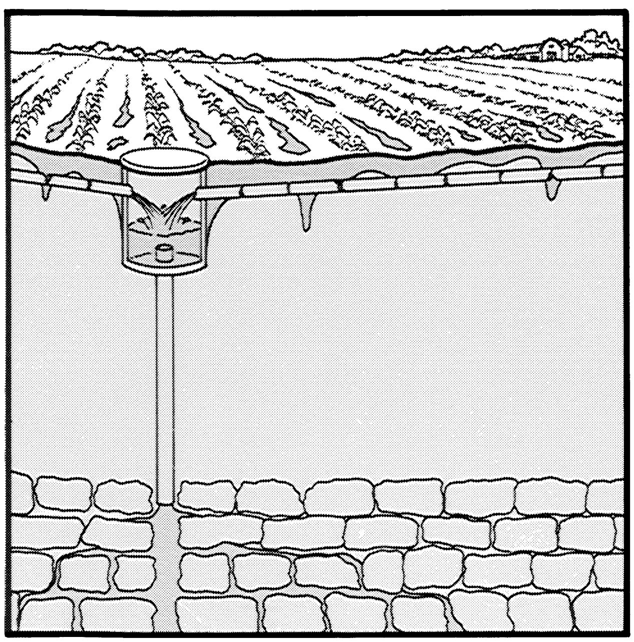
AGRICULTURAL DRAINAGE WELLS IN IOWA:

Hydrogeologic Settings and Water-Quality Implications

Technical Information Series 24



Iowa Department of Natural Resources
Larry J. Wilson, Director
April 1993

AGRICULTURAL DRAINAGE WELLS IN IOWA:
Hydrogeologic Settings and Water-Quality Implications

Technical Information Series 24

Prepared by:

R.D.Libra and G.R.Hallberg

Environmental Geology Section, Geological Survey Bureau
Iowa Department of Natural Resources

Supported, in part, by: the Iowa Groundwater Protection Act of 1987;
The Iowa Department of Agriculture and Land Stewardship,
Division of Soil Conservation through the
Integrated Farm Management Demonstration Project; and through grants from the
U.S.Environmental Protection Agency, Region VII, Nonpoint Source Program

April 1993

Iowa Department of Natural Resources
Larry J. Wilson, Director

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

AGRICULTURAL DRAINAGE WELLS IN IOWA: HYDROGEOLOGIC SETTINGS AND WATER-QUALITY IMPLICATIONS

Iowa Department of Natural Resources, Geological Survey Bureau
Technical Information Series 24, 1993, 39p.

R.D. Libra and G.R. Hallberg

ABSTRACT

Many of Iowa's soils seasonally contain excess water that can hinder field operations or crop growth. In these areas, farm fields often have been drained artificially by buried tile lines leading to drainage ditches and streams. Another, but less common outlet is the agricultural drainage well (ADW), a drilled shaft that funnels excess water underground into bedrock aquifers. The ADWs are discharge points for tile-drainage lines; some are also designed to take surface runoff. ADWs in Iowa discharge into fractured carbonate (limestone or dolomite) aquifers, because these units can accept large quantities of drainage water with little susceptibility to clogging. These aquifers are also widely used as sources of domestic, industrial, and municipal water supplies.

Data from a merged state-federal registration list suggest that there are about 442 ADWs in Iowa, draining about 47,000 acres (73 mi^2). Individual ADWs are reported to drain anywhere from 2 to 720 acres, with a median drainage area of 80 acres. Reported well depths range from 12 to 400 feet, with a median depth of 85 feet. About 80% of all registered ADWs are located in 3 areas, Floyd County, Humboldt-Pocahontas counties, and Wright County, where they drain between 6,500 and 15,000 acres, accounting for 2% to 5% of the area of the individual counties. Individual townships within each county have a maximum of 25 to 60 ADWs.

The effects of ADWs on groundwater quality in a given area depend on numerous factors, including the volume and quality of drainage water, the number of ADWs and acreage drained in a given area, and the hydrogeologic setting and hydraulic properties of the affected aquifer. These factors are site specific and/or recharge-event specific, making prediction of ADW effects difficult. ADWs deliver contaminants into carbonate aquifers in various hydrogeologic settings with a range of natural vulnerability (i.e., without ADWs) to contamination. Aquifer vulnerability to contamination is relatively great in shallow-bedrock aquifer (within 50 feet of the surface) and karst (numerous sinkholes) areas but deep-bedrock aquifer (greater than 50 feet from the surface) regions are generally protected from surficial contamination. The overall depth distribution of contamination is a function of various factors including transport time. Hydraulic parameters and age-dating of groundwaters from deep bedrock aquifer areas suggests that the majority of this groundwater exceeds four decades in age, predating the intense use of commercial nitrogen fertilizer and most herbicides.

The majority of ADWs in Iowa bottom in the upper part of the first bedrock aquifer they penetrate. Over 75% appear to have more than 100 feet of the aquifer "beneath" them. Therefore the most acute effects of ADW inputs are likely to be within the shallower parts of the aquifers. Water-supply wells completed in the shallower parts of the aquifer are likewise those most directly affected. These are also the wells and portions of the aquifers most directly affected by natural routes of contamination, making it difficult to ascertain the impacts of ADWs in many areas.

Hydrogeologic conditions and numbers of ADWs vary among the three main ADW areas. Floyd County is dominated by shallow bedrock and karst conditions, and hence, is inherently susceptible to contamination even without ADWs. 92 ADWs are registered in Floyd County, draining about 11,500 acres, or 4% of the county. Reported depths suggest 75% of the ADWs are less than 150 feet deep, and bottom in the upper portions the uppermost Devonian aquifer. Approximately 40% of the ADWs are in deep bedrock areas, 20% penetrate into the deeper part of the upper bedrock aquifer and about 4% penetrate into the confined middle aquifer. In these latter three settings, surficial contaminants would not likely occur in the groundwaters without ADWs.

In contrast, Wright County is primarily a naturally "protected" deep-bedrock aquifer area, and susceptibility to contamination by natural processes is very low. Here 41 registered ADWs drain about 6,550 acres, or 1.9% of the county. ADWs are deeper in Wright County than in the other ADW areas, with 55% of the reported depths being 200 feet or more. Because of the thickness of glacial deposits, any surficial contaminants in the Mississippian bedrock aquifer in this area likely result from ADW inflow. The Humboldt-Pocahontas ADW area is divided equally between susceptible and protected hydrogeologic environments, though overall susceptibility appears less than in Floyd County. Some karst features occur, but are much less common than in Floyd County. In the two counties, 202 ADWs are registered; draining approximately 23,300 acres, about 3% of the two-county area.

The proportion of recharge to the bedrock aquifer groundwaters contributed by the ADWs in the major ADW areas is impossible to measure and difficult to estimate accurately. Adjusting prior modeling studies with the drainage areas estimated from ADW registration data provides a reasonable range of values, suggesting the proportion of recharge to the bedrock aquifers supplied by ADWs is likely about 6% to 28%.

Where ADWs occur in karst-shallow-bedrock aquifer regions, closure of ADWs might divert water to losing streams and/or natural sinkholes; simply diverting water and contaminants from one path of rapid entry into the aquifer to another. These areas are already highly susceptible to contamination, regardless of the ADWs, and shallow groundwater in these areas has already been adversely affected by naturally-delivered contamination. This dilemma emphasizes the need for improved agricultural management to reduce contaminant loadings in drainage water, regardless of its fate. Diverting water from ADWs may afford more processing of the drainage water in the surface environment, and therefore reduce contaminant concentrations before the drainage enters the aquifer.

Various investigations in Floyd, Humboldt, and Pocahontas counties have provided similar insights to the water-quality effects of ADWs. Noticeable effects in water-supply wells are most likely to occur within 1-1.5 miles of clusters of ADWs. These effects are more readily recognized in areas where the aquifer receiving ADW inputs is protected from surficial contamination, i.e., deep bedrock aquifer areas. In susceptible shallow bedrock and karst areas, the effects of ADWs often cannot be recognized because of the regional contamination that occurs, delivered by natural processes. Monitoring data shows that the effects of ADWs vary temporally; punctuated by rapid hydrologic and chemical responses during periods of significant ADW recharge, with discernible effects dissipating between these periods.

INTRODUCTION

Iowa agriculture benefits from two important natural resources, the rich soils that blanket the state's landscape, and sufficient precipitation, in most years, to produce large crop yields. While adequate precipitation is essential for crop growth, many of Iowa's soils, particularly in the north-central part of the state, are poorly drained and at times contain excess water that can hinder field operations or ruin crops. In these areas, farm fields are often artificially drained by buried tile lines leading to drainage ditches or streams. Another, but less commonly used outlet is the agricultural drainage well (ADW), a drilled shaft that funnels excess drainage water into underground bedrock aquifers (Fig. 1). The upper parts of these wells are often cistern-like structures that form the discharge point for tile-drainage lines; some wells are also designed to take surface runoff. ADWs are generally 5 to 10 inches in diameter and are cased from the land surface into the underlying bedrock. Virtually all ADWs in Iowa discharge into fractured carbonate (limestone or dolomite) aquifers. (Aquifers are units of rock or soil that readily conduct water and yield water to wells.) Because of their fractured nature, these units can accept large quantities of drainage water quickly and they have a lesser susceptibility to clogging with sediment and other suspended matter, compared to other aquifer materials (e.g., sandstone). These carbonate aquifers are also excellent sources of groundwater for domestic, industrial, and municipal water supplies.

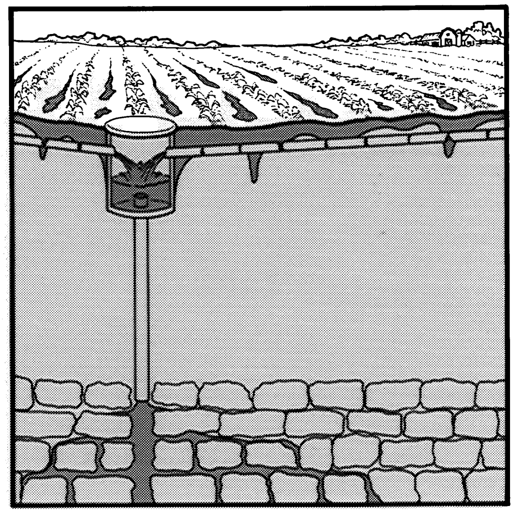


Figure 1. Schematic diagram of an ADW designed to accept tile drainage water.

The quality of water ADWs deliver to aquifers depends upon several factors, including: whether tile drainage, surface runoff, or both are discharging to the well; land use and management of the area drained; and climatic factors that control the timing and volume of infiltration and runoff. Cooperative studies by the Iowa Department of Agriculture and Land Stewardship (IDALS) and Iowa State University (ISU) are currently providing further documentation of these relationships (e.g., IDALS, 1992). In general, water entering ADWs from tile drainage typically has greater concentrations of nitrate than water from surface runoff; direct surface runoff into ADWs often contains detectable herbicides, with concentrations typically greater than in tile effluent (Baker et al., 1985). Influent surface water could contain bacteria and potentially pathogenic organisms that would not likely occur in tile effluent. Tile drainage and surface water inflow to ADWs is generally intermittent. Beyond the routine delivery of drainage water with typical agricultural contaminants to aquifers, ADWs pose an additional risk to groundwater quality. ADWs are pathways by which substances accidentally spilled on the land surface may directly enter groundwater. Some ADWs are connected to drainage systems that accept water from road ditches. Therefore spills or leaks of harmful substances into these ditches could quickly and directly impact groundwater supplies.

ADWs are not widely used throughout Iowa, but rather are concentrated in just a few areas. Therefore, their effects on groundwater are relatively localized.This introduction will discuss the basic properties and distribution of ADWs in the state. The remainder of the report will summarize the hydrogeologic setting of the areas of the state where most ADWs occur, and what the relationship between ADWs and the hydrogeology may imply for groundwater and drinking-water quality in these areas.

ADWs in Iowa

The actual number of functioning ADWs in Iowa is not precisely known. ADWs have recently been registered with both the Iowa Department of Natural Resources (DNR) and the U.S. Environmental Protection Agency (EPA). These two registration lists largely overlap, though not completely. Both lists are incomplete, in all probability, and both likely contain registrations for features that are not really ADWs. Staff from IDALS and the DNR-Geological Survey Bureau (DNR-GSB) merged the registration lists to develop a composite tabulation for this basic analysis. The merged list suggests there are 442 unique ADWs registered in Iowa. The number and distribution of ADWs provided by the DNR and EPA lists are generally in agreement with previous estimates (Mustermann et al., 1981; Hallberg et al., 1985). Unless stated otherwise, in this report the term "registered ADWs" refers to those on the merged state-federal list.

Registration information concerning locations, ADW depths, and areas drained was supplied by ADW owners, and only some of this information has been field verified. Information concerning the area drained was reported for 297 wells (67%). Accurate estimation of the area drained is dependent upon determining the location and extent of the subsurface drainage systems connected to the ADWs, which are often poorly known. The registration data are the best available, however. Assuming these data are representative and reasonably accurate, the tile and/or surface drainage from an estimated 46,750 acres (about 73 square miles) discharges to ADWs. Reported areas drained by individual ADWs range from 2 to 720 acres (Table 1). The median drainage area was 80 acres; 25% drain 40 acres or less, and 25% drain 140 acres or more. Reported depths of ADWs range from 12 feet to 400 feet. The median reported depth is 85 feet; 25% are 50 feet deep or less, and 25% are 140 feet deep or deeper.

From a statewide perspective, as suggested by the estimated number of ADWs and the area they drain, these wells are relatively minor features; the area drained accounts for less than 0.15% of the area of the state. The Iowa State-Wide Rural Well-Water Survey (SWRL; Hallberg et al., 1990; Kross et al., 1990) provided statistically valid information on rural well-water quality and site characteristics for Iowa. As part of the survey, detailed questionnaires and on-site inventories were completed that included an assessment of whether ADWs were located on the property. Statewide, the SWRL sample estimates <0.6% of rural residences have ADWs on their property. (From this very small subsample of the SWRL survey, no sites reporting ADWs had any pesticide detections or nitrate concentrations above the drinking water-standard or Health Advisory Level (HAL)). Sinkholes are natural features that can have impacts on groundwater quality similar to ADWs. For perspective, there are about 30 times as many sinkholes in Iowa than ADWs. The SWRL survey indicates that sinkholes were present on, or in the vicinity of 2.1% of rural residences.

ADWs: County and Local Perspectives

While ADWs are relatively minor features at the state level, over 80% of the registered ADWs are concentrated within only 4 counties: Humboldt, Pocahontas, Wright, and Floyd. About 90% of the projected area in the state drained by ADWs occurs in these 4 counties. Figures 2 and 3 are adaptations of the *"Groundwater Vulnerability Regions of Iowa"* map (GVRI; Hallberg and Hoyer, 1991) and show the distribution of ADWs within the 4 main counties and surrounding areas. (Note that the GVRI shows only state-registered ADWs. However, the general distribution of all registered ADWs mimics that shown on the GVRI.) Table 2 summarizes, on a statewide basis and for these 4 counties, the estimated number of ADWs and area drained, along with the percentage these areas represent in each county. Similar statistics are also given for the remainder of the state, exclusive of the 4 main ADW counties. The registration lists indicate the largest number of ADWs occur in Humboldt County where 164 are registered. Of the 4 main ADW counties, Wright County has the fewest registered wells, 41. Outside these 4 counties, only 82 ADWs were registered. The largest number found in any other county was 13, in Mitchell County. In each of

Table 1. Summary of ADW drainage areas and depths from registration reports.

