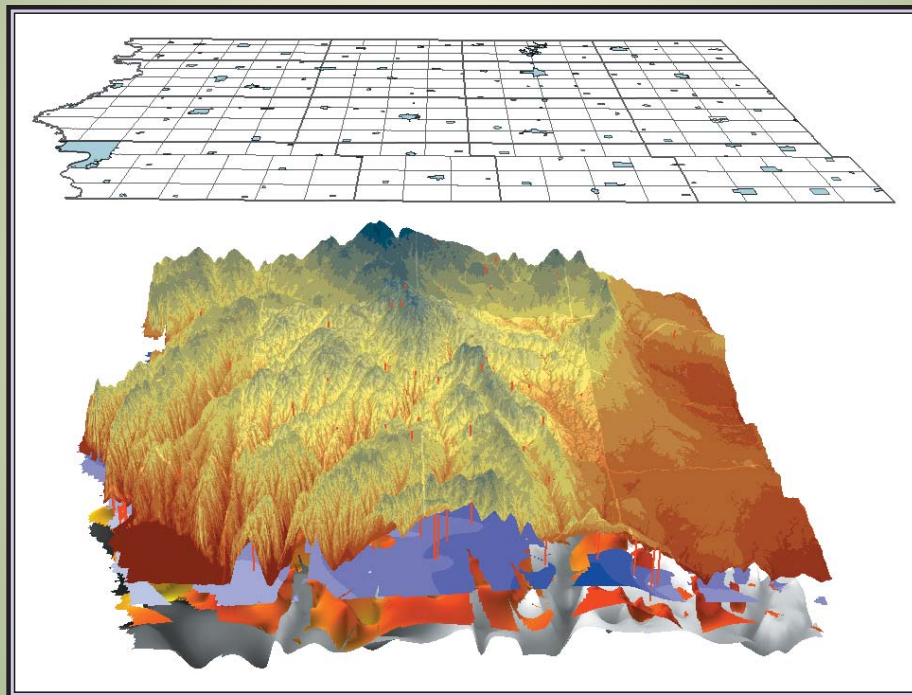


Groundwater Quality Evaluation of the Dakota Aquifer in Northwest Iowa

Iowa Geological and Water Survey
Water Resources Investigation Report No. 1C



Iowa Department of Natural Resources
Richard Leopold, Director
October 2008

COVER

Three-dimensional view (from south to north) of the Dakota Aquifer study area in northwest Iowa. Wells are shown in red, Lower Dakota Aquifer potentiometric surface in blue, top of the Lower Dakota Aquifer in brown, and top of the underlying confining layer in gray. The 16-county outline is shown above the land surface for reference.

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Water Resources Investigation Report No. 1C**

Prepared by

Robert Rowden, Geologist

October 2008

**Iowa Department of Natural Resources
Richard Leopold, Director**

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Introduction

The Iowa Geological and Water Survey (IGWS) plans and implements programs that result in the acquisition of comprehensive information on the mineral and water resources of Iowa, with emphasis on water supply developments and monitoring the effects of environmental impacts on water quality (www.igsb.uiowa.edu/about/mission.htm).

Some of the most frequently asked questions of the Iowa Geological and Water Survey concern groundwater quality, and since about 80 percent of Iowans use groundwater as their drinking water source, an understanding of how the geology of Iowa affects the natural quality of our groundwater and its vulnerability to contamination from human activity is in our best interest. Iowa's geologic framework determines where groundwater occurs, the direction and speed of its movement, whether it can be withdrawn from the ground, where and when it will return to the land surface, and its natural quality. Geologic information is essential when planning for better and sustainable use, protection, and management of Iowa's water resources.

Many people are unaware of the close connection between groundwater, surface water, watersheds, and biological habitats. Groundwater, like surface water, flows downhill from areas of higher pressure to areas of lower pressure. The saturated water table beneath the land surface converges with springs, seeps, streams, lakes, and wetlands at lower elevations, and during periods when the water table is higher, groundwater discharges into these surface waters. During periods when the water table is lower than the surface water levels, surface water is dispersed back to the water table. As a result of this unseen connection between groundwater and surface water, changes in water quality caused by natural or human activity in one part of the hydrologic system can affect changes in water quality in other parts of the system.

Pollutants that affect water quality may come from point or nonpoint sources, or a combination of both. Point source pollution is the introduction

of an impurity into surface water or groundwater from an easily identifiable, distinct location through a direct route, while nonpoint source (NPS) pollution is the introduction of impurities into surface water or groundwater, through a non-direct route and from sources that are diffuse in nature. Discharges from point sources are often continuous and easier to identify and measure, while discharges from nonpoint sources can be continuous or intermittent, are often associated with rainfall or snowmelt events, and may occur less frequently and for shorter periods of time. Because of these properties, point sources are somewhat easier to control. Examples of point sources of pollution include industrial plants, commercial businesses, and wastewater treatment plants. Examples of NPS pollution include runoff and leachate from agricultural fields, animal feeding operations, construction sites, lawns, gardens, and failing septic systems and runoff from streets and parking lots. In Iowa, most surface water and groundwater contamination is caused by nonpoint source pollution.

While groundwater and surface water can both be affected by naturally occurring and anthropogenic contamination from point and nonpoint sources, groundwater is more hidden from view and difficult to sample. Rapid changes in the water quality of surface water bodies can occur from contaminated runoff and infiltration recharge from rainfall and snowmelt, while changes in groundwater quality usually take longer because the recharging water has to infiltrate through layers of soil and rock on its way to the aquifer. For some deep aquifers in Iowa this infiltration recharge can take more than 10,000 years to reach the aquifer. In contrast, for aquifers developed in shallow alluvial sands and gravels, or shallow fractured limestones, this recharge can be almost immediate.

The ability to protect and improve Iowa's natural resources, while utilizing them to benefit society, requires proactive, long-range planning based on accurate and current geologic and hydrologic information. In the past, most funding for water resource studies has come from the state general fund. However, continued reductions in

Bedrock Aquifer Systems across Iowa

Northwest to Southeast

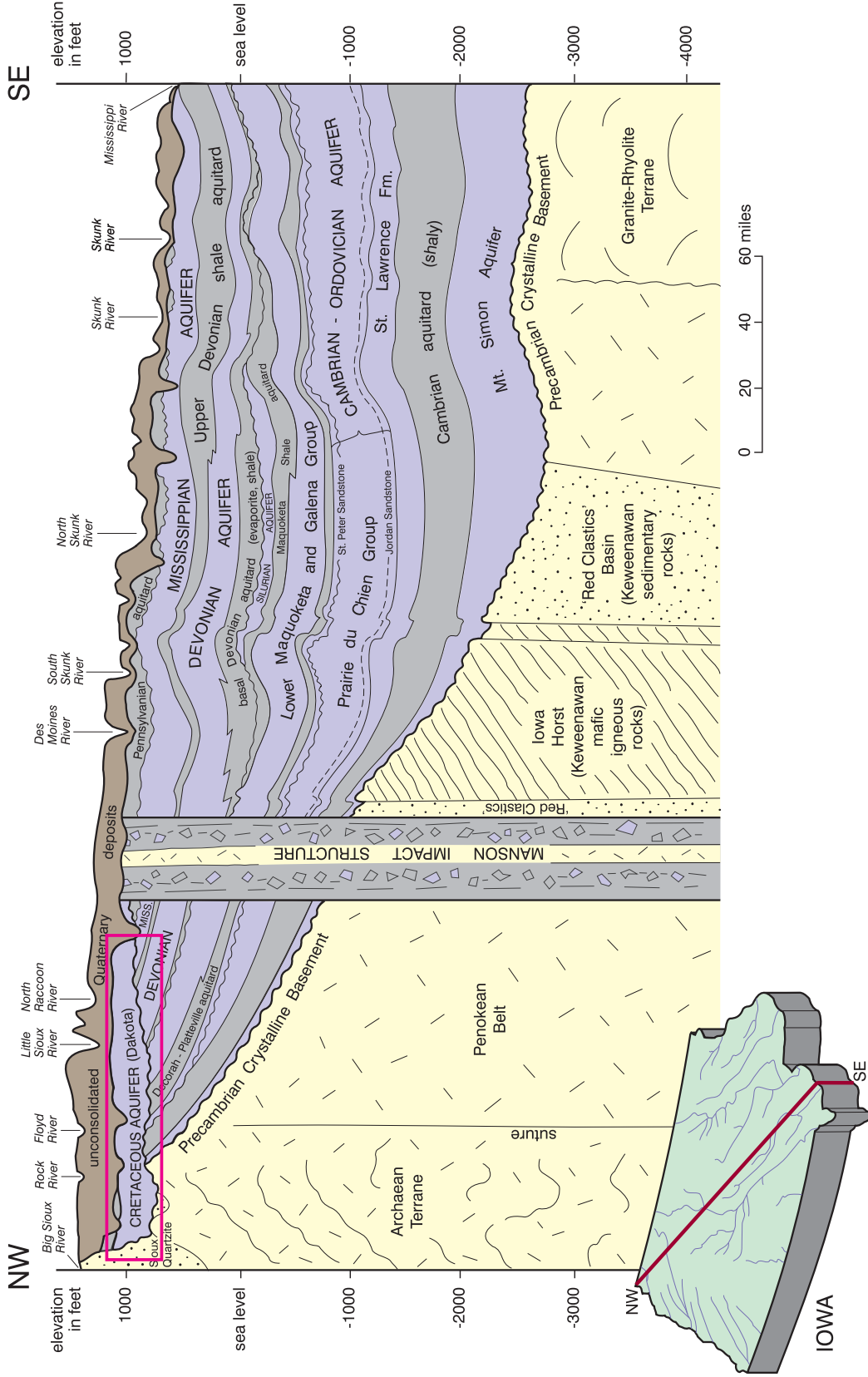


Figure 1. Cross-sectional view of Iowa’s major aquifers and aquitards from northwest to southeast (modified from Iowa’s Groundwater Basics by Prior, et al., 2003). Aquifers in Iowa are named according to their geologic age or the stratigraphic interval in which they occur. The Cretaceous age Dakota Aquifer is shown inside of the red rectangle.

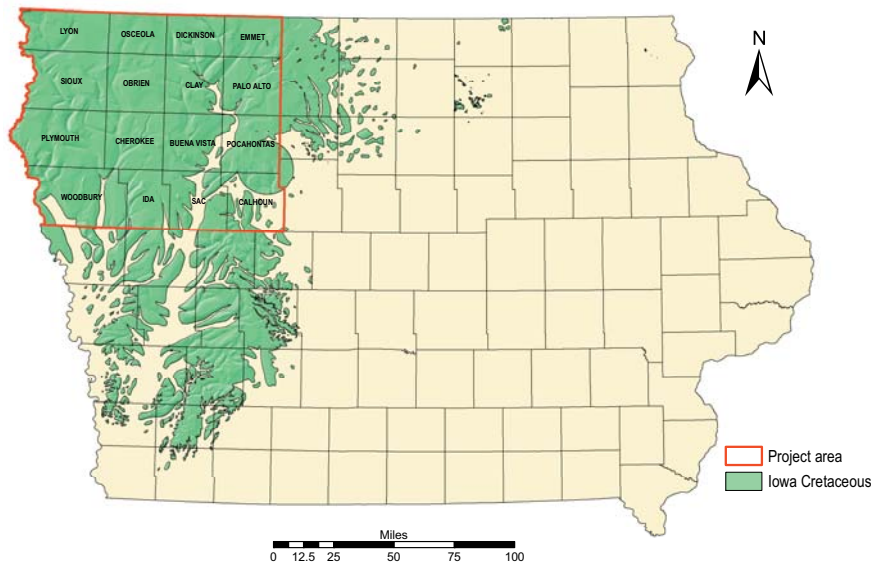


Figure 2. Area of occurrence and significant use of the Dakota Aquifer in western Iowa (modified from Iowa’s Groundwater Basics by Prior, et al., 2003).

general fund revenues and geologic and hydrologic staffing over the last 20 years have made it difficult for the Iowa Geological and Water Survey to conduct the preemptive investigation and research necessary to carry out water resource studies that are needed to create and maintain a forward looking, integrated, and comprehensive Water Resources Management plan.

Following a proposal in 2007 from the Iowa Survey for \$1.65 million for annual funding to characterize the availability, quality, use, and sustainability of Iowa’s surface and groundwater resources, state legislators approved a one-time appropriation of \$480,000 to support water resource studies, such as the Dakota Aquifer study which began in 2007. Currently efforts are underway to secure sustainable funding for continued study and management of Iowa’s water resources through an improved water resource permitting system.

This report is part of the ongoing Water Resources Management plan to delineate the occurrence, movement, availability, use, and chemical quality of groundwater from Iowa’s major aquifers for better and sustainable management of Iowa’s groundwater resources. As more wells are completed in these aquifers and more stratigraphic, construction, and water-quality data are interpreted and entered into our databases, our knowledge of these valuable resources will improve and our evaluation of them will be refined.

Iowa’s Geologic Framework and the Dakota Aquifer Study Area

Iowa’s groundwater resources are stored in shallow unconsolidated aquifers and in five deeper bedrock aquifers that are generally separated by widespread confining beds, or aquitards, that slow the movement of water between the aquifers (Figure 1). The unconsolidated aquifers include alluvial sand and gravel deposits found along stream valleys and in ancient buried river valleys, and sand and gravel deposits found within glacial drift. The bedrock aquifers are usually sandstone, siltstone, limestone, or dolomite, and sometimes are a combination of all of these rock types. The major bedrock aquifers in Iowa were deposited between 75 to 550 million years ago (mya), and include, from youngest to oldest: the Cretaceous (Dakota), Mississippian, Silurian-Devonian, Cambrian-Ordovician (Jordan), and Dresbach (Mt. Simon).

The first aquifer to be studied for the Water Resources Management plan is the Dakota, which is used for private and public water supplies in western Iowa (Figure 2). This aquifer is composed of two members: thinly bedded and well sorted Woodbury Member shales and very fine- to fine-grained sandstones, and the underlying thickly bedded and poorly-sorted Nishnabotna Member fine- to very course-grained sandstones (Munter,

et al., 1983). These deposits formed in riverine environments 100 mya. Woodbury rocks form a minor aquifer with low to moderate yields, which grades to a confining layer, while Nishnabotna rocks form a major aquifer capable of yielding greater than 1,500 gallons per minute (gpm) in some areas. Because of the greater continuous areal extent and higher yields, the initial modeling and groundwater resource evaluations concentrated on the lower part of the Dakota Aquifer within 16 counties in northwest Iowa (Gannon, et al., 2008; Rowden, 2008).

For this water quality evaluation, the upper and lower members of the aquifer are not distinguished because there is currently not enough well data to determine if there are consistent differences in water quality between the upper and lower members. It appears that there may be differences, and that a major factor influencing the water quality may be the depth of the aquifer and the type of materials overlying it. In general, the lower part of the Dakota has greater yield potential, but probably poorer natural water quality. For practical purposes, domestic supplies often use the upper portion of the aquifer because drilling costs are lower, and they do not need large yields. Public and industrial users that need greater yields must use the lower portion of the aquifer, even if the quality of the water is poorer.

The individual sandstone beds within the Dakota Aquifer range from less than 10 feet to more than 150 feet in thickness, and while the cumulative thickness of the sandstone also varies widely, it generally ranges from 200 to 300 feet in thickness throughout much of the study area. The sandstones are confined over most of the study area by 200 to 400 feet of clay-rich glacial till as well as by thick shale, siltstone, thin chalky limestone, and lignite (low-grade coal). Most wells developed in the aquifer range from 100 to 600 feet deep in the area. The confining beds underlying the aquifer include Dakota shales, undifferentiated Paleozoic rocks, and Precambrian crystalline rock.

Water flows through the Dakota Aquifer from the north-central part of the study area to the east,

south and southwest, with recharge coming from infiltration through the land surface and confining materials (Burkart, 1984). Discharge from the aquifer is to the underlying Paleozoic aquifers and to the alluvium and glacial outwash deposits along the Missouri and Big Sioux rivers in the southwest part of the study area. Flow toward bedrock valleys may reflect discharge to Quaternary sand and gravel deposits in the valleys.

Background Information, Data Sources, and Methods used for Evaluation

For those unfamiliar with the basic principles of geology, hydrology, and groundwater quality, a good review of these topics as well as a general discussion of the occurrence, use, and vulnerability of Iowa's groundwater resources is included in a publication titled: *Iowa's Groundwater Basics* (Prior, et al., 2003). This publication is available in PDF format from the Iowa Geological and Water Survey at www.igsb.uiowa.edu/, and is also available in book form free of charge from the Iowa Geological and Water Survey, located at 109 Trowbridge Hall, Iowa City, Iowa 52242-1319.

The water quality data used to generate maps for this report are from a database that is available from the Iowa Geological and Water Survey's Natural Resources Geographic Information System (NRGIS) Library (www.igsb.uiowa.edu/nrgislib/) as a downloadable shapefile named GW_Quality.zip. This GIS groundwater quality database, which can be thought of as a map layer or coverage, was constructed to characterize Iowa's aquifers and determine if contamination from human activity has increased in any of the aquifers in recent years. The database is divided into two separate map layers named "General" and "Contaminant," with the General map layer containing naturally occurring constituents including metals, physical characteristics (total dissolved solids, pH, etc.) and radionuclides, and the Contaminant map layer accommodating nutrients, anthropogenic contaminants such as volatile organic compounds and pesticides. The map layers include geographically indexed,

or geo-referenced, data from wells completed in all of Iowa's major aquifers. Both layers contain over 8,000 analyses of unfinished water, collected from over 2,000 wells, with a combined total of over 300 sampled parameters. The samples have been collected over many years by numerous individuals from private, public, and government sectors from public and private wells across Iowa. Most samples are from public water supplies and were analyzed by the University of Iowa Hygienic Laboratory (UHL), but samples from a variety of projects, including aquifer and water studies, contaminant plume mapping, and maximum contaminant level compliance monitoring, and analyses from other laboratories are also included in the map layers.

To be useful, the map layers from this report will be made available in an understandable and accessible format, similar to the Iowa Geological and Water Survey's hydrologic atlas (www.iowadnr.gov/mapping/index.html) where the information can be integrated and presented on a variety of maps at appropriate scales. While the hydrologic atlas is an interactive map server application (IMS), the water plan information will be based on newer, web-based server applications that will provide on-line access for those without desktop GIS software who want to view pre-selected GIS map layers of interest. For those who have desktop GIS software, the new series of map layers, known as coverages or themes, will also be accessible from the NRGIS Library.

GIS software stores geographically indexed information in layers and allows users to analyze spatial relationships and map them. The information can be represented in two dimensions as points, lines, polygons and grid cells, or in three dimensions as triangular irregular network (TIN) data with x, y, and z values, and a series of edges connecting these points to form triangles. Like grids, TINs are used to represent continuous surfaces such as a landscape, but unlike grids, TINs have a vertical component such as thickness or elevation. GIS software tools allow the user to create three-dimensional layers and perform mathematical calculations on them. The software also allows the user to query, or sort, the geo-ref-

erenced data much like a spreadsheet program. The water quality maps in this report focus on naturally occurring constituents, and are grids that were constructed with desktop GIS software using data from wells completed in the Dakota Aquifer. As grids, the data can be represented as two- or three-dimensional layers. The data sets for the maps were constructed by querying the General coverage for wells completed only in the Dakota Aquifer, then this new coverage was queried for the individually mapped constituents. For wells with multiple occurrences of the same constituent from different samples, the constituent concentrations were averaged. The well point locations for the averaged constituents were then converted to a grid using a topo to raster tool, the grid was then clipped using the outline of the sixteen counties in northwest Iowa as a boundary condition, and then the grid was contoured using a raster surface contour tool.

Water Quality Basics

Water quality is a major factor in the development of a water supply, and problems in quality can arise from a multitude of sources, both natural and anthropogenic. As groundwater moves through sediments and rocks, it dissolves some of the more soluble minerals, adding to the water's total dissolved solids (TDS). In general, deeper aquifers contain older groundwater that has been in contact with rocks longer, so they have higher concentrations of various dissolved solids. Carbonate minerals are common and soluble, and contribute dissolved calcium (Ca), magnesium (Mg) and bicarbonate (HCO_3) to groundwater. Sulfur-bearing minerals like gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) and pyrite (FeS_2), while less common, add sulfate (SO_4) to the water. Other minerals and buried organic matter can add dissolved or gaseous constituents such as iron (Fe), manganese (Mn), arsenic (As), hydrogen sulfide (H_2S), ammonia (NH_3), methane (CH_4) and radioactive compounds like radium (Ra) and radon (Rn). Because water is an excellent solvent, it retains a signature of the geologic materials that it passes through over time. These natural con-

ity of water are unregulated and use Secondary Maximum Contaminant Levels (SMCLs) to define acceptable levels of contamination based on taste, odor, color and certain other non-aesthetic effects of drinking water. Contaminants that affect health include bacteria, nitrate (NO₃), pesticides, radionuclides, organic chemicals, arsenic and lead (Pb).

Contaminants that affect the aesthetic quality of water, but do not affect health, at least in small quantities, include sulfate, total dissolved solids, calcium, magnesium, hydrogen sulfide, iron, manganese and iron bacteria. SMCLs for these constituents are often exceeded for long periods without obvious detrimental effects, although the water may have a bad odor and be unpalatable. In many areas, the best water that is locally available may have aesthetic problems, but is still widely used. For constituents that affect health, the regulated MCLs can not be exceeded legally, even for short periods.

