 1, 4, and 5 (or see Plate 6, "Potential Surface Hazard" map) revealed that over 95% of the sinkholes mapped occur in areas of less than 25 feet (7.5 m) of sediments over the bedrock, and all of the sinkholes occur within the areas of less than 50 feet (15 m) of sediment over the bedrock. Review of existing data suggests that the maximum thickness of sediments in the sinkhole areas is about 35 feet (10.5 m).

Other karst features (caves, etc.) extend into areas of thicker sediments (over 50 feet). However, if sinkholes have formed in these areas of thicker sediments, either by collapse of a cavern or by solutional widening of joints, they are not apparent at the landsurface. It is not known at this time if the thickness of Quaternary sediments has affected the development of the sinkholes or merely controls their appearance at the landsurface.

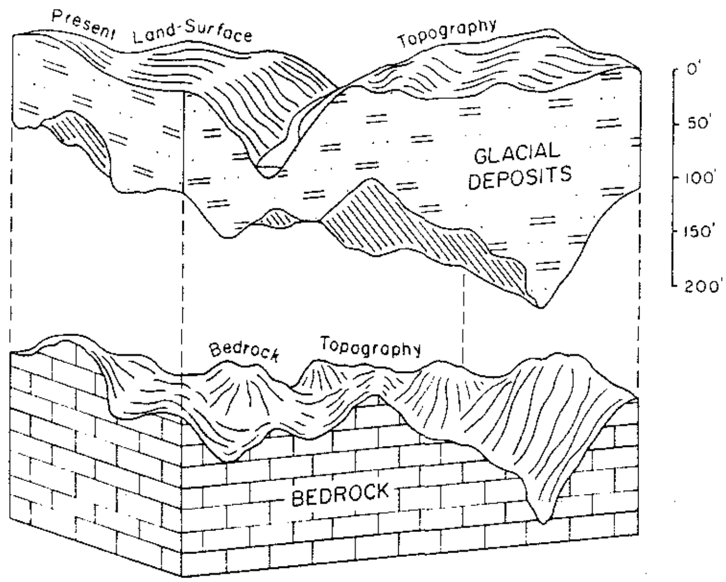

Figure 3. Block diagram illustrating the relationship between the thickness of Quaternary "soil" materials (glacial deposits) and the depth to the bedrock surface. The thickness of the glacial deposits is equivalent to the depth to the bedrock surface from the present land-surface. The relationship may be complex because the topography developed on the present land-surface may not coincide with the topography on the bedrock surface.

Although, these maps (Plates 4 and 5) were compiled for the evaluation of the karst regions, they will also provide useful information for other purposes. The thickness of sediments effects the degree of connection between the surface water and ground water. Whether sinkholes are present or not, in areas where bedrock aquifers are at or near the landsurface the aquifers are still susceptible to contamination by infiltration of surface water. Thus, it is necessary to understand the areal distribution of shallow bedrock to fully evaluate the areas where a hazard exists for surface contamination of groundwater supplies, and to be able to compare the ground-water quality data between the karst and non-karst areas. Thus, these maps may also be useful for preliminary evaluation of sites for such things as land-application of liquid wastes and landfills, which should be avoided where bedrock aquifers are near the surface (Hallberg, 1980). Karst featues have also caused a variety of problems for proper foundations for large structures among other engineering problems. The maps will give some indication of what to expect in an area so that these factors can be considered in preliminary design estimates.

All of these factors outlined contribute to the development of the groundwater flow system within the carbonate aquifers. The development of this system of solutional subsurface features in large part controls the development of the sinkholes. Some factors, such as sediment thickness over the carbonate bedrock may not influence development of sinkholes, but may only control where they appear at the land surface.

PRINCIPAL HAZARD AREAS

Based on the detailed analysis of the physical, geologic setting of the northeast Iowa karst regions an assessment can be made of the areas which have the potential for degradation of bedrock aquifer ground-water quality from surface contamination. The mapped areas of potential hazards to the bedrock aquifers are shown on Plate 6. The map was constructed from the information presented on Plate 1, the sinkhole distribution, Plate 2, the bedrock geologic map, and Plates 4 and 5, the bedrock outcrop and depth to bedrock maps.

The general hazard area, shown on Plate 6, includes several different delineations. The outer boundary line of the hazard area is marked by the contour line indicating less than 50 feet (15 m) depth to bedrock (from Plate E). The line in the interior of the hazard area delineates the area of less than 25 feet (7.5 m) depth to bedrock. The solid areas are a generalization of the areas with concentrations of sinkholes (from Plate 1). The patterned areas, labeled I, II, and III, are underlain by particular bedrock geologic units, which present unique conditions within the hazard area (generalized from Plate 2). In some areas of limited extent or control, generalizations have been made from the depth to bedrock map.

Although the delineation of these various areas are based on their physical setting, the determination of the "hazards" was an interactive process with the evaluation of the ground-water quality data. The same physical information was used to subdivide the area into 3 different geologic settings for categorizing and analyzing the ground-water quality data (which will be outlined in following sections of the report). The three settings which are used to categorize the ground-water quality samples are: 1. Karst - areas with a concentration of sinkholes, and bedrock less than 50 feet (15 m) in depth; 2. Shallow Bedrock - areas with common bedrock out-crop and bedrock generally less than 50 feet (15 m) deep, but with few or no sinkholes; 3. Deep Bedrock -areas where bedrock is generally deeper than 50 feet (15 m) below the land surface. Analysis of the ground water quality data shows that the Karst areas exhibit the highest and most significant nitrate contamination. Close behind the Karst areas are the other Shallow Bedrock regions which are delineated. The discussion of the ground-water quality data will detail the significant differences in water quality which occur between these areas.

The principal hazard areas are subdivided into a variety of regions, based on their physical setting. The primary hazard areas delineated are the regions marked by the concentrated occurrence of sinkholes. These areas are generalized from Plate 1, and outline areas where at least 2 sinkholes occur within a one-mile radius of each other. Over 95% of all the sinkholes are found in areas of less than 25 feet (7.5 m) of soil materials over the bedrock. With the limited resolution of the available regional information, the upper limit for the appearance of the sinkholes is approximately 30-35 feet (about 10 m) of sediment cover.

The areas of sinkhole concentrations and surrounding areas of shallow bedrock delineate regions where well-developed near-surface karst occurs. These areas provide the greatest potential for direct connection between surface waters and ground water in the carbonate aquifers. As an example of the potential magnitude of the problem, Aley (1977) in a study of karst-basins in Missouri estimated that 1.7 times as much water entered the karst aquifers through discrete recharge --through sinkholes, losing streams, and other soil-mantled karst features --than entered the aquifer through "normal" diffuse recharge --the slow infiltration of water through soil and rock micropores.

Whether or not sinkholes are present in areas where bedrock aquifers are at or near the land surface, the aquifers are still susceptible to contamination by infiltration of surface waters. This is again particularly true of carbonate aquifers. In these carbonate rocks, even if karst development has not proceeded to the stage of developing sinkholes, rapid infiltration of surface water can still occur along such avenues as open joints, which are moderately widened by solutional processes. Aley (1977) estimated that 5 times as much recharge to karst aquifers occurred through discrete macro-features such as these, than occurred by diffuse recharge in similar landscape settings. This potential is also illustrated by the rapid response of karst springs to rainfall events, even when no surface runoff into sinkholes or streams was observed (Thomas and Phillips, 1979). Drew (1970) showed that infiltration in this manner is much slower than through sinkholes, but may constitute significant volumes of recharge water to a carbonate aquifer. Thus, all of the areas of less than 25 feet depth to carbonate aquifers pose the next level of hazardous area shown on Plate 6.

Sandstone aquifers may also be marked by joints and fractures near the land-surface. These openings provide avenues of secondary permeability which may allow more rapid, discrete, infiltration into the aquifer, though to a lesser extent than in the carbonate aquifers. Thus, Area I on Plate 6 is delineated as another level of hazard area. This shallow bedrock region is underlain in large part by sandstones (e.g., St. Peter, Jordan) and minor carbonate (e.g., Prarie du Chien) rocks which constitute the Cambro-Ordovician aquifer. Although these rock units are not as prone to surface contamination as the fractured carbonate rocks, high nitrate concentrations are known from relatively shallow sandstone wells in the region.

The degree of hazard in shallow bedrock Areas II and III (Plate 6) is generally low, but is subject to local geologic conditions. These areas are underlain by aquicludes. Aquicludes are rock units of low hydraulic conductivity which inhibit ground-water recharge and movement, and thus are not sources of water to wells. Area II delineates the region underlain by thick remnants of the Brainard Shale Member of the Maquoketa Formation. Area III outlines the region where Upper Devonian shales and shaly limestones are at shallow depth. Locally water is produced from these formations, and locally the shales may be thin. These two shale units overlay important carbonate aquifers, the Galena and Cedar Valley respectively.

Because of the limited resolution possible in mapping the depth to bedrock, especially in matching these physical settings with the water quality data, the outer limit of the hazard area is outlined by the less than 50 feet (15 m) depth to bedrock contour. The remaining area shown on Plate 6 is marked by greater than 50 feet, depth to bedrock. Bedrock in the deepest areas is buried by nearly 500 feet of soil materials (see Plate 5). It should be noted that the analysis of the water-quality data in this report indicates that all shallow wells, regardless of the aquifer, are prone to contamination by nitrates. Thus, throughout the entire 22 county study area there is a potential hazard to shallow alluvial and drift wells as well.

For perspective, the total 22 county study area (Plate 6) constitutes about 13,400 square miles (34,700 sq. km.). The sinkhole concentration areas only constitute about 2% of this area, about 268 square miles (690 sq. km.). However, the total hazard area covers 53% of this study region, over 6,800 square miles (17,600 sq. km). Significantly, this area constitutes the principal recharge area for many of Iowa's most important bedrock aquifers.

GROUND-WATER QUALITY

Northeast Iowa is generally considered to have an abundant supply of high-quality ground water. The many rivers with their associated alluvial water sources as well as the Cambro-Ordovician and Silurian Devonian bedrock aquifers are readily accessible and are capable of providing both large volumes of and high quality of water. The Silurian-Devonian carbonate aquifer is of particular importance and is the most accessible and hence most widely used aquifer in the region. The natural water quality in the aquifer is good. The water is hard, calcium-bicarbonate type, exhibiting less than 500 mg/l total dissolved solids over most of the study area (Coble, 1969). In the south and southwestern part of the study area, some problems with higher dissolved solids, sulfates, and iron occur. These are natural problems related to changes in the aquifer. These problems increase further south and southwest from the study area.

Within the study area however, many local cases of ground-water contamination in the carbonate aquifers (both the Silurian-Devonian and the Galena) have been reported over the years. These cases have generally involved contamination with high concentrations of nitrate and/or bacteria, or specific instances involving the disposal of dead animals, animal wastes, or creamery wastes. Some of these problems have been related to known discharges into sinkholes. In other cases the causes were unknown but may have been related to poor well construction, improper well placement, local infiltration of contaminants into the aquifer, or perhaps regional contamination of the aquifer. To assess any possible management strategy aimed at protecting ground water an understanding of the local and regional water quality is necessary. It is first necessary to demonstrate whether or not regional degradation of water quality is occurring.

To address these problems several different sets of water-quality data were evaluated. Some of the data sets are regional in scope, while others are local and more detailed. In this evaluation the data were separated into various categories for comparative purposes and to isolate various separable, contributing factors. Such factors as geologic setting (karst vs. non-karst areas), aquifer, well-depth, or local environmental factors, were used where appropriate to summarize the data into meaningful groups. Research on ground-water quality often suffers from sampling problems. These include: 1. sample size, having large enough data sets to be statistically meaningful; 2. geographic distribution, having a well-distributed data set to enable regional conclusions to be drawn; and 3. sample controls, having precise information about the water source(s), the well's construction, and the well's placement. Unfortunately as the sample size increases and the distribution improves the control is decreased. Conversely as the control of individual data increases, sample size and distribution suffer dramatically.

The particular water-quality data analyzed in this study were restricted to nitrate (NO_3^-) concentration and total coliform bacteria. The review was restricted to these parameters because they are the only widely available data that are of concern for health standards that may be uniquely related to ground-water contamination from surface sources. Pesticide data could be very important, but are not readily available. Other chemical parameters, such as phosphates and chloride may also be related to surficial contamination of ground water. Data could be reviewed for these parameters also. However, very little data is available. Nitrate and bacterial analyses are routinely run because of their potential hazard to human health.

Public Health and Drinking Water Quality

Nitrates are a particular health hazard to human infants. Digestion of nitrate-rich water can cause or contribute to methemoglobinemia (Comly, 1945; Walton, 1951). A small percentage of adults from particular ethnic groups exhibit a hereditary tendency toward methemoglobinemia also (NRC, 1978).

Statistics reveal that over 2,000 cases of methemoglobinemia in infants related to water supplies have been reported in the United States since 1945. Of these cases, all but one has been reported for children using a non-community supply (Musterman, 1980). This is clearly a problem for concern in rural, private water supplies. High nitrate concentrations in water may also contribute to various health problems in livestock (Adams, et al., 1966; Seerly, et al., 1965; Hallberg, 1976).

Another potential health problem currently being studied, is the possible relationship between high nitrate water and the synthesis of nitrosamines in humans. Many nitrosamines are carcinogens. Excessive levels of nitrate in drinking water may represent a precursor to nitrosamine synthesis if conditions are appropriate (NRC, 1978). Drinking water standards currently consider nitrate levels in excess of 45 mg/l as unsafe.

Bacterial contamination is a more easily understood health problem. Pathogenic bacteria and viruses occur in runoff from animal and human waste (Morris and Johnson, 1969). Where this runoff enters a surface water supply, or seeps into a well, obvious health problems may arise. The bacteria data reported in this study are counts of total coliform bacteria derived from various methods. Coliform bacteria are not a health problem themselves, but their occurrence may indicate the presence of other bacteria, such as salmonella, which can cause health problems. Even small amounts of bacteria in drinking water are considered unsatisfactory.

Water-Quality Data Sets

Obviously, to determine the possible effects of best management practices (BMPs) on the "karst" area one must try to gain an understanding of what chemical water-quality effects are related to the "karst." This is a non-trivial problem, greatly aided by defining where the karst areas are, but hindered by the water quality data itself. To gain as complete a picture as possible several strategies were employed. Records from the University Hygienic Laboratory (UHL) were the most extensively used for regional analyses. Records from the Watstore data file were also used for this purpose. Both provide large sample sizes needed for the regional research. For the purpose of analysis the data from these sources were separated into categories by geologic setting, well depth, and water sources (aquifer) as best they could be sorted. Previously published and unpublished studies were reviewed. These studies were generally restricted to small areas but they provide controlled data necessary to isolate factors affecting ground-water quality parameters.

Various statistical and analytical methods were applied to the data. Analysis techniques varied over the course of the study because of the nature of the data sets, the purpose of the analysis, and the results of prior analyses.

University Hygienic Laboratory Data Set

The data most extensively used in this study was supplied by the University Hygienic Laboratory (UHL). These data consist of water analyses entirely from private water sources and the control on it is poor. About three-fourths of the individuals sending samples for analysis supplied well-depth information based on their records or memories. Location is known only to the resident's return postal address. No information is obtained on actual well location, construction, or production zone. Since samples are voluntarily sent in for analysis, the data are most likely biased towards lower quality water, as residents often submit samples when they suspect or know they have water quality problems. Further, residential well construction and maintenance is often not of the highest standards. An unknown but probably significant portion of analyses are submitted for precautionary reasons alone--curiosity, birth of a child, purchase of a new home, etc.

The UHL data set consists of 6039 analyses of nitrate concentration and 8130 total coliform bacterial analyses performed between January, 1977, and December, 1980, from samples from the 22 county study area. The data was previously tabulated by UHL staff. This tabulation was graciously made available to IGS.

The UHL runs nitrate analyses using the U.S. Environmental Protection Agency method 353.2 (Methods of Chemical Analysis of Water and Waste, EPA-600/4-79-020). Results are recorded as miligrams per liter (mg/l).

Total coliform bacteria are reported as a most probable number (MPN) of individuals per 100 milliliters. We have reported the results as "classes" 0, 1, 2, 3, 4 and 5. These represent the number of tubes showing a positive result for coliform bacteria as an analysis is run. These "classes" are associated with a statistical probability for the amount of coliform bacteria in

Table 1. Total coliform bacteria per 100 ml, from MPN analysis at UHL.

Class (Number of positive tests for coliform bacteria)	Most Probable Number of coliform bacteria per 100 milliliters	95% confidence interval (number of coliform bacteria)
0	<2.2	0 - 6
1	2.2	0.1 - 12.6
2	5.1	0.5 - 19.2
3	9.2	1.6 - 29.4
4	16	3.3 - 52.9
5	>16	8 - infinite

the sample. The MPN represents a mean with 95% confidence limits established. Table 1 relates the "classes" used in this analysis with the MPN and the confidence limits.

The tabulated data provided by UHL had previously been aggregated by town and county. County results are discussed later in this report. However, these county aggregates were not considered suitable for analysis of the karst problem. More precise locations were believed necessary to separate potential aquifers and compare different geologic settings.

An attempt was made to refine the locaton data. Names and mailing addresses were researched in Fayette County. This was a very slow process and proved fruitless as only about 50% of the locations could be ascertained with any degree of certainty. Finally, the analyses were compiled by sample centers. Samples centers were defined as the post office address to which the UHL analysis results were returned. Clearly this procedure has limitations. Precise geographic locations are sacrificed. Further, results could be returned to an address which does not reflect the general vicinity of the source of the water sample. The review of Fayette County suggests that this affects a minimum number of samples. However, the benefit was speed of analysis and a geographic breakdown far superior to aggregation by county.

Sample centers were assigned to geologic settings based on their locations, the expected range of geological settings the postal address might include, and the boundaries of selected geological criteria. Many subjective, professional judgements were excercised in this process. Centers located within an area where concentrations of sinkholes had been mapped were assigned to the Karst area category. Those located in areas where bedrock was mapped at depths less than 50 feet, but where concentrations of sinkholes did not exist, were assigned the Shallow Bedrock area. Sample centers located where bedrock was buried by more than 50 feet of "soil" were assigned to the Deep Bedrock category. This process took place concurrent with sinkhole mapping and depth-to-bedrock isopachous mapping. The data were aggregated into a total of 247 different sample centers. Appendix 2 associates the sample centers to the town names and assigned geologic setting.

Sample centers were also assigned to alluvial or non-alluvial classes. This was based on the center's location in relation to major stream valleys. In these areas, a significant portion of the center's analyses could be expected to be from wells finished in the river alluvium (alluvial aquifer). Note that this procedure assigned each sample center to one category in each of two groups: 1. Karst, Shallow Bedrock, or Deep Bedrock, and 2. Alluvial and Non-Alluvial.

Initially the data was handled manually. Percentages of samples from the sample centers exceeding 45 mg/l nitrate and exceeding class 0 for bacteria were compiled. These were compiled twice, for wells less than 100 feet deep and wells of all depth classes. Results of this are compiled in Appendix 3 and shown graphically in Plates 7, 8, 9 and 10.

This process was less than totally successful. As a result the data was coded and entered into the computer for selective retrieval, descriptive statistical display, and computation using the Statistical Analysis System (SAS) programs. A standard numerical place code was applied to the sample center and entered along with the geologic settings and depth classes (0-49, feet, 50-99, 100-149, 150-499, 150-499, >500, unknown). Analysis date and actual depths were not entered in order to save data entry time. The numerical place code used for each sample center is used on the plates (e.g., Plate 8) for identification. The place codes (town numbers) are related to town name of the sample centers (rural route postal station) in Appendix 3.

Although these are clearly limitations on the locatonal and geological controls of the UHL data set, the very large numbers of samples involved should overcome these problems.

WATSTORE Data File

The U.S. Geological Survey's Water Storage and Retrieval System (WATSTORE) contains over 8000 chemical analyses of Iowa ground-water. The file includes data contributed through various state and federal agencies since the 1930's, with most analyses performed by the University Hygienic Laboratory.

Control on the data is excellent and includes source of water (aquifer), geographic location, and in many cases, well construction information. Because most of the analyses came from routine sampling of public water supplies, the wells represented in the file are probably deeper, newer and better constructed than would be found in a truly random sampling of all public and private wells in the state. Thus, it is not truly representative of rural domestic water supplies.

From the WATSTORE file, there were 1331 water analyses from 387 public wells and 501 analyses from 352 private wells, for a total of 1832 records within the study area. This data was also processed using the proprietary Statistical Analysis System (SAS). Only nitrate concentrations are available from this data, because the municipal supplies are chlorinated to eliminate any bacterial problems.

Other Data Sets

Several other data sets were investigated for supplimentary and comparative purposes. Generally, these are less extensive although considerable control may exist for them. These included an unstudied compilation of water quality analyses collected in 1975 by IGS staff, a mass sampling of Mitchell County wells in 1969-70 and several published and unpublished studies.

Statistical Methods

The nitrate and coliform bacteria values do not form a normal statistical distribution. In appearance the nitrate data forms one-half a bell-shaped distribution. Frequency-distributions of the nitrate data vary in detail, depending on what subgroup is analyzed, but all have the same general appearance as that shown in figure 4, the frequency distribution for all the UHL nitrate data. In all subgroups, or categories, that the nitrate data were subdivided into the distributions all had a mode (most frequently occurring value) of less-than-detectable (zero), and as such, no analyses can occur below it. Data with skewed frequency-distributions are summarized most effectively using percentiles, including the 50th percentile or median.

Similarly, the coliform analyses are not normally distributed (figure 5). Furthermore, the bacteria data are not true numerical values, but rather only ranked probability classes.

Descriptive statistical terms used to discuss the data and to compare between groups will include percentiles, especially medians, for the nitrate data and modes and percentages for both nitrate and bacterial data.

Nonparametric statistical tests are used to make inferential interpretations of the data sets. These tests are free from assumptions of normal distributions. The two tests employed are the Kolmagorov-Smirnov two sample test and the X^2 (Chi square) K independent sample test as outlined by Siegel (1956). They are tests of "goodness-of-fit." The Kolmagorov-Smirnov Test was used to compare entire distributions, one against another, based on a null hypothesis. It answers the question--what is the probability that the two particular sample distributions compared could be drawn from the same general distribution? The X^2 test was used to determine the level of significance of differences among these groups. It compares actual occurrences against expected occurrances by testing the null hypothesis that there is no difference.

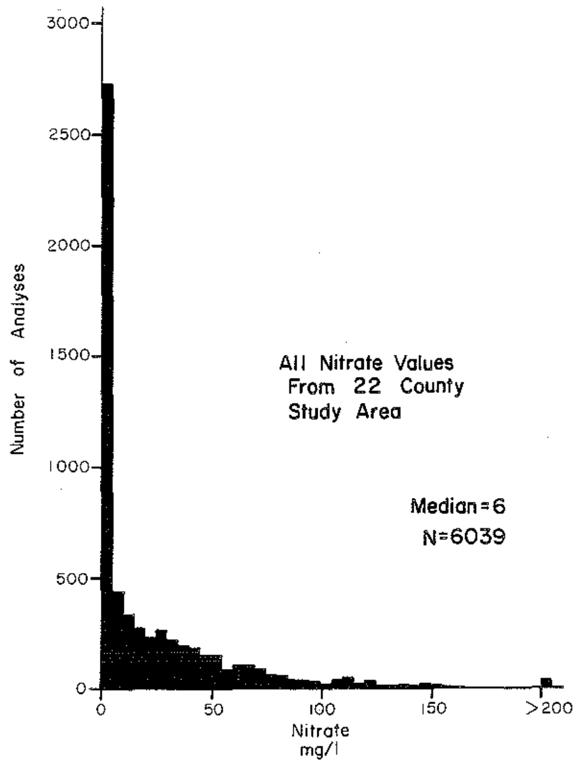

Figure 4. Frequency distribution for all the UHL nitrate analyses from the study area.

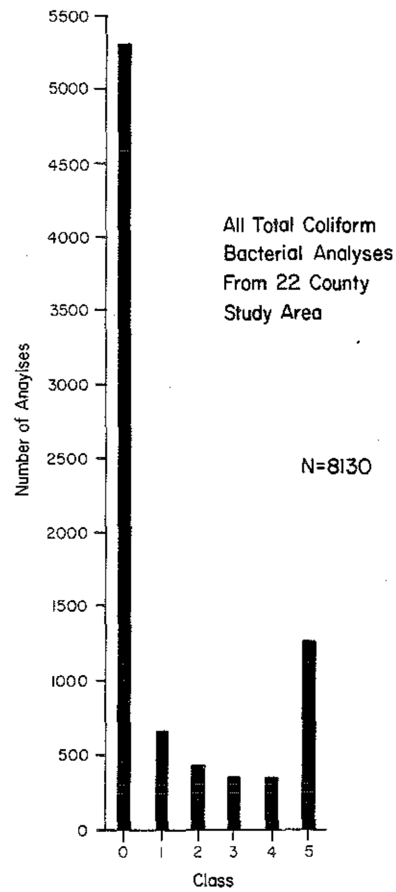

Figure 5. Frequency distribution for all the UHL coliform bacteria analyses from the study area.

Statistical evaluations compared the water quality data between or among the different geologic settings and well depth categories. The first null hypothesis tested could be stated generally as: water quality is independant of geologic setting (Karst, Shallow Bedrock, Deep Bedrock or Alluvial, Non-Alluvial). Another null hypothesis tested can be stated as: water quality is independent of well depth. Significance levels rejecting the null hypothesis are reported in the text and Appendices 4 and 5. The smaller the number, the greater the probability that the categories compared are different from each other. For the Kolmogorov-Smirnov test, significance levels are reported from >0.1 to 0.001 and the X^2 test significance levels are reported from >.99 to 0.001.

Emphasis was placed on the Kolmogorov-Smirnov test because it compared the distribution of data for one group directly against another group and, therefore, allowed interpretations to be more specific. Furthermore, it is considered a more powerful test (Siegel, 1956). It was used to compare the data between the different geologic settings and depth classes from the UHL and Watstore data sets. Therefore it was employed both on the numerical distributions of nitrate data and the probability class distributions of bacteria data.

The X^2 test was applied only to groups of data. It was used to compare among the three geologic settings according to threshold health criteria. Thus it compared, among the geologic settings, the frequency of occurrence of <45 mg/l nitrate analyses versus those >45 mg/l nitrate, and safe (Class 0) bacterial levels versus unsatisfactory and unsafe (Classes 1, 2, 3, 4 and 5) bacterial levels. It was also applied to data hand compiled early in the research where groups consisting of ranges in percentages failing these thresholds were compared among the Karst, Shallow Bedrock and Deep Bedrock regions.

Results of Analysis of Water-Quality Data

County Summary Results

Table 2 shows the county-wide totals of nitrate analyses and total coliform bacterial analyses which exceed 45 mg/l nitrate or safe bacterial levels. For the entire study area, 18% of the 6070 analyses exceeded the nitrate standard and 35% of the 8204 bacterial analyses were found unsatisfactory or unsafe. Table 2 shows that elevated levels of nitrate (above 45 mg/l) and occurrences of coliform bacteria are not uncommon. Of the counties having significant concentrations of sinkholes, Mitchell, Floyd, and Clayton Counties are above the average for the entire study area in both high nitrate and bacterial analyses. Winneshiek and Fayette Counties are above the study area average in bacterial levels, but not in nitrate, while Allamakee County is below the regional average in both. The highest county values in both water quality categories are found in counties not marked by extensive sinkhole concentrations. Butler and Jackson Counties have the highest percentage of wells with greater than 45 mg/l nitrate, while Tama and Marshall Counties have the highest percentage of unsatisfactory analyses for bacteria. Butler and Jackson Counties do have extensive Shallow Bedrock areas (Plate 6). While the counties with significant karst development generally have high percentages in the nitrate and bacteria groupings, the levels found are not consistently above the range found in non-karst areas of northeast Iowa, and on a county-wide aggregate basis, the levels are not outstanding.

Table 2 . County summary of water quality. Data was compiled from University Hygienic Laboratory analyses made from 1977-1980. Figures shown are numbers of analyses.

	Nitrates			Total Coliform Bacteria		
County	>45 mg/l	N	%>45 mg/l	Unsatisfactory or Unsafe	N	% Unsatisfactory or Unsafe
Allamakee	52	325	16	111	352	32
Benton	35	327	11	159	384	41
Black Hawk	6	68	9	28	96	29
Bremer	69	463	15	169	586	29
Buchanan	55	309	18	153	485	32
Butler	112	344	33	126	426	30
Chickasaw	37	254	15	91	338	27
Clayton	57	324	18	210	476	44
Clinton	55	377	15	154	560	28
Delaware	73	298	24	112	359	31
Dubuque	49	216	23	88	272	32
Fayette	58	469	12	233	627	37
Floyd	72	307	23	165	441	37
Grundy	20	109	18	39	113	35
Howard	25	139	18	63	190	33
Jackson	84	314	27	165	452	37
Jones	36	229	16	106	322	33
Linn	17	208	8	65	348	19
Marshall	22	137	16	100	217	46
Mitchell	49	203	24	107	262	41
Tama	25	270	9	189	388	49
Winneshiek	64	380	17	214	510	42
TOTAL AREA	1072	6070	18	2847	8204	35

Results of Area Weighted Data Analysis, Based on Health Standard Thresholds

Appendix 3 lists the sample centers and the number of analyses for each center which exceeded accepted health standards for drinking water for nitrate and bacteria. The conventional standards of greater than 45 mg/l for nitrate and unsatisfactory (Class 1) or unsafe (Class 2-5) bacterial analyses are used. The sample centers, and a summary of the data, are plotted in Plates 7, 8, 9 and 10. On all these plates each center is shown, graphically summarizing the sample number and the number of "unsafe" analyses. The data displayed on these plates is tabulated in Appendices 6 and 7, which summarize the number of sample centers having the various percentage ranges of analyses exceeding the health standards in the different geologic settings.

Review of these data indicate that bacterial contamination is common and widespread in rural areas. Twenty-eight percent of the rural sample centers have more than 50% unsafe bacterial analyses, from wells less than 100 feet deep. This shows that a serious number of private tap-water samples, derived from relatively shallow ground-water sources, exhibit bacterial contamination. Plate 9 shows that the distribution of bacterial contamination of these shallow wells is widespread throughout the study area. Even when all well depths are considered (Plate 9; Appendix 6), 17% of the sample centers still reveal over half of the analyses have elevated bacterial levels. It is interesting to note that Plate 9 suggests that the worst sample centers may be grouped into two general areas: 1. Marshall, Tama and Benton Counties where bedrock is generally deep; and 2. Winneshiek, Allamakee, Fayette and Clayton Counties where bedrock is generally shallow and sinkholes are common.