	Minimum	Maximum	1st Quartile	Median	3rd Quartile
ADW drainage area, acres:	2	720	40	80	140
ADW depth, feet:	12	400	50	85	140

the main counties, between 6,500 and 15,000 acres are estimated to drain to ADWs; across the rest of the state, ADWs appear to drain a total of about 5,600 acres (Table 2). The areas of the main counties drained by ADWs accounts for between 2 to 5.5% of the area of the respective counties; across the rest of the state the percentage of area drained by ADWs is 100 times less. The significantly greater numbers of ADWs and area drained within the main counties obviously suggests a significantly greater potential to affect groundwater quality in these counties, relative to their effect at the state level. But ADWs are not uniformly distributed, even within these counties, and the primary concern must be focused on the local level.

ADWs are concentrated within particular areas of the main ADW counties, in part related to the accessibility of the carbonate aquifers and because of difficulties in achieving drainage via ditches or tiles in these areas. From the registration list, one township in Wright County has about 30 ADWs, and one township in Floyd County contains 25. Two townships in Humboldt County each contain 50 ADWs, and one township in Pocahontas County has almost 60 drainage wells. A four-township region of Humboldt-Pocahontas counties contains 190 registered ADWs. This is nearly 85% of all ADWs registered in these two counties, and 43% of those registered statewide. In some individual sections (1 square mile), as many as 10 ADWs appear to be present. The effect of ADWs on groundwater quality will be most profound in such areas of concentration.

Groundwater Vulnerability: A Frame of Reference

ADWs deliver contaminants into carbonate aquifers in various hydrogeologic settings that have a range of *natural* vulnerability to contamination. Iowa's important aquifers are mantled by a variable thickness of low-permeability surficial cover materials (e.g., glacial deposits and/or shales) that limit the rate and volume of water and contaminant movement from the land surface to the groundwater, and then to depth into the groundwater of the aquifer. Various studies show that the vulnerability to contamination of the water in an aquifer can often be related to the thickness of these overlying deposits. In many regions of Iowa, groundwater exhibits the presence of contaminants related to agriculture, industry, waste disposal and other activities of society without the presence of ADWs. Iowa studies have examined water-quality data to define the occurrence of contamination and the relative vulnerability of aquifers. These relations have been used to map and examine the spatial distribution of relative vulnerability, as well. Vulnerability mapping provides a framework for understanding why and where contamination is likely to occur because of hydrogeologic conditions. An understanding of the spatial and depth distribution of this natural vulnerability is a prerequisite for evaluating the impact of other pathways for contaminant movement to aquifers — such as ADWs.

Hallberg and Hoyer (1982) defined hydrogeologic regions for 22 counties in northeast-

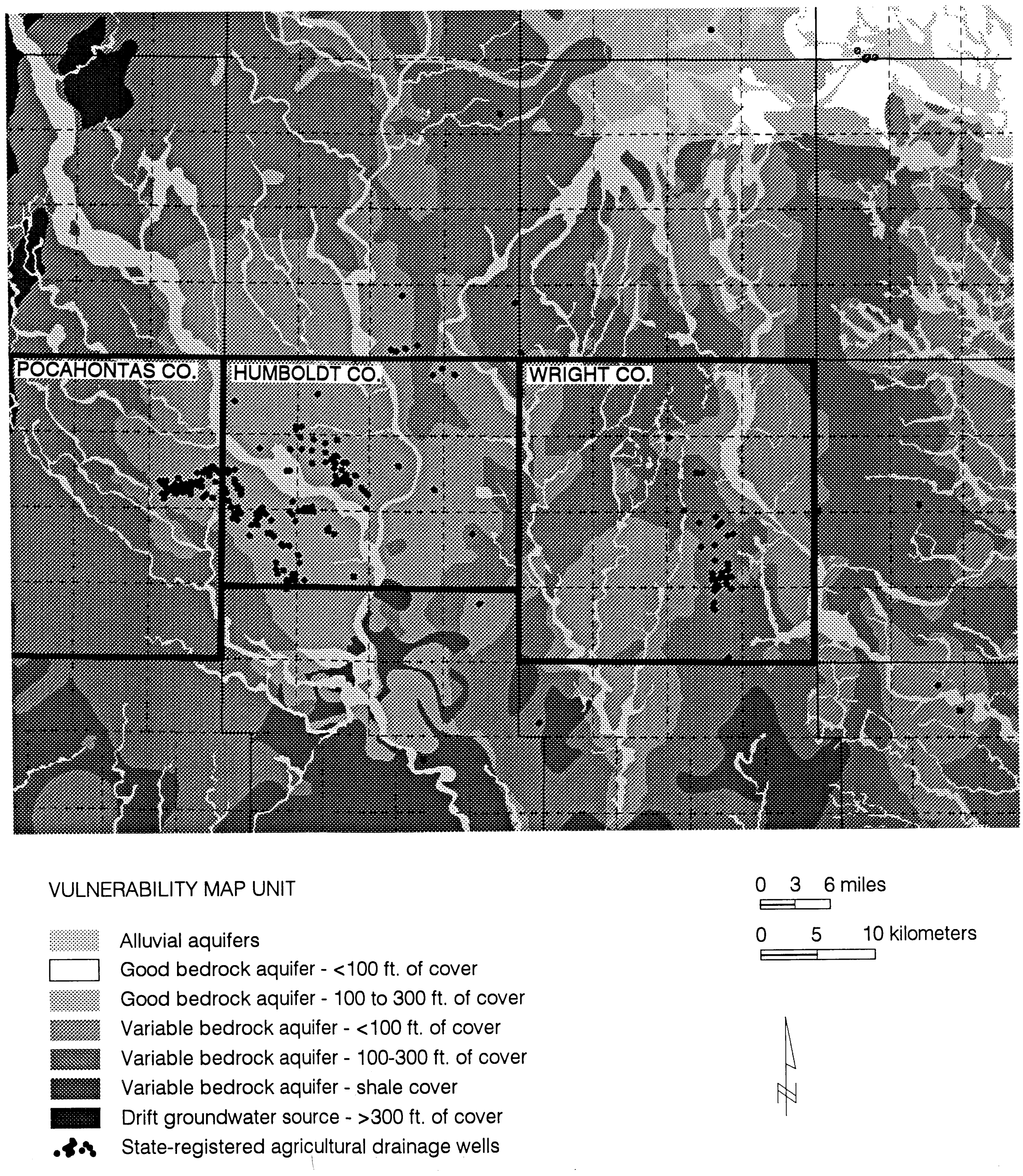


Figure 2. Modified version of the GVRI map (Hallberg and Hoyer, 1991) for the Humboldt, Pocahontas, and Wright County areas. Cover refers to the thickness of aquitard covering the underlying bedrock aquifer.

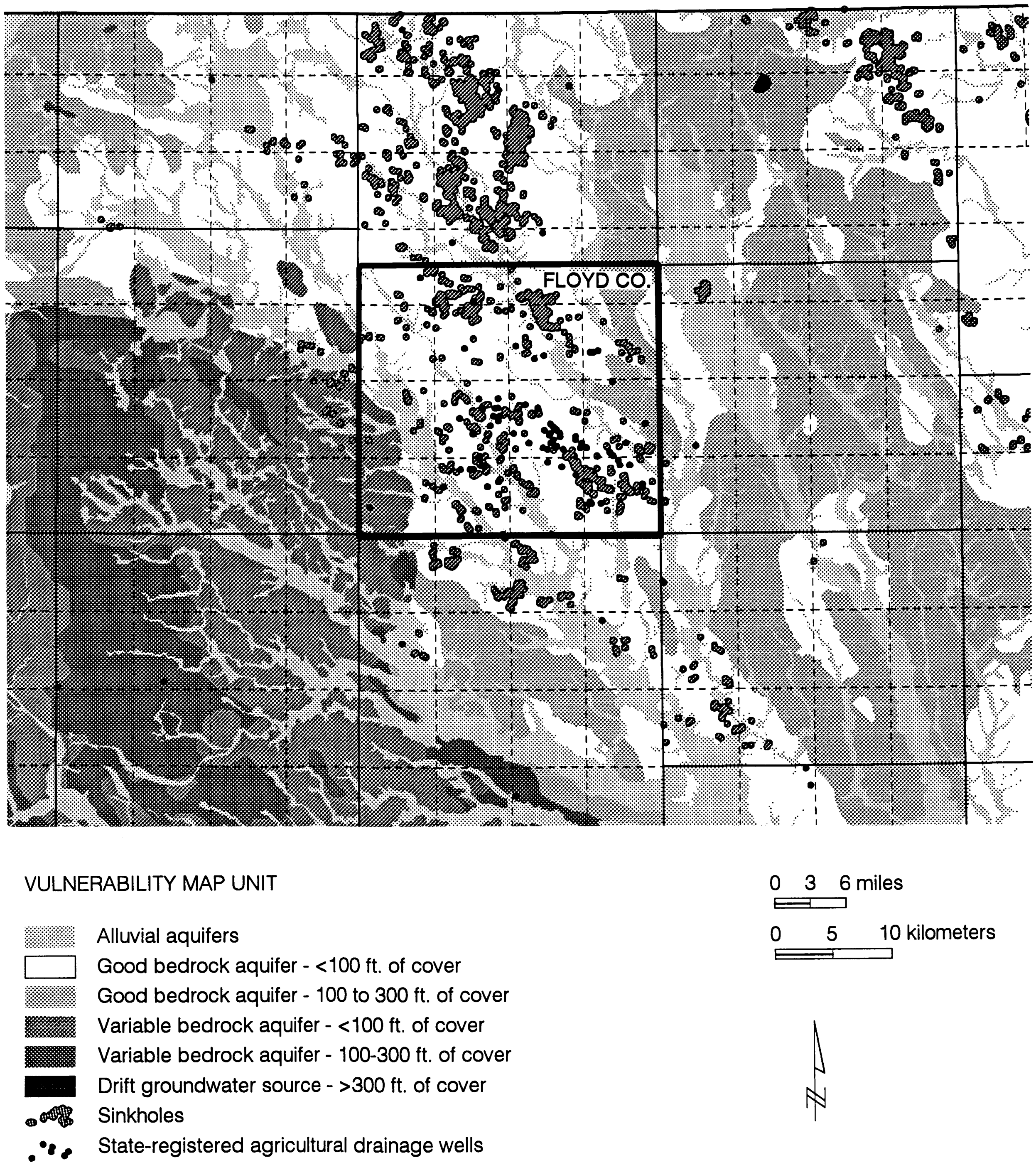


Figure 3. Modified version of the GVRI map (Hallberg and Hoyer, 1991) for the Floyd County area. Cover refers to the thickness of aquitard covering the underlying bedrock aquifer.

Table 2. State and county summary of ADW data; from registration reports.

	State Total	Floyd County	Wright County	Humboldt County	Pocahontas County	Other Counties
Number of ADWs:	442	92	41	164	63	82
ADWs/sq mile:	0.008	0.2	0.08	0.36	0.12	0.001
Acres drained by ADWs:	46,750	11,500	6,550	14,500	8,600	5,600
% of land area:	0.13%	4%	2%	5%	2%	0.02%

ern Iowa based on varying susceptibility to contamination from surficial sources. These regions include: 1) deep-bedrock aquifer areas, where more than 50 feet of low-permeability glacial deposits (and/or shales) overlie the uppermost bedrock aquifer; 2) shallow-bedrock aquifers, where the low permeability "cover" is less than fifty feet thick; and 3) karst areas, where depth to bedrock is generally less than 30 feet and concentrations of sinkholes occur. Hallberg and Hoyer analyzed existing University Hygienic Laboratory data on nitrate concentrations from these regions, and showed that wells drilled into bedrock in the deep-bedrock regions were largely free from nitrate (Table 3). In contrast, nitrate concentrations from wells in the shallow bedrock and karst areas showed measurable nitrate to depths of 200 feet. Later investigations illustrate that similar relationships exist between the presence of herbicides in well water and hydrogeologic regions (Hallberg et al., 1983, 1984; Libra et al., 1984). Note that the 50 foot thickness of low-permeability deposits used by Hallberg and Hoyer (1982) to define "protected" deep-bedrock areas should not be viewed as a "magic" thickness beyond which recent surficial contamination cannot possibly have reached. Some locales with greater than 50 feet of low-permeability cover may exhibit contamination, while some locales with less than 50 feet of cover may be effectively protected. Lateral groundwater flux also plays a role in the resultant water quality at specific sites. However, the potential for contamination is significantly reduced as the thickness of low-permeability cover increases, particularly when exceeding 50 feet.

This overall depth distribution of contamination is a function of various processes that may degrade, attenuate, or dilute contaminants, as well as transport time of the groundwater carrying the contaminants. It is partially explained by the hydraulic conductivity of the surficial glacial deposits overlying the aquifers. These materials are aquitards and, while there is downward movement of water through them, the rate of movement is quite slow where the deposits are thick, unweathered, and not significantly fractured. Measured and estimated hydraulic parameters suggest it takes decades (or longer) for water from the surface to penetrate a 50 foot cover of such materials. Isotopic analysis (for tritium) of groundwaters in such areas show that the majority of water present is older than about 1955 (e.g., Hallberg, 1989). This timing predates the period when commercial nitrogen fertilizer became heavily used, and when most herbicides came into widespread use.

While the occurrence of contaminants, and their average concentrations, decline with depth, most studies show that the degree of contamination is statistically similar in populations of wells to depths of 100 feet, particularly in the vulnerable shallow-bedrock regions. The statewide SWRL survey data again show the greatest statistical difference in water quality is between wells that are <100 feet and those >100 feet in depth (Kross et al., 1990). Well depth is a separate variable from thickness of

Table 3. Median nitrate-N concentration data, summarized by hydrogeologic region and well-depth. Data from 6,039 water-well samples, from 22 counties in northeastern and east-central Iowa, analyzed during 1977-1980 by the University Hygienic Laboratory (after Hallberg and Hoyer, 1982; Hallberg et al., 1983a, b).

Well depth	Hydrogeologic Region (Depth to regional aquifer)						
	Deep (> 50 ft)		Shallow (< 50 ft)		Karst (< 30 ft and sinkholes)		Total area
feet	Median nitrate-N concentration, mg/L						
< 50	7.3	a, x	5.8	a, x	6.2	a, x	6.2
50 - 99	1.3	a, y	4.2	a, x	7.6	a, x	4.0
100 - 149	< 1.0	a, z	3.6	a, y	5.1	a, x	1.6
150 - 199	< 1.0	a, z	1.3	a, y	2.2	a, y	1.6
200 - 249	< 1.0	a, z	< 1.0	a, z	< 1.0	a, z	< 1.0
250 - 299	< 1.0	a, z	1.0	a, z	< 1.0	a, z	< 1.0
300 - 499	< 1.0	a, z	< 1.0	a, z	< 1.0	a, z	< 1.0
> 500	< 1.0	a, z	< 1.0	a, z	< 1.0	a, z	< 1.0
Median nitrate-N Total for area	< 1.0	a	2.0	b	4.2	c	1.3

a, b, c - Medians within row followed by different letter indicate statistically significant differences at $p < 0.001$

x, y, z - Medians within column followed by different letter indicate statistically significant differences at $p < 0.001$

aquitard mantle, but the two parameters are typically inter-related.

The *Groundwater Vulnerability Regions of Iowa* map (Hallberg and Hoyer, 1991) represents a recent refinement of the earlier work on groundwater susceptibility mapping, and extends coverage over the entire state. The GVRI uses the 100-foot thickness of low permeability cover for defining areas where bedrock aquifers are more or less susceptible to contamination; it also defines areas where bedrock aquifers are likely, less likely, or unlikely to be used for domestic water supplies. Where bedrock aquifers are less likely or unlikely to be used, shallow wells, completed within the relatively low-permeability glacial deposits, are more likely to be used by rural residents. These wells are generally open to the top of the water table. As the water table is often only 5 to 15 feet below the land-surface, the shallow groundwater produced by these wells is inherently susceptible to surficial contamination. In addition, the GVRI indicates where alluvial sand and gravel aquifers are present at or near the surface; these aquifers may generally be considered susceptible to contamination. The locations of mapped sinkholes and state-registered ADWs are also shown.