Publications about water quality and its effects on health are available from the U.S. Environmental Protection Agency (USEPA) at www.epa.gov/safewater/, the U.S. Geological Survey (USGS) at water.usgs.gov/owq/ and the Iowa Geological and Water Survey at www.igsb.uiowa.edu/service/wateres.htm.

Wells can reveal much about the present condition of an aquifer, and periodic well water sampling can document the presence or absence of natural and anthropogenic contaminants and changes in water quality through time. Although groundwater is generally more protected and usually takes longer to respond to contamination than surface water, groundwater contamination can be much more difficult to discover and take much longer to clean up. The General and Contaminant data sets each currently contain 728 different water quality analyses collected from 139 wells completed in the Dakota Aquifer within the study area.

Information for wells in this report and other wells across Iowa, including geologic framework, well design and construction, static and pumping water levels and pumping rates, may be reviewed in the Iowa Geological and Water Sur-

vey's geologic site and sample tracking program (GEOSAM) at gsbdata.igsb.uiowa.edu/geosam/. This information is related by a unique site identification number (wnumber) and includes the owner name, county name, location (i.e. township, range and section), well depth and site type. This database currently contains over 65,000 records that can be searched by wnumber, location, county name, owner name, USGS 7.5' topographic quadrangle name or any combination of these. For many sites, a scanned strip log, which is a graphic representation of the site stratigraphy, or a driller's log is available.

Water quality standards for uses other than drinking water are often different than those listed in Table 1, and the requirements for different industrial uses can be quite variable. The concentrations of the constituents and properties of water from the Dakota Aquifer are displayed on the following maps so that potential users can decide if the water is suitable for their particular needs. Comments concerning acceptability are based on drinking water standards developed by the USEPA and are included to show where the aquifer contains the most desirable water quality. It was assumed that if the wells were pumped for several hours or longer that the water sample was representative of the Dakota Aquifer.

Anthropogenic Contaminants

Before discussing the natural water quality maps of the Dakota Aquifer, derived from the General data set, some comments concerning broad trends of anthropogenic contaminants including nitrate-nitrogen (NO₃-N), some common pesticides, benzene and trichloroethylene (TCE) are included in the following paragraphs. Arsenic and lead, which are included in the General data set, but are not presented on chemical characteristic maps, are also briefly discussed.

Anthropogenic contaminants are usually not found in water from the Dakota Aquifer because the aquifer is protected from surface contamination in most areas by thick overlying glacial drift and shale. The most likely settings to find wells with anthropogenic contamination are ar-

eas where the aquifer is very shallow and/or not protected by relatively impermeable overlying materials. Faulty or improperly maintained well construction and distribution systems can also allow contaminated groundwater and surface water into deeper wells. As discussed, the analytical results for anthropogenic contaminants in well water in Iowa are included in the Contaminant data set in the NRGIS Library.

The primary inorganic nitrates (NO_3) that may contaminate drinking water are potassium nitrate and ammonium nitrate, both of which are widely used as fertilizers. Since nitrates and nitrites (NO_2) are very soluble and do not bind to soils, they have great potential to migrate into groundwater. In addition, they do not evaporate, so they generally remain in groundwater and surface water until they are consumed by plants or other organisms. NO_3 -N concentrations in water from the Dakota Aquifer are generally much lower than the 10 milligrams per liter (mg/L) MCL for NO_3 -N, in part, because Dakota rocks contain very little nitrogenous material, and in part, because the aquifer is protected by relatively thick overlying glacial drift, and in some areas, shale. From a total of 512 well water analyses for NO_3 -N, 253 analyses showed concentrations below method quantitation levels, and from the detected concentrations, only two were greater than the MCL for NO_3 -N. A water analysis from the City of Oyens Well No. 1 (W-34653) collected on 03/03/1953 showed a NO_3 -N concentration of 22.7 mg/L. Upon closer inspection, this sample was found not to be representative of the aquifer since it was taken from a depth of 37 feet during a pump test performed before well construction was completed. After the well was completed, all subsequent water analyses have shown very low to non detectable concentrations of NO_3 -N. A water analysis from the City of Truesdale Well No. 1 (W-8104) collected on 06/28/1961 showed a NO_3 -N concentration of 40.9 mg/L. Preliminary investigation revealed that this sample may not have been representative of the aquifer since it was taken from a pump, located some distance from the wellhead. In addition, comparison of other constituents included in the analysis with

previous analyses from the well, also suggested that the sample did not come from Well No. 1, and an analysis of a sample taken at the wellhead on the same date showed a non-detectable level of NO_3 -N.

Atrazine is a white, crystalline solid organic compound. It is a widely used herbicide for control of broadleaf and grassy weeds and was estimated to be the most heavily used herbicide in the United States from 1987 through 1989. Atrazine's most extensive use is for corn and soybeans in Illinois, Indiana, Iowa, Kansas, Missouri, Nebraska, Ohio, Texas, and Wisconsin. Beginning in 1993, its uses were greatly restricted. Microbial activity and other chemicals may break down atrazine in soil and water, particularly in alkaline conditions. However, the breakdown products, or degradates, of atrazine are often more persistent in the environment than the parent compound. Sunlight and evaporation do not reduce atrazine's presence, and while it may bind to some soils, it generally tends to leach into groundwater.

Alachlor is an odorless, white solid. Its greatest use is as an herbicide for control of annual grasses and broadleaf weeds in crops, primarily on corn, sorghum, and soybeans. It was the second most widely used herbicide in the United States, with particularly heavy use on corn and soybeans in Illinois, Indiana, Iowa, Minnesota, Nebraska, Ohio, and Wisconsin. When released to soil, alachlor can be broken down by bacteria and sunlight, usually within two months. However, alachlor does not bind to most soils very well and may either vaporize or leach into groundwater. Sunlight and bacterial action are also important for degrading alachlor in surface water, but evaporation generally does not occur. Once alachlor enters groundwater, its breakdown is very slow.

Atrazine and alachlor were each detected in 2 of 62 samples analyzed for herbicides from Dakota wells in the study area. The detected concentrations were an order of magnitude below the 0.003 mg/L MCL for atrazine and 0.002 mg/L MCL for alachlor. Analyses from the City of Rinard Well No. 2 (W-41663) of a sample collected on 08/02/1991 showed a concentration of 0.0001

mg/L for both atrazine and alachlor. Very low concentrations of trifluralin, metribuzin and cyanazine were also found in this sample. There is little construction or geologic information available for this well, which was constructed in 1968, but municipal records indicate that the well is 317 feet deep. The well is located in an area where the lower part of the Dakota Aquifer is often absent, and the upper bedrock may be Pennsylvanian rather than Dakota. At a depth of 317 feet, the well probably penetrates Mississippian rocks. In 1992 the well started pumping sand, so it is possible that there are construction problems. The absence of stratigraphic and construction information makes it difficult to determine the source of herbicides found in this well.

The other atrazine detection, 0.0002 mg/L, occurred in a sample from the Sioux City River No. 10 Well (W-42503) collected on 08/19/1994. No other detectable concentrations of herbicides were found in the sample. This well is 155.5 feet deep with 95 feet of casing, and is located very near the Missouri River. Stratigraphic information for the well shows that the Dakota Aquifer is directly overlain by sands and gravels from the land surface down to the top of the aquifer, so at this location the Dakota is very susceptible to contamination from the land surface.

The second detection of alachlor, 0.0001 mg/L, occurred in a sample from the City of Auburn Well No. 3 (W-6210) collected on 07/28/1989. No other detectable concentrations of herbicides were found in the sample. When this well was constructed in 1952, no lithologic samples were taken from 0 to 185 feet below the land surface, but the interval directly overlying the aquifer, from 185 to 215 feet, consists of poorly sorted sands and gravels. A nearby city well (W-5390) shows sandy till from 0 to 180 feet below the land surface. Well construction records indicate that only the top 20 feet of this well casing was grouted, so the combination of age, inadequate grouting and lack of impermeable material directly overlying the aquifer may make this well susceptible to contamination from the land surface.

Fonofos is an organophosphate used as a soil insecticide against insect pests. It was used ex-

tensively in the Midwest, primarily on corn, but was also applied to a variety of other agricultural crops, vegetables and fruits. It is a clear, light yellow liquid with an aromatic odor. The production of fonofos was discontinued in 1998, with a one-year grace period to permit the exhaustion of existing stocks before the end of 1999. It is only slightly soluble in water and usually does not migrate into water rapidly following soil application. In water systems, fonofos may adsorb onto organic material such as suspended solids and sediment. No detectable concentrations of fonofos were found in the eight Dakota well water samples that were analyzed.

Benzene is a clear, colorless aromatic liquid that is highly flammable. It is used as a building block for making plastics, rubber, resins and synthetic fabrics like nylon and polyester. It is also used as a solvent in printing, paints, dry cleaning, etc. Benzene is often released to air from fumes and exhaust connected with its use in gasoline and fumes from its production and use in manufacturing other chemicals. There are also discharges into water from industrial effluents and losses during spills. When benzene is released to soil, it either evaporates very quickly or leaches into groundwater. It can be broken down by some soil microbes and may also be degraded in some groundwater environments. When benzene is released to surface water, it usually evaporates within a few hours. There were no detectable concentrations of benzene found in the 203 Dakota well water samples that were analyzed.

Trichloroethylene (TCE) is a colorless or blue organic liquid with a chloroform-like odor. The greatest use of TCE is to remove grease from fabricated metal parts and some textiles. Environmental releases of TCE are often due to air emissions from metal degreasing plants. Wastewater from metal finishing, paint and ink formulation, electrical/electronic components, and rubber processing industries also may contain TCE. When released to soil TCE either evaporates or leaches into groundwater, and when released to surface water, it evaporates quickly. TCE was detected in 66 of the 170 samples that were analyzed. All detections occurred in three wells owned by the

city of Sioux City. One, 0.0015 mg/L, occurred in water from the Sioux City River No. 10 Well (W-412503) on 07/25/2003. Another, 0.0011 mg/L, was found in water from the Sioux City Water Supply Well No. 22 (W-57175) on 03/07/2005, and 64 detections, ranging from 0.0012 to 0.0089 mg/L, were found in water from the Sioux City River No. 3 Well from 02/28/2001 through 06/13/2007. Nine of the detected concentrations, ranging from 0.00089 to 0.0054 mg/L, were above the 0.005 mg/L MCL for TCE.

Stratigraphic information for the two Sioux City River wells shows that the Dakota Aquifer is directly overlain by silty clays and/or sands and gravels from the land surface down to the top of the aquifer, so at these locations the aquifer is very susceptible to contamination from the land surface. As discussed, River No. 10 is 155.5 feet deep with 95 feet of casing, and is located very near the Missouri River. River No. 3 is 312 feet deep, and is also located very near the Missouri River. There is no casing information for this well. Well No. 22 is 361 feet deep, with bedrock at a depth of 95 feet. There is also no casing information for this well, which is located 0.65 miles north of the Missouri River. The driller's log for this well shows sand and clay from 1 to 6 feet, clay from 6 to 53 feet, and gravel with rocks and intermittent limestone from 53 to 95 feet, overlying the bedrock. The Iowa Geological and Water Survey's Groundwater Vulnerability Regions of Iowa Special Map Series II (www.igsb.uiowa.edu/inforsch/gwvuln.htm) shows that even though this well is more than one-half mile north of the Missouri River, it is located within the alluvial aquifer of the Missouri and Floyd rivers. It is possible that the contamination found in these three wells is coming from the alluvial sands and gravels, rather than from the Dakota Aquifer.

Arsenic is a semi-metal element that is odorless and tasteless. It is present in more than 200 mineral species, the most common of which is arsenopyrite. Arsenic enters drinking water supplies from natural deposits in the earth or from agricultural and industrial practices. Because it occurs naturally in the environment and as a by-product of some agricultural and industrial ac-

tivities, it can enter drinking water through the ground or as runoff into surface water sources. A geochemical survey of Iowa that was conducted in cooperation with the USGS (www.igsb.uiowa.edu/nrgislibx/) shows that from 1,063 soil samples collected across Iowa, the average concentration of arsenic in shallow soil was 9.2 mg/L. Since the natural background concentration on the land surface is almost 4 orders of magnitude greater than the 0.01 mg/L MCL for arsenic, it can sometimes be difficult to distinguish whether detections of arsenic in groundwater are from natural or anthropogenic sources. Arsenic was detected in 25 of the 49 water samples that were analyzed, at concentrations ranging from 0.001 to 0.11 mg/L. Eleven samples, ranging from 0.014 to 0.11 mg/L, were above the 0.01 mg/L MCL. Two exceedances of the MCL, 0.014 and 0.016 mg/L, occurred at the Yetter City Well No. 1 (W-27071) on 11/12/2002 and 03/06/2003. The City of Alta Wells No. 4 (W-14165) and No. 5 (W-28754) had exceedances both at 0.014 mg/L on 05/21/2003. Water from the West Bend City Well No. 2 (W-3595) exceeded the MCL twice at concentrations of 0.022 mg/L on 07/23/2001 and 0.019 mg/L on 08/21/2002. The Mallard City Well No. 3 (W-2863) exceeded the MCL three times at concentrations of 0.11 mg/L on 08/15/1984 and 0.080 mg/L on 11/06/2002 and 03/05/2003. The Mallard City Well No. 5 (W-34311) exceeded the MCL at concentrations of 0.089 mg/L on 11/06/2002 and 0.098 mg/L on 03/05/2003. The high percentage and wide distribution of detections, as well as the variation in well depths of affected wells, suggest that most of the arsenic found in these wells is from naturally occurring sources.

Lead is a metal found in some natural geologic deposits. It is also commonly used in household plumbing materials and water service lines. The greatest exposure to lead is through swallowing or breathing in lead paint chips and dust. Typically, lead gets into drinking water after the water leaves local treatment plants or wells. The source of lead in household water is usually from pipes or solder in a home's plumbing caused by corrosion of lead pipes or solder. The most common problem is with brass or chrome-plated brass faucets

and fixtures which can leach significant amounts of lead into the water, especially hot water. Dissolved oxygen, low pH (acidity) and low mineral content in water are common causes of the corrosion. The previously mentioned geochemical survey of Iowa shows that, from 1,063 soil samples collected across Iowa, the average concentration of lead in shallow soil was 20.9 mg/L. There is no MCL for lead in drinking water, but if more than 10% of tap water samples exceed an EPA action level of 0.015 mg/L, water systems must take additional steps to reduce corrosivity. No detectable concentrations of lead were found in the 62 well Dakota water samples that were analyzed.

Naturally Occurring Contaminants

Figures 3 through 21 are chemical characteristic maps based on analyses of naturally occurring constituents in water from wells completed in the Dakota Aquifer. Some of the wells penetrate the full extent of the aquifer and some are completed in only the upper part. As mentioned, private wells tend to be completed in the upper part, while public and industrial wells usually penetrate the full extent of the aquifer to obtain greater yields. Differences in water quality between the upper and lower parts of the aquifer may be significant in areas where the upper part of the aquifer is not protected from relatively rapid recharge of water by low-permeable materials like thick glacial tills and shales, while the lower part of the aquifer is protected by low-permeable shales and lignites.

For mapping purposes, sampled constituents yielding results below method quantitation limits were assigned a concentration equal to one half of the value of the quantitation limit of the constituent at the time of sampling. These values were then plotted and used for contouring if they were the only analysis of the constituent from a well. For wells with multiple occurrences of the same constituent from different analyses, the constituent concentrations were averaged and then plotted and contoured.

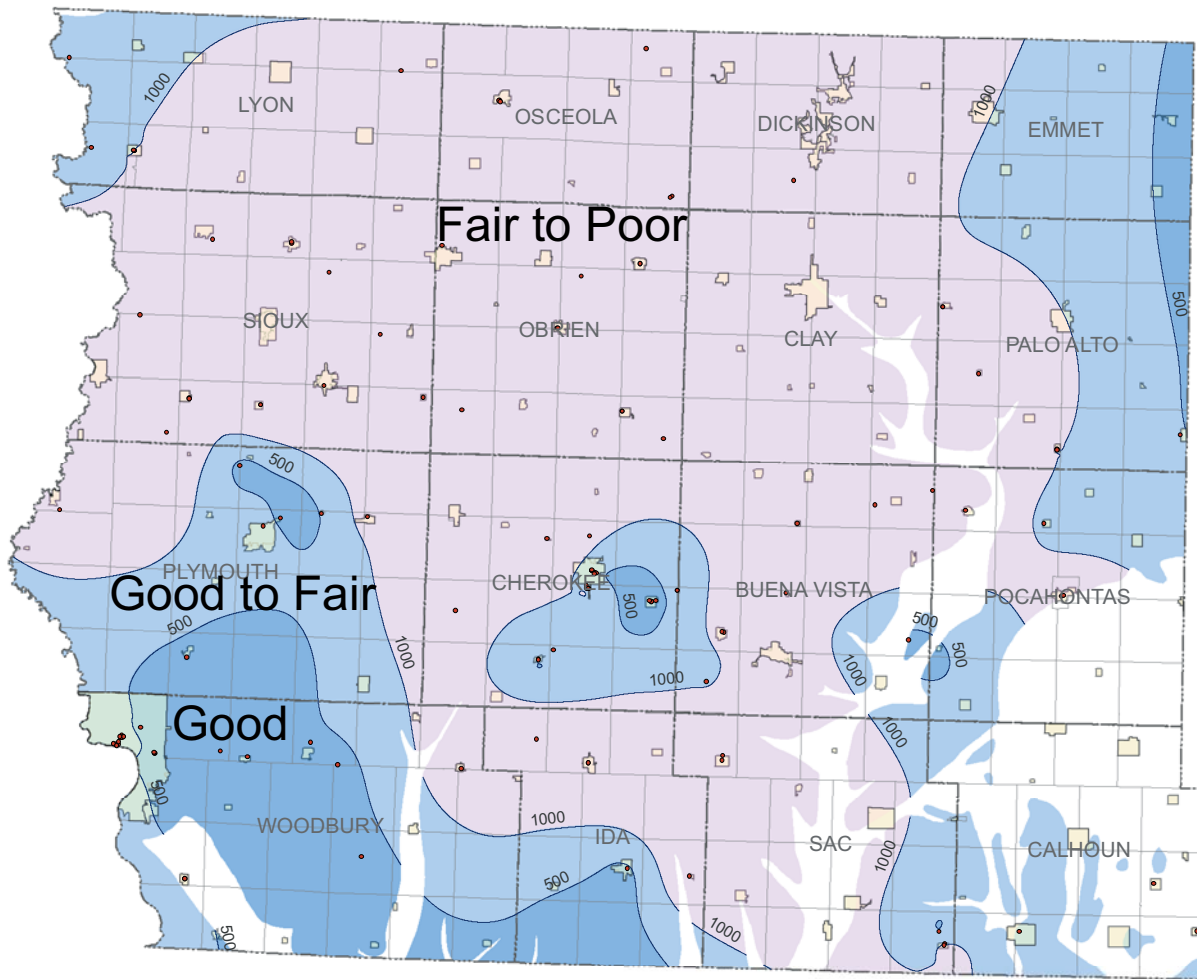
Water is an excellent solvent, which picks up impurities from the materials that it comes into

contact with. The most common substances that contribute to the total dissolved solids (TDS) in groundwater are the inorganic constituents of calcium, magnesium, and sodium, which are cations, and bicarbonate, chloride and sulfate, which are anions. Inorganic constituents that contribute minor amounts to groundwater TDS include potassium, a cation, nitrate and fluoride, both anions, and silica. As discussed, there are also many other elements dissolved in water, including gases and metals. Concentrations of these dissolved substances are often reported as mg/L, which is equivalent to parts per million (ppm) in freshwater, since the weight of a liter of water with dilute concentrations of dissolved constituents at groundwater temperatures is about 1,000 grams, or one million milligrams. Concentrations of trace amounts of dissolved constituents are often listed as micrograms per liter ($\mu\text{g/L}$) or parts per billion (ppb). By definition, the dissolved solids must be small enough to be filtered through a sieve measuring 2 micrometers.

While TDS are not considered a primary pollutant, high levels of TDS can indicate hard water, and may lead to scale buildup in pipes, reduced efficiency of water filters and hot water heaters and cause aesthetic problems such as a bitter or salty taste. Although TDS are generally not considered a health hazard, water treatment is recommended when TDS concentrations exceed the EPA's 500 mg/L SMCL, and further testing may be warranted, as water with a high TDS concentration may indicate elevated levels of ions that may pose a health concern, such as aluminum, arsenic, copper, lead, nitrate and others.

Total dissolved solids are often used as an indicator of the aesthetic characteristics of drinking water and as an aggregate indicator of the presence of a broad array of chemical contaminants. For drinking purposes, water is considered good when it contains less than 500 mg/L of TDS, fair when it contains 500 to 1,000 mg/L and poor when greater than 1,000 mg/L of TDS are present.