A review of Appendices 5, 6 and 7 reveal that the number and percentage of nitrate analyses exceeding health standards is significant, but less common than unsafe bacterial analyses. Inspection of Plates 7 and 8 reveals little obvious pattern to the communities having either low or high percentages of analyses exceeding 45 mg/l nitrate.

The distributions shown in Appendices 6 and 7 were submitted to X^2 analysis in order to assess if meaningful differences occurred among the three geologic settings in the percentage of analyses exceeding health standards from the sample centers. To conduct the analysis the lowest two percentage categories were combined because the number (N) in the 5-19% category for bacteria analyses and 5-9% category for nitrate analysis was low. Also, this more closely separated the percentage categories into even intervals.

Submitting this data set to statistical analysis is open to question. Using this data set for statistical analysis equalizes the sample centers and gives an area-weighted bias as opposed to a sample number bias. Some communities had many samples, others very few, but in this test each sample center had an equal status. The aggregations by percentage classes is certainly arbitrary and open to question. These were the first statistical analyses performed on the water-quality data. These analyses were done in the early phases of the research to provide some simple insights into the data.

The results of the X^2 analysis strongly suggested that the coliform bacterial content of the sampled water, especially from the shallow wells, is not distinctive among the three geologic regions. The significance levels of 0.7, derived from the comparison of samples from all wells among the three regions, and 0.98, derived from the comparison of samples from wells less than 100 feet deep, show that there is no significant difference in the coliform bacteria data among the three geologic settings.

The comparison of the differences in the nitrate data showed substantially greater statistical significance, but were still relatively low. A significance level of 0.05 was found, for the comparison of nitrate values for samples from all wells, and 0.3 for samples from wells less than 100 feet deep. For both nitrate and bacteria, the data from shallower wells showed much less significant differences than the data from all wells.

Conclusions drawn from these analyses included: 1. there were not many meaningful differences that could be found by evaluating the data in relation to a threshold value, such as the health standards; 2. the value of the individual sample analyses must be used for statistical manipulation; 3. the analysis of the distribution of the actual data would allow finer stratification of the data, and greater statistical insight (especially if entered in the computer for manipulation); 4. nitrate data seemed more strongly related to the different geologic settings; 5. bacterial data were very insensitive to geological setting; and 6. data from the shallower wells seemed particularly insensitive to differences in geological setting. With this background the UHL data was entered into the computer for further analysis.

Results of Analysis of Total Coliform Bacterial Data

A total of 8130 bacterial analyses conducted by UHL, using the MPN method, between 1977 and 1980 were entered into the computer and used for analysis. The data distribution from the entire study area were plotted earlier in figure 5. Table 3 summarizes the results by geologic setting. A complete breakdown of the data by geologic setting and well depth categories is included in Appendix 8. Note that class 0 (safe) is always the largest class, regardless of geologic setting or well depth, and always contains more than 50% of all the analyses no matter how the data is stratified. For shallow wells or deep wells, for the Karst areas or Deep Bedrock areas, for Alluvial vs. Non-Alluvial areas, the pattern of the data distribution remains the same.

Statistical Significance Levels of Total Coliform Bacterial Data

The Kolmogorov-Smirnov test was applied to many combinations of total coliform bacteria cumulative distributions. Each geologic setting was compared against each other setting, well depth class by well depth class, and in total. Further, the Karst area data was compared to all other areas (Non-Karst areas), and Alluvial to Non-Alluvial groups. Further, well depth class groups were compared against each other within a geologic setting. Appendix 5 contains the significance level of each test. For comparative purposes a X^2 test was applied among these geologic settings for limited depth classes. Table 4 summarizes the results of these procedures along with appropriate comparative results from the Kolmogorov-Smirnov tests and the area weighted X^2 analysis described earlier.

The Kolmogorov-Smirnov tests, taken as a whole (Appendix 5) reveal generally insignificant statistical differences in the total coliform bacterial data distributions. Significant differences are not found within any depth class between geologic settings, except in the 150-499 foot class. In this depth range, significant differences occur between the Karst and Shallow Bedrock (significant at .005 level) and Karst and Deep Bedrock (0.25) areas. In both comparisons the Karst region has considerably more (up to 10%) unsatisfactory and unsafe (>class 0) wells. The data in this depth class has some effect on the significance of the comparison between the total data set (all well depths) for the different geologic settings. Yet the difference between the Karst and Non-Karst (Shallow and Deep Bedrock) areas is only significant at the .025 level, and between the Karst and Shallow Bedrock areas is significant at the .005 level. Of particular importance is the generally insignificant

Table 3 . Percentage of analyses in each total coliform bacterial class for each geologic setting. Analyses were conducted between 1977 and 1980 by the University Hygienic Laboratory to which IGS is indebted for supplying the data.

Geologic Setting	Class						
	0	1	2	3	4	5	N
Karst	61.3	8.1	5.5	5.2	4.4	15.5	1440
Bedrock, shallow	66.8	7.0	4.7	3.9	3.8	13.9	3695
Bedrock, deep	64.5	7.9	4.0	3.9	3.9	15.7	2995
Total Region	65.8	7.4	4.6	4.1	4.0	14.9	8130
Karst	61.3	8.1	5.5	5.2	4.4	15.5	1440
Non-Karst	65.8	7.4	4.4	3.9	3.9	14.7	6690
"Alluvial"	66.7	6.9	4.5	4.0	3.5	14.3	4690
"Non-Alluvial"	62.7	8.3	4.6	4.3	4.5	15.6	3440

(<.1) differences found between depth classes within the same geologic setting (Appendix 5). Only in the Shallow Bedrock group were 100-149 foot wells found significantly (.001) different than other depth wells, and this group is only significantly different than the deeper wells in the Shallow Bedrock setting. In most instances the distributions of bacteria data in the different well depth classes can be considered to be drawn from one general, statistical population.

The X^2 analysis provides some contrast to the Kolmogorov-Smirnov test results (Table 4). Shallow wells clearly have insignificant (.7, .8) differences among the three geologic settings (Karst, Shallow and Deep) for occurrences of safe (Class 0) and not safe (Class 1-5) wells. Wells 50-149 feet are significantly different (.01) among regions, and by inspection the Karst area wells have much lower occurrences of safe conditions and Deep Bedrock area wells have much higher occurrences of safe condition than would be predicted by the total population. The .001 significance level of the X^2 test contrasts strongly with the levels of the Kolmogorov-Smirnov test for all well depths.

Differences found between statistical tests are not surprising, as all tests work differently, evaluate data differently and were handled by the researchers differently. It does make it more difficult to generalize, however, and more weight in interpretation is being placed on the Kolmogorov-Smirnov values because they are more specific in their comparisons. Further research on the apparent discrepancies might prove enlightening.

Table 4. Summary comparison of significance levels of three statistical tests applied to total coliform bacteria data analyzed by the University Hygienic Laboratory, 1977-1980, from the northeast Iowa study area.

	Statistical Test and Significance Level		
	Kolmogorov-Smirnov[1]	χ^2[2]	χ^2[3]
Well Depth			
<50 feet	>.1	.7	---
	>.1		
	>.1		
<100 feet	---	.8	.98
50-149 feet	>.1	.01	---
	>.1		
	>.1		
All	.005	.001	.7
	>.1		
	>.1		

1. Kolmogorov-Smirnov test compares one cumulative distribution against another. Significance levels are listed in this order: Karst versus Shallow Bedrock, Karst versus Deep Bedrock, Shallow versus Deep Bedrock.

2. Chi-square test run on all data from three groups (Karst, Shallow and Deep Bedrock) with the categories of class 0 and class >0.

3. Chi-square test conducted on data aggregated to sample centers to get an area weighted bias from three groups (Karst, Shallow and Deep Bedrock) with the categories 0-19% >class 0, 20-34% >class 0, 35-50% >class 0, and >50% >class 0.

Discussion of Bacteria Data

Contamination of rural domestic supplies is very common and widespread geographically, with nearby 35% of all analyses in the study area exhibiting elevated bacterial levels. Inconsistent and generally insignificant statistical separations were found between the geologic settings and between the well depth classes. In conclusion, it seems that the UHL total coliform bacteria data set is rather insensitive to measuring contamniation of carbonate aquifers in the Karst areas. Further, the bacteria data are rather insensitive to all geologic controls. This does not mean that bacterial data cannot be utilized in the future, and it may be useful if better control is applied to the sampling technique.

Bacteria is widely known to be filtered through soil materials. Within the Karst area, sinkholes provide common opportunities for bacteria-laden surface waters to enter the ground-water system with little or no filtration. As such, it seems conceivable that 36.5% of the water analyses from wells 100-149 feet could be contaminated. However, when 35.4% of the wells from the same depth class in the Deep Bedrock area are also found to be unsatisfactory or unsafe it seems inconceivable that the water source, or aquifer, is the problem. In the Deep Bedrock area, the water would have been filtered through at least 50 feet of Quaternary materials as well as possible bedrock. This should have removed any bacteria.

The evidence suggests that bacterial contamnation is predominantly site-specific in origin. At least, local sources of bacteria seem to overwhelm bacterial problems related to geologic setting in the data set. Contamination seems to be related to the water delivery system. The UHL data are principally "tap water" samples. The samples are generally taken from a household tap, and thus measure parameters in the entire water-system, not just from the well or the aquifer. Uncased wells, wells with faulty casing, porous water storage devices such as cisterns, cracked water pipes or incorrect sampling at the tap would result in homogenizing the data, region to region, depth class to depth class. Each could add bacteria regardless of water source used.

Inspection of the data suggests that bacterial water quality is not totally independent of well depth or geologic setting. Appendix 8 shows that deeper wells tend to be more safe than shallower wells. However, deeper wells tend to be better constructed and maintained because they are generally newer and more expensive. Local areas with prevalent nitrate problems, shown on Plate 10, in the northeast and southwest portions of the study area may be a result of local well construction/maintenance practices as well. However, there is no clear, consistent, and significant relationship between the bacterial data and geologic setting or well depth categories.

The frequency of contamination throughout the area suggests that water system problems are very common. Education of people on proper well construction and maintenance or construction standards may be necessary to counteract this widespread water system problem.

Results of Analysis of the Nitrate Data

Table 5 presents a statistical summary of the 6,039 UHL nitrate analyses which were evaluated from the study area. Appendix 9 provides a more complete presentation of the nitrate data giving the particular quantiles and quartiles for the various categories. Several pertinent trends are obvious. Median values generally decrease with increasing well depth and with changes from the Karst to the Shallow Bedrock and Deep Bedrock geologic settings. Except for minor discrepancies, especially in the wells less than 50 feet deep, nitrate values decrease at each percentile with depth and comparisons among the geologic settings reveal progressive decreases at comparable percentiles from the Karst through the Deep Bedrock regions. As the relationships are very similar, median values are presented for most discussion purposes and will be used as a measure of the difference existing among groups. The UHL nitrate concentration data was statistically tested much like the coliform data set. Geologic settings were compared in total and by depth classes using the Kolmogorov-Smirnov test. Similarly, depth classes were compared against each other within a geologic region. The data were also aggregated to compare Karst with Non-Karst and Alluvial with Non-Alluvial settings. Chi-square tests were applied for comparative purposes to selected data sets based on the health standard of 45 mg/l nitrate.

The Kolmogorov-Smirnov tests found highly significant (.001) differences in the distribution of nitrate values between each geologic setting (Appendix 4). This included comparisons of the three major regions Karst, Shallow Bedrock and Deep Bedrock as well as Karst versus Non-Karst and Alluvial versus Non-Alluvial. This is strongly supported by the X^2 test which separated the three major geologic settings at the .001 significance level (Table 6).

When the distribution of nitrate values in various well depth classes were compared between the Karst, Shallow Bedrock, and Deep Bedrock settings, significant differences were found between many distributions, but not all. Wells less than 50 feet deep have high median nitrate values (Table 5) but are inseparable or insignificantly different both by Kolmogorov-Smirnov and X^2 tests (Table 6). The distribution of nitrate values in Deep Bedrock areas separate significantly from both the Karst or Shallow Bedrock areas in all well depth categories between 50 and 499 feet, and the medians in the Deep Bedrock areas reflect considerably lower nitrate concentrations. The distributions in the Karst and Shallow Bedrock areas merge with increasing well depth, being significantly different (.001) at 50-99 feet, significant to the .1 level at 100-149 feet and there is no significant difference below 150 feet. At these greater depths, significance levels vary between groups. Wells deeper than 500 feet are not significantly different between any categories. As would be expected from this discussion, the Karst area is easily separated from the total Non-karst area in all but the <50 foot and >500 foot depth categories (Appendix 4).

Statistical evaluations of the depth classes within a particular geologic setting provides variable results. Within the Karst area, the 100-149 foot depth class contrasts strongly (.001 level) with the deeper, 150-499 foot class and the shallower 50-99 foot class (.005), but not with the 0-49 foot class (>.1; see Appendix 4). This corresponds to the median differences seen in Table 5.

Table 5 . Median nitrate values analyzed by the University Hygienic Laboratory from 22 Northeast Iowa counties between January 1977 and December 1980. Nitrate values are in milligrams per liter; number of analyses appear in parenthesis after the values along with the percentage of total N within each geologic setting. Analyses are of unsolicited samples from private wells sent in for testing.

Well Depth (feet)	Geologic Setting: Karst	Shallow Bedrock	Deep Bedrock	Total
0-49	28(61-6%)	26(216-8%)	33(316-14%)	28(593)
50-99	34(214-19%)	19(407-15%)	6(371-17%)	18(992)
100-149	23(271-25%)	16(435-16%)	0(375-17%)	7(1081)
150-499	3(349-32%)	5(786-29%)	0(591-27%)	0(1726)
>500	0(14-1%)	0(71-3%)	0(40-2%)	0(125)
UNKNOWN	22(195-18%)	7(803-30%)	0(524-24%)	5(1522)
Total	19(1104)	9(2718)	0(2217)	6(6039)

The break from a median of 23 (100-149') to 3 mg/l (150-499') is especially noticeable. In the Shallow Bedrock region, the 100-149 foot well depth group is inseparable from that above it (50-99 feet) as reflected by the similar medians (16 versus 19 mg/l) but contrasts significantly (.001) with the deeper well group (150-499 feet) which has a much lower median nitrate value (5 mg/l). In the Deep Bedrock region, significant changes are found between the more shallow well depth classes as reflected by the sharp decrease in median nitrate values.

Alluvial and Non-Alluvial areas are significantly differentiated down to 150 feet (Appendix 4). Alluvial areas reflect higher nitrate levels in general than Non-Alluvial areas (Table 7). Only in the 0-49 foot class is this reversed. This probably reflects the strong bias of the Alluvial class to large alluvial sources and the Non-Alluvial class to small alluvial sources. Most sample centers designated as Alluvial are located along major rivers. The Non-Alluvial class generally comes from upland positions of the landscape. As noted previously both these classes include sample centers which are also classed as Karst, Shallow Bedrock, and Deep Bedrock geologic settings. With lack of accurate well control for the samples this comparison is difficult to interpret.

Discussion of Nitrate Data

The nitrate distribution data provide a sharp contrast to the bacterial distributions as they seem to reflect geologic controls quite strongly. Systematic variations are found both between geological settings and with well depth. The one notable exception is in the very shallow well depth group (0-49 feet).

These shallow wells consistently have the highest level of nitrates for a particular well depth class. This 0-49 foot well depth class represents its own

Table 6. Summary comparison of significance levels of three statistical tests applied to nitrate data analyzed by the University Hygienic Laboratory, 1977-1980, from the northeast Iowa study area.

	Statistical Test and Significance Level		
Well Depth	Kolmogorov-Smirnov[1]	χ^2[2]	χ^2[3]
<50 feet	>.1	.05	---
	>.1		
	.025		
<100 feet	---	.01	.3
50-149 feet	.001	.001	---
	.001		
	.001		
All	.001	.001	.05
	.001		
	.001		

1. Kolmogorov-Smirnov test compares one cumulative distribution against another. Significance levels are listed in this order: Karst versus Shallow Bedrock, Karst versus Deep Bedrock, Shallow versus Deep Bedrock.

2. Chi-square test run on all data from three groups (Karst, Shallow and Deep Bedrock) with the categories of <45 mg/l and class >45 mg/l.

3. Chi-square test conducted on data aggregated to sample centers to get an area weighted bias from three groups (Karst, Shallow and Deep Bedrock) with the categories 0-9% >45 mg/l, 10-19% >45 mg/l, 20-29% >45 mg/l, and >29% 45 mg/l.

Table 7. Median nitrate values from the entire 22 county study area data set. Data was obtained from the University Hygienic Laboratory between 1977 and 1980. As the actual ground-water sources are unknown for the samples, the data set was forced in a classification of "alluvial" and "non-alluvial" based on the sample center's proximity to major alluvial water sources. Thus, the median values represent greater ("alluvial") and lesser ("non-alluvial") potentials for significant influence by major alluvial aquifers. Medians are reported in milligrams per liter.

Well Depth (feet)	"Alluvial"	"Nonalluvial"
0-49	21(329-10%)	40(264-10%)
50-99	25(571-17%)	9(421-16%)
100-149	14(627-18%)	0(454-17%)
150-499	0(905-27%)	0(821-31%)
500	0(63-2%)	0(62-2%)
UNKNOWN	7(897-26%)	0(625-24%)
Total	9(3392)	3(2647)

group of data; statistical tests found no significant differences, between the different geologic settings (Karst, Shallow Bedrock, and Deep Bedrock), in this depth range. The data distribution (figure 6) of this depth class shows considerable spread toward higher nitrate values (compare with figure 4). This well depth class would contain samples from a variety of aquifers, from shallow alluvial to shallow bedrock sources. As an example of the complications in this depth class, note that the highest median nitrate value on Table 5 in the 0-49 foot depth class is 33 mg/l. This value occurs in the Deep Bedrock area. However, in the Deep Bedrock area bedrock is greater than 50 feet in depth from the land surface. Thus, the shallow wells in this area must be either alluvial wells or shallow drift wells. These statistics indicate that shallow wells are showing high nitrate concentrations regardless of the aquifer or geologic setting involved. Analysis of Watstore data from all over Iowa also indicates that the highest nitrates are found in these very shallow well, regardless of the aquifer or geologic setting involved. Thus, these shallow wells are not included in the further discussion and comparison of the Karst, Shallow Bedrock, and Deep Bedrock areas.

An attempt was made to further evaluate this problem by grossly classifying the sample centers into "Alluvial" and "Non-Alluvial" groups. As previously described this is not a "clean" separation, but the Alluvial sample centers would clearly include water samples from shallow wells in major alluvial aquifers, whereas shallow wells in the "Non-Alluvial" group would include wells from small alluvial systems, drift wells, as well as bedrock wells. As shown on Table 7 the median nitrate concentration (40 mg/l) for the "Non-Alluvial" group is nearly twice the value as the "Alluvial" group. The meaning of this is not entirely clear, it may suggest that shallow bedrock, drift, and alluvial wells from small alluvial aquifers have higher nitrate levels

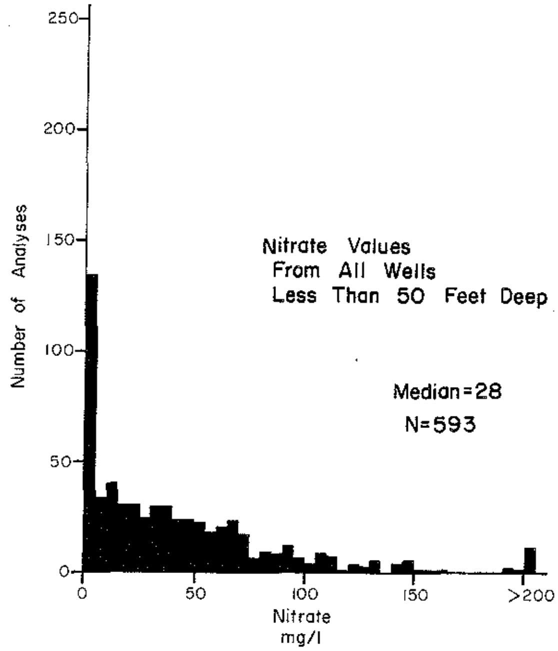

Figure 6. Frequency distribution of nitrate analyses for UHL samples from wells less than 50 feet deep.

than wells in large alluvial systems. However, the control of potential water sources of this data aggregation is too poor to allow any definitive statement.

One other general, but very important feature of the distribution of the nitrate data must be reviewed. The modal value, or concentration, of the nitrate analyses from any geologic setting, or any depth class is zero (less than detectable). This is illustrated in figures 4 and 6 for the entire data set and for the shallow wells (see figure 7 also). This indicates that the natural background level of nitrate is very low (essentially zero) throughout the region, in all the aquifers. Also, nitrate levels systematically decrease with increasing well depth. Coupled with the low background level the direction of increasing concentrations should reflect the source of the nitrate. This data clearly suggests that the source of the nitrate is the land surface.

The nitrate data that describes the effects of the Karst areas are found in the deeper than 50 foot well depth classes from the various geologic settings. Medium nitrate values from regions where bedrock is buried by more than fifty feet of "soil materials" are substantially lower than nitrate values where there is less than fifty feet to bedrock (Karst and Shallow Bedrock). The median nitrate value for the entire Deep Bedrock area (aggregating all well-depth classes) is zero. The greater thickness of Quaternary "soil-materials" over the bedrock seems to have a significant effect on water-quality, by preventing much interaction with surface water either through diffuse infiltration through the soil or by direct interaction, such as where surface water may enter sinkholes in the Karst areas.

The Karst regions clearly exhibit significantly higher concentrations than the other geologic settings (Table 5). A comparison of the median nitrate concentrations, summarized in Table 8, shows how strong a contrast there is between the Karst and Non-Karst areas. Statistically this regional difference is significant at the .001 level, for all well depth classes between 50 and 499 feet (Appendix 4).

Both the Karst and Shallow Bedrock areas exhibit high nitrate concentrations in the 50-149 foot depth range, and these concentrations are much greater than in the Deep Bedrock area (Table 5). These differences which separate the Karst, Shallow Bedrock, and Deep Bedrock regions in the 50-149 foot depth range are highly significant (Table 6).

These high median nitrate values found from 50-149 feet in the Karst and Shallow Bedrock regions decline markedly with greater depth (150-499 feet). Yet their nitrate concentration in the 150 to 499 foot depth range (medians of 3 and 5 mg/l) is still greater than in the Deep Bedrock region (0 mg/l; Table 5). In this depth range there is no significant difference (>.1) between the Karst and Shallow Bedrock areas, yet the distribution of nitrate values in both areas is significantly different (.001) from the Deep Bedrock region (Appendix 4). Thus, while the Karst area is substantially different from the Non-Karst area, perhaps the largest difference is between the Karst-Shallow Bedrock areas versus the Deep Bedrock areas.

This difference can be seen graphically in Figure 7. It shows the general trend of decreasing nitrate concentration from the Karst to the Shallow Bedrock to the Deep Bedrock regions. Note that while the mode of the data remains at zero it increases in magnitude (number of analyses) toward the Deep Bedrock regions. Conversely, these graphic distributions also show the increasing spread of the data towards more frequent, higher nitrate concentrations towards the Karst areas. The median nitrate values describe this difference most clearly. The major difference between the Karst-Shallow Bedrock areas and the Deep Bedrock areas is in the greater thickness of Quaternary "soil materials" overlying (and protecting) the bedrock aquifers.

The various Karst areas do exhibit greater nitrate levels than in surrounding areas classified as Shallow Bedrock (Table 5). This difference would seem to be the effect of the sinkholes in the Karst regions. The differences between these regions in different well depth classes provides some additional insight. The difference between the Karst and Shallow Bedrock nitrate distribution in the 50-99 foot depth class is highly significant (.001); their difference in the 100-149 foot depth class is weakly significant (.1); and there is no significant difference (>.1) below this depth (Appendix 4). Several inferences can be made from this data.

These data suggest that the influence of karst development on ground-water quality in the carbonate aquifers is only significant to rather shallow depths, 100 to 150 feet at most. A measure of the relative importance of karst development and sinkholes may be the significantly higher median nitrate concentrations in Karst areas versus the Shallow Bedrock areas.

Below 100 feet there is little or no significant difference in the nitrate concentrations between the Karst and Shallow Bedrock areas. Both areas show significantly higher nitrates compared to the Deep Bedrock regions through the

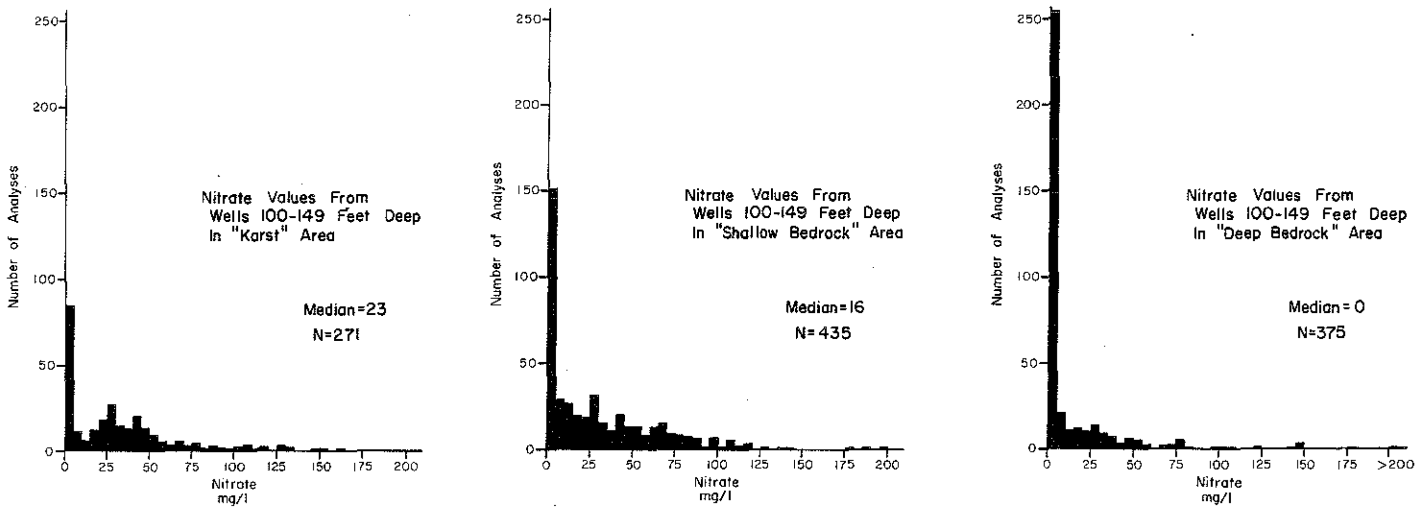

Figure 7. Frequency distribution of nitrate analyses for UHL samples from the 100-149 foot well-depth class from the Karst, Shallow Bedrock and Deep Bedrock regions.

150-499 foot depth range, although the greatest differences occur in the 50-149 foot depth range. These higher nitrates in the Shallow Bedrock region likely result from diffuse infiltration from the land surface into the aquifer, conducted along solutional conduits, which are more poorly developed than in the Karst areas. Some of the water, especially at depth, may also reflect lateral transport through the aquifer. This same diffuse infiltration also takes place in the Karst areas; the major difference in the two areas is that the Karst areas, locally, have better solutional conduits and sinkholes. The data analyzed for this project suggests that the effect on ground-water quality of this increased karst development may be limited to depths of about 100 feet, or at most 150 feet. The contributions of sinkholes to nitrate contamination in the carbonate aquifers, by inference, may be indicated by the significant difference in median nitrate content between the Karst areas (34 mg/l) and the Shallow Bedrock areas (19 mg/l) in the 50-99 foot depth range.

This discussion also emphasizes why the entire area of less than 50 feet depth to bedrock (Karst and Shallow Bedrock regions) is mapped as the area of "Potential Surface Hazards to Bedrock Aquifers," on Plate 6. As described by the nitrate data the Karst area is more prone to surficial contamination, but it is followed closely behind by the Shallow Bedrock region. These conclusions are graphically summarized on Plate 11.

Plate 11 shows the total "hazard" area (in white) in relation to a summary of the median nitrate concentrations, for all the sample centers, for samples from the critical 50 to 149 foot depth range. It is visually apparent that the great majority (about 80%) of the sample centers, with medians greater than 20 mg/l nitrate, occur within the hazard area. The remaining sites (about 20%) were classified as Deep Bedrock sample centers, but half of those occur on the very border of the hazard area. These sites were classified conservatively, before the analysis of the water quality data, and very likely

Table 8. Median nitrate values compared between the Karst and the Non-Karst (Shallow and Deep Bedrock) areas in the 22 county study area. Data was obtained from analyses performed at the University Hygienic Laboratory between 1977 and 1980. The number of analyses is indicated in parentheses.

Well Depth (feet)	Karst Area	Non-Karst Area (Shallow and Deep Bedrock)
50 - 99	34 (214)	13 (788)
100 - 149	23 (271)	1 (811)
150 - 499	3 (349)	0 (1377)
>500	0 (14)	0 (111)
All known well depths	18 (848)	0 (3077)

include Shallow Bedrock samples, in a strict sense. The number of Karst and Shallow Bedrock sample centers is about equally divided. This should emphasize that whatever management strategies may be developed to protect ground water in this region, must consider the extensive Shallow Bedrock regions as well as the Karst areas (in the strict sense of this report).

Comparison of Water Quality in Different Karst Areas

Using the UHL data a comparison was made between the different karst terrains to see if any significant differences occurred. The data from the Floyd and Mitchell County karst areas, formed on Devonian rocks in a low-relief landscape, were compared to data from the karst areas in Clayton, Allamakee and Winneshiek Counties, where the karst features are formed in the Galena and Silurian rocks in a high-relief landscape. The results are tabulated in Table 9. In the 100 to 499 foot well-depth ranges the median values differ substantially. This suggests that there may be distinct differences in the hydrology between the two Karst areas. Statistical tests are impractical because of the low number of analyses in some of the well-depth groups. Kolmogorov-Smirnov tests were run comparing the total nitrate distribution between the two areas. No significant difference was found. However, the substantial differences in the medians in the different depth ranges suggest that nitrate contamination is extending to greater depth in the high-relief Galena karst areas in particular.

Land-use trends in the two areas are similar. Figure 8 shows the increase in acreage of row-crops on soils where the carbonate rocks are within 5 feet of the land surface. These would be the most critical areas where nitrate fertilizers could easily leach into the fractured limestone or runoff into sinkholes. Both the actual acreage and the trends are very similar for Mitchell and Clayton Counties. This suggests that possibly some difference in the ground-water hydrology may be allowing the greater depth penetration of nitrates in the Galena karst region.

