APPENDIX A

Description of Hydrogeologic Basins

Description of Hydrogeologic Basins

A description of the basin definitions, boundaries, and hydrogeology for the hydrogeologic basins is presented below. Table A-1 lists for each basin the names, ages, and codes for the geologic units, as cited in the surficial geology maps in the hydrologic atlases of Oklahoma.

The 12 hydrologic atlases are available from the Oklahoma Geological Survey. The digital surficial geology sets from the hydrologic atlases are available on the Internet at http://wwwok.cr.usgs.gov/gis/geology/index.html. The digital surficial geology map of Hydrologic Atlas 3 does not include the alluvium and terrace deposits. To identify the alluvium and terrace deposits in the Ardmore and Sherman quadrangles, refer to Sheet 1 in Hydrologic Atlas 3 (Hart, 1974).

Alluvium and Terrace Deposits

Alluvium and terrace deposits are Quaternary in age, and occur along modern and ancient streams throughout the state. They encompass the outcrop of alluvium, terrace deposits, and dune sand.

Alluvium and terrace deposits along the major rivers (Salt Fork of the Arkansas, Arkansas, Cimarron, Beaver-North Canadian, Canadian, Washita, North Fork of the Red, and the Red) extend from 1-15 miles from the river banks. Terraces represent older, higher stages of the rivers that have since cut their channels deeper (OWRB, 1995).

Alluvium and terrace deposits consist mainly of unconsolidated deposits of gravel, sand, silt, and clay. Along large streams, these deposits consist of clay and silt at the surface, grading downward into coarse sand and gravel at the base (Carr and Bergman, 1976). The alluvium located along minor streams is composed of fine-grained sand containing varying amounts of silt and clay (Bingham and Bergman, 1980). Volcanic ash is found in some terrace deposits.

The thickness of the alluvium and terrace deposits ranges from a few feet to about 200 feet. Terrace deposits on upland areas and alluvium along tributaries generally are thin, less than 50 feet. Deposits are sometimes overlain by sand dunes, sometimes as thick as 150 feet.

Water is available from saturated layers of sand and gravel, and well yields are largest where the coarse sand and gravel layers are thickest (Carr and Bergman, 1976). Yields of wells generally range from 10-500 gpm, but can locally be greater than 1,000 gpm. The alluvium and terrace deposits are major sources of water for irrigation, public water, and industrial supply. Water obtained from shallow wells in the alluvium of local stream channels is used across the state for domestic purposes and to supply stock wells.

Recharge rates and hydraulic conductivity values were obtained from groundwater basin studies on the alluvium and terrace deposits of the Cimarron River, North Canadian River, Washita River, and North Fork of the Red River; and the Enid Isolated Terrace, Tillman Terrace, and Gerty Sand (Adams and Bergman, 1996; Christenson, 1983; Davis and Christenson, 1981; Havens, 1989; Kent, 1980; Kent and Naney, 1978; Kent and others, 1982, 1984, 1987).

Recharge rates range from 0.9-3.7 in/yr, and hydraulic conductivity values generally range from 300-1,000 gpd/ft^2.

Antlers

The Antlers hydrogeologic basin is the outcrop of the Early Cretaceous-age Antlers Sandstone, DeQueen Limestone, and Holly Creek Formation. The basin encompasses parts of Atoka, Bryan, Carter, Choctaw, Johnston, Love, Marshall, McCurtain, and Pushmataha counties in southeastern Oklahoma.

In outcrop the Antlers Sandstone consists of sand, clay, conglomerate, and limestone. The upper part of the formation consists of beds of sand, poorly cemented sandstone, sandy shale, silt, and clay (Hart and Davis, 1981). Small portions of the Holly Creek Formation and DeQueen Limestone are exposed in eastern McCurtain County. The Holly Creek Formation consists of lenticular beds of gravel, clay, and sandy clay, and the DeQueen Limestone is limestone interbedded with silt and conglomerate (Marcher and Bergman, 1983).

The Antler aquifer extends southward in the subsurface, where it is overlain by younger Cretaceous formations that comprise the Cretaceous hydrogeologic basin. The subsurface portion of the Antlers aquifer is not included in the vulnerability assessment. However, it should be noted that recharge to the subsurface portion of the aquifer is primarily from rainfall that percolates into the outcrop portion.