Previous Investigations: ADWs

Mustermann et al. (1981) produced an extensive review of ADWs in Iowa, and made numerical estimates of their effects within the main ADW zones of Floyd, Wright, and Humboldt-Pocahontas counties. Their calculations were based on estimates of: 1) the volume of subsurface drainage water injected via ADWs; 2) the nitrate-N concentration of the drainage water; and 3) the volume of other groundwater recharge and inflow that is avail-

Table 4. Parameter assumptions used by Mustermann et al. (1981), and calculated, estimated impacts of ADWs on groundwater quality.

Parameter	Units	Floyd Co.	Wright Co.	Humboldt-Pocahontas Co.
Groundwater Recharge	acre-feet inches	39,000 6.6	34,400 2.6	68,900 3.0
Subsurface Drainage via ADWs		------------ *10-30% of annual precipitation* ---------- *160 acres/well*		
Area Assumed Draining to ADWs	acres	4,000	8,000	32,000
ADW drainage as % of all groundwater recharge in ADW areas		3-8%	11-34%	9-30%
Nitrate-N concentration in drainage water	mg/L	---------------- *10-20 mg/L* ----------------------		
Nitrate-N concentration of resultant groundwater in bedrock aquifer	mg/L	0.5 - 1.6	1.0 - 5.0	1.0 - 7.0

able to "dilute" the inputs of ADWs. This other (natural) recharge was assumed to be free of nitrate. Table 4 summarizes the assumptions used for these estimates. Groundwater recharge was calculated using Darcy's Law, assuming an average vertical hydraulic conductivity (K) for the glacial till units that overly the ADW-affected bedrock aquifers. A K value of 0.002 ft/day was used for the Floyd County ADW area; 0.001 ft/day was used for the other ADW areas. Values for till thickness and vertical hydraulic gradients were extrapolated from various regional publications by DNR-GSB and the U.S. Geological Survey (e.g., Horick and Steinhilber, 1973; Hansen, 1975; 1978), and from data on-file at DNR-GSB. Complete mixing of the drainage water with the nitrate-free groundwater recharge was assumed.

Mustermann et al.'s calculations suggest that other groundwater recharge is sufficient to dilute the ADW inputs resulting in groundwater beneath the ADW zones having an *average* nitrate-N concentration less than the USEPA HAL (10 mg/L NO_3-N), even under their estimate of "worst-case" conditions: 30% of precipitation becoming drainage to ADWs, with the drainage having an average nitrate-N concentration of 20 mg/L. They note that this degree of dilution would not necessarily occur locally. The assumptions used by Mustermann et al. (1981) are necessarily based on regional averages and simplified assumptions, and the authors indicate that the estimates are likely accurate only to within a factor of ten. While most of their assumptions are reasonable, in some areas the assumption of nitrate-free groundwater recharge is clearly not valid. Also, there are some differences in the estimated areas drained by ADWs between Mustermann et al. (1981) and this summary (see Tables 2 and 4). The greatest differences are for Floyd County where they significantly underestimated the number of ADWs, and therefore the area of the county drained, compared to the registration reports.

Baker and Austin (1984) investigated ADW effects in the Humboldt-Pocahontas County area. Their investigations included modeling of the quality and quantities of runoff and tile drainage that might reach typical ADWs; modeling of the effects of the ADW inputs to the groundwater system; and a three-time sampling of domestic water-supply wells within and away from concentrations of ADWs, in a variety of hydrogeologic settings with differing susceptibility to contamination (i.e., Hallberg and Hoyer, 1982). In general, Baker and Austin (1984) suggested that: 1) ADWs negatively impact groundwater, including groundwater used for drinking water supplies, within 0.5-1.2 miles (1-2 km) of clusters of ADWs; 2) not all wells located within these distances appear to be affected; and 3) the impacts were generally more significant with respect to nitrate than with respect to pesticide concentrations in drinking water wells. The authors also stressed the temporal aspects of the inputs to ADWs.

Cherryholmes and Gockel (1987) monitored the nitrate and herbicide concentration of tile drainage water entering 8 ADWs in Floyd County in June, July, and September 1986. During June and July, all 8 ADWs were receiving drainage. Nitrate-N concentrations in the influent drainage varied from 6.9 to 25.0 mg/L; all the drainage contained detectable herbicides. In June, drainage to six of the wells contained at least three of the following compounds: alachlor, atrazine, cyanazine, metribuzin, or metolachlor; drainage to the other two wells contained only atrazine. In July, five of the wells received drainage with combinations of two of the following compounds: atrazine, metribuzin, or metolachlor. Drainage to the other wells contained only atrazine or metolachlor. By September, only 3 of the ADWs were still receiving drainage. Herbicides were still present in the drainage water flowing to the three ADWs.

The DNR-GSB investigated ADW impacts in the Floyd County area during 1985-86 (Libra and Hallberg, 1985; Libra, 1988; unpublished GSB data). These investigations included: 1) drilling several core penetrations of the pertinent geologic units in the area, to allow for refined hydrostratigraphic analysis of these units; 2) completing these coreholes as observation-well nests, and monitoring water levels and water quality at these; and 3) monthly monitoring of water quality, for 18 months, at private wells within and away from concentrations of ADWs, in a variety of hydrogeologic settings with differing susceptibility to contamination. Some monitoring has continued in the area.

An example of the effects that ADWs can have on groundwater is illustrated in data from two of the DNR-GSB observation-well nests in Floyd and Mitchell counties. The sites are located in similar hydrogeologic settings — with 40 to 60 feet of aquitard materials overlying Devonian carbonate aquifers. Contamination from surficial sources through natural, direct vertical recharge is limited to non-existent in such a setting (see Libra et al., 1984). Both the well nests contain four bedrock wells that are finished in comparable positions within the vertical thickness and stratigraphic framework of the Devonian aquifers. Well nest FM2 is located in Mitchell County, removed from registered or otherwise known ADWs. Well nest FM3 is located in Floyd County, within one mile of at least five ADWs; the closest is about 500 feet away and approximately 300 feet deep. The other ADWs are more shallow, approximately 100-125 feet deep. These observation wells were typically monitored on a monthly to quarterly basis from February 1985 through June 1986, and again from October 1988 through October 1992. Figures 4 and 5 show groundwater levels and nitrate-N concentrations for well nests FM2 and FM3, respectively, for the period October 1985 through June 1986.

Of particular interest are the hydrologic and water quality responses of the well nests during March 1986, when significant snow melt, accompanied by heavy rains, occurred during a 2-3 day period. This recharge had little short-term effect at well nest FM2, as the relatively thick cover of aquitard materials limits recharge inputs of water and chemicals to the underlying aquifers. In contrast, groundwater elevations at nest FM3 show a rapid rise; direct field observations indicated that much of the rise occurred during recharge event.

At this time, relatively large volumes of tile drainage water were observed entering the nearest drainage well and the water level in the drainage well rose above the land surface. The rise in water levels at FM3 was a result of the inputs to this and other local drainage wells. Significant increases in nitrate-N concentrations occurred in some, but not all of the bedrock research-wells in this nest. During dry periods prior to this recharge event, nitrate-N concentrations were typically less than 1 mg/L and always below 3 mg/L. During the event, samples were collected from the wells twice, three days apart. The highest concentration measured in the shallowest well was 30 mg/L NO_3-N, 3 times the U.S. Environmental Protection Agency's-Health Advisory Level (HAL), and the herbicide atrazine was also detected. There was no chemical response noted in the two wells of intermediate depth, although samples collected during other relatively wet periods have contained detectable nitrate-N.

Nitrate-N concentrations in the deepest well rose to 4 mg/L, but no herbicides were present. Drainage entering the nearest ADW, over 300 feet deep (similar to the deepest monitoring well), contained 12 mg/L NO_3-N and also no herbicides. While the nearest ADW appears to have delivered the nitrate-N (and no herbicides) to the deepest well, drainage to the ADW had a lower nitrate-N concentration than observed in the most shallow monitoring well. This suggests inputs from the other, more shallow ADWs nearby, impacted the shallowest well at FM3.

Another recharge event occurred in late May 1986, and provides further insights. Drainage to the deep ADW nearest FM3 contained 14 mg/L NO_3-N, 3 ug/L cyanazine, and 6 ug/L metolachlor. Groundwater from the deepest research well at FM3 contained 6 mg/L NO_3-N, 0.4 ug/L cyanazine, and 0.9 ug/L metolachlor. The shallowest well produced water with 17 mg/L NO_3-N, but no herbicides. The nearest ADW again appears to directly affect the deepest monitoring well, while the shallowest well must be affected by another ADW(s). Note that when dry conditions occurred again, and drainage inputs were minimal, nitrate-N concentrations from water in these wells returned to

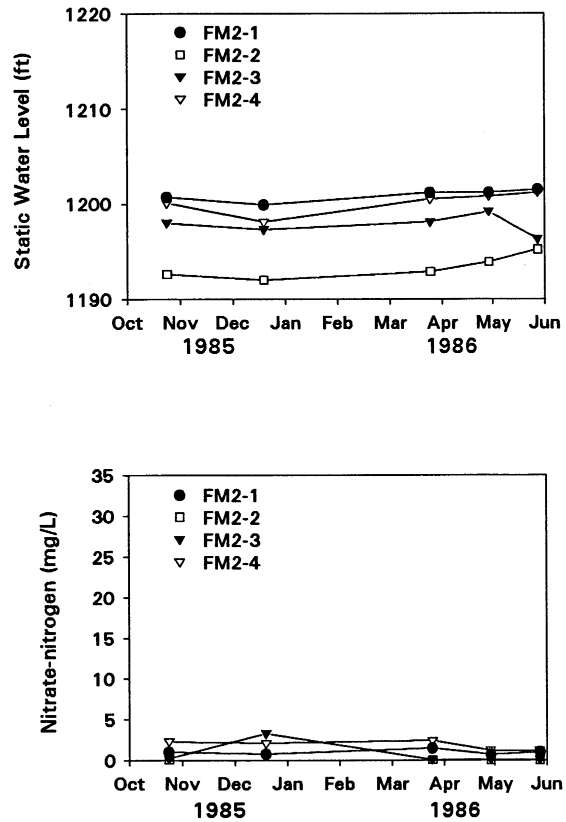


Figure 4. Potentiometric elevations and nitrate-N concentrations at well nest FM-2. Open intervals of the observation wells are: FM2-1, 60-70 feet; FM2-2, 110-150 feet; FM2-3, 190-250 feet; FM2-4, 280-340 feet.

less than 3 mg/L, and herbicide concentrations dropped below detection limits. During the period FM3 was monitored (1985-1986 and 1988-1992), the highest nitrate-N concentrations measured at the FM3 wells were, from the shallowest to deepest, 54 mg/L, 1.8 mg/L, 7.2 mg/L, and 8.5 mg/L, respectively. Many of the private wells in the area are approximately in the same range of depths as the two shallowest wells at FM3. Therefore, the data from this well nest illustrates the type of effects ADW inputs may have on local drinking-water wells. The groundwater record from these monitoring wells illustrates that the impact from ADWs is punctuated by rapid hydrologic and chemical re-

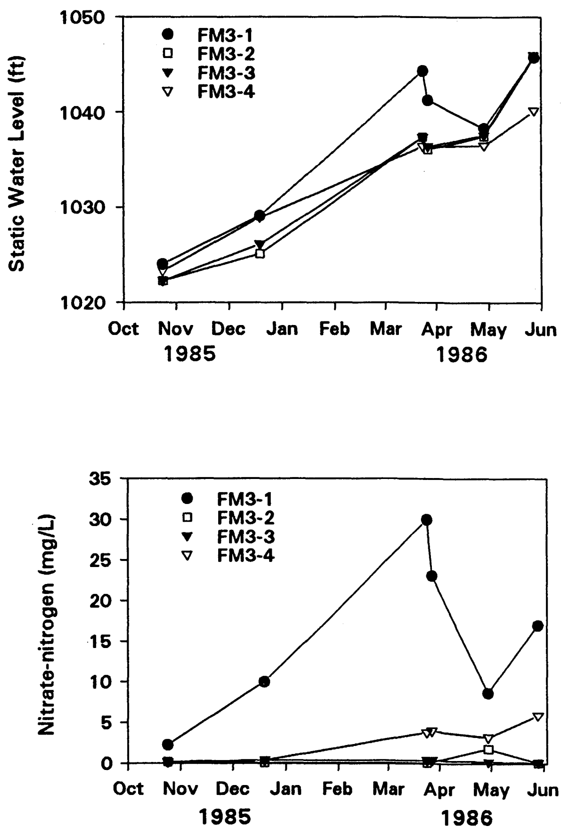


Figure 5. Potentiometric elevations and nitrate-N concentrations at well nest FM-3. Open intervals of the observation wells are: FM3-1, 95-110 feet; FM3-2, 170-210 feet; FM3-3, 260-305 feet; FM3-4, 350-365 feet.

sponses during periods of significant ADW recharge, and that the effects dissipate between these periods.

In general, the DNR-GSB investigations concur with the conclusions of Baker and Austin (1984); while ADWs do negatively impact groundwater and drinking water within 0.5 to 1.5 miles of numerous ADWs, not all wells within this distance show ADW impacts and the apparent impacts vary with time. ADW impacts were most noticeable following runoff and/or infiltration generating conditions, when surface and/or tile drainage is delivered to the groundwater via ADWs. During extended dry periods drainage inputs are insignificant, and ADW impacts are less, or not, noticeable. These investigations also showed that ADW effects were difficult to identify in the areas that are naturally susceptible to contamination.

THE MAJOR ADW AREAS

There are three major areas where ADWs are concentrated in Iowa. These are in Floyd County, Humboldt-Pocahontas counties, and Wright County. The hydrogeologic settings of these regions are outlined below, particularly in relation to the distribution of the ADWs.

Floyd County

Figure 6 is a modified version of the GVRI map for Floyd County, showing the depth to the underlying bedrock aquifer, or the thickness of the aquitard covering the bedrock aquifer. The black circles show the locations of ADWs; the open circles the locations of sinkholes. While there are a few ADWs registered in the surrounding counties they are overwhelmingly concentrated in Floyd County in this region. The majority of ADWs in Floyd County are located in the south, particularly the south-central part of the county, between the valleys of the Cedar and Shell Rock Rivers.