Table 9. Comparison of median nitrate values from different karst terrains, tabulated by well depth categories.

	Floyd-Mitchell Counties		Clayton-Allamakee-Winnesheik Counties	
Well Depth	Median Nitrate mg/l	Number of Wells	Median Nitrate mg/l	Number of Wells
(<50)	(11)	(10)	(38)	(4)
50-99	26	43	30	29
100-149	3	30	21	20
150-499	0	45	13	107
>500	--	--	0	8
Unknown	1	26	13	6
TOTAL	19	154	16	196

Most of the Floyd-Mitchell county sinkholes are located in a low-relief landscape near the point of bedrock aquifer discharge to the Cedar River. The sinkholes in the Galena aquifer of Clayton, Allamakee and Winneshiek Counties occur in an upland between the Upper Iowa and the Turkey rivers. Discharge to these streams are relatively far from the surface recharge areas and the surficial nitrate may be moving much more deeply into the aquifer.

This interpretation must be used with some caution. The high levels of nitrate found in the area of the Galena aquifer for the 100-149 foot well depth group are not in excess of nitrate levels found throughout the Karst region as a whole in the study area. They are not even much higher than levels found in the Shallow Bedrock regions. Rather, the Floyd-Mitchell values are comparatively quite low. However, the high nitrate values in the 150-499 foot class in Clayton, Allamakee and Winneshiek Counties are very high.

It would be important to see at what depth within this range the values decrease substantially. Wells from the St. Peter Sandstone aquifer would be within this depth range at about 400 feet. The large number of samples from this rather deep well-depth class, is also unusual compared to the number of samples typically in this depth class in other distributions. IGS records and experience in the region suggest that the samples from this depth range would be a composite of deep penetration Galena wells, and deeper wells finished in the St. Peter. The high nitrate values may result from two related reasons: 1. deeper than typical nitrate contamination in the Galena-carbonate aquifer; and 2. higher than typical nitrate values in the comparatively deep St. Peter wells. As will be described, Tjostem and others (1977), show evidence for nitrate contamination in St. Peter wells where the Galena aquifer has not been cased off in the well. This issue requires some further research.

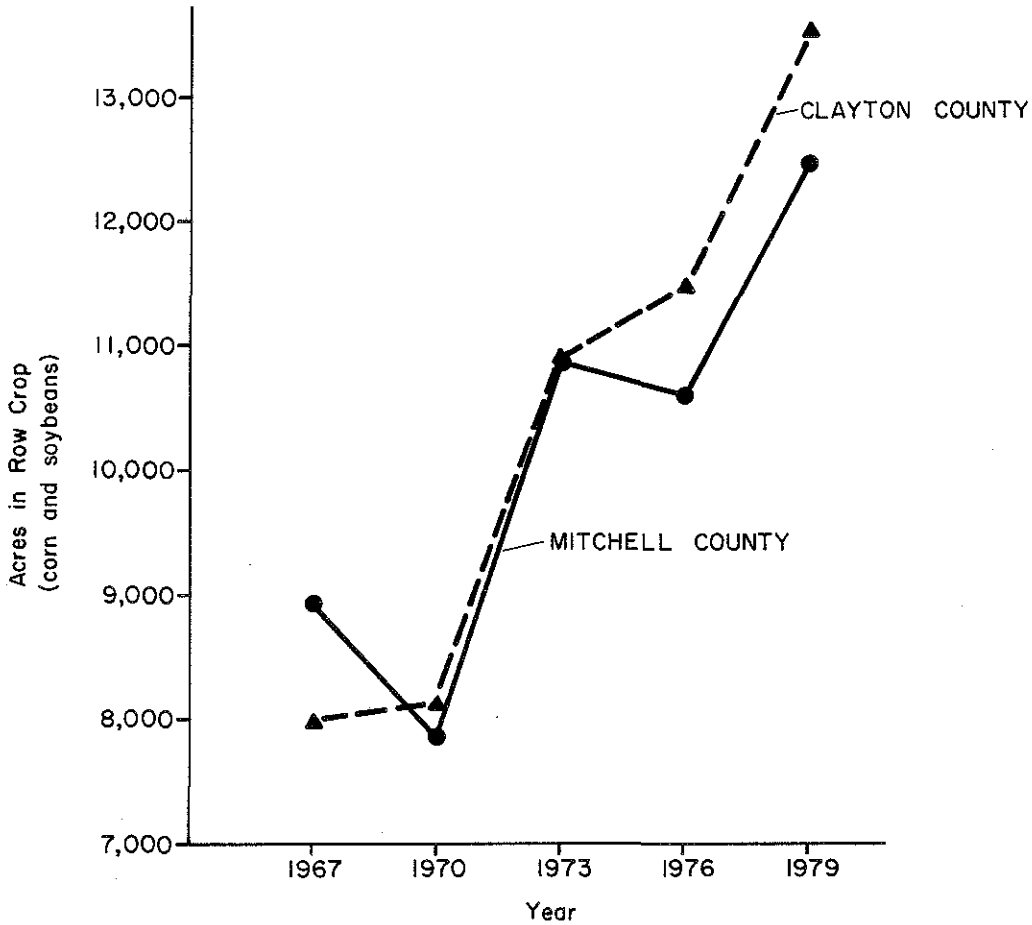

Figure 8. Increase in row-crop acreage on soils with less than 5 feet of surficial sediments over carbonate rocks in Mitchell and Clayton Counties (from unpublished data provided by G. A. Miller, Iowa State University).

Water Quality Variation Within an Aquifer

A substantial problem of using the UHL data set is the lack of control on the exact water source for the samples. The vague locations and no knowledge of the well construction are problematic enough, but in some depth categories, in some areas, there are a range of aquifers which could be the source of the water. The very large number of samples help to overcome these problems. However, because of these concerns, the Watstore file was used to see if the conclusions derived from the UHL data could be substantiated from a data set with much better geologic control.

Data from the Cedar Valley (Devonian) aquifer were used because there were a substantial number of water-quality analyses from both Karst and Non-Karst regions. In the Karst areas, from 155 samples from Cedar Valley wells less than 300 feet deep, 37% of the samples had detectable levels of nitrate. In the

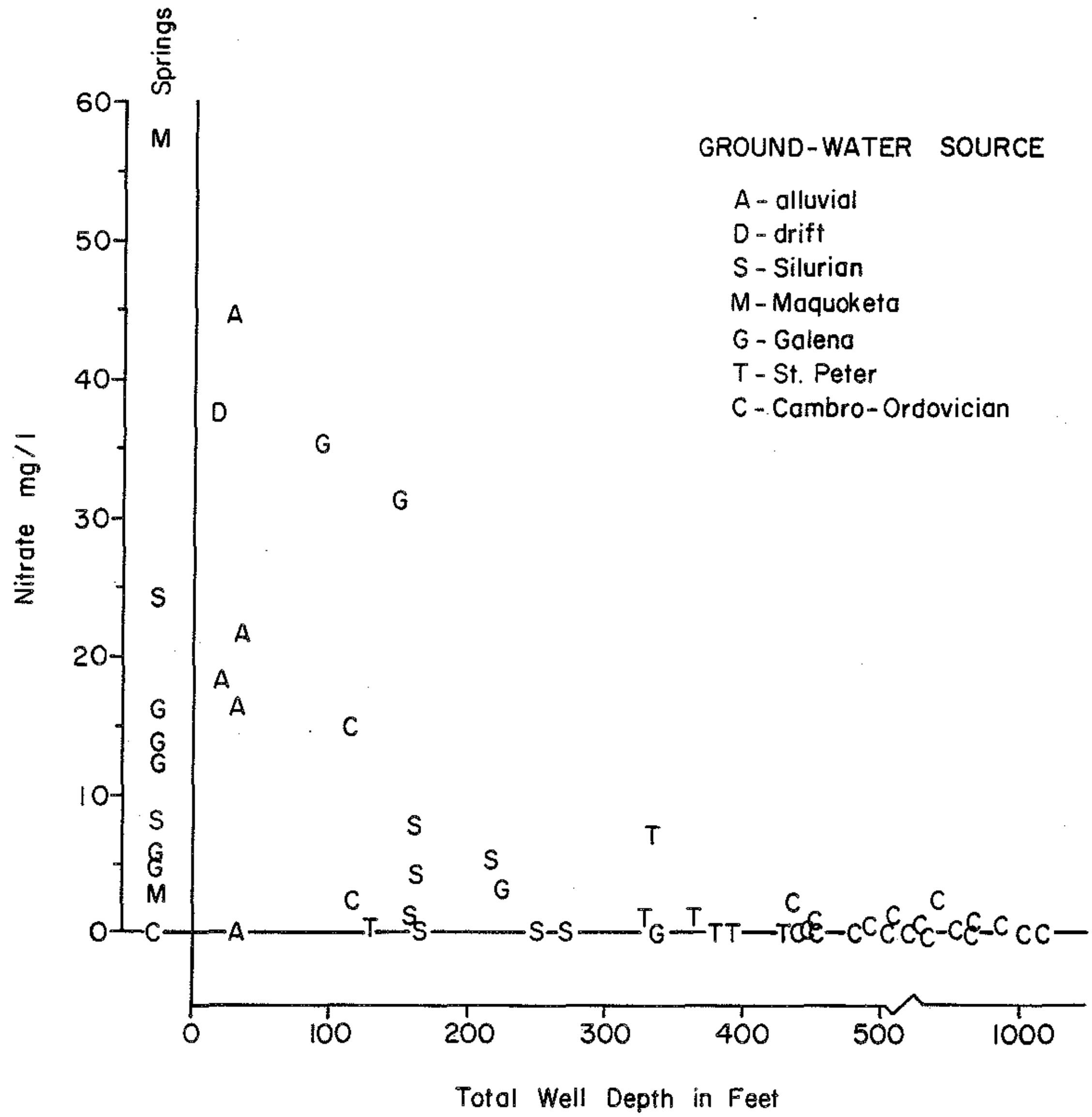

Figure 9. Nitrate concentration versus well depth for different aquifers in Clayton County (data from Steinhilber, et al., 1961).

Non-Karst area 23% of the 98 analyses had detectable levels. More significantly, in the Karst area 15% of the samples were in excess of 15 mg/l nitrate, whereas in the Non-Karst areas only 2% of the samples exceeded this limit. The 15 mg/l value was used as an arbitrary threshold for comparison, because 98% of the Non-Karst area samples fell below this value. There is a clear indication that the Non-Karst areas had less common elevated nitrate levels than the Karst areas. This is consistent with the findings from the UHL data set; the Karst areas have higher levels of nitrate in the ground water in the carbonate aquifers.

Another small set of water quality data, with good geologic control shows similar results. Figure 9 summarizes data on nitrate concentrations plotted versus well depth, for 62 water samples from Clayton County, from a variety of aquifers. The data is from a published report on the water resources of Clayton County (Steinhilber, et al., 1961). Some of the data were collected as early as 1934 but the majority of the samples were collected between 1950 and 1954, during field work for the published report. Figure 9 shows the same inverse relationship between nitrate concentration and well depth as the other data sets. Even when all the samples from different aquifers are lumped together, this trend is apparent. The highest nitrate values recorded are from alluvial wells, a "drift" well, and from wells or springs in the Karst formations, the Silurian, Galena, and Maquoketa rocks.

Temporal Variations in Water Quality

Short-Term Variations

One problem that arises in the analysis of the water quality data is that nitrate and coliform concentrations in ground water may fluctuate seasonally (Singh and Sekhon, 1978). This is particularly true where the nitrate is derived from surficial sources (Ayers and Branson, 1973; Piskin, 1973; Walker, 1973). An example of seasonal fluctuations is shown in figure 10, from water samples taken from a well in the Karst area of Winneshiek County (Tjostem, et al., 1977). The extreme changes in the coliform bacteria counts also point out the limitations of a single analyses of water from a site, and highlights the problem of analyzing (and drawing conclusions from) the coliform data in the regional data sets.

Another example of how this may effect the data analysis is shown in figure 11. Figure 11 shows a plot of the percentage of well water samples containing greater than 45 mg/l nitrate, summarized by month from the Watstore data. There is a significantly different peak in high nitrate analyses in the April through June period. These seasonal fluctuations may affect the conclusions that can be drawn from data that is seasonally restricted. It would be informative to study how these fluctuations vary, or whether or not they occur, in wells of different depths, and in different hydrogeologic settings. Water sources which show such fluctuations must be intimately associated with surface activities, either because of the nature of the aquifer or from problems with the individual water system.

These short term variations may create problems for interpreting some data sets. The UHL data however, is derived from all seasons of the year and the large sample numbers should integrate these effects.

Long-Term Trends

The Watstore data includes water-quality analyses dating back to the 1930's. This data was also analyzed for any trends over time from the 1930's to the present. However, it is difficult to find any consistent trends by analysis of data from individual wells. Figure 12 summarizes the data from

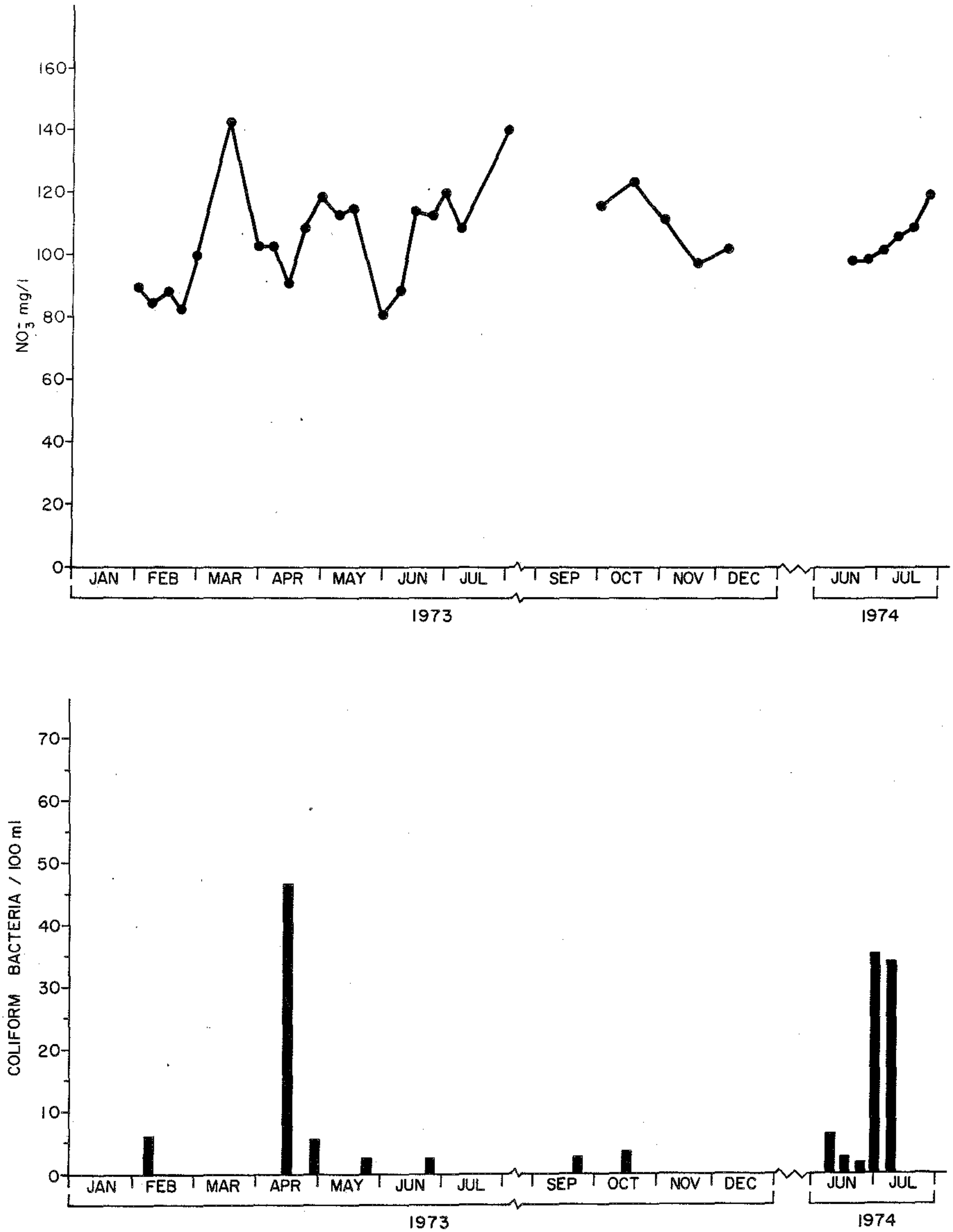

Figure 10. Variation of nitrate concentration and counts of coliform bacteria over time for a well in Winneshiek County (from Tjostem, et al., 1977).

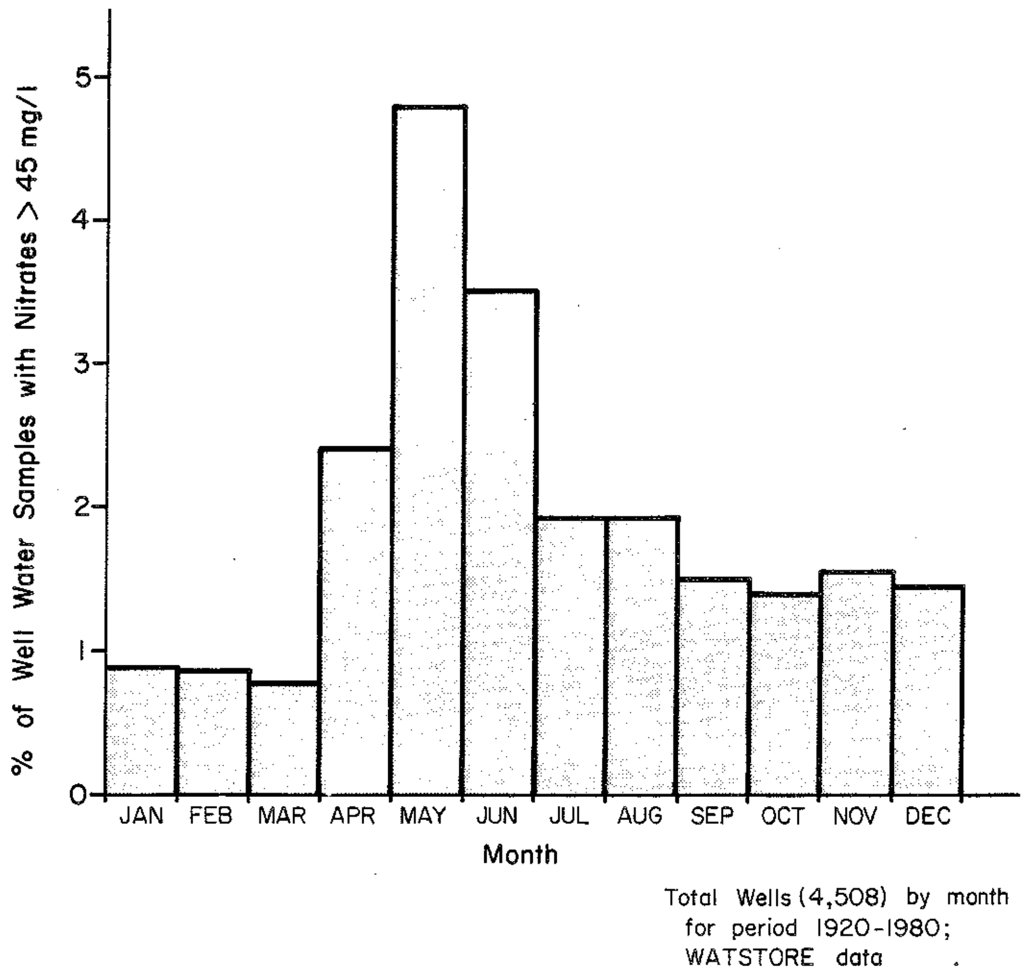

Figure 11. Histogram showing the seasonal variations in the percentage of well water samples exceeding 45 mg/l nitrate, from the Watstore file.

four wells over time, to illustrate the variations present in the data. All the wells are from the Devonian and Silurian carbonate aquifers of the various Karst areas. Obviously, there is no consistent trend apparent. Well C shows a substantial increase in nitrate in the 1960's and 1970's; well 2 shows a dramatic decrease at this same period of time. Both wells are from the same well field near Clarksville in Butler county. One interesting point is that a well at Janesville (figure 12, v) shows the same magnitude of nitrate concentration in 1934 as it does in the 1970's. Unfortunately, no single well has enough data over this time span to sort out the effects of seasonal variations, and little can be concluded from the scant data from these individual sites.

Table 10. Median nitrate concentration by decade, for water samples submitted during April through June, from wells less than 150 feet deep, from WATSTORE data.

Decade	Median Nitrate mg/l	N
1930s	1.8	15
1940s	7.1	18
1950s	3.3	21
1960s	24.5	76
1970s	14.0	3

Statewide data in the Watstore file were used to compute yearly and 10-year median nitrate concentrations. Again, no obvious temporal trend was apparent. However, using segregated data from the Watstore file some temporal trends can be seen. As discussed, nitrate contamination is principally a problem of shallow wells. Also, as shown, high nitrates principally show up in late spring samples (see figure 11). Thus, to see if any trend was apparent with time, median nitrate concentrations were calculated for samples taken in April through June from wells which were less than 150 feet deep. Median values computed by decade are shown in Table 10. The data are summarized by decade because there are not enough samples on a yearly basis to be meaningful. Although, the significance of 10-year median values may be questioned, an apparent trend with time is suggested. There is an order of magnitude increase in the median nitrate concentrations in the 1960's and 1970's. The timing of this increase coincides with the 6 to 8 fold increase in the use of chemical nitrogen fertilizers which took place in the 1960's (Harmon and Duncan, 1978).

One of the few opportunities to compare larger data sets over time is provided by data from a mass water-testing program conducted in Mitchell County. In 1969 a program of testing water from private wells was begun to ascertain the presence of pollutants in the area. It was directed by Mr. Edgar Dorow, County Extension Director, Iowa State University, Cooperative Extension Service. 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. The data or results were never published but were summarized on mimeographed sheets which were distributed. The summaries compared test results to U.S. Public Health Service (U.S.P.H.S.) standards of 0 colonies of coliform bacteria/100 ml, and 10 ppm nitrate-N (45 mg/l nitrate).

In the Mitchell County program a total of 434 water samples, from 420 wells, were tested during October and November of 1969, and January of 1970. The samples were collected from throughout the County. Of these 434 samples, 35% (153 failed to meet U.S.P.H.S. bacteria standards, and 22% (96) failed to meet U.S.P.H.S. nitrate standards. Combining the results 45% (197) of the samples failed to meet U.S.P.H.S. standards for bacteria <u>and/or</u> nitrate.

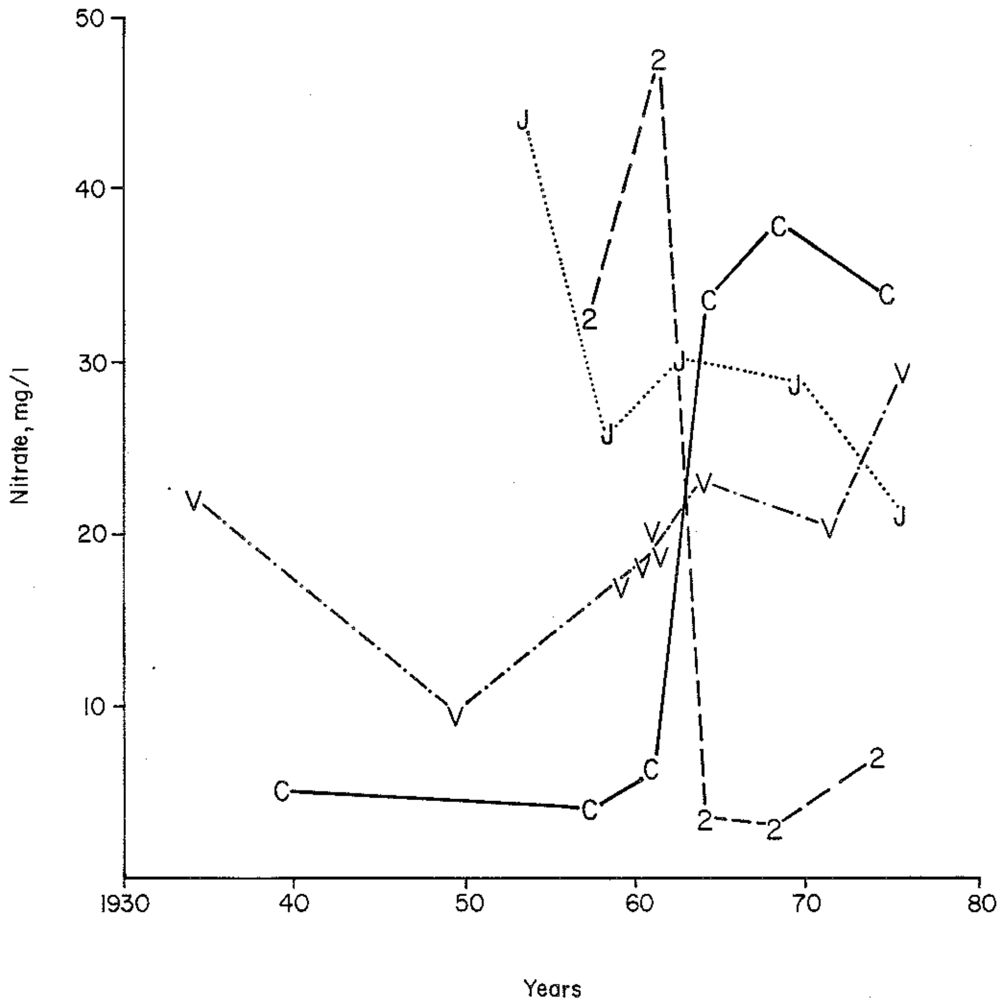

Figure 12. Nitrate concentration versus time for selected municipal wells with long periods of record, from the Watstore file. All wells are finished in the Silurian-Devonian carbonate aquifer. There is no clear temporal trend apparent from such data.

The data was also summarized geographically in relation to the "sinkhole area" in the central and western portions of Mitchell County. Approximately 247 wells were sampled in the sinkhole area and 173 wells outside of the sinkhole area. In the sinkhole area 28% (70) of the wells exceeded 45 mg/l nitrate, but outside of the sinkhole area only 10% (18) of the wells exceeded this limit. Also, nearly half of the wells exceeding the limit outside of the sinkhole area were thought to be contaminated because they were shallow sand-point wells associated with turkey feeding operations.

Within the sinkhole area 39% (97) of the wells failed the U.S.P.H.S. standards for coliform bacteria. Outside of the sinkhole area 30% (50) exceeded the bacteria standard.

In this study local environmental factors were also associated with poor water quality. The wells which failed to meet U.S.P.H.S. standards were, on the average, more shallow, had less depth of casing, and were older than wells that passed U.S.P.H.S. standards. Also, 57% of the wells that had pits around the well head failed to meet the U.S.P.H.S. criteria.

A review of UHL data from 1971 through 1980 shows that little has changed in the seven to eleven year period since the Mitchell County study. Slight increases in the percentages of analyses exceeding standards were identified: for nitrate 24% (1977-80) versus 22% (1969-70) and for coliform bacteria 41% (1977-80) versus 35% (1969-70). No significant trend can be postulated for these small changes, however, as the early study was conducted by canvass methods during fall and winter, and the UHL data came from people who wanted their water tested and includes samples from all seasons of the year.

Few firm conclusions about long-term trends in ground-water quality can be made from the existing data in Iowa. This is an important issue, which must be remedied so that data is available in the future to assess such changes. Sample analyses by UHL should be stored and maintained for future comparative purposes. Mechanisms to accomplish this should be developed. But further, a statewide network of water quality monitoring must be established and maintained so that controlled data can be obtained for analyses. This should include such things as "nested" wells in the carbonate aquifers, so that monitoring at different depths may be accomplished. The apparent drop of nitrate levels in the 150 foot depth range in the Karst and Shallow Bedrock areas is an example of a phenomena which should be monitored. Is this a function of the hydrologic system which keeps the deeper portions of the aquifer less contaminated with nitrate, or is it only a matter of time until nitrates reach these depths? There are many such important questions which cannot be answered at this time.

Local Environmental Effects on Water Quality

Many investigations have documented the contamination of shallow ground water by nitrates from surficial sources such as human and animal sewage and chemical fertilizers (Singh and Sekon, 1978; Piskin, 1973). Several detailed studies have also shown that the actual nitrate concentrations recorded in a given area vary directly with local land use practices, which are sources of nitrate, such as proximity to feedlots or sewage disposal systems (Walker, 1973; Aulenbach, 1974), differences in cropping patterns (Viets, 1971; Steward, et al., 1968), and/or differences in amounts of N-fertilizer used (Singh and Sekon, 1976; Peele and Gillingham, 1972; Nightingale, 1972; Olsen, et al., 1970).

Some of these studies indicate or imply that the concentration of nitrate from a given well is a function of well placement and/or design in relation to land-use (e.g., Walker, 1973). Some data from Iowa also provide insight into this aspect of the problem.

Tjostem and others' (1977) study of wells and ground water in the karst area of Winneshiek and Allamakee Counties provide several interesting observations.