Recharge rates ranging from 0.32-0.96 in/yr were used to simulate recharge in a calibrated groundwater flow model of the aquifer. Simulated aquifer hydraulic conductivity values range from 0.87-3.75 ft/day, or 6.5-28 gpd/ft^2 (Morton, 1992).

The Antlers aquifer is a major aquifer in Oklahoma. Large-capacity wells tapping the aquifer commonly yield 100-500 gpm, with reported production as high as 1,700 gpm. Morton (1992) estimated that 4,600 acre-feet of water was pumped in 1980 for public supply, irrigation, and industrial uses. Wells completed in the Holly Creek Formation generally yield 10-50 gpm (Marcher and Bergman, 1983).

Arbuckle-Simpson

The Arbuckle-Simpson hydrogeologic basin consists of the Arbuckle and Simpson groups of Late Cambrian to Middle Ordovician age and the Sylvan Shale, Fernvale Limestone, and Viola Limestone of Ordovician age, where they are exposed at the surface. Also included in the basin are the Woodford Shale and Hunton Group of Devonian and Silurian age. The basin overlies about 500 mi^2 in Carter, Johnston, Murray, and Pontotoc counties in south-central Oklahoma.

The western part of the basin, referred to as the Arbuckle Hills, is characterized by a series of ridges formed on intensely folded and faulted rocks. The eastern part of the basin, called the Arbuckle Plains, is characterized by a gently rolling topography formed on relatively flat-lying, intensely faulted limestone beds. A few small karst features have developed in the western part of the basin from solution of the underlying carbonate rocks (Fairchild and others, 1990).

The Arbuckle and Simpson groups comprise the Arbuckle-Simpson aquifer, which consists of limestone, dolomite, and sandstone. The rocks were subjected to intensive folding and faulting associated with major uplift of the area during Early to Late Pennsylvanian time. Sandstone beds in the Simpson Group have intergranular porosity, but the rocks of the Arbuckle Group have almost no intergranular porosity; all void space is in joints, fractures, and solution channels (Fairchild and others, 1990).

Recharge to the aquifer, based on the total average annual base flow from streams that drain the area, is 4.7 in/yr, or 12% of the annual average precipitation (Fairchild and others, 1990). The average transmissivity of the aquifer is estimated at 15,000 ft^2/day. Based on an average saturated thickness of about 3,500 feet in the outcrop area (Fairchild and others, 1990), the average hydraulic conductivity is about 4 ft/day, or 30 gpd/ft^2.

Wells in the Arbuckle-Simpson aquifer commonly yield 25-600 gpm of water that is of good quality, generally less than 500 mg/L dissolved solids (OSDH, 1983). Water is used for municipal, industrial, commercial, agricultural, and domestic purposes (Fairchild and others, 1990).

Arbuckle-Timbered Hills

The Arbuckle-Timbered Hills hydrogeologic basin in southwestern Oklahoma encompasses parts of Caddo, Comanche, and Kiowa counties. It contains rocks of the Late Cambrian to Middle Ordovician-age Arbuckle and Timbered Hills groups exposed at the surface. Also included in the basin are the Ordovician-age Viola Limestone and Bromide Formation that crop out in a few isolated areas near the Kiowa-Washita county line. South of the Wichita Mountains, part of the Arbuckle-Timbered Hills aquifer is overlain by as much as 2,000 feet of younger rocks (Havens, 1977). This portion of the aquifer is not included in the vulnerability assessment.

Rocks of the Arbuckle and Timbered Hills groups consist of limestone, dolomite, siltstone, sandstone, conglomerate and shale (Havens, 1977). The outcrop area of the Arbuckle-Timbered Hills aquifer is known as the Limestone Hills or Slick Hills. The rocks are intensely folded and faulted; as a result, most groundwater movement is made possible by solution of the limestone and dolomite along bedding planes, fractures, and faults (Havens, 1983). Recharge to the Arbuckle-Timbered Hills aquifer probably is less than 2% of the average annual precipitation of about 30 inches (Havens, 1977).

Availability of groundwater in the Limestone Hills is erratic because of faulting and folding. Most wells are 500 feet deep or more, and water generally is under artesian conditions. Flowing wells and springs yield as much as 100 gpm (Havens, 1983). Wells and springs provide water for domestic use and a rural water district (Havens, 1977).