Hydrogeologic Setting

Floyd County is underlain by Devonian-age bedrock units, predominantly carbonate (i.e., limestone and dolomite) rocks with lesser amounts of shale; these rocks may exceed 400 feet in thickness. The carbonate rock units are aquifers, rock units which readily conduct and yield water to wells. The Devonian carbonate aquifers are utilized as a water source by the vast majority of rural residents, and most municipalities in the region. The relatively low permeability shale units act as aquitards, rock units that limit or restrict groundwater movement into or between the aquifers. The Devonian units are overlain by a variable thickness of Quaternary-age glacial deposits, predominantly glacial till. Locally, shaley sandstones of Cretaceous age (Wind-

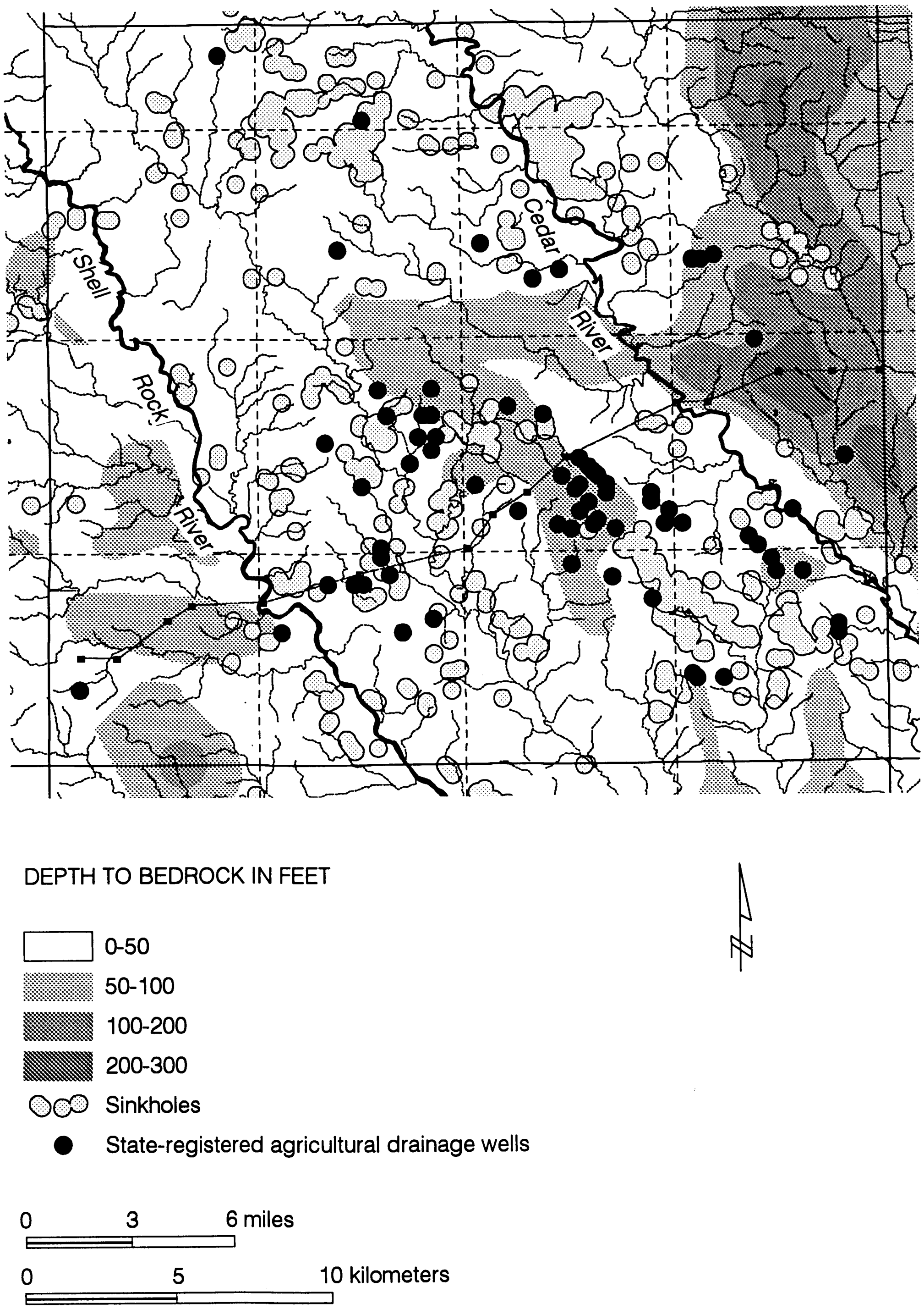


Figure 6. Modified version of the GVRI map (Hallberg and Hoyer, 1991) for Floyd County, showing depth to bedrock (or thickness of aquitard cover). State-registered ADWs and mapped sinkholes are also shown. Line locates cross-section shown on Figure 7.

row Formation) are preserved between the Devonian rocks and the glacial deposits. The Quaternary and Cretaceous deposits are generally aquitards and where thick, limit the rate and volume of groundwater movement downward to the Devonian aquifers.

Floyd County is predominantly a shallow-bedrock aquifer area (after Hallberg and Hoyer, 1982), i.e., it exhibits less than 50 feet of cover of aquitard materials over the bedrock aquifer. Nearly three-fourths of the county falls into this hydrogeologic region category (Fig. 6; Table 5), and therefore is susceptible to contamination, regardless of the presence of ADWs or sinkholes. Mapped sinkholes are more common than ADWs; there are 6 times as many sinkholes as ADWs in the county (Fig. 6).

Figure 7 is a cross-section of the hydrogeologic setting for southern Floyd County; aquitards are indicated by shading, while aquifers are unshaded. Particularly important aquitards include: the surficial glacial deposits; the Chickasaw Shale Member and the Pinicon Ridge Formation, which are shales and divide the carbonate units into an "upper" aquifer (Shell Rock-Lithograph City-Coralville Formations), "middle" aquifer (Bassett Member of the Little Cedar Formation), and "lower" aquifer (Spillville Formation). Devonian strata are underlain by Ordovician rocks (e.g., Brainard Shale of the Maquoketa Formation) that act as a regionally-extensive aquitard. Over much of the northeast quarter of Iowa these rocks form the base of the relatively shallow groundwater system (shallow and intermediate flow system) that supplies water to domestic wells, provides baseflow to area streams, and which may be affected by ADWs.

Investigations in Floyd County and adjacent areas have indicated that contamination (by nitrate and some pesticides) from surficial sources is common within the upper Devonian aquifer in shallow-bedrock aquifer areas (Libra et al., 1984; Libra and Hallberg, 1985). Where the aquitard cover is thicker, contamination of the upper aquifer is relatively rare. Contamination generally decreases with depth within the upper aquifer, even below areas of thin cover. Contamination is rare within the middle and lower Devonian aquifers. Analysis

Table 5. Percentage distribution of relevant GVRI map units, Floyd County.

Map Unit	Percentage of county
Thickness of Surficial Aquitard, or Depth to Bedrock Aquifer:	
<50 ft	73.2%
50 to 99 ft	17.9%
100 to 199 ft	7.7%
200 to 299 ft	1.2%

of isotopes (tritium) in the groundwater in the region suggests that relatively recent recharge water (younger than 1955) generally has not reached these lower units in Floyd County.

The distribution of relatively high- and low-permeability geologic units exerts a major control on the three-dimensional movement of groundwater. The other major control is related to surface topography. Topographically high areas generally are recharge zones, where groundwater moves downward from the water table. Topographically low areas are generally discharge areas, where groundwater is moving upwards towards the water table and the land surface. The most important discharge zones in humid climates are usually entrenched streams and rivers, which occupy the lowest areas of the landscape and can efficiently carry away the discharged groundwater. Such streams are sometimes called gaining streams. The main discharge zones in the Floyd County area are the valleys of the Cedar and Shell Rock Rivers (Figs. 6 and 7). In general, groundwater flows from high elevation recharge areas between the rivers, downward through the Quaternary and Cretaceous aquitard, and into the upper Devonian aquifer. Flow is then through this aquifer towards the river valleys, and ultimately upwards to the discharge zones along the rivers. The Chickasaw Shale acts as a barrier limiting downward flow to deeper aquifers and it also limits upward flow from the deeper aquifers into the upper aquifer and the discharge zones along

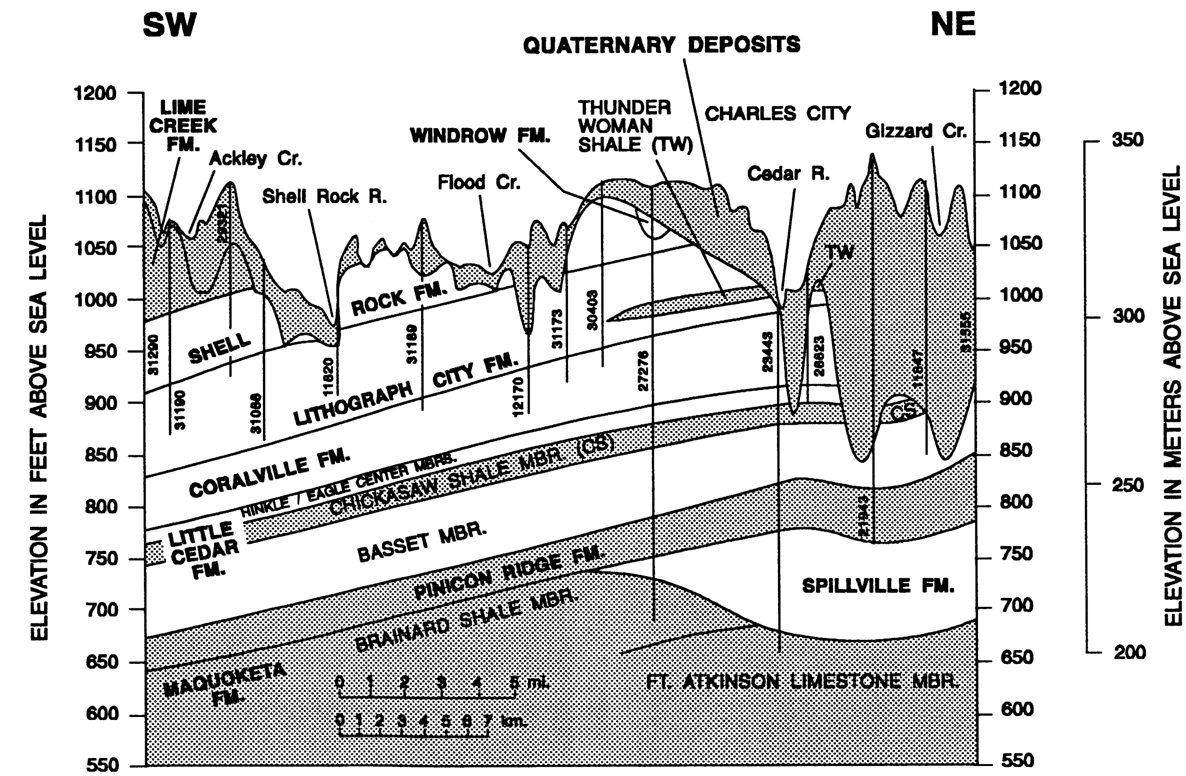


Figure 7. Geologic cross section of Floyd County. Aquitard units are shaded. Line of section is shown on Figure 6.

the rivers. Therefore, most of the groundwater discharging to the rivers is unlikely to have moved upwards from any deeper than the shale.

Some portion of the groundwater moves laterally at more shallow depths, and may discharge to tributary streams and even ditches, particularly during periods of high water tables. Finally, there is a component of groundwater flow that is directed to the south (i.e., "out" of Figure 7, and "towards" the reader). This is a result of generally higher elevations to the north (i.e., "into" Figure 7), towards the headwaters of the Cedar and Shell Rock Rivers.

Streams are also shown on Figure 6. In parts of Floyd County, streams lose water to the groundwater system; that is, the water that runs off the land and into some streams, leaks through the stream bed and recharges the groundwater system, instead of the other way around. This is not an uncommon occurrence in areas of very shallow bedrock, particularly carbonate bedrock where sinkholes or fractures may be present in stream beds. The losing stream reaches have not been precisely delineated, but they are associated with areas of sinkholes shown on Figure 6. The exact fate of water lost from streams in Floyd County is unclear. For a significant volume of streamflow to be lost, the water must be entering relatively permeable, solutionally enlarged zones (areas where openings such as fractures and/or bedding planes have been enlarged as the carbonate rock is slowly dissolved by circulating groundwater) that are capable of transmitting the water. In many karst-carbonate rock settings, these zones tend to form preferentially below stream valleys (Alley, 1977). Where this occurs, water lost from streams flows in a "downstream" direction, remaining largely within these elongate zones that parallel stream valleys at some depth below the valley floor. Shallow groundwater from the surrounding aquifer would also tend

Table 6. Distribution of ADW depths, Floyd County; from registration reports.

Depth Range	% of ADWs	Cumulative %
< 50 ft	30.6%	30.6%
50 - 99 ft	28.5%	59.1%
100 - 149 ft	18.4%	77.5%
150 - 199 ft	10.2%	87.7%
200 - 249 ft	8.2%	95.9%
250 - 299 ft	2.0%	97.9%
> 300 ft	2.0%	100.0%

to flow towards these zones. Such settings are complex, and the regime of the streams may vary over time with changing hydrologic conditions; stream reaches that lose water during dry, or dry-to-normal periods, may become gaining reaches following significant recharge events. This recharge results in relatively high water tables, which may allow groundwater to discharge to the bed of a normally losing stream reach.

Recharge rates for the upper Devonian aquifer in Floyd County have not been studied in detail. As previously noted, Mustermann et al. (1981) estimated an average recharge rate of about 6.6 inches per year. An additional estimate was made for this review by assessing baseflow discharge, which is supplied by groundwater, from a major stream in the area. This was done using a baseflow indexing method (Institute for Hydrology, 1980) for the Cedar River at Charles City, utilizing U.S. Geological Survey daily discharge records for the period 1964-1988 (Carol Thompson, DNR-GSB, unpublished data). This method suggests that 69% of Cedar River's average annual discharge of 8.94 inches, or 6.2 inches, was supplied by groundwater. While estimating groundwater recharge from stream baseflow requires simplifying assumptions, the close agreement between the recharge estimated by this method, and that derived by Mustermann et al. (1981), suggests that these values are reasonable.

Hydrogeologic Setting and ADWs

State-registered ADWs in Floyd County are shown on Figure 6. The merged state-federal registration lists suggest that there are about 92 ADWs in the county. Extrapolation of the reported acres drained by individual ADWs, which were available for about 50 wells, to all registered ADWS, suggests that about 11,500 acres of land in the county drain to ADWs. This equals about 4% of the county land area. Based on data from the EPA Underground Injection Control Inventory (UICI) and field observations by consultants for IDALS Alternative Outlet Study (AOS), about 30% of the ADWs located in fields in Floyd County have intakes for surface water. Depths were reported for about one-half (49) of the registered ADWs in Floyd County, and Table 6 summarizes the distribution of depths. About 60% of the reported well depths are less than 100 feet; and only 4% are greater than 250 feet deep. Extrapolating to the merged registration list suggests that 28 wells would be less than 50 feet deep and about 55 wells would be less than 100 feet deep. Based on this extrapolation about 4 wells are greater than 250 feet deep.

Reported ADW locations and depths were used to estimate bottom-hole elevations for the ADWs; these, along with published (Witzke and Bunker, 1984, 1985) and unpublished GSB stratigraphic data were used to evaluate the stratigraphic intervals penetrated by individual ADWs. Adequate information for this evaluation was available for about one-half of the registered ADWs in the county. Extrapolating from the reported depths, 95% of these ADWs (87 wells) are completed above the Chickasaw Shale (i.e., in the upper aquifer) and about 39% (36) bottom more than 200 feet above the top of the shale (Fig. 7). An additional 36% (33 wells) end between 100 and 200 feet above the shale. This suggests that 75% of the ADWs (or 69 of the reported 92 wells) do not penetrate the lower 100 feet of the upper aquifer. About 20% of the ADWs (18 wells) do penetrate the lower one hundred feet of the upper aquifer and about 4% (4 wells) go deeper and end within the middle aquifer. The ADWs (about 22 wells) which penetrate to within 100 feet of the Chickasaw Shale, or continue through into the middle aquifer, are likely to deliver agriculturally-derived contaminants into groundwater that is otherwise relatively protected from surficial contamination.