The water quality of the Dakota Aquifer tends to be fair to poor throughout most of the study area, and good to fair towards the corners of the



Legend

- Sampled wells (number [n] = 121)
- Water quality contour lines in milligrams per liter

Concentration of total dissolved solids in water from the Dakota Aquifer in milligrams per liter

- < 500 Water quality is good
- 500 - 1,000 Water quality is good to fair
- > 1,000 Water quality is fair to poor

Figure 3. Water quality, from good to poor, based on total dissolved solids concentration, in mg/L, in water from the Dakota Aquifer in northwest Iowa.

study area (Figure 3). The areas of poorer water quality result from high concentrations of TDS (between 500 and 3,000 mg/L), particularly sulfate and calcium carbonate, which are common minerals picked up by groundwater in contact with the confining layers above. Areas of better water quality are found where confining layers are thin and porous pathways allow for more rapid recharge by less mineralized, younger water. This occurs most notably in the southwest, southeast and northeast portions of the study area where the aquifer is closer to the land surface. As discussed, older groundwater contains more TDS because the water has been in contact with the surrounding materials longer, allowing more time for dissolution of minerals into the water.

Figure 4 shows the distribution of TDS within the study area. In southeastern Osceola County, significant differences in water quality have been found in two Dakota wells that are located within about 360 meters of each other. These wells are completed in different members of the aquifer. Well D38 (W-25898) is a 662 feet deep, nested well, with an interval screened into the Woodbury Member at a depth of 333 to 345 feet. Analyses of a sample taken from this interval on 05/21/1980 showed a TDS concentration of 1,680 mg/L. Well D39 (W-25899) is 500 feet deep and screened into the Nishnabotna Member from 490 to 500 feet below the land surface. Analyses of water taken from this well on 05/21/1980 and 05/30/1980 showed TDS concentrations of 2,380 and 2,090 mg/L, respectively. Gamma log information from well D38 suggests there are interbedded shales, silts and fine grained sandstones between the Woodbury and Nishnabotna members. These materials appear to be separating older, more mineralized water in the Nishnabotna from relatively younger, less mineralized water in the Woodbury. Consistently differing values of other analyzed constituents and water levels from the wells measured on the same dates confirm hydrologic separation of the two members.

Treatment options for TDS depend on the nature of the cations and anions present in the water. For example, a water softener can reduce problems associated with calcium, magnesium and

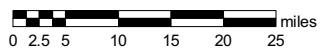
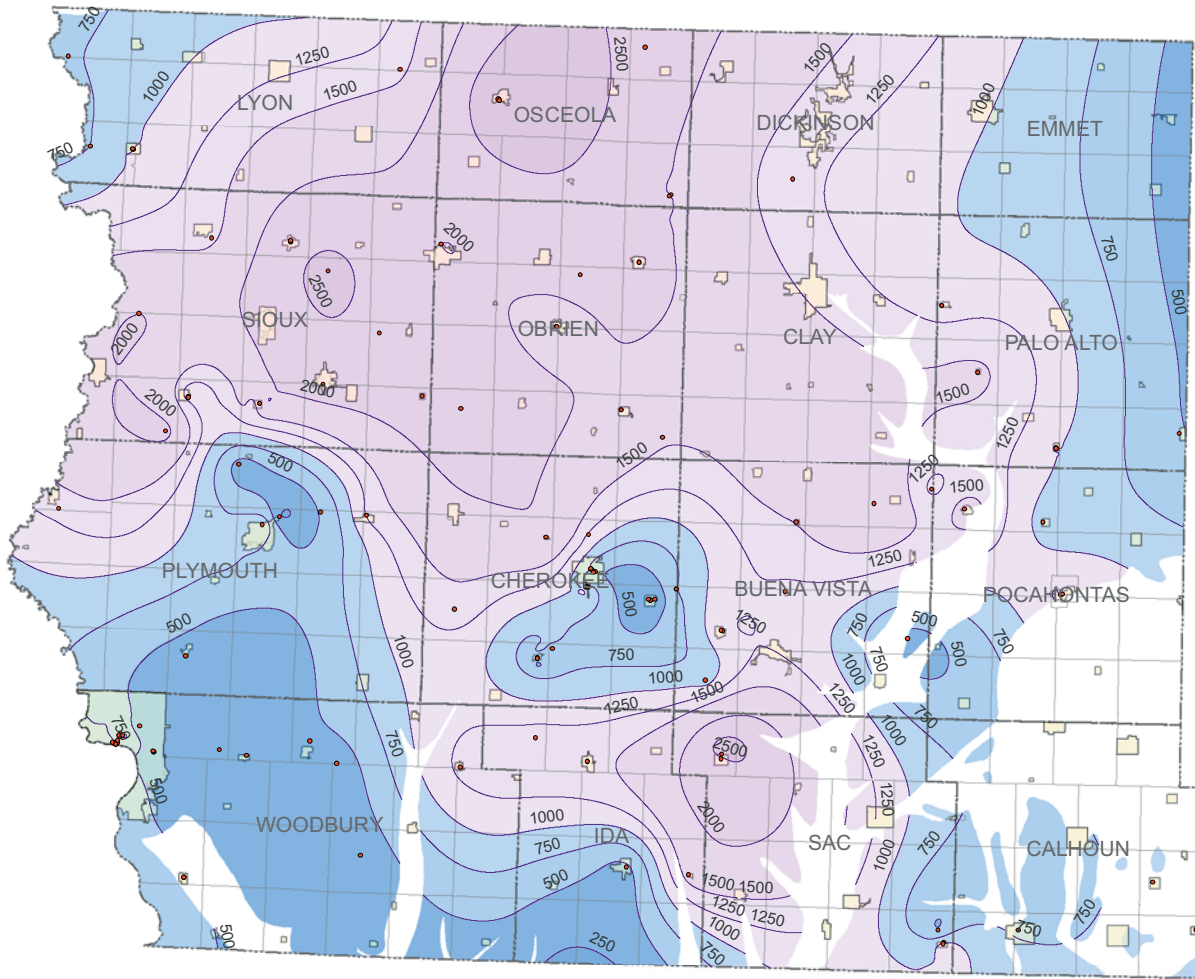
iron, while reverse osmosis or distillation may be recommended to treat elevated TDS levels associated with high levels of sodium or potassium. Carbon filtration and electro dialysis are also effective in removing TDS from drinking water.

Sulfate (SO_4) is a substance that occurs naturally in Iowa's deeper groundwater. It results from the dissolution of soil and rock formations that contain sulfate minerals, like pyrite (FeS_2), as groundwater moves through them. At elevated levels, sulfate can give water a bitter or astringent taste, and may cause corrosion of plumbing, particularly copper piping.

Health concerns regarding sulfate in drinking water have been raised because diarrhea may be associated with the ingestion of water containing high levels of sulfate. Of particular concern are groups within the general population that may be at greater risk from the laxative effects of sulfate when they experience an abrupt change from drinking water with low sulfate concentrations to drinking water with high sulfate concentrations. The EPA currently has a SMCL of 250 mg/L for sulfate based on aesthetic metrics such as taste and odor.

Figure 5 shows the distribution of dissolved sulfate in water from the Dakota Aquifer within the study area being very similar to that of TDS. Sulfate concentrations are below the SMCL for public water supplies in the southwest and northeast parts of the study area where confining layers are thin, and recharge is relatively rapid. Like TDS concentrations, sulfate concentrations show significant differences in the two wells in southeastern Osceola County that are in close proximity of each other, but are completed in different members of the aquifer. Analyses of a sample taken on 05/21/1980 from D38, which is completed in the upper part of the aquifer, showed a dissolved sulfate concentration of 820 mg/L, while analyses of water taken on 05/21/1980 and 05/30/1980 from D39, in the lower part of the aquifer, showed dissolved sulfate concentrations of 1,300 and 1,100 mg/L, respectively.

Reverse osmosis, ion exchange and distillation will effectively remove sulfate from drinking water, while softening and filtration will not.



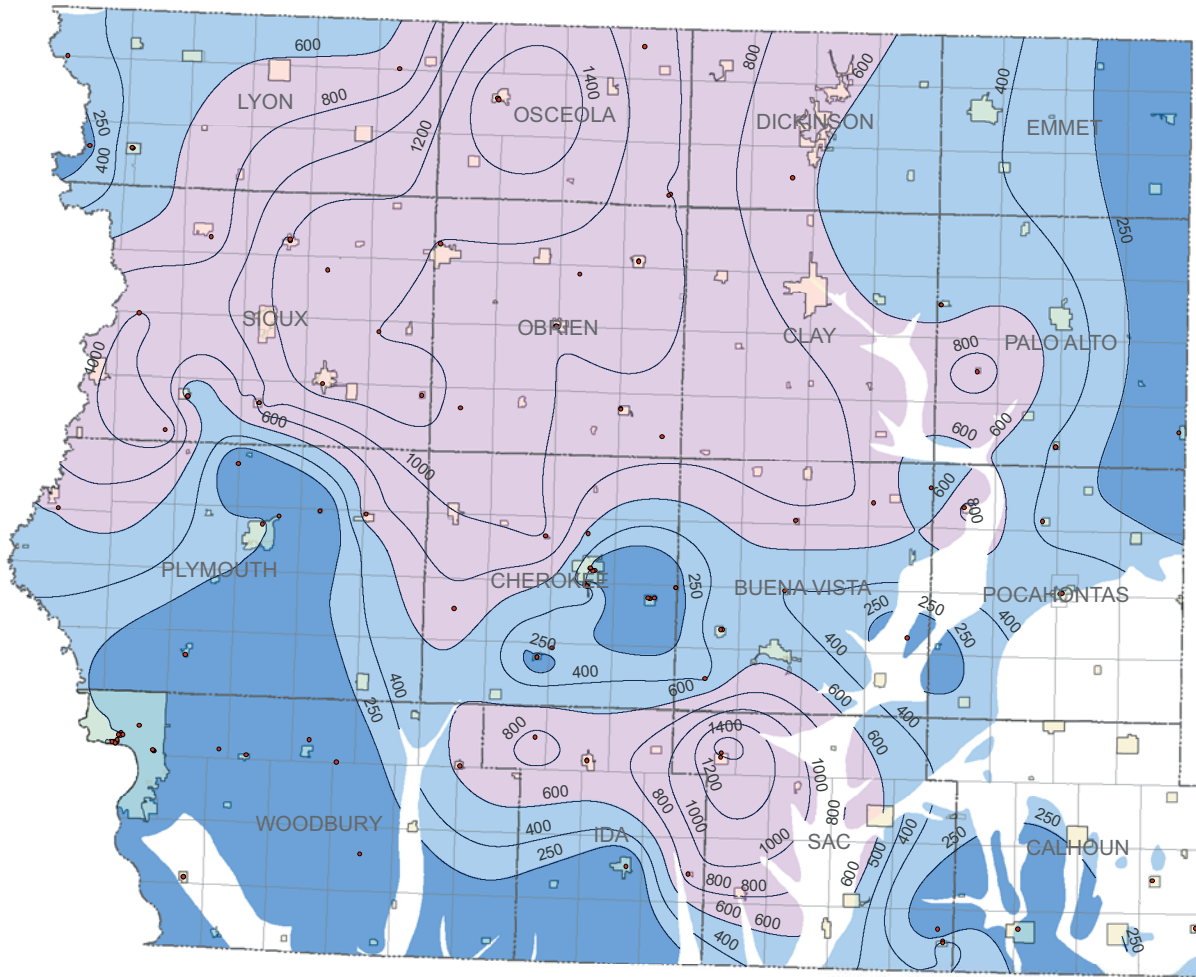
Legend

- Sampled wells (n = 121)
- Lines of equal total dissolved solids concentration in milligrams per liter

Concentration of total dissolved solids in water from the Dakota Aquifer in milligrams per liter

	< 250		750 - 1,000		1,500 - 2,000
	250 - 500		1,000 - 1,250		2,000 - 2,500
	500 - 750		1,250 - 1,500		> 2,500

Figure 4. Distribution of total dissolved solids, in mg/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 121)
- Lines of equal dissolved sulfate concentration in milligrams per liter

Concentration of dissolved sulfate in water from the Dakota Aquifer in milligrams per liter

- < 250 Area where the sulfate concentration is less than the maximum recommended level proposed for public water supplies
- 250 - 600 Area where the sulfate concentration is more than the maximum recommended level but considered acceptable because most users can adjust to it
- > 600 Area where sulfate concentration is high enough to affect the taste of water and also have a laxative effect

Figure 5. Distribution of dissolved sulfate, in mg/L, in water from the Dakota Aquifer in northwest Iowa.

Softening may actually make laxative effects worse by changing magnesium or calcium sulfate into sodium sulfate.

Hard water primarily consists of calcium (Ca^{2+}) and magnesium (Mg^{2+}) metal cations and sometimes other dissolved compounds such as bicarbonates and sulfates. Calcium usually enters the water as either calcium carbonate (CaCO_3), in the form of limestone and chalk, or calcium sulfate (CaSO_4), in the form of other mineral deposits. The predominant source of magnesium is dolomite ($\text{CaMg}(\text{CO}_3)_2$).

Water hardness is often measured in terms of CaCO_3 content, with soft water containing less than 60 mg/L, moderately hard water having 60 to 120 mg/L, hard water containing 120 to 180 mg/L and very hard water having more than 180 mg/L of CaCO_3 . Hard water is generally not considered harmful, and may even provide some Ca and Mg for dietary needs. Currently there is no MCL or SMCL for hardness. However, excessive levels of hardness can limit the lathering of soap, cause scale buildup in pipes and appliances, and have significant esthetic and economic effects, limiting the utility of the water.

The water from the Dakota Aquifer is very hard throughout most of its area of occurrence, ranging from less than 200 mg/L to more than 1,500 mg/L (Figure 6). As with TDS and sulfate, the areas with lower CaCO_3 concentrations are in the southwest and northeast portions of the study area, where overlying materials are thinner, and recharge is more rapid. Like TDS and sulfate concentrations, hardness concentrations show significant differences in the two wells in southeastern Osceola County that are in close proximity to each other, but are completed in different members of the aquifer. Analyses on 05/21/1980 from D38, in the upper part of the aquifer, showed a dissolved CaCO_3 concentration of 933 mg/L, while analyses on 05/21/1980 and 05/30/1980 from D39, in the lower part of the aquifer, showed concentrations of 1,330 and 1,180 mg/L, respectively.

Figures 7 and 8 show the distribution of dissolved calcium and magnesium within the study area as being similar to that of the previously dis-

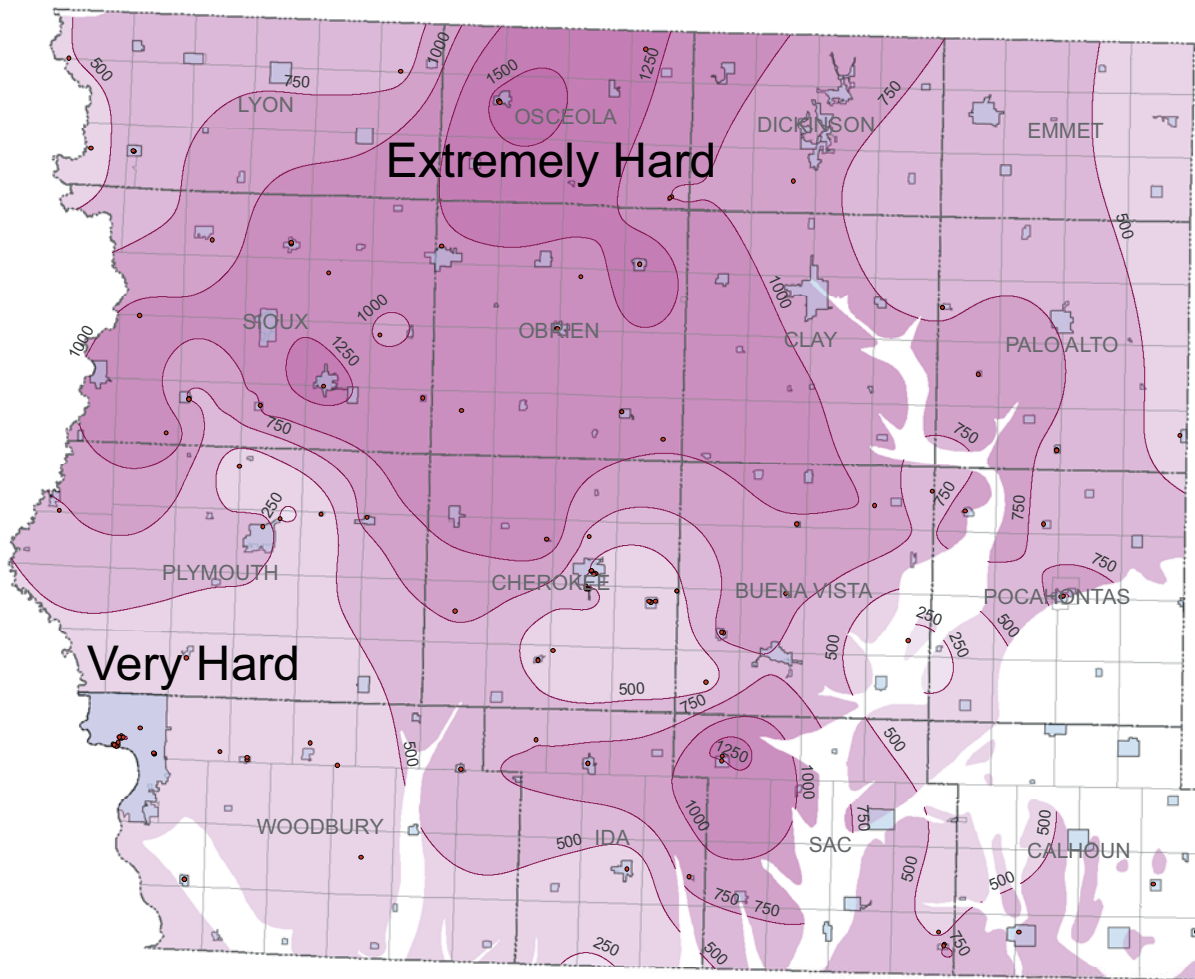
cussed constituents. Currently there is no MCL or SMCL for calcium or magnesium for public water supplies.

As with TDS, sulfate and hardness concentrations, significant differences in calcium and magnesium concentrations occur in wells D38 and D39, that are in near proximity, but are completed in different members of the aquifer in southeastern Osceola County.

Water hardness can be reduced by using either packaged water softeners or mechanical ion exchange water softening units. Because of the sodium content of softened water, some individuals may be advised by their physician not to install water softeners, to soften only hot water or to bypass the water softener with a cold water line to provide unsoftened water for drinking and cooking. Softened water is not recommended for watering plants, lawns and gardens due to its sodium content.

Freshwater is often defined as water containing less than 1,000 mg/L of TDS. The freshwater in the Dakota Aquifer in Iowa is usually a calcium, magnesium and sulfate type of water. Within the study area, most of the Dakota Aquifer contains saline water, primarily dissolved sodium and chloride (Figures 9 and 10). Regionally, the main source of this saline water is from the dissolution of rock salt (NaCl) in Permian rocks underlying the Dakota Aquifer. In Iowa, these rocks are absent, and the aquifer is underlain by undifferentiated Paleozoic rocks and Precambrian crystalline rock.

Although most Dakota sediments probably contained seawater during deposition of the marine shales and sandstones or after deposition when the sea covered these units, nearly all of that seawater was very slowly flushed out by recharge from the land surface. However, saltwater from areas with underlying Permian rocks has been slowly intruding into the aquifer for millions of years. This salt-dissolution brine replaced the seawater source of salinity long ago. During more recent geologic time, freshwater recharge from the land surface is again slowly flushing saltwater from the Dakota Aquifer in some areas.