Arkansas Novaculite

The Arkansas Novaculite hydrogeologic basin encompasses parts Latimer, McCurtain, and Pushmataha counties in southeastern Oklahoma. The basin is on two structural features in the Ouachita Mountains geologic province: the Potato Hills Anticlinorium, which straddles the Latimer-Pushmataha county line, and the Broken Bow uplift in south central McCurtain County. The Ouachita Mountains are characterized by broad synclines and narrow anticlines separated by steep, southward-dipping thrust faults and broken by many small faults. Rocks of Mississippian, Devonian, Silurian, and Ordovician age comprise the basin.

The primary water-yielding formations in the basin are the Bigfork Chert and the Arkansas Novaculite. These formations consist of novaculite and chert with some interbedded shale and sandstone. The highly broken and fractured rocks can potentially yield moderate to large amounts of water. However, because of their remoteness, few wells have been drilled into these formations, and their potential can only be inferred (Marcher and Bergman, 1983).

Average annual precipitation is about 48 inches. The amount of groundwater recharge is unknown, but it probably does not exceed 1% of total precipitation due to the steep slopes, thin soils, and low permeability of the bedrock (Marcher and Bergman, 1983).

Blaine

The Blaine groundwater basin underlies approximately 850 mi^2 of southwestern Oklahoma, and includes all or parts of Harmon, Jackson, and Greer counties. The basin consists of the Permian-age Blaine Formation and Dog Creek Shale. The basin is bounded on the east by the eastern limit of the outcrop of the Blaine Formation; on the south and west by the Oklahoma-Texas state border, and on the north by the Salt Fork of the Red River.

The Blaine Formation consists of a cyclic series of interbedded gypsum, shale, and dolomite. Water is obtained from cavities, solution channels, and fractures present in the gypsum and dolomite beds. Solution openings are formed when percolating rain water and circulating groundwater dissolve beds of soluble gypsum ($CaSO_4 \cdot 2H_2O$) and dolomite ($CaMg(CO_3)_2$) (Johnson, 1990b). The Dog Creek Shale overlies the Blaine Formation in much of the basin, and contributes limited amounts of water. The Dog Creek consists of up to 200 feet of red-brown shale with thin gypsum and dolomite beds in the lower 50 feet of the formation (Johnson, 1990a).

Karst features, such as caves, sinkholes, disappearing streams, and springs, occur within the basin, making the basin very vulnerable to contamination. Karst features are most abundant near streams, where fresh water percolates into the gypsum. Karst development is generally highest in areas where the Blaine crops out and where the Dog Creek Shale is less than 60 feet thick; it is lowest where the Dog Creek Shale is greater than 100 feet (Johnson, 1990b; Runkle and McLean, 1995).

Natural recharge to the basin occurs from infiltration of precipitation and from streams that flow across sinkholes. Recharge is greatest where the Dog Creek Shale is less than 60 feet. Average recharge to the aquifer is estimated to be 1.5 in/yr, or 6% of the average annual precipitation of 24 inches (Runkle and McLean, 1995).

Hydraulic conductivity varies considerably in the basin. It is greatest where dissolution of gypsum and dolomite occurs, in areas of high recharge. Using a groundwater flow model of the aquifer, Runkle and McLean (1995) estimated the average hydraulic conductivity for areas of low recharge to be 4 ft/day (30 gpd/ft^2) and the average value for areas of high recharge to be 71 ft/day (531 gpd/ft^2). Hydraulic conductivity is suspected to be much higher in local areas where cavern development is extensive.

Water from the Blaine aquifer is of fair to poor quality, with the total dissolved solids (TDS) ranging from 1,500-5,000 mg/L. The water has high concentrations of calcium and sulfate, reflecting dissolution of the gypsum beds. Analysis of 26 groundwater samples from the OWRB monitoring network indicates the mean TDS concentration is 3,761 mg/L, and the mean sulfate concentration is 1,351 mg/L (OWRB, 1993). These concentrations are well above the secondary maximum contaminant levels of 500 and 250 mg/L, for TDS and sulfate, respectively.

The highly mineralized aquifer is a potential source of drinking water, as defined by the EPA, but is not currently used as a drinking water supply. However, the aquifer is a major source of irrigation water in the basin. Irrigation wells are typically 50-300 feet deep and yield 300-2,000 gpm.

