Geohydrology of the Weldon Spring Ordnance Works, St. Charles County, Missouri

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ABBREVIATIONS USED IN THIS REPORT

AEC	U.S. Atomic Energy Commission
COE	U.S. Army Corps of Engineers
DGLS	Missouri Division of Geology and Land Survey
DOE	U.S. Department of Energy
GIS	Geographic Information System
GWOU	Ground-Water Operable Unit
PMC	Project Management Contractor
RI	Remedial Investigation
RQD	Rock Quality Designation
USGS	U.S. Geological Survey
WSCP	Weldon Spring chemical plant
WSOW	Weldon Spring ordnance works
WSQ	Weldon Spring quarry
WSSRAP	Weldon Spring Site Remedial Action Project
WSTA	Weldon Spring training area

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Bedrock units at the Weldon Spring ordnance works in St. Charles County, Missouri, dip to the northeast at about 60 feet per mile, as measured by the top of the Chouteau Group. The top of the bedrock forms a generally east-west trending ridge through the Weldon Spring training area and the Weldon Spring chemical plant. This surface contains a large, broad bedrock low centered about the unnamed tributary to Dardenne Creek that contains Burgermeister spring. The low has been interpreted to be a paleodrainage that existed before deposition of glacial drift. This feature consists of smaller, more elongate paleovalleys at and west of the chemical plant where more dense drillhole data provide better definition.

The uppermost bedrock unit throughout most of the ordnance works is the Burlington-Keokuk Limestone of Mississippian age. It is subdivided based on weathering characteristics into a lower, unweathered unit; an upper, weathered unit; and a strongly weathered subunit of the weathered unit. The unweathered unit is a light to medium gray, coarse to less commonly fine crystalline, thin to massive bedded, fossiliferous, cherty limestone. The unweathered unit can be silty or argillaceous, or can locally be dolostone or siltstone. The weathered unit is characterized by an increase in mostly horizontal fractures and partings, increased porosity, vugs, voids, breccia, and discoloration by iron oxides. A strongly weathered subunit of the weathered unit is identified in some monitoring wells where these features are particularly abundant or intense.

The overburden units are, in ascending order: residuum, basal till, glacial till, including a glacial outwash subunit, the Ferrelview Formation, loess, alluvium, and fill. Some of the thickest overburden occurs in the northern part of the training area and north of the training area and may be caused by a larger thickness of glacial drift. The paleodrainage centered about the unnamed tributary to Dardenne Creek that contains Burgermeister spring appears to have been partially filled by glacial drift, and a surface-water divide now exists southeast of the tributary.

The upper, more permeable part of the shallow aquifer consists of the residuum, basal till, glacial outwash (where there is no glacial till below it), and the weathered unit of the Burlington-Keokuk Limestone. The lower, less permeable part of the shallow aquifer consists of the unweathered unit of the Burlington-Keokuk Limestone and the Fern Glen Formation. Generally, the upper part of the shallow aquifer thins to the north, reflecting the thin to absent weathered unit north of the training area and chemical plant. A glacial drift confining unit consists of parts of the glacial till and the Ferrelview Formation. Ground water as recharge and discharge probably moves in fractures through this unit. It confines ground water where the potentiometric surface of the shallow aquifer is above its base. There are stream reaches where the streams have cut through the glacial drift confining unit to expose the underlying shallow aquifer.

A potentiometric surface map of the shallow aquifer shows a large ground-water mound in the south-central part of the training area. This

mound is part of a generally east-west trending ground-water ridge through the training area and the chemical plant that defines a ground-water divide. Precipitation that percolates downward through fractures in the glacial drift confining unit recharges the shallow aquifer. Where the glacial drift confining unit is not present, precipitation can be expected to recharge the shallow aquifer more readily. There is the potential for ground-water flow in permeable overburden units where the potentiometric surface is above the top of bedrock. Generally, the residuum and locally other overburden units of the shallow aquifer potentially become more important as mediums of ground-water flow north and downgradient of the ground-water ridge. This is probably limited where clay-rich zones in the residuum confine ground water below in the bedrock. Because the thickness of the weathered unit generally decreases to the north, it generally becomes a less important medium of ground-water flow downgradient to the north. Also to the north, the potentiometric surface of the shallow aquifer is above the base of the glacial drift confining unit over a large area, indicating that the aquifer is confined. Upward ground-water gradients measured in monitoring well pairs, Burgermeister and other springs, the gaining unnamed tributary to Dardenne Creek upstream of Burgermeister spring, and Dardenne Creek indicate ground-water discharge in the northern part of the ordnance works.

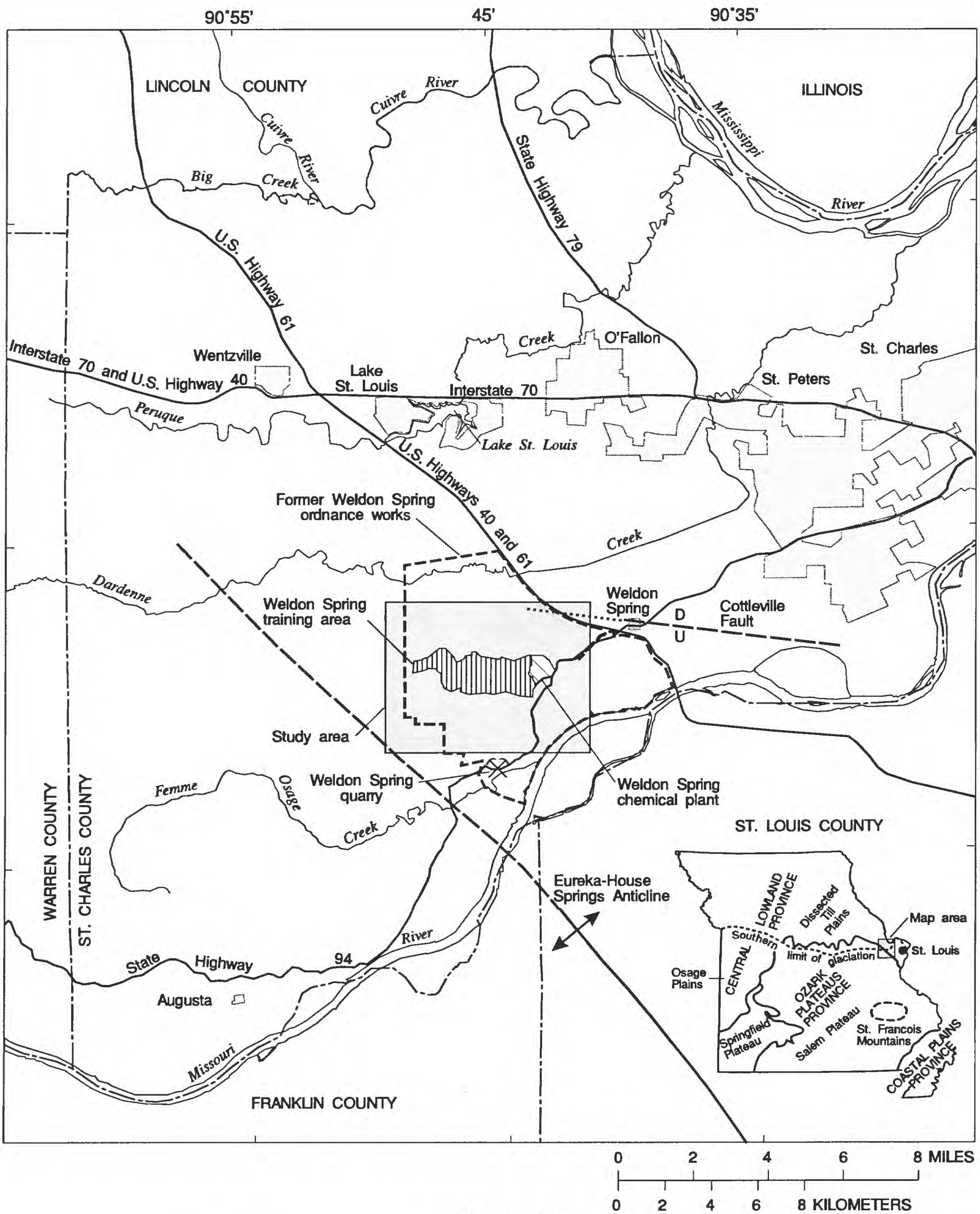
INTRODUCTION

During World War II, the Weldon Spring ordnance works (WSOW) was a U.S. Army explosives production facility that occupied 17,232 acres of land in St. Charles County, Missouri (fig. 1). The Weldon Spring chemical plant (WSCP), a 217-acre section of the WSOW, was operated by the U.S. Atomic Energy Commission (AEC) from 1957 to 1966 for processing uranium (fig. 1). These two activities resulted in localized nitroaromatic and radioactive contamination of soil, ground and surface water, and buildings (International Technology Corporation, 1992, 1993; MK-Ferguson Company and Jacobs Engineering Group, 1992). Disposal of wastes and demolition debris from the WSOW and the WSCP in the Weldon Spring quarry (WSQ) in the southern part of the WSOW (fig. 1) also resulted in contamination of ground and surface water (MK-Ferguson Company and Jacobs Engineering Group, 1992). Details regarding the production and subsequent demolition of the WSOW can be found in reports by International Technology Corporation (1993), Schumacher (1993), and Schumacher and others (1993). Details regarding the operation of the WSCP can be found in reports by MK-Ferguson Company and Jacobs Engineering Group (1992), Schumacher (1993), and Kleeschulte and Emmett (1986).

The former WSOW currently (1996) consists of several different properties and owners. The U.S. Army (hereafter referred to as the Army) retains ownership of 1,655 acres of the former WSOW, known as the Weldon Spring training area (WSTA; fig. 1). The WSCP, immediately east of the WSTA, and the WSQ are owned by the U.S. Department of Energy (DOE). In addition to the Army and DOE, other current (1996) owners of the former WSOW property are the Missouri Department of Conservation (August A. Busch Memorial Wildlife Area and Weldon Spring Conservation Area), the St. Charles County Consolidated School District (Francis Howell High School), the University of Missouri, the Missouri Highway and Transportation Department (pl. 1), the Weldon Spring Heights subdivision, and a private golf course.

Contaminant-related studies and clean-up activities conducted by the DOE at the WSCP and WSQ are referred to as the Weldon Spring Site Remedial Action Project (WSSRAP). Contaminant-related studies and activities on the remainder of the WSOW, including the WSTA, are being conducted by the U.S. Army Corps of Engineers (COE).

In 1995, the Army and DOE prepared a joint ground-water operable unit (GWOU) work plan to address ground-water contamination at the WSOW (Argonne National Laboratory, 1995). This work plan currently (1996) is being used for the preparation of a joint Army and DOE ground-water remedial investigation (RI) report for the WSOW. To prepare the joint work plan, it was necessary to integrate geologic and ground-water data collected independently by the Army and DOE into a comprehensive geohydrologic description of the WSOW. This would facilitate the correlation of water-quality data between Army and DOE monitoring wells and, thereby, contribute to the understanding of the extent of contamination and potential spread of



EXPLANATION

ANTICLINE—Dashed where approximately located (from McCracken, 1971)

D / U FAULT—Approximately located; dashed where inferred; dotted where concealed or postulated. U, upthrown side; D, downthrown side (from Whitfield and others, 1989) contamination at the WSOW. The U.S. Geological Survey (USGS) conducted a study from 1993 to 1996 in cooperation with the COE to create a common data base for Army and DOE geohydrologic data and to use these data together with USGS and Missouri Division of Geology and Land Survey (DGLS) data to develop a comprehensive geohydrologic description of the WSOW, exclusive of the WSQ.

Purpose and Scope

The purpose of this report is to present the results of the geohydrologic study of the WSOW. This report contains a geohydrologic description of the WSOW, which consists of descriptions of the geology and ground-water hydrology. The geohydrologic description of the WSOW integrates Army, DOE, USGS, and DGLS data collected mostly from 1983 to 1995. An important component of this study was the re-logging of bedrock and overburden core samples from Army monitoring wells and bedrock core samples from some DOE monitoring wells. Emphasis was placed on re-logging the Burlington-Keokuk Limestone[1]. Geologic descriptions presented in this report also are based on down-hole geophysical logging of some monitoring wells and onsite mapping of overburden units. The ground-water hydrology of aquifers and confining units is described, including interpretations regarding the occurrence and movement of ground water. This report does not address contaminant distribution and movement or surface-water hydrology.

Physical Setting of the Weldon Spring Ordnance Works

The WSOW is situated along the boundary between the Dissected Till Plains of the Central Lowland Province and the Salem Plateau of the Ozark Plateaus Province (Fenneman, 1938; fig. 1). An east-west trending ridge occurs in the southern part of the WSTA and WSCP. This ridge divides surface water flowing south to the Missouri River from water flowing north to the Mississippi River. South of this divide, streams are strongly incised and the topography is rugged. North of the divide, stream incision is less pronounced and the topography consists of gently rolling hills sloping to the north. Average annual precipitation is 38.5 in. (inches; National Oceanic and Atmospheric Administration, 1994).

Previous Studies

The WSOW has been the subject of much investigation. This section briefly mentions some of the studies that have described the geology or ground-water hydrology of the WSOW, exclusive of the WSQ, or the region. Reports by Kleeschulte and Emmett (1986) and Kleeschulte and Emmett (1987) also summarize geologic, hydrologic, and contaminant investigations, and summaries of several geologic investigations also are presented in the report by Meyer, Jr. (1991).

The geology and ground-water hydrology of the WSOW were summarized and additional data requirements were identified in the joint Army and DOE GWOU work plan (Argonne National Laboratory, 1995). Work to meet these requirements was conducted in 1995 by the Army and the DOE and consisted of installing several new monitoring wells, drilling three angle (30° from vertical) borings, conducting hydraulic conductivity tests on these borings and some monitoring wells, conducting tracer tests, and measuring water levels in wells.

Before the joint Army and DOE RI, which currently (1996) is being prepared, the Army and the DOE completed separate RIs. The RI completed by the Army for the WSOW (International Technology Corporation, 1992) characterized the contamination of soils, surface water, sediments, and manmade structures at the WSOW, exclusive of the WSTA, WSCP, and the WSQ. The RI completed by the Army for the WSTA (International Technology Corporation, 1993) described the geohydrology at the WSTA and the remainder of the WSOW, excluding the WSCP and the WSQ, and also characterized contamination at the WSTA. Monitoring wells were installed, soil and rock cores were logged, monitoring wells and springs were sampled, and water levels in wells were measured (International Technology Corporation, 1993). The results of quarterly water-level measurements and water-quality analyses were reported in quarterly ground-water monitoring reports for the WSOW, exclusive of the WSCP and WSQ (International Technology Corporation, 1996).

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[1]Usage follows nomenclature of the Missouri Division of Geology and Land Survey.

The RI for the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992) contains the results of geologic and hydrologic studies performed by the DOE as part of the WSSRAP. It contains several structure contour maps of the WSCP and vicinity. Data generated in support of the RI also are presented in other reports (MK-Ferguson Company and Jacobs Engineering Group, 1989, 1990). Geologic, geotechnical, and hydrologic data for the RI also are summarized in a report evaluating the suitability of the WSCP site as a location for a mixed low-level radioactive and hazardous waste disposal facility (MK-Ferguson Company and Jacobs Engineering Group, 1991). A report by Durham (1992) summarizes a numerical model to simulate ground-water flow in the shallow aquifer at the WSCP and also presents geologic and hydrologic data from the RI. Annual ground-water monitoring results are presented in annual environmental reports (MK-Ferguson Company and Jacobs Engineering Group, 1996).

Before the beginning of the WSSRAP in 1986, several investigations were conducted at the WSCP. A decommissioning study at the WSCP and WSQ was performed, which involved installing several monitoring wells at the WSQ (National Lead Company of Ohio, Inc., 1977). A preliminary geologic characterization was made at the raffinate pits at the WSCP, which contain wastes from the processing of uranium and thorium (Berkeley Geosciences Associates, 1984). That characterization was based on data from seven monitoring wells installed to the top of bedrock. A more extensive characterization of the raffinate pits area was done in 1983 (Bechtel National, Inc., 1984) that included the installation of additional boreholes, monitoring wells and piezometers, and excavating trenches and conducting geophysical surveys. Work performed by Bechtel National, Inc. (1987) as part of an investigation to site a disposal facility at the WSCP included boreholes, monitoring wells, trenches, geophysical surveys, aquifer testing, and water-quality sampling.

The USGS was first involved in geologic and hydrologic investigations at the WSOW in 1943 and 1944, following a request by the War Department to investigate contamination of ground and surface water by "red water" from WSOW production processes. Wells and springs were sampled, and water-table mapping indicated that ground water north of the ground-water divide at the WSOW discharged to Dardenne Creek (V.C. Fishel and C.C. Williams, U.S. Geological Survey, written commun., 1944). A later investigation by the USGS evaluating the water availability at the WSOW summarized the regional geology (Roberts, 1951). In 1983, a 3-year study was initiated to determine the extent and magnitude of ground- and surface-water contamination from the WSCP and the WSQ. Regional geology and hydrology; water-quality data from the raffinate pits, nearby streams, and the shallow aquifer collected from 1984 through 1986; seepage-run data for several streams; and discharge data for several springs are included in several reports (Kleeschulte and Emmett, 1986, 1987; Kleeschulte and others, 1986). Data (including water-level data) collected from 1986 through 1989 as part of Phase II of that study are presented by Kleeschulte and Cross (1990). Regional and local geology and hydrology, including contaminant transport, background water quality, and the results of a regional three-dimensional ground-water flow model are presented by Kleeschulte and Imes (1994). Contaminant attenuation in the overburden and bedrock, the geochemistry of the interstitial water in sludges of the raffinate pits, the geochemical controls on the extent and magnitude of contaminant migration from the raffinate pits within the overburden, and the sources of increased concentrations of contaminants in the shallow aquifer in the vicinity of the WSCP are given by Schumacher (1990, 1993). Geochemical, hydrologic, and water-quality data collected from 1990 through 1992 to characterize the geochemistry of the overburden and to determine the environmental fate of nitroaromatic compounds at the WSTA and vicinity properties are presented by Schumacher and others (1993). Geochemical, hydrologic (including water-level data), and water-quality data collected from 1992 through 1995 at the WSOW are presented by Schumacher and others (1996).

The DGLS has conducted investigations at the WSOW for several years. The bedrock geology for two 7-1/2 minute quadrangles in which the WSOW is located has been mapped (Whitfield, 1989; Whitfield and others, 1989). An investigation to better define the relation between precipitation, surface runoff, and ground-water recharge to and discharge from the shallow aquifer at the WSOW was conducted by the DGLS from 1987 through 1990 (Missouri Division of Geology and Land Survey, 1991). Results of dye tracing, stream gaging, water-level monitoring, a karst features inventory, geophysical surveys, onsite reconnaissances, and the delineation of recharge areas are presented in that report, along with a discussion of previous DGLS dye traces. The DGLS also conducted an investigation from 1990 to 1991 to identify shallow ground-water discharge points around the WSTA (Price, 1991). Results of additional dye tracing, a karst features inventory, water-level monitoring, and the delineation of recharge areas are presented in that report. Results of a DGLS investigation to identify overburden units and define the engineering and chemical properties of these units at the WSTA are given by Rueff (1992). That study involved the use of trenches, pits, and borings at the trenches to determine and map the overburden units and laboratory testing of the overburden units to determine engineering properties.