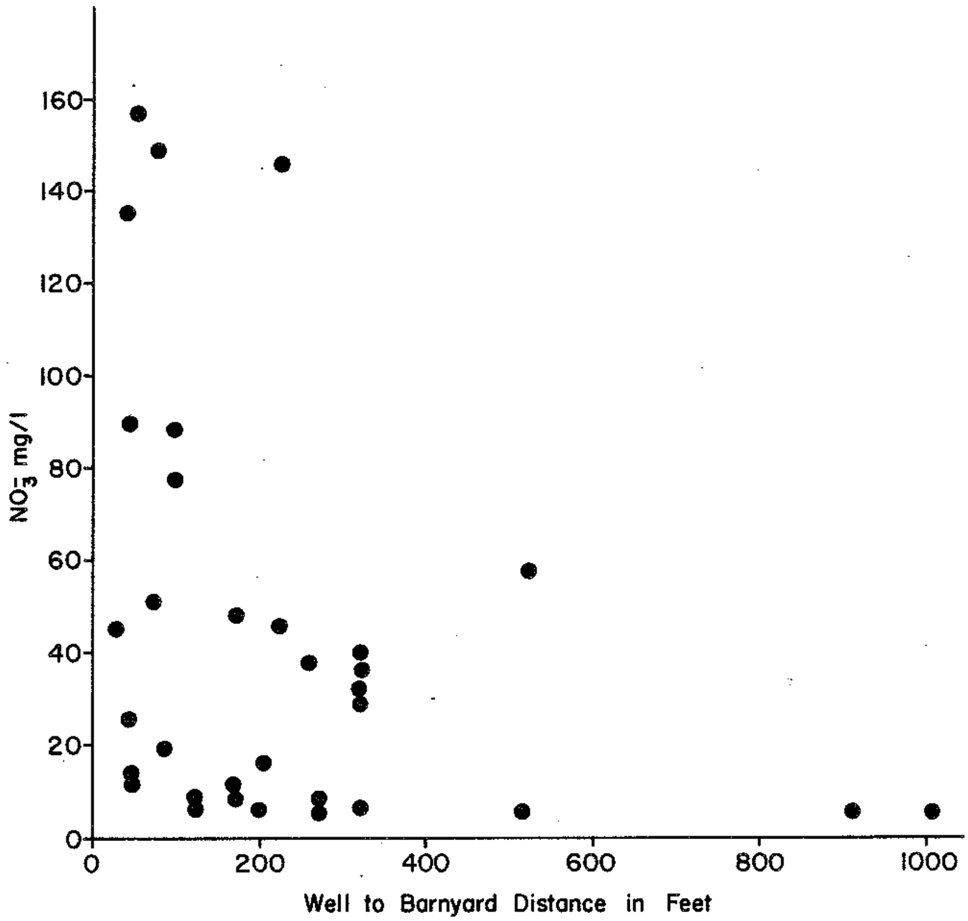

Figure 13. Nitrate concentration in well water samples versus distance to local barnyard (after Tjostem, et al., 1977).

From a study of 33 wells, they found a correlation (significant at the .05 confidence level) between the nitrate concentration in the well water and the proximity of the well to the "barnyard" on the farm. Their results are shown in figure 13.

Tjostem and others (1977) also documented the influence proper well casing has on water quality. Figure 14 shows a plot of nitrate concentration over time in the water from three wells within a few hundred feet of each other in Winneshiek County. All three wells are drilled through the Galena Limestone and finished in the underlying St. Peter sandstone at depths of about 350 feet. The upper well is a farm well, located 35 feet from the barnyard. This well does not case out the Galena Limestone, and thus the well gets water from both the near surface Galena and the St. Peter. The other two wells are about 250 feet from the farm well, and are nearly identical in depth, and both are associated with "suburban" rural houses. The significant difference in these wells is that one is cased through the Galena and only admits water from the St. Peter Sandstone, while the other is uncased like the farm well. The distinct differences in nitrate content illustrate the importance of adequate well construction on the quality of the water obtained.

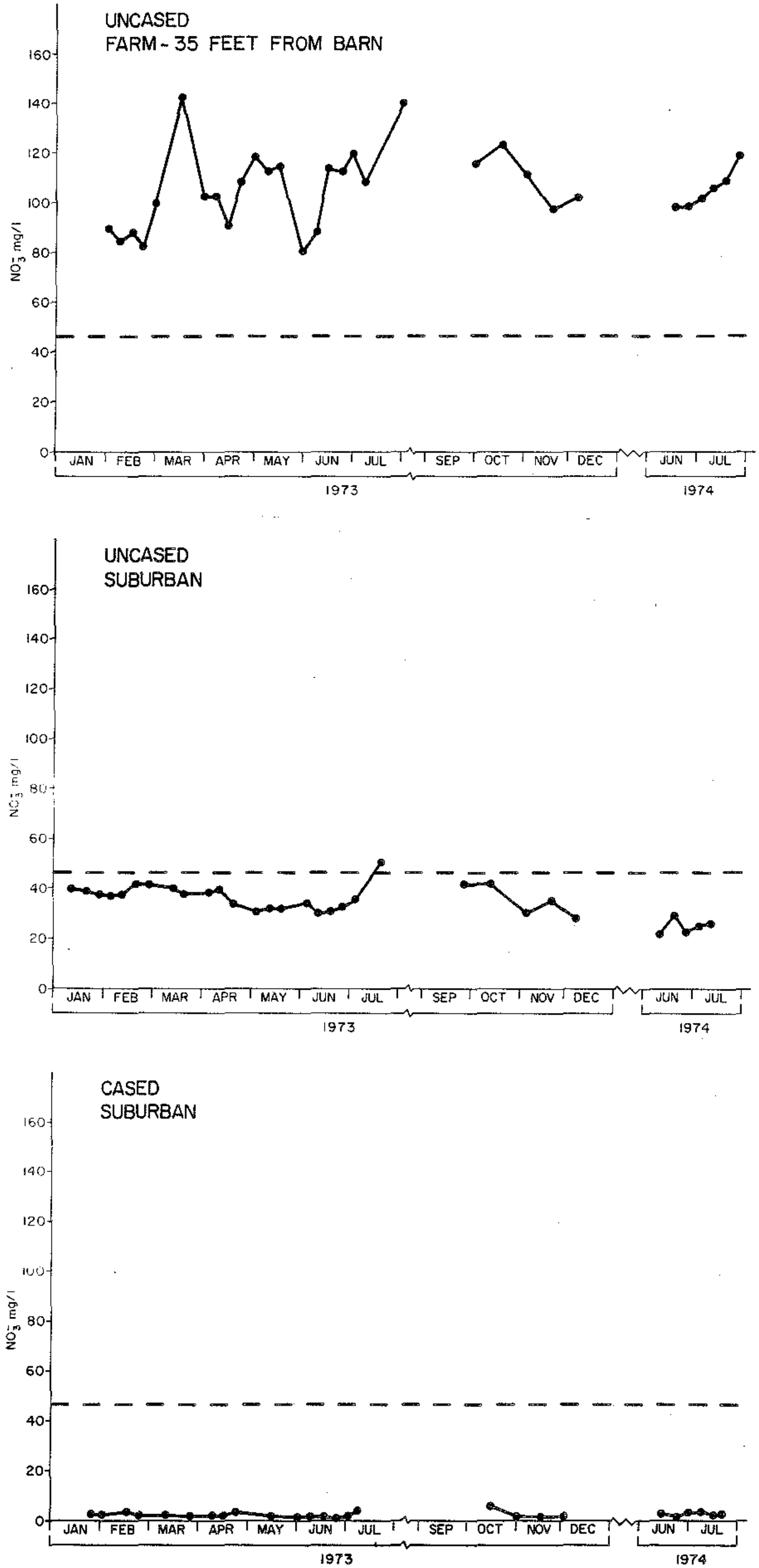

Figure 14. Nitrate concentration vs. time for 3 neighboring wells with different placement and construction features (from Tjostem, et al., 1977).

A summary of Tjostem and others (1977) data on similar wells in Winneshiek County is shown in Table 11. The data illustrate that the uncased St. Peter wells show contamination by nitrate and coliform similar to the Galena. Not only does the lack of casing effect the water quality of these wells, but dependant upon the head relations in the aquifers this can also introduce surficial contaminants into the deep aquifer.

Another example of local effects on water quality may be illustrated in figure 15. The data shown are from water samples collected by IGS staff in October, 1975, during an inventory of 52 wells in the Silurian Karst area in southwestern Clayton and northestern Fayette Counties. The data shows the typical relationship of decreasing nitrate concentration with increasing well depth. Some observations on the wells or water quality were also made, and are given in the notes with figure 15. Several of the wells with high nitrate may in part reflect problems with well placement (figure 15; notes 1-4). These wells are either in barnyards or receive surface drainage into the well. Numbers 6 and 7 suggest construction problems.

Observations for samples numbered 5, 8, and 9, indicate other problems noted in the karst aquifers; water quality problems (turbidity, nitrate, bacteria, taste, and/or odor) are encountered after rains or during spring thaw and runoff. This is because of the direct connection between the land surface and the aquifer. Wells which have sediment problems must be in connection with solution voids in the limestone aquifer which are large enough to move sediment. These wells may be particularly prone to contamination with other chemicals, such as pesticides, which may travel with the sediment.

Summary: Ground-Water Quality

All pertinent and readily accessible data on ground-water quality were compiled for analysis. The data evaluated were restricted to nitrate concentration and coliform bacteria, because these two parameters are the most widely available, they are related to health standards, and are uniquely related to ground-water contamination from surface sources. The data set used most extensively was provided by the University Hygienic Laboratory (UHL) and included over 6,000 nitrate analyses and over 8,000 bacterial analyses from the study area. All were from well water samples within the study area which were analyzed by UHL during 1977 through 1980. Various other data were analyzed, including the WATSTORE data file, and a variety of published and unpublished studies which provided greater geologic controls, but were limited in number and areal extent. Extensive data stratification and statistical tests were applied to the UHL data.

Many conclusions can be drawn from the various data sets evaluated. The concentration of nitrate or bacteria in the ground water may fluctuate seasonally, where a water source (the well or the aquifer) interacts with surface activities. This seasonal fluctuation can seriously affect the conclusions drawn from some data sets. Local studies demonstrate that the degree of nitrate and/or coliform contamination for a given well may be related to on-site

Table 11. A comparison of nitrate concentration and coliform bacteria counts in water from the Galena aquifer and the St. Peter Aquifer. Contamination introduced into St. Peter wells through inadequate casing is also illustrated (From Tjostem, et al., 1977).

	Wells terminating in St. Peter Sandstone, (Galena Limestone cased out)	Wells terminating in St. Peter Sandstone, (Galena Limestone *not* cased out)	Wells terminating in Galena Limestone
Number of wells sampled	25	25	50
Range of well depths in feet	230-560	230-407	20-170
Average depth in feet	355	306	100
Range of nitrate (NO_3) concentration in mg/l.	0.7-12	0.9-140	0.3-154
Average nitrate (NO_3) concentration in mg/l.	1.7	28.9	23.9
Number of wells contaminated with 1 or more coliforms/100 ml.	3	15	32
Number of wells contaminated with 8 or more coliforms/100 ml.	0	8	21

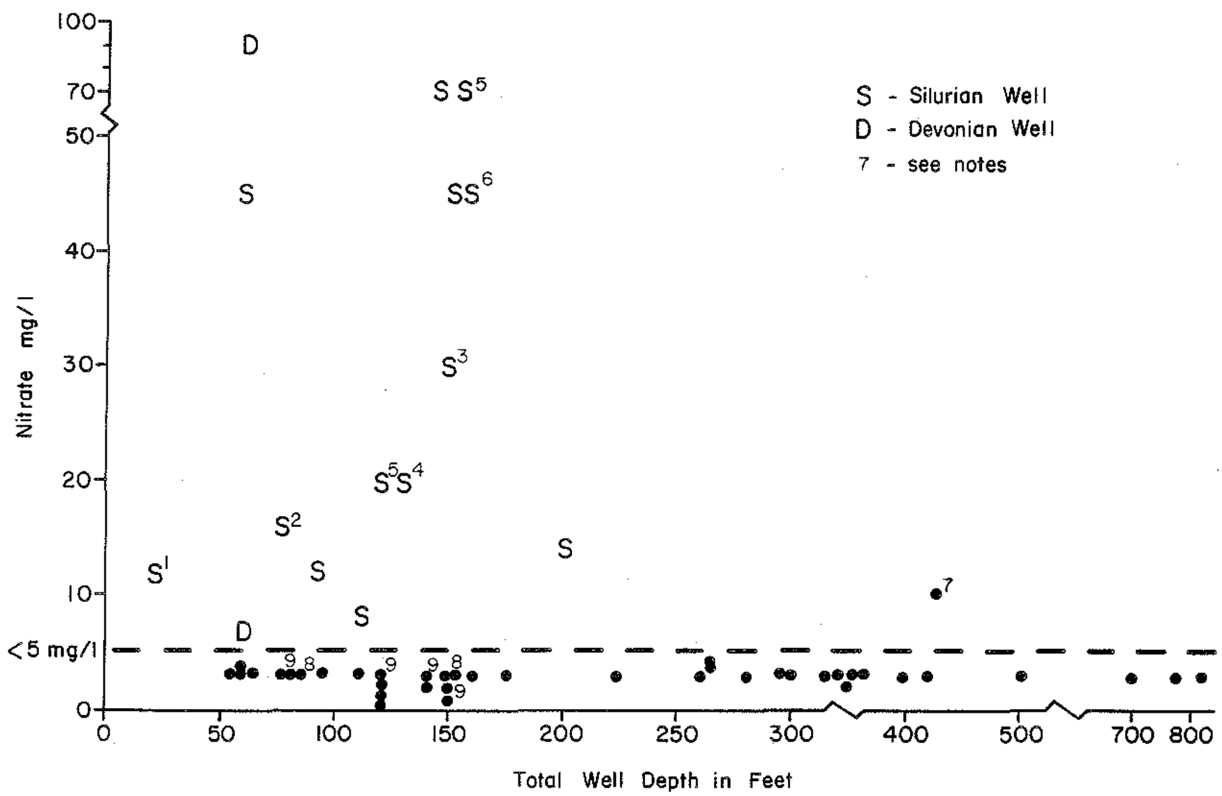

Figure 15 . Nitrate concentration versus well depth, from wells in the Silurian-Devonian aquifer in Clayton and Fayette County. Wells inventoried by IGS staff in 1975. See footnotes below.

1. Surface drainage into well.

2. "When creek is high it seeps into well."

3. Well located in stockyard.

4. Water not good in spring, takes runoff from stockyard.

5. Wells have sediment or turbidity problems after rain and in spring.

6. Sample from hydrant in barnyard, water-line is suspected to be leaky and contaminated.

7. Deep well but shallow casing.

8. Silurian wells - owners report some nitrate, bacteria, and/or turbidity problems after rain.

9. Silurian wells - owners report bad water odor or taste after rain.

factors such as poor well placement and/or construction. Poor well placement and/or construction is not always just an individual problem; such wells may allow contaminants to spread into the aquifer as well, dependant on the hydrologic setting. A review of the various water-quality data pointed out that there is no readily availabale data that is adequate for assessing long-term changes in water-quality. The data was usable for assessing the present problems of the Karst areas, however.

The frequency-distribution of nitrate values shows two features, in all the data sets. The nitrate values always exhibit a modal value of zero (or less than detectable), and the frequency of observations decreases with increasing nitrate value. This was true for any breakdown of the data used (i.e., by geologic setting, by aquifer, by well-depth classes, etc.). Also, in all data sets evaluated, nitrate concentrations decrease with increased well depth, regardless of the aquifer involved.

The potential contributions of nitrate from natural sources were reviewed and these sources are not likely to be significant. The fact that the modal concentration of nitrate for all the geologic regions, well depth classes, etc., was zero (or less than detectable) clearly indicates that the background level of nitrate from natural sources is very low. The elevated levels of nitrate found in water supplies can be attributed to various surficial sources, such as infiltration and runoff from barnyards, feedlots, septic systems and other forms of waste disposal, and of course the widespread use of nitrate fertilizers.

Although there are many problems in the analysis of the water-quality data (such as the seasonal variations) the large number of samples in the UHL data set will overcome many of these problems. The UHL data was compiled over a four-year period and effectively integrates many of these variations. Because the UHL samples cannot be accurately located (i.e., to legal coordinates) the data was aggregated by rural route postal addresses. The data was assigned to 247 sample centers--or towns which constituted the rural route postal stations. The data for each of the sample centers was aggregated into categories by well depths. Further, using the maps which characterized the physical setting of the region, each sample center was classified as part of either the Karst, Shallow Bedrock or Deep Bedrock geologic setting.

The data analysis shows that coliform bacterial contamination of rural water supplies is widespread; 35% of all the UHL analyses record unsatisfactory or unsafe levels of coliform. However, the distribution of elevated bacterial levels is relatively uniform among all geologic settings and well depths. This suggests that bacterial contamination is introduced from the well or the water-system and not as a result of aquifer contamination. The UHL data consists largely of "tap" water samples, not samples directly from the well, so these variables cannot be adequately addressed. Also, the MPN method for coliform counts, used by UHL, makes statistical analysis difficult, and the results vague. Further research is needed because case studies indicate that bacterial contamination of ground water can be a problem in the Karst areas. Overall the bacterial data does indicate that water-system problems which introduce bacteria are very common and present a serious potential health problem.

The results of the analysis of the nitrate data are much more clear. Statistically, the concentration of nitrates clearly decreases with increasing well depth. In general, the highest nitrate values occur in samples from wells less than 50 feet deep. Data from wells between 0 and 49 feet deep uniformly show high median nitrate values, regardless of the geologic region they come from. Data analyzed for the state as a whole show identical results. This indicates that shallow wells in Iowa--regardless of the aquifer involved--are susceptible to contamination by nitrates, and indeed are exhibiting significantly high levels of nitrate.

In the Karst and Shallow Bedrock regions, where the soil cover is thin over the carbonate aquifers, significantly high levels of nitrate occur to depths of 150 feet in the bedrock aquifers. Ground-water supplies in the Karst region in wells from 50-150 feet in depth show significantly higher levels of nitrate contamination. In the 50-99 foot well depth group the median value for nitrate in the Karst regions (34 mg/l) is 1.8 times higher than in the Shallow Bedrock regions (19 mg/l) and nearly 6 times greater than in the Deep Bedrock regions (6 mg/l). These differences are highly significant statistically. As evident in the median nitrate values (Table 5) the Karst areas show the greatest nitrate contamination, and are followed closely by the Shallow Bedrock region.

Nitrate contamination in the Karst regions is most pronounced to a depth of 100 feet. At greater depths the median nitrate concentrations in the Karst areas decrease and are similar to those in the Shallow Bedrock Area. This suggests that the diffuse infiltration of nitrates, the process which dominates in the Shallow bedrock regions, is a significant factor and is the process which produces the elevated levels of nitrate found to depths of 150 feet in the carbonate aquifers. The significance of the sinkholes and better developed solutional conduits in the Karst regions may be viewed as the pronounced difference in median nitrate concentrations (15 mg/l) between the Karst and Shallow Bedrock regions in the 50-99 foot depth range. Thus, if management strategies are developed to try to improve or protect ground-water quality in the carbonate aquifers, the entire Shallow Bedrock area, as well as the Karst areas, must be included in the considerations. The entire Shallow Bedrock and Karst hazard area constitute 53% of the study area, or over 6,800 square miles of important recharge area for these bedrock aquifers.

As a matter of perspective, it must be pointed out that all of these median nitrate values are below the 45 mg/l nitrate drinking water standard. However, a median of 34 mg/l in the 50-99 foot range in the Karst areas also means that 50% of all the analyses in this group are in excess of 34 mg/l. For the study area as a whole, 18% of all the samples exceeded the 45 mg/l threshold. Within the different geologic settings, 25% of analyses from the Karst areas, 19% in the Shallow Bedrock, and 15% in the Deep Bedrock areas exceeded 45 mg/l.

As noted above, local well-placement and construction affect the degree of nitrate and coliform contamination recorded by an individual well sample. As discussed, local factors seem to strongly affect the results of the analysis of the bacterial data. The high, significant correlations of the nitrate data with geologic setting however, indicate regional aquifer effects, not just water-system problems. This is supported by the many reports of newly-drilled wells in the carbonate aquifers which have high nitrate levels, and by the presence of nitrates in water samples from karst springs. The nitrate concentration recorded from any particular well will likely be a function of the regional level of nitrate in the aquifer, and the local source effects. Wide variations in nitrate levels will occur in local areas because of these variables. Wells which only intercept small fractures in the carbonate rocks will tend to have lower nitrate concentrations and lesser seasonal fluctuations than wells which are open to larger conduits. This is related to the nature of ground-water flow in the carbonate aquifer system. In this regard there are many unanswered questions, such as, will nitrate concentrations in the carbonate aquifers continue to increase? Or have these concentrations reached an equilibrium with current land use and recharge factors? A long term, ground-water quality monitoring network will be needed to answer such questions.

Another issue of concern is whether or not the significant nitrate contamination noted in the Karst regions is symptomatic of contamination by other widely used chemicals. Few data are available. What little data there are, clearly shows that pesticides are also entering the carbonate aquifers. The fate of these chemicals in the ground-water system is unclear, as are the health effects of small concentrations of these chemicals. Although further research is needed, this clearly is not a desirable situation.

GROUND-WATER FLOW SYSTEMS IN CARBONATE AQUIFERS

The details of ground-water flow in carbonate (karst) aquifers can be very complex. This is particularly true where the carbonate rocks have well-developed conduits through which the water flows (White, 1977). The principal permeability and flow path for ground water in these aquifers is through secondary openings, generally along vertical or high-angle joints and fractures and horizontal bedding planes or other stratigraphic features. This results in much greater irregularity in the distribution of hydraulically conductive zones than in a clastic (e.g., sandstone) aquifer where more of the flow is diffuse through the pores between grains. The secondary openings in the carbonate rocks often form a reticulate, boxwork pattern of near-vertical and more horizontal openings and conduits (e.g., Powell, 1977). These openings may be variably spaced, and are generally comprised of linear segments, aligned or controlled by structures or stratigraphic features in the rocks.

In these settings the ground-water flow takes on very localized characteristics. Although the flow direction is still controlled by the hydraulic head, or pressure distribution in the aquifers, an individual parcel of water may follow a complex route through a series of these linear openings.

The degree of enlargement caused by solution and the configuration of these fractures and conduits control the rate and direction of the flow and the productivity of the carbonate aquifer. On the detailed, or site-specific level, these irregularities make it very difficult to predict well-yields from an aquifer (Parizek, 1976), because such yields are dependant on the probability of intersecting appropriate fractures. These irregularities on the site-specific level, make it very difficult to use standard techniques for aquifer evaluation.

When conduits become well developed and the solutional activity in the carbonate rocks influences the land-surface producing karst topography, such as sinkholes, even the surface-water hydrology becomes affected (LeGrand and Stringfield, 1973). In general, ground-water and surface-water flow systems are analyzed as separate entities. This is reasonable in most settings because the time-scale for flow events in the ground-water system is quite long compared to that for the surface-water system. In well-developed karst aquifers this distinction between surface (or channel) flow and ground-water (diffuse) flow breaks down, and it is also this factor that gives carbonate aquifers many of their unique characteristics and makes their analysis so difficult (White, 1977). As sinkholes become prominent and capture surface drainage, sometimes swallowing whole streams, surface runoff joins the ground-water system, and becomes "internal runoff" in the subsurface conduits in the aquifer. Diffuse ground-water flow is still present in the karst aquifer, but the transfer of water from recharge in and out of storage is much faster in the conduit part of the system than in the diffuse part of the system (White, 1977).

Ground-water flow in large aquifers commonly translocates water from one surface-water basin to another, but nowhere is this more apparent than in the karst aquifer. In karst regions surface water, including even moderate size streams may be "swallowed" by sinkholes and piped into the ground-water system and then translocated through conduits to springs which then discharge to the surface water system in another basin (e.g., Ruhe, 1975, 1977). An example of this occurs in the karst terrain in the Galena Group rocks (see Plate 2) in Clayton County, Iowa. In this area dye-tracing has verified that portions of the drainage of Silver Creek and Robert's Creek are diverted into the ground water, and then flow under the lower reach of Robert's Creek, finally resurfacing at Big Spring which discharges into the Turkey River (Heitmann, 1980).

As discussed, these unique features of the karst landscape and carbonate aquifers create concern for ground-water quality. The direct connection with the land surface allows the entrance of surface water into the ground water regime. Also the open nature of conduit flow provide little filtration and dispersion of contaminated surface water. As an example of the open nature of these flow systems, it is not uncommon to see corn stalks or beverage cans discharged from large springs or found in cave streams in northeast Iowa.

Many of these complexities of carbonate aquifers are only problems for site-specific predictions and in aquifer analysis techniques such as pump test data. Thrailkill (1968) demonstrated that the pattern of flow in a carbonate aquifer is similar under Darcy (diffuse), laminar, or turbulent flow, given the regional dimensions of most carbonate rock units. Thus, on the larger scale the flow system can be generalized from the analysis of the head (or piezometric) relationships as in any other aquifer.

Another important consideration in carbonate aquifers is the vertical distribution of conduit or solution channel systems. The greatest solutional activity, and consequently the most pronounced conduit development, takes place in the upper part of the zone of saturation (Thrailkill, 1968; LeGrand and Stringfield, 1973). Thus, except in karst regions that have undergone radical vertical (up as well as down) fluctuations in the elevation of the zone of saturation over long periods of geologic time, the volume of conduits or solution channels in the rock tends to decline almost exponentially with depth below the water table (LeGrand and Stringfield, 1973). This is typical of the carbonate aquifers in Iowa. Over time this results in a well-developed relatively shallow conduit system grading downward to a diffuse ground-water flow system at depth in the carbonate aquifer. Where the conduit system is better developed, it is generally better connected via land-surface features to the surface-water system, and it may become progressively "decoupled," at depth. According to White (1977, p. 184): "As the effective decoupling becomes larger, the shallow conduit system becomes linked more and more tightly to the surface drainage system while the diffuse flow system may retain its regional character. The exchange of water between the conduit and diffuse system becomes as poorly coupled as in the exchange between surface and ground water in a porous medium aquifer." The reason for such decoupling would in part be caused by the large contrast in hydraulic conductivity between the shallow conduit flow system and the deeper diffuse flow system. This contrast in properties also results in very different response times to recharge events for example. This vertical decoupling may, in part, explain why extensive nitrate contamination is confined to the more shallow portions (less than 150 feet depth) of the carbonate aquifers in the Karst regions of northeast Iowa.

Description of Ground-Water Flow

in the Carbonate Aquifers of Northeast Iowa

Plate 12 shows the configuration of the piezometric surface of the Silurian-Devonian carbonate aquifer for the 22-county study area. The Silurian-Devonian aquifer forms the shallowest bedrock aquifer over much of the study area (see Plate 2). This map was compiled from static water-level data at IGS.

The piezometric contours only represent the upper surface of the head distribution in the aquifer. At any given point the exact flow path will be controlled by the vertical head distribution throughout the aquifer, for which little data is available. However, in general, 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 contour lines. Plate 13 shows the principal streams and surface-water divides in the study area. A comparison of Plate 12 and Plate 13 shows that the major surface water divides and ground-water divides are generally similar in location. The piezometric map also indicates that ground water flows from these divides and discharges to the major streams. Undoubtedly some deeper, more regional flow may complicate this picture, but the 3-dimensional head data that is available (e.g., Munter, 1980) supports this conclusion. The shallow portions of the flow-system certainly discharge to the major rivers such as the Cedar, Shell Rock, Wapsipinicon, and Maquoketa. This is an important characteristic when considered with the distribution of the Karst areas formed in the aquifer.

There are two principal Karst areas in the Silurian-Devonian aquifer (Plates 1 and 2): one along the Cedar and Shell Rock Rivers in Mitchell, Floyd, and adjacent counties; and a second Karst area along the erosional edge of the aquifer (Plate 12) the Silurian escarpment, in Clayton and Fayette Counties and vicinity (Plate 2) and a smaller, related area along the erosional edge of the Devonian rocks (Plate 2) in Howard County. These two areas of concentrated sinkholes are very different in character: the Mitchell-Floyd area is in the region of low relief in the heart of the aquifer; the Clayton-Fayette Karst is along the very edge of the aquifer in terrain marked by high relief.

An important characteristic of the sinkhole distribution in the Mitchell-Floyd area is that the majority of the sinkholes occur close to the major streams or their tributaries. As discussed, the aquifer discharges to the Cedar River. Thus, it is most likely that surface water which enters the aquifer through the sinkholes in this area would be contained in the shallow portion of the flow-system. It does not seem likely that significant amounts of recharge to the deeper, regional portions of the flow would occur in these sinkhole areas.

In the high relief terrain of the Clayton-Fayette County Karst a different setting is found. First, the majority of the sinkholes in this area are concentrated in the immediate vicinity of the topographic escarpment, or bluff, which marks the edge of the carbonate rocks, which make up the aquifer in this area. The escarpment is deeply dissected by streams which drain from the escarpment to the Turkey River or its tributaries. The high relief, and the abrupt physical termination of the aquifer combine to produce a relatively narrow zone of ground-water flow, with a very steep hydraulic gradient, toward the escarpment. This flow system is quite local in nature, and no attempt can be made to show it on Plate 12. In this area numerous springs discharge from the Silurian rocks along the escarpment, and ultimately drain to the Turkey River. This flow system is maintained (perched) by the underlying aquiclude formed by the thick shales in the underlying Maquoketa Formation.

Studies of pollutant travel paths, dye tracing, and the mapping of cave passages and fractures (see Bounk, 1981, Hansel, 1976) all indicate that the ground-water flow system in this area is local, shallow, and generally discharges toward the escarpment. Exact flow-paths may be complex however, related to the orientation of solutional conduits, influenced by the rock structure. A dye-tracing experiment conducted for this study provides a good illustration.

Dye-Tracing in the Silurian Karst of Fayette County

Between May 28 and July 9, 1981, three dye-tracing experiments were conducted in the Silurian karst of Fayette County, by Michael Bounk of IGS. The study area is shown in figure 16. It is located about 2 miles (3.2 km) northeast of West Union. The area was chosen for the dye-tracing study because it could be related to ongoing geologic research in the area (see Bounk, 1982) involving Dutton's and Soward's Caves (figure 16, A and B).

The area is along the Silurian escarpment, which here faces northeast. The heavy dashed line on figure 16 marks the approximate lower contact of the Silurian rocks (Su) with the underlying shales of the Maquoketa Formation (Om). In this area the thickness of the Silurian is only about 50 feet (15 m). This area is near the northern edge of the occurrence of the Silurian rocks (Plate 2). To the north and west the Silurian thins and eventually is totally absent, having been removed by erosion prior to deposition of the Devonian carbonate rocks. These Devonian carbonate rocks overlie the Silurian in the dye-tracing study area. The Silurian and Devonian carbonate rocks are in hydrologic connection and karst solution features are continuous between the two. Sinkholes in the vicinity of D (dye-injectection point) are developed, in part, in Devonian rocks. The contact between the Silurian and Devonian rocks is not generally exposed because the uplands are mantled by Pleistocene (Wisconsinan) age loess. Dutton's Cave (Figure 16, A), Mittelstadt Cave (C), and Soward's Cave (B) are all formed in Silurian rocks.

Figure 16 shows a generalization of the surface topography (50 foot contours taken from more detailed 7.5 minute, U.S.G.S. quadrangle maps), streams, the location of sinkholes and sinkhole complexes, and the locations of the caves mentioned. Also shown are pertinent surface water divides. The northwest-trending divide in the southeast portion of the map separates the area into streams flowing northeast directly into the Turkey River (which is just off the northeastern edge of the map), and streams flowing south to join Otter Creek, which joins the Turkey River several miles to the east and south. The north-trending secondary divide separates the surface drainage in the valley above Soward's Cave from the surface drainage in the valley above Dutton's Cave. The surface drainage-basins of the 3 sinkhole areas where dye was injected are also shown (figure 16, C, D, E). Except during major runoff events most of the surface runoff in these areas disappears into these sinkholes. Field tiles also drain into sinkholes D and E.