Boone

The Boone hydrogeologic basin in northeastern Oklahoma encompasses all of Delaware County and portions of Ottawa, Craig, Mayes, Cherokee, and Adair counties. It consists of the Mississippian, Devonian, and Ordovician strata exposed at the surface. The basin is in the Ozark Uplift geologic province, where erosion has cut deep, V-shaped valleys into a flat plateau.

The Boone aquifer consists of the Mississippian Keokuk and Reeds Spring formations and the St. Joe Group, commonly called the *Boone Chert* or *Boone Formation*. The maximum thickness of the aquifer ranges from less than 5 feet in parts of Adair and Delaware counties to about 400 feet in Ottawa County. The Boone Formation consists of dense, fine-grained limestone and massive gray chert. Where the chert is fractured, the formations are permeable (Imes and Emmett, 1994; Marcher and Bingham, 1971). The Boone Formation contains lead and zinc ores that were mined extensively in the tri-state mining district of northeastern Oklahoma, southeastern Kansas, and southwestern Missouri from about 1890 to 1970 (Christenson and others, 1994).

The Boone aquifer is absent from erosion in a few areas in Delaware, Cherokee, and Adair counties. In these areas the Chattanooga Shale of Devonian age and the Burgen Sandstone, Sylvan Shale, and Cotter Dolomite of Ordovician age are exposed at the surface. The Burgen Sandstone and Cotter Dolomite are part of the underlying Roubidoux aquifer.

Younger Mississippian formations overlie the Boone Formation along the western and southern edges of the Boone hydrogeologic basin. Formations include the Mississippian-age Pitkin Limestone, Fayetteville Shale, Batesville Sandstone, Hindsville Limestone, and the Moorefield Formation. These units consist of alternating sequences of low-permeability shale and low-permeability to relatively permeable limestone, sandstone, and coal. Locally, these rocks contain permeable zones and aquifers (Imes and Emmett, 1994).

Recharge to the Boone hydrogeologic basin is almost entirely from direct infiltration of precipitation. The factors that make the outcrop of the Boone Formation favorable to groundwater recharge also make it vulnerable to contamination. Precipitation may quickly infiltrate the unsaturated zone because soil and subsoil in the Ozarks is thin, near-surface faults and fracture systems are common, and dissolution of the carbonate rocks is widespread. Although slopes are often steep, the trees, grass and other vegetation hold the water, reducing the loss through runoff. Sinkholes in parts of the area are capable of large intakes from *disappearing* streams. In the mining area, abandoned mine shafts, wells, and test holes can be conduits for water to enter the aquifer (Reed and others, 1955).

Most of the wells in the Boone hydrogeologic basin are used for domestic purposes, although some are used for agriculture (such as poultry operations), commercial, and public supply purposes. An examination of more than 2,000 well drillers' logs indicated that estimated yields range from 0.3 to more than 100 gpm, with most wells yielding less than 25 gpm.

Cedar Hills

The Cedar Hills hydrogeologic basin is the outcrop area of the Permian-age Cedar Hills Sandstone. The basin encompasses parts of Alfalfa, Garfield, Major, and Woods counties in northwestern Oklahoma. The Cedar Hills Sandstone consists of fine-grained sandstone interbedded with layers of siltstone and shale. Wells commonly yield 150-300 gpm (OSDH, 1983).

Central Oklahoma

The Central Oklahoma hydrogeologic basin is the outcrop area of the Central Oklahoma aquifer, as delineated by the USGS (Parkhurst and others, 1996). The digital boundaries were obtained from Runkle and Rea (1997). The basin encompasses all or parts of Cleveland, Lincoln, Logan, Oklahoma, Payne, and Pottawatomie counties in central Oklahoma. The northern boundary of the basin is the Cimarron River, and the southern boundary is the Canadian River. The basin is bounded on the east by the eastern limit of the outcrop of the Oscar Group; and on the west by the western limit of the outcrop of the Garber Sandstone. The eastern part of the basin is characterized by low hills, and the western part by a gently rolling plain (Parkhurst and others, 1996).

The basin consists primarily of the Permian-age Garber Sandstone and Wellington Formation. It also includes the Permian-age Chase, Council Grove, and Admire groups, as described by Parkhurst and others (1996). These groups are the same as the Pennsylvanian-age Oscar Group, described in the hydrologic atlases. The western third of the aquifer is overlain by younger rocks in the Hennessey Group, and is not included in the vulnerability assessment.