The locations of monitoring wells that were installed at the WSOW as part of previous investigations are shown on plates 1 and 2. The densest coverage of monitoring wells is at and in the vicinity of the WSCP. Most of these monitoring wells were installed by the DOE and are denoted as MW-series wells. The locations of these monitoring wells and a large number of geotechnical borings at the WSCP also drilled by the DOE are shown on plate 2. The DOE also installed five deep monitoring wells: MWGS-1 and MWGS-2, located immediately south of the WSCP, and MWGS-3, MWGS-4, and MWGS-5, located north of the study area in the August A. Busch Memorial Wildlife Area. The Army also has installed a large number of monitoring wells, denoted as (1) MWV- and MWVR- for monitoring wells completed in the overburden; (2) MWS- for monitoring wells completed in the shallow bedrock; and (3) MWD- for monitoring wells completed in the deep bedrock. These wells and the USGS-series monitoring wells installed by the USGS in 1986 are located at the WSOW exclusive of the WSCP and WSQ (pl. 1). Well clusters, consisting of two or more monitoring wells, occur in several places throughout the WSOW. Several active or abandoned domestic wells for which geologic data exist are identified by a DGLS well log number (pl. 1). One of these wells (4843) is located on the WSTA and is referred to as the "Army well."

Approach

The study area includes most of the former WSOW and some properties outside the boundary of the former WSOW (fig. 1). This area was chosen because it includes almost all the monitoring wells and geotechnical borings used to characterize the subsurface geology of the WSOW, exclusive of the WSQ. Reference to the WSOW in this report generally refers to the study area.

To develop a comprehensive geohydrologic description of the WSOW, the first task was to review the geologic data that were available and identify any inconsistent terminology or data. Inconsistencies were possible between the descriptions of the geology at the WSCP by DOE and throughout the rest of the WSOW by the Army. Several documents were reviewed, including the RI reports for the WSTA (International Technology Corporation, 1993), the WSOW (International Technology Corporation, 1992), and the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992). Monitoring well drill core logs were reviewed. Based on the review, correlation of geology from the WSCP to the WSTA and other parts of the WSOW was difficult because the Army and the DOE did not use the same terminology to describe bedrock drill cores and did not subdivide the Burlington-Keokuk Limestone in the same way. In addition, verification of unit contacts for Army cores was needed. Specifically, while both agencies described monitoring wells as shallow or deep and the Burlington-Keokuk Limestone as upper or lower, only the DOE subdivided the Burlington-Keokuk Limestone into a weathered unit and an unweathered unit at the WSCP (fig. 2). Because the upper, weathered unit is more permeable than the underlying unweathered unit (MK-Ferguson Company and Jacobs Engineering Group, 1992), contaminated ground water probably flows more readily through the weathered unit. However, it was not clear initially if these same units could be described outside the WSCP and, if so, what criteria could be used to define them.

Bedrock cores had previously been collected by the Army and DOE during monitoring well installation and, in the case of the DOE, also from geotechnical borings at the WSCP. The USGS and a representative of the DOE Project Management Contractor (PMC) familiar with the criteria used to make unit differentiations worked together to ensure consistency of geologic descriptions of the bedrock by the Army and DOE. After several of the Army and DOE bedrock cores were reviewed jointly, the differentiation of weathered and unweathered units of the Burlington-Keokuk Limestone, which had been applied by the DOE (MK-Ferguson Company and Jacobs Engineering Group, 1992), was adopted to describe the Army cores, and common criteria for differentiating units were developed. A previously unrecognized subunit of the weathered unit, termed the strongly weathered subunit, was identified in some Army and DOE cores. Several Army cores were logged jointly in detail. Several DOE cores were reviewed jointly to verify that both the USGS and the DOE PMC representative agreed on the location of the weathered unit/unweathered unit contacts previously identified by the DOE PMC, and strongly weathered subunits were identified where present. The USGS logged the remainder of the Army cores and photographed all the Army cores for future reference. These logs contain rock descriptions and measurements of core recovery, rock quality designation (RQD), and fractures per foot. The DOE PMC representative reviewed the logs and photographs of the remainder of the DOE cores, which had previously been taken by the DOE PMC, to confirm the top of bedrock and the weathered unit/unweathered unit contacts and to identify strongly weathered subunits.

Whereas all the DOE drill cores are from the Burlington-Keokuk Limestone, some of the Army monitoring wells penetrate older units. The Burlington-Keokuk Limestone/Fern Glen Formation contact was identified in several Army cores after some assistance from a representative of the DOE PMC to define this contact.

Because overburden units had previously been identified in core samples only from DOE monitoring wells and geotechnical borings, overburden samples from all but two Army monitoring wells were reviewed to identify overburden units. Because these samples had been stored for several years, some of the samples were desiccated, causing difficulty in identifying overburden units in some cases. To supplement these overburden data, the stream banks of parts of Schote Creek and its tributaries in the northern part of the WSTA and the southern part of the August A. Busch Memorial Wildlife Area upstream of Lake 35 (pl. 1) were examined to identify these overburden units.

Down-hole natural gamma logging was done in several Army and DOE monitoring wells. The purpose of logging these wells was to determine characteristic natural gamma activities for the weathered unit and the strongly weathered subunit that correlated with the core and to then identify these units in the few monitoring wells where no core existed.

A geographic information system (GIS) data base was developed for the monitoring wells, geotechnical borings, domestic wells, and DGLS overburden trenches. This data base contains geologic data, water-level data, and well construction data, such as surface and top-of-casing altitudes and screen and sand pack intervals. Construction data for Army monitoring wells are from International Technology Corporation (1993). Construction data for DOE monitoring wells are from MK-Ferguson Company and Jacobs Engineering Group (1992) and were also provided by the DOE PMC. Some revisions to the top of bedrock and unit contacts for DOE cores were made based on the DOE PMC representative's review of DOE core logs and photographs. Geologic and well construction data for domestic wells are from drill cuttings logs prepared by the DGLS and stored at the DGLS well log library in Rolla, Missouri.

The GIS data base was used to produce several maps. Data for surface altitude maps were plotted, hand-contoured, and digitized. Thickness maps were prepared by mathematically determining surface altitudes on a 1,000-ft (foot) center grid, subtracting the grid values on one surface from those on the overlying surface, and hand-contouring these thickness data along with drill hole thickness data. This procedure allows thickness contours to more accurately reflect unit thicknesses than if only drill hole thickness data were used. However, only drill hole data were used to create the thickness map of the strongly weathered subunit, because this subunit occurs anywhere in the weathered unit and is, therefore, not defined by surfaces above and below it. The GIS data base was used to plot data for a potentiometric surface map using depth-to-water measurements made by the USGS. Two maps were made by subtracting the potentiometric surface from geologic structure surfaces. The GIS data base also was used to plot data for two hydrogeologic sections.

Acknowledgments

The author thanks P.C. Patchin of the Morrison Knudsen Corporation, who worked closely with the author to standardize geologic descriptions of bedrock units for the Army and DOE and helped the author compile geologic data for DOE monitoring wells and geotechnical borings. Appreciation is also extended to Julie Reitinger of MK-Ferguson Company for her assistance in compiling geologic, water-level, and well-construction data for DOE monitoring wells. The author thanks J.L. Bognar, formerly with Jacobs Engi-

SYSTEM	SERIES	STRATIGRAPHIC UNIT [(a)]		THICKNESS, IN FEET [(b)]		LITHOLOGY	GEOHYDROLOGIC UNIT	REMARKS
QUATERNARY	HOLOCENE	Alluvium		0 - 120		Silt, sand, gravel	Alluvial aquifer	The St. Charles County well field is located in the Missouri River alluvium in the southern part of the Weldon Spring ordnance works
	PLEISTOCENE	Loess		0 - 11		Silty clay to silt	Not classified	None
		Ferrelview Formation		0 - 22		Clay to silty clay	Glacial drift confining unit	Confines the shallow aquifer only where base of unit is below potentiometric surface of shallow aquifer, mainly in August A. Busch Memorial Wildlife Area
		Glacial till		0 - 47		Sandy and silty clay to clayey silt, with scattered rock fragments		
			Glacial outwash		0 - 30 [(c)]	Sand to clayey, sandy silt	Upper part of the shallow aquifer	Occurs as a subunit of the glacial till at monitoring wells MWS-108, MWVR-24, MWD-106, and possibly also DGLS trench T-6
		Basal till [(d)]		0 - 10		Sandy, clayey, silty gravel or gravelly silt		Appears to be present mainly in western and north-central parts of chemical plant and eastern training area
MISSISSIPPIAN	OSAGEAN	Residuum [(e)]		0 - 38		Clay, chert, silt, sand; locally contains limestone fragments		Lithology is variable. Where clay-rich, it may locally confine ground water
		Burlington-Keokuk Limestone [(f)]	Weathered unit	0 - 185	0 - 112.5	Limestone; gray to orange-brown, commonly silty, argillaceous, cherty, porous, vuggy, fractured. Locally siltstone		Weathered unit overlies unweathered unit where both are present. Strongly weathered subunit of the weathered unit is identified where weathering features are particularly abundant or intense
			Unweathered unit		0 - 113(+)	Limestone; light to medium gray, cherty. Locally silty or argillaceous. Locally dolostone, siltstone	Lower part of the shallow aquifer	
		Fern Glen Formation		0 - 67		Cherty dolostone and limestone		Commonly vuggy; some quartz- or calcite-lined geodes
			Meppen Limestone Member		0 - 18	Massive chert-free limestone		
	KINDERHOOKIAN	Chouteau Group		0 - 45(+)		Shaley, finely crystalline limestone	Confining unit	None
		Bachelor Formation		0 - 2		Sandstone		
DEVONIAN	UPPER	Sulphur Springs Group	Bushberg Sandstone	0 - 45	0 - 20	Sandstone		
			Glen Park Limestone		0 - 25	Fossiliferous, oolitic limestone with clay seams		
ORDOVICIAN	CINCINNATIAN	Maquoketa Shale		0 - 11		Calcareous or dolomitic shale		Identified in study area only at monitoring well MWGS-2

Figure 2. Generalized stratigraphic column for the Weldon Spring ordnance works, showing geohydrologic units (modified from Kleeschulte and Imes, 1994).

SYSTEM	SERIES	STRATIGRAPHIC UNIT (a)	THICKNESS, IN FEET (b)	LITHOLOGY	GEOHYDROLOGIC UNIT	REMARKS
ORDOVICIAN	MOHAWKIAN	Kimmswick Limestone	41 - 104	Coarsely crystalline limestone; cherty near base	Middle aquifer	Oldest unit to crop out in study area
		Decorah Group	25 - 36 (+)	Interbedded limestone and shale	Confining unit	None
		Plattin Limestone	70 - 125	Finely crystalline limestone		
		Joachim Dolomite	80 - 105	Finely crystalline silty dolostone, siltstone, shale		
		St. Peter Sandstone	120 - 150 (g)	Sandstone	Deep aquifer	
	CANADIAN	Powell Dolomite	50 - 60 (g)	Dolostone		
		Cotter Dolomite	200 - 250 (g)	Cherty dolostone with shale		
		Jefferson City Dolomite	160 - 180 (g)	Dolostone		
		Roubidoux Formation	150 - 170 (g)	Dolostone, sandstone		
		Gasconade Dolomite	(h)	Cherty dolostone, sandstone		Deepest unit in St. Charles County to supply water to public water-supply wells
CAMBRIAN	UPPER	Eminence Dolomite	(h)	Dolostone		High salinity may prevent use of water in study area
		Potosi Dolomite	(h)	Dolostone, quartz druse		
		Derby-Doerun Dolomite	(h)	Dolostone, siltstone, shale	Confining unit	Aquifer characteristics unknown at study area; confining unit in Ozark region
		Davis Formation	(h)	Shale, dolostone, limestone		
		Bonneterre Formation	(h)	Dolostone	Not classified	St. Francois aquifer in Ozark region but yield and salinity unknown in study area
		Lamotte Sandstone	(h)	Sandstone		
PRECAMBRIAN		Igneous rocks (undifferentiated)		Igneous rocks	Confining unit	None

a) Bedrock stratigraphy conforms with Missouri Division of Geology and Land Survey stratigraphy presented in Thompson (1995). Bedrock stratigraphy differs slightly from stratigraphy for the Weldon Spring ordnance works area presented in Whitfield (1989) and Whitfield and others (1989).

b) Unless otherwise indicated, maximum thicknesses shown are maximum thicknesses at wells. Thicknesses may be greater in other parts of study area where well data do not exist.

c) Subunit thickness is 30 feet at monitoring well MWS-108, 7 feet at MWVR-24R, 1 foot at MWD-106, and possibly 2 feet at DGLS trench T-6.

d) Unit is part of U.S. Department of Energy nomenclature (MK-Ferguson Company and Jacobs Engineering Group, 1992) not recognized by Rueff (1992). Thin intervals of this unit have tentatively been identified by the U.S. Geological Survey at monitoring wells MWS-3 and MWS-21.

e) Residuum is composed of the residual material from the weathering of the uppermost bedrock unit and possibly younger rocks, including locally post-Mississippian rocks. The uppermost bedrock unit in most places is the Burlington-Keokuk Limestone.

f) Usage follows nomenclature of the Missouri Division of Geology and Land Survey.

g) Unit thicknesses are from Kleeschulte and Imes (1994).

h) Insufficient data to make thickness estimates.

Figure 2. Generalized stratigraphic column for the Weldon Spring ordnance works, showing geohydrologic units (modified from Kleeschulte and Imes, 1994)—Continued.

neering Group, for his assistance in identifying the Fern Glen Formation in Army cores and T.L. Thompson of the DGLS for providing information regarding the stratigraphy of bedrock units at the WSOW. The input of L.A. Durham of Argonne National Laboratory and Jeff Carman of Jacobs Engineering Group regarding the geohydrology of the WSCP also was helpful.

GEOHYDROLOGY OF THE WELDON SPRING ORDNANCE WORKS

This section presents a discussion of the geohydrology of the WSOW with emphasis on the geologic framework. The geology of the WSOW is described in separate sections for bedrock and overburden. Structure and thickness maps are included to show unit distributions, altitudes, and thicknesses. The section on bedrock geology presents the structural setting of the WSOW and descriptions of bedrock units. The section on overburden geology presents descriptions of unconsolidated units and a thickness map of the overburden. The ground-water hydrology at the WSOW is described in separate sections on geohydrologic units and ground-water flow. Interpretations are concentrated on the shallow aquifer of a three-aquifer system that has previously been described for St. Charles County (Kleeschulte and Imes, 1994).

Bedrock Geology

The bedrock geology of the WSOW is described in two separate sections. The section on general structure describes regional and local structure, including bedding attitude, faults, joints, and the top of bedrock surface. The section on stratigraphy describes bedrock stratigraphy, lithology and weathering characteristics, and the distribution and thickness of units.

General Structure

The WSOW is on the extreme northeast flank of the Ozark Dome, one of several domes and arches, together with intracratonic basins that define the overall structure of the midcontinent region of the United States (Snyder, 1968). Uplift of the Ozark Dome produced a broad area of Paleozoic rocks that dip peripherally away from the Precambrian St. Francois Mountains in southeastern Missouri (Snyder, 1968). This regional dip, together with the northwest-trending Eureka-House Springs Anticline located about 1 mi (mile) southwest of the WSOW (fig. 1), accounts for the northeast dip of the rocks at the WSOW. This dip is illustrated in structure-contour maps of the top of the Fern Glen Formation, the Bushberg Sandstone, and the St. Peter Sandstone over an area much larger than the WSOW (MK-Ferguson Company and Jacobs Engineering Group, 1992). It also is shown in several structure-contour maps of geohydrologic units in St. Charles County (Kleeschulte and Imes, 1994). Results of this study confirm a northeast dip at the WSOW, as illustrated by the top of the Chouteau Group (base of the Fern Glen Formation) that dips about 60 feet per mile to the northeast (pl. 3). Structure contours of the top of the Fern Glen Formation are shown on plate 4. Because of the gradational facies contact between the Fern Glen Formation and the overlying Burlington-Keokuk Limestone (Thompson, 1986), this surface is a less reliable indicator of structure than the top of the Chouteau Group. The northeast dip also is reflected in the regional outcrop pattern of bedrock units, where progressively younger units are exposed from southwest to northeast. Bedrock units older than the Burlington-Keokuk Limestone crop out in the southern part of the WSOW (pl. 5) as a consequence of northeast dipping strata and deep incision by tributaries to the Missouri River. More details concerning regional structural features are presented by Kleeschulte and Imes (1994).

The WSOW does not contain any definitively mapped faults. However, a fault, which has been inferred east of the study area, is postulated to extend into the northeastern part of the study area (Whitfield and others, 1989; fig. 1; pl. 5). The fault, known as the Cottleville Fault, is a normal fault with the north side downthrown and is estimated to have occurred between Pennsylvanian and Quaternary time (J.W. Whitfield, Missouri Division of Geology and Land Survey, oral commun., 1992). Also, a northwest-trending reverse or thrust fault has been interpreted in the western part of the WSOW and northwest of the WSOW, based on drill cutting logs for three domestic wells (MK-Ferguson Company and Jacobs Engineering Group, 1992). However, surficial geologic mapping by the DGLS (Whitfield and others, 1989) and this study did not indicate a fault in the western part of the WSOW, although for this study drill-core data in this area are sparse.

Vertical joint sets have been mapped at the WSOW. MK-Ferguson Company and Jacobs Engineering Group (1992) concluded that joint sets are oriented northwest and northeast and a minor set is oriented north. Mapping of joints at quarries and exposures along drainages near the WSQ showed a major set oriented N70°W to N80°W, two secondary sets oriented N50°W to N60°W and N60°E to N80°E, and a minor set oriented north (MK-Ferguson Company and Jacobs Engineering Group, 1992). Earlier mapping of the limestone bluffs near the WSQ showed a major joint set oriented N70°W and two less prominent sets oriented N60°E and north (Berkeley Geosciences Associates, 1984). Roberts (1951) lists two joint sets in the WSOW area—one set oriented from N30°W to N60°W and the other set oriented from N30°E to N72°E. International Technology Corporation (1993) also described two joint sets in the WSOW—one oriented N3°W to N65°W and the other oriented N30°E to N72°E. MK-Ferguson Company and Jacobs Engineering Group (1992) indicated that some stream segments are controlled by joint orientations. The predominant stream segment mean orientation is N65°W, another set of stream segments has a mean orientation of N38°E, and a third set has a mean orientation of N10°W (MK-Ferguson Company and Jacobs Engineering Group, 1992). Several tributaries of Dardenne Creek trend from N40°E to N50°E (V.C. Fischel and C.C. Williams, written commun., 1944).

The control for the altitude of the top of the bedrock surface (pl. 5) is core data and auger refusals at monitoring wells, geotechnical borings and borings at DGLS trenches, and DGLS logs of domestic wells. Auger refusal refers to a situation whereby an auger drill can penetrate no further because of resistance and is normally regarded as the top of bedrock. However, drill augers can be prematurely stopped by a chert bed or boulder in the residuum. The altitude of the top of bedrock has been adjusted for a few data points where this is thought to have occurred. In areas where control data are densely spaced, such as at the WSCP, plate 5 shows that the top of the bedrock has strong relief. Strong relief over short distances is indicated locally at well clusters, such as MWS-23 and MWD-23, where the two altitudes of the top of bedrock differ by 19 ft (table 1, at the back of this report). Because the core log for MWS-23 (J.G. Schumacher, U.S. Geological Survey, written commun., 1992) indicates that the lower part of what was identified as overburden may instead be fracture-fill material in bedrock, the altitude of the top of bedrock for MWD-23 was used for the altitude of the top of bedrock map (pl. 5). Less local relief is indicated on plate 5 where data are less dense. Little subsurface data exist south of the WSTA; contours are dashed to reflect the lack of data and are approximately located to show the top of bedrock surface similar to but slightly lower in altitude than the land surface. The altitude of the top of the bedrock also is approximated where a distinct residuum/bedrock contact is difficult to identify. Because the upper part of the bedrock is weathered in many areas and because residuum is essentially extremely weathered rock, the contact between the two is gradational, and the assigned value is approximate in some cases. Also, because the USGS-series monitoring wells were not cored, the bottom of casing was assumed to be the top of bedrock, and this value is, therefore, approximate.