Figure 6, modified from the GVRI map, shows ADW locations in relation to the depth to bedrock. Most ADWs are located in shallow bedrock areas, where the cover of low-permeability glacial materials is less than 50 feet thick. About 58% of the wells on the state registration list are in shallow bedrock aquifer areas, which are susceptible to contamination even without ADWs. Further, as shown on Figure 6, many ADWs are in, or near areas where sinkholes occur, as well ("karst" hydrogeologic areas of Hallberg and Hoyer, 1982; Libra et al., 1984). In fact, some of the registered ADWs in these areas are "improved" sinkholes; sinkholes that have been structurally altered through addition of an inlet pipe to more efficiently accept drainage water and to prevent them from filling up. The remaining ADWs lie in areas of thicker cover where contamination is unlikely. A large number of these occur within a cluster that lies just southeast of the center of the county. This cluster includes the three deepest ADWs reported in the county.

Implications for Water-Quality

The drainage water discharged by ADWs mixes with the groundwater contained within the receiving aquifer. Initially, this mixing is with groundwater from the immediate interval penetrated by the ADW. Further mixing occurs as the ADW discharge joins the groundwater flow-system and moves and disperses down flow towards discharge zones. As discussed, the major discharge zones in the area are the Shell Rock and Cedar Rivers. Tributary streams, or possibly high-permeability solution zones within the bedrock below losing reaches of tributary streams, likely act as discharge zones for groundwater that circulates at relatively shallow depths. Therefore, inputs from relatively shallow ADWs may flow towards tributaries, while inputs from deeper ADWs likely follow flow paths leading to the major rivers. At what depth ADWs should be considered relatively deep or shallow in this context cannot be stated. However, those ADWs that bottom more than 200 feet above the top of the Chickasaw Shale are likely contributors to the more shallow flow system. ADWs that penetrate to within 100 feet of the shale likely contribute some of their input to the deeper flow system. However, as ADWs are typically uncased through the entire bedrock section they penetrate, even deep ADWs will discharge water into the upper parts of the bedrock aquifer. ADW water that is delivered into the deeper flow system, or into the middle aquifer, will likely flow toward the rivers and also toward the southeast. The Cedar and Shell Rock incise into these lower units downstream from the Floyd County region. In these areas, groundwater from the deeper aquifers would discharge toward the rivers.

As previously discussed, Mustermann et al. (1981) estimated the volume of nitrate-free groundwater recharge available to mix with and dilute estimated ADW inputs in Floyd County. While the volumes of water used in their analysis were generally reasonable, the acres drained by ADWs, and therefore ADW inputs, appear to have been underestimated. Also, the concept of dilution with "nitrate-free" recharge is a questionable assumption, particularly in this area. While nitrate-free recharge may enter the upper aquifer beneath areas with a relatively thick cover of glacial materials, recharge in shallow bedrock areas is likely to contain significant nitrate along with detectable herbicides (Libra et al., 1984). In fact, because of the normal background contamination apparent in much of the shallow bedrock aquifer and karst areas the dilution potential (e.g., for nitrate) for ADW input water is limited, as is the potential to ascertain any impacts specifically caused by ADWs.

Table 7 summarizes water-quality observations

Table 7. Summary of private well water-quality data by hydrogeologic region and well depth; from population-based sampling studies in Floyd and Mitchell counties, 1986-1987.

Well depth range	% wells in depth range	% wells in depth range in hydrogeologic regions: v shallow bedrock	karst	shallow bedrock	deep bedrock	ADW	% ADWs in depth range
feet	%	%	%	%	%	%	%
< 50	9%	6%	7%	15%	0%	5%	31%
50-99	23%	44%	13%	30%	5%	14%	29%
100-149	26%	17%	43%	21%	18%	38%	18%
150-199	24%	17%	27%	22%	41%	19%	10%
200-299	10%	11%	3%	9%	14%	19%	2%
>300	7%	6%	7%	4%	23%	5%	2%
% of all wells:		11%	17%	46%	13%	13%	

Well depth range	% wells in depth range	% wells with >10mg/L nitrate-N in hydrogeologic regions: v shallow bedrock	karst	shallow bedrock	deep bedrock	ADW	% ADWs in depth range
feet	%	%	%	%	%	%	%
< 50	9%	0%	100%	33%	0%	0%	31%
50-99	23%	63%	25%	12%	0%	0%	29%
100-149	26%	67%	23%	0%	0%	0%	18%
150-199	24%	100%	38%	6%	0%	0%	10%
200-299	10%	0%	0%	14%	0%	0%	2%
>300	7%	0%	0%	0%	0%	0%	2%
% of all wells:		37%	30%	19%	0%	0%	

Well depth range	% wells in depth range	mean annual nitrate-N concentration: v shallow bedrock	karst	shallow bedrock	deep bedrock	ADW	% ADWs in depth range
feet	%	mg/L	mg/L	mg/L	mg/L	mg/L	%
< 50	9%	8.4	17.5	7.3	0.0	6.6	31%
50-99	23%	9.6	5.6	9.6	0.1	3.2	29%
100-149	26%	14.4	7.9	2.2	0.0	3.3	18%
150-199	24%	3.1	7.6	2.6	0.2	3.6	10%
200-299	10%	0.0	1.7	6.0	0.1	2.5	2%
>300	7%	0.0	8.0	1.9	2.3	6.4	2%
mean of all wells:		7.8	8.0	5.5	0.6	3.5	

Well depth range	% wells in depth range	% wells with pesticide detections: v shallow bedrock	karst	shallow bedrock	deep bedrock	ADW	% ADWs in depth range
feet	%	%	%	%	%	%	%
< 50	9%	100%	100%	58%	0%	100%	31%
50-99	23%	86%	50%	79%	0%	67%	29%
100-149	26%	67%	92%	41%	25%	50%	18%
150-199	24%	67%	100%	50%	22%	0%	10%
200-299	10%	0%	0%	71%	67%	25%	2%
>300	7%	100%	50%	33%	20%	100%	2%
% of all wells:		74%	83%	60%	30%	43%	

by well-depth and by hydrogeologic region for Floyd and Mitchell counties. These data were derived from a population-based statistical survey of the two counties and represent a systematic sampling of 10% of all the farm wells; 184 wells were sampled four times during 1986 and 1987 (Hallberg, 1989). Wells within 1.5 miles of ADWs were removed from their hydrogeologic region category and placed into the ADW area category for this analysis. The ADW category includes 13% of the wells. This summary illustrates the difficulty inherent in assessing the water-quality impacts of ADWs in this area. As noted above, much of the area is susceptible to contamination from natural recharge processes in the shallow bedrock and karst areas. There are few significant differences between the ADW area wells and the other hydrogeologic areas for the water quality parameters measured in this study. The water quality from ADW area wells, as might be expected from their distribution, typically fall in between the protected, deep-bedrock areas and the shallow bedrock areas. No wells in the ADW area exhibited NO_3-N >10 mg/L, similar to the deep bedrock region wells. Yet the mean annual nitrate-N concentration is greater in all depth categories then those from the deep bedrock areas, and are similar to the shallow bedrock region. The deepest wells in the ADW area group, with elevated mean NO_3-N concentrations and increased proportion of pesticide detections, may be reflecting the deep injection from some ADWs, as illustrated in Figures 4 and 5. As discussed with Figures 4 and 5, it is only where the ADWs occur in the deep bedrock regions that any water-quality impact can be discerned, because contamination in the shallow bedrock and karst regions is so widespread, as clearly illustrated in Table 7.

Summary: Floyd County

The various hydrogeologic settings in Floyd County complicate understanding the actual water-quality impacts of ADWs. The majority of ADWs discharge water into the shallow portion of the upper Devonian aquifer. The majority of ADWs are located in shallow bedrock aquifer and karst areas; some ADWs are actually "improved" sinkholes within the karst areas. Even without ADWs, these areas are highly susceptible to contamination through normal infiltration recharge and the delivery of recharge through sinkholes. The groundwater in these regions contains elevated concentrations of nitrate-N and the presence of some pesticides, even where ADWs are not present. Work to date has not found significantly different chemical water-quality in such areas with or without ADWs.

The water delivered into the aquifer from ADWs with surface intakes would be similar to that delivered by an open sinkhole or open fracture in a losing stream bed. However, most sinkholes are not "open"; most are soil-filled and simply enhance infiltration because they collect water. ADWs with surface intakes, by their structural design, are probably more efficient at delivering a larger volume of water into the aquifer than are sinkholes. ADWs with surface intakes can deliver contaminants that would not be common to normal infiltration recharge (bacteria, large particulates, suspended matter), and where they efficiently convey surface runoff they may intermittently deliver into the groundwater the higher concentrations of some contaminants that occur in runoff.

Where the ADWs deliver water into the upper aquifer in deep bedrock areas (an estimated 42% of the ADWs, or about 40 wells), into the deeper portion of the upper aquifer (an estimated 20% of the ADWs, about 18 wells) or into the confined middle aquifer (an estimated 4%, about 4 wells) they indeed have a discernible impact on the water-quality of the aquifer, as shown in Figure 5 (previous section). Past work suggests that the majority of groundwater in these hydrogeologic settings is pre-1955 in age. and therefore is characterized by very low nitrate-N concentrations and a lack of pesticides and surficial bacteria.

Humboldt and Pocahontas Counties

Figure 8 is a modified version of the GVRI map for Humboldt and Pocahontas counties, showing the depth to the underlying bedrock aquifer, or the thickness of the aquitard covering the bedrock aquifer. Black circles indicate the location of state-registered ADWs. Most of the ADWs in these

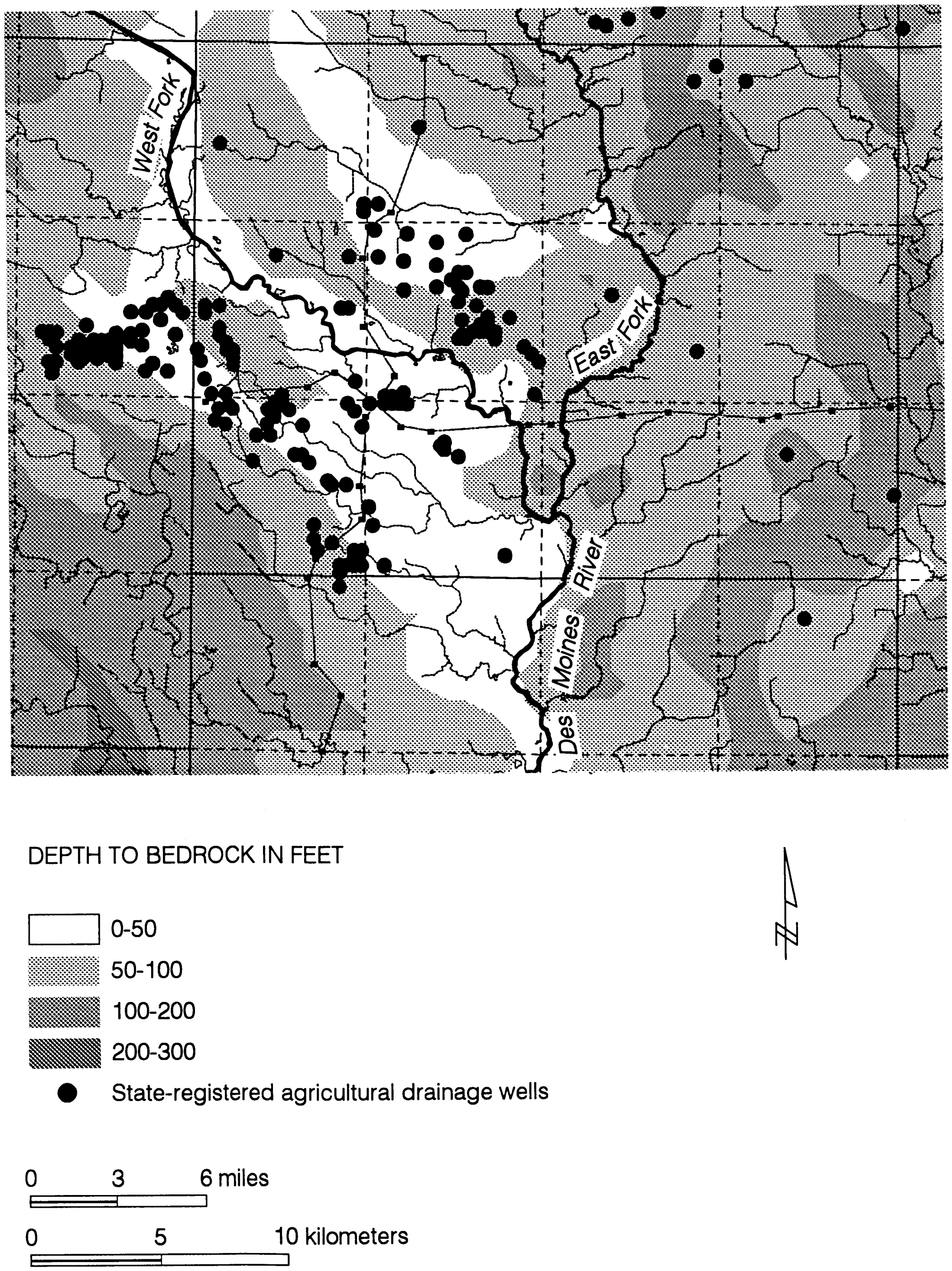


Figure 8. Modified version of the GVRI map (Hallberg and Hoyer, 1991) for Humboldt and Pocahontas counties, showing depth to bedrock (or thickness of aquitard cover). State-registered ADWs are also shown. Lines locate cross-sections shown on Figures 9 and 10.

counties are located within about six miles of the West Fork of the Des Moines River, just upstream from its confluence with the East Fork at Humboldt. All of the state-registered ADWs in Pocahontas County are located within an area smaller than one-half of a township. A few ADWs are scattered across eastern Humboldt and southeast Kossuth counties.

Hydrogeologic Setting

Humboldt and Pocahontas counties are underlain by Mississippian-age bedrock, predominantly carbonates, that are used as aquifers by most rural residents and many small municipalities. The Mississippian carbonates include the Gilmore City and Maynes Creek Formations (Woodson and Bunker, 1989). These rocks reach a maximum thickness approaching 300 feet. There are no regionally extensive confining beds within this rock sequence; therefore, these formations constitute the Mississippian aquifer in this area. Figure 9 is an east-west cross-section extending from the Humboldt-Pocahontas County line into Wright County, and Figure 10 a north-south section through western Humboldt County; the lines of the sections are shown on Figure 8. The Gilmore City Formation, where it has not been thinned by erosion, is about 150 feet thick. Erosion has thinned or completely removed the Gilmore City in parts of western Humboldt and eastern Pocahontas counties, significantly reducing the total thickness of the Mississippian aquifer. The Maynes Creek is typically about 125 feet thick, but is somewhat thinner in areas where erosion has removed the overlying Gilmore City and parts of the Maynes Creek itself. The Mississppian carbonate strata are underlain by the Mississippian Prospect Hill Formation and by Devonian-age carbonate strata. The Prospect Hill likely acts as a confining bed separating the Mississippian aquifer from the underlying Devonian units, but its hydrologic properties are not well understood. Quaternary-age glacial deposits, predominantly low-permeability glacial till, overlie the Mississippian units. These deposits vary from less than 30 feet to over 200 feet thick in the area. Where thick, the glacial deposits act as a confining bed, limiting the rate of downward groundwater movement to the Mississppian aquifer. Locally, isolated erosional remnants of Cretaceous-age strata (Dakota Formation), mainly sandstones and shales, are preserved below the glacial deposits, and above the Mississippian aquifer. Sandstone units readily transmit groundwater, while the shales may be considered confining beds.

Figure 10 also shows the Manson structure, a roughly circular feature with a diameter of about 22 miles, and a vertical extent of over 10,000 feet. This structure formed when an asteroid hit the earth about 65 million years ago (Hartung and Anderson, 1988). The impact caused an uplift of the surrounding rocks to occur (Woodson and Bunker, 1989); as shown on Figure 10, the Mississppian strata dip away from the structure as a result. Fracturing of the Mississippian strata may be enhanced near the structure because of the impact (Anderson and Ludvigson, 1989). With respect to the hydrology of the Mississippian aquifer and overlying units, the Manson structure can be thought of as a huge, relatively impermeable cylinder. ADWs have been drilled within one mile of the edge of the structure in Pocahontas County. The low permeability of the materials within the structure itself explains why no functioning ADWs are located within the area it underlies.