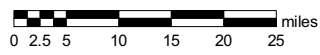
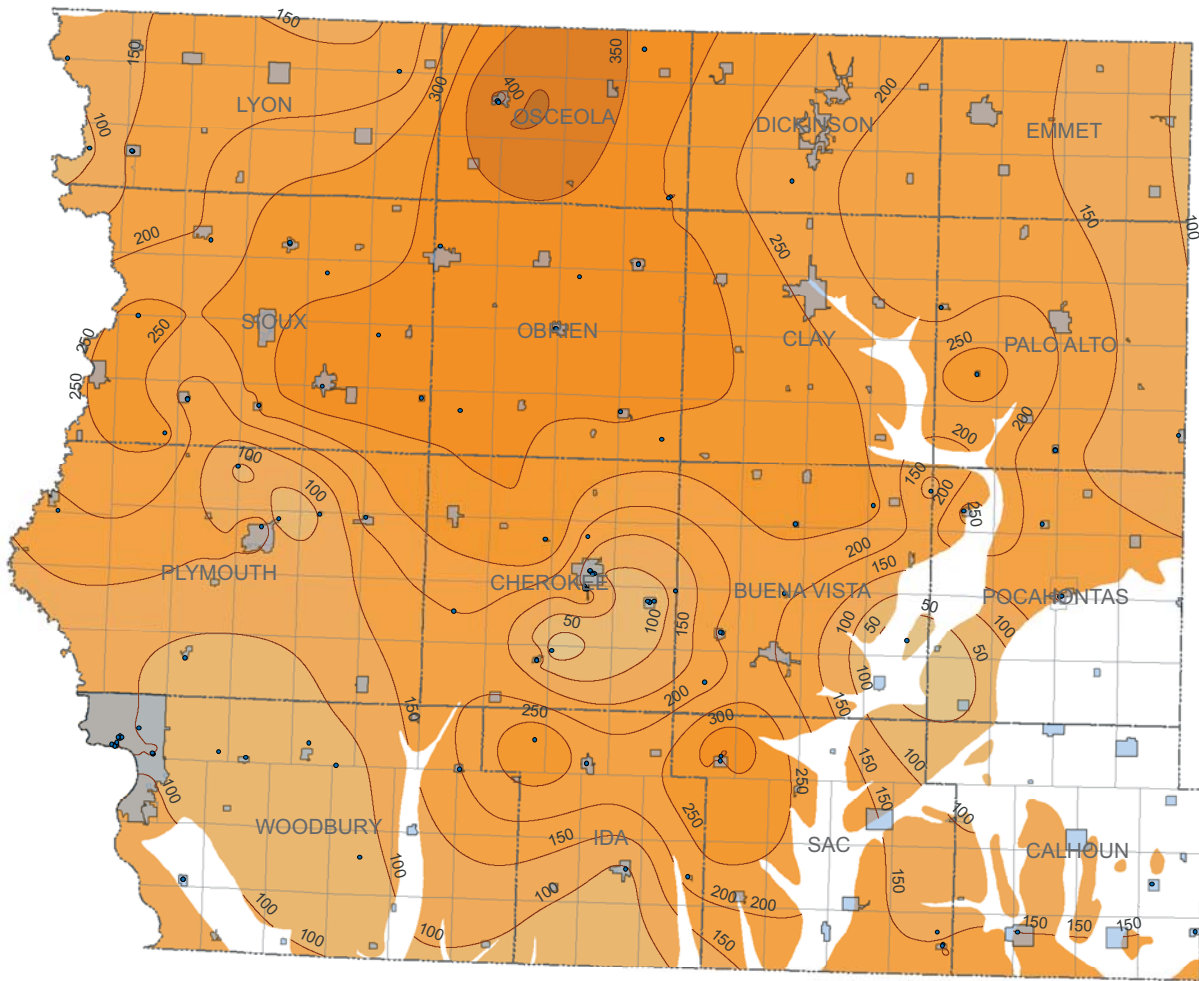
Legend

- Sampled wells (n = 123)
- Lines of equal dissolved hardness as CaCO₃ concentration in milligrams per liter

Concentration of dissolved hardness as CaCO₃ in water from the Dakota Aquifer in milligrams per liter



Figure 6. Distribution of dissolved CaCO₃, in mg/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 121)
- Lines of equal dissolved calcium concentration in milligrams per liter

Concentration of dissolved calcium in water from the Dakota Aquifer in milligrams per liter

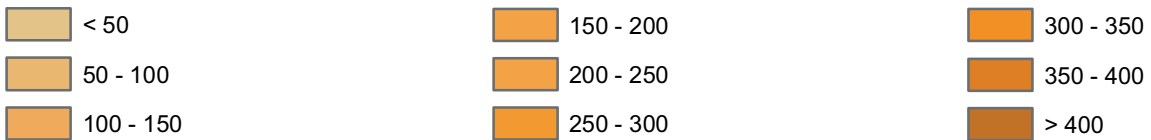
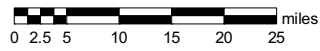
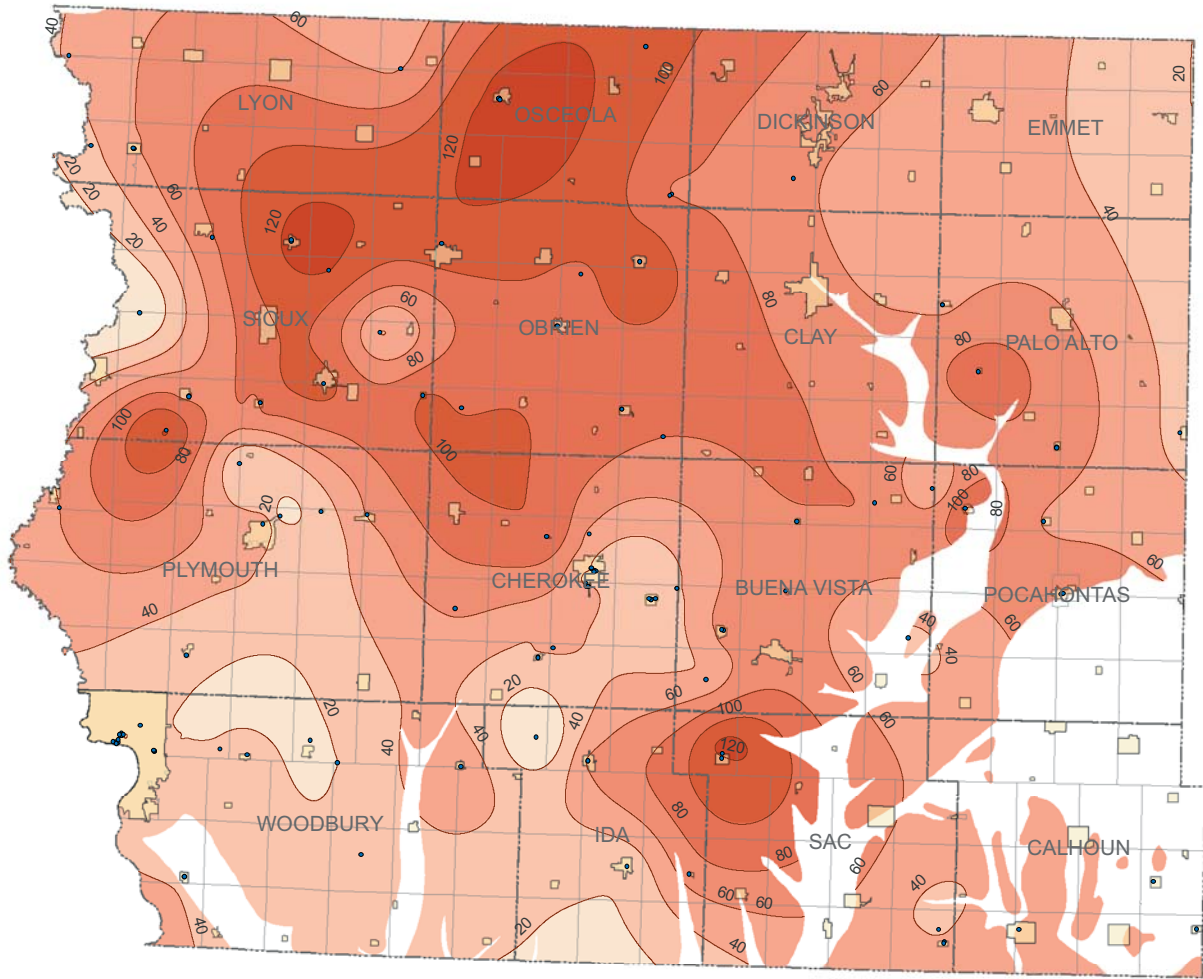


Figure 7. Distribution of dissolved calcium, in mg/L, in water from the Dakota Aquifer in northwest Iowa.



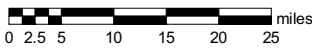
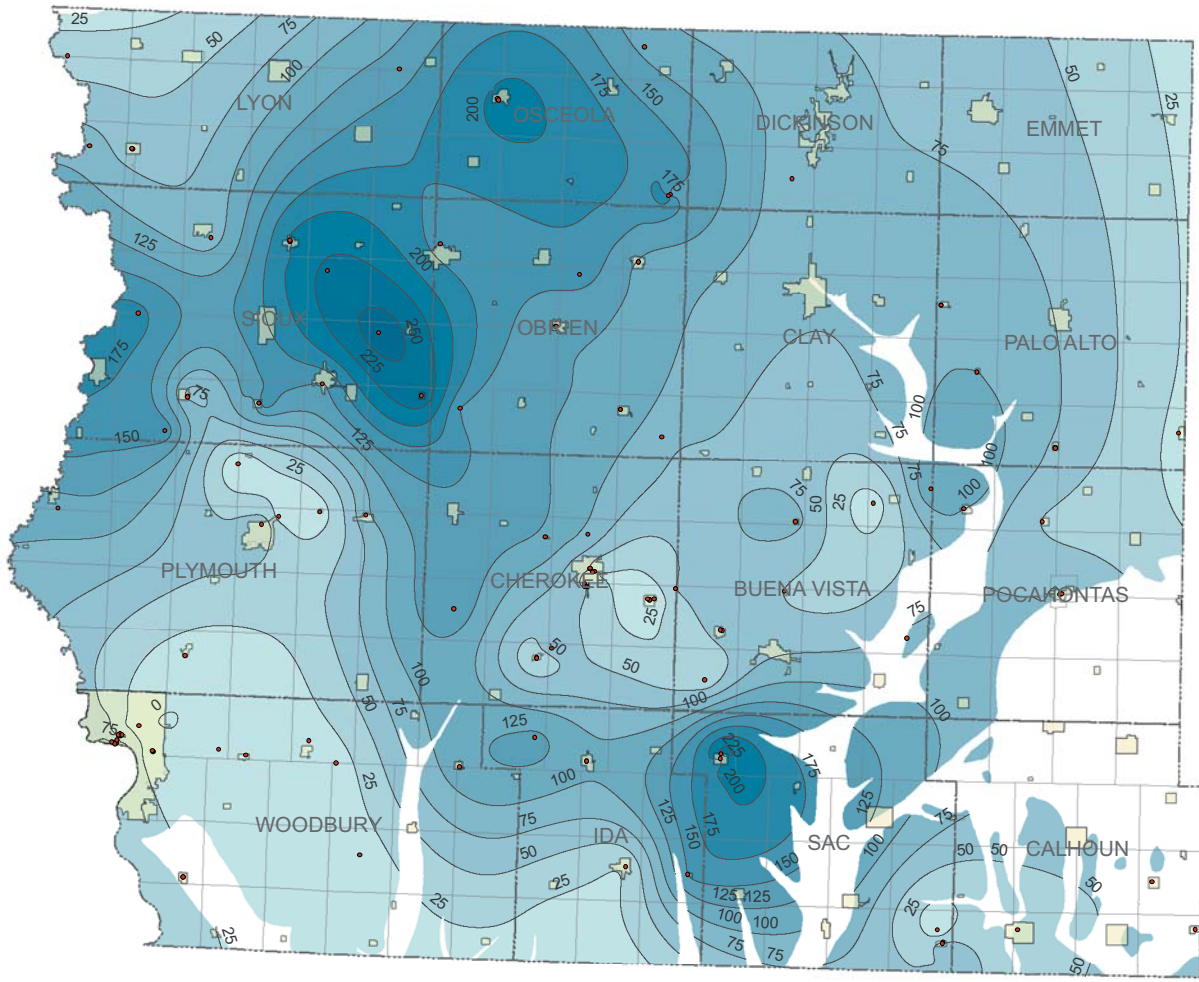
Legend

- Sampled wells (n = 121)
- Lines of equal dissolved magnesium concentration in milligrams per liter

Concentration of dissolved magnesium in water from the Dakota Aquifer in milligrams per liter



Figure 8. Distribution of dissolved magnesium, in mg/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 120)
- Lines of equal dissolved sodium concentration in milligrams per liter

Concentration of dissolved sodium in water from the Dakota Aquifer in milligrams per liter

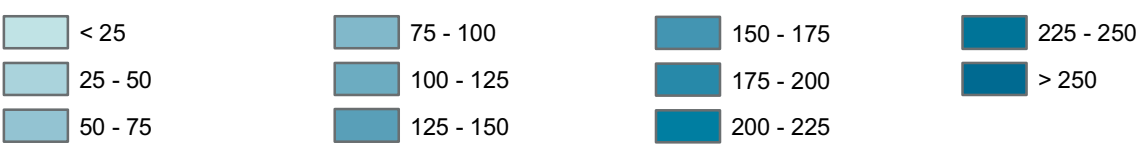
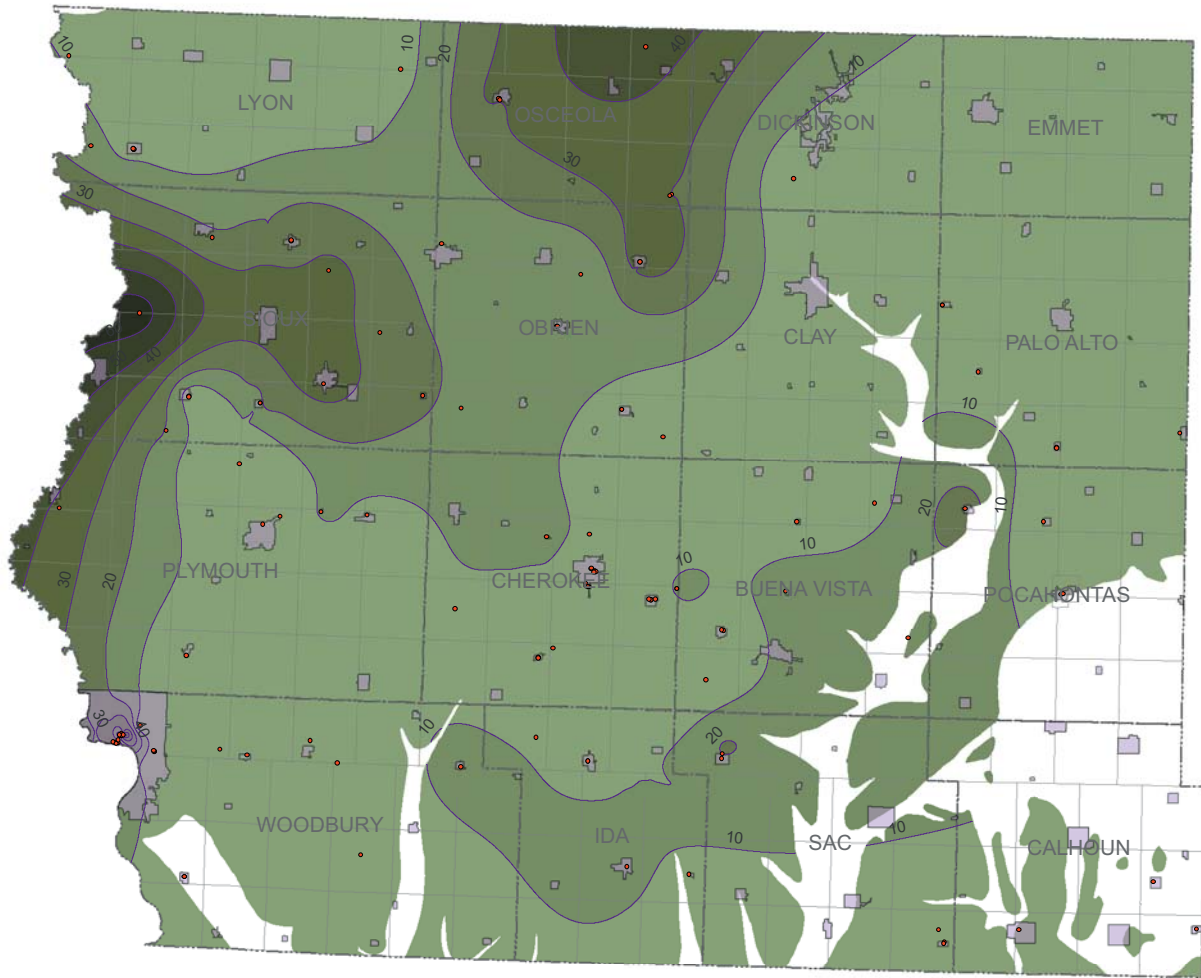


Figure 9. Distribution of dissolved sodium, in mg/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 120)
- Lines of equal dissolved chloride concentration in milligrams per liter

Concentration of dissolved chloride in water from the Dakota Aquifer in milligrams per liter



Figure 10. Distribution of dissolved chloride, in mg/L, in water from the Dakota Aquifer in northwest Iowa.

The past occurrence of saline water in the Dakota Aquifer resulted in the adsorption of large amounts of sodium on clays within the shales, siltstones and sandstones of the Dakota rocks. In areas where relatively freshwater of calcium-bicarbonate type slowly flushes the saline water from the aquifer, a process of natural softening of the water may occur, as dissolved calcium and magnesium is adsorbed on the clays and releases sodium to solution. The decrease in calcium concentration may then allow calcite to dissolve in areas where it is present in the aquifer, thereby supplying additional calcium and bicarbonate to the water. The added calcium is then available for more cation exchange with sodium. Some additional bicarbonate may also be generated from slow oxidation of organic matter trapped in the aquifer. The combined effect of these processes may increase dissolved sodium and bicarbonate concentrations, while decreasing dissolved calcium, magnesium and chloride concentrations in some parts of the aquifer.

Figure 9 shows a convergence of sodium contour lines in southeastern Osceola County that results from the previously discussed differing water qualities yielded from well D38, completed in the Woodbury member, and well D39, completed in the Nishnabotna member of the aquifer. Currently there is no MCL or SMCL for sodium for public water supplies, but there is a 20 mg/L EPA guidance level.

The distribution of dissolved sodium and chloride within the study area is similar to that of previously discussed constituents, with lower concentrations occurring in the northwest, northeast and southwest portions of the area where the aquifer is nearer the land surface, and recharge is relatively more rapid. Sodium concentrations range from less than 25 to more than 250 mg/L, while chloride concentrations range from less than 10 to more than 70 mg/L, remaining well below the 250 mg/L SMCL for dissolved chloride for public water supplies throughout the area.

Although sodium levels in drinking water from most public water systems are unlikely to be a significant contribution to adverse health effects, people with hypertension or cardiovascular

disease should avoid drinking water with more than 20 mg/L of sodium.

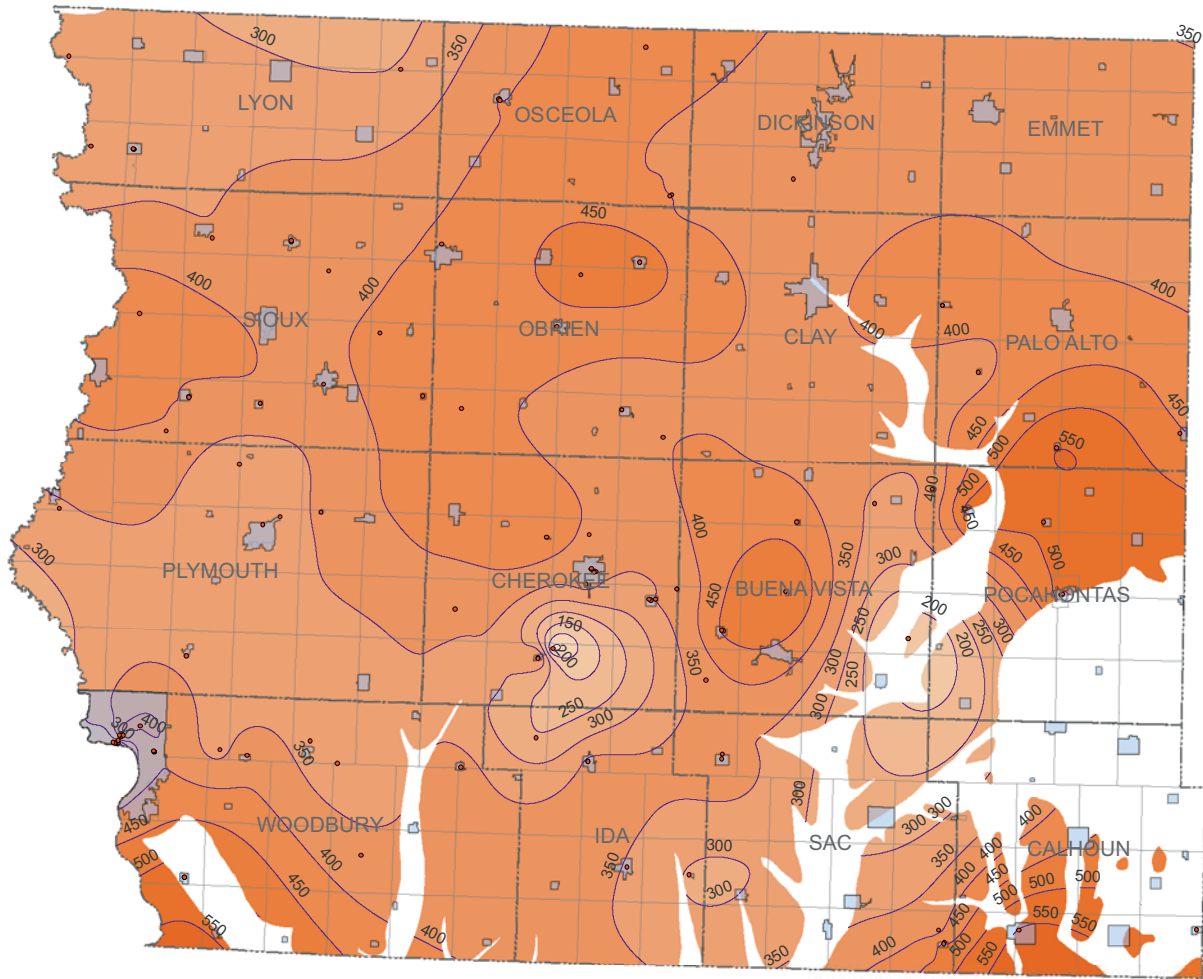
Other problems associated with excessive levels of sodium and chloride in water include the corrosion of piping due to the compounds formed with chloride. For example, magnesium chloride can generate hydrochloric acid when heated. The rate of corrosion and amount of iron dissolved into water from piping increases as the sodium chloride content of the water increases. The chloride ion is instrumental in breaking down films that protect ferrous metals and alloys from corrosion, and is one of the main causes for the pitting of stainless steel. Even though the potential damage to a water system can be serious, the SMCL for chloride is due strictly to the objectionable salty taste produced in drinking water.