The top of bedrock forms a generally east-west trending ridge in the southern to central part of the WSTA and the southern part of the WSCP (pl. 5). The elevated position and proximity of the WSOW relative to the Missouri River and the deep incision by tributaries to the Missouri River have resulted in a steeper slope of the top of bedrock to the south of this ridge than to the north. The top of the bedrock north of the ridge is characterized by lows in the bedrock surface that trend approximately northward. Overlying the bedrock north of the ridge is residuum and glacial deposits. The surface drainage has changed since preglacial time because of the deposition of glacial drift, and the preglacial surface drainage, as shown by the altitude of the top of bedrock (pl. 5), is aligned with the present drainage only in places. A large, broad low in the bedrock surface centered about the unnamed tributary to Dardenne Creek (fig. 1) that contains Burgermeister spring (pl. 5) is interpreted to be one such paleodrainage. Farther south, at and west of the WSCP where more dense drill-hole data provide better definition, this large feature consists of smaller, more elongate depressions in the top of bedrock surface (pl. 5). These have been referred to as troughs (Kleeschulte and Imes, 1994) or paleochannels (MK-Ferguson Company and Jacobs Engineering Group, 1992). In this report they are referred to as paleovalleys to distinguish them from the larger paleodrainage they compose.

Stratigraphy

Stratigraphic and geohydrologic data and relations for the WSOW are shown in a stratigraphic column (fig. 2), monitoring well data tables (tables 1, 2), and hydrogeologic sections (figs. 3, 4; pl. 1). The

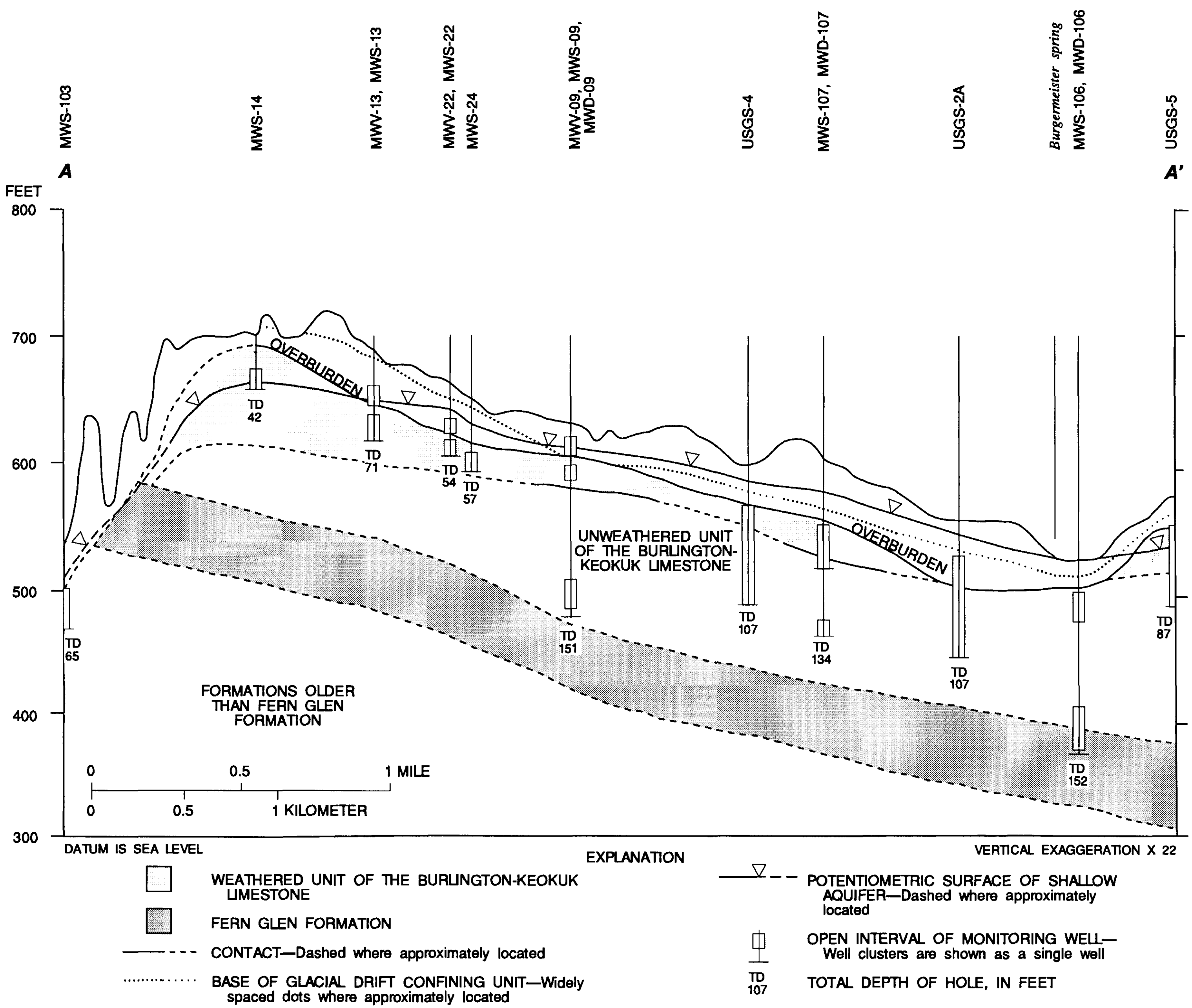

Figure 3. Hydrogeologic section *A-A'* (location of section shown on plate 1).

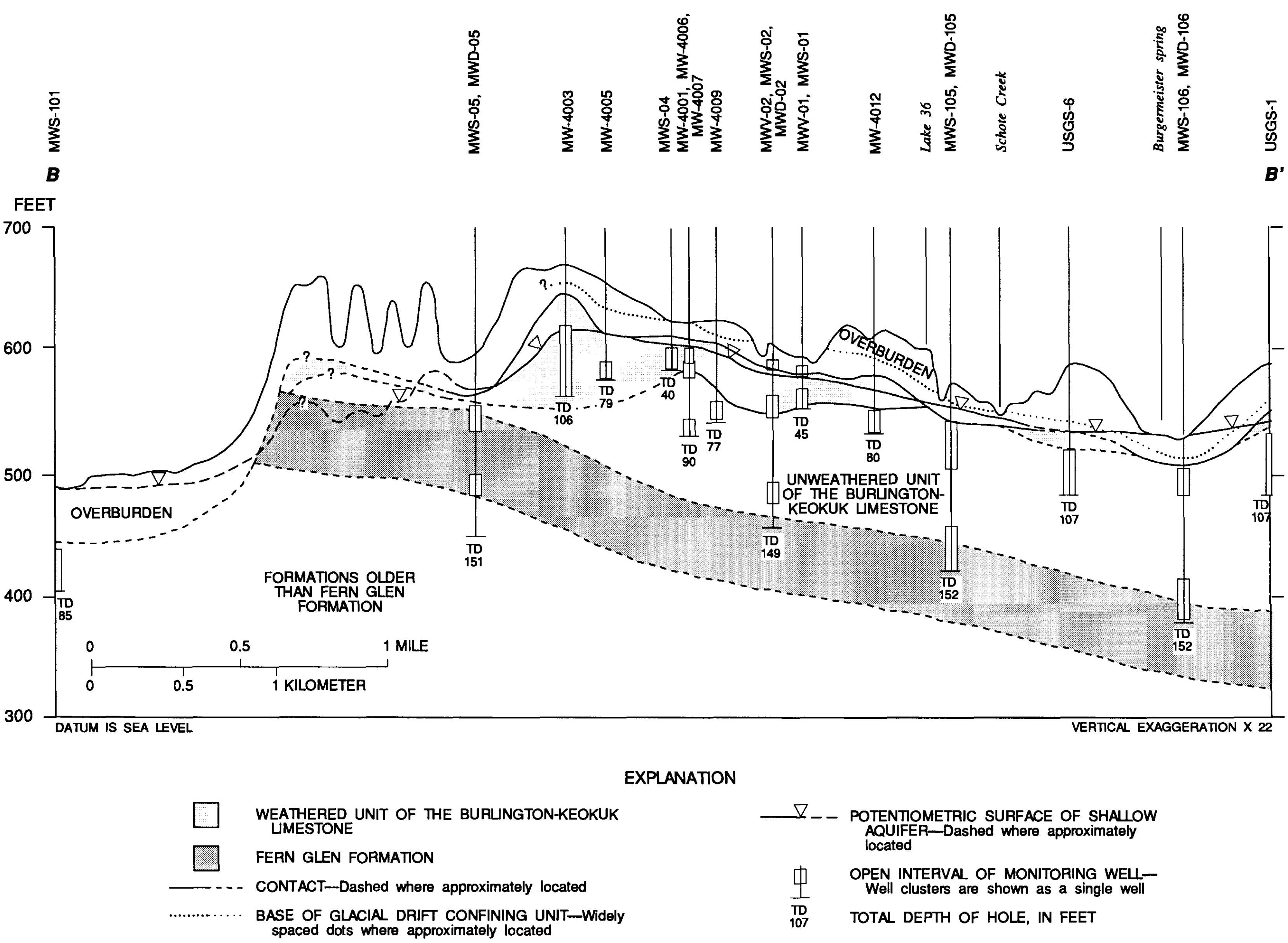

Figure 4. Hydrogeologic section *B-B'* (location of section shown on plate 1).

stratigraphic column (fig. 2) was modified from a stratigraphic column for St. Charles County in a report by Kleeschulte and Imes (1994). Modifications reflect changes specific to the WSOW, changes from re-logging drill cores, or changes in DGLS stratigraphic groupings and nomenclature (Thompson, 1995). Other sources of information for this stratigraphic column are Whitfield (1989), Whitfield and others (1989), MK-Ferguson Company and Jacobs Engineering Group (1992), and Rueff (1992). Bedrock stratigraphy and selected well construction data for Army monitoring wells, USGS-series monitoring wells, MWGS-series monitoring wells, and the "Army well" are given in table 1. Bedrock stratigraphy and selected well construction data for all other currently (1996) active and abandoned DOE monitoring wells are presented in table 2, at the back of this report. Stratigraphic data for the DOE geotechnical borings are on file at the office of the U.S. Geological Survey, Rolla, Missouri. Hydrogeologic sections that terminate near Burgermeister spring are shown in figures 3 and 4; the locations of these sections are shown on plate 1. Hydrogeologic section A-A' (fig. 3) is drawn approximately parallel to the down-dip direction, and the dip is distorted by the vertical exaggeration of the section. Because both hydrogeologic sections represent the surfaces depicted by surface-altitude maps, the contacts on the sections are curved rather than straight lines between monitoring wells.

Little information is available for the deep bedrock units at the WSOW, particularly the upper Cambrian units. The deepest public-water-supply well in St. Charles County is completed in the Gasconade Dolomite of Ordovician age. The oldest unit to crop out in St. Charles County is the Cotter Dolomite (fig. 2), which crops out in the extreme southwestern part of the county about 7 mi southwest of the WSOW (Missouri Division of Geology and Land Survey, 1977). Any knowledge of units deeper than the Gasconade Dolomite comes from a few oil and gas exploration holes in St. Charles County and from projections of information from areas to the south where these units are shallower and more data are available.

The Kimmswick Limestone of Ordovician age (fig. 2) is the oldest bedrock unit to crop out in the study area. It forms the valley floor of the Little Femme Osage Creek (pl. 1) and its tributaries in the southwestern part of the study area (Whitfield, 1989). The uppermost bedrock unit encountered at monitoring wells MWS-101 and MWS-102 (pl. 1) is the Kimmswick Limestone. Monitoring well MWS-102 was completed in the Decorah Group, which is the oldest unit for which drill core information exists in the study area. South of the study area, the Plattin Limestone of Ordovician age forms the valley floor of the Little Femme Osage Creek (P.C. Patchin, Morrison Knudsen Corporation, written commun., 1995).

The Maquoketa Shale of Ordovician age has been reported to be present only in the eastern part of St. Charles County, east of the WSOW (Kleeschulte and Imes, 1994). However, about 10 ft of Maquoketa Shale has been identified in DGLS logs of drill cuttings from two deep monitoring wells installed by the DOE: MWGS-2 (DGLS log 28669), which is south of the WSCP (pl. 1), and MWGS-5 (DGLS log 28672), which is approximately 0.8 mi north of the central part of the study area (not shown on the plates) on the August A. Busch Memorial Wildlife Area (logs on file at the well log library of the Missouri Division of Geology and Land Survey, Rolla, Missouri). Strong peaks in the natural gamma logs for both monitoring wells correlate at slightly higher altitudes with the intervals of Maquoketa Shale identified in the logs. The Maquoketa Shale, however, has not been identified in DGLS well logs for any domestic wells at the WSOW, and it was not identified in cores from the two Army monitoring wells (MWD-18 and MWS-103) that intersected the part of the stratigraphic section where the Maquoketa Shale occurs. The Maquoketa Shale appears to be absent over most of the WSOW and is probably present only as isolated post-Ordovician erosional outliers.

Upper Devonian Series formations at the WSOW are the Glen Park Limestone and the Bushberg Sandstone, which form the Sulphur Springs Group (Thompson, 1995). The previous definition of the Sulphur Springs Group at the WSOW included an unnamed shale, the Glen Park Limestone, the Bushberg Sandstone, and the Bachelor Formation. The Sulphur Springs Group previously was assigned to the Upper Devonian Series and the Kinderhookian Series of Mississippian age (Whitfield, 1989; Whitfield and others, 1989). Incomplete intervals of the Sulphur Springs Group are present in cores from three monitoring wells. The entire interval is present at monitoring well MWD-18, where it is 20 ft thick.

Mississippian rocks of the Kinderhookian Series are the Bachelor Formation and the Chouteau Group (Thompson, 1995). The Bachelor Formation is present in cores from two monitoring wells (MWD-05 and MWD-18) where it is a thin (1–2 ft) quartz sandstone. The Chouteau Group is a finely crystalline limestone with many shale seams and is present in cores from two monitoring wells where its thickness is 21 ft (MWD-18) and 23 ft (MWD-05). The partial thickness of the Chouteau Group at one domestic well (DGLS log 11390; pl. 1) that was completed partially in the Chouteau Group is 45 ft.

Mississippian rocks of the Osagean Series are the Fern Glen Formation and the Burlington-Keokuk Limestone. The Fern Glen Formation is present in cores from six monitoring wells, but its entire thickness was penetrated by only one monitoring well (MWD-05), where it is 67 ft thick. The Fern Glen Formation in these cores generally is a finely crystalline dolostone and less commonly limestone, with chert interbedded or as nodules. Parts of the Fern Glen Formation are characterized by "pinpoint" porosity (abundant pores as large as approximately 1/16 in. in diameter). It also commonly contains some quartz- or calcite-lined or -filled vugs, as large as 1 in. in diameter, which have been called geodes (Whitfield, 1989; Whitfield and others, 1989; John Bognar, Jacobs Engineering Group, oral commun., 1993). A massive, finely to coarsely crystalline limestone generally free of chert, known as the Meppen Limestone Member, occurs as the basal unit of the Fern Glen Formation and is 18 ft thick at monitoring well MWD-05. A 15-ft thickness is reported for the Meppen Limestone Member in Whitfield and others (1989).

The Burlington-Keokuk Limestone is the uppermost bedrock unit throughout most of the WSOW, and, consequently, more drill core data exist for it than for any other unit. Little information exists for the Burlington-Keokuk Limestone south of the WSTA; except for monitoring wells installed at the WSQ, only three monitoring wells have been installed south of the WSTA. The Burlington-Keokuk Limestone has been removed by erosion at all three of those locations. Geotechnical borings drilled south of the WSTA before the construction of the WSOW (pl. 1) were drilled only to the top of bedrock.

The Burlington-Keokuk Limestone is divided into an upper weathered unit and a lower unweathered unit. The term "unweathered" is used in a relative sense because some of the weathering features that characterize the weathered unit also occur in the unweathered unit, but less commonly and at a lower intensity. Although this weathering may occur anywhere in the unweathered unit, it is more common near the top where the contact with the weathered unit generally is gradational.

The unweathered unit of the Burlington-Keokuk Limestone is a light to medium gray, coarse to less commonly fine crystalline, thin to massive bedded, fossiliferous, cherty limestone that can be silty or argillaceous, or can locally be dolostone or siltstone. The chert is white to, less commonly, gray or blue-gray and occurs as thin beds, lenses, and nodules. The limestone can be extremely cherty or relatively chert free, as noted in the lower part of the Burlington-Keokuk Limestone at some of the deeper monitoring wells. The dolostone is brown and occurs at some of the monitoring wells as distinct beds interbedded with limestone in the lower part of the Burlington-Keokuk Limestone. The contact between the Burlington-Keokuk Limestone and Fern Glen Formation is gradational and difficult to identify because of their facies relation (Thompson, 1986).

The topography of the top of the unweathered unit is shown on plate 6. The top of the unweathered unit is shown as a surface, although the contact between the weathered and unweathered units generally is gradational. No information exists for this surface south of the WSTA. Because many of the Army monitoring wells in the WSTA are completed in the weathered unit and do not reach the unweathered unit, the altitude of the top of the unweathered unit is not known for much of the WSTA. Because the weathered unit is thin or absent in most monitoring wells north of the WSTA and WSCP, the top of the unweathered unit is the same as or is close to the top of bedrock over much of this area. This similarity between the top of the unweathered unit and the top of bedrock exists in the paleodrainage centered about the unnamed tributary to Dardenne Creek that contains Burgermeister spring, but only partially at the paleovalleys to the south (pl. 5). A depression exists in the top of the unweathered unit in the western part of the WSTA. This area is centered on monitoring well MWD-15 where the weathered unit is considered to compose the entire Burlington-Keokuk Limestone. However, the Burlington-Keokuk Limestone at monitoring well MWD-15 is not weathered throughout the entire thickness, but instead contains alternating intervals of weathered and unweathered rock. The value used on plate 6 for this monitoring well is the top of the Fern Glen Formation. If more data were available, this deeply weathered area might be shown to be smaller with some elongation, reflecting structural (joint) control, as has been suggested for the bedrock paleovalleys at the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992).

The top of the unweathered unit also can be represented by the depth of weathering, as defined by the depth from land surface to the top of the unweathered unit (pl. 7). An inverse relation exists between the depth to the top of the unweathered unit and the altitude of the top of the unweathered unit (pl. 6). That is, areas where the depth to the unweathered unit is large correspond to some degree to "lows" in the altitude of the top of the unweathered unit. The patterns do not exactly correspond because the depth to the top of the unweathered unit contains a variable amount of overburden.

The weathered unit of the Burlington-Keokuk Limestone is characterized by alterations that have been superimposed on the rock by weathering. These alterations are lithology and color changes, an increase in porosity, and an increase in fractures.