The Garber Sandstone and Wellington formations consist of fine-grained sandstone interbedded with siltstone and mudstone, and the Oscar Group consists of beds of fine-grained sandstone, shale, and thin limestone. Values for hydraulic conductivity of sandstone, calculated from specific-capacity data on drillers' logs, range from 0.16 -120 ft/day (1.20-898 gpd/ft^2), with a median of 4.5 ft/day (33.7 gpd/ft^2). The median recharge rate of the basin, calculated from base-flow discharge measurements, is 1.61 in/yr (Parkhurst and others, 1996).

The Central Oklahoma aquifer is used extensively for municipal, industrial, commercial, and domestic water supplies. Wells completed in the Garber Sandstone and Wellington Formation can yield as much as 600 gpm, but generally yield from 200-400 gpm. Wells completed in the Oscar Group generally yield 10-100 gpm (Parkhurst and others, 1996).

Cretaceous

The Cretaceous hydrogeologic basin is the outcrop of the Upper and Lower Cretaceous-age rocks that overly the Antlers Sandstone. The basin encompasses parts of Bryan, Choctaw, Love, Marshall, and McCurtain counties in southeastern Oklahoma. The basin lies within the Gulf Coastal Plain, where relief is low, and topography is gently rolling to hilly. Soils are thick and permeable and can intercept considerable amounts of precipitation (Marcher and Bergman, 1983).

The Lower Cretaceous units include the Goodland Limestone, Walnut Clay, Kiamichi Formation, Caddo Formation, Bokchito Formation, Bennington Limestone, and the Grayson Marlstone. The Upper Cretaceous units include the Woodbine Formation and the Eagle Ford Formation. Typical deposits in the basin consist of a sequence of shale, sandstone, siltstone, and limestone units (Marcher and Bergman, 1983). Water is derived in small quantities from thin sandstone units and from cracks and solution openings in limestone units (Davis, 1960). Groundwater is used primarily for household and stock water, and some is used for public water supply.

Elk City

The Elk City hydrogeologic basin is in western Oklahoma, and encompasses parts of Beckham, Custer, Roger Mills, and Washita counties. It is defined by the outcrop of the Elk City Sandstone.

The Elk City Sandstone is composed of very friable sandstone. The aquifer supplies groundwater for irrigation, domestic, and industrial purposes (Becker and others, 1997a). Wells commonly yield 25-300 gpm of water (OSDH, 1983). Lyons (1981) estimated hydraulic conductivity values of 6.7, 66.8, and 100.3 ft/day (50, 500, and 750 gpd/ft^2) and recharge rates of 2.0, 3.92, and 4.0 in/yr by simulating groundwater flow in a computer model.

Mesozoic

The Mesozoic hydrogeologic basin is comprised primarily of Jurassic, Triassic, and Cretaceous-age rocks that crop out in the northwestern corner of Cimarron County, in the Oklahoma Panhandle. Also included in the basin is the Tertiary-age basalt that forms the cap rock of Black Mesa. Topography of the basin is characterized by many buttes capped by sandstone (Hart and others, 1976).

The Mesozoic rocks in the basin consist of interbedded sandstone, limestone, shale, and dolomite. Minor quantities of water may be obtained from the Dakota Sandstone and the Cheyenne Sandstone Member of Cretaceous age; the Morrison Formation and the Exeter Sandstone of Jurassic age; and the Dockum Group of Triassic age (Sapik and Goemaat, 1973).

Ouachita Mountains

The Ouachita Mountains hydrogeologic basin encompasses parts of Atoka, Latimer, LeFlore, McCurtain, Pittsburg, and Pushmataha counties in southeastern Oklahoma. The northern edge of the basin is defined by the Carbon fault, the western edge by the Choctaw fault, and the southern edge by the outcrop of Cretaceous rocks in the Gulf Coastal Plain. The basin consists of intensely folded and faulted Pennsylvanian and Mississippian-age rocks.

The basin is in the Ouachita Mountains geologic province, which is characterized by broad synclines and narrow anticlines separated by steep, southward-dipping thrust faults and broken by many small faults. The Ouachita Mountains have the most rugged topography in Oklahoma, with an average relief of several hundred feet and local relief that exceeds 1,700 feet. The ridges are held up by hard, resistant sandstones; valleys are carved into soft, easily eroded shale (Marcher and Bergman, 1983).