Reverse osmosis will reduce chloride by 90 to 95% and sodium by 94 to 98%, because of its salt rejection capabilities. Electrodialysis and distillation are also effective in reducing the chloride and sodium content of water. In addition, a strong base anion exchanger, which is the later portion of a two-column deionizer, does an excellent job at removing chlorides from water for industrial applications.

Bicarbonate (HCO_3^-) is the ion normally responsible for alkalinity or the buffering capacity of water to neutralize acids or resist changes in pH. It is a natural corrosion inhibitor in soft water systems. Bicarbonate alkalinity is introduced into the water by CO_2 dissolving carbonate-containing (CO_3) minerals and rocks like calcite and dolomite.

Figure 11 shows the distribution of dissolved bicarbonate within the study area as being different than that of previously discussed constituents. The concentrations are lower in small, localized areas in Cherokee, Buena Vista, Pocahontas, Ida and Sac counties, rather than becoming progressively lower towards the corners of the study area.

pH is a measure of the acidity or alkalinity of a solution, and is a measure of the activity of dissolved hydrogen ions (H^+). Pure water has a pH of 7, while acids have a pH of less than 7 (more hydrogen ions than water), and bases have a pH greater than 7 (less hydrogen ions than water).



Legend

- Sampled wells (n = 112)
- Lines of equal dissolved bicarbonate concentration in milligrams per liter

Concentration of dissolved bicarbonate in water from the Dakota Aquifer in milligrams per liter

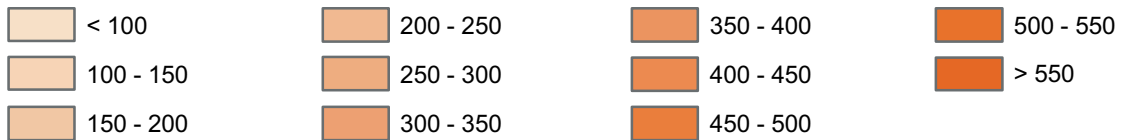


Figure 11. Distribution of dissolved bicarbonate, in mg/L, in water from the Dakota Aquifer in northwest Iowa.

Alkalinity control is important in boiler feed water, cooling tower water and in the beverage and textile industry.

There is no correlation between increased alkalinity due to bicarbonate and poor health. The evaluation of alkalinity as a health based standard in drinking water is difficult because the character of alkalinity may vary due to pH, calcium, magnesium, sodium, potassium, sulfates and total dissolved solids. Currently there is no MCL or SMCL for bicarbonate.

In the pH range of 5.0 to 8.0, there is a balance between excess CO_2 and bicarbonate ions. Removing free CO_2 through aeration can reduce bicarbonate alkalinity. Feeding acid into the water to lower the pH can also reduce alkalinity. At a pH of 5.0, there is only CO_2 and no alkalinity. A strong base anion exchanger will also remove alkalinity.

Fluoride (F^-) is a common constituent of many minerals like fluorspar (CaF_2) and apatite ($\text{Ca}_5(\text{PO}_4)_3\text{F}$). It is the reduced form of fluorine (F). Municipal water treatment plants commonly add fluoride to finished water for prevention of tooth decay and generally maintain a level of 1.5 to 2.5 mg/L. Concentrations of fluoride above 5 mg/L are detrimental to tooth structure. High concentrations of fluoride can occur in waste water from the manufacture of glass and steel, as well as from foundry operations. Organic fluorine is present in vegetables, fruits and nuts. Inorganic fluorine, under the name of sodium fluoride (NaF), is a waste product of aluminum and is used in some rat poisons.

In the Dakota Aquifer, elevated concentrations of dissolved fluoride are usually associated with sodium-bicarbonate waters. Dissolved fluoride concentrations can range from over 1 to several mg/L in comparison with less than 1 mg/L in calcium-bicarbonate type waters in the aquifer. The high fluoride concentrations are probably derived from the dissolution of apatite minerals. The low calcium concentration resulting from the cation exchange that produced the sodium-bicarbonate water probably allows the calcium minerals to dissolve. Some fluoride adsorbed or weakly attached to clays may also be released in the higher

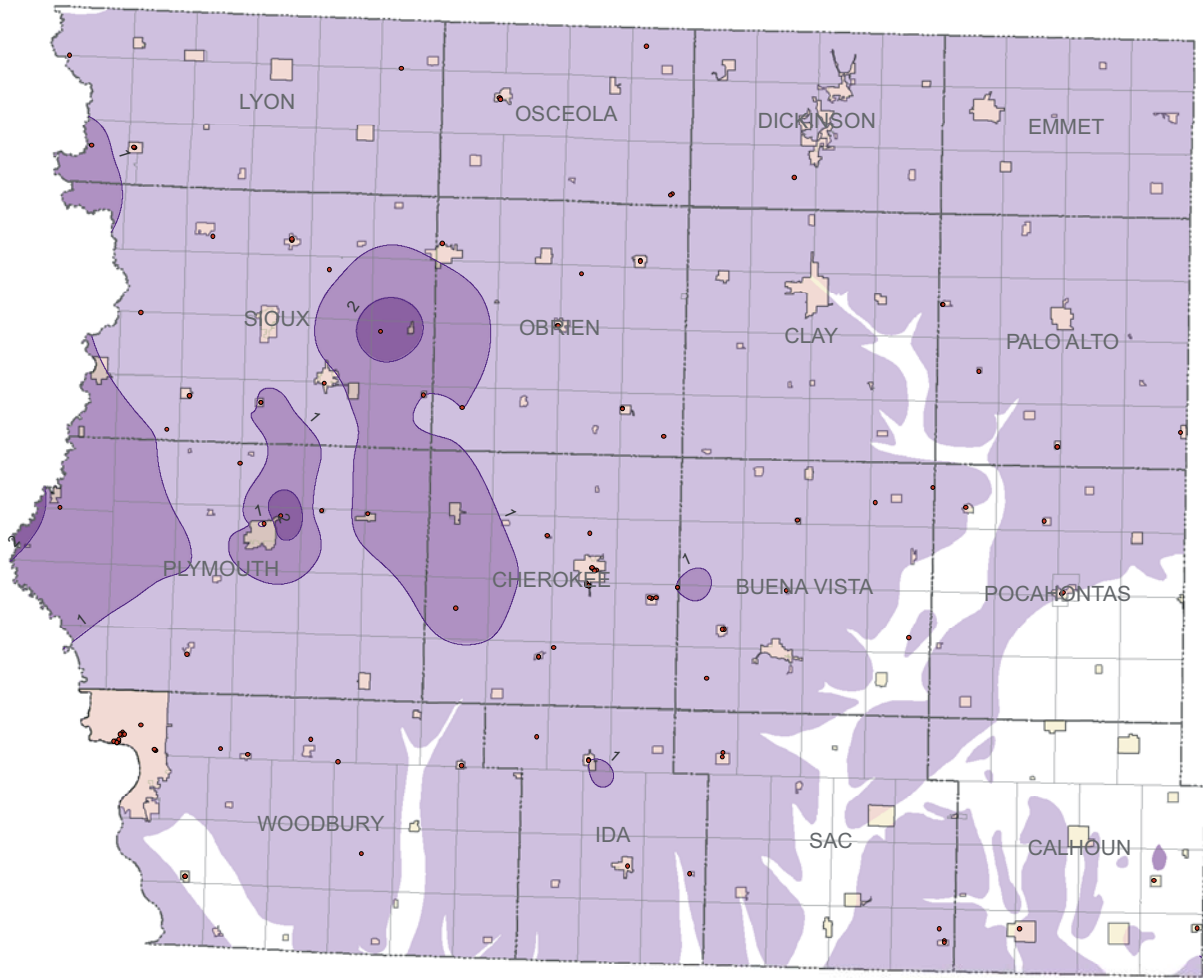
pH waters by exchange with hydroxyl ions (OH^-). Figure 12 shows the distribution of dissolved fluoride within the study area as being different than that of previously discussed constituents like TDS and sulfate. Fluoride concentrations are above the 4 mg/L MCL in small, localized areas in Sioux and Plymouth counties.

Sources of fluoride include tap water, toothpaste, infant formula, processed cereals, juice, soda, tea, beer, wine, mechanically deboned chicken, fish, seafood, Teflon pans, fluoridated salt and cigarettes. Excessive levels of fluoride can cause a number of health problems, such as neurotoxicity, cancer, changes in bone structure and mottling of teeth.

Fluoride can be reduced in drinking water by reverse osmosis, anion exchange and distillation. Adsorption by calcium phosphate, magnesium-hydroxide or activated carbon will also reduce the fluoride content of drinking water. Reverse osmosis will remove 93 to 95% of the fluoride.

Iron and manganese concentrations are difficult to assess because both constituents oxidize and precipitate readily in the presence of air. Unless special sampling procedures are used, the concentrations reported from water analyses can be very different from the concentrations found in the aquifer. In addition, iron dissolution from the well casing and distribution system can increase the iron content of the water.

Iron occurs naturally in groundwater in three forms: ferrous (Fe^{+2}) or clear waste iron, ferric (Fe^{+3}) or red water iron and heme ($\text{C}_{34}\text{H}_{32}\text{O}_4\text{N}_4\text{Fe}$) or organic iron. Each form can exist alone or in combination with others. Ferrous iron is often ferrous bicarbonate ($\text{Fe}(\text{HCO}_3)_2$). With this type of iron, the water is clear when drawn but then turns cloudy when it comes in contact with air, and the air oxidizes the ferrous iron and converts it to ferric iron. Ferric iron, or ferric hydroxide ($\text{Fe}(\text{OH})_3$), is visible in the water when drawn; hence the name "red water iron." Heme iron is organically bound iron complexed with decomposed vegetation. The organic materials complexed with the iron are called tannins or lignins. These organics cause the water to have a weak tea or coffee color. Certain types of bacteria use



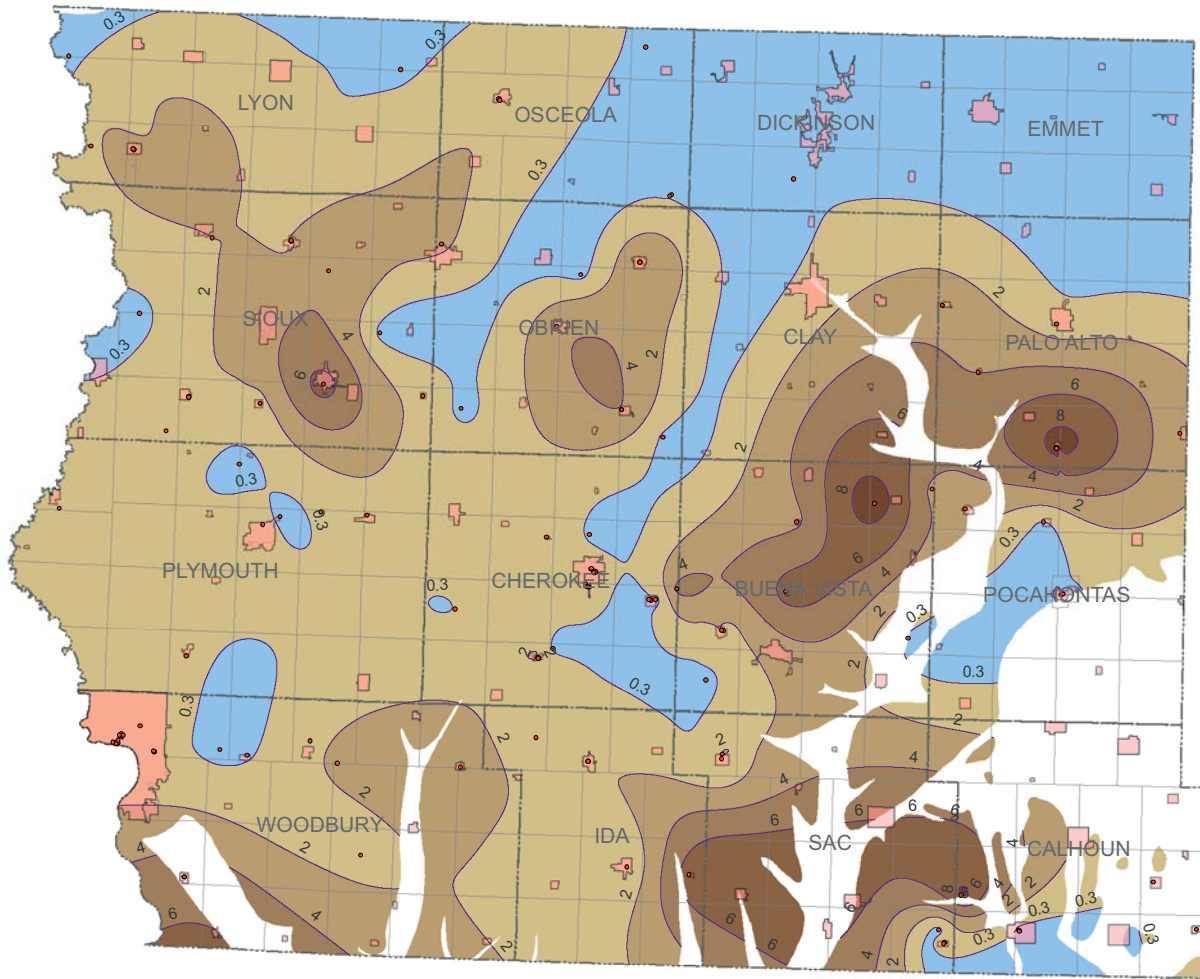
Legend

- Sampled wells (n = 120)
- Lines of equal dissolved fluoride concentration in milligrams per liter

Concentration of dissolved fluoride in water from the Dakota Aquifer in milligrams per liter

- < 1 Area where fluoridation of the water may be considered in order to increase the fluoride concentration to more desirable levels (0.8 to 1.2 mg/L) for public water supplies
- 1 - 2 Area where the fluoride concentration is less than the maximum recommended level (2.0 mg/L) for public water supplies
- > 2 Area where the fluoride concentration is greater than the maximum recommended level (2.0 mg/L) but less than the maximum contaminant level (4.0 mg/L) for public water supplies

Figure 12. Distribution of dissolved fluoride, in mg/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 124)
- Lines of equal dissolved iron concentration in milligrams per liter

Concentration of dissolved iron in water from the Dakota Aquifer in milligrams per liter

<p> < 0.3</p> <p> 0.3 - 2</p> <p> 2 - 4</p>	<p>Area where the dissolved iron concentration is less than the maximum recommended level (0.3 mg/L) for public water supplies</p>	<p> 4 - 6</p> <p> 6 - 8</p>	<p> > 8</p>
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Figure 13. Distribution of dissolved iron, in mg/L, in water from the Dakota Aquifer in northwest Iowa.

iron as an energy source and oxidize the iron from its ferrous state to its ferric state and deposit it in the slimy gelatinous materials that surround them. These bacteria grow in stringy clumps and are found in most iron bearing waters. They can cause infestation problems in wells and water distribution systems.

Figures 13 and 14 show the distribution of dissolved iron and manganese within the study area as being different from each other, as well as being different from that of the previously discussed constituents.

Dissolved iron concentrations are above the 0.3 mg/L MCL for iron throughout most of the study area, except for the northeast corner, while manganese concentrations are above the 0.05 mg/L MCL for manganese everywhere except for a few small, localized areas.

In low concentrations, iron and manganese are not hazardous to health, but are considered secondary or aesthetic contaminants. Small amounts of iron are essential for good health, as it helps transport oxygen in the blood. In the United States, tap water supplies approximately 5% of the dietary requirement for iron.

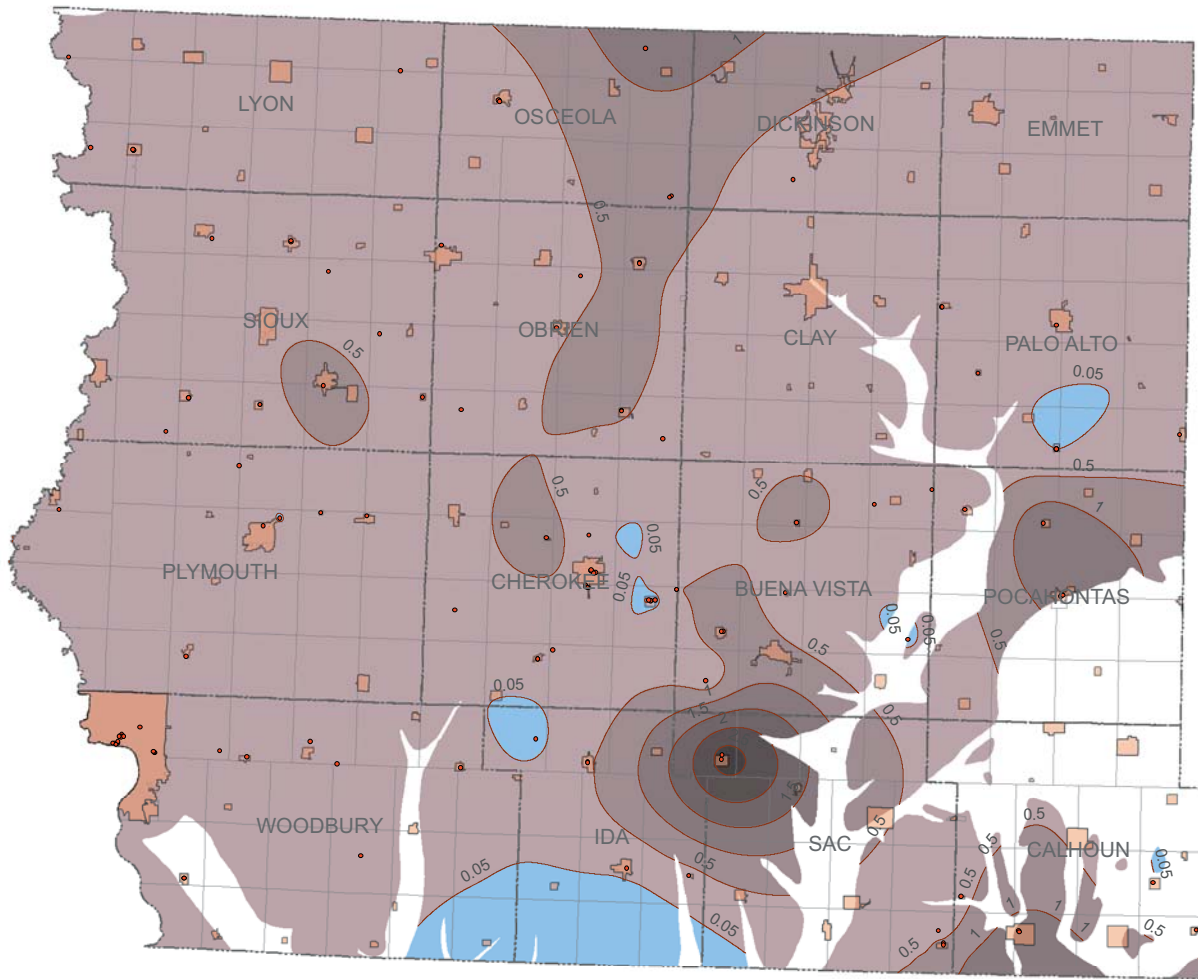
Manganese (Mn^{+4} , Mn^{+2}) is present in many soils and sediments as well as in rocks whose structures have been changed by heat and pressure. It is used in the manufacture of steel to improve corrosion resistance and hardness, and is considered essential to plant and animal life. Manganese is known to be important in building strong bones and may be beneficial to the cardiovascular system. It may be found in deep well water at concentrations as high as 2 to 3 mg/L, and is hard to treat because of the complexes it can form which are dependent on the oxidation state, pH, bicarbonate-carbonate-OH ratios and the presence of other minerals, particularly iron.

Fine-grained sediments in the Dakota Aquifer and overlying rocks often contain pyrite (FeS_2). This weathers to produce dissolved iron and sulfate. The iron can then oxidize and precipitate as iron oxide (FeO) and oxyhydroxide ($FeOOH$) which produces the red to orange coloration commonly occurring in Dakota strata. The solution from pyrite weathering is acidic and dissolves

additional calcite in a natural neutralization process. These processes increase the calcium and sulfate concentrations dissolved in Dakota waters. Rocks overlying the aquifer such as the Graneros Shale often contain gypsum ($CaSO_4 \cdot 2H_2O$), which is very soluble. Water passing through these rocks can have relatively high concentrations of calcium and sulfate from dissolving the gypsum, substantially increasing the calcium and sulfate content of waters in the upper aquifer.

Within the study area, dissolved iron concentrations range from less than 0.3 to about 9 mg/L, while manganese concentrations range from less than 0.05 to nearly 3 mg/L. The greater concentrations occur in two types of environments. One is in the outcrop or subcrop area of the Dakota Aquifer where recharge with dissolved oxygen reaches strata containing pyrite. As mentioned, the oxidation of pyrite is a source of sulfate and dissolved iron in groundwater. These waters can have a pH between 6 and 7, which is very slightly acidic. The other environment exists where reactions with dissolved constituents and sediments have essentially completely consumed dissolved oxygen and produced a chemically reducing environment. This commonly occurs in the confined portion of the aquifer because the water is ancient and no recent recharge with significant oxygen can enter. The reducing environment allows iron, manganese and some other heavy metals to dissolve from the sediments. These waters can sometimes have a high enough hydrogen sulfide (H_2S) content to give a "rotten egg" odor. Ammonium ion (NH_4^+) levels can be over 1 mg/L in the reducing environment.