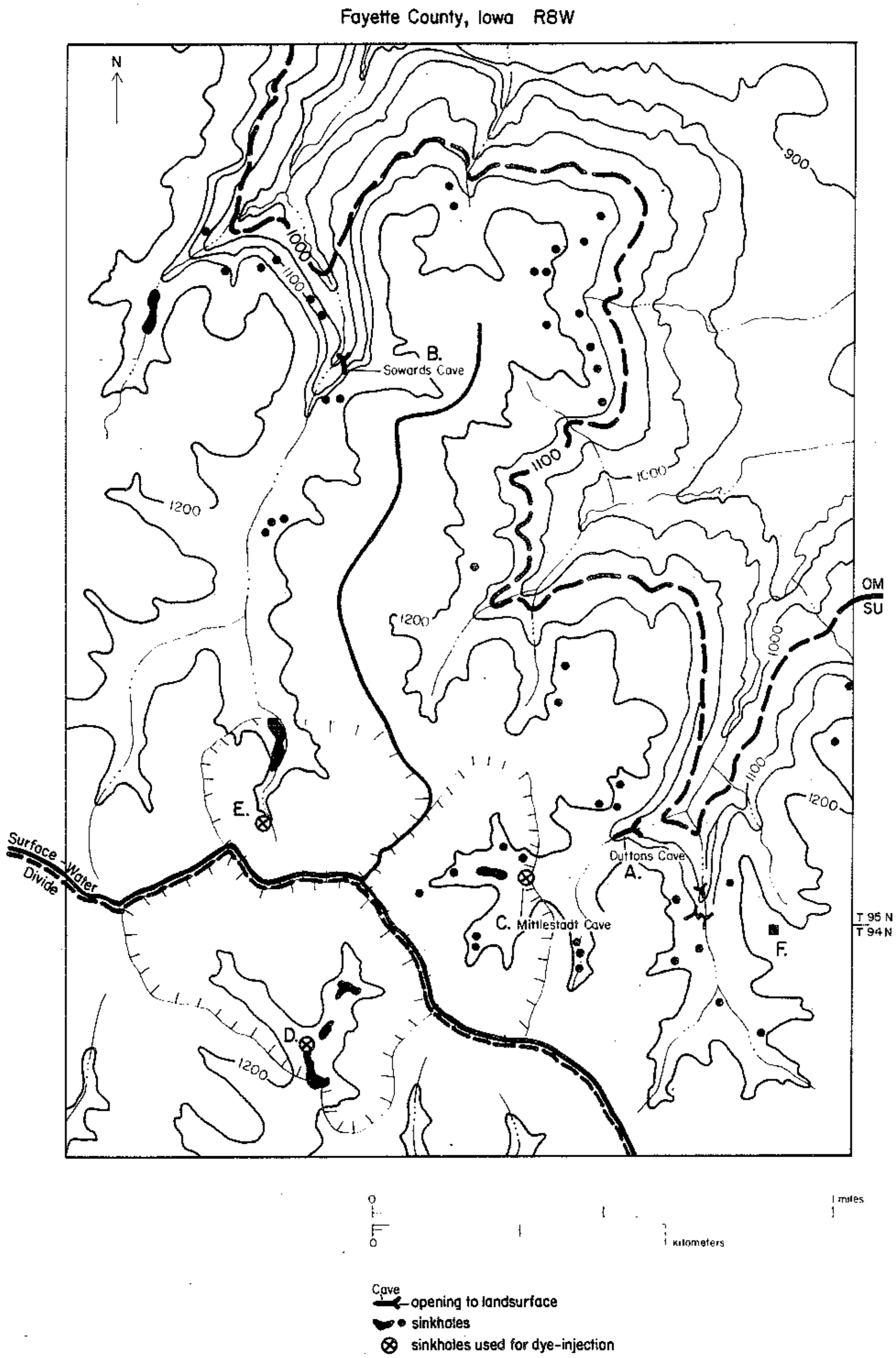

Figure 16. Location and topography, Fayette County dye tracing study.

Dutton's, Mittlestadt, and Soward's Caves all are formed in Silurian rocks and consist of prominently joint-controlled passageways (Bounk, 1982). Soward's Cave consists of three different accessible levels. All of the caves are now above the normal water-table, and are partly air-filled. Cave streams in the passages generally descend down through other solution conduits to the zone of saturation in the Silurian. The water from Soward's cave has been previously traced, and it emerges from springs in the valleys below the cave entrance. The spring discharges from the lower portion of the Silurian rocks above their contact with the Maquoketa Shales. During major runoff events at least the lower portions of these cave systems fill with water which issues as temporary springs into the valley. Discharge from the springs below Duttons's Cave is sufficient to maintain flow in the minor stream in the valley year round.

The three dye-tracing experiments were conducted at about two week intervals. Fluorescein dye and charcoal detection packets were used, following standard dye-tracing procedures (Aley and Fletcher, 1976). Before the initial dye injection, and after each subsequent dye injection, detection packets were checked to make sure no significant quantity of dye was discharging before the next dye-trace was attempted. All known prominent springs, which emerge from the Silurian in the area, were monitored with detection packets. These include the springs below Dutton's and Soward's Caves, the springs associated with the small caves southeast of Dutton's and four other springs outside the mapped area of figure 16. Dye was injected sequentially into the sink at Mittlestadt Cave (figure 16, C; 2 June 1981), sinkhole D (18 June 1981) and sinkhole E (2 July 1981). Water was hauled in to flush the dye into Mittlestadt. At sinkholes D and E tile effluent water was used. The specific sinks used for dye injection were chosen because of their open nature, allowing dye to readily enter the aquifer, and because of their accessibility with water.

The three sinkhole areas studied are associated with three entirely different surface-water drainage basins --all draining different directions. However, all the dye-tracing experiments showed the same results. Dye was traced from all three sinkhole areas to the springs below Dutton's Cave (figure 16, A). No dye was detected at any of the other springs.

The drainage basin for sinkhole E is shown to encompass the sinkhole complex to the north of E. Field work, joint and solution conduit measurements, and exploration of cave passages suggest that all of these sinks are related and likely drain into related conduits in the subsurface.

These field measurements of joint orientations and mapping of cave passages suggest several things about the direction of the ground-water flow in the area also. Figure 17 (heavy lines) shows the major joint-controlled trends which the caves and valleys exhibit in the area. In Dutton's Cave for example, individual passages follow various joint trends, but the overall trend of the cave follows a N 60-70° E trend down-valley (figure 17, 1), and thus, down the hydrologic gradient. The ground-water drainage in the Mittlestadt Cave area also likely follows this prominent N 60-70° E conduit trend down-valley below Dutton's. The flow path from sinkhole D likely follows another prominent conduit trend, oriented between N 0 and 20° E (figure 17, 2), to the north, which may then join the Mittlestadt-Dutton's conduit (1). The likely flow-path from sinkhole E is not as easily speculated. Joint trends and geomorphic evidence suggest that the ground-water may follow conduits along another prominent trend of N 60° W (3), or perhaps another northwest trend (4).

Fayette County, Iowa R8W

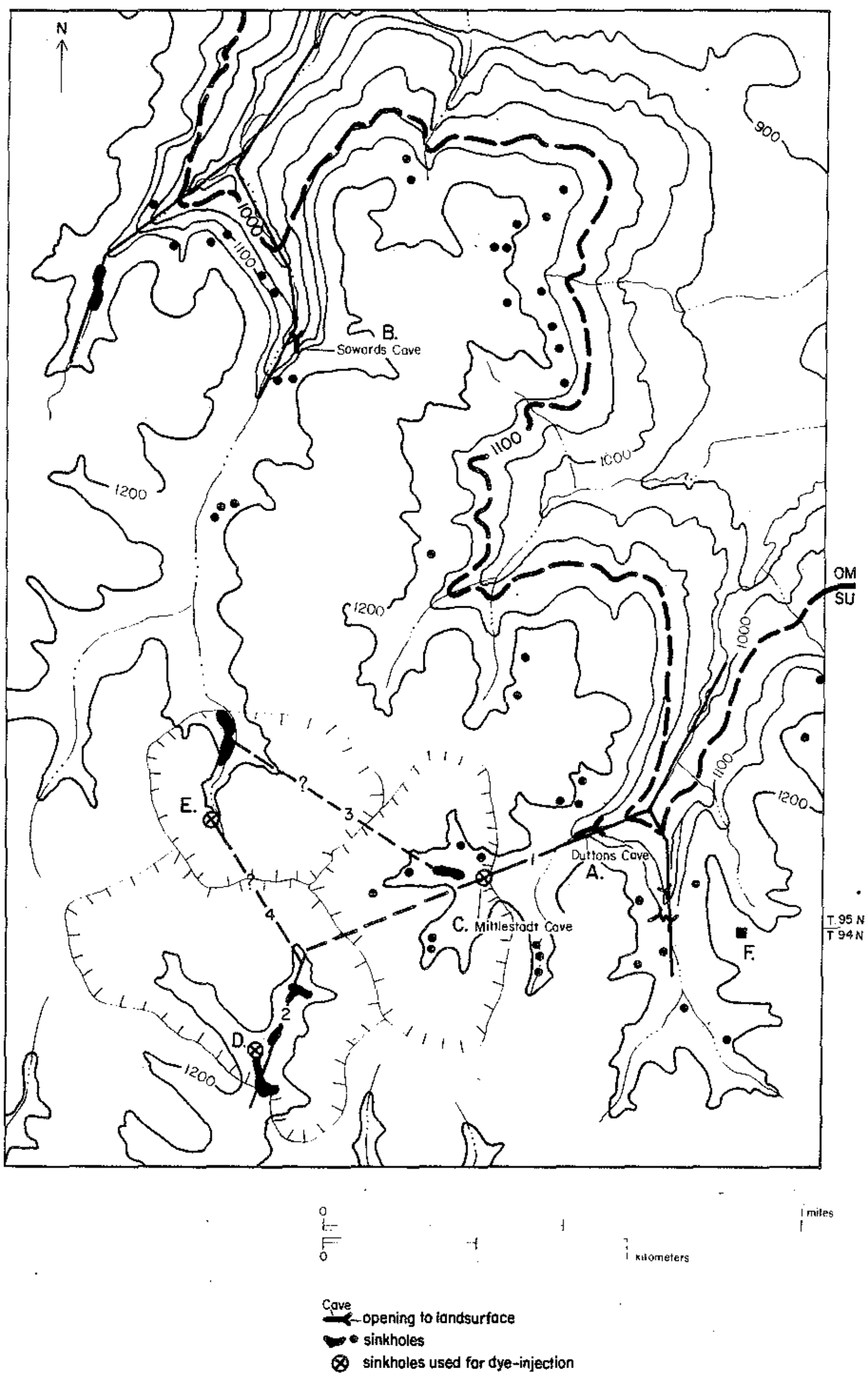

Figure 17. Fayette County dye-tracing study area, showing known (heavy solid lines) and inferred (dashed) linear conduits in area.

Each follows the hydraulic gradient toward the Silurian escarpment; discharging at Dutton's Cave spring to flow toward the Turkey River. Thus, even though the surface-drainage in this area has evolved to carry runoff in three different directions, the karst ground-water conduit system has extended back under this divide, and "pirates" the ground water down gradient toward the Turkey River. Although, the flow-path of the ground water may be rather "angular," following linear, joint or fracture controlled conduits, it must follow the steep hydraulic gradient toward the face of the Silurian escarpment.

As an additional part of this study, water samples were taken from the tiles lines discharging into sinkholes D and E. No Silurian wells occur in the ground-water basin defined by spring A and sinkholes C, D, and E, but a 110 foot deep Silurian well was sampled at F. Unfortunately, no samples were taken from the spring. Two sets of samples were taken at each site; one on 1 July and a second on 5 July 1981. The results are summarized in Table 12. The most significant result of these analyses is that they document pesticides such as Atrazine and Lasso discharging directly into sinkholes which carry them into the ground-water system, as verified by the dye-tracing.

Ground-Water Flow in the Karst Area in the Galena Aquifer

The other major Karst area occurs in the Galena Group rocks which outcrop in northern Clayton, southeast Allamakee, and western Winneshiek Counties (see Plates 1 and 2). Locally, the Galena carbonate aquifer has been an important source of shallow ground water for many years. Over the past two decades nitrate contamination of wells in the Galena has become prevalent enough that most dairy farms have had to drill deeper, cased wells into the St. Peter Sandstone, which underlies the Galena. Many domestic wells are still finished in the Galena, however.

The Galena aquifer is exposed in another unique geomorphic and hydrogeologic setting. The rocks of the Galena Group form a broad stream-dissected plateau in their outcrop area. In the middle of the outcrop area the landscape is gently rolling, but the major river valleys (Turkey, Yellow, Upper Iowa) are deeply entrenched. Along these river valleys and along the eastern erosional edge of the Galena (Plate 2) a steep bluff, or escarpment is present, upheld by the massive carbonate rocks. This physical setting is like a smaller-scale version of the Silurian-Devonian carbonate aquifer; there is a more regional flow system in the interior of the aquifer, and many small, local flow systems located in the proximity of the bluffs along the major stream valleys and the erosional escarpment.

Dye-tracing studies (Heitmann, 1980), other analyses of the Galena aquifer (Steinhilber, et al., 1961), and on-going studies at IGS show that the major ground water divides are roughly coincident with the principal "sub-basin" divides (Plate 13); the Turkey-Yellow, Yellow-Upper Iowa divides. Ground water in the Galena flows from these divides toward, and then discharges along these major valleys. As discussed previously, dye tracing in the Galena aquifer in Clayton County by the Iowa Conservation Commission (Heitmann, 1980) showed that water influent into sinkholes, just south of the Turkey-Yellow River divide, flows into the aquifer, then flows under major tributary streams such as Silver and Robert's Creeks, and ultimately discharges through Big

Table 12. Range of ground-water quality in tile and well water from Fayette County Dye Tracing study.

Location	Nitrogen Species: Ammonia	Nitrogen Species: Nitrite (mg/l)	Nitrogen Species: Nitrate	Coliform Bacteria MPN	Pesticides: Atrazine (ug/l)	Pesticides: Lasso
Tile effluent Sinkhole D	0-0.3	0-0.7	14	ND	0.46-0.56	0.03
Tile effluent Sinkhole E	ND	ND	10-17	ND	0.40-0.81	ND-0.09
Well F	ND	ND	1.7-1.8	2	ND	ND

(ND - none detected)

Spring along the Turkey River. Piezometric data and unpublished gaging on Robert's Creek shows that Robert's Creek loses water to the ground-water system in the Galena over much of its length. Only in the lower reaches of Robert's Creek, as it enters the terrain more deeply dissected into the Galena rocks, near the Turkey River valley, does it begin to receive ground-water discharge <u>from</u> the Galena. This is shown by Galena discharge at the St. Olaf spring (Heitmann, 1980). Thus, as the major river valleys in the Galena are approached the ground-water flow system is broken up into smaller, local components which discharge to tributary streams, as well as the principal streams such as the Turkey River.

An additional item of concern, regarding the Galena aquifer is the deep dissection of the principal streams. Well records from the alluvial valley of the Turkey River suggest that the stream valleys may have been cut down 50 feet deeper than the modern floodplain, which have aggraded subsequently. The deep dissection throughout the Galena outcrop area will provide steep hydraulic gradients. This also may indicate that the zone of saturation in the Galena may have had a wide range of vertical fluctuations in the geologic past. This in turn suggests that well-developed solutional conduit systems may be present in the Galena to proportionally greater depths than in the Silurian-Devonian aquifer. This may explain the apparently more pervasive nitrate contamination in the Galena, which has caused many of the dairy operations in the region to seek other sources of water.

The analysis of the water-quality data, summarized in Table 9, also suggests higher nitrate values at greater depths within the Galena than in the Silurian-Devonian aquifer. This data (Table 9) shows that the median nitrate content is zero for deeper wells (150 to 499 feet deep) in the Floyd-Mitchell Karst area, whereas the median nitrate content in wells of this depth is 13 mg/l in the Karst areas in Clayton-Allamakee-Winneshiek counties which are largely in the Galena aquifer.

Summary: Ground-Water Flow Systems and Water Quality in Northeast Iowa

The details of carbonate aquifer flow systems can be very complex because of the configuraton of underground conduits through which the ground water flows. The nature and configuration of fractures and conduits, which control the flow and productivity in these aquifers may also make it very difficult to predict yields from such aquifers. However, these problems are principally of concern in local or site-specific analyses. On a regional basis, the flow system can be generalized from the analysis of the piezometric relationships, as in any aquifer.

Solution conduit systems develop principally in the upper part of the zone of saturation. Typically the volume of conduit channels, representing the gross hydraulic conductivity of the aquifer, will decrease substantially with depth below the piezometric surfce. Ground-water flow at depth flow will be more diffuse and regional in character.

As solution activity proceeds through geologic time, and conduit systems increase, and karst topography is developed, producing such features as sinkholes, even the surface water system is affected. As sinkholes become prominent and capture surface drainage, sometimes swallowing whole streams, surface runoff joins the ground-water system, often allowing contaminated surface water to enter the subsurface conduits in the aquifer.

The open nature of conduit flow may provide little natural filtration, absorption, diffusion or dispersion of contaminated surface water. As an example of the open nature of these flow systems, it is not uncommon to see large objects such as corn stalks or even occasional beverage cans discharge out the karst aquifers through large springs in northeast Iowa.

As shallow solutional conduits become better developed, the shallow conduit flow system may become effectively decoupled from the deeper diffuse flow system because of large contrasts in hydraulic conductivity. This may help to contain major contamination in the shallow portion of the aquifer.

Analysis of the regional ground-water flow system in the Silurian-Devonian aquifer shows that ground-water divides are roughly coincident with major regional surface water divides, and that ground water discharges to the principal streams such as the Cedar River. Karst areas are concentrated in two settings in the Silurian-Devonian rocks: a belt adjacent to the Cedar River in the Floyd-Mitchell County area; a second region along the erosional escarpment of the Silurian in Clayton and Fayette Counties. The majority of the Karst areas in the Cedar River basin are concentrated near discharge areas for the aquifer (i.e., near major streams). With this distribution, most of the contaminants entering the aquifer in the Karst areas should be maintained in the shallow portion of the ground-water flow system. This fortuitous situation, plus the possible decoupling effects, mentioned above, should keep most of the surficial contamination in the shallower portions of the ground-water flow system in much of the region. These factors may explain the significant decrease in nitrate contamination with depth in the Silurian-Devonian aquifer, as well as the significant difference in ground-water nitrate concentrations between the Karst and Deep Bedrock regions. However, an alternative which cannot be ruled out is that there simply has not been enough time for surficial contaminants, such as nitrate, to diffuse into the deeper regional portions of the aquifers. There is no adequate data to evaluate this possibility at this time.

In the Karst areas concentrated along the Silurian escarpment, high relief creates a steep hydraulic gradient toward the escarpment and the Turkey River. This results in a narrow belt of local ground-water flow systems which discharge to springs along the escarpment. Surficial contamination may reach greater depths within the Silurian rocks here because the aquifer has less saturated thickness than in the lower relief regions to the south and east. The concentration of sinkholes adjacent to the escarpment and the steep hydraulic gradient should contain most surficial contamination within the narrow belt of local flow systems within the aquifer. It seems unlikely that significant surface-water contaminants could enter the aquifer here and diffuse regionally to the south and east.

The other major Karst area occurs in the Galena Group rocks in Clayton, Allamakee, and Winneshiek Counties. Sinkholes are widespread throughout the outcrop area of the Galena. The Galena area is deeply entrenched along the valleys of the Turkey, Yellow, and Upper Iowa Rivers. Ground-water divides roughly parallel the major surface-water basin divides of these three streams. Ground water flows from these divides and discharges along these three principal streams, flowing under major tributaries. Near these deeply entrenched valleys, and along the eastern erosional edge of the Galena, smaller, local flow systems are developed. Because of the deep dissection in the area it seems likely that well-developed solutional conduit systems may be present in the Galena aquifer to proportionally greater depths than in the Silurian-Devonian aquifer. This may be the reason for the apparent higher nitrate concentrations found at greater depths in the Galena aquifer. This also may explain the apparently more pervasive water-quality problems which have caused most dairy operators in the area to seek water sources other than the Galena.

SOURCES OF GROUND-WATER QUALITY PROBLEMS: NORTHEAST IOWA

Before any effective discussion of remedial measures for water-quality problems can begin, the sources of these problems must be clearly addressed. There are many potential sources of water-quality problems, both natural and man-made.

The Nitrate Problem

Unsafe (>45 mg/l) nitrate concentrations in water supplies are a world-wide problem (Singh and Sekhon, 1978). The source of the nitrate has been attributed to a variety of sources, both natural and man-induced. Freeze and Cherry (1979) state that dissolved nitrogen in the form of nitrate is the most common contaminant identified in ground water. The reason nitrates are a problem is that, in the range of concentrations which typically occur in ground water, nitrate is not limited by solubility constraints, and because of its anionic form it is very mobile (Freeze and Cherry, 1979).

Although nitrate is the main form in which nitrogen occurs in ground water other forms are also present such as ammonium, ammonia, nitrite, elemental nitrogen, nitrous oxide, and organic nitrogen. These other forms are generally present in very low concentrations (see Table 12, for example). All of these nitrogen forms are also present in the soil environment (Bremner, 1965), where much of the nitrate that reaches the ground-water system originates (either naturally or artificially). In general, in the oxidizing environment in the soil, elemental nitrogen and nitrous oxide may be lost as a gas. Ammonium may be adsorbed on clays, or along with nitrite and organic-N oxidized (mineralized) to nitrate, facillitated by a variety of biologic and inorganic mediators (Bartlett, 1981; Bremner, 1965).

Removal of nitrate from the soil environment may take place in several ways. The most significant amount of nitrate removal is accomplished by plants which utilize N to metabolize amino acids and protein. Ammonium may be adsorbed by clay minerals. A decline in the redox potential may also promote denitrification, a complicated mechanism which will eventually reduces nitrate to elemental nitrogen or nitrous oxide, which may then be given off as a gas. 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 biodegradeable carbon and biologic (microbial) mediation (Stumm and Morgan, 1970; Singh and Sekhon, 1978).

Nitrate that is not used by organisms or "denitrified" from the soil, may be mobilized in infiltrating water, leached out of the rooting zone of plants, and enter the ground-water system below. Once in the ground-water system, nitrate appears to be quite stable and mobile. The only natural process which will remove the nitrate from ground water is the denitrification process.

Little is known about denitrification in ground water. The redox potential in ground water will evolve toward conditions suitable for denitrification (Freeze and Cherry, 1979; Stumm and Morgan, 1970) however, the ground-water environment lacks sufficient sources of carbon and microbial mediators which are needed to catalyze the reaction (Viets and Hageman, 1971). This limits the rate of denitrification, even when suitable redox conditions exist.

Evidence for denitrification in ground water in limited areas has been documented (Gillham and Cherry, 1978; Steenvoorden, 1976, Gambell, et al., 1975). Also, since residence times are long and flow rates slow in many ground-water settings, some denitrification may still occur. However, the pervasive nature of nitrate problems world-wide (Singh and Sekhon, 1978) suggest that denitrification in ground water is not significant enough to naturally resolve the problem. Thus, once nitrate has reached the ground water it appears to be a persistent and mobile contaminant.

Sources of Nitrate

Nitrate concentrations in Iowa's surface and ground waters has generally been attributed to runoff or leaching from feedlots and barnyards (animal wastes), home and municipal sewage disposal (human wastes), other forms of solid waste disposal, industrial effluent, and the pervasive use of N-fertilizers (Coble, 1969; Morris and Johnson, 1969; among others). Yet this has never been adequately documented, nor have other sources been evaluated.

Many recent detailed studies in the U.S. of severe nitrate problems in ground water have shown evidence that natural sources are the cause of the nitrate contamination. Several studies suggest that rock formations high in natural nitrogen compounds are major contributors of nitrate contamination (Strathouse, et al., 1980; Silver and Fielden, 1980; Singh and Sekhon, 1978). In Texas, and other areas, detailed geochemical work on nitrogen isotopes (Kreitler and Jones, 1975; Wolterink, et al., 1979), indicate that naturally high nitrogen content in the soils was the source of most of the nitrate in the ground water rather than human and animal wastes, as had been suspected. Farming practices likely caused the accelerated oxidation of soil organic nitrogen to nitrate, but the source was from natural occurrence (Kreitler and Jones, 1975).

Several natural sources of nitrate must be considered in Iowa. These are the carbonate rocks forming the Karst areas, the Quaternary sediments overlying these rocks, and mineralization of organic nitrogen in the soil profile.

Chalk and Keeney (1971) analyzed the nitrate contents of carbonate rocks in Wisconsin, which are direct stratigraphic equivalents of karst-forming rocks in Iowa. They found concentrations which varied from <2.5 ppm nitrate-N (<10 ppm nitrate) to a high of 37 ppm nitrate-N (167 ppm nitrate). They suggested that these carbonates are potential sources of nitrate to percolating waters. Scrutiny of their data, however, does not suggest that this source can be significant.

Sixty-four percent of their samples, (the mode of their data) had less than their reported detection limits of 2.5 ppm nitrate-N (10 ppm nitrate), and over 90% of their analyses have less than 7.5 ppm nitrate-N (34 ppm nitrate). Using Chalk and Keeney's data for average density of these rocks, the mass of nitrate in these rocks can be calculated. At 1 ppm nitrate-N (4.5 ppm nitrate) these carbonate rocks could potentially provide 2.5 g nitrate-N (11.3 g nitrate) per cubic meter of rock dissolved. At 10 ppm (the 95th percentile of their data) 25 g nitrate-N (113 g nitrate) per cubic meter could be released. At this extreme range of their data it would only require a four-fold dilution (4 cubic meters of water, to one cubic meter limestone) to produce a nitrate concentration of about 30 mg/l--approximately the median value for 50 to 99 feet deep wells in the Karst areas (Table 5). This is a totally unreasonable possibility. It takes long periods of geologic time to dissolve these carbonate rocks, to form the karst solutional features. In terms of orders of magnitude it takes thousands of years, and even greater volumes of water to produce the karst solution features (Thrailkill, 1968). From dye-tracing studies through the karst-conduits in northeast Iowa, water flow velocities of 70 to 500 meters per hour (500-3500 ft/day) have been reported (Heitmann, 1980). Obviously, this does not allow much residence time for a unit volume of water to dissolve the rock. In short, because of the long time and large volumes of water involved, the carbonate rocks cannot be considered to be a significant source of nitrate. Some black shales in Iowa undoubtedly contain greater concentrations of natural nitrogen. However, they are volumetrically unimportant, particularly in northeast Iowa.

The Quaternary deposits, particularly the loess are another potential source. Boyce, and others (1976) report natural nitrate-N concentrations typically between 25 and 45 ppm nitrate-N (100-200 ppm nitrate) in thick loess in the dry regions of southwestern and central Nebraska. They also reported that irrigation had caused significant leaching of the nitrate. Such natural concentrations of nitrate in the loess may be related to the source area of the loess, or quite likely to climatic conditions. No similar concentrations of nitrate are known from the loess (or other Quaternary sediments) in Iowa or Illinois. In Quaternary deposits similar to Iowa's, (Walker, 1973) demonstrated that the nitrate in ground water in rural areas of Illinois was derived from fertilizers and from runoff and disposal of animal and human wastes.

Another source of nitrate is the natural mineralization and mobilization of organic nitrogen in the soil profile. Bremner (1965) estimated that 1-3% of the organic-N is mineralized per year. Keeney and Gardner (1970) point out that this release of organic-N is further stimulated by cultivation, and that the nitrate levels in some aquifers may simply be the result of the onset of farming a century or more ago. This process certainly contributes nitrate to the environment, but it does not seem likely that these contributions to ground water are highly significant. First, depending on the soil-type and the soil-drainage conditions, mineralization may release 30 to perhaps 80 lbs/acre (30-160 kg/ha) nitrate. Much of this would be utilized by plants. If not, concentrations of nitrate would build-up in the soil below the rooting zone. No evidence has been found for excessive natural nitrate concentrations in the C-horizons of Iowa soils. Only with excessive applications of N-fertilizer has nitrate build-up in the soil been documented (Schuman, et al., 1975). Some nitrate leaching into ground water will occur even with recommended rates of fertilization on row-crops (Schuman, et al., 1975; Baker and Johnson, 1981). Fertilizer application rates are much greater than natural rates of N-mineralization, however. Rainfall is another source of natural nitrogen input to the soil and water system. However, overall concentrations in rainwater are low compared to the other sources, particularly when considering fertilization rates (Tabatabai and Laflen, 1976; Baker and Johnson, 1981).

Overall, there are no apparent natural sources of nitrogen in Iowa which could contribute significant nitrate concentrations to the ground-water system. Various water-quality data support this.

As previously discussed, the seasonal fluctuation in nitrate from ground water samples points to a surficial source of contamination, resulting from seasonal application of N-fertilizer and the seasonal flushing of nitrate accumulated in the soil from unused fertilizer and animal wastes. Studies in other regions have also documented an increase in ground-water nitrate over many years, related to increased use of N-fertilizers (Singh and Sekhon, 1978; Piskin, 1974). Similar trends have been alluded to for Iowa (Morris and Johnson, 1969) but have never been documented. The previous discussion of temporal variations in water quality in Iowa presented some data that is suggestive of such a trend, but is far from conclusive. In general, there is no adequate data available to establish such a long-term trend in water quality for Iowa.