The weathered unit commonly is a porous, silty and argillaceous, cherty limestone, or less commonly siltstone. The silty and argillaceous material is concentrated by the solution of carbonate minerals and the accumulation of insoluble silts and clays during the weathering process. The silty and argillaceous limestone and siltstone, as well as the purer limestone, commonly are orangish-brown because of discoloration by iron oxides. This discoloration permeates the rock as well as occurring along fracture and parting surfaces.

Porosity in the weathered unit is greater than in the unweathered unit and ranges from "pinpoint" ("sponge-like", where pores are particularly abundant) porosity to solution vugs and larger openings (voids), some of which are associated with breccia. Vugs can be sites of core breakage and can contribute to low core recovery and low RQD, which is a measure of the competency of the rock. Vugs and larger voids can be filled or partially filled by clay or a mixture of clay, silt, and chert gravel (MK-Ferguson Company and Jacobs Engineering Group, 1992). The removal of this fill by drilling fluid results in poor core recovery. Loss of fluid during drilling also is associated with zones of core loss (MK-Ferguson Company and Jacobs Engineering Group, 1991). Garstang (1991) states that voids appear to have limited vertical and lateral continuity and that no open subsurface network of voids was identified using a downhole camera. The chert in the weathered unit commonly is porous and, in extreme cases, chalky.

The weathered unit contains a large number of horizontal fractures and partings along bedding planes. Horizontal fracture and parting surfaces commonly show some rounding, which may be evidence of solution of carbonate minerals. The surfaces commonly have carbonate minerals and iron and manganese oxides precipitated on them. Vertical and oblique fractures also occur and exhibit the same solution and precipitation features. Vertical and oblique fractures, however, are not present as much in core as horizontal fractures because they probably are less common and are less likely than horizontal fractures to be intersected by vertical drill holes. The core from two angled holes drilled by DOE showed vertical fractures spaced an average of 10 ft apart and a horizontal-to-vertical fracture ratio of approximately 20:1 (MK-Ferguson Company and Jacobs Engineering Group, 1992). The vertical fractures tend to be enlarged and clay filled near the land surface and become tight at shallow depths (MK-Ferguson Company and Jacobs Engineering Group, 1992). Both horizontal and vertical fractures are not limited to the weathered unit nor to shallow depths. These features may occur anywhere, but are more common in the weathered unit. Chert beds and lenses tend to be fractured into many small pieces along variably oriented fractures, which is an indication that the chert is more brittle than the limestone and that at least some of the fractures are due to drilling. However, secondary iron and manganese oxide mineralization occurs along some of the chert fracture surfaces, indicating that some of the breakage occurred along pre-existing fractures. The density of fractures and partings in the weathered unit results in lower values of RQD than values for the unweathered unit and probably contributes to the generally lower core recovery in the weathered unit.

The weathered unit is present in most of the WSOW where data exist (pl. 8), but its presence is not determined south of the WSTA where no core data exist for the Burlington-Keokuk Limestone. The weathered unit is present at all monitoring wells and geotechnical borings at the WSTA and WSCP, except at MWD-18 (pl. 1) where the Burlington-Keokuk Limestone is not present. For a few monitoring wells in well clusters, core drilling began below the bottom of the weathered unit, and the presence of the weathered unit is indicated by another monitoring well in the well cluster (tables 1, 2). At the August A. Busch

Memorial Wildlife Area north of the WSTA and WSCP, the weathered unit is absent or generally thin compared to its thickness at the WSCP and WSTA (pl. 8). Except for monitoring well MWD-15 (pl. 1), where the weathered unit is considered to compose the entire Burlington-Keokuk Limestone and is 112.5 ft thick, and monitoring well MW-4003 (pl. 1) that also has an unusually thick section of the weathered unit (83.2 ft), the weathered unit ranges from 0 to 66.5 ft thick. Some monitoring wells were not completed deep enough to penetrate the unweathered unit, particularly over much of the WSTA, and are shown with a separate symbol on plate 8 to indicate partial thicknesses for the weathered unit. Some correspondence exists between the thickness of the weathered unit (pl. 8) and the top of bedrock (pl. 5). For example, the paleovalley that extends through the eastern part of the WSCP also is shown as a thin (less than 20 ft in places) area of the weathered unit. Also, a "high" in the top of the bedrock surface (pl. 5) in the western part of the WSCP partially corresponds to an area of thick weathered unit (pl. 8).

A strongly weathered subunit of the weathered unit of the Burlington-Keokuk Limestone has been identified where weathering features are particularly abundant or intense. Typically, this subunit contains intervals of poorer core recovery than the remainder of the weathered unit. Some of these intervals probably are voids where the clay fill has been removed by drilling fluid. In a few cases where the core loss is extreme and occurs immediately below auger refusal, the core loss interval has been reinterpreted to represent residuum, and the top of bedrock has been adjusted from previous logs. Another lithologic feature common in the strongly weathered subunit is breccia. The breccia is vuggy and is characterized by chert and less commonly by limestone fragments in a weakly cemented, sandy, clayey, and sometimes limey matrix. Poor core recovery from breccia intervals is common.

The strongly weathered subunit has a more limited distribution than the weathered unit at the WSTA and WSCP, although data are sparse in the east-central part of the WSTA (pl. 9). Drill-core data north of the WSTA and WSCP, although not as dense as at the WSTA and WSCP, do not indicate the presence of the strongly weathered subunit in this area, except immediately north of the WSCP. There are no core data for the strongly weathered subunit south of the WSTA and WSCP.

The thickness map of the strongly weathered subunit (pl. 9) is based partially on some assumptions. Where present at the WSTA, the strongly weathered subunit occurs only in the uppermost part of the weathered unit in the monitoring wells that penetrate the total thickness of the weathered unit. Based on this occurrence, the strongly weathered subunit is assumed not to be present in monitoring wells at the WSTA that penetrate a substantial but incomplete thickness of the weathered unit without intersecting the strongly weathered subunit. For the same reason, if a substantial amount of weathered unit exists below the strongly weathered subunit in monitoring wells at the WSTA, that amount of strongly weathered subunit is assumed to be its total thickness. These assumptions cannot be made at and in the vicinity of the WSCP where the strongly weathered subunit is not always at the top of the weathered unit and where more than one interval of strongly weathered subunit can occur. The largest known thickness of the strongly weathered subunit is at monitoring well MW-2009 (pl. 2), where it is a minimum of 33.5 ft thick. For DOE monitoring wells with more than one interval of strongly weathered subunit, the sum of individual intervals was used to construct plate 9. The DOE has suggested that zones of strongly weathered Burlington-Keokuk Limestone seem to be relatively continuous across the WSCP (J.C. Dille and P.C. Patchin, Morrison Knudsen Corporation, written commun., 1994).

The thickness of the strongly weathered subunit (pl. 9) does not correspond well with the thickness of the weathered unit (pl. 8). A lack of correspondence is most obvious at monitoring well MWD-15 (pl. 1), where the entire Burlington-Keokuk Limestone is considered to be the weathered unit, but where no strongly weathered subunit is present. Also, little correspondence is seen between the thickness of the strongly weathered subunit (pl. 9) and the topography of the top of bedrock (pl. 5).

Down-hole natural gamma geophysical logs were completed for several monitoring wells that have drill core to determine characteristic natural gamma activities for the weathered unit and the strongly weathered subunit and to determine if any other geophysical signals existed. Natural gamma activity is due to radioactive decay of clay minerals (Keys and MacCary, 1971). The clay mineral content is higher in the weathered unit than in the unweathered unit at the WSOW. Generally, the natural gamma activity decreased with depth, indicating a decrease in weathering. For most natural gamma logs, however, it was difficult to identify distinct geophysical changes that correlated with the weathered unit/unweathered unit contact, that identified a strongly weathered subunit, or that confirmed the top of bedrock. Despite this general lack of definition, natural gamma logs were used to identify the weathered unit and the top of bedrock at two monitoring wells (USGS-1 and USGS-6) for which drill core does not exist.

The Warsaw Formation, which is shale and cherty limestone, overlies the Burlington-Keokuk Limestone, but it has not been identified as bedrock at the WSOW. The DGLS (Whitfield and others, 1989; Missouri Division of Geology and Land Survey, 1991) has shown that the Warsaw Formation crops out in the eastern part of the WSCP and to the east and north of the WSCP. However, these areas probably are residuum with residual Warsaw-type chert, instead of Warsaw Formation bedrock (Peter Price, Missouri Division of Geology and Land Survey, oral commun., 1995).

Overburden Geology

The stratigraphy of overburden units at the WSCP is presented in the RI report for the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992). Overburden units at the WSOW were not identified by the Army as part of their RI, but were the subject of a later investigation at the WSTA (Rueff, 1992). As part of that study, overburden units were exposed by excavating several trenches, and borings were drilled at the trenches. Also, overburden units were identified by interpreting descriptions contained in logs previously prepared for the monitoring wells as part of the RI (International Technology Corporation, 1992), but the overburden samples from the monitoring wells were not logged. These overburden samples were reviewed to identify overburden units as part of this study (data on file at the office of the U.S. Geological Survey, Rolla, Missouri). For many monitoring wells, the units that were identified did not agree with the interpretations made by Rueff (1992). The overburden stratigraphy presented by DOE for the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992) and the overburden stratigraphy presented by Rueff (1992) for the WSTA also differ slightly. The overburden stratigraphy presented in figure 2 for the entire WSOW is intended to unify the two and, therefore, differs slightly from both.

The lowermost overburden unit is residuum, which is the residual material resulting from the chemical weathering of rock. Residuum is derived from the uppermost bedrock units and younger units that were once present. Residuum at the WSOW consists of insoluble clay, chert, silt, and sand and locally contains limestone fragments. The residuum is variable in composition, both spatially and vertically, ranging from clay-rich to chert-rich. Chert ranges from broken gravel-size fragments to beds of sufficient thickness to stop drill augers prematurely above the top of bedrock. Although loss of drilling fluid into the residuum has been reported during drilling at the WSCP (Bechtel National, Inc., 1984; MK-Ferguson Company and Jacobs Engineering Group, 1991), no voids have been reported in the residuum at the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1991). Information regarding possible voids in the residuum throughout the remainder of the WSOW is not available.

The overburden at monitoring well MWS-08 (pl. 1) contains 20 ft of white to cream-colored clay, tentatively identified as kaolinite, that is interpreted to be part of the residuum. This occurrence of kaolinite may be similar to kaolinite deposits of the fire clay districts of east-central Missouri. Clay deposits have been reported in St. Charles County, although no mining has been reported there (McQueen, 1943). Clay deposits were mined as nearby as St. Louis County to the east of St. Charles County, Warren County to the west, and Franklin County to the southwest (Searight and Patterson, 1967). Clay deposits can occur as filled sinkholes, some of which are in the Burlington-Keokuk Limestone (McQueen, 1943).

Basal till, which occurs above the residuum and below the glacial till, is described for the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992), and this terminology has been adopted for the WSOW in this report (fig. 2). This unit, which ranges from 0 to 10 ft thick, is a sandy, clayey, silty gravel, or gravelly silt, characterized by angular chert loosely bound in a silty matrix. It occurs in areas of bedrock lows and is thin or absent in areas of bedrock highs (MK-Ferguson Company and Jacobs Engineering Group, 1992). Basal till has been identified in two Army monitoring wells (MWS-03 and MWS-21; pl. 1) on the east side of the WSTA (monitoring well logs on file at the U.S. Geological Survey Office, Rolla, Missouri).

Rueff (1992) identified what was termed a "preglacial deposit" in four trenches in the south-central part of the WSTA in the same stratigraphic position as the basal till. The "preglacial deposit" is described as thin (as much as 4.5 ft thick) silt, silty clay, silty sand, and clay. Kaolinite composes 60 to 80 percent of the clay-size fraction of three samples of the "preglacial deposit" from one trench (Schumacher and others, 1993). Because at least some of the clay in the "preglacial deposit" may be residual kaolinite, as described previously, this unit may be residual in origin. Alternately, Rueff (1992) suggests that the "preglacial deposit" could be glacial outwash, which would likely correlate with glacial outwash deposits identified in three Army monitoring wells (fig. 2). Because at least part of the "preglacial deposit" may belong to other overburden units, its existence as a distinct unit at the WSOW is not clear, and it is not shown in the stratigraphic column for the WSOW in this report (fig. 2).

The glacial till, or clay till of DOE terminology, consists of sandy and silty clay to clayey silt, with scattered chert, limestone, igneous and metamorphic gravel and cobbles. The glacial till also is characterized by hairline fractures and joints (Rueff, 1992; J.G. Schumacher, U.S. Geological Survey, oral commun., 1994). Iron and manganese oxides have been noted near these fractures as staining and nodules (Rueff, 1992). This unit occurs throughout most of the WSCP and WSTA, but is thickest in the northern part of the WSTA (47 ft thick in a boring at DGLS trench T-8), thins to the south, and is thin to absent along the southern part of the WSTA. The thickness of the glacial till determined for this report at some Army monitoring wells, particularly MWS-05 (0 ft) and MWS-08 (4 ft) along the southern part of the WSTA, is less than that estimated by Rueff (1992; 22 ft at MWS-05; 22.5 ft at MWS-08). The southern terminus of the glacial till, which is due to nondeposition or erosion, is not well defined, but probably is in the southern part of and in places south of the WSTA. The distribution and thickness of the glacial till north of the WSTA and WSCP are not as well known as they are at the WSTA and WSCP because the data are less dense; however, 32 ft of glacial till has been identified at monitoring well MWS-107 (pl. 1). Thirty feet of fining-upward, medium-coarse sand to clayey, sandy silt that overlies residuum and underlies the Ferrelview Formation (fig. 2) has been identified as glacial outwash at monitoring well MWS-108 (pl. 1). Although glacial till is not present at monitoring well MWS-108, the glacial outwash is considered a subunit of the glacial till (fig. 2) because glacial outwash also has been identified in two other Army monitoring wells (MWD-106 and MWVR-24; pl. 1) with glacial till above and below it. Glacial outwash also may be present below glacial till at DGLS trench T-6 (pl. 1).

The Ferrelview Formation, which overlies the glacial till, is a clay to silty clay with scattered sand, gravel, and rock fragments. It typically has less sand and more clay than the underlying glacial till and has many hairline fractures or macropores (Rueff, 1992). Theories for the origin of the Ferrelview Formation include it being glacial till plain sediment or a result of in-situ weathering of glacial till or loess (Rueff, 1992; MK-Ferguson Company and Jacobs Engineering Group, 1992). The Ferrelview Formation is similar in appearance to the glacial till. It was difficult to differentiate the two in the review of Army overburden samples. The distribution of the Ferrelview Formation probably is similar to that of the glacial till.

Loess overlies the Ferrelview Formation (fig. 2). Rueff (1992) identified two loess units, the Roxana Silt and the overlying Peoria Loess. Two loess units were not recognized by the DOE until they were identified in 1995 during the drilling of monitoring well MW-4024 (pls. 1, 2; P.C. Patchin, written commun., 1995). However, the generic term loess is used by the DOE (MK-Ferguson Company and Jacobs Engineering Group, 1992) and is used in this report. The loess is silty clay to silt, has a sporadic distribution (MK-Ferguson Company and Jacobs Engineering Group, 1992), and can be as much as 11 ft thick.

Locally, alluvium overlies older overburden units or bedrock (fig. 2). Its composition varies greatly depending on location and is as much as 120 ft thick in the floodplain of the Missouri River (fig. 1).

Variable thicknesses of fill occur throughout the WSOW because of past earthmoving activities as part of the construction of the WSOW and WSCP. In extreme cases (raffinate pit dikes), the fill is as thick as 30 ft (MK-Ferguson Company and Jacobs Engineering Group, 1992). Alternatively, past earthmoving activities have removed overburden for use elsewhere as fill. Approximately 15 to 20 ft of overburden is estimated to have been removed at monitoring well MWS-14 (pl. 1; J.G. Schumacher, oral commun., 1995).

The thickness of the overburden varies throughout the WSOW (pl. 10). The overburden thickness data for plate 10 are based in part on some new and reinterpreted top-of-bedrock data that were not used for previous overburden thickness maps (MK-Ferguson Company and Jacobs Engineering Group, 1992; Rueff, 1992). Data that represent extreme cases of cut or fill also are not included on plate 10. Isopach lines were not extended south of the WSTA and WSCP because of the sparse drill-hole data there. Some of the thickest overburden occurs in the northern part of the WSTA and north of the WSTA, but because overburden samples were not collected for some of the monitoring wells in this area (MWGS- and USGS-series monitoring wells), data for individual overburden units do not exist for these wells. The larger overburden thicknesses may be caused by larger thicknesses of glacial drift, rather than thicker residuum. For example, the glacial till/residuum contact at a boring at the DGLS trench T-8 (pl. 1) is at a depth of 61 ft from the land surface (Rueff, 1992). Less glacial drift was deposited south of the bedrock "high" in the WSTA (pl. 5), which may be the result of the bedrock high impeding the flow of the ice sheet to the south or the removal of glacial drift by postglacial erosion (Rueff, 1992). Thick overburden occurs in some places where the top of the bedrock is low (pls. 5, 10). For example, the paleodrainage centered about the unnamed tributary to Dardenne Creek that contains Burgermeister spring appears to have been partially filled by glacial drift, and a surface-water divide now exists southeast of the tributary. Also, the paleovalley that extends through the eastern part of the WSCP aligns with a linear area of thick overburden on the overburden thickness map.

Geohydrologic Units

The geohydrologic units in St. Charles County include an alluvial aquifer and shallow, middle, and deep bedrock aquifers separated from each other by confining units (Kleeschulte and Imes, 1994; fig. 2). The St. Francois aquifer is even deeper (fig. 2), but it is at such great depths in St. Charles County that its hydrologic properties and water quality are not well known. The geohydrologic units at the WSOW are shown in figure 2, which is modified from Kleeschulte and Imes (1994) for specific conditions at the WSOW. These modifications are revisions in the stratigraphy (discussed in the Bedrock Geology and Overburden Geology sections of this report); the inclusion of residuum, basal till, and glacial outwash in the shallow aquifer; and the definition of a leaky confining unit, termed the glacial drift confining unit.

Permeability and hydraulic conductivity data for the residuum, basal till, and glacial outwash are limited. The permeability of the residuum is considered to be variable because of its heterogeneous composition (MK-Ferguson Company and Jacobs Engineering Group, 1992). Bognar (1991) stated that a hydraulic conductivity value of 2.8 ft/day (feet per day) for the residuum at the WSCP was estimated by the DGLS based on data from other locations. Although the residuum is considered to be part of the shallow aquifer, it may locally be a confining unit where it is particularly clay-rich. Hydraulic conductivity measurements at the residuum/bedrock contact at the WSCP range from 0.4 to 267 ft/day, but these data probably are not representative of the residuum (MK-Ferguson Company and Jacobs Engineering Group, 1992). The permeability of the basal till probably is larger than that of some other overburden units because of its large sand and gravel content (MK-Ferguson Company and Jacobs Engineering Group, 1992). The glacial outwash is a local feature and is thick at only one monitoring well (MWS-108 where it is 30 ft thick; pl. 1). Its sandy composition indicates that it is permeable. It is considered a part of the shallow aquifer only where no glacial till occurs below it (MWS-108 and possibly DGLS trench T-6; pl. 1).