Humboldt and Pocahontas counties are predominantly deep-bedrock areas, using the terminology of Hallberg and Hoyer (1982; see Fig. 8). Table 8 summarizes the distribution of GVRI map units for the counties. About 75% of Humboldt and 95% of Pocahontas County is underlain by greater than 50 feet of relatively low-permeability glacial deposits. Shallow bedrock conditions are more common in the area where most ADWs are located. Here, roughly one-half of the land surface is underlain by less than 50 feet of glacial deposits, and one-half by 50 to 100 feet. Where glacial deposits are greater than 50 feet thick, groundwater within underlying aquifers is unlikely to be affected by surficial contaminants that are delivered by natural processes (Hallberg and Hoyer, 1982). This area of north-central Iowa is underlain by the youngest glacial deposits found in the state. These materials are less weathered and fractured, and less perme-

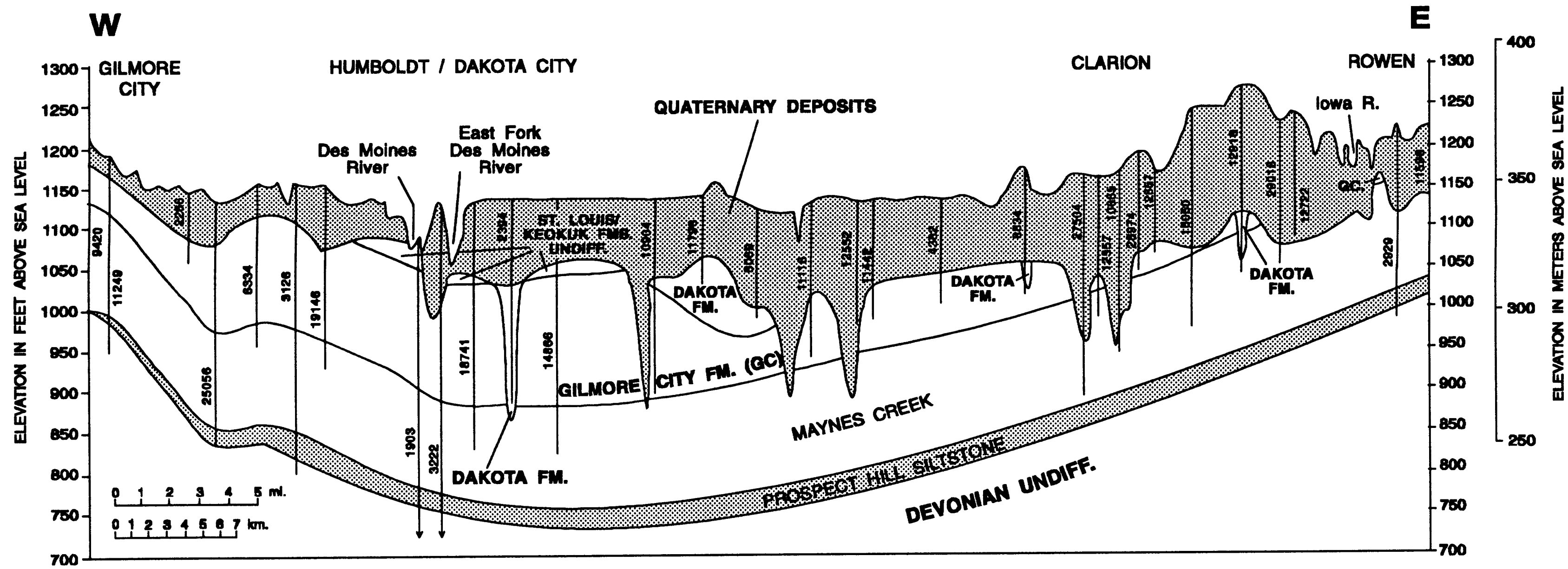


Figure 9. East-west geologic cross section across Humboldt and Wright counties. Aquitard units are shaded. Line of section is shown on Figures 8 and 11.

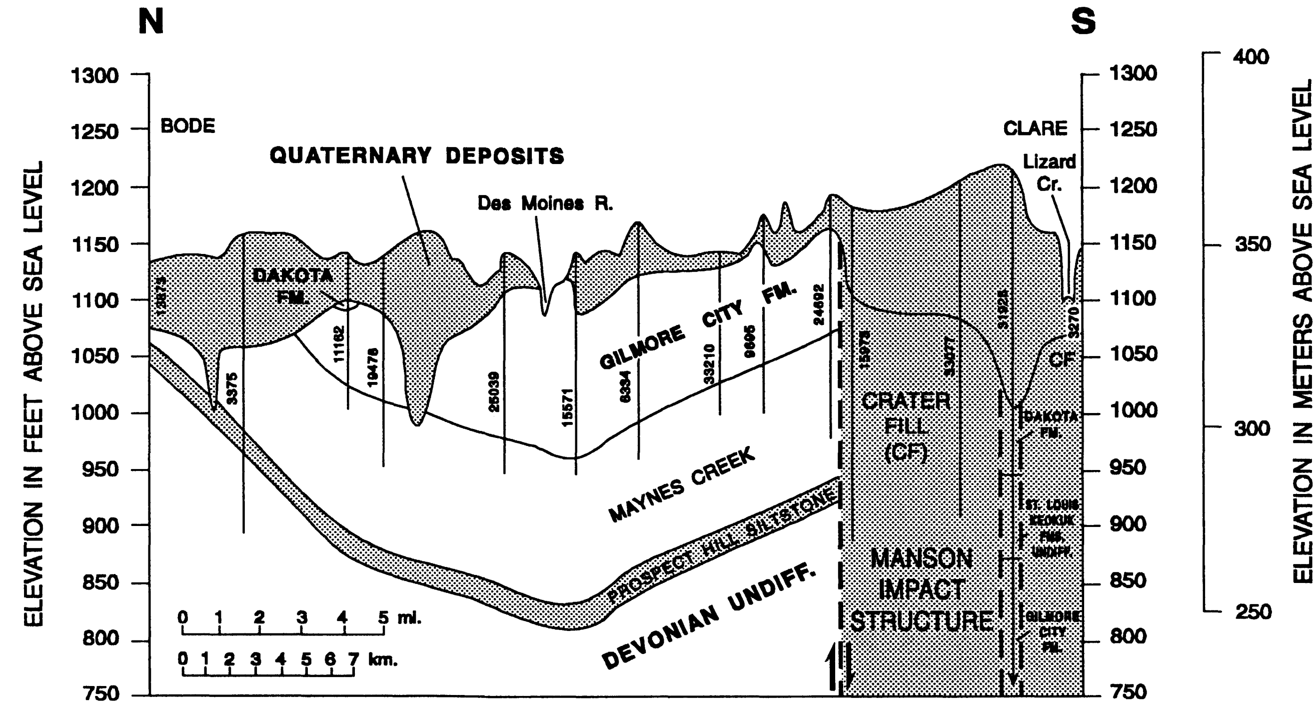


Figure 10. North-south geologic cross-section across western Humboldt and Webster counties. Aquitard units are shaded. Line of section is shown on Figure 8.

able, at depth, than their older counterparts in other parts of the state (Bruner and Lutenegger, 1993; Jones et al., 1992). Additionally, a variety of evidence suggests a greater potential for nitrate reduction within these deposits (e.g., Kross et al., 1990). Therefore, in north-central Iowa, a thickness of glacial deposits of less than 50 feet may provide significant protection to the underlying aquifers.

Some sinkholes and other karst features occur within the shallow rock areas in Humboldt and Pocahontas counties. Such features have not been well studied in this area, but are considerably less common than in Floyd County.

Recharge to the Mississippian aquifer occurs in upland areas outside the main stream valleys. Groundwater moves downward through the glacial deposits beneath the uplands and into the aquifer. Both downward and lateral groundwater flow exists within the aquifer below uplands. The East Fork, and particularly the West Fork of the Des Moines River (Fig. 8) are the major discharge areas for the Mississippian aquifer in the main ADW area in Humboldt and Pocahontas counties (e.g., Horick and Steinhilber, 1973), and lateral groundwater flow within the aquifer is toward these river valleys. Smaller streams likely receive some discharge from groundwater that is flowing laterally within the glacial deposits or within the aquifer at shallow depths, particularly in areas with a relatively thin cover of glacial deposits. Mustermann et al. (1981) estimated recharge to the Mississippian aquifer in this area at 3.2 inches/year. Baseflow indexing (Institute for Hydrology, 1980) for the Des Moines River at Humboldt for the period 1964-1988 (Carol Thompson, GSB, unpublished data) suggests that 57% of the river's average annual discharge for this period, 5.53 inches per year, is derived from groundwater. This would suggest a groundwater recharge rate of about 3.15 inches/year, essentially the same as estimated by Mustermann et al. (1981). The lower recharge rate estimated for this area, relative to Floyd County, likely results from a combination

Table 8. Distribution of relevant GVRI map units, Humboldt and Pocahontas counties.

Thickness of Surficial Aquitard, or Depth to Bedrock Aquifer:	Humboldt % of County	Pocahontas % of County
<50 ft	25%	4%
50-99 ft	60%	13%
100-199 ft	15%	43%
200-299 ft	---	24%
>300 ft	---	16%

of three factors. First, rainfall is somewhat lower in this area, compared to Floyd County. Second, Floyd County is underlain by older glacial deposits which have weathered and fractured to greater depths than the younger deposits in Humboldt and Pocahontas counties, giving them a greater ability to transmit groundwater downward to the underlying bedrock. Finally, the glacial deposits are generally thicker in Humboldt and Pocahontas counties than they are in Floyd County.

Hydrogeologic Setting and ADWs

State-registered ADWs in Humboldt and Pocahontas counties are shown on Figure 8. The merged state-federal registration list suggests there are 164 ADWs in Humboldt and 63 ADWs in Pocahontas County. Acres drained were reported for 125 ADWs (76%) in Humboldt and 38 ADWs (60%) in Pocahontas County. Extrapolating the acreage reported for these wells to all ADWs suggests that about 15,200 acres in Humboldt and 8,075 acres in Pocahontas County are drained by ADWs. This accounts for 5.5% and 2.2% of the total area of these counties, respectively. Data from the EPA-UICI and IDALS-AOS suggest that 35% of the ADWs located within fields in Humboldt County have surface-water intakes, while only 3% of those in Pocahontas County are so designed. The Humboldt County engineer estimates there are 49 surface-water intakes, located in ditches, that are connected to ADW drainage systems in the county. The Pocahontas County engineer estimates there are 40 such intakes. Depths were reported for 81 ADWs (49%) in Humboldt and 29 ADWs (46%) in Pocahontas County. The distributions of reported depths are given in Table 9. About two-thirds of the reported depths are less than 100 feet in Humboldt County and only 6% are greater than 150 feet deep. Two wells are reportedly 400 feet deep. Extrapolating to the merged registration list suggests there are 109 ADWs less than 100 feet deep, and only 10 are greater than 150 feet deep. In Pocahontas County, almost 70% of the reported ADW depths are less than 100 feet, with only one well reported to be deeper than 150 feet Extrapolating to the merged registration list suggests there are about 43 wells shallower than 100 feet deep, and only two wells deeper than 150 feet. About two-thirds of the depths reported from Pocahontas County ADWs fall within a narrow depth range, 80 to 110 feet.

Reported ADW depths and locations were used to estimate bottom-hole elevations for the ADWs; these, along with data from GSB well-log files, were used to evaluate the stratigraphic interval penetrated by individual ADWs. This could be done with confidence for 57 ADWs in Humboldt and 23 ADWs in Pocahontas County. Results are summarized on Table 10. In Humboldt County, available data suggest that over 75% of the ADWs bottom in the Gilmore City Formation, with almost half ending within 100 feet of the contact between the Gilmore City and the underlying Maynes Creek Formation (Figs. 9 and 10). About 16% of the

Table 9. Distribution of ADW depths, Humboldt and Pocahontas counties; from registration reports.

	Humboldt		Pocahontas	
Depth Range	%	Cumulative %	%	Cumulative %
<50 ft	31%	31%	14%	14%
50-99 ft	36%	67%	55%	69%
100-149 ft	12%	79%	28%	97%
150-199 ft	15%	94%	3%	100%
200-249 ft	2%	96%	--	
250-299 ft	2%	98%	--	
>300 ft	2%	100%	--	

ADWs end in the Maynes Creek, with about 13% bottoming within 100 feet of base of the Maynes Creek and, therefore, the base of the Mississippian aquifer. Six percent of the ADWs are deep enough to completely penetrate the Mississippian aquifer, and likely penetrate into, and bottom in Devonian strata below. In Pocahontas County, all ADWs end in the Maynes Creek, as the Gilmore City Formation has been almost completely removed by erosion. About 43% of the ADWs end within 100 feet of the base of the Maynes Creek. None of the these appear to bottom closer than about 80 feet above the base of the Maynes Creek.

Implications for Water Quality

In Humboldt County, the potential for water quality degradation by ADWs appears greatest in the shallower parts of the aquifer. Thirty percent of the ADWs with reported depths end more than 100 feet above the top of the Maynes Creek Formation (Figs. 9 and 10), and therefore more than 225 feet above the base of the Mississppian aquifer. Almost 80% of the ADWs with reported depths bottom above the top of the Maynes Creek, and are therefore more than 125 feet above the base of the Mississippian aquifer. As ADWs are generally uncased through bedrock, to allow maximum drainage, even deep ADWs contribute water to shallow parts of the aquifer. ADW inputs mix with groundwater within the aquifer, and further mixing occurs as the ADW inputs enter the groundwater flow system and move toward discharge zones along streams, particularly the West Fork of the Des Moines River.

In Pocahontas County, over 40% of the ADWs with reported depths reach to within 100 feet of the base of the Mississippian aquifer. This is a result of a thinner aquifer here, relative to most of Humboldt County, rather than deeper ADWs. The presence of a significantly thinner aquifer suggests less potential for mixing of ADW inputs with pre-existing aquifer water. This is likely compounded by the effects of the Manson Structure, which limits the movement of groundwater into the area where ADWs are concentrated. In both Humboldt and Pocahontas counties, the greatest potential for significant groundwater contamination from ADWs occurs within and downgradient from concentrations of ADWs, and is likely greater in the upper one-half of the aquifer. As indicated by Baker and Austin (1984) and Baker et al. (1985), some of these affects may be apparent 1-1.5 miles downgradient from ADW clusters.

Wright County

Figure 11 is a modified version of the GVRI map for Wright County, showing the depth to the underlying bedrock aquifer, or the thickness of

Table 10. Stratigraphic intervals at the bottom of ADWs, Humboldt and Pocahontas counties.

Humboldt County

	Feet above the base of the: Gilmore City Fm. >100	Gilmore City Fm. <100	Maynes Creek Fm. >100	Maynes Creek Fm. <100	Below the Mississippian Aquifer
% of ADWs	30%	48%	3%	13%	6%

Pocahontas County

	Feet above the base of the: Maynes Creek Fm. >100	Maynes Creek Fm. <100
% of ADWs	57%	43%

the aquitard covering the bedrock aquifer. Black circles on the maps show a 0.25 mile (400 meter) radius circle around state-registered ADWs. Most of the ADWs in Wright County are located in three north-south aligned townships, in an upland area between the valleys of the Iowa River and White Creek.