Another often cited generalization is that the nitrate concentration in streams increases with discharge (Coble and Roberts, 1971; Wahl, et al., 1978). This implies that the nitrate is related to land-surface runoff and

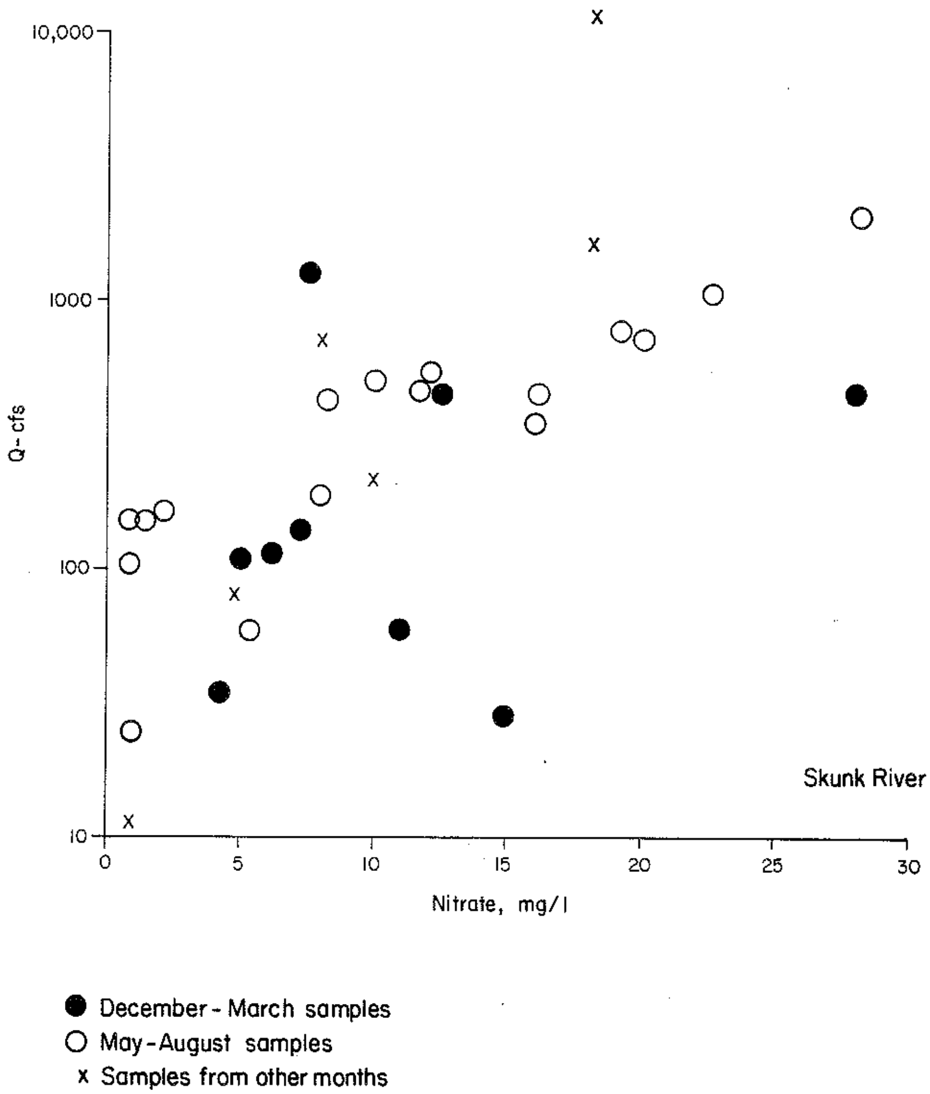

Figure 18. Plot of nitrate concentration versus discharge for water samples from the Skunk River at Oskaloosa (data from Coble and Roberts, 1971.

not ground-water base-flow contributions. This general trend can be seen in figure 18. In this data, from the Skunk River, an overall direct linear relationship between nitrate and stream discharge is apparent. However, the relationship is not really that simple. Samples taken in May through August (figure 18, open circles) show a very strong direct relationship. Winter samples (December through March; figure 18, solid circles) however, show more of an inverse relation with discharge. This trend is more apparent in figure 19, which summarizes more detailed data from December through March samples from the Iowa River collected by UHL. Although these trends are opposite in character, they both support the contention that the source of much of the nitrate is derived from land-surface runoff. The summer discharge events clearly involve runoff from N-fertilized agricultural land, soil erosion, livestock

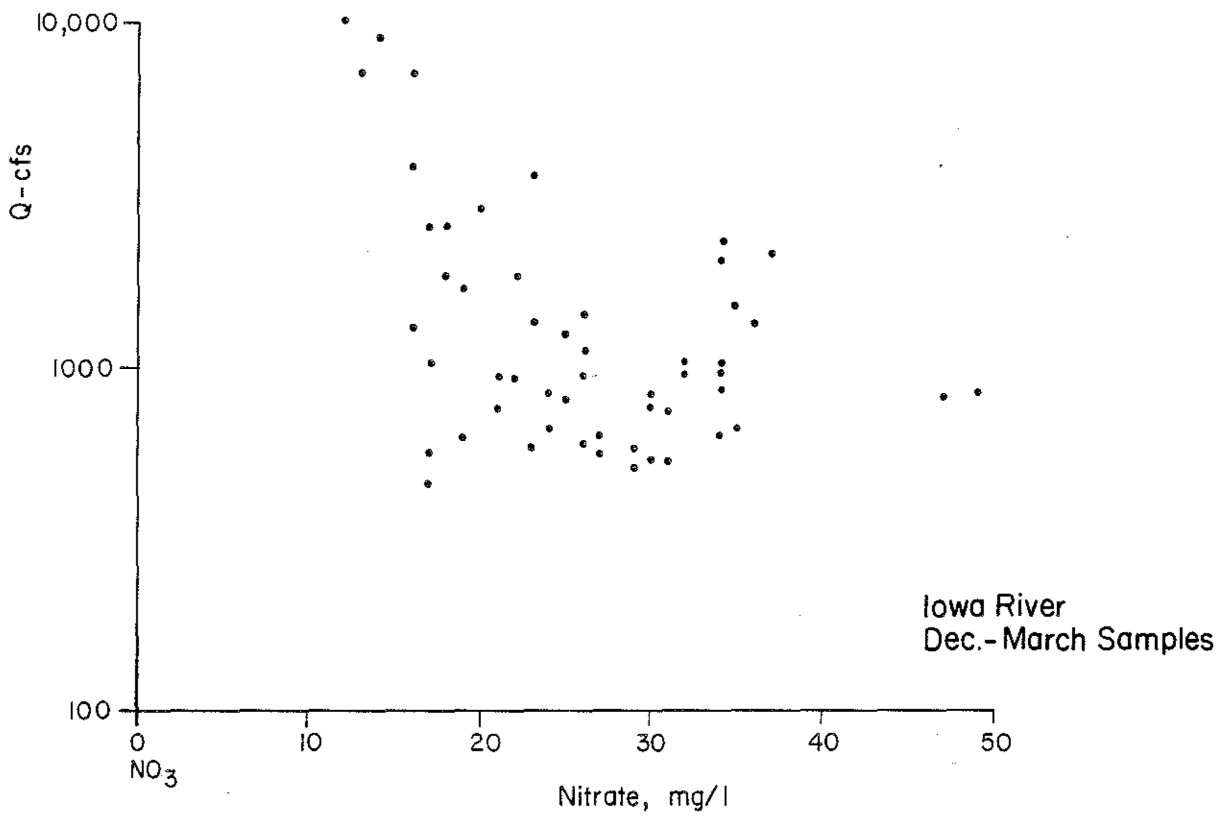

Figure 19. Plot of nitrate concentration versus discharge from the Iowa River, for water samples taken in December through March (unpublished data from UHL).

operations, and tile drainage effluent. The winter-discharge events will reflect, in part, clean snow-melt runoff which then dilutes the background levels of nitrate in the stream system.

Perhaps the most clear-cut line of evidence for the source of nitrates is found in the analysis of the large regional water-quality data sets. As noted, the distribution of nitrate values always exhibits a modal value of zero (or less than detectable) for all the geologic regions evaluated, for all the aquifers evaluated, and for all the well-depth categories. This clearly indicates that the background level of nitrate from natural sources is very low. The elevated levels of nitrate found in water supplies can be attributed to infiltration and runoff from barnyards, feedlots, septic tanks and other forms of waste disposal, and the widespread use of N-fertilizaters on cultivated land. Furthermore, the decrease in nitrate concentration with increasing well depth in all geologic settings, also points to a surficial source such as fertilizer (Piskin, 1973; Ayers and Branson, 1973). However, these findings may be complicated by effects related to the nature of the flow system.

The relationship between local environmental factors and nitrate concentration shown in the local water-quality studies is also a good indication of the surficial source of the nitrate contaminants (Walker, 1973). Often this is viewed as a problem for the individual well. But depending how the well is used, poor well construction is another avenue which allows surficial contaminants to spread into the aquifer.

Poor well construction and/or locations have been cited as the principal cause for high nitrates in well-water samples (Morris and Johnson, 1969; Coble, 1969). This is certainly a major factor, particularly in shallower wells, and is supported by the interpretations of the bacterial data from this report. However, the research of this report also clearly indicates that some regional aquifer contamination by nitrate is occurring also.

Bacterial Contamination of Ground Water

Contamination with pathogenic bacteria is a common problem in surface water supplies in Iowa. Streams often receive runoff from the land, containing fecal bacteria and viruses from livestock operations, and also receive effluent from untreated home sewage and occasionally from municipal sewage disposal systems. Bacterial contamination of wells is another indication of surficial contamination of ground-water supplies. The general cause for bacteria in ground-water samples is poor well construction or placement (Morris and Johnson, 1969; Romero, 1970, Tjostem, et al., 1977).

Most ground water does not contain harmful levels of bacteria. As water percolates through soil or sediment, to recharge an aquifer, or as water moves through the small pores of an aquifer, most of the bacteria and viruses are removed. This process involves actual filtration and a variety of chemical, physical, and biological effects, such as: oxidation and various chemical changes which may kill the bacteria; temperature changes; or the bacteria may be destroyed by the natural soil bacteria, for example. Great numbers of bacteria are effectively removed from water by percolation through just a few feet of fine sand (Romero, 1970; Beer and Effert, 1981). Bacteria often do not reach, or at least do not travel very far in the typical ground-water environment.

Bacterial contamination of a well often occurs because surface drainage from barnyards, for example, is allowed to run into or seep into the well. If a well is placed too close to a feedlot or to a septic tank, or other forms of home-sewage disposal systems, bacteria-laden water may be able to flow the short-distance without being adequately filtered, and then seep into the well. Various factors may influence the seepage rate and distance bacteria can effectively travel (see Romero, 1970). Besides improper well placement or construction, other factors can lead to bacterial problems in home-water supplies, such as leaky water lines, or poorly placed, permeable water storage systems.

The carbonate aquifers however, are also prone to larger scale bacterial contamination because of their direct contact with surface water and the open flow in conduits. For example, surface-water runoff from a feedlot may run into a sinkhole and directly enter the ground-water system without any filtration. Flow through a large solution conduit may not provide any filtration and in the subsurface may not provide significant aeration to destroy the bacteria either. Studies in karst terrain in Missouri (Harvey and Skelton, 1968) show that bacteria from sewage plant effluent, which entered a solution conduit, persisted in the ground water to its discharge point from a spring. Although the effluent was diluted, the bacteria were not removed.

Bacteria may also persist and move long distances along the much smaller fractures which occur in the carbonate rocks (Allen and Morrison, 1973). This has much broader implications for all of the Karst and Shallow Bedrock areas in northeast Iowa. With a very thin soil mantle over the rock, bacteria-laden water may readily infiltrate the inconspicuous fractures which are pervasive in the carbonate rocks.

Runoff into surface water and infiltration from barnyards, feedlots, and sewage systems are obvious sources of bacteria (and nitrates) which may enter the karst aquifers. Home sewage disposal often is inconspisuous but can be a serious problem in the Karst and Shallow Bedrock areas (Hallberg, 1981). In these areas there may not be sufficient soil material for the proper operation of a conventional septic tank and lateral filter field operation. This may allow the infiltration of effluent into the fractured rock. Worse yet there are many documented cases where home sewage effluent is discharged directly into sinkholes. In most instances this was done for convenience, and generally out of ignorance of the possible consequences. Alternative waste water disposal systems (mound or double sand filters) should be used in these areas (Beer and Effert, 1981).

Along this same line, many cases have occurred where dead animals and other organic materials, such as creamery wastes have been dumped into sinkholes. Such cases provide additional local sources of possible pathogens that may infiltrate the ground water in the Karst area.

The analysis of the coliform bacteria data used for this study did not find any conclusive evidence that bacteria problems were related to the Karst areas. However, the data show that bacteria problems are very widespread, and are likely related to local environmental factors. Such local factors complicate the analysis and may obscure any contamination unique to the Karst areas. However, the data does show substantially more wells with coliform bacterial problems, than would be predicted from the whole data set. Case studies have shown that bacterial contamination may become more than just a local problem related to an individual well in the Karst areas. This is a problem which will require more detailed study in northeast Iowa.

Sources of Surficial Contamination to Ground Water in the Karst Regions

Sources of surficial contaminants to the ground water in the karst regions have been repeatedly mentioned throughout the report. In this section specific details of these various sources will be discussed. Two processes must be considered in the delivery of these contaminants: downward leaching of material with percolating recharge water into the aquifer; and runoff from the land surface. In most settings, runoff water is not of great concern in ground-water contamination, except where surface water percolates into the ground to recharge an aquifer. As described, surface runoff and streams may directly enter the ground-water system in the Karst area. Thus, the non-point sources of pollutants to surface water, such as soil erosion, runoff and tile-drainage water containing chemicals from agricultural land (see Baker, 1980), are perhaps the most important sources of contaminants entering the ground water system in the Karst areas.

In a study of the problems of agricultural drainage wells Musterman and others (1981) concluded that nitrates and pesticides from agricultural tile and surface drainage waters are the major contaminants of concern for public health in the drainage-well injectant. These findings are appropriate because drainage wells are essentially man-made sinkholes, and most of the drainage wells are located in carbonate aquifers. To their list we would add the concern for bacterial contamination previously discussed. Various other chemicals are involved in agricultural runoff and home sewage leachate, but few are as persistent or as large a concern for public health as nitrates, pesticides, and bacteria. Thus, the ensuing discussion will deal principally with sources of these contaminants.

Miscellaneous Point Sources

A variety of point sources of pollutants exist in the karst areas. One source is the common use of sinkholes to dispose of solid waste. As would be expected, field surveys by IGS staff and published reports (Heitmann, 1980), show a wide variety of materials have been dumped in sinkholes, including domestic garbage, dead animals, manure, spoiled grain, pesticide containers, and a variety of scrap metal products. Many of these products may contribute contaminants to the ground water through the sinkholes. Diseased animal carcasses have caused bacterial problems in wells in this region in the past. A few sinkholes are known which served as municipal garbage dumps in the past. These sites were abandoned for regulated regional landfills and were covered with soil. However, they continue to be a threat to ground water. During the fall of 1981 at one such site in Clayton County, the soil and garbage collapsed into the sinkhole, depositing it in a solution conduit.

With the establishment of regulated, regional landfills such dumping is not as common anymore. Some still continues on the local level, even though there are some regulations regarding dumping in sinkholes.

Occasional discharge from municipal sewage treatment facilities and industrial effluent into surface water will also contribute some possible contaminants. Again, this is a much less frequent problem now than in the past. Such waste disposal is regulated but it still happens infrequently.

The disposal of creamery wastes into sinkholes and streams is a recurrent problem in northeast Iowa (e.g., Heitmann, 1980). Even though there are rules and regulations to prohibit this, it still occurs. Better enforcement of these regulations and clarificatin of regulations regarding dumping into sinkholes might help to improve the situation.

Runoff from feedlots and livestock operations is another obvious source of ground-water contamination. In places, IGS staff have observed this runoff discharging directly into sinkholes. Many feedlots also occur in areas where thin soil materials overlie the jointed carbonate rocks. As discussed in preceeding sections, this may allow substantial infiltration of water with elevated nitrate levels and bacteria into the joints or fractures in the rock. This is a potential problem throughout the shallow-rock hazard area (Plate 6), not just in the sinkhole areas.

Effluent from home sewage disposal is another common source of bacteria and nitrates, as previously discussed. Even where conventional septic tank-filter fields are properly installed they may still leach contaminants to the ground water where soil materials are thin over the fractured rock (Hallberg, 1981). Again, this is a problem throughout the delineated hazard areas. Use of alternative home sewage systems should be encouraged in these areas. State Health Department rules already prohibit the discharge of home sewage systems into sinkholes. This practice continues, partly out of ignorance of the potential consequences, partly because the rules are impossible to enforce.

Another point source, of sorts, are agricultural drainage wells. Although these are now illegal many old ones do exist. In the study area they occur most frequently in the Floyd-Mitchell County area and discharge into the same carbonate aquifers as the sinkholes. Because of their small numbers they probably do not have nearly as significant an impact on water quality as the sinkholes (Musterman, et al., 1981).

A similar minor source which has been noted is the use of sinkholes for road drainage. Drainage ditches along county roads often are graded to sinkholes. In some instances grates have even been placed over the sinkholes so that they don't plug up with debris. In some areas this is unavoidable, but this practice should not continue where it can be avoided.

Non-Point Sources

Non-point sources are the major concern for ground-water quality in the Karst areas. These sources are also the most difficult to resolve. Of primary concern is the infiltration of water, the discharge of tile-drainage water, and direct land-surface runoff of water and eroded soil, which contain nitrates and pesticides (see Baker, 1980).

The amount of these products lost from the land are affected by a number of variables, including: the application rate of N-fertilizer, both past and present; crop type, crop yield and rotation; tillage and land-treatment practices; the soil-type, especially certain physical parameters such as organic matter content and texture; slope of the land surface; the moisture regime of the soil; seasonal precipitation, as well as the rate and timing of particular precipitation events; and evapotranspiration (Schuman, et al., 1975; Burwell, et al., 1976; Amemiya, 1977; Singh and Sekhon, 1978; Baker, et al., 1978; Musterman, et al., 1981; Baker and Johnson, 1981). These variables interact in a complex fashion also. For example, during a dry year, corn yields may be depressed resulting in less plant uptake and removal of N from the soil. If this is followed by heavy fall or spring rains it may result in higher nitrate infiltration or runoff than normal. If heavy rains immediatley follow tillage or pesticide applications significant soil and chemical losses may occur.

Although the system is complex, some generalizations can be made.

Nitrates

Excess, unused nitrate may be leached downward through the soil, below the depth of plant utilization. If it is, it may reach the water table and enter the ground-water system of an aquifer. With the variations of weather patterns and other factors which effect crop yields some nitrate leaching will always occur. However, the most certain cause of excess nitrate buildup in the soil and leaching to the water table is "over-fertilization." Application of N-fertilizer in excess of optimal-recommended amounts may result in significant nitrate accumulation in the soil profile (Schuman, et al., 1975; Gast, et al., 1978). In western Iowa, Burwell, et al. (1976), showed that fields fertilized at 2.5 times the recommended rate leached nearly 3 times as much nitrate into the shallow ground water as areas fertilized at the recommended rate.

The fractured nature of the carbonate rocks create conditions very conducive to the leaching of nitrate into the shallow carbonate aquifers (Barker and Foster, 1981). Particularly where the soil cover over the carbonate rocks is thin (Plate 4) these fractures may act as vertical macropores in the subsoil. Particularly when the soil has had a chance to drain and dry somewhat, a new rainfall, or infiltration event may cause significant and rapid water movement through macropores, in lieu of piston flow which displaces all the soil water (Thomas and Phillips,1979; Quisenberry and Phillips, 1976). This results in increased movement of nitrate and other solutes through the macropores (Shufford, et al., 1977; Baker and Johnson, 1981; Pettyjohn, 1982). Leaching is not as thorough with flow down macropores as it is with displacement flow, but it will produce nitrate leaching that would not occur if all the water went into displacement flow. Again, this is of concern in the entire shallow bedrock hazard area (Plate 6).

The leaching of nitrate to shallow aquifers is of concern in all areas of Iowa, not just the Karst areas. Indeed the analysis of the water quality data presented in this report shows that shallow aquifers throughout Iowa are exhibiting significant levels of nitrate contamination. Using recommended amounts of N-fertilization no nitrate build-up has been found below the rooting zone (Schuman, et al., 1975; Baker, 1980; Baker and Johnson, 1981). Although minor leaching to the ground water may still occur (Schuman, et al., 1975; Burwell, et al., 1976; Baker and Johnson, 1981) adherence to optimal, recommended application rates will minimize the risk of pollution from nitrate leaching (Singh and Sekhon, 1978; Hallberg, 1976).

Tile-drainage effluent and discharge from ephemeral streams in Iowa exhibit varying concentrations of nitrate but usually exceed 45 mg/l (Baker, et al., 1978). Shallow tile drainage is particularly troublesome because it increases nitrate losses from the subsoil (Baker and Johnson, 1977; Harmon and Duncan, 1978). If this nitrate had remained in the soil, the greater residence time may have allowed greater plant uptake and more denitrification to take place. Dependent on fertilization rates and rainfall patterns tile drainage can remove excessive amounts of nitrate from the subsoil and deliver it to surface water systems. Nitrate concentrations in surface runoff from row-cropped areas are generally much less than in shallow tile-line effluent (Baker, et al., 1978)

Nitrate concentrations in tile-line effluent in Iowa vary. In reviewing reported values, Musterman, and others (1981), found these concentrations to range from about 3.5 to 195 mg/l nitrate (see also Baker and Johnson, 1977). The concentrations in comparative studies were always higher than surface runoff waters which ranged from less than 1 to about 75 mg/l nitrate. During peak tile-discharge periods, the tile effluent may significantly increase the nitrate concentration of even large streams (Baker and Johnson, 1977). Though surface water-stream flow does dilute the concentration.

Musterman and others (1981) monitored the injectant water at four agricultural drainage wells in Humboldt County, Iowa. Three of these wells collected principally tile drainage water. The nitrate concentrations of this effluent averaged from about 14 to 90 mg/l. The fourth well received principally surface runoff water and it averaged about 16 mg/l nitrate.

Flow-weighted average concentrations (i.e., concentrations related to the actual volume of tile discharge over time) provide more meaningful summaries of concentrations in the tile effluent. Flow-weighted data is available from studies in Johnson, Floyd (Musterman, et al., 1981), and Story Counties (Baker and Johnson, 1981). Ten tile lines in Johnson County were monitored for ten months. Measured concentrations varied from about 7 to 130 mg/l nitrate, with a flow-weighted mean concentration of about 47 mg/l nitrate. In Floyd County 2 sites gave mean concentrations of 41 and 61 mg/l nitrate. In Story County tiles lines under normal N-fertilization rates varied from about 80 to 90 mg/l nitrate, while a tile line under a heavily fertilized experimental plot had a flow-weighted mean concentration of about 180 mg/l nitrate. In a review of various data Musterman and others (1981) concluded that a flow-weighted concentration of 45 mg/l nitrate was a reasonable mean value for tile discharge water for Iowa and that a reasonable maximum for normal farming would be about 90 mg/l nitrate.

These concentrations in tile effluent water are particularly significant because tile-discharge may contribute from 30 to 80% of the drainage from fairly level, tile-drained land in the Midwest (Baker and Johnson, 1977). This takes on even greater meaning in the Karst areas because many tile lines discharge directly into sinkholes, providing a direct route for the nitrates from the field to the ground-water system. Where tile lines don't drain directly into sinkholes, they will discharge into streams of varying size. Some of these streams will also discharge through sinkholes, open shafts in their beds, or through diffuse means into the ground water in the Karst region.

The other consideration in non-point sources is surface runoff and soil erosion. Surface runoff water will carry with it eroded soil particles (sediment), nitrates and other nutrients and chemicals, which will travel both in solution and attached to the sediment. Flow-weighted average nitrate concentrations in surface runoff range from less than 1 to about 75 mg/l nitrate, but are typically in the range of 5 to 25 mg/l nitrate (Baker, 1980). As with other forms of N loss, nitrate is the dominant form, generally four to five times higher than ammonium. Nitrate concentrations in surface runoff are generally less than the concentrations in tile drainage, but the relative importance of each depends on local conditions which effect the total volume, or flow-weighted contributions from each source.

Nitrate losses in surface runoff vary and are affected by the many variables outlined above. However, most studies indicate that nitrate losses are not strongly affected by the level of N-fertilization (Baker, 1980). The reason may be that nitrate losses in surface runoff are relatively small, generally less than 5% of the fertilizer N applied (Baker, 1980; Musterman, et al., 1981). By contrast, nitrate losses through tile drainage may range as high as 40% of applied N (Musterman, et al., 1981).

Rainfall simulation studies in Iowa show that N-losses with runoff water are small compared to N-losses with the eroded sediment (Barisas, et al., 1978; see also Hubbard, et al., 1982). Many conservation tillage practices were ineffective in reducing the water soluble nutrients, however they did reduce total nutrient losses by controlling soil erosion. Other studies have shown that much of the N associated with the sediment, however, is organic-N (Baker, 1980). Organic-N is not immediately available, and must be mineralized to form nitrate, thus its impact on water quality is not clear.

The sediment derived from soil eroson is a problem for water quality by itself. Again, in the Karst regions, many wells which have chemical water quality problems are also noted to have turbidity problems. Surface water and its sediment load may enter open conduits in the Karst areas, producing turbidity problems especially during runoff events.

Considerations of control measures, or best-management practices (BMP) to improve water quality in the Karst areas must address both land-treatment for runoff and soil eroson as well as existing tile-drainage systems. This makes the problem very complex because many types of land treatment which reduce soil erosion and runoff increase infiltration. This may increase leaching of nitrate and increase tile discharge (Baker and Johnson, 1977; Baker, 1980). Tile drainage, in some areas already yields significant contributions to stream flow (Baker and Johnson, 1981), and may be the largest contributor of nitrate in portions of the Karst areas already.

Optimizing the efficiency of N-fertilizer must be part of any management plan to reduce the risk of nitrate polluton (Singh and Sekhon, 1978; Hallberg, 1976). Baker and Johnson (1981) provide an appropriate summary statement: "To avoid NO_3-N leaching losses and increase efficiency of N use, better management practices are needed, not only for high-fertility practices, but also for modest fertilization. Methods, number and timing of applications, the chemical form used and the use of nitrification inhibitors are some of the factors that can be manipulated to better match N availability to crop need. More experimental work and continued development and use of mathematical models are needed to determine what combination of these factors should be used to maximize the efficiency of N use for the different conditions of soils, weather and management that exist."

Pesticides

Pesticides could not be evaluated as a parameter of ground-water quality in the Karst areas because almost no data exists. Pesticides must be of concern, however. As stated earlier, is the significantly higher nitrate values of the Karst region symptomatic of ground-water contamination with other widely used chemicals, such as pesticides? Some facets of this question can be addressed.

Various reports state that pesticides are generally not found in ground or tile drainage water, but when they are it is usually at dilute concentrations (Baker, 1980, p. 282). However, it is worth repeating that there is not that much data available, particularly for ground water. Most records of pesticide contamination in wells are from accidental spills (Morris and Johnson, 1969).

Other reports indicate that pesticides are common in surface water in Iowa, particularly when the water is turbid from land surface runoff (Morris and Johnson, 1969; Musterman, et al, 1981; UHL Communication, 1981). The interaction of runoff water, surface water and ground water in the Karst areas again suggests that pesticides pose a potential problem.

Some data exist to highlight this problem. As noted, during the dye-tracing study in Fayette County water samples were taken from tile lines emptying into two sinkholes. The effluent from both tile lines showed the presence of Atrazine and Lasso. This effluent water went into the sinkhole and directly into the karst ground-water system. The concentrations were low (υg/l, ppb range) but they were present and clearly enter the ground-water system.

Musterman and others (1981) monitored the injectant water to four agricultural drainage wells in a carbonate aquifer in Humboldt County. As noted previously, the water entering these wells is a reasonable analogy to the water running into a sinkhole. During low-flow, principally from tile lines (in late May, 1980) they found the following ranges of concentrations for different pesticides in the injectant: Bladex, ND-0.83 υg/l; Lasso, ND-0.80 υg/l, Sencor, ND-0.41 υg/l; and Dieldrin 0.005-0.016 υg/l. Following a rain storm they found the following concentrations in the injectant, which included tile effluent and turbid surface runoff: Bladex, 0.70-80.0 υg/l; Lasso, 0.70-55.0 υg/l; Sencor, ND-0.20 υg/l; Banvil, 0.09-12.0 υg/l; and Dieldrin 0.007-0.028 υg/l. They also sampled a nearby well and after the runoff event produced the higher concentrations of pesticides they found 2.7 υg/l Lasso and 0.15 υg/l Sencor in the water from the well. These examples illustrate that undoubtedly some pesticides are entering the ground-water system in the Karst areas.

Pesticides may be of some lesser concern at present day since the highly persistent, and more toxic chlorinated hydrocarbon pesticides (DDT, DDE, Aldrin, Dieldrin, etc.) have been banned. Many of the modern organic pesticides have half-lives of only a few weeks (Baker and Johnson, 1979), Atrazine being a noteable exception. However, the health consequences of injection of even these small quantities (υg/l or ppb range) are unclear.

It is interesting to note the presence of Dieldrin in Musterman and others' (1981) 1980 sample. Dieldrin may be a degradation product from Aldrin, but both were banned many years before this, yet it continues to show up in samples such as these. The chlorinated hydrocarbons have a high persistence and also attach to sediment. Thus, it is likely that some of these products may also be stored in sediment in the conduits of the karst ground-water system. Future studies should attempt to sample and analyze such deposits.

Nearly all studies have shown that pesticide concentrations in tile effluent are quite low, less than 1 υg/l. Except in unusual circumstances, most of the pesticide losses are in surface water and sediment runoff (Baker and Johnson, 1977). Some pesticides attach and travel more with the sediment while others travel in the water (Amemiya,1977). Generally though, because of the greater volume of water, the major part of pesticide losses occur in solution in runoff water (Baker and Johnson, 1979). Thus, many types of conservation tillage and erosion control will not necessarily control pesticide losses (Baker, 1980; Baker and Johnson, 1979). This factor, combined with the short half-life of most modern pesticides, make the timing of rainfall events after pesticide application a critical factor in the amount of pesticide loss. Rainfall within a few days following application will cause much greater losses than 7 to 10 days later. Given these factors, it is suggested that pesticide incorporation (not feasible for some pesticides) may be a BMP (Baker, 1980). It is also a matter of education to point out that such chemicals should not be applied shortly before an expected rainstorm. However, it is also a reality that this is not always feasible.

Summary: Non-Point Sources

The delivery of nitrates and pesticides into the ground-water system in the Karst areas is complex and occurs by direct infiltration, tile drainage, and surface water and sediment runoff which enter sinkholes, as well as from point sources.

Although little data is available, pesticides undoubtedly enter the ground-water system in the Karst area, albeit in very low concentrations. The health effects of this are unclear. It also seems likely that now-banned chlorinated hydrocarbon pesticides may be "in storage" in sediment in the karst conduit systems.

Control programs or BMPs must take into account many complex variables as well as the nature and needs of particular farm operations. Conservation measures which reduce sediment and surface water runoff, thus reducing sediment, nutrient and pesticide losses in runoff, may also increase tile drainage and nitrate losses through tile discharge. Any program to alleviate these problems must consider the nature and extent of already existing tile drainage. Tile drainage will be a much greater factor in the Floyd-Mitchell County Karst areas than in the remaining Karst areas. Simple measures, such as incorporation of pesticides, and better N-management recommendations are a must. Many of these measures can only be achieved through effective public education.