The permeability of the glacial till and Ferrelview Formation is substantially less than that of the underlying overburden units, the Burlington-Keokuk Limestone, and the Fern Glen Formation that compose the shallow aquifer (fig. 2). The hydraulic conductivity of the glacial till at the WSCP averages 6.5×10^{-5} ft/day based on in-situ constant head permeability tests (Bognar, 1991) and averages 3.4×10^{-5} ft/day based on in-situ slug tests (MK-Ferguson Company and Jacobs Engineering Group, 1992). Hydraulic conductivity from laboratory measurements ranges from 9.1×10^{-6} to 0.01 ft/day and averages 7.4×10^{-5} ft/day for the glacial till and ranges from 1.1×10^{-5} to 0.01 ft/day and averages 1.3×10^{-4} ft/day for the Ferrelview Formation at the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992). In-situ constant head permeability tests of the Ferrelview Formation averaged 6.6×10^{-5} ft/day at the WSCP (Bognar, 1991).

The glacial till and the Ferrelview Formation together, or separately where only one is present, compose the glacial drift confining unit, with the exception that the glacial outwash subunit is part of the shallow aquifer where there is no glacial till below it (MWS-108 and possibly DGLS trench T-6; pl. 1; fig. 2). Because ground water as recharge and discharge probably moves in fractures through the glacial till and the Ferrelview Formation, the glacial drift confining unit can be regarded as a leaky confining unit. Although it does not actually confine ground water throughout most of the WSTA and WSCP where the potentiometric surface of the shallow aquifer is below its base, it confines ground water locally, particularly to the north of the WSTA and WSCP where the potentiometric surface is above its base. The structure of the base of the glacial drift confining unit, which is the same as the top of the residuum, except where glacial outwash and basal till locally occur (fig. 2), is shown on plate 11. The structure of the base of the glacial drift confining unit is similar to the top of bedrock surface (pl. 5); the paleodrainage centered about the unnamed tributary to Dardenne Creek containing Burgermeister spring and the bedrock paleovalleys west of and at the WSCP are reflected by lows in this surface. Reaches where streams have cut through the glacial drift confining unit to expose the underlying shallow aquifer also are shown on plate 11. These reaches were approximately located by projecting where streambed altitudes are below the base of the confining unit and examining stream banks along parts of Schote Creek and its tributaries. Because the confining unit has been removed in these reaches, the shallow aquifer can be considered to extend to the land surface. The extent of these conditions transverse to the stream is not known. The glacial till confining unit is thin to absent in other places including but not limited to the southern part of the WSTA (pl. 11). The southern terminus of the glacial till confining unit is probably in the southern part of and in places south of the WSTA.

Kleeschulte and Imes (1994) include the Fern Glen Formation with the Burlington-Keokuk Limestone in the shallow aquifer. Although hydraulic conductivity data are insufficient to verify this inclusion (there is only one monitoring well completed in the Fern Glen Formation and four monitoring wells that straddle the Fern Glen Formation/Burlington-Keokuk Limestone contact), the physical appearance of the Fern Glen Formation indicates that inclusion in the shallow aquifer is warranted. The Fern Glen Formation generally is more porous and vuggy than the lower, unweathered Burlington-Keokuk Limestone, and it probably is at least as permeable.

The weathered and the unweathered units of the Burlington-Keokuk Limestone are geologic units that are distinguished from each other based on physical characteristics. Because these physical characteristics increase the ability of the weathered unit to transmit water, these units can also be regarded as geohydrologic units. For example, the lower RQD of the weathered unit as compared to that of the unweathered unit is mainly a function of the larger number of mostly horizontal fractures and partings that transmit water. The voids and breccia zones in the weathered unit also are more permeable, although the voids are sometimes at least partially clay-filled (Carman, 1991). This distinction of the weathered unit and the unweathered unit as different geohydrologic units has been recognized for the WSCP and vicinity by the DOE (MK-Ferguson Company and Jacobs Engineering Group, 1992) and can also be applied to the remainder of the WSOW. Hydraulic conductivity data from both the WSCP and the remainder of the WSOW support this distinction. Hydraulic conductivities measured by DOE for the WSCP and vicinity using slug tests range from 5×10^{-3} to 0.75 ft/day (average of 0.09 ft/day) for 17 monitoring wells completed in the unweathered unit and from 0.06 to 12.8 ft/day (average of 1.97 ft/day) for 7 monitoring wells and piezometers completed in the weathered unit (compiled from data in Durham, 1992). Durham (1992) states that most of the higher hydraulic conductivity values are from monitoring wells in the northern one-half of the WSCP. Hydraulic conductivities measured by the Army for the WSTA and for the WSOW north of the WSTA and WSCP using slug tests range from 1.3×10^{-4} to 0.01 ft/day (average of 1.4×10^{-3} ft/day) for 9 monitoring wells completed in the unweathered unit and from 6.8×10^{-4} to 0.08 ft/day (average of 0.01 ft/day) for 12 monitoring wells completed in the weathered unit (compiled from data in International Technology Corporation, 1993). The difference in the hydraulic conductivities measured by the Army and DOE may reflect different slug test methods used or differences in well construction. However, the trend for both sets of measurements is the same—the weathered unit generally has higher hydraulic conductivities than the unweathered unit.

The strongly weathered subunit of the weathered unit is characterized by increased amounts or a greater intensity of the same characteristics that distinguish the more permeable weathered unit from the less permeable unweathered unit. These characteristics include lower RQD, lower core recovery, more breccia and vugs, and increased porosity. This subunit would, therefore, appear to be a more permeable unit than the rest of the weathered unit. However, because monitoring wells generally are only partially completed in the strongly weathered subunit, hydraulic conductivity data are sparse, and the hydrologic significance of the strongly weathered subunit has not been clearly demonstrated. Two DOE monitoring wells are completed exclusively in the strongly weathered subunit; a slug test was performed on one of these. Four Army monitoring wells are completed exclusively in the strongly weathered subunit; slug tests were performed on two of these. Hydraulic conductivities determined from 8 packer tests exclusively on the strongly weathered subunit ranged from 0.25 to 24 ft/day (average of 8.57 ft/day), and hydraulic conductivities from 16 packer tests exclusively on the weathered unit without any strongly weathered subunit ranged from less than 1.8×10^{-3} to 25.8 ft/day (average of 3.42 ft/day; compiled from data in Bechtel National, Inc., 1987).

The weathered unit, residuum, basal till, and glacial outwash (where there is no glacial till below it) is the upper, more permeable part of the shallow aquifer, which overlies the lower, less permeable part of the shallow aquifer (unweathered unit of the Burlington-Keokuk Limestone and the Fern Glen Formation; fig. 2). The contact between the upper and lower parts of the shallow aquifer is gradational. A thickness map of the upper part of the shallow aquifer is shown on plate 12. The upper part of the shallow aquifer is thickest at two monitoring wells (MWD-15 and MW-4003; pls. 1, 8) where the weathered unit is thickest. A partial thickness of the upper part of the shallow aquifer is shown on plate 12 for much of the WSTA because the bottom of the weathered unit was not penetrated by many monitoring wells. The bedrock paleovalley that extends through the eastern part of the WSCP (pl. 5) is reflected as a thin upper part of the shallow aquifer (pl. 12) because the weathered unit is thin there (pl. 8). Generally, the upper part of the shallow aquifer thins to the north, reflecting the thin to absent weathered unit north of the WSTA and WSCP. The thickness of the upper part of the shallow aquifer also is larger in the vicinity of monitoring well MWS-108 (pl. 1) because of the thick (30 ft) glacial outwash at this location.

The geologic units in which monitoring wells are completed are shown in tables 1 and 2 and are shown on a well completion map (pl. 13). These monitoring wells include those that are presently (1996) active, inactive, and have been abandoned. The open interval consists of the well screen and sand filter pack or the uncased part of open bedrock wells. This map facilitates correlation of data from well to well throughout the WSOW, regardless of whether the wells are Army or DOE monitoring wells. Because of long completion intervals for some DOE monitoring wells, many more monitoring wells at and in the vicinity of the WSCP are completed in both the weathered and unweathered units than there are at the WSTA or other parts of the WSOW. Many of the Army monitoring wells at the WSTA are completed in the weathered unit of the Burlington-Keokuk Limestone, but the base of this unit was not penetrated during the drilling of some of these monitoring wells. Fewer Army monitoring wells are completed in the unweathered unit of the Burlington-Keokuk Limestone than DOE monitoring wells. Some of the deeper Army monitoring wells are at least partially completed in units below the Burlington-Keokuk Limestone. Geologic data are not available to determine specific units in which most of the USGS-series monitoring wells and some DOE monitoring wells are completed. Several clusters of two or more monitoring wells exist and, especially at the WSCP, commonly consist of one monitoring well completed in the weathered unit and one completed in the unweathered unit. Other monitoring well clusters consist of one monitoring well straddling the weathered unit/unweathered unit contact and the other well completed in only one of these units (pl. 13). Other combinations exist, including well clusters with one well completed in the overburden unit and the other well completed in the weathered unit, or with one of the monitoring wells in a unit below the Burlington-Keokuk Limestone.

Ground-Water Flow

Ground-water flow at the WSOW has been described previously both at a small scale for the WSTA and the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992; International Technology Corporation, 1993) and at a larger scale for all of St. Charles County (Kleeschulte and Imes, 1994). The latter report includes the results of simulation of ground-water flow for the three-aquifer system. This section is not a comprehensive description of all aspects of ground-water flow at the WSOW. Instead, this section presents interpretations of ground-water flow in the shallow aquifer at the WSOW that are based on an improved understanding of the geohydrologic framework of the WSOW resulting from this study.

The WSCP is located in part of the shallow aquifer recharge area. This is demonstrated for the WSCP by downward hydraulic head gradients in most monitoring well clusters, most of which have the deeper monitoring well completed in the unweathered unit. Historical hydraulic head differences for these well clusters range from less than 1 ft to generally less than 10 ft, although a few monitoring well clusters have larger hydraulic head differences. One well cluster (MW-2018 and MW-2019; pl. 2) historically shows a hydraulic head difference of as much as 25 ft (data on file at the U.S. Geological Survey office, Rolla, Missouri). The vertical component of the hydraulic head gradient at this well cluster, measured between the midpoints of the open intervals of the monitoring wells, is approximately 0.43 ft of hydraulic head per foot of altitude. Monitoring well clusters composed of a monitoring well completed in the weathered unit and a deeper well straddling the weathered unit/unweathered unit contact show historical downward hydraulic head differences that generally are less than 1 ft.

The WSTA generally is considered part of the recharge area for the shallow aquifer. However, historical water-level data collected by the Army show that both downward and upward hydraulic head differences exist (International Technology Corporation, 1995), depending on local conditions. Downward hydraulic head differences indicate ground-water recharge, and upward hydraulic head differences may indicate local discharge zones along streams. Downward hydraulic head differences are more common at Army monitoring well clusters consisting of a monitoring well completed in the overburden unit and at least one monitoring well completed in the bedrock. A downward hydraulic head difference ranging from less than 1 ft to as much as 6 ft exists most or all of the time at six of these monitoring well clusters. However, an upward hydraulic head difference of less than 2 ft historically exists between one monitoring well completed in the bedrock and its paired monitoring well completed in the overburden (MWS-09 and MWV-09; pl. 1). Upward hydraulic head differences of less than 2 ft also occasionally exist at two other monitoring well pairs completed in the overburden and bedrock (MWV-01 and MWS-01, MWV-13 and MWS-13; pl. 1). Six monitoring wells completed in the overburden are normally or occasionally dry. The upward hydraulic head differences and the overburden monitoring wells that are dry probably are the result of topographic positions and locations adjacent to streams. Most monitoring wells and well clusters are along streams that have either been classified as losing streams (Missouri Division of Geology and Land Survey, 1991; Price, 1991) or not classified but where streambed altitudes are above the potentiometric surface. The potentiometric surface is below the bottom of the overburden monitoring wells that are dry. The upward hydraulic head differences between monitoring wells along streams that are completed in the overburden and the bedrock indicate upward ground-water flow. Ground water discharges to gaining reaches of streams, but does not discharge to streams where the potentiometric surface is below the streambed. Instead, ground water can flow from the bedrock to the overburden where the overburden is permeable.

Both upward and downward hydraulic head differences exist at Army monitoring well pairs completed in the bedrock at the WSTA. Less than a 2-ft upward hydraulic head difference historically exists between monitoring well MWD-02, which is completed in the unweathered unit of the Burlington-Keokuk Limestone, and monitoring well MWS-02, which is completed mostly in the weathered unit of the Burlington-Keokuk Limestone (pl. 1). An upward hydraulic head difference of less than 0.5 ft also exists between monitoring wells MWD-06 and MWS-06 (pl. 1), both of which are completed in the unweathered unit. An upward hydraulic head difference of 12 to 17 ft exists between monitoring well MWD-05, completed in the Fern Glen Formation, and monitoring well MWS-05, which straddles the Burlington-Keokuk Limestone/Fern Glen Formation contact (pl. 1). These two monitoring wells are located along a stream in a steeply incised valley (pl. 1). An upward hydraulic head difference ranging from 30 to 50 ft exists between monitoring wells MWD-18 and MWS-18 (pl. 1), which also are located in a steeply incised valley. Both of these monitoring wells are completed in formations deeper than the Fern Glen Formation and, therefore, are below the shallow aquifer (table 1; fig. 2). However, the water-level measurements for monitoring well MWS-18 are suspect, possibly because of poor hydraulic connection between the aquifer and the monitoring well (Price, 1991). Historic downward ground-water hydraulic head differences between Army bedrock monitoring well pairs at the

WSTA generally were about 1 ft between monitoring wells MWS-09 (completed in the strongly weathered subunit of the weathered unit) and MWD-09 (completed in the unweathered unit) and generally less than 2 ft between monitoring wells MWS-15 and MWD-15 (which are both completed in the weathered unit). Limited water-level data from recently (1995) installed monitoring wells indicate downward hydraulic head differences of approximately 1 ft between monitoring wells MWS-23 (completed in the weathered unit) and MWD-23 (completed in the unweathered unit), and approximately 4 ft between monitoring wells MWS-25 (completed in the weathered unit) and MWD-25 (completed mostly in the unweathered unit).

A potentiometric surface map of the shallow aquifer was prepared using mainly water-level measurements collected by the USGS on September 25 and 26, 1995 (pl. 14; Schumacher and others, 1996). Water levels measured in September 1994 (Schumacher and others, 1996) were used for a few monitoring wells for which water-level measurements in September 1995 were not available. The different measurement date did not affect the position of potentiometric contours because the water levels generally do not vary substantially with time (Kleeschulte and Imes, 1994). For the same reason, this map is considered to be representative of the potentiometric surface at any time. Where water-level measurements were available for two or more monitoring wells in a well cluster, the measurement in the uppermost unit was used. Measurements of perched ground water that exists locally in the overburden at the WSCP (MK-Ferguson Company and Jacobs Engineering Group, 1992) were not used. Because the water level in the weathered unit can be expected to be higher than in the underlying unweathered unit in recharge areas and where only one well is present and it is in the unweathered unit, the water level was not used except as a general guide to position potentiometric contours. Where no weathered unit is present and the unweathered unit is at the top of the bedrock, as is the case for some monitoring wells north of the WSTA and WSCP away from the main area of recharge, the water level in the unweathered unit generally was used. Where the only well present straddles the weathered unit/unweathered unit contact, as is the case for many of the DOE monitoring wells surrounding the WSCP, the water level was used. Other information used to position potentiometric contours on plate 14 is the altitude of the streambeds and springs (Missouri Division of Geology and Land Survey, 1991; Price, 1991). The altitudes of perennial streams and springs were used as data values; potentiometric contours were drawn below the altitudes of intermittent streams and springs.

The potentiometric surface map of the shallow aquifer (pl. 14) shows a large ground-water mound in the south-central part of the WSTA. This mound is part of a generally east-west trending ground-water ridge through the WSTA and WSCP that defines a ground-water divide approximately coincident with the surface-water divide. The ground-water ridge indicates ground-water recharge. Areas north and south of the ground-water ridge are downgradient from it. The downgradient position of monitoring wells USGS-02, USGS-07 (pl. 1), and MWGS-03 (approximately 0.8 mi north of the central part of the study area) is reflected by small tritium concentrations in water samples from these wells (Schumacher, 1993).

Precipitation that percolates downward through fractures in the glacial drift confining unit recharges the shallow aquifer. Where this unit is not present, such as where the streams have incised through it (pl. 11) and probably in parts of the southern part of the WSTA and south of the WSTA, precipitation can be expected to recharge the shallow aquifer more readily. Reaches where the streams are projected to have eroded through the glacial drift confining unit (pl. 11) correspond to some of the losing stream reaches that are identified in Missouri Division of Geology and Land Survey (1991), Price (1991), and Kleeschulte and Emmett (1986) and are shown on plate 14. The removal of the glacial drift confining unit and exposure of the underlying shallow aquifer facilitates the loss of streamflow to the subsurface.

Ground-water flow in the upper part of the shallow aquifer is not limited to the weathered unit of the Burlington-Keokuk Limestone, but can also occur locally in permeable overburden units. The relation of the potentiometric surface of the shallow aquifer (pl. 14) and the top of bedrock (pl. 5) is shown on plate 15. This relation also is shown in hydrogeologic sections A-A' (fig. 3) and B-B' (fig. 4). The potentiometric surface is below the top of bedrock for most of the recharge area along the ground-water divide, and parts of the permeable weathered unit and strongly weathered subunit are unsaturated. Locations where the potentiometric surface is above the top of bedrock (pl. 15) indicate the potential for ground-water flow in permeable overburden units. However, ground water may be confined to the bedrock in some places by clay-rich zones in the residuum. During drilling, the overburden was dry at some monitoring wells until drilling penetrated the overburden/bedrock contact (M. Jank, International Technology Corporation, oral commun., 1995). Therefore, ground-water flow may not occur in the overburden in all areas indicated on plate 15. The potential for ground-water flow in permeable overburden units exists at places along the ground-water ridge, along parts of bedrock paleovalleys at the WSCP where the top of bedrock is low (MK-Ferguson Company and Jacobs Engineering Group, 1992; pls. 5, 15), in the north central part of the WSTA, and throughout much of the August A. Busch Memorial Wildlife Area north of the WSTA and WSCP, downgradient from the ground-water ridge. Generally, the residuum and locally other overburden units of the shallow aquifer, particularly the 30-ft thick glacial outwash subunit at monitoring well MWS-108 (pl. 1), potentially become more important as mediums of ground-water flow north and downgradient of the ground-water ridge, but are probably less important where clay-rich zones in the residuum confine ground water below in the bedrock. Also, because the thickness of the weathered unit generally decreases to the north and the unit is absent at several monitoring wells at the August A. Busch Memorial Wildlife Area (pl. 8), the weathered unit generally becomes a less important medium of ground-water flow downgradient to the north, and the more permeable upper part of the shallow aquifer becomes thinner (pl. 12).

Along the ground-water ridge that defines the recharge area, the potentiometric surface of the shallow aquifer generally is well below the base of the glacial drift confining unit (pl. 16). The presence of an unsaturated thickness of the shallow aquifer below the confining unit means that the aquifer is an unconfined (water table) aquifer in this area, even though it is below a confining unit. Downgradient to the north, the potentiometric surface gradually rises in relation to the base of the confining unit (pl. 16; figs. 3, 4). Farther north, the potentiometric surface is above the base of the glacial drift confining unit over a large area, indicating that the aquifer is confined (pl. 16; figs. 3, 4). This area of confined conditions is centered around the unnamed tributary to Dardenne Creek that contains Burgermeister spring and discharges to Lake 34 (pl. 16).