Concentrations of iron and manganese greater than their MCLs may cause deposits and staining of clothing and plumbing fixtures. The stains are dark brown to black in nature. The use of chlorine bleach in the laundry can cause the stains to set. The chemistry of manganese in water is similar to that of iron. High levels of iron or manganese in water can also produce an unpleasant odor and taste. Organic materials can tie up manganese in the same manner as iron; therefore destruction of the organic matter is a necessary part of manganese removal.



Legend

- Sampled wells (n = 123)
- Lines of equal dissolved manganese concentration in milligrams per liter

Concentration of dissolved manganese in water from the Dakota Aquifer in milligrams per liter

<p> < 0.05</p> <p> 0.05 - 0.5</p> <p> 0.5 - 1.0</p>	<p>Area where the dissolved manganese concentration is less than the maximum recommended level (0.05 mg/L) for public water supplies</p>	<p> 1.0 - 1.5</p> <p> 1.5 - 2.0</p>	<p> 2.0 - 2.5</p> <p> > 2.5</p>
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Figure 14. Distribution of dissolved manganese, in mg/L, in water from the Dakota Aquifer in northwest Iowa.

Ferrous iron can be removed with a softener, provided it is less than 0.5 mg/L for each grain of hardness and the pH of the water is greater than 6.8. If the ferrous iron is more than 5.0 mg/L, it must be converted to ferric iron by contact with an oxidizing agent such as chlorine, before it can be removed by mechanical filtration. Heme iron can be removed by an organic scavenger anion resin or by oxidation with chlorine followed by mechanical filtration. Oxidizing agents such as chlorine will also kill iron bacteria if it is present.

The temperature of groundwater remains relatively constant throughout the year. Groundwater temperature depends primarily on depth, and aside from places with geothermal activity, the temperature of groundwater within a hundred feet of the land surface is about the same as a region's mean annual air temperature. In Iowa, this ranges from about 48 degrees Fahrenheit (°F) or 9 degrees Celsius (°C) in northern Iowa to about 52 °F or 11 °C in southern Iowa. In general, the deeper the well, the warmer the water, and in the Midwest, the groundwater temperature increases about 1.4 °F for every hundred feet of depth. This rate of increase is known as the geothermal gradient. The temperature of groundwater is important for industrial users as well as for geothermal heating and cooling applications.

Figure 15 shows the distribution of temperature, in °C, of water from the Dakota Aquifer. Within the study area, temperatures range between 6 and 14°C.

Radioactivity and Groundwater

Radioactivity is the process whereby unstable atomic nuclei, or radionuclides, release energetic subatomic particles. There are three major types of radiation that may be released: alpha particles, beta particles and gamma rays. These are positively charged, negatively charged and neutral, respectively. Natural radiation comes from cosmic rays from space and naturally occurring radioactive materials that exist in rocks, soil, food, water and air in our environment. Human exposure to radioactivity is sometimes measured in rads, where one rad

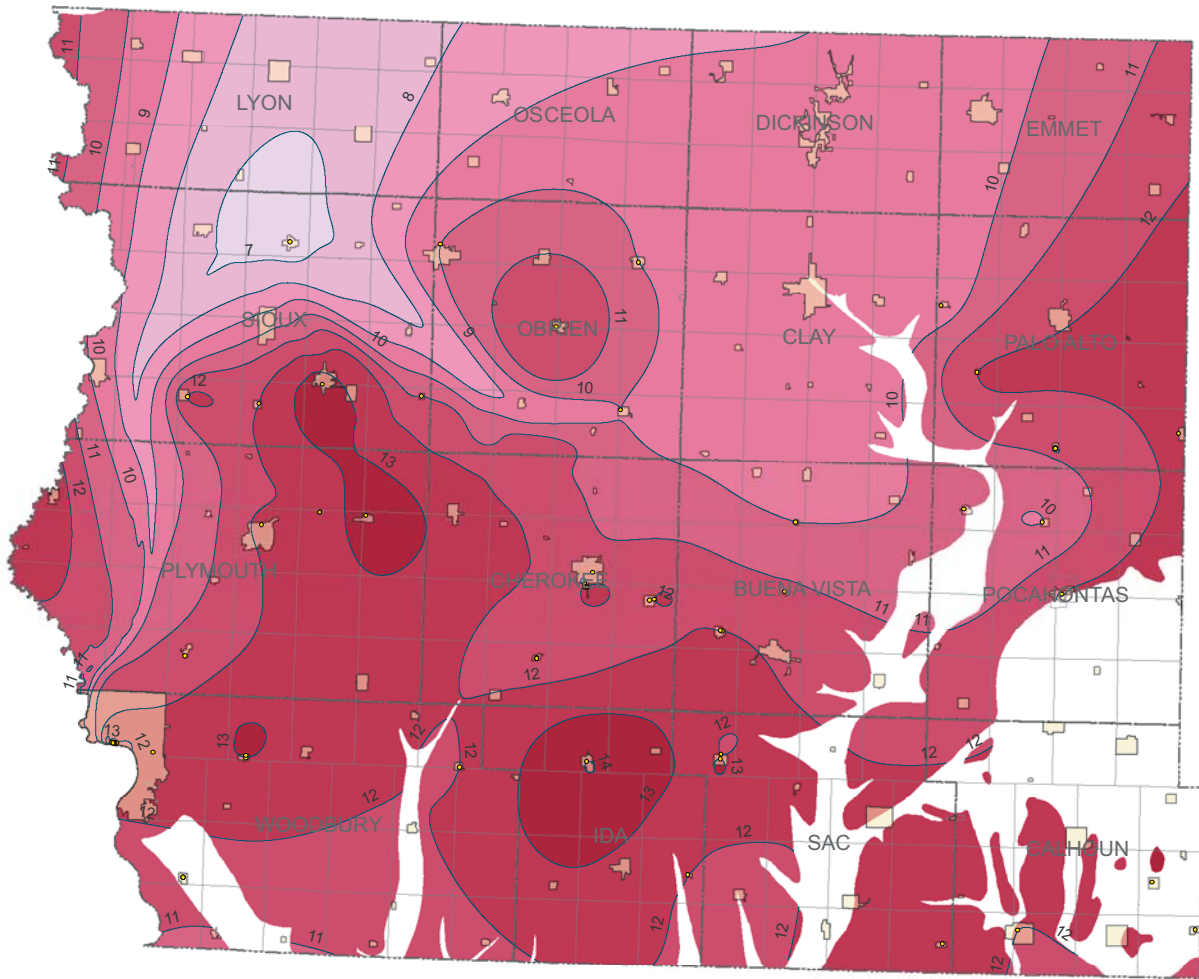
represents 0.01 joule of energy absorbed per kilogram of tissue.

Radium (Ra) is a radioactive metal that occurs naturally in trace amounts in rocks, soils and groundwater. As radium decays, it continually releases energy in the form of alpha particles, beta particles and gamma rays, as well as radon (Rn) gas, which are part of the natural radiation to which all life is exposed. Radium readily dissolves in groundwater, especially in areas where acidic conditions (low pH levels) occur. Radioactive decay is often measured in picocuries (pCi), where one pCi is equivalent to 0.037 nuclear disintegrations per second.

Within the study area, fewer samples have been analyzed for radionuclides than for other constituents, in part, because radionuclides are often analyzed using a screening procedure. For samples in the data set from a joint USGS-IGWS water quality study, when gross alpha activity exceeded 5 pCi per liter (pCi/L), an equivalent sample was analyzed for radium-226 (Ra²²⁶). Then, if the radium-226 concentration exceeded 3 pCi/L, an equivalent sample was analyzed for radium-228 (Ra²²⁸). Within the entire general data set, there were 17 samples analyzed for tritium (³H), 24 samples for radon-222 (Rn²²²), 36 samples for radium-228, 73 samples each for gross alpha and gross beta activity and 152 samples were analyzed for radium-226. The accuracy of contouring of the radionuclide maps in this report, especially those based on fewer well samples, would benefit from a larger and better distributed data set.

Most radionuclides in groundwater result from contact of the water with rocks. The content of these elements in groundwater and hence the levels of radioactivity depend on a combination of several factors, including the concentrations of these elements in the aquifer rocks, chemical reactions and the physical processes of decay, along with the flow rate and age of the groundwater.

One factor determining the occurrence of radioactivity in groundwater is geology. Abundance of parent elements of the decay products is typically associated with high activity of one or several radionuclides in the associated groundwater. Sedimentary rocks, such as shale and phosphate,



Legend

- Sampled wells (n = 54)
- Lines of equal water temperature in °C

Temperature in °C of water from the Dakota Aquifer



Figure 15. Distribution of temperature, in °C, of water from the Dakota Aquifer in northwest Iowa.

are predominantly enriched in uranium (U) and thus the decay product of the uranium decay chain, radium-226, characterizes the associated groundwater. Similarly, rocks such as granite are enriched in uranium and thorium (Th), so associated groundwater contains their decay products, radium-226 and radium-228.

A factor that controls mobilization of radionuclides from aquifer rocks is the chemical condition of the groundwater, which can result in significant leaching of these elements into groundwater. In particular, levels of acidity (pH), salinity, temperature and oxidation of groundwater affect radionuclide mobilization. In addition, the geochemical properties of each radionuclide determine its availability in water. Radium, for example, can be kept out of groundwater by sorption onto clay minerals, precipitation with secondary minerals and radioactive decay. Many studies have shown that an exchange reaction with clay minerals is the predominant process that controls radium activity in low-saline groundwater.

High radium levels in wells in some agricultural areas have been associated with agricultural recharge, which induces nitrification and reduces pH (Vengosh, 2006). This enhances the extraction of radium from exchange sites on clay minerals, and consequently increases the radium levels in the associated groundwater. Since pollution from nitrate is one of the most frequent forms of groundwater contamination worldwide, additional side effects, such as the formation of acidic water and the rise of radionuclides in groundwater, may have severe consequences in the future.

Many studies have shown that salinity also plays a major role in radium distribution. Groundwater from aquifers in parts of the Midwest shows an almost linear correlation between radium-226 and salinity (Vengosh, 2006). Generally, in freshwater conditions, most of the radium remains in the aquifer rocks, while in saline conditions the radium escapes from the rocks and results in high concentrations in groundwater.

Other studies have shown that groundwater with no oxygen is typically enriched in radium. The increased radium activity in oxygen-free water is thought to come from the mobilization of

manganese (Vengosh, 2006). With oxygen present, radium strongly bonds to manganese oxide, but in oxygen-free conditions, manganese oxide is no longer stable, and both radium and manganese are released into the associated groundwater.

Temperature is also an important factor that enhances radium leaching from rocks, and since temperature increases with depth, deeper wells generally have greater radium concentrations, if parent materials are present. In addition, because radium leaching from rocks is enhanced by both temperature and salinity, mineralized thermal springs that are used as a source of bottled mineral water may have high concentrations of radium.

The final factors affecting the movement of radionuclides into groundwater are the age of the groundwater and the physical relationship between the decay rates of the radionuclides and the flow rate of the groundwater. In general, older groundwater has been in contact with the geologic parent materials longer, allowing more time to accumulate radioactive decay products. In like manner, slower groundwater flow rates encourage greater enrichment of both short- and long-lived radionuclides, since slower moving groundwater is in contact with the radionuclides longer.

Isotopes are forms of the same element that have different numbers of neutrons in the nucleus. Tritium is the common name for hydrogen-3 (^3H), which is a radioactive isotope of hydrogen (H). Like ordinary hydrogen (^1H) and deuterium (^2H), tritium has a single proton in its nucleus. Unlike ordinary hydrogen, deuterium has one neutron and is stable, while tritium contains two neutrons and is unstable. Tritium decays spontaneously to helium-3 (^3He) through ejection of a beta particle and has a half-life of 12.32 years. Tritium behaves like ordinary hydrogen and can replace it in water molecules so it readily cycles through hydrologic and biologic components of the environment.

The unit of measure of tritium in water is the tritium unit (TU), which equals 1 tritium atom in 10^{18} hydrogen atoms. In picocuries per liter (pCi/L), 1 TU is 3.19 pCi/L. Tritium occurs in very small quantities naturally, as it is produced

in the upper atmosphere by cosmic rays. Natural levels of tritium in precipitation are on the order of 1 to 5 TU or about 3.2 to 16 pCi/L. Nuclear-weapons testing during the 1950s and 1960s created relatively large amounts of tritium in the atmosphere, so tritium can be used to estimate whether groundwater has been recharged before or after about 1953. The amount of tritium in infiltrating precipitation that becomes groundwater recharge is controlled primarily by the amount of tritium in the atmosphere when the precipitation formed, plus the length of time it takes for water to move from the land surface into an aquifer. Because tritium decays with a half-life of 12.32 years, groundwater that does not contain detectable tritium is inferred to have infiltrated into the subsurface prior to 1953. Conversely, groundwater that contains detectable tritium is inferred to contain at least some water that infiltrated after 1953. Because tritium is decaying rapidly, it is becoming more difficult to use bomb tritium to date the age of groundwater; however, scientists can also use the ratio of tritium to its decay product helium-3 (^3He) to date groundwater (the time since the water last equilibrated with the atmosphere). The $^3\text{H}/^3\text{He}$ dating method can be used to date groundwater recharged within the past 30 years.

Figure 16 shows the distribution of tritium in water from the Dakota Aquifer in northwest Iowa. Within the study area, the only detected concentrations of tritium above 10 pCi/L were from Sioux City River No. 2 (W-4291) at 39.7 pCi/L, Sioux City River No. 8 (W-42501) at 31.7 pCi/L and Sioux City River No. 3 (W-4292) at 16.4 pCi/L. These wells are all located very near the Missouri River, in an area where the alluvial sands and gravels associated with the river directly overlie the Dakota Aquifer. It is probable that the aquifer is receiving relatively rapid recharge of tritiated water from the overlying alluvium in this area. The next highest tritium concentrations were found in Aurelia City Well No. 2 (W-696) at 1.9 pCi/L and Aurelia City Well No. 3 (W-36215) at 1.2 pCi/L.

The small data set for tritium suggests that within the study area, most parts of the aquifer are being recharged by infiltration from precipi-

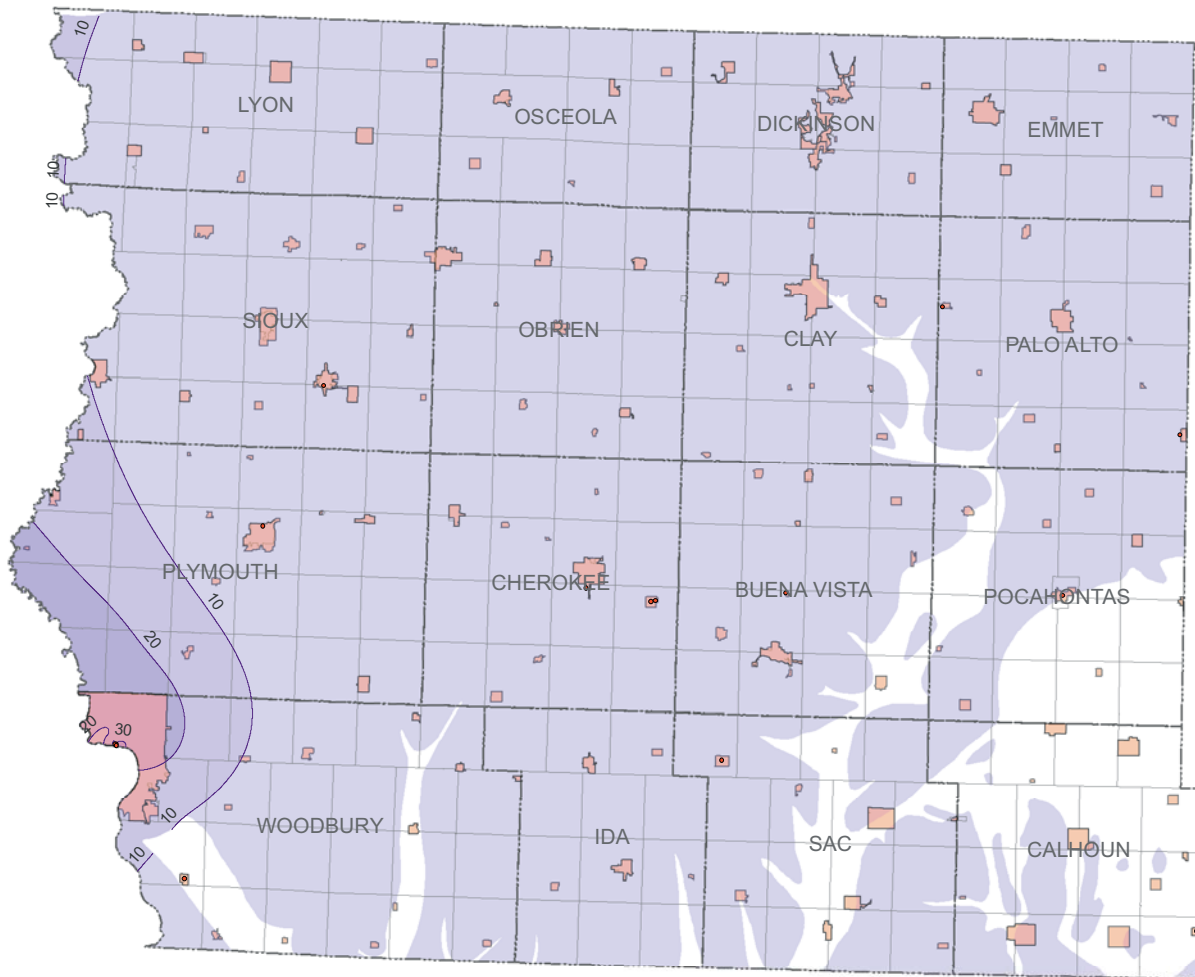
tation that occurred prior to nuclear-weapons testing in the 1950s and 1960s.

Tritium's main commercial uses include medical diagnostics and sign illumination, especially "EXIT" signs. However, commercial tritium use accounts for only a small fraction of the tritium used worldwide. Tritium's primary function is to boost the yield of both fission and thermonuclear weapons.

Tritium's short half-life and low concentration in nature necessitates artificial production. However, due to safety and health concerns, the Department of Energy (DOE) has not had an operating tritium production facility since 1988. Even at low levels, tritium has been linked to developmental and reproductive problems, genetic abnormalities and other health problems in laboratory animals. There is also evidence of adverse health effects on populations near facilities which utilize it. Tritium most commonly enters the environment in gaseous form (T_2) or as a replacement for one of the hydrogen atoms in water (HTO). This tritiated water can replace ordinary water in human cells, and once it is in living cells, it can replace hydrogen in organic molecules in the body. Thus, despite tritium's low radiotoxicity in gaseous form and its tendency to pass out of the body rapidly as water, its health effects are made more severe by its property of being chemically identical to hydrogen. Currently there is a 20,000 pCi/L MCL for tritium.

As discussed, radon (Rn) is a naturally occurring gaseous radioactive element formed by the atomic disintegration of radium. It is estimated to cause thousands of deaths each year by people breathing it, and is the second leading cause of lung cancer in the United States. Radon-222 (Rn^{222}) is one of the radionuclides of most concern when found in drinking water.

Figure 17 shows the distribution of radon-222 in water from the Dakota Aquifer in northwest Iowa. Within the study area, radon-222 concentrations range from 20 to about 400 pCi/L, remaining well below the EPA's 4,000 pCi/L MCL for radon-222. Nine of the twenty-four samples analyzed were above the 10 pCi/L detection limit for radon-222.



Legend

- Sampled wells (n = 15)
- Lines of equal tritium concentration in picocuries per liter

Concentration of tritium in water from the Dakota Aquifer in picocuries per liter

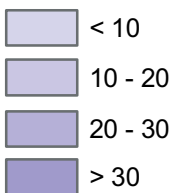


Figure 16. Distribution of tritium, in pCi/L, in water from the Dakota Aquifer in northwest Iowa. The extent of water with tritium concentrations greater than 10 pCi/L is probably exaggerated by the contouring of the small data set. The actual extent is most likely limited to areas where the Dakota is rapidly recharged by Missouri River alluvium.

Radon comes from the natural decay of radium that is found in nearly all soils. A geochemical survey of Iowa that was conducted in cooperation with the USGS shows that from 1,063 shallow soil samples collected across Iowa, the average concentrations of uranium and thorium, the parent compounds of radium, were 50 and 11.4 ppm, in turn.

Radon gas typically moves up through the ground to the air above and into buildings through cracks and holes in foundations. The radon becomes trapped in buildings where it can build up. Any building may have a radon problem, and of the two main sources for radon in a building's indoor air, the radon entering a building through the soil is usually a much greater risk compared with the radon that may enter the building through tap water.

The entire state of Iowa is considered to have a predicted average indoor radon screening level of greater than 4 pCi/L (epa.gov/radon/zone-map/iowa.htm), so most homes in Iowa should be tested for radon, and if a test shows levels greater than 4 pCi/L, a second test should be performed. Testing for radon is relatively easy and inexpensive.

There are several methods to reduce radon in a home, but the one primarily used is a vent pipe system and fan, which pulls radon from beneath a house and vents it to the outside (www.epa.gov/radon001/pubs/citguide.html). This system, known as a soil suction radon reduction system, does not require major changes to a home. Sealing foundation cracks and other openings makes this kind of system more effective and cost-efficient. If radon is entering a home through tap water, the radon can be easily removed from the water by aeration or carbon filtration.