Hydrogeologic Setting

Figures 9 and 12 are geologic cross-sections across Wright County. Pertinent geologic units are the same here as in Humboldt and Pocahontas counties, and they play similar hydrologic roles (i.e. aquifers vs. confining beds). As is shown on the cross-sections, erosion has significantly thinned the Gilmore City Formation; across much of the area there is less than 50 feet of the Gilmore City remaining. Erosion has had less effect to the south, where the full thickness of the formation is preserved (Fig. 12). Locally, complete removal of the Gilmore City has occurred, and the Maynes Creek Formation is the uppermost Mississippian bedrock encountered. A relatively thick cover of glacial deposits, generally 100 to 200 feet thick, mantles the bedrock.

As is shown on Figure 11, Wright County is predominantly a deep bedrock area. Bedrock is less than 50 feet from the surface in only about 5% of the county. Across 45% of the county, bedrock lies 50 to 100 feet below the surface, and is deeper than 100 feet over the remaining 50% of the county. Over 100 feet of glacial materials overly the bedrock aquifer in the part of the county where most ADWs are located. As was discussed in the previous section, the upper part of the glacial sequence in north-central Iowa was deposited by the most recent glaciation. These deposits likely give greater protection to the underlying aquifer, for any given thickness, than the older deposits that cover much of the state. The Mississippian aquifer in Wright County is therefore largely protected from surficial contamination that is delivered by natural processes.

Recharge to the groundwater system occurs in the upland area where most ADWs are located. Flow is directed downward through the relatively thick glacial deposits and into the Mississppian aquifer. Existing potentiometric maps for the Mississppian aquifer in north-central Iowa (Horick and Steinhilber, 1973; Buchmiller et al., 1985) do not clearly indicate lateral groundwater-flow directions in Wright County, and suggest little groundwater flow is directed towards nearby stream discharge zones. While the Iowa River potentially is a discharge area for the aquifer in the county, upward groundwater flow from the aquifer to the river is impeded by the relatively thick cover of glacial deposits present beneath the valley, and lateral groundwater flow is therefore not directed

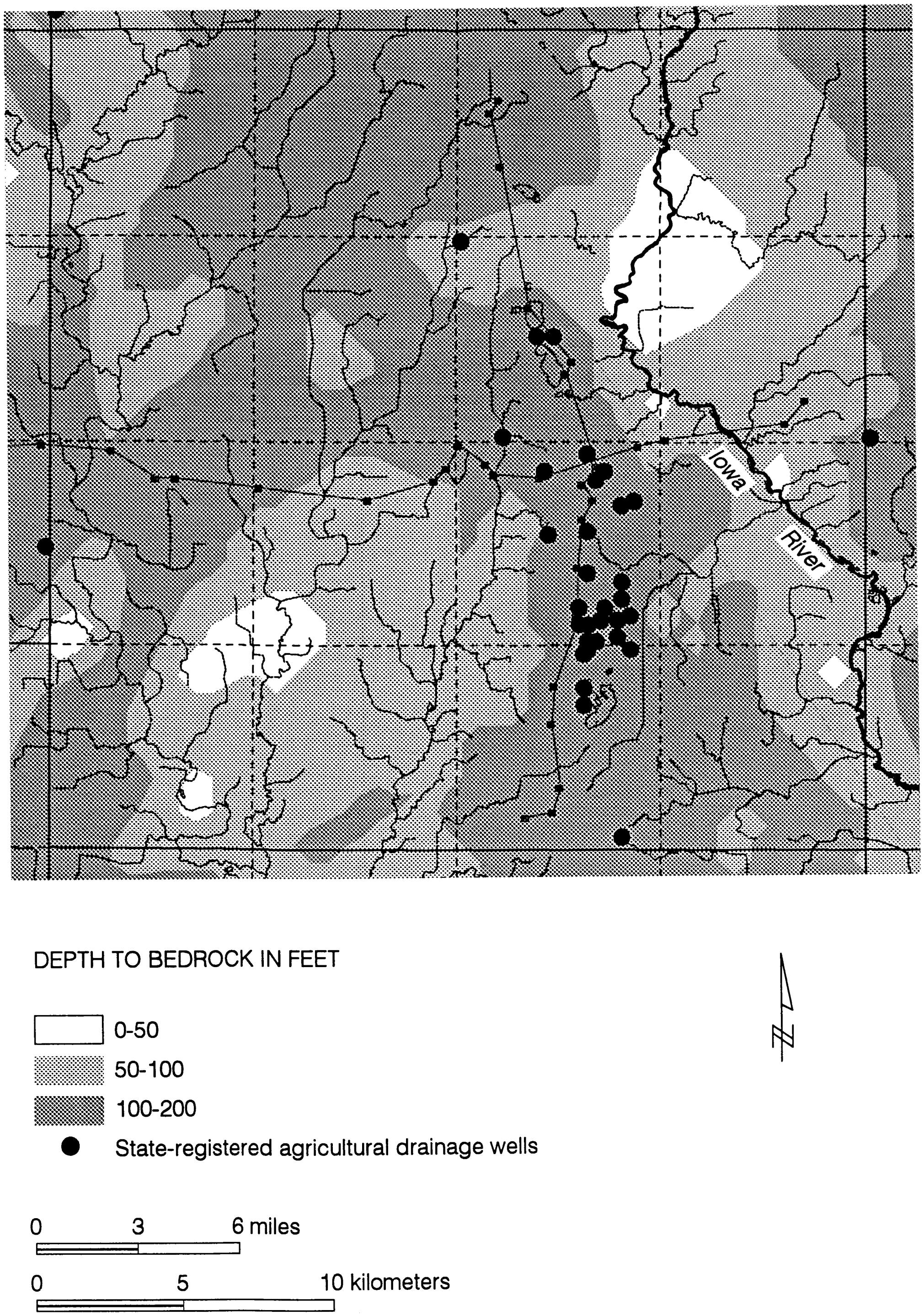


Figure 11. Modified version of the GVRI map (Hallberg and Hoyer, 1991) for Wright County, showing depth to bedrock (or thickness of aquitard cover). State-registered ADWs are also shown. East-west line locates the cross-section shown on Figure 9. North-south line locates the cross-section shown on Figure 12.

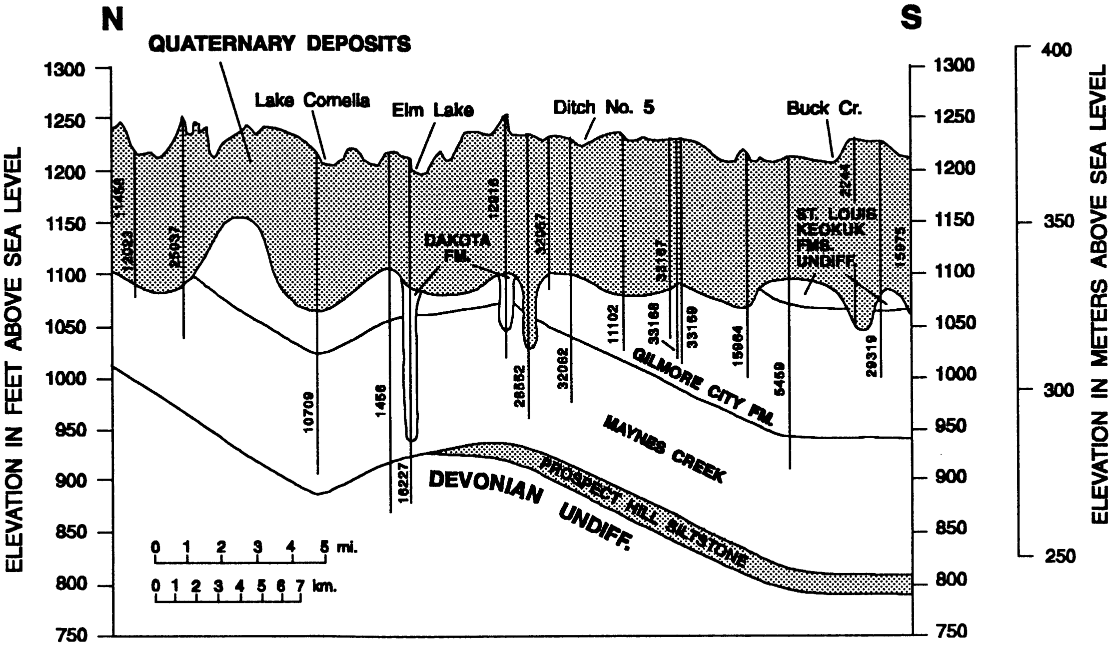


Figure 12. North-south geologic cross section across Wright County. Aquitard units are shaded. Line of section is shown on Figure 11.

towards the river. Recharge rates for the Mississippian aquifer in Wright County are likely similar to those estimated for Humboldt and Pocahontas counties, about 3.2 inches/year. Mustermann et al. (1981) estimated recharge at 2.6 inches/year.

Hydrogeologic Setting and ADWs

State-registered ADWs are shown on Figure 11. The merged state-federal registration list suggests there are 41 ADWs in the county. Extrapolating the reported acreage drained for these ADWs to all those on the merged list suggests about 6,550 acres of Wright County drain to ADWs; this accounts for 1.9% of the county. Data from the EPA-UICI and IDALS-AOS suggest that a third of the ADWs located in fields in Wright County have surface-water intakes. Depths were reported for only 17 of the ADWs and these are summarized in Table 11. Only 12% of the reported depths are less than 100 feet, a result of the thick cover of glacial deposits in this area. About 35% are in the 100-to 199-foot range, while 47% are 200 to 299 feet deep. The remaining ADW, representing 6% of the reported depths, is about 300 feet deep. Extrapolating to the merged registration list suggests there are 5 ADWs less than 100 feet deep in the county, about 14 ADWs in the 100-to 199-foot range, and 20 in the 200- to 299 foot-range. Two wells may exceed 300 feet. Stratigraphically, 65% of the ADWs in Wright County bottom in the Gilmore City Formation, and 53% of all the ADWs bottom less than 100 feet above the top of the underlying Maynes Creek Formation. The remaining 35% end within the Maynes Creek, with 29% bottoming 70 to 90 feet above of the base of the Formation.

Implications for Water Quality

There is currently no specific information concerning the water quality affects of ADWs in Wright County. However, given the relatively similar geologic setting in Wright County and in Humboldt and Pocahontas counties, a few general comments can be made. ADW effects in Wright County should be similar to those in Humboldt-Pocahontas counties, but moderated by the lower number and density of ADWs. The thick cover of glacial deposits in

Table 11. Distribution of ADW depths in Wright County; from registration reports.

Depth Range	%	Cumulative %
<100 ft	12%	12%
100-199 ft	35%	47%
200-299 ft	47%	94%
>300 ft	6%	100%

Wright County suggests that any surficial contaminants within the Mississippian aquifer results from contaminated water bypassing the thick cover of glacial deposits — most likely via ADWs.

SUMMARY AND CONCLUSIONS

Iowa agriculture benefits from two important natural resources, the rich soils that blanket the state's landscape, and sufficient precipitation, in most years, to produce large crop yields. While adequate precipitation is essential for crop growth, many of Iowa's soils, particularly in the north-central part of the state, are poorly drained and at times contain excess water that can hinder field operations or ruin crops. In these areas, farm fields are often artificially drained by buried tile lines leading to drainage ditches or streams. Another, but less common method is the agricultural drainage well (ADW), a drilled shaft that funnels excess drainage water into underground bedrock aquifers. The upper parts of these wells are typically cistern-like structures that form the discharge point for tile-drainage lines; some wells are also designed to take surface runoff. ADWs are generally 5 to 10 inches in diameter and are cased from the land surface into the underlying bedrock. Virtually all ADWs in Iowa discharge into fractured carbonate (limestone or dolomite) aquifers. Because of their fractured nature, these units can accept large quantities of drainage water and they have little susceptibility to clogging with sediment and other material, compared to other aquifer materials (e.g., sandstone). These carbonate aquifers are also widely used sources of groundwater for domestic, industrial, and municipal water supplies. ADWs are not widely used in Iowa, but rather are concentrated in just a few areas. Therefore, their effects on groundwater are localized. For perspective, there are about 30 times as many sinkholes in Iowa as ADWs, and they also occur in the same aquifers.

ADWs have recently been registered with both the Iowa Department of Natural Resources (DNR) and the U.S. Environmental Protection Agency (EPA). These two registration lists largely, though not completely, overlap. Both lists are likely incomplete, and both likely contain registrations for features that are not really ADWs. Examination and merger of the state and federal ADW registration lists suggests there are 442 ADWs registered in Iowa. The number and distribution of ADWs provided by the registration lists are generally in agreement with previous estimates.

Registration information concerning locations, ADW depths, and area drained was supplied by ADW owners, and only some of this information has been field verified. These are, however, the best data available, and this review assumes these data are representative and reasonably accurate. Data from the merged registration list suggest that ADWs drain about 47,000 acres (73 sq. mi.) statewide. Individual ADWs are reported to drain anywhere from 2 to 720 acres, and have a median drainage area of 80 acres. Reported well depths range from 12 to 400 feet, with a median depth of 85 feet.

About 80% of the registered ADWs are concentrated in four counties: Floyd, Humboldt, Pocahontas, and Wright. Within these counties ADWs drain between 6,500 and 15,000 acres, accounting for 2% to 5% of the area of the individual counties. But ADWs are not uniformly distributed, even within these counties, and the primary concern must be focused on the local level. Individual townships within each county have a maximum of 25 to 60 ADWs, and a 4-township area in Humboldt and Pocahontas counties contains about 190 ADWs, or 43% of all those registered statewide.

ADWs deliver contaminants into carbonate aquifers in various hydrogeologic settings with a range of natural vulnerability to contamination. Various studies show that aquifer vulnerability to contamination is relatively great under natural conditions of recharge (i.e., without ADWs) in the upper, shallow portions of aquifers in shallow-bedrock and karst areas. In these regions, the bedrock aquifers lie beneath less than 50 feet of a surficial aquitard, i.e., low-permeability surficial cover materials. The occurrence and concentration of contaminants decrease with depth and the lower portions of these aquifers appear to be less vulnerable. Aquifers that are overlain by over 50 feet of surficial aquitard are generally protected from surficial contamination (deep bedrock aquifer regions). This overall depth distribution of contamination (i.e., more pronounced in shallow bedrock regions and in shallow wells) is a function of various processes that may degrade, attenuate, or dilute contaminants, as well as the transport time of the groundwater carrying the contaminants. While there is downward movement of water through the surficial aquitards, the rate of movement is quite slow where the deposits are thick, unweathered and unfractured. Measured and estimated hydraulic parameters suggest it takes decades for water from the surface to penetrate a 50 foot cover of such materials. Isotopic analysis (for tritium) of groundwaters in such areas show that the majority of water present is older than about 1955. This timing predates the period when commercial fertilizer became heavily used, increasing nitrate loading, and when most herbicides came into widespread use. An understanding of the spatial and depth distribution of natural vulnerability is a prerequisite for understanding the impact of the ADWs.

The actual effects of ADWs on groundwater quality in a given area will depend on numerous factors. One factor is the volume of drainage delivered to the aquifer, which is a function of the acreage drained by ADWs in a given area, and the type of drainage involved (i.e., surface water versus tile drainage). This is strongly influenced by climatic conditions, affecting runoff and infiltration volume, and therefore varies greatly with time. Another factor is the concentration of contaminants in the drainage. Concentrations are a function of the landuse and management practices on the acreage drained and the type of drainage involved. Concentrations will vary temporally, as a function of the changes in hydrologic conditions, particularly in relation to seasonal application periods.