Upward ground-water gradients, indicating ground-water discharge, exist at the five Army monitoring well clusters at the August A. Busch Memorial Wildlife Area (monitoring wells MWS-105 and MWD-105; MWS-106 and MWD-106; MWS-107 and MWD-107; MWS-109 and MWD-109; and MWS-112 and MWD-112; pl. 1). Hydraulic heads above land surface exist at monitoring well MWD-106 and sometimes at monitoring well MWS-106. Other ground-water discharge features in the northern part of the study area include Burgermeister and other springs (Missouri Division of Geology and Land Survey, 1991; Price, 1991) and the gaining unnamed tributary to Dardenne Creek upstream of Burgermeister spring (Kleeschulte and Emmett, 1986), although other streams reaches in the vicinity are losing (pl. 14). In the northern part of the WSOW, north of the study area, ground water discharges to Dardenne Creek, which flows to the Mississippi River (Kleeschulte and Imes, 1994; fig. 1). Where the aquifer is confined in discharge areas, ground water probably discharges mainly through fractures in the glacial drift confining unit.

Burgermeister spring is an important point of ground-water discharge, and it contains contaminants that can be traced to operations at the WSCP and WSOW (Schumacher, 1993). From 1985 through 1990, the mean annual discharge from the spring ranged from 0.19 to 0.26 ft^3/s (cubic foot per second; Kleeschulte and Imes, 1994). Ground water discharging from Burgermeister spring has been traced from the east fork of the west tributary of Schote Creek, with a traveltime estimated between 12 and 24 hours, and from the middle fork of the west tributary of Schote Creek, with a travel time of 62 hours (Missouri Division of Geology and Land Survey, 1991). Both of these tributaries are in a different surface-water basin than Burgermeister spring. Ground-water flow to Burgermeister spring also has been traced from angle hole AH-2004 (pl. 2), with a traveltime of 2-1/2 to 3 days, and from MW-2032 (pl. 2), with a traveltime of 7 to 9 days (P.C. Patchin, oral commun., 1996). Other sources of ground water to Burgermeister spring include the raffinate pits and probably the east tributary of Schote Creek (Schumacher, 1993). A potentiometric-surface trough centered around Burgermeister spring indicates the convergence of ground-water flow to the Burgermeister spring area (pl. 14). This trough approximately aligns with the bedrock paleodrainage (pl. 14). This alignment has been interpreted to indicate that depressions on the top of bedrock (paleovalleys) may be areas of increased permeability (Kleeschulte and Imes, 1994).

Ground-water flow in the shallow aquifer has been characterized as diffuse with superimposed discrete flow zones (Kleeschulte and Imes, 1994). Dye traces (Missouri Division of Geology and Land Survey, 1991; Price, 1991) demonstrate discrete ground-water flow to springs. Although monitoring well density decreases north of the WSCP, existing data indicate that the weathered unit thins to the north, including along the flow path to Burgermeister spring (pl. 8). The weathered unit is absent at monitoring well MWD-105, which is along the flow path, and at monitoring well MWD-106, which is near Burgermeister spring (pls. 1, 8). Because of this and the existence of the bedrock paleodrainage, ground water that flows toward Burgermeister spring may have a substantial component that flows through the residuum or at the residuum/bedrock contact. Also, as ground water flows toward Burgermeister spring, the shallow aquifer changes from an unconfined to a confined aquifer (pl. 16; figs. 3, 4). Ground water flows from one surface-water basin to another, but, based on existing data, does not cross a subsurface bedrock high. The topographic high that separates surface-water basins is not due to a subsurface bedrock high, but is instead due to an increased thickness of overburden that may be glacial in origin (pls. 5, 10).

Little monitoring well data exist south of the WSTA and WSCP to trace ground-water flow from the east-west trending ground-water ridge that represents the recharge area. A number of perennial and intermittent springs occur along the deeply incised tributaries to the Missouri River in this area, particularly in the southeastern part of the WSOW, and dye traces to some of these springs have been conducted (Missouri Division of Geology and Land Survey, 1991; Price, 1991). These springs are mostly in the Burlington-Keokuk Limestone (Missouri Division of Geology and Land Survey, 1991). Generally, the potentiometric surface gradient is greater to the south than to the north of the ground-water ridge, reflecting the topographic control over the potentiometric surface. Because the bedrock dips to the northeast, the potentiometric surface slopes counter to it south of the ground-water divide, whereas it slopes in the same direction north of the divide. Because of the bedrock dip, bedrock units become progressively older to the southwest. The intersection of the top of the Fern Glen Formation (pl. 4) with the potentiometric surface is approximately shown on the potentiometric surface map as a dashed line, south of which the Burlington-Keokuk Limestone is unsaturated, and the potentiometric surface of the shallow aquifer is in the Fern Glen Formation (pl. 14). The intersection of the top of the Chouteau Group (pl. 3) with the potentiometric surface is approximately shown as a dotted line on the potentiometric surface map, south of which the Fern Glen Formation is unsaturated. This line is the southern boundary of the saturated part of the shallow aquifer.

SUMMARY

A geohydrologic description of the Weldon Spring ordnance works (WSOW) was developed to facilitate the correlation of water-quality data between U.S. Army (Army) and U.S. Department of Energy (DOE) monitoring wells and, thereby, contribute to the understanding of the extent of contamination and potential spread of contamination at the WSOW. The U.S. Geological Survey (USGS) conducted a study from 1993 to 1996 in cooperation with the U.S. Army Corps of Engineers (COE) to create a common data base for Army and DOE geohydrologic data, and to use these together with USGS and Missouri Division of Geology and Land Survey (DGLS) data to develop a comprehensive geohydrologic description of the WSOW, exclusive of the Weldon Spring quarry (WSQ).

The WSOW is on the extreme northeast flank of the Ozark Dome. Uplift of the Ozark Dome produced a broad area of Paleozoic rocks that dip peripherally away from the Precambrian St. Francois Mountains in southeastern Missouri. This regional dip, together with the northwest-trending Eureka-House Springs Anticline located about 1 mile southwest of the WSOW, accounts for the northeast dip of the rocks at the WSOW—about 60 feet per mile for the top of the Chouteau Group. The Burlington-Keokuk Limestone of Mississippian age is the uppermost bedrock unit throughout most of the WSOW. Bedrock units older than the Burlington-Keokuk Limestone crop out in the southern part of the WSOW, a consequence of northeast dipping strata and deep incision by tributaries to the Missouri River.

The top of the bedrock forms a generally east-west trending ridge in the southern to central part of the Weldon Spring training area (WSTA) and the southern part of the Weldon Spring chemical plant (WSCP). Because subsurface data are sparse south of the WSTA, the top of bedrock is approximated in this

area. The top of the bedrock north of the ridge, where monitoring well data are available, contains a large, broad bedrock low centered about the unnamed tributary to Dardenne Creek that contains Burgermeister spring. This is interpreted to be a paleodrainage that existed before the deposition of glacial drift. This feature consists of smaller, more elongate paleovalleys at and west of the WSCP where more dense drill hole data provide better definition.

The unweathered unit of the Burlington-Keokuk Limestone is a light to medium gray, coarse to less commonly fine crystalline, thin to massive bedded, fossiliferous, cherty limestone that can be silty or argillaceous, or can locally be dolostone or siltstone. The contact between the Burlington-Keokuk Limestone and the underlying Fern Glen Formation is gradational and difficult to identify because of their facies relation. The weathered unit of the Burlington-Keokuk Limestone, which overlies the unweathered unit where both are present, is characterized by alterations that have been superimposed on the rock by weathering. These alterations are lithology and color changes, an increase in porosity, and an increase in mostly horizontal fractures and partings, some of which have undergone solution. The silty and argillaceous limestone and siltstone, as well as the purer limestone, commonly are orangish-brown because of discoloration by iron oxides. This discoloration permeates the rock as well as occurring along fracture and parting surfaces. Vugs and voids, some of which are associated with breccia, can be filled or partially filled by clay or a mixture of clay, silt, and chert gravel, and the removal of this fill by drilling fluid results in poor core recovery. Loss of fluid during drilling also is associated with zones of core loss. Weathering features occur throughout the Burlington-Keokuk Limestone, but are more common in the weathered unit. A strongly weathered subunit of the weathered unit has been identified where these features are particularly abundant or intense. Where present, it occurs as a single subunit at the top of the weathered unit at the WSTA, but can occur as more than one subunit anywhere in the weathered unit at and in the vicinity of the WSCP.

The weathered unit is present at all the monitoring wells and geotechnical borings at the WSTA and the WSCP, except at one where the Burlington-Keokuk Limestone is not present. At the August A. Busch Memorial Wildlife Area, north of the WSTA and WSCP, the weathered unit is absent or is generally thin compared to that at the WSCP and WSTA. Except for two monitoring wells where the weathered unit is unusually thick, the thickness of the weathered unit ranges from 0 to 66.5 feet. The strongly weathered subunit has a more limited distribution than the weathered unit.

The overburden units are, in ascending order: residuum, basal till, glacial till, including a glacial outwash subunit, the Ferrelview Formation, loess, alluvium, and fill. The residuum is variable in composition, ranging from clay-rich to chert-rich, contains chert, silt, and sand, locally contains limestone fragments, and is locally kaolinite-rich. The basal till is a sandy, clayey, silty gravel, or gravelly silt, characterized by angular chert loosely bound in a silty matrix. The glacial till consists of sandy, silty clay to clayey silt, with scattered chert, limestone, igneous, and metamorphic gravel and cobbles, and is characterized by hairline fractures and joints with iron and manganese oxide staining and nodules. As much as 30 feet of fining-upward, medium-coarse sand to clayey, sandy silt, identified as glacial outwash, has locally been identified as a subunit of the glacial till. The Ferrelview Formation overlies the glacial till and is a clay to silty clay with scattered sand, gravel and rock fragments, with typically less sand and more clay than the underlying glacial till, and with many hairline fractures or macropores. The Ferrelview Formation is similar in appearance to the glacial till, and it was difficult to differentiate the two in the review of Army overburden samples. Overlying the Ferrelview Formation is loess, which is silty clay to silt and has a sporadic distribution. Locally, alluvium and fill overlie older overburden units or bedrock. Some of the thickest overburden occurs in the northern part of the WSTA and north of the WSTA and may be caused by a larger thickness of glacial drift, rather than thicker residuum. The paleodrainage centered about the unnamed tributary to Dardenne Creek that contains Burgermeister spring appears to have been partially filled by glacial drift, and a surface-water divide now exists southeast of the tributary.

The shallow aquifer of a previously defined three-bedrock-aquifer system for St. Charles County was modified in this study to include permeable overburden units (residuum, basal till, and glacial outwash where there is no glacial till below it) with the Burlington-Keokuk Limestone and the Fern Glen Formation. The shallow aquifer was further defined by an upper, more permeable part, which consists of the permeable overburden units and the weathered unit of the Burlington-Keokuk Limestone, and a lower, less permeable part, which consists of the unweathered unit of the Burlington-Keokuk Limestone and the Fern Glen Formation. Generally, the upper part of the shallow aquifer thins to the north, reflecting the thin to absent weathered unit north of the WSTA and WSCP.

A glacial drift confining unit, consisting of parts of the glacial till and the Ferrelview Formation, was defined in this study. Because ground water as recharge and discharge probably move in fractures through this unit, it is considered to be a leaky confining unit. Although it does not actually confine ground water throughout most of the WSTA and WSCP where the potentiometric surface of the shallow aquifer is below its base, it confines ground water locally, particularly to the north of the WSTA and WSCP where the potentiometric surface of the shallow aquifer is above its base. There are stream reaches where the streams have cut through the glacial drift confining unit to expose the underlying shallow aquifer.

A potentiometric surface map of the shallow aquifer shows a large ground-water mound in the south-central part of the WSTA. This mound is part of a generally east-west trending ground-water ridge through the WSTA and the WSCP that defines a ground-water divide approximately coincident with the surface-water divide. Precipitation that percolates downward through fractures in the glacial drift confining unit recharges the shallow aquifer. Where the glacial drift confining unit is not present, precipitation can be expected to recharge the shallow aquifer more readily. Reaches where streams are projected to have eroded through the glacial drift confining unit correspond to some of the losing stream reaches that have been identified by the DGLS and the USGS.

Along most of the ground-water ridge that defines the recharge area, the potentiometric surface of the shallow aquifer is below the top of bedrock. There is the potential for ground-water flow in permeable overburden units where the potentiometric surface is above the top of bedrock. This condition exists at places along the ground-water ridge, along parts of bedrock paleovalleys at the WSCP, in the north central part of the WSTA, and throughout much of the August A. Busch Memorial Wildlife Area north of the WSTA and WSCP. Generally, the residuum and locally other overburden units of the shallow aquifer potentially become more important as mediums of ground water flow north and downgradient of the ground-water ridge, but are probably less important where clay-rich zones in the residuum confine ground water below in the bedrock. Because the thickness of the weathered unit generally decreases to the north and is absent at several monitoring wells at the August A. Busch Memorial Wildlife Area, the weathered unit generally becomes a less important medium of ground-water flow downgradient to the north.

Along the ground-water ridge that defines the recharge area, the potentiometric surface of the shallow aquifer generally is well below the base of the glacial drift confining unit, indicating that the aquifer is an unconfined aquifer in this area. Downgradient to the north, the potentiometric surface is above the base of the glacial drift confining unit over a large area, indicating that the aquifer is confined. Upward ground-water gradients measured in monitoring well pairs, Burgermeister and other springs, the gaining unnamed tributary to Dardenne Creek upstream of Burgermeister spring, and Dardenne Creek indicate ground-water discharge in the northern part of the WSOW.

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TABLES

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well

[Except as noted, stratigraphic intervals are interpretations of the cored interval only and are not extrapolated above or below the cored interval or from nearby wells; BK, Burlington-Keokuk Limestone; SW, strongly weathered subunit of the weathered unit of the Burlington-Keokuk Limestone; W, weathered unit of the Burlington-Keokuk Limestone; UNW, unweathered unit of the Burlington-Keokuk Limestone; FG, Fern Glen Formation; CH, Chouteau Group; BCH, Bachelor Formation; SS, Sulphur Springs Group; MK, Maquoketa Shale; KM, Kimmswick Limestone; DC, Decorah Group; PT, Plattin Limestone; JM, Joachim Dolomite; SP, St. Peter Sandstone; ft, feet; OVB, overburden; ?, questionable; --, not present; ND, no data; DGLS, Missouri Division of Geology and Land Survey; values are depths below land surface, in feet, except as noted; well construction data from International Technology Corporation (1993) and from data on file at the U.S. Geological Survey, Rolla, Missouri]

					Unit interval					
					Burlington-Keokuk Limestone (BK)					
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter-pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Fern Glen Formation (FG) (ft)	Chouteau Group (CH) (ft)
MWV-01	595.8	OVB	7.3-15.0	15.0	ND	ND	ND	ND	ND	ND
MWS-01[b]	595.9	BK (12 W, 5 UNW)	26.0-43.0	15.2	15.2-44.6[c]	15.2-23.0	15.2-38.0	38.0-44.6[c]	ND	ND
MWV-02	603.1	OVB	8.8-16.8	17.0	ND	ND	ND	ND	ND	ND
MWS-02	603.9	BK (15.3 W, 2.7 UNW)	37.8-55.8	15.5	ND	ND	ND	ND	ND	ND
MWD-02[b]	604.1	BK (UNW)	107.5-125.0	17.1[d]	17.1-133.5[c]	17.1-27.4[c]	17.1-53.3[c]	53.3-133.5	133.5-149.3[c]	ND
MWS-03[b]	633.7	BK (2.7 W, 14.3 UNW)[f]	46.0-63.0	41.0	41.0-59.5[c]	--	41.0-48.7	48.7-59.5[c]	ND	ND
MWS-04[b]	622.5	BK (11.4 SW, 7.6 W)	20.6-39.6	11.0[d]	11.0-39.6[c,e]	11.0-32.0[e]	11.0-39.6[c,e]	ND	ND	ND
MWS-05	599.1	BK (5.6 UNW)/FG (17.6)	43.8-67.0	35.0	ND	ND	ND	ND	ND	ND
MWD-05[b]	599.1	FG (18)/CH (0.1)	98.0-116.1	37.0	37.0-49.4	--	37.0-41.4	41.4-49.4	49.4-116.0	116.0-138.6
MWS-06	619.8	BK (UNW)	40.0-60.0	21.8	ND	ND	ND	ND	ND	ND
MWD-06[b]	619.9	BK (UNW)	112.1-129.5	21.9	21.9-150.0[c]	21.9-37.5	21.9-37.5	37.5-150.0[c]	ND	ND
MWS-07[b]	639.4	BK (10.6 SW, 8.4 W)[f,g]	44.0-63.0	43.5[d]	43.5-60.0[c,e]	43.5-54.6[c]	43.5-60.0[c,e]	ND	ND	ND
MWV-08	688.8	OVB	9.8-23.8	23.8	ND	ND	ND	ND	ND	ND
MWS-08[b]	688.9	BK (7.5 SW, 7.5 W)[f,g]	27.5-42.5	26.5[d]	26.5-41.5[c]	26.5-35.0	26.5-41.5[c]	ND	ND	ND
MWV-09	634.5	OVB	10.4-25.4	25.4	ND	ND	ND	ND	ND	ND
MWS-09	634.2	BK (SW)	31.6-46.6	25.0	ND	ND	ND	ND	ND	ND
MWD-09[b]	634.6	BK (UNW)	121.4-146.0	25.8	25.8-151.1[c]	25.8-53.0	25.8-53.0	53.0-151.1[c]	ND	ND
MWS-10[b]	652.5	BK (SW)	27.0-43.0	23.1	24.0-60.0[c,h]	24.0-54.0[h]	24.0-54.0[h]	54.0-60.0[c]	ND	ND
MWS-11[b]	674.8	BK (5.1 SW, 11.2 W)[f]	40.7-57.0	30.5	30.5-55.0[c]	30.5-45.8	30.5-55.0[c]	ND	ND	ND
MWS-12[b]	655.0	BK (3 SW, 14 W)	31.0-48.0	22.1	22.5-49.1[c,h]	22.5-34.0[h]	22.5-49.1[c,h]	ND	ND	ND

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

	Unit interval								
Well	Bachelor Formation (BCH) (ft)	Sulphur Springs Group (SS) (ft)	Maquoketa Shale (MK) (ft)	Kimmswick Limestone (KM) (ft)	Decorah Group (DC) (ft)	Plattin Limestone (PT) (ft)	Joachim Dolomite (JM) (ft)	St. Peter Sandstone (SP) (ft)	Remarks
MWV-01	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-01[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWV-02	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-02	ND	ND	ND	ND	ND	ND	ND	ND	Units open to well based on MWD-2 stratigraphy
MWD-02[b]	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock at 13.2?
MWS-03[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-04[b]	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock at 14.6?
MWS-05	ND	ND	ND	ND	ND	ND	ND	ND	Units open to well based on MWD-5 stratigraphy
MWD-05[b]	138.6-140.8	140.8-150.5[c]	ND	ND	ND	ND	ND	ND	
MWS-06	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units open to well based on MWD-6 stratigraphy
MWD-06[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-07[b]	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock at 37.5 or 54.6?
MWV-08	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-08[b]	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock at 33.0?
MWV-09	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-09	ND	ND	ND	ND	ND	ND	ND	ND	Unit open to well based on MWD-9 stratigraphy
MWD-09[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-10[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-11[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-12[b]	ND	ND	ND	ND	ND	ND	ND	ND	