Bedrock in the Ouachita Mountains basin consists mainly of shale, siliceous shale, and sandstone. Geologic units include the Lynn Mountain Formation, Wapanucka Limestone, Johns Valley Shale, and Jackfork Group of Pennsylvanian age and the Stanley Group of Mississippian age. These rocks have been subjected to low-grade dynamic metamorphism that has increased their brittleness so that they have been broken by folding and faulting. The capability of the bedrock to store and transmit water depends almost entirely on fractures formed by folding and faulting. Well yields range from a few gallons per minute to as much as 50 gpm (Marcher and Bergman, 1983).

Annual precipitation averages about 48 inches. The amount of groundwater recharge is unknown, but it probably does not exceed 1% of total precipitation due to steep slopes, thin soils, and low permeable bedrock (Marcher and Bergman, 1983).

Ogallala

The Ogallala basin encompasses Cimarron, Texas, and Beaver counties in the Oklahoma Panhandle, and parts of Harper, Ellis, Woodward, Dewey, and Roger Mills counties in western Oklahoma. The basin boundaries are defined by the outcrop of the Ogallala Formation. Also included in the basin are some isolated outcrops of Triassic, Jurassic, and Cretaceous-age rocks that are hydraulically connected to the aquifer.

The Ogallala aquifer (also called the High Plains aquifer) is the principal source of water in the Oklahoma Panhandle, and is used extensively for irrigation. The aquifer commonly yields 500 to 1,000 gpm and can yield up to 2,000 gpm in thick, highly permeable areas (Hart and others, 1976; Havens and Christenson, 1984). An analysis of drillers' logs indicates the average depth to the first water zone in the basin is greater than 100 feet. Topography is moderately flat.

The Ogallala basin is composed of semi-consolidated layers of sand, silt, clay, and gravel. Locally, deposits have been cemented with calcium carbonate to form impermeable beds of limestone and caliche near the surface (Hart and others, 1976; Havens and Christenson, 1984).

Havens and Christenson (1984) developed a groundwater flow model of the High Plains aquifer in Oklahoma. In the calibrated model, they used recharge values of 0.23 and 0.45 in/yr in the western and eastern portions, respectively. They used hydraulic conductivity values of 8.28, 16.2, and 19.3 ft/day (62, 121, and 144 gpd/ft^2) for the western, central, and eastern portions, respectively.

Pennsylvanian

The Pennsylvanian hydrogeologic basin encompasses much of the eastern half of the state. The basin consists of all the Pennsylvanian rocks that crop out in Oklahoma and that are not in the Vamoosa-Ada or Ouachita Mountains hydrogeologic basins. The basin is bordered on the west by the western extent of the Vanoss Formation, and does not include rocks in the Oscar Group. Although the hydrologic atlases assign a Pennsylvanian age to the Oscar Group, the more recently assigned Permian age by Lindberg (1987) is used in this study. Also included in the basin are some Mississippian rocks exposed along the flanks of the Arbuckle-Simpson basin.

The basin is composed of interbedded sandstone, shale, siltstone, and limestone. Water is obtained primarily from the sandstone layers. In areas where sandstone beds are thin or fine-grained, yields are less than 10 gpm; in many areas the yields are too small to supply enough water for household use. In areas where the fine-grained sandstone is thickest or where the rocks are broken by faults, wells can yield as much as 25 gpm (Bingham and Moore, 1975; Bingham and Bergman, 1980; Marcher and Bingham, 1971; Marcher, 1969). The Noxie Sandstone Member of the Chanute Formation, in the northern parts of Osage, Washington, and Nowata counties, may yield as much as 50 gpm (Marcher, 1969).

In most of the basin, erosion has formed a gently rolling surface interrupted by east-facing escarpments and isolated buttes capped by resistant sandstone and limestone (Hart, 1974; Bingham and Bergman, 1980). The northeastern portion is along the western margin of the Ozark Plateau, where gently dipping rocks are broken by faults trending northeast-southwest (Marcher and Bingham, 1971).

Average annual precipitation ranges from about 28 inches in the western part of the basin to about 42 inches in the southeastern part (Bingham and Moore, 1975; Hart, 1974). An estimated 1.5-3.5 inches are available to recharge the groundwater (Bingham and Moore, 1975).