SUMMARY AND CONCLUSIONS

Northeastern Iowa is generally considered to have Iowa's most abundant supplies of good quality ground water. Yet in recent decades public officials and private citizens have expressed concern for the continued quality of their public and private well- or ground-water supplies. This concern stems from many local cases of contaminated water and reports from well drillers having increased difficulty in finishing wells with high-quality water. These problems arise because many of the most important water-bearing bedrock units, or aquifers in the region are comprised of limestone or dolomite, collectively referred to as carbonate rocks. Such carbonate rocks comprise the Silurian-Devonian aquifer, a thick, widespread source of ground water, as well as the Galena aquifer, a more geographically restricted aquifer in northeast Iowa.

Ground-water quality problems arise in carbonate aquifers because of their unique properties. In these carbonate aquifers, water movement occurs along "cracks" in the rock instead of through pores between individual grains. These cracks are secondary openings related to the structural and stratigraphic features of the rock. Carbonate rocks are subject to chemical solution, and as water moves through these cracks it slowly dissolves the adjacent rock. Over time these secondary openings are enlarged, and the ground water moves through a series of interconnected openings which range from microscopic fractures to large caves. The flow of water in these large openings is analagous to flow through a pipe; it may be very rapid and there is not the natural filtration that typically takes place in ground-water flow.

Another consequence of the solution of carbonate rocks is the development of unique land-surface features, collectively referred to as karst topography. One of the more conspicuous and important features is the sinkhole. Sinkholes form as a consequence of rock solution and collapse. At the surface, sinkholes appear as conical depressions. As depressions the sinkholes will collect surface drainage, and occasionally they will intercept and "swallow" entire streams. This is one of the major problems with sinkhole regions. The sinkholes provide a direct conduit for surface water to run directly into the underground cavities in the limestone, and join the ground-water system. These surface waters, and the contaminants they may carry, can reach the ground water in a wholly unfiltered state. As a consequence, carbonate aquifers are highly susceptible to contamination by surface runoff from agricultural or industrial land, effluent from sewage or waste disposal, or surface spills of various kinds. Also, sinkholes often have been used as discharge points for drainage tiles and even septic systems. Furthermore, sinkholes provide a common and convenient, though potentially dangerous, place to dispose of solid waste materials. Observations and case studies in Iowa have shown local occurrences where everything from solid refuse, to old chemical containers, car bodies, creamery wastes, and even dead animals have been dumped into sinkholes. Out-of-site is not necessarily out-of-mind in these instances, because this dumping has sometimes seriously contaminated local water supplies.

These localized cases have naturally raised the question of whether regional contamination of these aquifers is occurring. If so, it could threaten Iowa with long-term water-quality problems and could impact public health as well as local economies. If this is happening, are widespread control measures necessary to alleviate this contamination? To answer such questions, more fundamental issues must be addressed first: Where are the karst areas? What are their relationships to the ground-water flow system? Is there any evidence for regional degradation of ground-water quality? Until this study there has been no systematic analysis of Iowa's karst areas or the potential regional water-quality problems that might be associated with them. This study focused on 22 counties in northeast Iowa, which include the principal karst areas of Iowa.

Distribution of Sinkholes in Northeast Iowa

Using detailed, modern, soil survey maps, IGS well and quarry records, other field records, and IGS color-infrared aerial photography, the distribution of sinkholes, areas of bedrock outcrop, and the depth to bedrock was mapped. Over 12,700 sinkholes were mapped in the area. One township had more than 1,000 sinkholes. The actual number of sinkholes is not static, however, as new sinkholes continue to form every year.

There are three main areas of sinkhole concentrations: 1. In the area of exposure of the Galena rocks, in southwestern Allamakee County and adjacent areas; 2. Along the topographic escarpment of Silurian rocks in southern Clayton County and adjacent areas; and 3. In the outcrop area of Middle Devonian age limestones adjacent to the Cedar River particularly in Mitchell and Floyd Counties. The Galena rocks are an important source of ground water locally in northeast Iowa, and the Silurian-Devonian rocks form one of eastern Iowa's most important aquifers.

A review of the soil and well record information shows several things. First, sinkholes only appear in areas where there is less than about 30 feet of unconsolidated-soil materials over the bedrock. Within the study area the depth to bedrock varies from 0 to nearly 500 feet. The depth-to-bedrock maps compiled for this analysis are the most complete maps of their kind ever produced in Iowa. These maps will have utility for other environmental and engineering purposes.

Using all this geologic information, the study area was subdivided into three geologic regions: 1. Karst--areas with significant concentrations of sinkholes; 2. Shallow Bedrock--areas where bedrock occurs within 50 feet of the land surface, but which are not marked by numerous sinkholes; 3. Deep Bedrock--areas where bedrock is deeply buried, more than 50 feet beneath the land surface. These subdivisions were used to evaluate the potential hazards to the carbonate aquifers from surficial contamination, and to evaluate the ground-water quality data. Both the Karst and Shallow Bedrock areas present potential hazards to the bedrock aquifers, because of the shallow depth to bedrock. Because of the sinkholes the potential problems in the Karst areas are greater, but the Shallow Bedrock areas must also be dealt with cautiously. This view is supported by other studies on water movement and water quality in analogous areas, as well as the water quality data in this report.

Ground-Water Quality

All pertinent and readily accessible data on ground-water quality were compiled for analysis. The data evaluated were restricted to nitrate concentration and coliform bacteria, because these two parameters are the most widely available, they are related to health standards, and are uniquely related to ground-water contamination from surface sources. The data set used most extensively was provided by the University Hygienic Laboratory (UHL) and included over 6,000 nitrate analyses and over 8,000 bacterial analyses from the study area. All were from well water samples within the study area which were analyzed by UHL during 1977 through 1980. Various other data were analyzed, including the WATSTORE data file, and a variety of published and unpublished studies which provided greater geologic controls, but were limited in number and areal extent. Extensive data stratification and statistical tests were applied to the UHL data.

Many conclusions can be drawn from the various data sets evaluated. The concentration of nitrate or bacteria in the ground water may fluctuate seasonally, where a water source (the well or the aquifer) interacts with surface activities. This seasonal fluctuation can seriously affect the conclusions drawn from some data sets. Local studies demonstrate that the degree of nitrate and/or coliform contamination for a given well may be related to on-site factors such as poor well placement and/or construction. Poor well placement and/or construction is not always just an individual problem; such wells may allow contaminants to spread into the aquifer as well, dependant on the hydrologic setting. A review of the various water-quality data pointed out that there is no readily availabale data that is adequate for assessing long-term changes in water-quality. The data was usable for assessing the present problems of the karst areas, however.

The frequency-distribution of nitrate values shows two features, in all the data sets. The nitrate values always exhibit a modal value of zero (or less than detectable), and the frequency of observations decreases with increasing nitrate value. This was true for any breakdown of the data used (i.e., by geologic setting, by aquifer, by well-depth classes, etc.). Also, in all data sets evaluated, nitrate concentrations decrease with increased well depth, regardless of the aquifer involved.

The potential contributions of nitrate from natural sources were reviewed and these sources are not likely to be significant. The fact that the modal concentration of nitrate for all the geologic regions, well depth classes, etc., was zero (or less than detectable) clearly indicates that the background level of nitrate from natural sources is very low. The elevated levels of nitrate found in water supplies can be attributed to various surficial sources, such as infiltration and runoff from barnyards, feedlots, septic systems and other forms of waste disposal, and of course the widespread use of nitrate fertilizers.

Although there are many problems in the analysis of the water-quality data (such as the seasonal variations) the large number of samples in the UHL data set will overcome many of these problems. The UHL data was compiled over a four-year period and effectively integrates many of these variations. Because the UHL samples cannot be accurately located (i.e., to legal coordinates) the data was aggregated by rural route postal addresses. The data was assigned to 247 sample centers--or towns which constituted the rural route postal stations. The data for each of the sample centers was aggregated into categories by well depths. Further, using the maps which characterized the physical setting of the region, each sample center was classified as part of either the Karst, Shallow Bedrock or Deep Bedrock geologic setting.

The data analysis shows that coliform bacterial contamination of rural water supplies is widespread; 35% of all the UHL analyses record unsatisfactory or unsafe levels of coliform. However, the distribution of elevated bacterial levels is relatively uniform among all geologic settings and well depths. This suggests that bacterial contamination is introduced from the well or the water-system and not as a result of aquifer contamination. The UHL data consists largely of "tap" water samples, not samples directly from the well, so these variables cannot be adequately addressed. Also, the MPN method for coliform counts, used by UHL, makes statistical analysis difficult, and the results vague. Further research is needed because case studies indicate that bacterial contamination of ground water can be a problem in the Karst areas. Overall the bacterial data does indicate that water-system problems which introduce bacteria are very common and present a serious potential health problem.

The results of the analysis of the nitrate data are much more clear. Statistically, the concentration of nitrates clearly decreases with increasing well depth. In general, the highest nitrate values occur in samples from wells less than 50 feet deep. Data from wells between 0 and 49 feet deep uniformly show high median nitrate values, regardless of the geologic region they come from. Data analyzed for the state as a whole show identical results. This indicates that shallow wells in Iowa--regardless of the aquifer involved--are susceptible to contamination by nitrates, and indeed are exhibiting significantly high levels of nitrate.
In the Karst and Shallow Bedrock regions, where the soil cover is thin over the carbonate aquifers, significantly high levels of nitrate occur to depths of 150 feet in the bedrock aquifers. Ground-water supplies in the Karst region in wells from 50-150 feet in depth show significantly higher levels of nitrate contamination (summarized in Table 13). In the 50-99 foot well depth group the median value for nitrate in the Karst regions (34 mg/l) is 1.8 times higher than in the Shallow Bedrock regions (19 mg/l) and nearly 6 times greater than in the Deep Bedrock regions (6 mg/l). These differences are highly significant statistically. As evident in the median nitrate values (Table 13) the Karst areas show the greatest nitrate contamination, and are followed closely by the Shallow Bedrock region.

Nitrate contamination in the Karst regions is most pronounced to a depth of 100 feet. At greater depths the median nitrate concentrations in the Karst areas decrease and are similar to those in the Shallow Bedrock Area. This suggests that the diffuse infiltration of nitrates, the process which dominates in the Shallow bedrock regions, is a significant factor and is the process which produces the elevated levels of nitrate found to depths of 150 feet in the carbonate aquifers. The significance of the sinkholes and better

Table 13. Summary of median nitrate values (in mg/l) from UHL analyses from study area.

Well Depth Category (feet)	Karst Median	Geologic Setting Shallow Bedrock Median	Deep Bedrock Median	Total Median
50 - 99	34	19	6	18
100 - 149	23	16	0	7
150 - 499	3	5	0	0
over 500	0	0	0	0
Unknown	22	7	0	5
Total excluding less than 50 feet and unknowns.	18	9	0	3

developed solutional conduits in the Karst regions may be viewed as the pronounced difference in median nitrate concentrations (15 mg/l) between the Karst and Shallow Bedrock regions in the 50-99 foot depth range. Thus, if management strategies are developed to try to improve or protect ground-water quality in the carbonate aquifers, the entire Shallow Bedrock area, as well as the Karst areas, must be included in the considerations. The entire Shallow Bedrock and Karst hazard area constitute 53% of the study area, or over 6,800 square miles of important recharge area for these bedrock aquifers.

As a matter of perspective, it must be pointed out that all of these median nitrate values are below the 45 mg/l nitrate drinking water standard. However, a median of 34 mg/l in the 50-99 foot range in the Karst areas also means that 50% of all the analyses in this group are in excess of 34 mg/l. For the study area as a whole, 18% of all the samples exceeded the 45 mg/l threshold. Within the different geologic se ttings, 25% of analyses from the Karst areas, 19% in the Shallow Bedrock, and 15% in the Deep Bedrock areas exceeded 45 mg/l.

As noted above, local well-placement and construction affect the degree of nitrate and coliform contamination recorded by an individual well sample. As discussed, local factors seem to strongly affect the results of the analysis of the bacterial data. The high, significant correlations of the nitrate data with geologic setting however, indicate regional aquifer effects, not just water-system problems. This is supported by the many reports of newly-drilled wells in the carbonate aquifers which have high nitrate levels, and by the presence of nitrates in water samples from karst springs. The nitrate concentration recorded from any particular well will likely be a function of the regional level of nitrate in the aquifer, and the local source effects. Wide variations in nitrate levels will occur in local areas because of these variables. Wells which only intercept small fractures in the carbonate rocks will tend to have lower nitrate concentrations and lesser seasonal fluctuations than wells which are open to larger conduits. This is related to the nature of ground-water flow in the carbonate aquifer system. In this regard there are many unanswered questions, such as, will nitrate concentrations in the carbonate aquifers continue to increase? Or have these concentrations reached an equilibrium with current land use and recharge factors? A long term, ground-water quality monitoring network will be needed to answer such questions.

Another issue of concern is whether or not the significant nitrate contamination noted in the Karst regions is symptomatic of contamination by other widely used chemicals. Few data are available. What little data there are, clearly shows that pesticides are also entering the carbonate aquifers. The fate of these chemicals in the ground-water system is unclear, as are the health effects of small concentrations of these chemicals. Although further research is needed, this clearly is not a desirable situation.

Ground-Water Flow Systems

Ground-water flow systems in carbonate aquifers are complicated because of the complexities of flow through solution conduits, and the intimate interaction that develops between the surface-water and ground-water systems. The volume and extent of the conduit systems tend to decrease markedly with depth below the piezometric surface in a carbonate aquifer. This may "decouple" the shallow conduit system from the deeper portions of the aquifer which are marked more by diffuse flow through much smaller openings. This decoupling takes place because of the contrast in hydraulic conductivity between the shallow, open, conduit flow-system and the deeper diffuse flow-system. From the extant data the overall nature of the ground-water flow systems in the carbonate aquifers can be generalized.

By relating the sinkhole distribution to the ground-water flow system some inferences about water quality conditions can be made. In the interior of the Silurian-Devonian aquifer area the majority of the sinkholes occur in the proximity of discharge areas, such as the Cedar River. Surface contaminants, such as nitrate, should likely be contained in the shallow part of the flow system. This may, in part, explain why significant nitrate contamination is confined to relatively shallow depths (150 feet) in the Karst areas. An alternative which must be considered, because of the lack of detailed vertical head data in the aquifer, is that there has not been enough time for the nitrates to diffuse into the deeper portions of the aquifer. The available evidence suggests that the majority of the surface contaminants should be confined in the shallow portion of the aquifers.

The most notable exception to this is in the Karst area in the Galena aquifer. Data on the physical setting of the Galena suggest that prominent karst solutional conduits will extend to relatively greater depths, and some of the nitrate data support this likelihood.

The effects of the prominent sinkhole terrain along the Silurian escarpment are confined to a narrow belt of shallow local flow systems, which drain toward the escarpment and the Turkey River. Surface contaminants in this area may penetrate relatively deeply into the Silurian rocks, because of the steep hydraulic gradient and because there is relatively little saturated thickness in the aquifer near the escarpment.

Because of the interaction with the land surface in the Karst areas, the carbonate aquifers are very susceptible to contamination from a wide variety of hazardous substances which may be locally spilled or discharged at the land surface. However, on the regional level, nitrates, bacteria and pesticides are the three general contaminants derived from the land surface, which are of concern for public health, in the ground water in the Karst areas. A variety of sources for these contaminants can be identified.

Sources of Ground-Water Quality Problems

Two processes must be considered in the delivery of these contaminants: downward leaching of material with percolating recharge water; and runoff from the land surface which may enter the karst ground-water system through sinkholes. A number of general point sources can be identified such as: the dumping of various wastes into sinkholes; the disposal of creamery wastes into streams and sinkholes, which has been a recurrent problem in northeast Iowa; occasional discharge from municipal sewage treatment facilities and industrial effluents into surface waters which drain into the bedrock aquifers; runoff and infiltration from feedlots and livestock operations agricultural drainage wells (particularly in the Floyd-Mitchell County area); road drainage into sinkholes; the direct discharge of home sewage effluent into sinkholes; and the indirect seepage of home sewage effluent into the carbonate bedrock. There are many rules and regulations which already exist to control these point sources. Some are effective, some are not. Some of these practices continue, partly out of ignorance of the potential impact on drinking water, partly because some of the rules are impossible to enforce.

With the present state of knowledge it is impossible to quantify the relative inputs from point sources. The nature of land use in northeast Iowa and studies of agricultural drainage wells suggest that the major source of contaminants is from non-point sources related to agricultural land. However, even if point sources are very minor contributors they should be eliminated whenever possible through control measures, through expanded, effective public education, and with innovative practices. For example, in the Karst areas there are many examples where home sewage effluent is discharged directly into sinkholes. In part this continues because of a lack of understanding of the consequences. Alternative home sewage treatment systems should be encouraged in shallow rock areas where even properly designed septic systems with lateral fields may leach effluent into the rock.

Non-point sources from agricultural lands are likely the major concern for ground-water quality in the Karst areas. These sources are also the most difficult to resolve. Of primary concern is the infiltration of water, the discharge of tile-drainage water, and direct land-surface runoff of water and eroded soil, which contain nitrates and pesticides. Given the complex interaction of climate and farming practices some delivery of these contaminants into the ground-water in the Karst areas is unavoidable. Tile drainage may be an especially significant factor. Tile drainage water nearly always exceeds 45 mg/l nitrate, and volumetrically may be a major contributor to the flow of small streams which lose water to the karst aquifers. Many tile lines drain directly into sinkholes as well.

Control programs or BMPs must take into account many complex variables as well as the nature and needs of particular farm operations. Conservation measures which reduce water runoff, thus reducing sediment, nutrient, and pesticide losses in surface water, may also increase tile drainage and nitrate losses through tile discharge. Any program to alleviate these problems must consider the nature and extent of existing tile drainage.

Although more research is needed in this area, such measures as incorporation of pesticides and better N-management recommendations are a must. Such measures will take the integrated cooperation of many agencies. Many of these measures can only be achieved through effective public education.

RECOMMENDATIONS

The research and conclusions presented in this report indicate that there is significant, regional, nitrate contamination of ground water in the carbonate aquifers of northeast Iowa. This contamination is related to surface activities and occurs in areas where there is thin protective soil cover over the carbonate bedrock, and is enhanced where sinkholes conduct surface drainage directly into the ground-water system. Although these regional problems were addressed in this project, many important details have not been adequately resolved. These details are important elements which must be considered if an effective, long-term management scheme for the protection of these groundwater resources is to be developed.

The recommendations outlined here fall into three general categories: 1. Water-quality data base needs; 2. Further research needs; and 3. Consideration of control measures. Although particular recommendations may be categorized, these groupings overlap and are clearly interrelated. Many of the recommendations are considerations which must be addressed by agencies other than DEQ or IGS. Some of these items should be addressed by a consortium of agencies and/or experts because the technical issues are complex and they necessarily must be merged with equally complex social, economic and political issues.

Water-Quality Data Base Needs

Monitoring of ground-water quality should be expanded. As noted, existing water-quality data sets are inadequate for the evaluation of many problems. For example, extant data do not allow clear assessment of water quality changes over time. A baseline of water-quality information must be established so that future problems can be evaluated. A carefully designed, statewide sampling network should be developed in conjunction with existing sampling programs. The following items, at least, should be addressed in such a program.

1. The network wells should be available for long-term monitoring.

2. Accurate information on the well construction, geology, water system, local environmental factors and pumping should be available for the wells sampled.

3. The network should be comprised of wells finished at various depths, within various aquifers. Preferably wells should allow access for water-level measurements to be made through time.

4. The network must include more than municipal wells. The network must include all aquifers of significant areal extent and/or importance. Municipal wells alone are not satisfactory as they are often drilled

to obtain deeper, better quality water supplies, and often will not provide data which reflects the conditions of rural domestic wells. Thus, private wells and/or drilled research wells are needed also.

5. Water-quality parameters tested should include a variety of standard biological, chemical and radiological analyses. Pesticide analyses should be included occasionally where appropriate.

6. Sampling frequencies must take into account seasonal variations in water-quality particularly from wells in shallow aquifers, and Karst-carbonate aquifers.

7. The network should clearly include shallow wells from a variety of water sources, particularly in alluvial and carbonate aquifers.

8. To further evaluate some of the problems in the Karst and Shallow Bedrock regions outlined in this report, the sampling network should include wells nested at different depths in the carbonate aquifers. This would provide badly needed data on the vertical head distribution in these aquifers, as well as allow the monitoring of possible water quality changes in the deeper parts of the carbonate aquifers.

Another consideration in developing a data base is to make existing sampling programs, such as the UHL analyses of domestic wells, more useful. The research results presented here has shown that, in spite of inherent data control problems, the UHL data is important for research purposes. The large number of samples and their wide geographic distribution makes them invaluable. However, the utility of the UHL data could be greatly enhanced. Several considerations are outlined:

1. Of particular benefit would be to improve the locational accuracy of the sample sites, by asking for the legal location (township, range, section) of the well. Many rural residents know this information, but perhaps the help of County Cooperative Extension Service personnel could be enlisted to aid residents where needed.

2. Asking for information on well construction and the water-system would also be useful. For example--Is the well cased? Is there a pit around the well head? Is a cistern used for water storage? Answers to these questions would enhance the utility of the data and could also allow UHL to provide more useful information to the rural resident about the nature of a water-quality problem.

3. Confidentiality of the individuals submitting the samples is an important issue. Certainly this can be maintained while making this data more usable for public benefit. The research presented here demonstrates that this data can be utilized while preserving the individual's right to privacy.

4. The UHL data should be computerized for greatest utility. A mechanism to facilitate a change towards computerizing the data <u>and</u> maintaining it for many years should be sought.

5. Consideration should be given to changing the method of bacterial analysis. The currently used MPN method produces data which are somewhat difficult to evaluate. This is particularly true for Class 5 (MPN >16) which aggregates a large number of analyses, and does not give extreme bacterial values an accurate representation. If an economic method could be used which would provide an actual numerical count it would provide much more usable data for future studies. UHL is currently considering this change, and is conducting tests of its feasibility.

Further Research Needs

Many of the water-quality data base needs address long term monitoring for the assessment of Iowa's water resources. If a management scheme is to be developed for the particular problems of the carbonate aquifers, addressed in this report, there are more immediate, detailed research questions which must be answered. These research needs must focus on the details of issues which are raised in this report. Among the needed considerations are:

1. Detailed water-sampling is needed in a karst area where the many variables affecting the water-quality analyses can be controlled and/or evaluated. The sampling should be done in concert with detailed information on:

    a. geology and hydrogeology and distribution of karst features of the area.

    b. well depth and water source.

    c. well and water system construction.

    d. local environmental conditions in relation to well placement. This will facilitate sorting out the influence of local factors from the regional water quality.

2. Sampling for nitrate and bacteria should be done frequently to examine the temporal variations in these parameters in relationship to seasonal changes.

3. Other water-quality constituents should be analyzed. Particularly the fate of pesticides should be evaluated in relation to the interaction of the surface-water and ground-water systems.

4. The problem of bacterial contamination in the karst aquifers should be evaluated. This will necessitate isolating water quality changes between the aquifer and individual water-system effects (see item 1c and 1d above).

5. The role of land-use in relation to the Karst and Shallow Bedrock areas and ground-water quality should be evaluated. The interrelationship of point/non-point sources with diffuse and direct recharge

to the aquifer is necessary to begin evaluating specific control measures, as well as their relative effectiveness.

6. The depth of ground-water contamination in the carbonate aquifers is an important issue. The observations presented in this report suggest that over most of the extent of the Silurian-Devonian aquifer the nitrate contamination is contained above a depth of about 150 feet. This should be further evaluated. We must try to determine how permanent this change is; if contaminant levels are at a "steady-state" or if they are likely to slowly increase at greater depths. This is a difficult task and would likely require the installation of nested research wells (see item 8, water quality data needs).

Many of these items are currently being addressed in the second phase of this research program. This second phase is being conducted near Elkader, in Clayton County, in cooperation with DEQ, U.S.D.A., Soil Conservation Service, the Iowa Conservation Commission, and I.G.S.

Consideration of Control Measures

Definition of specific control measures and best management practices to protect the carbonate aquifers in the Karst and Shallow Bedrock areas is difficult. Before control measures can be fully evaluated, further research is necessary to answer some of the detailed questions outlined in the preceeding section. The development of a management strategy must meld the scientifically defined system with existing social, political and economic realities.

One general conclusion seems obvious, however. Public education and cooperation will have to play a major role in any meaningful management strategy. The hazard area is large, and the sources of contaminants are diverse and widespread. They range from infiltration and runoff from row-crop land, to problems with domestic water systems, home sewage disposal systems, industrial discharges, and to tile-drainage systems. Rules and regulations exist for many of the point sources, but they are not all enforceable on a consistent and continual basis.

Just as the sources of the problem are diverse, so are the people and agencies involved in the resolution, including various governmental entities, rural residents, farmers, well drillers, plumbers, tiling contractors, county engineers and sanitarians, agribusiness people, etc. Each has to understand the effects their actions can have on their water supplies and each has to be made aware of recommended practices as well as rules which can help protect their resources. Further, cooperation is necessary among the various scientific and engineering groups who study the problem. They must work together to succesfully integrate a management plan. Many of these problems are not realistically controllable through rules and regulations. Effective implementation must address incentives (such as cost-sharing conservation measures) and a concerted effort for effective public education. It seems that a working group comprised of representatives from the natural resources, health and agricultural agencies--particularly including the Cooperative Extension Service and the U.S.D.A.-Soil Conservation Service, and perhaps representatives from agribusiness and farm organizations, should be formed to address these issues of education and cooperation.

Some specific areas for consideration can also be outlined. For point source problems these particular items should be addressed:

1. Existing rules and regulations regarding dumping and waste disposal in sinkholes need to be clarified. Some legal decisions have cited the definition of "sinkhole" as too vague. Further, should streams which lose water totally or partially into the carbonate aquifers be included in such rules?

2. The enforcement of rules regarding home-sewage treatment systems needs to be addressed. The use of "alternative systems" should also be reviewed.

3. The need for better well construction, better water system design, and better well-placement criteria deserves attention. There is also a need for better well abandonment procedures. These issues can be addressed through rules and regulations and/or with professional and public education.

In the complex area of non-point source problems, certain general topics must be addressed in the consideration of BMP's:

1. Appropriate ways to affect better N-fertilizer and pesticide application and management, to reduce losses.

2. Consideration and review of land-treatment practices, both structural and non-structural, to find appropriate measures for the unique setting of the Karst regions.

3. These considerations must include the effects and relationships with existing tile-drainage systems.

4. These considerations should also include practices related to the smaller, unregulated livestock operations.

5. An evaluation should be made of the effectiveness of filling sinkholes as a land treatment practice.

Again, the evaluation and design of non-point BMP's will clearly require the inputs from an interdisciplinary group from various agricultural and water resources disciplines.

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APPENDICES

Appendix 1. Soil survey reports and maps used for mapping of bedrock outcrops and sinkholes (only categories 1 and 2 below, could be used for sinkhole mapping).

1. Modern soil surveys; surveys compiled on an aerial photographic base, since 1950, scale of maps 1:15, 840.

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Clayton Co. - Kuehl, R.J., 1978, Soil survey of Clayton County, Iowa, Advance Report, Part I and II: U.S.D.A., Soil Conserv. Ser., and Ia. Agric. Home Econ. Exp. Sta., 184 p., plus maps.

Clinton Co. - Boeckman, L.E., and Sabata, L.R., 1978, Soil survey of Clinton Co., Iowa, Advance Report, Part I and II: U.S.D.A., Soil Conserv. Ser., and Ia. Agric. Home Econ. Exp. Sta., 210 p., plus maps.

Dubuque Co. - Soil survey in progress; unpublished information provided L.E. Boeckman and R. A. Greenough, U.S.D.A., SCS.

Delaware Co. - Soil survey in progress; unpublished information provided by R.J. Wisner and R.A. Greenough, U.S.D.A., S.C.S.

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Appendix 2 . List by counties showing assignment of sample centers to geologic settings.