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter-pack or open-hole interval (ft)	Top of bed-rock (ft)	Unit interval					
					Burlington-Keokuk Limestone (BK)					
					BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Fern Glen Formation (FG) (ft)	Chouteau Group (CH) (ft)
MWV-13	690.3	OVB	27.0-41.5	41.5	ND	ND	ND	ND	ND	ND
MWS-13[b]	690.2	BK (W)	48.1-71.1	40.5	41.0-71.1[c,h]	--	41.0-71.1[c,h]	ND	ND	ND
MWS-14[b]	702.8	BK (SW)[f,g]	24.9-41.8	7.0[d]	7.0-40.0[c,e]	7.0-40.0[c,e]	7.0-40.0[c,e]	ND	ND	ND
MWS-15	654.7	BK (2.9 SW, 13.6 W)[g]	31.5-48.0	26.4[d]	ND	ND	ND	ND	ND	ND
MWD-15[b]	654.3	BK (W)	117.0-133.5	26.0[d]	26.0-138.5[e]	26.0-34.0[e]	26.0-138.5[c]	--	138.5-160.0[c]	ND
MWV-16	649.5	OVB	25.0-39.0	39.7	ND	ND	ND	ND	ND	ND
MWS-16[b]	649.7	BK (W)	47.0-66.0	38.5	38.5-67.5[c]	--	38.5-67.5[c]	ND	ND	ND
MWV-17	658.5	OVB	4.0-17.0	17.0	ND	ND	ND	ND	ND	ND
MWS-17[b]	657.7	BK (1.5 W, 16.0 UNW)	32.0-49.5	19.0	19.5-49.5[c,h]	--	19.5-33.5[h]	33.5-49.5[c]	ND	ND
MWV-18	599.6	OVB	6.0-19.0	19.6	ND	ND	ND	ND	ND	ND
MWS-18	600.2	CH (15.5)/BCH (1.1)/SS (3.5)	54.9-75.0	20.0	ND	ND	ND	ND	ND	ND
MWD-18[b]	599.8	KM	113-129.5	20.0	--	--	--	--	20.0-48.7	48.7-70.0
MWS-19A[b,i]	646.8	--	--	36.5	36.5-60.0[c]	--	36.5-60.0[c]	ND	ND	ND
MWS-19[b]	646.8	BK (W)[f]	46.0-61.5	37.0	38.0-60.5[c,h]	--	38.0-60.5[c,h]	ND	ND	ND
MWS-20[b]	667.2	BK (10 W, 6 UNW)[f]	45.0-61.0	36.1	36.4-60.7[c,h]	--	36.4-55.0[h]	55.0-60.7[c]	ND	ND
MWS-21[b]	641	BK (SW)	36.5-50.9	36.3	36.5-50.9[c,h]	36.5-50.9[c,h]	36.5-50.9[c,h]	ND	ND	ND
MWV-22	661.9	OVB	25.0-37.6	37.6	ND	ND	ND	ND	ND	ND
MWS-22[b]	661.9	BK (W)	41.0-53.9	37.8	38.1-53.9[c,h]	--	38.1-53.9[c,h]	ND	ND	ND
MWS-23[b]	707	BK (W)	56.7-70.0	54.5	55.6-72.4[c,h]	--	55.6-72.4[c,h]	ND	ND	ND
MWD-23[b]	707.9	BK (UNW)[f]	113.0-125.5	36.5	38.3-125.5[c]	--	38.3-100.2	100.2-125.1[c]	ND	ND
MWV-24[b,i]	655	--	--	36.5	37.6-55.0[c,h]	--	37.6-55.0[c,h]	ND	ND	ND
MWS-24[b]	654.6	BK (W)	42.0-57.4	39.2	39.4-57.4[c,h]	--	39.4-57.4[c,h]	ND	ND	ND
MWVR-24	640	OVB	26.7-41.0	41.0	ND	ND	ND	ND	ND	ND

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

Well	Unit interval								Remarks
	Bachelor Formation (BCH) (ft)	Sulphur Springs Group (SS) (ft)	Maquoketa Shale (MK) (ft)	Kimmswick Limestone (KM) (ft)	Decorah Group (DC) (ft)	Plattin Limestone (PT) (ft)	Joachim Dolomite (JM) (ft)	St. Peter Sandstone (SP) (ft)	
MWV-13	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-13[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-14[b]	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock at 35.0?
MWS-15	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units open to well based on MWD-15 stratigraphy; auger refusal in MWS-15 at 15.0
MWD-15[b]	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock at 16.0 (auger refusal) or 34.0?
MWV-16	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-16[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWV-17	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-17[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWV-18	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-18	ND	ND	ND	ND	ND	ND	ND	ND	Units open to well based on MWD-18 stratigraphy
MWD-18[b]	70.0-71.1	71.1-91.0	--	91.0-150.3[c]	ND	ND	ND	ND	
MWS-19A[b,i]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-19[b]	ND	ND	ND	ND	ND	ND	ND	ND	Previously referred to as MWS-19B
MWS-20[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-21[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWV-22	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-22[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-23[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWD-23[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWV-24[b,i]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-24[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWVR-24	ND	ND	ND	ND	ND	ND	ND	ND	

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

					Unit interval					
					Burlington-Keokuk Limestone (BK)					
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter-pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Fern Glen Formation (FG) (ft)	Chouteau Group (CH) (ft)
MWS-25	680.8	BK (W)	47.0-59.6	36.2	ND	ND	ND	ND	ND	ND
MWD-25[b]	681.1	BK (0.8 W, 11.5 UNW)	102.2-114.5	36.5	36.5-114.5[c]	--	36.5-103.0	103.0-114.5[c]	ND	ND
MWS-26[b]	672.4	BK (W)	41.5-54.5	40.6	40.6-65.0[c]	--	40.6-65.0[c]	ND	ND	ND
MWS-101[b]	489.5	KM	50.0-85.0	44.0	--	--	--	--	--	--
MWS-102[b]	479.2	DC	57.5-90.0	53.0	--	--	--	--	--	--
MWS-103[b]	527.7	SS (5)/KM (32)	28.0-65.0	24.0	--	--	--	-	--	--
MWS-104[b]	564.7	BK (20.9 W, 12.2 UNW)[f]	22.9-56.0	15.5	16.1-54.9[c,h]	--?	16.1-43.8[h]	43.8-54.9[c]	ND	ND
MWS-105	573.7	BK (UNW)	30.2-69.2	28.7	ND	ND	ND	ND	ND	ND
MWD-105[b]	573.7	BK (15.1 UNW)/FG (21.9)[f]	115.3-152.3	28.9	28.9-130.4	--	--	28.9-130.4	130.4-150.0[c]	ND
MWS-106	530.7	BK (UNW)	25.0-48.0	21.8	ND	ND	ND	ND	ND	ND
MWD-106[b]	531.0	BK (18.1 UNW)/FG (15.4)	114.7-148.2	23.5	23.5-132.8	--	--	23.5-132.8	132.8-151.5[c]	ND
MWS-107[b]	607.2	BK (26.5 W, 7 UNW)	52.0-85.5	49.0	49.0-85.5[c]	--	49.0-78.5	78.5-85.5[c]	ND	ND
MWD-107[b]	607.2	BK (UNW)	121.5-134.0	46.0	46.0-134.0[c]	--	46.0-79.0	79.0-134.0[c]	ND	ND
MWS-108[b]	604.4	BK (UNW)[f]	52.0-85.0	50.3	50.3-84.3[c]	--	--	50.3-84.3[c]	ND	ND
MWS-109	550.3	BK (UNW)	41.2-75.5	22.0	ND	ND	ND	ND	ND	ND
MWD-109[b]	550.4	BK (19.8 UNW)/FG (14.4)	105.1-139.3	21.8	21.8-124.9	--	--	21.8-124.9	124.9-149.8[c]	ND
MWS-110[b]	604.8	BK (24 W, 10.5 UNW)	55.0-89.5	15.5	15.5-89.5[c]	--	15.5-79.0	79.0-89.5[c]	ND	ND
MWS-111[b]	620.8	BK (W)	42.0-75.2	35.5	35.7-75.2[c,h]	--	35.7-75.2[c,h]	ND	ND	ND
MWS-112[b]	572.6	BK (4.8 W, 7.7 UNW)	23.7-36.2	18.0	18.0-62.5[c]	--	18.0-28.5	28.5-62.5[c]	ND	ND
MWD-112	572.9	BK (UNW)?	93.3-105.8	18.3	ND	ND	ND	ND	ND	ND

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

	Unit interval								
Well	Bachelor Formation (BCH) (ft)	Sulphur Springs Group (SS) (ft)	Maquoketa Shale (MK) (ft)	Kimmswick Limestone (KM) (ft)	Decorah Group (DC) (ft)	Plattin Limestone (PT) (ft)	Joachim Dolomite (JM) (ft)	St. Peter Sandstone (SP) (ft)	Remarks
MWS-25	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units open to well based on MWD-25 stratigraphy
MWD-25[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-26[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-101[b]	--	--	--	44.0-85.0[c]	ND	ND	ND	ND	
MWS-102[b]	--	--	--	53.0-54.0	54.0-90.0[c]	ND	ND	ND	
MWS-103[b]	--	24.0-33.0	--	33.0-65.3[c]	ND	ND	ND	ND	
MWS-104[b]	ND	ND	ND	ND	ND	ND	ND	ND	Strongly weathered subunit from 22.9 to 43.8?
MWS-105	ND	ND	ND	ND	ND	ND	ND	ND	Units open to well based on MWD-105 stratigraphy
MWD-105[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-106	ND	ND	ND	ND	ND	ND	ND	ND	Units open to well based on MWD-106 stratigraphy
MWD-106[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-107[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWD-107	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-108[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-109	ND	ND	ND	ND	ND	ND	ND	ND	Units open to well based on MWD-109 stratigraphy
MWD-109[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-110[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-111[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWS-112[b]	ND	ND	ND	ND	ND	ND	ND	ND	
MWD-112	ND	ND	ND	ND	ND	ND	ND	ND	Retrofit of USGS-7; top of bedrock from MWS-112

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

					Unit interval					
					Burlington-Keokuk Limestone (BK)					
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter-pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Fern Glen Formation (FG) (ft)	Chouteau Group (CH) (ft)
USGS-1	589	BK (UNW)	57-107	38 ?	38(?)-107[c,j]	ND	38-48 ?	48-107[c] ?	ND	ND
USGS-2	554	BK	at 50	50[k]	at 50[j]	ND	ND	ND	ND	ND
USGS-2A	559	OVB (24)?/BK (57)	26-107	50 ?	50(?)-107[c,j]	ND	ND	ND	ND	ND
USGS-3	585	BK	66-80	66[k]	66-80[c,j]	ND	ND	ND	ND	ND
USGS-4	601	BK	30-107	30[k]	30-107[c,j]	ND	ND	ND	ND	ND
USGS-5	580	BK	23-87	23[k]	23-87[c,j]	ND	ND	ND	ND	ND
USGS-6	590	BK (UNW)	70-107	56 ?	56(?)-107[c,j]	ND	56-70 ?	70-107 ?	ND	ND
USGS-7[l]	572.9	BK (UNW)?	32-105.8	18.3	18.3-105.8[c,j]	ND	ND	ND	ND	ND
USGS-8	625	BK	60-107	60[k]	60-107[c,j]	ND	ND	ND	ND	ND
USGS-9	590	BK	24-90	24[k]	24-90[c,j]	ND	ND	ND	ND	ND
MWGS-1	647.7	?/KM	?-320	22.6	ND	ND	ND	ND	ND	ND
MWGS-2[m]	647.1	JM (14)/SP (16.5)	631-661.5	22	22-180	ND	ND	ND	180-245	245-265
MWGS-3	485	BK	?-98.5	29.7	ND	ND	ND	ND	ND	ND
MWGS-4	484.7	?/KM	?-310	29.4	ND	ND	ND	ND	ND	ND
MWGS-5[m]	485.3	SP ?	612-620	30	30-135	ND	ND	ND	135-185	185-228
Army Well (DGLS 4843)	670	BK (103.5)/FG (50)/ CH (28)/SS (12)	41.5-235	41.5[k]	110-145	ND	ND	ND	145-195	195-223

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

Well	Unit interval								Remarks
	Bachelor Formation (BCH) (ft)	Sulphur Springs Group (SS) (ft)	Maquoketa Shale (MK) (ft)	Kimmswick Limestone (KM) (ft)	Decorah Group (DC) (ft)	Plattin Limestone (PT) (ft)	Joachim Dolomite (JM) (ft)	St. Peter Sandstone (SP) (ft)	
USGS-1	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units identified from gamma log
USGS-2	ND	ND	ND	ND	ND	ND	ND	ND	Well open only at bottom of casing
USGS-2A	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock assumed to be same as USGS-2 (top of bedrock in USGS-2A was earlier picked at 26 ft)
USGS-3	ND	ND	ND	ND	ND	ND	ND	ND	
USGS-4	ND	ND	ND	ND	ND	ND	ND	ND	
USGS-5	ND	ND	ND	ND	ND	ND	ND	ND	
USGS-6	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units identified from gamma log
USGS-7[1]	ND	ND	ND	ND	ND	ND	ND	ND	Well has been retrofitted to MWD-112; top of bedrock from MWS-112
USGS-8	ND	ND	ND	ND	ND	ND	ND	ND	
USGS-9	ND	ND	ND	ND	ND	ND	ND	ND	
MWGS-1	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock approximated from MW-4019 (nearby); units open to well based on stratigraphy in paired well MWGS-2
MWGS-2[m]	--	265-285	285-296	296-400	400-428	428-540	540-645	645-661.5[c]	Top of bedrock approximated from MW-4019 (nearby)
MWGS-3	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units open to well based on MWGS-5 stratigraphy; MWGS-3, MWGS-4, and MWGS-5 are clustered; well is located north of study area
MWGS-4	ND	ND	ND	ND	ND	ND	ND	ND	Top of bedrock and units open to well based on MWGS-5 stratigraphy; MWGS-3, MWGS-4, and MWGS-5 are clustered; well is located north of study area
MWGS-5[m]	--	228-259	259-268	268-353	353-378	378-509	509-610 ?	610-620[c] ?	Bottom 10 ft probably St. Peter Sandstone; MWGS-3, MWGS-4, and MWGS-5 are clustered; well is located north of study area
Army Well (DGLS 4843)	--	223-235	ND	ND	ND	ND	ND	ND	Samples start in Burlington-Keokuk Limestone, below top of bedrock

Table 1. Stratigraphic and selected well construction data for U.S. Army monitoring wells, USGS-series and MWGS-series monitoring wells, and the Army well—Continued

[a]Weathered unit interval in the third column does not include the strongly weathered subunit interval.
[b]Cored; geologic log of bedrock prepared as part of this study.
[c]Core or well ends in unit; bottom of unit not intersected.
[d]Top of bedrock is questionable.
[e]Unit interval is different if the top of bedrock is identified at a different depth.
[f]Open interval of well extends below bottom of core; bottom part of open interval assumed to be same unit as bottom of core.
[g]Units open to well may be different if top of bedrock is identified at a different depth.
[h]Core starts in unit, below top of bedrock.
[i]Well is abandoned.
[j]No samples or geologic log available. Burlington-Keokuk Limestone interval inferred from other wells and geologic-structure maps.
[k]Top of bedrock is assumed to be approximately at bottom of casing.
[l]Well has been retrofitted and renumbered.
[m]Formation contacts, except for the Maquoketa Shale, are from DGLS logs of drill cuttings (DGLS 28669 for MWGS-2, DGLS 28672 for MWGS-5). Because of the lag time for cuttings to come to the surface for collection during drilling, these contacts may be slightly higher in altitude than the logs indicate. The Maquoketa Shale was identified from a gamma log, and this log indicates that the Maquoketa Shale is at a slightly higher altitude than the drill-cutting log indicates.

Table 2. Stratigraphic and well construction data for U.S. Department of Energy monitoring wells

[Stratigraphic intervals are interpretations of the cored interval only and are not extrapolated above or below the cored interval, or from nearby wells; BK, Burlington-Keokuk Limestone; SW, strongly weathered subunit of the weathered unit of the Burlington-Keokuk Limestone; W, weathered unit of the Burlington-Keokuk Limestone; UNW, unweathered unit of the Burlington-Keokuk Limestone; ft, feet; OVB, overburden; ?, questionable; --, not present; ND, no data; values are depths below land surface, in feet, except as noted; except as noted, data are from P.C. Patchin, Morrison Knudsen Corporation; Julie Reitinger, MK-Ferguson Company; and MK-Ferguson Company and Jacobs Engineering Group (1992)]

					Unit interval				
					Burlington-Keokuk Limestone (BK)				
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter-pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Remarks
MW-2001[b]	611.8	BK (21.7 W, 10.7 UNW)[c]	31.6-64.0	26.5	26.5-60.0[d]	--	26.5-53.3	53.3-60.0[d]	
MW-2002[b]	623.8	BK (W)[c]	31.7-64.0	28.5[e]	28.5-60.0[d,f]	--	28.5-60.0[d,f]	ND	Top of bedrock at 24.5 (auger refusal)?; paired with MW-2021
MW-2003[b]	637.1	BK (3.7 W, 2.5 SW, 7.3 W, 9.0 SW)[c]	41.5-64.0	38.8[e]	38.8-59.0[d,f]	45.2-47.7 55.0-59.0[d]	38.8-59.0[d,f]	ND	Top of bedrock at 32.5 (auger refusal)?
MW-2004[g]	642.8	BK (9.6 W, 4.9 SW, 1.2 W, 7.0 UNW)[c]	54.3-77.0	37.0[e]	37.0-72.0[d,f]	37.0-51.7[f] 63.9-68.8	37.0-70.0[f]	70.0-72.0[d]	Top of bedrock at 51.7?; paired with MW-2029
MW-2005	635.7	BK (1.7 SW, 6.8 W, 3.8 SW, 18.7 W)[c]	50.0-81.0	44.8[e]	44.8-76.0[d,f]	44.8-51.7[f] 58.5-62.3	44.8-76.0[d,f]	ND	Top of bedrock at 32.7?; paired with MW-2022
MW-2006	634.2	BK (3.5 W, 3.8 SW, 6.6 W, 6.9 SW, 10.3 W, 12.9 UNW)[c]	27.0-71.0	22.6	22.6-65.5[d]	30.5-34.3 40.9-47.8	22.6-58.1	58.1-65.5[d]	Paired with MW-2026
MW-2007	651.9	BK (9.3 W, 4.4 SW, 13 W, 10.0 UNW)[c,h]	62.3-99.0	59.0	59.0-94.0[d]	71.6-76.0 ?	59.0-89.0	89.0-94.0[d]	Possible SW 59.0-66.8; SW 71.6-76.0 is questionable
MW-2008[b,g]	622.7	BK (17.3 W, 11.7 UNW)[c]	34.0-63.0	31.5	31.5-57.0[d]	--	31.5-51.3	51.3-57.0[d]	Paired with MW-2025
MW-2009[g]	636.3	BK (SW)[c]	27.2-58.6	20.5	20.5-54.0[d]	20.5-54.0[d]	20.5-54.0[d]	ND	
MW-2010	642.9	BK (W)[c]	37.2-64.0	32.8	32.8-59.0[d]	--	32.8-59.0[d]	ND	
MW-2011	653.2	BK (34.8 W, 7.7 UNW)[c]	36.5-79.0	32.0	32.0-74.0[d]	--	32.0-71.3	71.3-74.0[d]	Paired with MW-2030
MW-2012[b]	634.8	BK (21.7 W, 18.5 UNW)[c]	29.3-69.5	25.5	25.5-60.0[d]	--	25.5-51.0	51.0-60.0[d]	
MW-2013	645.4	BK (28.7 W, 15.0 UNW)[c]	31.3-75.0	27.5	27.5-70.0[d]	--	27.5-60.0	60.0-70.0[d]	Clustered with MW-2027 and MW-2033
MW-2014	647.6	BK (7.2 W, 10.8 SW, 9.0 W)[c]	37.0-64.0	33.0	33.0-59.0[d]	33.0-36.7 44.2-55.0	33.0-59.0[d]	ND	
MW-2015	657.7	BK (0.4 SW, 15.3 W, 4.7 SW, 2.7 W, 15.6 UNW)[c]	47.3-86.0	45.5	45.5-80.5[d]	45.5-47.7 63.0-67.7	45.5-70.4	70.4-80.5[d]	Paired with MW-2028