The number, spacing, and depth of ADWs delivering the drainage will affect both the volume of ADW water delivered into the aquifer and how uniformly contamination is spread through the aquifer. The hydrogeologic setting of an ADW area will also affect the resulting water quality in relation to the volume and concentration of inputs. Naturally protected aquifers contain relatively older groundwater that is contaminant-free; this groundwater is available to dilute ADW inputs. In aquifers that are not protected, contaminants are delivered to groundwater by natural processes, and these groundwaters will have a lesser dilution capacity. The rate at which ADW inputs will mix with pre-existing groundwater, and begin to move with the groundwater, will depend upon the volume of drainage inputs, the hydraulic properties of the affected aquifer, and the groundwater-flow system existing within the aquifer. The flow system will also control the direction and depth to which the affected groundwater will travel.

The above discussion focuses on the effects ADWs have on the quality of groundwater within the receiving aquifer. Additional factors are involved in assessing the impact on nearby water-supply wells. These include well and casing depths and how they relate to ADW depths, the location of the water wells with respect to the groundwater flow-system, and the distance between the water wells and the ADWs. All these factors are dependent upon both site specific and recharge-event specific conditions, and make prediction of ADW effects in a given area difficult.

The majority of the drainage wells in the major ADW areas in Iowa bottom in the upper part of the aquifer they penetrate. Over 75% appear to have more than 100 feet of aquifer "beneath" them. Therefore the most acute effects of ADW inputs are likely to be within the shallower parts of the aquifers. Water-supply wells completed in the shallower parts of the aquifer are likewise those most directly affected. These are also the wells and portions of the aquifers most directly affected by natural routes of contamination, making it difficult to ascertain the impacts of ADWs in many areas.

Hydrogeologic conditions and numbers of ADW registrations vary between the three main ADW areas. In Floyd County, relatively shallow bedrock (i.e., vulnerable) conditions predominate, and the generally thin glacial deposits that mantle the bedrock are older than those in the other ADW areas. An integrated drainage network is present, but at places it is associated with sinkholes and losing stream reaches. Hence, much of Floyd County is inherently susceptible to contamination even without ADWs. Ninety-two ADWs are registered in Floyd County, draining about 11,500 acres, or 4% of the county. Reported ADW depths suggest the 75% of the drainage wells are less than 150 feet deep, and bottom in the upper portions the uppermost Devonian aquifer. Most of this water would flow through local and intermediate flow systems, discharging to local streams or the Cedar and Shell Rock Rivers. Approximately 40% of the ADWs are located in deep bedrock aquifer areas, 20% penetrate into the deeper portions of the upper bedrock aquifer, and about 4% penetrate into the confined, middle aquifer. In these settings, surficial contaminants would not likely occur in the groundwaters without ADWs.

Wright County presents the greatest contrast to Floyd County in terms of its hydrogeologic setting. It is primarily a naturally "protected" deep bedrock aquifer area. Depth to bedrock exceeds 100 feet, and often 200 feet, in the part of the county where most ADWs are located. The glacial deposits here include those most recently deposited, and are less weathered, fractured, and permeable than in Floyd County. Additionally, this relatively young landscape lacks an integrated drainage network. Susceptibility of the Mississippian bedrock aquifer to contamination by natural processes is extremely low. There are 41 ADWs registered in Wright County, draining about 6,550 acres, or 1.9% of the county. ADWs are deeper in Wright County than in the other ADW areas, with 55% of the reported depths being 200 feet or more. Stratigraphically, however, an estimated 70% of the ADWs bottom within the upper portions of the aquifer in the region. Because of the depth of the aquifer and the thickness of glacial deposits, most of the groundwater flow in the aquifer is regional and would move out of Wright County before it could discharge to major stream systems. Also, given the thick aquitard cover, any surficial contaminants in the Mississippian aquifer in this area likely result from ADW inflow.

Roughly half of the Humboldt-Pocahontas ADW area is a shallow bedrock aquifer area (underlain by less than 50 feet of glacial materials), and roughly half is a deep aquifer area. Thus, the area appears relatively equally divided between susceptible and protected regions. However, the young glacial deposits here, similar to Wright County, likely provide greater protection than the older deposits that cover most of the state (e.g., Floyd County). As in Wright County, an integrated drainage system is largely lacking. Some karst features such as sinkholes and losing stream reaches occur in the shallow bedrock regions, but are much less common than in Floyd County. Roughly two-thirds of the reported ADW depths are less than 100 feet. An estimated 87% of the ADWs in Humboldt County bottom in the upper portion of the Mississippian bedrock aquifer, more than 100 feet above the base of the aquifer. The Mississippian aquifer thins significantly in the Pocahontas County part of the ADW area. Hence, in Pocahontas County, an estimated 43% of the ADWs bottom within the lowest 100 feet of the aquifer. Most of the groundwater flow in the bedrock aquifer in this region should be in local and intermediate flow systems, discharging to the West Fork and East Fork of the Des Moines River.

The proportion of recharge to the bedrock aquifer groundwaters contributed by the ADWs in these regions is impossible to measure and difficult to even estimate accurately. One perspective is to review the total area drained by the ADWs, which amounts to between 2% to 5% of the areas of the four counties. Because the ADWs provide direct access into the bedrock, and because some ADWs also divert surface runoff into the aquifer, they are more efficient than natural processes relative to their drainage area. Prior modeling studies estimated a range of values for the proportion of recharge for the four primary ADW areas; these studies used appropriate estimates of hydraulic properties. The estimated drainage areas used differ from those summarized from the registration data in this report. The prior modeled estimates can be adjusted by the current estimates of drainage area. For all three ADW areas, Floyd County, Humboldt-Pocahontas counties, and Wright County the range of estimates are similar; the likely proportion of recharge to the bedrock aquifers supplied by ADWs ranges from about 6% to 28%.

Where ADWs occur in karst-shallow bedrock aquifer regions, a significant question arises regarding the impact of closure of ADWs that would divert water into waterways that lead to natural sinkholes and/or losing streams (i.e., that lose water into the bedrock aquifer). This may simply divert water and contaminants from one path of entry into the aquifer to another. These areas are already highly susceptible to contamination, regardless of the ADWs, and shallow groundwater in these areas has already been adversely affected by natural processes. This dilemma emphasizes the need for improved management to reduce contaminant delivery. There are other considerations, as well. Diverting water from a more direct pathway (e.g., an ADW) may afford more processing of the drainage water in the surface environment. Most sinkholes and losing streams are filled with soil materials, and the water must infiltrate through the soil materials. This added exposure might allow greater potential for adsorption and further biogeochemical processing and degradation of contaminants. If surface drainage water is entering the ADW, rerouting the flow might afford greater opportunity for removal of possible pathogens and other contaminants unique to surface water. Where deep ADWs are involved, this might translocate possible contaminants from a deeper aquifer setting (where such contaminants might not otherwise occur) into the shallow bedrock environment (where they are delivered through more natural processes). The groundwater that enters an aquifer in losing stream reaches tends to be contained in a relatively shallow flow system, paralleling the stream system, and likely discharging to the area master stream (e.g., the Cedar or Shell Rock River in Floyd County; the Des Moines River in Humboldt-Pocahontas counties).

Various investigations, primarily in Floyd County and Humboldt-Pocahontas counties, have provided similar insights to the water-quality effects of ADWs. Noticeable effects in water-supply wells are most likely to occur within 1-1.5 miles of clusters of ADWs. These effects are more readily recognized in areas where the aquifer receiving drainage water inputs is protected from surficial contamination, i.e., deep bedrock aquifer areas. In susceptible shallow bedrock and karst areas, the effects of ADWs cannot be recognized because of the regional contamination that occurs, delivered by natural processes. Monitoring data shows that the effects of ADWs vary temporally; punctuated by rapid responses, hydrologically and chemically, during periods of significant ADW recharge, and that discernible effects dissipate between these periods.

ACKNOWLEDGMENTS

The Geological Survey Bureau's investigations of ADWs over many years have been supported, in part, through the Iowa Groundwater Protection Act, and by cooperating agencies including the Iowa Department of Agriculture and Land Stewardship, Division of Soil Conservation (IDALS-DSC), the Integrated Farm Management Demonstration Project, the U.S. EPA, Region VII, UIC and Nonpoint Source Programs, the University Hygienic Laboratory, the University of Iowa Department of Preventive Medicine and Environmental Health, and the Iowa State University Extension Service.

Thanks are due the many GSB contributors to, and reviewers of, this report. Greg Ludvigson and Bill Bunker contributed discussions of the bedrock stratigraphy of the major ADW areas, and constructed the cross-sections of those areas for this report. Bernie Hoyer has provided leadership to these studies over many years. Jim Giglierano and Deb Quade contributed various analysis and graphics, as did Pat Lohmann, who also aided in the report design and layout. Carol Thompson, Mary Skopec, and others reviewed the report, and offered numerous useful comments. Dan Lindquist and staff, IDALS-DSC, provided leadership in developing the merged registration reports needed for this analysis. Various staff from IDNR-Environmental Protection Division, IDALS-DSC, and Iowa State Unviersity contributed suggestions constructive reviews to the final document.

REFERENCES

Alley, T., 1977, A model for relating land use and ground-water quality in southern Missouri, *in* Hydrologic problems in karst regions, Western Kentucky University, Bowling Green, KY, p. 323-332.

Anderson, R. R., and Ludvigson, G. A., 1989, The Manson Impact Structure and its effects on the rocks of the Gilmore City Formation in the Hallet and Midwest limestone quarries, Gilmore City, Iowa, *in* Woodson, F. J., ed., An Excursion to the Historic Gilmore City Quarries: Geological Society of Iowa, Guidebook 50, p. 23-33.

Baker, J. L. and Austin, T. A., 1984, Impact of agricultural drainage wells on groundwater quality: U.S.E.P.A. Contract Report #G007228010, ISU-ERI-Ames-85183, 238 p.

Baker, J.L., Kanwar, R.S., and Austin, T. A., 1985, Impact of agricultural drainage wells on groundwater quality: Journal of Soil and Water Conservation, v. 40, p. 516-520.

Bruner, D. R., and Lutenegger, A. J., 1993, Measurement of saturated hydraulic conductivity in fine-grained glacial tills in Iowa, *in* Daniel, D. E., and Trautwein, S. J., eds., Hydraulic Conductivity and Waste Contaminant Transport in Soils, ASTM STP 1142, American Society for Testing and Materials, Philadelphia, PA., in press.

Buchmiller, R., Gaillot, G., and Soenksen, P. J., 1985, Water Resources of North-Central Iowa: Iowa Geological Survey Water Atlas #7, 93 p.

Cherryholmes, K. L., and Gockel, M. L., 1987, Iowa agricultural drainage well assessment report: U.S.E.P.A., Contract Report #G007273010, University Hygenic Laboratory, Iowa City, IA, 26 p.

Hallberg, G.R., 1989, Nitrate in groundwater in the United States, In Follett, R.F., ed., Nitrogen Management and Groundwater Protection. Elsevier Sci. Pub., Amsterdam, The Netherlands, Chapter 3, p. 35-74.

Hallberg, G. R., and Hoyer, B. E., 1982, Sinkholes, hydrogeology, and groundwater quality in northeast Iowa: Iowa Geological Survey Contract Report #81-5500-04, 120 p.

Hallberg, G. R., Hoyer, B. E., Bettis, E. A. III, and Libra, R. D., 1983a, Hydrogeology, water quality, and land management in the Big Spring basin, Clayton County, Iowa: Iowa Geological Survey Open-File Report 83-3, 191 p.

Hallberg, G.R., Hoyer, B.E., Libra, R.D., Bettis, E.A. III, and Ressmeyer, G.G., 1983b, Additional regional groundwater quality data from the karst-carbonate aquifers of northeast Iowa: Iowa Geological Survey Open-File Report, 83-1, 16 p.

Hallberg, G. R., Libra, R. D., Bettis, E. A. III, and Hoyer, B. E., 1984, Hydrogeologic and water-quality investigations in the Big Spring basin, Clayton County, Iowa: Water Year 1984: Iowa Geological Survey Open-File Report 84-4, 231 p.

Hallberg, G. R., Hoyer, B. E., Dorpinghaus, M., Ludvigson, G. A., 1985, Estimates of rural wells in Iowa: Iowa

Geological Survey Open-File Report 85-1, 18 p.

Hallberg, G. R., Kross, B. C., Libra, R. D., Burmeister, L. F., Weih, L. M. B., et al., 1990, The Iowa state-wide rural well-water survey: design report: a systematic survey of drinking water quality: Iowa Department of Natural Resources,Geological Survey Bureau Technical Information Series 17, 135 p.

Hallberg, G. R., and Hoyer, B. E., 1991, Groundwater vulnerability regions of Iowa: Iowa Department of Natural Resources, Geological Survey Bureau. Special Map Series II.

Hansen, R. E., 1975, Bedrock topography of northeast Iowa: U. S. Geological Survey Map I-933.

Hansen, R. E., 1978, Bedrock topography of north-central Iowa: U. S. Geological Survey Map I-1080.

Hartung, J. B., and Anderson, R. R., 1988, A compilation of information and data on the Manson Impact Structure: Lunar and Planetary Institute, LPI Report 88-08, 32 p.

Horick, P. J. and Steinhilber, W. L., 1973, Mississippian aquifer of Iowa: Iowa Geological Survey, Miscellaneous Map Series 3.

Iowa Department of Agriculture and Land Stewardship, 1992, Agricultural drainage well research and demonstration project: Annual Report, 1992, 48 p.

Institute for Hydrology, 1980, Catchment characteristic estimation manual: Low Flow Studies Rept. #3, Oxfordshire, U. K., 28 p.

Jones, L., Lemar, T., and Tsai, Chjin-Ta, 1992, Results of two pumping tests in Wisconsin age weathered till in Iowa: Groundwater, vol. 30, no. 4, p.529-538.

Kross. B. C., Hallberg, G. R., Bruner, D. R., Libra, R. D., Rex, K. D., et al., 1990, The Iowa state-wide rural well-water survey water quality data: initial analysis: Iowa Department Natural Resources, Geological Survey Bureau, Technical Information Series 19, 142 p.

Libra, R. D., Hallberg, G. R., Ressmeyer, G. G., and Hoyer, B. E., 1984, 1. Groundwater quality and Hydrogeology of Devonian-carbonate aquifers in Floyd and Mitchell counties, Iowa: Iowa Geological Survey Open-File Report 84-2, p. 1-106.

Libra, R. D. and Hallberg, G. R., 1985, 1. Hydrogeologic observations from multiple core holes and piezometers in the Devonian-carbonate aquifers in Floyd and Mitchell counties, Iowa: Iowa Geological Survey Open-File Report 85-2, p. 1-19.

Libra, R. D., 1988, Agricultural drainage wells and groundwater quality: Iowa Geology, #13, p. 22-3.

Mustermann, J. L., Fisher, R. A., and Drake, L., 1981, Underground injection control in Iowa: U.S.E.P.A. Contract Report G007165 01.

Witzke, B. J., and Bunker, B. J., 1984, 2. Devonian stratigraphy of north-central Iowa: Iowa Geological Survey Open-File Report 84-2, p. 107-145.

Witzke, B. J., and Bunker, B. J., 1985, 2. Stratigraphic framework for the Devonian aquifers in Floyd and Mitchell counties, Iowa: Iowa Geological Survey Open-File Report 85-2, p. 18-32.

Woodson, F. J. and Bunker, B. J., 1989, Lithostratigraphic framework of Kinderhookian and early Osagean (Mississippian) strata, north-central Iowa, *in* Woodson, F. J., ed., An Excursion to the Historic Gilmore City Quarries: Geological Society of Iowa, Guidebook 50, p. 3-18.

Iowa Department of Natural Resources
Energy and Geological Resources Division
Geological Survey Bureau
109 Trowbridge Hall
Iowa City, Iowa 52242-1319
(319) 335-1575