Alpha particles are a type of ionizing radiation ejected by the nuclei of some unstable atoms. They are large subatomic fragments consisting of 2 neutrons and 2 protons with a charge of +2. Elements that emit alpha particles include actinium (Ac), americium-241 (Am^{241}), plutonium-236 (Pu^{236}), uranium-238 (U^{238}), thorium-232 (Th^{232}), radium-226, radon-222 and polonium-210 (Po^{210}). Since the number of protons in the nucleus of an

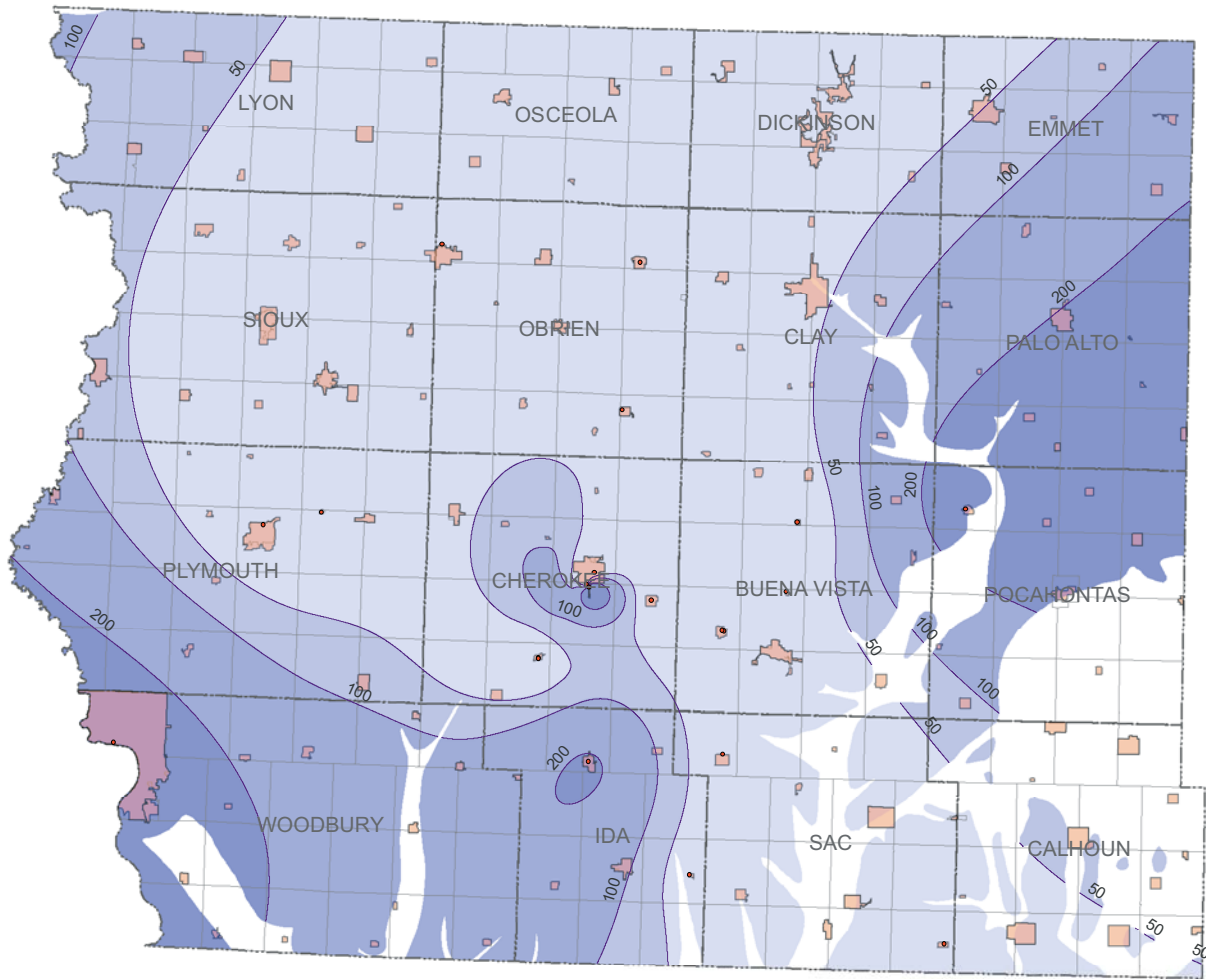
atom determines the element, the loss of an alpha particle changes the parent atom to a different element. Most alpha emitters occur naturally in the environment.

Figure 18 shows the distribution of gross alpha particles in water from the Dakota Aquifer in northwest Iowa. Within the study area, gross alpha particles were detected in sixty-five of seventy-three samples, with concentrations ranging from less than 1 to 44 pCi/L. Six samples were above, and one equaled, the 15 pCi/L MCL for gross alpha particles.

An analysis from Ireton City Well No. 3 (W-2310) showed the highest concentration of gross alpha particles at 44 pCi/L, followed by four analyses from West Bend City Well No. 2 (W-3595) at 31, 20, 17 and 16 pCi/L, and an analysis from Holstein City Well No. 2 (W-5120) at 25 pCi/L. The gross alpha particle concentration equaled the 15 pCi/L MCL in an analysis from Sioux City River No. 2 (W-4291). After all of the analyses were averaged for plotting, the average gross alpha particle concentration for the West Bend well was reduced below the MCL to 13.4 pCi/L because a single non-detection, combined with the four other analyses, lowered the average.

Most naturally occurring radioactive elements emit alpha particles as they decay. As mentioned, gross alpha activity is often used as a less expensive screening tool for determining the level of radium in drinking water. The detection of alpha particles in well water signals the presence of specific radioactive substances, and in the Midwest, it is often radium. There are other radioactive substances besides radium that may contribute to the gross alpha radiation in water, but analyses for these substances are usually not necessary because they are much less common locally.

The results of a gross alpha test can be used to determine if additional tests for radionuclides are needed. If short-term gross alpha test concentrations are less than 5 pCi/L, then no additional tests are needed because the water meets safety requirements. Whenever test concentrations exceed 5 pCi/L, but are less than 15 pCi/L, then combined radium tests may be needed, and in the



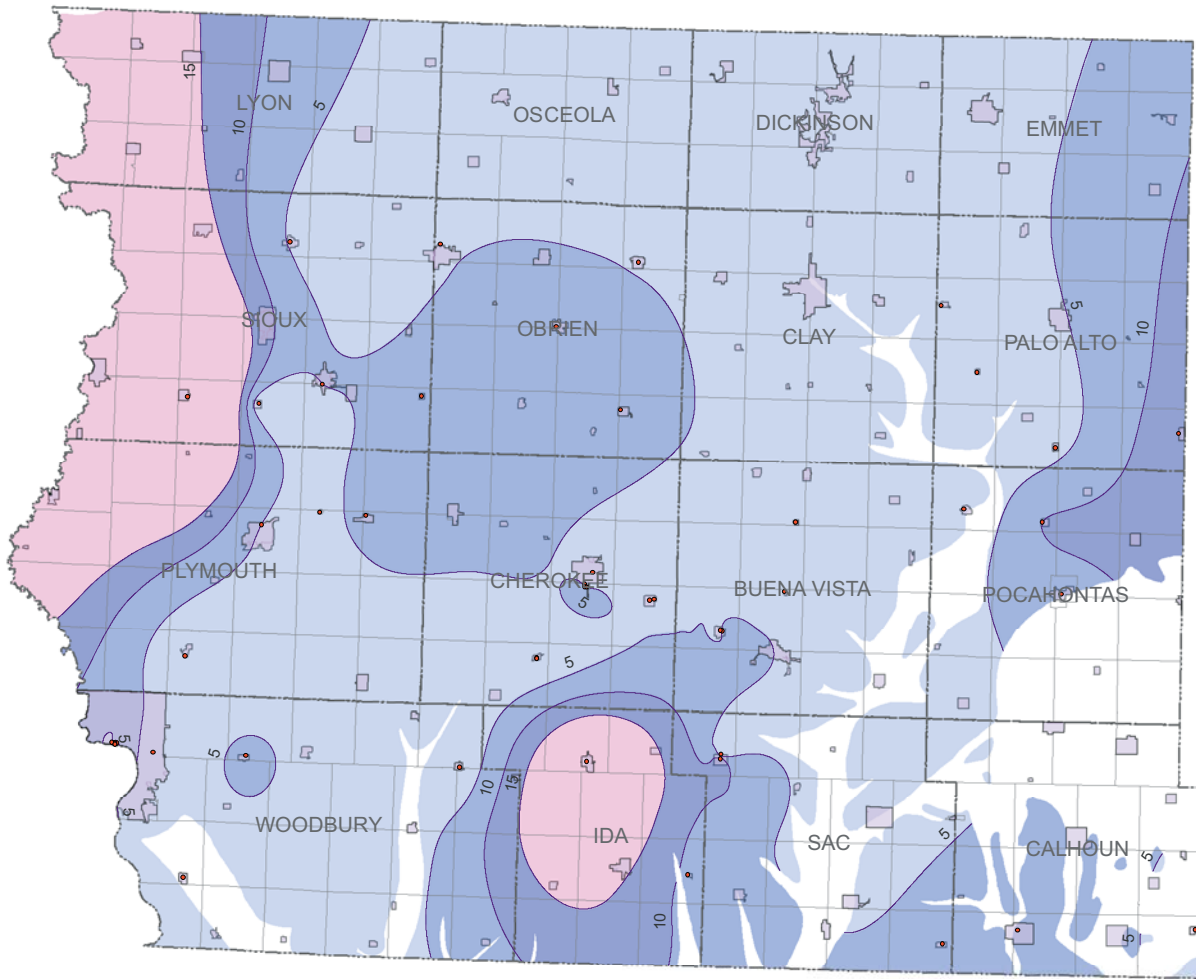
Legend

- Sampled wells (n = 21)
- Lines of equal radon-222 concentration in picocuries per liter

Concentration of radon-222 in water from the Dakota Aquifer in picocuries per liter

	< 50	The maximum contaminant level for radon-222 concentration for public water supplies is 4,000 picocuries per liter
	50 - 100	
	100 - 200	
	> 200	

Figure 17. Distribution of radon-222, in pCi/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 48)
- Lines of equal gross alpha particle concentration in picocuries per liter

Concentration of gross alpha particles in water from the Dakota Aquifer in picocuries per liter

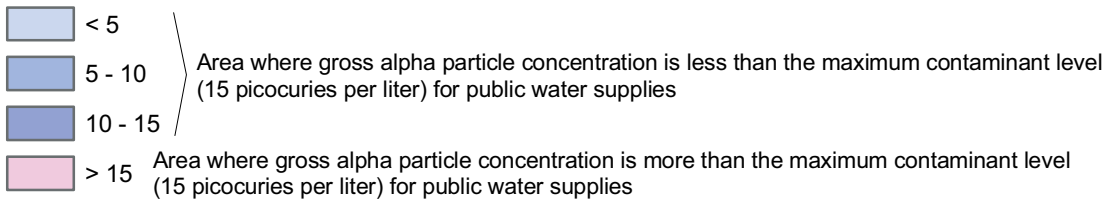


Figure 18. Distribution of gross alpha particles, in pCi/L, in water from the Dakota Aquifer in northwest Iowa.

event that short-term gross alpha activity exceeds 15 pCi/L, the result indicates an exceedance of the MCL for gross alpha particles and suggests that further testing for specific alpha emitters should be conducted.

External exposure to alpha particles is of far less concern than internal exposure, because alpha particles can not penetrate the outer layer of dead skin. However, if alpha emitters are inhaled, ingested or absorbed into the blood stream, sensitive tissue can be exposed to alpha radiation. The resulting biological damage increases the risk of cancer. In particular, alpha radiation is known to cause lung cancer in humans when alpha emitters are inhaled. The greatest exposure to alpha radiation for most people comes from the inhalation of radon and its decay products, several of which also emit alpha radiation.

Beta particles are subatomic particles that are ejected from the nucleus of some radioactive atoms. They are equivalent to electrons and have a charge of -1, but unlike electrons, which originate outside of the nucleus, beta particles originate in the nucleus. Elements that emit beta particles include tritium (^3H), cobalt-60 (Co^{60}), strontium-90 (Sr^{90}), technetium-99 (Tc^{99}), iodine-129 and -131 (I^{129} and 131) and cesium-137 (Cs^{137}). A geochemical survey of Iowa that was conducted in cooperation with the USGS shows that from 1,063 shallow soil samples collected across Iowa, the average concentrations of cobalt and strontium were 9.5 and 132 ppm, respectively.

While beta particles are emitted by atoms that are radioactive, the beta particles themselves are not radioactive. It is their energy, in the form of speed that causes harm to living cells. When transferred, this energy can break chemical bonds and form ions. Beta particle emissions occur when the ratio of neutrons to protons in a nucleus is too high. Scientists think that an excess neutron transforms into a proton and an electron, and the proton stays in the nucleus while the electron is ejected. Since the number of protons in the nucleus of an atom determines the parent element, the conversion of a neutron to a proton changes the radionuclide to a different element.

There are both natural and anthropogenic ra-

dionuclides that emit beta particles. Potassium-40 (K^{40}) and carbon-14 (C^{14}) are weak beta emitters that are found naturally in the human body. Some decay products of radon also emit beta particles, but its alpha-emitting decay products pose a much greater health risk.

Like gross alpha activity, gross beta activity can be used as a less expensive screening tool for determining the level of radionuclides in drinking water. The detection of beta particles in well water signals the presence of specific radioactive substances. If short-term gross beta test levels are less than 5 pCi/L, then no additional tests are needed because the water meets safety requirements. In the event that beta particle test levels exceed 5 pCi/L, but are less than 50 pCi/L, then testing for specific beta emitters may be needed, and whenever short-term gross beta activity exceeds 50 pCi/L in a public water supply, the sample must be analyzed for major radioactive constituents.

Figure 19 shows the distribution of gross beta particles in water from the Dakota Aquifer in northwest Iowa. Within the area, gross alpha particles were detected in seventy-two of seventy-three samples, with concentrations ranging from less than 1 to 35.5 pCi/L. None of the samples exceeded the 50 pCi/L screening level for major radioactive constituents.

Direct exposure to beta particles can redden or burn the skin. However, emissions from inhaled or ingested beta particle emitters are of much greater concern. Beta particles released directly into living tissue can cause damage at the molecular level and can disrupt cell function. Because they are much smaller and have less charge than alpha particles, beta particles generally travel further into tissues and, as a result, the cellular damage is more dispersed. Beta radiation can cause both acute and chronic health effects, although acute exposures are uncommon. The chronic effects result from low-level exposure over a long period of time (5 to 30 years), with the main chronic health effect from radiation being cancer. When taken internally beta emitters can cause tissue damage and increase the risk of cancer, with the risk increasing with increasing dosage.

The MCL for gross beta particle levels in drinking water is based on millirems per year (mrem/yr), rather than pCi/L. A millirem is a unit of absorbed radiation dose. The risk associated with a radiation dose of one millirem is about a 1 in 8 million risk of dying of cancer if large dose effects extrapolate linearly to zero. The loss in life expectancy from a 1 millirem dose is about 1.2 minutes. To convert a dosage exposure from a specific radionuclide measured in pCi/L, the Nuclear Regulatory Commission (www.nrc.gov/) publishes tables which provide estimates of the number of millirems harmful to various organs of the human body which will be given off by every picocurie of a variety of radioactive substances actually eaten. Currently the MCL for gross beta particles is 4 mrem/yr.

Softening, anion exchange, acid neutralization and cation exchange are methods used to remove gross alpha and gross beta particles from drinking water.

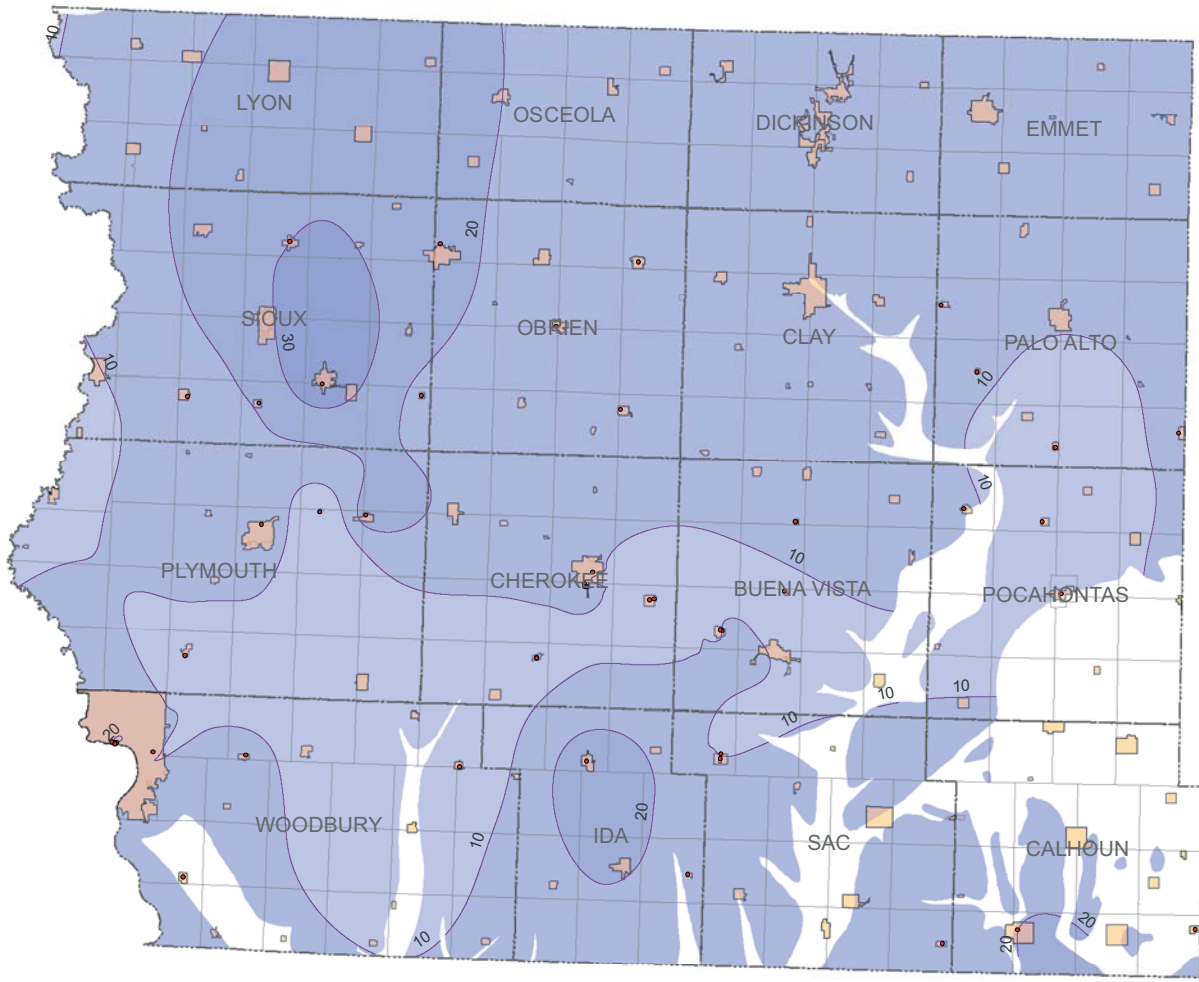
As discussed, radium is a decay product of uranium (U) or thorium (Th). It is over one million times more radioactive than the same mass of uranium and has 25 different known isotopes. Four of these isotopes, radium-223 (Ra^{223}), radium-224 (Ra^{224}), radium-226 (Ra^{226}) and radium-228 (Ra^{228}), are found in nature, with radium-226 being the most common. Radium-226 is a product of uranium-238 (U^{238}) decay and is formed when the nucleus of a helium atom (an alpha particle) is emitted from the nucleus of a decaying thorium-230 (Th^{230}) nuclide. It is the longest-lived isotope of radium with a half-life (amount of time it takes for half of the atoms in a sample to decay) of 1,602 years. The next longest-lived isotope is radium-228, a product of thorium-232 (Th^{232}) breakdown by the emission of an alpha particle. It has a half-life of 6.7 years. Radium-226 decays by the emission of an alpha particle to radon-222 (Rn^{222}), while radium-228 decays by the emission of an electron (beta particle) to actinium-228 (Ac^{228}).

Radium was formerly used in self-luminous paints for watches, nuclear panels, aircraft switches, clocks and instrument dials. Unfortunately, many watch dial painters died from the radium that had become stored in their bones. Soon after

this, the adverse effects of radioactivity became widely known, although radium was still used in dials as late as the 1950s. Recently, tritium (^3H), cobalt-60 (Co^{60}) and cesium-137 (Cs^{137}) have replaced radium in many applications because they are more powerful emitters, safer to handle, and are available in more concentrated form.

Because the human body metabolizes radium similar to the way that it metabolizes calcium, the ingestion of trace quantities of radium over time results in accumulation of radium in the skeleton. The radium that has accumulated in bone tissue decays into a series of short-lived daughter products, resulting in the emission of a number of alpha and beta particles over a short time span. As the radium and its daughter products decay, the produced energy can strip electrons from the atoms with which it collides. These electrons have a great capacity to break chemical bonds as they travel through living tissue, causing the release of additional electrons. The atoms in living tissue that lose electrons become ions at a high energy state, capable of producing chemical reactions that would not have been otherwise possible, resulting in damage to bones and other living tissue as well as to genetic material inside the tissue cells. In the end, the damage from continuous exposure to radium can potentially cause bone and sinus cancer.