Table 2. Stratigraphic and well construction data for U.S. Department of Energy monitoring wells—Continued

Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter pack or open-hole interval (ft)	Top of bed-rock (ft)	Unit interval: Burlington-Keokuk Limestone (BK): BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Remarks
MW-2016[b]	635.7	BK (1.8 SW, 86.0 UNW)[c]	62.7-150.5	54.0	57.7-148.6[d,i]	57.7-64.5[i]	57.7-64.5[i]	64.5-148.6[d]	Clustered with MW-2023, MW-2024, and MW-2032
MW-2017	657.9	BK (4.0 SW, 14.2 W, 6.8 SW, 6.8 W, 7.2 UNW)[c]	30.0-69.0	23.5[e]	23.5-64.0[d,f]	23.5-34.0[f] 48.2-55.0 ?	23.5-61.8[f]	61.8-64.0[d]	Top of bedrock at 29.0?; contacts of lower SW interval questionable; paired with MW-2034
MW-2018	661.7	BK (SW)[c]	37.4-69.0	32.5	32.5-65.0[d]	32.5-65.0[d]	32.5-65.0[d]	ND	Paired with MW-2019
MW-2019	661.5	BK (UNW)[c]	103.0-116.4	ND	81.0-116.0[d,i]	ND	ND	81.0-116.0[d,i]	Paired with MW-2018
MW-2020[j]	655.1	BK (7.5 SW, 23.8 W, 51.8 UNW)[h]	36.5-119.6	23.7[e]	36.5-119.6[d,i]	36.5-44.0[i]	36.5-67.8[i]	67.8-119.6[d]	Top of bedrock questionable because roller bit was used to 36.5; W/UNW at 47.5?; retrofit of MW-2044
MW-2021[b]	624.6	BK (UNW)[c]	96.3-111.0	ND	81.5-110.7[d,i]	ND	ND	81.5-110.7[d,i]	Paired with MW-2002
MW-2022	636.1	BK (UNW)	112.0-126.5	ND	100.5-128.0[d,i]	ND	ND	100.5-128.0[d,i]	Paired with MW-2005
MW-2023	635.8	BK (UNW)	68.5-91.5	ND	ND	ND	ND	ND	No log; unit open to well based on stratigraphy in MW-2016; clustered with MW-2016, MW-2024, and MW-2032
MW-2024	634.9	BK (UNW)	135.0-149.6	ND	ND	ND	ND	ND	No log; unit open to well based on stratigraphy in MW-2016.; clustered with MW-2016, MW-2023, and MW-2032
MW-2025[b,g]	622.2	BK (UNW)	94.0-108.6	ND	70.5-108.6[d,i]	ND	ND	70.5-108.6[d,i]	Paired with MW-2008
MW-2026	634.8	BK (UNW)	105.5-118.0	ND	81.0-118.0[d,i]	ND	ND	81.0-118.0[d,i]	Paired with MW-2006
MW-2027	644.3	BK (UNW)[c]	107.0-122.0	ND	80.2-120.0[d,i]	ND	ND	80.2-120.0[d,i]	Clustered with MW-2013 and MW-2033
MW-2028	657.8	BK (UNW)[c]	116.0-131.5	ND	91.6-131.2[d,i]	ND	ND	91.6-131.2[d,i]	Paired with MW-2015
MW-2029[g]	643.1	BK (UNW)	89.0-101.3	ND	ND	ND	ND	ND	No log; unit open to well based on stratigraphy in paired well MW-2004
MW-2030[b]	652.9	BK (12 W, 16.5 SW)	30.5-59.0	29.5	29.5-60.9[d]	42.5-60.9[d]	29.5-60.9[d]	ND	Paired with MW-2011

Table 2. Stratigraphic and well construction data for U.S. Department of Energy monitoring wells—Continued

					Unit interval				
					Burlington-Keokuk Limestone (BK)				
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Remarks
MW-2031[g]	660.6	OVB (3.0)/BK (9.5 W)	55.0-67.5	58.0	58.0-67.5[d]	--	58.0-67.5[d]	ND	
MW-2032	635.8	OVB (5.2)/BK (5.4 W)[h]	48.0-58.6	53.2[e]	53.2-60.0[d,f]	--	53.2-60.0[d,f] ?	ND	Top of bedrock at 48.5 (auger refusal)?; W/UNW at 58.5?; clustered with MW-2016, MW-2023, and MW-2024
MW-2033	644.8	OVB (0.1)/BK (23.1 W)	23.1-46.3	23.2	23.2-47.5[d]	--	23.2-47.5[d]	ND	Clustered with MW- 2013 and MW-2027
MW-2034	658.2	BK (14.3 W, 3.4 SW, 7.8 W)	34.5-60.0	34.5	34.5-60.0[d]	48.8-52.2	34.5-60.0[d]	ND	Paired with MW-2017
MW-2035	667.0	BK (10.3 W, 4.4 UNW)	62.8-77.5	35.0	35.0-77.5[d]	35.0-59.5	35.0-73.1	73.1-77.5[d]	
MW-2036	655.9	BK (2.7 SW, 2.6 W, 1.6 SW, 5.2 W, 3.4 UNW)	52.5-68.0	46.0	46.0-68.0[d]	46.0-55.2 57.8-59.4	46.0-64.6	64.6-68.0[d]	
MW-2037	656.7	BK (SW)[c]	45.5-63.5	40.0[e]	40.0-61.0[d,f]	40.0-61.0[d,f]	40.0-61.0[d,f]	ND	Top of bedrock at 43.5?
MW-2038	665.0	ND	55.0-71.5	52.5	ND	ND	ND	ND	Rock not cored; no samples or log
MW-2039	663.4	ND	53.3-69.0	44.5	ND	ND	ND	ND	Rock not cored; no samples or log
MW-2040	662.4	ND	54.5-74.0	44.5	ND	ND	ND	ND	Rock not cored; no samples or log
MW-2041	661.6	ND	61.5-82.0	43.0	ND	ND	ND	ND	Rock not cored; no samples or log
MW-2042	662.7	ND	56.0-77.5	43.5	ND	ND	ND	ND	Rock not cored; no samples or log
MW-2043	662.6	ND	56.5-75.0	45.0	ND	ND	ND	ND	Rock not cored; no samples or log
MW-2044	655.1	BK (6.9 SW, 20.1 W)[h]	37.1-64.1	23.7[e]	36.5-119.6[d,i]	36.5-44.0[i]	36.5-67.8[i]	67.8-119.6[d]	Retrofit of MW-2020; top of bed-rock questionable because roller bit was used to 36.5; W/UNW at 47.5?
MW-3001[g]	664.3	OVB (0.7)/BK (24.5 SW)	52.8-78.0	53.5[e]	53.5-90.0[d]	53.5-80.2	53.5-85.0	85.0-90.0[d]	Paired with MW-3002
MW-3002[b,g]	664.7	BK (UNW)	134.0-150.0	53.5[e]	65.0-150.0[d,i]	65.0-80.8[i]	65.0-80.8[i]	80.8-150.0[d]	Top of bedrock at 65.0?; paired with MW-3001

Table 2. Stratigraphic and well construction data for U.S. Department of Energy monitoring wells—Continued

					Unit interval				
					Burlington-Keokuk Limestone (BK)				
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Remarks
MW-3003	645.5	BK (2.2 W, 12.1 UNW) ?	75.7-90.0	28.0	ND	ND	ND	ND	No log; units open to well based on stratigraphy in MW-3007; clustered with MW-3006, MW-3007, and MW-3023
MW-3004[g]	653.5	OVB	13.7-21.8	ND	ND	ND	ND	ND	
MW-3005	663.4	OVB	24.3-37.0	ND	ND	ND	ND	ND	
MW-3006	645.9	BK (UNW)[c]	120.0-135.5	ND	98.0-135.3[d,i]	ND	ND	98.0-135.3[d,i]	Clustered with MW-3003, MW-3007, and MW-3023
MW-3007	645.6	BK (7.2 SW, 16.6 W, 3.4 SW, 11.8 W, 21.1 UNW)	39.0-99.1	25.0[e]	39.0-99.1[d,i]	39.0-46.2[i] 62.8-66.2	39.0-78.0[i]	78.0-99.1[d]	Top of bedrock questionable because roller bit was used to 39.0; 25.0-39.0 may be SW; clustered with MW-3003, MW-3006, and MW-3023
MW-3008[j]	645.2	BK (17.8 W, 5.7 SW, 8.5 W, 30.0 UNW)	39.0-101.0	28.0	39.0-101.0[d,i]	56.8-62.5	39.0-71.0[i]	71.0-101.0[d]	Retrofit of MW-3024
MW-3009[j]	644.3	BK (1.0 SW, 9.6 W, 43.8 UNW)	45.0-99.4	35.0	45.0-99.4[d,i]	45.0-46.0[i]	45.0-55.6[i]	55.6-99.4[d]	Retrofit of MW-3026
MW-3010[g]	665.0	BK (23.3 W, 14.9 UNW)	52.5-90.7	38.0	52.5-90.7[d,i]	--	52.5-75.8[i]	75.8-90.7[d]	
MW-3011	649.2	OVB	20.0-23.5	23.5	ND	ND	ND	ND	
MW-3013	641.5	OVB	?-22.0	ND	ND	ND	ND	ND	
MW-3015	640.1	OVB	?-20.0	ND	ND	ND	ND	ND	
MW-3016	664.0	OVB	?-51.0	ND	ND	ND	ND	ND	
MW-3017[g]	649.8	OVB	?-35.0	ND	ND	ND	ND	ND	
MW-3018	631.0	OVB	18.8-29.6	29.6	ND	ND	ND	ND	
MW-3019	660.1	BK (8.3 W, 6.0 UNW)	70.0-84.3	35.0	35.0-84.3[d]	35.0-61.8	35.0-78.3	78.3-84.3[d]	
MW-3022[g]	656.9	OVB (10.3)/BK (5.5 W)	35.2-51.0	45.5	45.5-51.0[d]	--	45.5-51.0[d]	ND	
MW-3023	645.9	BK (6.8 W, 13.9 SW, 5.3 W)	22.0-48.0	22.0	22.0-57.0[d]	28.8-42.7	22.0-57.0[d]	ND	Clustered with MW-3003, MW-3006, and MW-3007

Table 2. Stratigraphic and well construction data for U.S. Department of Energy monitoring wells—Continued

					Unit interval				
					Burlington-Keokuk Limestone (BK)				
Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter pack or open-hole interval (ft)	Top of bed-rock (ft)	BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Remarks
MW-3024	645.2	BK (UNW)	75.3-101.0	28.0	39.0-101.0[d,i]	56.8-62.5	39.0-71.0[i]	71.0-101.0[d]	Retrofit of MW-3008; paired with MW-3025
MW-3025	645.2	BK (W)	31.5-53.0	ND	ND	ND	ND	ND	Rock not cored; unit open to well based on stratigraphy in paired well MW-3024 (retrofit of MW-3008); land surface altitude approximate
MW-3026	644.3	BK (UNW)	74.3-99.4	35.0	45.0-99.4[d,i]	45.0-46.0[i]	45.0-55.6[i]	55.6-99.4[d]	Retrofit of MW-3009; paired with MW-3027
MW-3027	644.2	BK (10.9 SW, 9.6 W, 1.5 UNW)	35.0-57.0	ND	ND	ND	ND	ND	Rock not cored; paired with MW-3026; 35.0-45.0 in MW-3026 assumed to be SW; land surface altitude approximate
MW-4001[b]	621.1	BK (6.5 SW, 2.5 W, 7.0 UNW)	25.0-41.0	14.0	14.0-41.8[d]	14.0-31.5	14.0-34.0	34.0-41.8[d]	Clustered with MW-4006 and MW-4007
MW-4002[b]	632.7	BK (10 W, 5 SW, 14.5 W, 14.2 UNW)	41.0-84.7	26.0[e]	41.0-84.8[d,i]	51.0-56.0	41.0-70.5[i]	70.5-84.8[d]	Top of bedrock questionable because roller bit was used to 41.0
MW-4003[b]	669.4	BK (W)[h]	51.0-106.2	23.0[e]	52.0-106.2[d,i]	--	52.0-106.2[d,i] ?	ND	Top of bedrock questionable because roller bit was used to 52; W/UNW at 100?
MW-4004	651.7	BK (UNW)[c]	63.0-75.0	37.5[e]	37.5-74.0[d,f]	37.5-54.6[f]	37.5-63.0[f]	63.0-74.0[d]	Top of bedrock at 23.5 (auger refusal)?
MW-4005[b]	656.4	BK (1.4 W, ?)	63.9-78.8	44.2[e]	44.2-65.3[d,f]	44.2-51.5[f]	44.2-65.3[d,f] ?	ND	Top of bedrock at 30.0 (auger refusal) ?; core loss from 65.3-78.8 (reason unknown)
MW-4006	621.7	BK (W) ?	20.5-28.5	19.0[e]	ND	ND	ND	ND	Top of bedrock questionable (roller bit used; no core); clustered with MW-4001 and MW-4007
MW-4007[b]	621.5	BK (UNW)	77.0-90.0	ND	50.0-90.0[d,i]	ND	ND	50.0-90.0[d,i]	Clustered with MW-4001 and MW-4006
MW-4008[b]	635.5	BK (UNW)[c]	70.0-83.0	32.4	32.4-82.4[d]	32.4-45.2	32.4-57.4	57.4-82.4[d]	

Table 2. Stratigraphic and well construction data for U.S. Department of Energy monitoring wells—Continued

Well	Land surface altitude (ft above sea level)	Units to which well is open (thickness in ft)[a]	Filter pack or open-hole interval (ft)	Top of bed-rock (ft)	Unit interval: Burlington-Keokuk Limestone (BK): BK (ft)	Strongly weathered subunit (SW) (ft)	Weathered unit (W) (ft)	Unweathered unit (UNW) (ft)	Remarks
MW-4009[b]	624.2	BK (UNW)[c]	64.0-76.8	19.0	19.0-76.5[d]	19.0-41.3	19.0-54.6	54.6-76.5[d]	
MW-4010[b]	629.1	BK (6.2 W, 6.3 UNW)[c]	64.6-77.1	15.7	15.7-77.0[d]	--	15.7-70.8	70.8-77.0[d]	
MW-4011	626.9	BK (UNW)[c]	64.1-77.7	30.0	30.0-76.2[d]	--	30.0-58.7	58.7-76.2[d]	
MW-4012[b]	615.5	BK (UNW)	62.7-80.2	33.0[e]	33.0-80.2[d,f]	33.0-46.9[f]	33.0-60.7[f]	60.7-80.2[d]	Top of bedrock at 38.0?
MW-4013	606.7	BK (14.2 W, 8.3 UNW)	37.5-60.0	35.1	35.1-60.0[d]	-- ?	35.1-51.7	51.7-60.0[d]	Possible SW unit present, but questionable
MW-4014	607.3	BK (11.2 SW, 11.3 UNW)[h]	43.0-65.5	42.0[e]	42.0-66.4[d,f]	42.0-54.2[f]	42.0-54.2[f]	54.2-66.4[d]	Top of bedrock at 51.7?
MW-4015	617.8	BK (16.5 W, 6.7 UNW)[c]	40.0-63.2	13.0	13.0-60.1[d]	13.0-18.0	13.0-56.5	56.5-60.1[d]	
MW-4016	642.8	BK (2.6 W, 11.1 UNW)	71.6-85.3	30.0[e]	30.0-85.3[d,f]	30.0-49.6[f] 58.2-64.3 ?	30.0-74.2[f]	74.2-85.3[d]	Top of bedrock may be as deep as 39.6; lower SW unit questionable
MW-4017[b,g]	649.3	BK (15.7 W, 7.1 UNW)[c]	62.3-85.1	40.0	40.0-85.0[d]	--	40.0-78.0	78.0-85.0[d]	
MW-4018	647.7	BK (11.5 W, 6.5 UNW)[c]	61.5-79.5	44.0	44.0-78.5[d]	44.0-49.8	44.0-73.0	73.0-78.5[d]	
MW-4019	645.3	BK (13.3 W, 7.7 UNW)	40.0-61.0	20.2	20.2-59.5[d]	21.9-39.6	20.2-53.3	53.3-59.5[d]	
MW-4020	657.7	BK (2.5 W, 13.8 UNW)	65.0-81.3	36.0	36.0-81.3[d]	?	36.0-67.5	67.5-81.3[d]	
MW-4021	649.9	BK (2.6 W, 1.4 SW, 15 W, 3.0 UNW)[c,h]	49.0-71.0	26.5	26.5-69.7[d]	26.5-43.0 51.6-53.0 ?	26.5-68.0 ?	68.0-69.7[d] ?	Lower SW unit may be thicker; W unit may extend below 68
MW-4022	666.3	BK (UNW)	67.0-90.9	35.0	35.0-90.9[d]	35.0-60.2	35.0-60.2	60.2-90.9[d]	
MW-4023	646.6	BK (14.1 W, 2.4 SW, 7 W)[h]	30.5-54.0	28.9	28.9-70.0[d]	44.6-47.0	28.9-59.0	59.0-70.0[d]	
MW-4024	655.2	BK (W)	45.0-59.0	24.3	24.3-59.0[d]	35.2-44.2	24.3-59.0[d]	ND	
MW-4025	645.3	BK (W)	37.8-53.7	27.5	27.5-53.7[d]	--	27.5-53.7[d]	ND	
PW-1[g]	647.2	BK (24.5 W, 19.0 UNW)[c]	46.8-90.3	27.7	27.7-90.2[d]	--	27.7-71.3	71.3-90.2[d]	
PW-2[g]	657.0	BK (8.5 SW, 18.8 W, 17.2 UNW)[h]	42.5-87.0	36.5[e]	36.5-92.1[d,f]	36.5-51.0[f]	36.5-69.8[f]	69.8-92.1[d]	Top of bedrock at 51.0 ?
PW-3[g]	638.6	BK (23.2 W, 18.8 UNW)[c]	44.0-86.0	16.0	16.0-85.1[d]	21.0-37.5 ?	16.0-67.2	67.2-85.1[d]	

[a] Weathered unit interval in the third column does not include the strongly weathered subunit interval.
[b] Geologic log of bedrock prepared from core samples as part of this study.
[c] Open interval of well extends below bottom of core; bottom part of open interval assumed to be same unit as bottom of core.
[d] Core or well ends in unit; bottom of unit not intersected.
[e] Top of bedrock is questionable.
[f] Unit interval is different if the top of bedrock is identified at a different depth.
[g] Well is abandoned.
[h] Units open to well may be different if top of bedrock is identified at a different depth, or if unit intervals are reinterpreted.
[i] Core starts in unit, below top of bedrock.
[j] Well has been retrofitted and renumbered.