COUNTY	KARST Sample Centers in Karst areas.	SHALLOW BEDROCK Sample Centers in areas where bedrock is near the land-surface.
ALLAMAKEE	Waukon	Dorchester, Harpers Ferry, Lansing, New Albin, Postville, Waterville
BENTON	-----	Shellsburg, Urbana, Vinton
BLACKHAWK	-----	--------
BREMER	Waverly	Frederika, Janesville
BUCHANAN	-----	Brandon, Fairbank, Hazelton, Independence, Jesup Lamont, Littleton, Quasqueton
BUTLER	Bristow, Clarksville, Greene	Aplington, Austenville, Dumont
CHICKASAW	Nashua	Basset
CLAYTON	Elkader, Farmersburg, Luana, Monona, St. Olaf Strawberry Pt.	Clayton, Edgewood, Elkport, Garber, Garnavillo, Guttenberg, Littleport, Marquette, McGregor, Volga City
CLINTON	Andover	Bryant, Calamus, Camanche, Charlotte, Clinton, Elwood, Low Moor, Teeds Grove
DELAWARE	Colesburg, Delaware, Delhi, Hopkinton	Dundee
DUBUQUE	Richardsville	Bernard, Cascade, Dubuque, Durango, Epworth
FAYETTE	Fayette	Arlington, Clermont, Elgin, Randalia, St. Lucas, Wadena, Waucoma, West Union
FLOYD	Floyd	Charles City, Marble Rock, Nora Spring, Rockford, Rudd
GRUNDY	-----	--------
HOWARD	Chester, Crescoe, Lime Springs	--------
JACKSON	Baldwin	Andrew, Bellevue, Green Island, Hurtsville, La Motte, Maquoketa, Miles, Monmouth, Preston, Sabula, Spragueville, Springbrook, Swingle
JONES	Anamosa	Scotch Grove, Stone City, Monticello, Olin, Onslow, Wyoming
LINN	Robins	Cedar Rapids, Center Point, Central City, Coggon, Ely, Hiawatha, Springville, Toddville, Troy Mills, Viola
MARSHALL	-----	Ferguson
MITCHELL	Little Cedar, Mitchell, Osage	Carpenter, Orchard, St. Angsgar, Stacyville
TAMA	----	Montour
WINNESHIEK	Burr Oak	Calmar, Decorah, Ft. Atkinson, Freeport, Hesper, Spillville

COUNTY	DEEP-BEDROCK Sample Centers in areas where the bedrock is buried beneath a significant thickness of Pleistocene deposits (till and loess).	ALLUVIAL Sample Centers likely having a significant number of alluvial wells.
ALLAMAKEE	----	Harpers Ferry, Lansing, New Albin
BENTON	Atkins, Belle Plaine, Blairstown, Garrison, Keystone, Luzerne, Mt. Auburn, Newhall, Norway, Van Horne, Walford, Watkins	Belle Plaine, Luzerne, Norway
BLACKHAWK	Cedar Falls, Dunkerton, Gilbertville, Hudson, La Porte City, Waterloo	Cedar Falls, Dunkerton, Hudson, Waterloo
BREMER	Denver, Plainfield, Readlyn, Sumner, Tripoli	Frederika, Janesville, Plainfield, Sumner, Tripoli, Waverly
BUCHANAN	Aurora, Rowley, Stanley Winthrop	Fairbank, Independence, Lamont, Littleton, Rowley
BUTLER	Allison, Aredale, Kesley, New Hartford, Parkersburg, Shell Rock	Clarksville, Dumont, Green, Shell Rock
CHICKASAW	Alta Vista, Fredricksburg Ionia, Lawler, New Hampton	Basset, Noshua
CLAYTON	----	Clayton, Elkport, Garber, Guttenberg, Littleport, Marquette, McGregor, Volga City
CLINTON	Delmar, De Witt, Goose Lake, Grand Mound, Lost Nation, Welton, Wheatland	Camanche, Clinton, Goose Lake
DELAWARE	Earlville, Greeley, Manchester, Masonville, Petersburg, Ryan	Dundee, Hopkinton, Manchester, Masonville
DUBUQUE	Dyersville, Farley, Holy Cross, Luxemburg, New Vienna, Peosta, Worthington	Cascade, Dubuque, Dyersville, New Vienna
FAYETTE	Hawkeye, Maynard, Oelwein, Oran, Westgate	Clermont, Elgin, Fayette, Delwein, Wadena, Waucoma
FLOYD	Colwell	Charles City, Floyd, Marble Rock, Nora Spring, Rockford
GRUNDY	Beaman, Conrad, Dike Grundy Center, Holland, Reinbeck, Wellsburg	Holland
HOWARD	Elma	Chester, Elma, Lime Springs
JACKSON	----	Bellevue, Green Island, Maquoketa, Miles, Preston, Sabula, Spragueville
JONES	Center Junction, Martelle, Morley, Oxford Junction	Anamosa, Stone City, Monticello, Olin, Oxford Junction
LINN	Alburnett, Fairfax, Lisbon, Marion, Mt. Vernon, Palo, Walker	Cedar Rapids, Center Point, Central City, Coggon, Ely, Fairfax, Palo, Robins

	Sample Centers in areas where the bedrock is buried beneath a significant thickness of Pleistocene deposits (till and loess).	Sample Centers likely having a significant number of alluvial wells.
COUNTY	DEEP-BEDROCK	ALLUVIAL
MARSHALL	Albion, Clemons, Gilman, Green Mountain, Laurel, Marshalltown, Melbourne, Rhodes, State Center	Albion, Marshalltown, Melbourne
MITCHELL	McIntyre, New Haven, Riceville	Little Cedar, Mitchell, New Haven, St. Angsgar, Stacyville
TAMA	Buckingham, Chelsea, Clutier, Dysart, Elberon, Garwin, Glad-brook, Lincoln, Tama, Toledo, Tracer, Vining	Chelsea, Montour, Tama, Toledo
WINNESHIEK	Castalia, Ossian, Ridgeway	Decorah, Ft. Atkinson, Freeport, Spillville

Appendix 3 . Water Quality analyses by county and city. Data was obtained from the University Hygienic Laboratory on analysis conducted between 1977 and 1980.

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatisfactory or Unsafe
Allamakee	1192	Dorchester	24	0	25	9
	1850	Harper's Ferry	157	21	163	18
	2280	Lansing	36	3	37	14
	3020	New Albin	3	0	3	3
	3475	Postville	48	11	53	29
	4460	Waterville	15	4	18	9
	4475	Waukon	42	13	53	29
Benton	0225	Atkins	23	1	26	8
	0355	Belle Plaine	28	5	27	13
	0415	Blairstown	16	0	20	11
	1305	Elberon	1	0	7	3
	1590	Garrison	10	0	15	6
	2165	Keystone	1	9	10	3
	2535	Luzerne	22	7	22	12
	2950	Mt. Auburn	45	4	22	47
	3030	New Hall	7	0	7	2
	3135	Norway	18	3	22	8
	3940	Shellsburg	24	2	28	10
	4325	Urbana	2	0	3	1
	4350	Van Horne	8	2	13	4
	4390	Vinton	97	6	114	43
	4415	Walford	4	0	5	1
	4463	Watkins	13	4	18	12
Black Hawk	0665	Cedar Falls	2	1	22	2
	1235	Dunkerton	12	0	2	3
	1620	Gilbertville	3	0	2	0
	1980	Hudson	3	0	8	5
	2285	LaPort City	16	2	20	9
	4455	Waterloo	24	1	33	9
Bremer	1120	Denver	34	2	39	10
	1545	Frederick	7	4	13	6
	2070	Janesville	47	13	54	13
	3405	Plainfield	40	9	52	14
	3575	Readlyn	14	0	20	3
	4145	Sumner	61	4	81	20
	4275	Tripoli	42	1	63	28
	4480	Waverly	218	36	264	75

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatisfactory or Unsafe
Buchanan	0250	Aurora	23	5	41	16
	0495	Brandon	9	3	10	6
	1425	Fairbank	37	3	40	12
	1905	Hazelton	18	2	22	9
	2020	Independence	117	17	187	57
	2080	Jesup	23	11	30	10
	2265	Lamont	11	3	16	4
	2447	Littleton	2	1	4	1
	3525	Quasque	11	1	29	7
	3755	Rowley	32	5	61	19
	4070	Stanley	5	1	11	2
	4660	Winthrop	21	3	34	10
Butler	0085	Allison	29	2	46	20
	0150	Aplington	19	2	28	6
	0165	Aredale	4	0	4	1
	0252	Austinville	4	2	5	1
	0520	Bristow	10	2	8	2
	0775	Clarkesville	77	31	88	25
	1220	Dumont	25	4	28	10
	1735	Greene	68	26	85	34
	2157	Kesley	33	44	53	11
	3040	New Hartford	9	1	11	1
	3335	Parkersburg	34	6	44	10
	3935	Shell Rock	21	3	26	5
Chickasaw	0095	Alta Vista	17	5	20	8
	0305	Basset	1	0	1	0
	1540	Fredericksberg	37	6	42	5
	2035	Ionia	41	5	58	19
	3000	Nashua	61	13	80	30
	3035	New Hampton	68	5	104	25
	3144	Oak Grove	1	0	1	0
Clayton	0780	Clayton	1	1	1	1
	1300	Edgewood	20	8	22	6
	1330	Elkader	42	7	54	22
	1345	Elk Port	6	2	7	4
	1445	Farmersburg	19	8	24	15
	1570	Garber	16	1	22	11
	1580	Garnavillo	33	6	37	22
	1790	Guttenburg	51	1	99	35
	2435	Little Port	2	0	5	0
	2510	Luana	14	3	15	7

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatisfactory or Unsafe
	2565	McGregor	43	5	68	25
	2680	Marquette	3	0	4	3
	2885	Monona	28	6	37	20
	3835	St. Olaf	11	1	24	14
	4125	Strawberry Point	30	7	36	15
	4395	Volga City	6	1	19	10
Clinton	0125	Andover	9	4	9	3
	0537	Bryant	7	1	9	1
	0575	Calamus	14	1	24	4
	0595	Camanche	42	13	43	8
	0710	Charlotte	15	0	23	6
	0810	Clinton	85	11	191	46
	1095	Delmar	33	2	49	18
	1140	Dewitt	81	14	92	23
	1373	Elwood	4	0	6	1
	1660	Goose Lake	5	1	9	4
	1690	Grand Mound	35	4	43	15
	2490	Lost Nation	20	1	27	16
	2505	Low Moor	4	1	4	0
	4187	Teeds Grove	1	0	4	2
	4520	Welton	7	0	8	3
	4600	Wheatland	15	2	19	4
Delaware	0845	Colesburg	4	1	15	10
	1085	Delaware	4	1	3	3
	1090	Delhi	21	9	27	7
	1230	Dundee	19	7	27	7
	1280	Earlville	16	1	21	10
	1300	Edgewood	2	0	2	0
	1730	Greeley	5	1	5	2
	1960	Hopkinton	32	15	36	17
	2067	Jamestown	1	0	1	0
	2615	Manchester	129	36	147	37
	2715	Masonville	23	2	32	10
	3378	Petersburg	1	0	1	1
	3790	Ryan	14	0	15	7
Dubuque	0385	Bernard	21	8	26	11
	0640	Cascade	23	8	27	11
	1215	Dubuque	42	5	62	11
	1245	Durango				
	1255	Dyersville	38	12	48	20

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatis-factory or Unsafe
	1390	Epworth	19	4	18	1
	1440	Farely	23	7	26	10
	1955	Holy Cross	12	1	23	11
	2530	Luxemburg	2	0	2	0
	3075	New Vienna	21	2	20	9
	3365	Peosta	4	0	7	0
	3632	Richardsville	2	0	3	0
	4695	Worthington	9	2	10	4
Fayette	0180	Arlington	10	1	20	5
	0805	Clermont	18	3	25	15
	1325	Elgin	56	16	64	30
	1465	Fayette	44	4	75	36
	1895	Hawkeye	30	5	35	16
	2740	Maynard	11	0	15	3
	3165	Oelwein	47	3	82	26
	3213	Oran	5	0	9	3
	3550	Kandalia	30	12	34	11
	3825	St. Lucas	2	0	5	2
	4400	Wadena	14	1	15	8
	4465	Waucoma	25	2	39	7
	4560	Westgate	10	0	18	2
	4590	West Union	164	11	185	68
Floyd	0705	Charles City	168	35	226	70
	0880	Colwell	1	0	2	1
	1490	Floyd	34	4	58	20
	2655	Marble Rock	8	2	17	9
	3095	Nora Springs	33	9	48	20
	3690	Rockford	41	14	61	29
	3765	Rudd	21	8	27	15
Grundy	0340	Beaman	25	9	16	5
	0890	Conrad	11	0	14	5
	1160	Dike	6	0	9	4
	1770	Grundy Center	20	1	24	6
	1945	Holland	6	0	6	4
	3600	Reinbeck	17	3	23	9
	4745	Wellsberg	24	7	21	6
Howard	0735	Chester	4	1	4	0
	0965	Crescoe	81	9	110	34
	1370	Elma	24	3	32	9
	2400	Lime Springs	30	12	44	20

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatis-factory or Unsafe
Jackson	0130	Andrew	3	1	10	2
	0275	Baldwin	10	1	12	5
	0360	Bellevue	49	4	74	16
	0385	Benard	14	1	22	11
	1745	Green Island	8	2	15	7
	2000	Hurtsville	8	7	9	7
	2270	La Motte	15	9	17	5
	2645	Maquoketa	136	39	181	62
	2805	Miles	13	6	16	6
	2880	Monmouth	13	1	24	12
	3495	Preston	16	5	25	12
	3795	Sabula	4	0	7	3
	4040	Spragueville	12	4	21	7
	4045	Spring Brook	3	0	3	2
	4725	Zwingle	10	4	16	8
Jones	0120	Anamosa	45	1	87	29
	0640	Cascade	4	0	5	0
	0675	Center Junction	8	0	10	3
	2690	Martelle	12	1	16	6
	2900	Monticello	101	25	114	39
	2930	Morley	3	2	6	1
	3190	Olin	19	1	27	9
	3210	Onslow	3	0	2	1
	3290	Oxford Junction	7	0	15	5
	3877	Scotch Grove	13	6	18	7
	4102	Stone City	3	0	3	1
	4700	Wyoming	11	0	19	5
Linn	0060	Alburnett	1	0	2	0
	0670	Cedar Rapids	57	5	126	13
	0680	Center Point	8	1	8	2
	0690	Center City	10	1	12	4
	0835	Coggin	9	0	14	4
	1375	Ely	8	1	8	2
	1430	Fairfax	12	0	25	7
	1925	Hiawatha	2	0	2	0
	2425	Lisbon	20	3	26	6
	2670	Marion	13	1	20	5
	2670	Mt. Vernon	32	4	53	15
	3315	Palo	7	0	7	1
	3680	Robins	10	0	10	1
	4055	Springville	4	1	3	0
	4252	Toddville	5	0	6	0
	4278	Troy Mills	1	0	1	0

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatisfactory or Unsafe
	4393	Viola	2	0	3	0
	4420	Walker	7	0	22	5
Marshall	0055	Albion	3	1	6	4
	0800	Clemons	3	0	5	2
	1475	Ferguson	1	0	1	0
	1625	Gilman	10	3	15	6
	1747	Green Mountain	5	0	8	1
	2305	Laurel	4	2	5	1
	2685	Marshalltown	86	11	141	62
	2760	Melbourne	5	1	5	4
	3620	Rhodes	6	1	10	7
	4085	State Center	14	3	21	13
Mitchell	0620	Carpenter	11	2	16	7
	2433	Little Cedar	7	1	14	6
	2570	McIntire	16	0	20	2
	2855	Mitchell	6	1	9	2
	3043	New Haven	4	0	4	1
	3220	Orchard	16	3	18	8
	3235	Osage	104	36	124	59
	3625	Riceville	16	2	32	13
	3810	St. Ansgar	16	4	18	5
	4060	Staceyville	7	0	7	4
Tama	0542	Buckingham	14	3	15	5
	0725	Chelsea	8	0	13	10
	0825	Cultier	14	1	17	9
	1260	Dysart	22	2	27	10
	1305	Elberon	5	3	16	11
	1595	Garwin	20	1	29	12
	1635	Gladbrook	25	5	44	20
	2405	Lincoln	6	2	13	7
	2905	Montour	16	2	23	9
	4185	Tama	40	2	72	33
	4255	Toledo	53	0	61	30
	4285	Traer	45	4	62	35
	4385	Vining	3	0	3	0
Winneshiek	0563	Burr Oak	7	0	8	5
	0585	Calmar	42	17	32	60
	0650	Castalia	11	2	15	7
	1065	Decorah	211	26	282	100
	1510	Ft. Atkins	35	8	47	22

County	Town Number	City	Nitrate: Number of Analyses	Nitrate: Number Exceeding 45 mg/l	Bacteria: Number of Analyses	Bacteria: Number found Unsatis-factory or Unsafe
	1551	Free Port	8	1	10	0
	1923	Hesper	5	1	6	0
	3250	Ossian	18	3	28	18
	3640	Ridgeway	33	4	39	21
	4030	Spillville	3	0	3	2

Appendix 4 . Results of Kolmogorov-Smirnov test on distributions of nitrate analyses. The data was stratified by both depth and geologic setting. Data was obtained from the University Hygienic Laboratory on analyses conducted between 1977 and 1980.

Geologic Setting and Depths Compared		Significance Level
Karst & Non Karst	(all samples)	.001
Karst & Non Karst	(<50 feet)	> .1
Karst & Non Karst	(known depth samples >50 feet)	.001
Karst & Non Karst	(50 - 99 feet)	.001
Karst & Non Karst	(100 - 149 feet)	.001
Karst & Non Karst	(150 - 499 feet)	.001
Karst & Non Karst	(>500 feet)	> .1
Karst & Shallow	(all samples)	.001
Karst & Shallow	(<50 feet)	> .1
Karst & Shallow	(known depth samples >50 feet)	.001
Karst & Shallow	(50 - 99 feet)	.001
Karst & Shallow	(100 - 149 feet)	.10
Karst & Shallow	(150 - 499 feet)	> .1
Karst & Shallow	(>500 feet)	> .1
Karst & Deep	(all samples)	.001
Karst & Deep	(<50 feet)	> .1
Karst & Deep	(known depth samples >50 feet)	.001
Karst & Deep	(50 - 99 feet)	.001
Karst & Deep	(100 - 149 feet)	.001
Karst & Deep	(150 - 499 feet)	.001
Karst & Deep	(>500 feet)	> .1
Shallow & Deep	(all samples	.001
Shallow & Deep	(<50 feet)	.025
Shallow & Deep	(known depth samples >50 feet)	.001
Shallow & Deep	(50 - 99 feet)	.001
Shallow & Deep	(100 - 149 feet)	.001
Shallow & Deep	(150 - 499 feet)	.001
Shallow & Deep	(>500 feet)	> .1
Karst & Alluvial	(all samples)	> .1
Karst & Alluvial	(<50 feet)	> .1
Karst & Alluvial	(known depth samples >50 feet)	.005
Karst & Alluvial	(50 - 99 feet)	.025
Karst & Alluvial	(100 - 149 feet)	.025
Karst & Alluvial	(150 - 499 feet)	.025
Karst & Alluvial	(>500 feet)	> .1

Alluvial & Non-alluvial	(all samples)	.001
Alluvial & Non-alluvial	(<50 feet)	.001
Alluvial & Non-alluvial	(known depth samples >50 feet)	.001
Alluvial & Non-alluvial	(50 - 99 feet)	.001
Alluvial & Non-alluvial	(100 - 149 feet)	.001
Alluvial & Non-alluvial	(150 - 499 feet)	.01
Alluvial & Non-alluvial	(>500 feet)	>.1
Karst (50-99') & all samples	(<50 feet)	>.1
Karst (100-149') & Karst	(<50 feet)	>.1
Karst (100-149') & Karst	(50 - 99 feet)	.005
Karst (100-149') & Karst	(150 - 499 feet)	.001
Karst (100-149') & Karst	(>500 feet)	.025
Shallow (100-149') & Shallow	(<50 feet)	.01
Shallow (100-149') & Shallow	(50 - 99 feet)	>.1
Shallow (100-149') & Shallow	(150 - 499 feet)	.001
Shallow (100-149') & Shallow	(>500 feet)	.001
Deep (100-149') & Deep	(<50 feet)	.001
Deep (100-149') & Deep	(50 - 99 feet)	.001
Deep (100-149') & Deep	(150 - 499 feet)	.01
Deep (100-149') & Deep	(>500 feet)	>.1
Karst vs. Shallow	(50 - 149 feet)	.001
Karst vs. Deep	(50 - 149 feet)	.001
Shallow vs. Deep	(50 - 149 feet)	.001

Appendix 5 . Results of Kolmogorov-Smirnov test on cumulative frequency distributions of total coliform analyses in each class. The distributions were taken data obtained from the University Hygienic Laboratory on analyses conducted between 1977 and 1980 and were stratified by both depth and geologic setting.

Geologic Setting and Depths Compared		Significance Level
Karst & Non Karst	(all samples)	.025
Karst & Non Karst	(50 feet)	> .1
Karst & Non Karst	(known depth samples 50 feet)	.10
Karst & Non Karst	(50 - 99 feet)	> .1
Karst & Non Karst	(100 - 149 feet)	> .1
Karst & Non Karst	(150 - 499 feet)	.005
Karst & Non Karst	(500 feet)	> .1
Karst & Shallow	(all samples)	.005
Karst & Shallow	(50 feet)	> .1
Karst & Shallow	(known depth samples 50 feet)	.10
Karst & Shallow	(50 - 99 feet)	> .1
Karst & Shallow	(100 - 149 feet)	> .1
Karst & Shallow	(150 -499 feet)	.005
Karst & Shallow	(500 feet)	> .1
Karst & Deep	(all samples)	> .1
Karst & Deep	(50 feet)	> .1
Karst & Deep	(known depth samples 50 feet)	> .1
Karst & Deep	(50 - 99 feet)	> .1
Karst & Deep	(100 - 149 feet)	> .1
Karst & Deep	(150 - 499 feet)	.025
Karst & Deep	(500 feet)	> .1
Shallow & Deep	(all samples)	> .1
Shallow & Deep	(50 feet)	> .1
Shallow & Deep	(known depth samples 50 feet)	> .1
Shallow & Deep	(50 - 99 feet)	> .1
Shallow & Deep	(100 - 149 feet)	> .1
Shallow & Deep	(150 - 499 feet)	> .1
Shallow & Deep	(500 feet)	> .1
Karst & Alluvial	(all samples)	.005
Karst & Alluvial	(50 feet)	> .1
Karst & Alluvial	(known depth samples 50 feet)	> .1
Karst & Alluvial	(50 - 99 feet)	> .1
Karst & Alluvial	(100 - 149 feet)	> .1
Karst & Alluvial	(150 - 499 feet)	.01
Karst & Alluvial	(500 feet)	> .1

Alluvial & Non-alluvial	(all samples)	.005
Alluvial & Non-alluvial	(<50 feet)	>.1
Alluvial & Non-alluvial	(known depth samples >50 feet)	>.1
Alluvial & Non-alluvial	(50 - 99 feet)	>.1
Alluvial & Non-alluvial	(100 - 149 feet)	>.1
Alluvial & Non-alluvial	(150 - 499 feet)	>.1
Alluvial & Non-alluvial	(>500 feet)	>.1
Karst (50-99') & all samples	(<50 feet)	>.1
Karst (100-149') & Karst	(<50 feet)	>.1
Karst (100-149') & Karst	(50 - 99 feet)	>.1
Karst (100-149') & Karst	(150 - 499 feet)	>.1
Karst (100-149') & Karst	(>500 feet)	>.1
Shallow (100-149') & Shallow	(<50 feet)	>.1
Shallow (100-149') & Shallow	(50 - 99 feet)	>.1
Shallow (100-149') & Shallow	(150 - 499 feet)	.001
Shallow (100-149') & Shallow	(>500 feet)	.001
Deep (100-149') & Deep	(<50 feet)	.05
Deep (100-149') & Deep	(50-99 feet)	>.1
Deep (100-149') & Deep	(150 - 499 feet)	>.1
Deep (100-149') & Deep	(>500 feet)	>.1
Karst & Shallow	(50 - 149 feet)	>.1
Karst & Deep	(50 - 149 feet)	>.1
Shallow & Deep	(50 - 149 feet)	>.1

Appendix 6 . Number of sample centers in each geologic setting, grouped by the percentage of samples from each center with unsafe total coliform bacteria analyses (above class 0).

For Wells Less Than 100 Feet Deep:

Geologic Setting	0-4%	5-19%	20-34%	35-50%	>50%	Total
	(Number of sample centers with a given percentage of samples above class 0.)					
Karst	6	1	5	6	8	26
Shallow Bedrock	19	3	22	20	24	88
Deep Bedrock	15	5	28	24	29	101
Total	40	9	55	50	61	215

For All Wells:

	0-4%	5-19%	20-34%	35-50%	>50%	Total
Karst	2	1	13	7	7	30
Shallow Bedrock	12	9	32	31	17	101
Deep Bedrock	6	13	36	37	18	110
Total	20	23	81	75	42	241

Appendix 7 . Number of sample centers in each geologic setting, grouped by the percentage of samples from each center which exceeded 45 mg/l nitrate.

For Wells Less Than 100 Feet Deep:

Geologic Setting	0-4%	5-9%	10-19%	20-29%	> 29%	Total
	(Number of sample centers, with a given percentage of samples with >45 mg/l nitrate.)					
Karst	13	0	1	6	10	30
Shallow Bedrock	50	1	10	11	29	101
Deep Bedrock	49	1	8	8	44	110
Total	112	2	19	25	83	241

For All Wells:

	0-4%	5-9%	10-19%	20-29%	> 29%	Total
Karst	5	2	7	6	10	30
Shallow Bedrock	27	14	20	17	23	101
Deep Bedrock	39	17	27	15	12	110
Total	71	33	54	38	45	241

Appendix 8. Percentage of total coliform bacterical analyses in classes by depth and geologic setting. Data was obtained from the University Hygienic Laboratory on analyses conducted between 1977 and 1980.

Class (%)

Depth	0	1	2	3	4	5	N	%N in Depth Class
Karst Area								
0-49	66.7	5.9	2.0	7.8	4.9	12.8	102	7%
50-99	59.8	7.9	5.3	6.0	5.3	15.8	266	18%
100-149	63.5	8.2	3.9	4.7	3.6	16.2	364	25%
150-499	61.0	7.4	5.9	5.2	4.6	16.1	461	32%
500+	72.2	11.1	---	---	5.6	11.1	18	1%
UNKNOWN	57.2	10.5	9.6	4.4	3.9	14.4	229	16%
Total	61.3	8.1	5.5	5.2	4.4	15.5	1440	
Shallow Bedrock								
0-49	59.6	6.0	5.1	5.4	2.7	21.1	332	9%
50-99	59.9	10.0	5.0	4.7	5.4	15.1	558	15%
100-149	60.0	7.9	6.4	5.1	4.1	15.6	567	15%
150-499	71.3	6.0	3.8	3.4	3.2	12.2	1048	28%
500+	84.9	2.8	3.8	.9	1.9	5.7	106	3%
UNKNONW	70.1	6.5	4.3	3.0	4.0	12.1	1084	29%
Total	66.8	7.0	4.7	3.9	3.8	13.9	3695	
Deep Bedrock								
0-49	61.4	5.9	3.0	3.0	3.2	23.6	407	11%
50-99	58.8	9.5	3.0	4.7	3.8	20.2	495	17%
100-149	64.6	7.7	5.1	4.6	3.9	14.1	545	18%
150-499	68.1	9.4	4.1	3.3	3.1	12.1	811	27%
500+	71.2	8.5	5.1	1.7	3.4	10.2	59	2%
UNKNOWN	65.8	6.2	4.3	4.4	5.5	13.9	687	23%
Total	64.5	7.9	4.0	3.9	3.9	15.8	2995	

Depth	0	1	2	3	4	5	N	%N in Depth Class
				Alluvial				
0-49	62.4	4.7	4.3	5.1	3.3	20.3	489	10%
50-99	61.3	8.1	4.5	4.9	4.8	16.3	750	16%
100-149	64.0	8.2	5.0	4.7	3.2	15.0	881	19%
150-499	70.3	6.5	4.1	3.5	3.1	12.6	1270	27%
500+	82.8	4.0	4.0	1.0	2.0	6.1	99	2%
UNKNOWN	68.7	6.7	4.8	3.4	3.7	12.7	1201	26%
Total	66.7	6.9	4.5	4.0	3.5	14.3	4690	
				Non-Alluvial				
0-49	59.9	7.7	2.8	3.7	3.1	22.7	352	10%
50-99	56.9	11.1	4.0	4.9	4.8	18.3	569	17%
100-149	60.3	7.6	5.7	5.0	4.9	16.5	595	17%
150-499	65.4	8.7	4.6	4.1	3.9	13.3	1050	31%
500+	75.0	7.1	3.6	1.2	3.6	9.5	84	2%
UNKNOWN	64.8	7.0	5.1	4.1	5.7	13.4	790	23%
Total	62.7	8.3	4.6	4.3	4.5	15.6	3440	
				Non-Karst (Shallow and Deep Bedrock)				
0-49	60.6	6.0	3.9	4.1	3.0	22.5	739	11%
50-99	59.4	9.8	4.1	4.7	4.7	17.5	1053	16%
100-149	62.2	7.8	5.8	4.9	4.0	15.4	1112	17%
150-499	69.9	7.5	3.9	3.4	3.2	12.2	1859	28%
500+	80.0	4.9	4.2	1.2	2.4	7.3	165	2%
UNKNOWN	68.4	6.4	4.3	3.6	4.5	12.8	1762	26%
Total	65.8	7.4	4.4	3.9	3.9	14.7	6690	
				Total Area				
0-49	61.4	6.0	3.7	4.5	3.2	21.3	841	10%
50-99	59.4	9.4	4.3	4.9	4.8	17.1	1319	16%
100-149	62.5	7.9	5.3	4.8	3.9	15.6	1476	18%
150-499	68.1	7.5	4.3	3.8	3.5	12.9	2320	29%
500+	79.2	5.5	3.8	1.1	2.7	7.7	183	2%
UNKNOWN	67.2	6.8	4.9	3.7	4.5	13.0	1991	24%
Total	65.0	7.5	4.6	4.1	4.0	14.9	8130	

Appendix 9. Distribution of nitrate values (mg/l) at selected quantiles. Data was collected for 22 northeast Iowa counties from samples voluntarily sent to and analyzed by the University Hygienic Laboratory.

Geologic setting and Well Selecting Criteria	Quantiles 10%	25%	50%	75%	90%	N
Entire Study Area						
<50'	0	6	28	60	96	593
50-99'	0	0	18	45	79	992
100-149'	0	0	7	36	66	1082
150-499	0	0	0	17	49	1726
>500'	0	0	5	29	60	1522
Total (all samples)	0	0	6	34	66	6040
Karst area						
<50'	0	0	28	54	89	61
50-99'	0	12	34	58	114	214
100-149'	0	0	23	42	74	271
150-499'	0	0	3	28	67	349
>500'	0	0	0	19	50	14
Unknown	0	0	22	43	85	195
Total Karst	0	0	19	44	79	1104
Bedrock, Shallow						
<50'	0	6	26	49	72	216
50-99'	0	0	19	43	74	407
100-149'	0	0	16	45	73	436
150-499'	0	0	5	26	58	786
>500'	0	0	0	3	21	71
Unknown	0	0	7	30	58	803
Total	0	0	9	36	65	2719
Bedrock, deep						
<50'	0	6	33	69	111	316
50-99	0	0	6	36	67	371
100-149'	0	0	0	10	36	375
150-499	0	0	0	0	16	591
>500'	0	0	0	0	7	40
Unknown	0	0	0	22	57	524
Total	0	0	0	22	60	2217

	10%	25%	50%	75%	90%	N
Non-Karst (Bedrock Shallow & Deep)						
<50'	0	6	29	61	98	532
50-99'	0	0	13	39	62	778
100-149'	0	0	1	30	65	811
150-499'	0	0	0	13	44	1377
>500'	0	0	0	0	17	111
Unknown	0	0	3	26	58	1327
Total	0	0	5	30	64	4936
Alluvial						
<50'	0	0	21	48	75	329
50-99'	0	0	25	49	79	571
100-149'	0	0	14	40	71	628
150-499'	0	0	0	20	50	905
>500'	0	0	0	0	17	63
Unknown	0	0	7	31	63	897
Total	0	0	12	40	71	2760
Non-Alluvial						
<50'	0	9	40	71	111	264
50-99'	0	0	9	39	76	421
100-149'	0	0	0	28	63	454
150-499'	0	0	0	13	49	821
>500'	0	0	0	4	31	62
Unknown	0	0	0	29	58	625
Total	0	0	3	30	67	2647
All samples of known depth >50'						
Karst	0	0	18	42	77	848
Bedrock, Shallow	0	0	9	36	68	1700
Bedrock, Deep	0	0	0	10	38	1377
Total	0	0	3	30	63	3925