Figure 20 shows the distribution of radium-226 in water from the Dakota Aquifer in northwest Iowa. Within the study area, radium-226 was detected in 142 of the 152 samples analyzed, with concentrations ranging from 0.1 to 15.2 pCi/L. Twenty of the analyses exceeded the 5 pCi/L MCL, which includes radium-226 and radium-228 combined, while two analyses, one from Cherokee City Well No. 10 (W-42300) and one from Sioux City Westside No. 20 (W-42500), showed radium-226 concentrations equal to the MCL. Seven of the exceedances, ranging from 5.1 to 10.2 pCi/L, occurred in water from Sioux City wells. Six exceedances, ranging from 11 to 13 pCi/L, were found in water from West Bend City Well No. 2 (W-3595). Three exceedances, ranging from 7.3 to 9.4 pCi/L, were from Holstein City Well No. 2 (W-5120), and two at 12 and 15.2



Legend

- Sampled wells (n = 48)
- Lines of equal gross beta particle concentration in picocuries per liter

Concentration of gross beta particles in water from the Dakota Aquifer in picocuries per liter

	< 10	If the average annual gross beta particle concentration exceeds 50 picocuries per liter in a public water supply, an analysis of the sample must be performed to identify the major radioactive constituents present
	10 - 20	
	20 - 30	The maximum contaminant level for gross beta particle concentration for public water supplies is 4 millirems per year
	> 30	

Figure 19. Distribution of gross beta particles, in pCi/L, in water from the Dakota Aquifer in northwest Iowa.

pCi/L occurred in water from Holstein City Well No. 1 (W-567). The two remaining exceedances of 5.8 and 6.1 pCi/L were sampled at Arthur City Well No. 4 (W-19840) and Milford City Well No. 1 (W-58628), respectively.

A study conducted in the mid-1970s of radium-226 and strontium-90 in well water from the Dakota Aquifer in Iowa documented a number of statistically high radium-226 concentrations scattered throughout the aquifer (pubs.er.usgs.gov). The study also found no correlation between radium-226 and other water quality parameters in water from the aquifer. The author proposed that the anomalous radium-226 concentrations and lack of correlation with other parameters may be due to the heterogeneity of materials in the aquifer, as well as local variations in the depositional environment of the aquifer. The large number of factors determining radioactivity in groundwater make interpretation of it difficult.

The USEPA estimates that the additional lifetime risk of cancer associated with drinking water that emits alpha-particle radiation at 15 pCi/L, or has a combined concentration of radium-226 and radium-228 of 5 pCi/L, is about 1 in 10,000. This means that if 10,000 people were to consume 2 liters of water containing 5 pCi/L of radium every day for 70 years, one additional fatal cancer would be expected in the 10,000 people exposed.

For public water supplies, if the average gross alpha particle activity of quarterly samples exceeds 5 pCi/L, testing for radium-226 and radium-228 is required. If the average gross-alpha particle activity in all samples is greater than 15 pCi/L, or if the combined concentration of radium-226 and radium-228 exceeds 5 pCi/L, the water system must be monitored quarterly for an extended period. Public water-supply systems that exceed radium or gross alpha standards are required to notify consumers on a quarterly basis.

Figure 21 shows the distribution of radium-228 in water from the Dakota Aquifer in north-west Iowa. Within the study area, radium-228 was detected in 12 of the 48 samples analyzed,

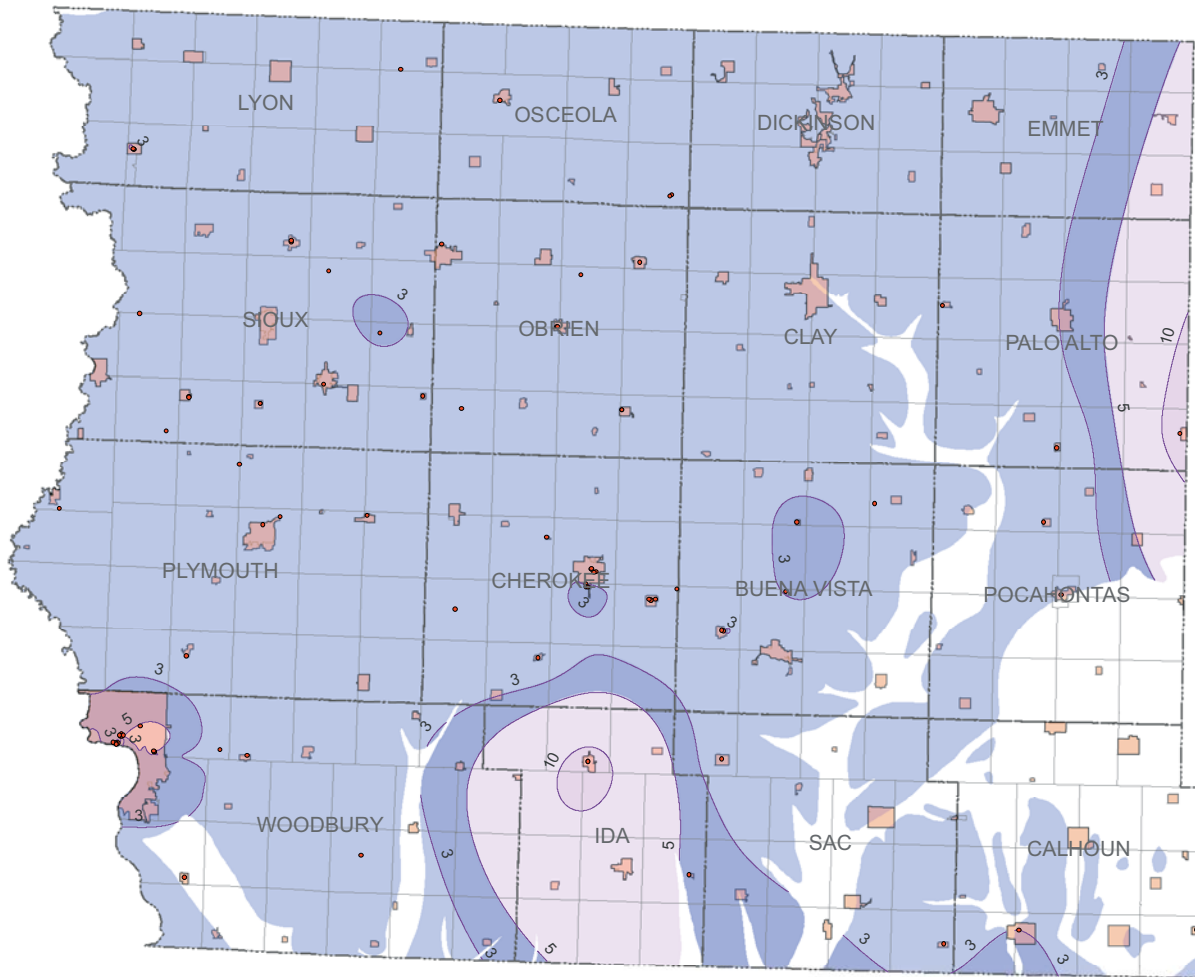
with concentrations ranging from 1 to 6 pCi/L. Two of the analyses exceeded the 5 pCi/L MCL for radium-226 and radium-228 combined. Both exceedances equaled 6 pCi/L, with one occurring in water from Hinton City Well No. 4 (W-40217), and the other occurring in water from Salix City Well No. 2 (W-41741). Because of the much shorter half-life, radium-228 is much less persistent in groundwater than radium-226.

Unlike radium-226, which poses a health hazard due to its long half-life, radium-228 poses a long-term hazard only if its parent, thorium-232, is present to provide a continuous supply of radium-228. If either isotope is swallowed in water or with food, most of it will quickly leave the body as waste, but some of it will enter the blood and be taken to all parts of the body, particularly to the bones. Small amounts of radium that are not deposited in bones will leave the body every day through waste. The inhalation risk from both isotopes is associated primarily with their decay products, radon and its short-lived daughters. Radon-222 is a decay product of radium-226, while radon-220 is a decay product of radium-228. The primary health hazard associated with radon is from inhalation of its short-lived decay products, alpha particles, which readily attach to dust particles.

Final Comments

The chemical characteristics of groundwater are determined by factors such as the mineral content of the soil and aquifer materials through which the water passes, the rate of groundwater movement, the length of time that water remains in an aquifer, the chemistry of the water when it was trapped during sediment deposition, the chemical and physical changes that take place in aquifer materials after they are deposited and the mixing of groundwater in an aquifer with water from adjacent hydrogeologic units and/or water from the land surface.

The quality of groundwater often refers to the type and concentration of dissolved substances in the water. As discussed, these substances may be naturally occurring or anthropogenic, from point



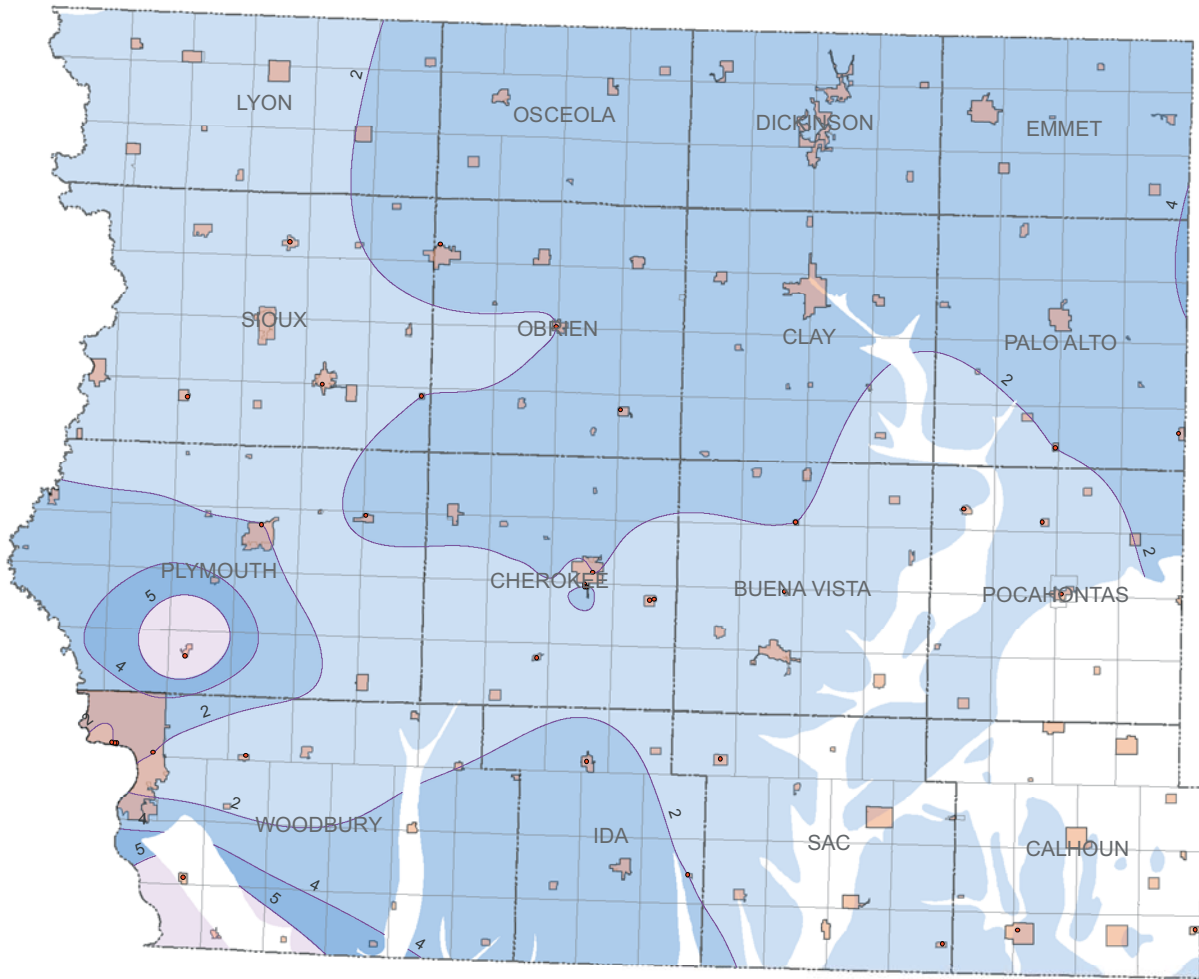
Legend

- Sampled wells (n = 85)
- Lines of equal radium-226 concentration in picocuries per liter

Concentration of radium-226 in water from the Dakota Aquifer in picocuries per liter

<div style="display: inline-block; width: 20px; height: 10px; background-color: #d9e1f2; border: 1px solid black; margin-right: 5px;"></div> <div style="display: inline-block; width: 20px; height: 10px; background-color: #4f81bd; border: 1px solid black; margin-right: 5px;"></div> <div style="display: inline-block; width: 20px; height: 10px; background-color: #e6d9f2; border: 1px solid black; margin-right: 5px;"></div> <div style="display: inline-block; width: 20px; height: 10px; background-color: #c09cf2; border: 1px solid black;"></div>	<p>< 3</p> <p>3 - 5</p> <p>5 - 10</p> <p>> 10</p>	<p>} Area where radium-226 concentration is less than the maximum contaminant level (5 picocuries per liter for radium-226 and -228 combined) for public water supplies</p> <p>} Area where radium-226 concentration is more than the maximum contaminant level (5 picocuries per liter for radium-226 and -228 combined) for public water supplies</p>
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Figure 20. Distribution of radium-226, in pCi/L, in water from the Dakota Aquifer in northwest Iowa.



Legend

- Sampled wells (n = 36)
- Lines of equal radium-228 concentration in picocuries per liter

Concentration of radium-228 in water from the Dakota Aquifer in picocuries per liter

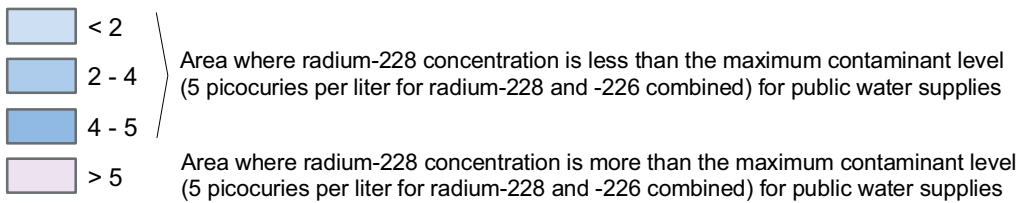


Figure 21. Distribution of radium-228, in pCi/L, in water from the Dakota Aquifer in northwest Iowa.

or nonpoint sources, and include dissolved gases, inorganic and organic solids and radionuclides. In addition, other particulates that might accompany water flowing from a well may be of concern. These may include sediment from the subsurface, microorganisms and chemical precipitates that might form as a result of the disturbances brought about by the well. The concentrations of these dissolved and particulate substances are of interest because they can affect health, limit the potential uses of the water and impact the operation of a well. One of the most common water supply considerations is whether the concentrations of constituents fall below mandated or recommended levels for drinking-water supplies, and if not, whether the water can be treated to comply with recommended standards.

The water delivered to homeowners from public-supply systems is usually treated to reduce the concentration of most potentially hazardous contaminants to below USEPA standards. Treatment such as ion-exchange softening, lime softening, and filtration, that are used to remove constituents like iron, can also appreciably reduce gross alpha radiation and radium concentrations in groundwater. Some municipalities may dilute water containing elevated concentrations of specific contaminants by blending it with surface water or water from aquifers containing lower concentrations of those contaminants. For those with private wells, water softeners, ion exchange, or reverse osmosis, as well as other treatment systems, can be installed in the home to reduce the concentration of both hazardous and nonhazardous contaminants in their water.

The Dakota Aquifer is the most extensive source of large quantities of groundwater in northwest Iowa. Individual sandstone beds within the aquifer range from less than 10 feet to more than 150 feet in thickness, while the cumulative thickness of the sandstone is greater than 200 feet throughout much of the western and north-central portions of study area. The aquifer is confined over most of the area by 200 to 400 feet of clay-rich glacial till as well as by thick shale, siltstone, thin chalky limestone and lignite. The confining beds underlying the aquifer include

Dakota shales, undifferentiated Paleozoic rocks and Precambrian crystalline rock. The aquifer is thin or absent in the extreme northwestern and southeastern portions of the study area, and is thicker toward the west and north-central parts of the area.

Water flows through the aquifer from the north-central part of the study area to the east, south and southwest, with recharge coming from infiltration through the land surface and confining materials. Discharge from the aquifer is to the underlying Paleozoic aquifers and to the alluvium and glacial outwash deposits along the Missouri and Big Sioux rivers in the southwest part of the study area. Flow toward bedrock valleys may reflect discharge to Quaternary sand and gravel deposits in the valleys.

In much of the study area, the Dakota contains the best water that is locally available, so it is widely used even though it may have aesthetic problems, such as high levels of iron, sulfate and hardness. The water quality of the aquifer tends to be fair to poor throughout most of the study area and good to fair towards the corners of the study area. Iron and manganese are above MCLs for public water supplies in many parts of the study area. The areas of poorer water quality result from high concentrations of TDS, particularly sulfate and calcium carbonate, which are common minerals picked up by groundwater in contact with the confining layers above. The highest concentrations of these constituents occur in recharge areas with thick overlying confining units. Localities of better water quality are found where confining layers are thin, and porous pathways allow for more rapid recharge by younger, less mineralized groundwater and surface water. This occurs in the corners of the study area where the aquifer is closer to the land surface. The absence of overlying shale, along with relatively thinner glacial drift, may contribute to better water quality in localized areas in Plymouth and Cherokee counties. In general, the lower part of the Dakota has greater yield potential, but probably poorer natural water quality than the upper part of the aquifer.

If yields from the Dakota Aquifer are signifi-

cantly increased in the future, the quality of the water in the aquifer may be degraded by upward leakage from underlying Paleozoic aquifers. Large withdrawals may reverse the natural flow from the Dakota into the underlying aquifers. This may currently be occurring near the city of LeMars, where concentrations of TDS and sulfate are abnormally high, and the potentiometric surface of the Dakota is below that of the underlying Paleozoic aquifers which contain water with higher concentrations of TDS and sulfate.

The small set of tritium analyses suggests that near Sioux City, the aquifer is receiving rapid recharge of tritiated groundwater from the overlying alluvium, while in most parts of the study area the aquifer is being recharged by infiltration from precipitation that occurred prior to nuclear-weapons testing in the 1950s and 1960s. The small set of other radionuclide analyses show that radon-222 is found in wells in many parts of the study area, at concentrations an order of magnitude below the MCL, and that gross alpha activity, radium-226, radium-228, or a combination of these constituents exceed their MCLs in some areas. As discussed, the accuracy of radionuclide mapping in this report would benefit from a larger and better distributed data set.

Although the groundwater quality of the Dakota Aquifer is relatively poor throughout much of the study area, many communities, industries, farms and homes use it because there are no other alternatives. Domestic supplies often use the upper portion of the aquifer because drilling costs are lower, and they do not need large yields, while public and industrial users that need greater yields use the lower portion of the aquifer, even if the water quality is poorer. With treatment, contaminants that affect health can usually be reduced to meet MCLs, and contaminants that affect the aesthetic qualities of water can often be reduced to acceptable levels.

As more wells are completed in the aquifer and more stratigraphic, construction and water-quality data are interpreted and entered into our databases, our knowledge of the Dakota Aquifer will improve and our evaluation of it will be refined.

Since most Iowans depend on groundwater for their drinking water supplies, current information is needed to protect Iowa's water resources from past, present and future sources of contamination, and to determine the vulnerability of aquifers based on the geologic framework that surrounds them. In order to progress beyond remediation and cleanup, and move toward contaminant prevention, it is necessary to refine our understanding of the varying geologic settings beneath Iowa, and how groundwater and surface water interact and travel through the soil and rock that constitute these settings.

Our natural resources, and in turn, the quality of our lives, are directly affected by the way we plan for and manage our lands and waters. A better understanding of groundwater within its geologic framework and its interaction with surface water will lead to better use, protection and management of Iowa's most valuable natural resource, groundwater.

ACKNOWLEDGEMENTS

This report utilizes geologic, hydrologic, and water quality data collected by well drillers, the United States Geological Survey, Water Resources Division, and the Iowa Department of Natural Resources, Iowa Geological and Water Survey.

The geologic and water-quality samples that the maps in this report are based on were collected over many years by numerous individuals from private, public, and government sectors from public and private wells across northwest Iowa. Most water samples are from public water supplies and were analyzed by the University of Iowa Hygienic Laboratory (UHL), but samples from a variety of projects, including aquifer and water studies, contaminant plume mapping, and maximum contaminant level compliance monitoring, and analyses from other laboratories may also be included in map layers. Most geologic samples are collected by well drillers during well construction, and while fewer in number, outcrop observations provide important information that can not be derived from well cuttings.

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This report is a component of the 2008 Water Resources Management program, which currently is being funded by legislative approval of a one-time appropriation of funds to support water resource studies in Iowa. Presently efforts are underway to secure sustainable funding for continued study and management of Iowa's water resources through an improved water resource permitting system.

Iowans are responsible for influencing legislators to fund natural resource programs and associated studies. They are often important cooperators involved in these studies, and hopefully they are the main benefactors of the research. Many thanks to those who have granted us access over the years, and allowed us to study their natural resources.

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