Permian

The Permian hydrogeologic basin encompasses much of the central and western part of the state. The basin consists of all the Permian rocks that crop out in Oklahoma that are not in the Blaine, Cedar Hills, Central Oklahoma, Elk City, or Rush Springs hydrogeologic basins. It is bordered to the east by the eastern extent of the Oscar Group. As discussed above, the Oscar Group is considered to be of Permian age, and not Pennsylvanian, as reported in the hydrologic atlases.

The Permian rocks consist mainly of red-brown shales, sandstones, and siltstones, with interbedded and disseminated gypsum in some formations (Bingham and Bergman, 1980; Carr and Bergman, 1976; Havens, 1977). In areas where sandstone beds are thin or fine-grained, yields are less than 10 gpm and, in many areas, the yields are too small to supply enough water for household use. In areas where the sandstone is thick or where the rocks are broken by faults, wells might yield as much as 25 gpm (Bingham and Moore, 1975; Bingham and Bergman, 1980; Hart, 1974; Marcher and Bingham, 1971; Marcher, 1969).

The topography of the basin ranges from gently rolling to rugged. The predominant topography consists of rolling plains, moderate valley slopes, and upland slopes of 2-20%. Land forms range from steep-sloped cuestas to narrow box canyons along streams. Resistant gypsum beds cap the highlands in some areas (Carr and Bergman, 1976; Morton, 1980). Average annual precipitation ranges from about 21 inches in the west to about 33 inches in the east (Carr and Bergman, 1976; Morton, 1980).

Rush Springs

The Rush Springs hydrogeologic basin is the Permian-age Rush Springs and Marlow formations of the White Horse Group, where they are exposed at the surface. Portions of the Rush Springs aquifer overlain by the less permeable Cloud Chief Formation are not included in the basin. The hydrogeologic basin is in western Oklahoma, and encompasses parts of Blaine, Caddo, Canadian, Comanche, Custer, Dewey, Ellis, Grady, Harper, Kiowa, Major, Stephens, Washita, Woods, and Woodward counties.

The Rush Springs Formation is a massive, fine-grained, poorly-cemented sandstone with some interbedded dolomite, gypsum, and shale. The Marlow Formation is composed of interbedded sandstones, siltstones, mudstones, gypsum-anhydrite, and dolomite (OSDH, 1983; Becker and Runkle, 1998). The amount of shale increases in Dewey County and farther north (OSDH, 1983).

The average recharge rate of the basin, calculated from base-flow discharge measurements, is about 2 in/yr, or about 7% of the average annual rainfall. Becker (1998) used hydraulic conductivity values of 0.8-10 ft/day (6-74.8 gpd/ft^2) to simulate groundwater flow in a groundwater flow model.

The Rush Springs aquifer is an important source of water for irrigation, livestock, industrial, municipal, and domestic use. Wells commonly yield 25-300 gpm (OSDH, 1983); some irrigation wells in Caddo County are reported to yield as much as 1,000 gpm (Carr and Bergman, 1976).

Tishomingo Granite

The Tishomingo Granite hydrogeologic basin is the 150-square-mile exposure of Cambrian and Precambrian igneous rocks in parts of Atoka, Johnston, and Murray counties in south-central Oklahoma.

The igneous rocks can be divided into the Colbert Porphyry of Cambrian age and the massive Precambrian granites. The Colbert Porphyry is a rhyolite that crops out in a few places in the western part of the Arbuckle Hills in Murray County. Precambrian Tishomingo and Troy Granites crop out east of the Arbuckle Hills in the Arbuckle Plains physiographic province, an area of gently rolling hills. The granites are 1.3 billion years old and about 10 miles thick (Hart, 1974). Hart (1974) speculates that the igneous rocks may yield small amounts of water.

Vamoosa-Ada

The Vamoosa-Ada hydrogeologic basin is the outcrop area of the Vamoosa-Ada aquifer as delineated by the USGS (Abbott and others, 1997). It is bounded to the south by the Canadian River. The basin extends over parts of Osage, Pawnee, Payne, Creek, Lincoln, Okfuskee, and Seminole counties in east-central Oklahoma.

The aquifer consists of the rocks of the Late Pennsylvanian-age Vamoosa Formation and overlying Ada Group. The aquifer is a sequence of fine-to very fine-grained sandstone, siltstone, shale, and conglomerates interbedded with very thin limestones (D'Lugosz and others, 1986).

Hydraulic conductivity values of the aquifer, estimated from recovery tests, range from 2-4 ft/day (30-120 gpd/ft^2), and average 3 ft/day (22 gpd/ft^2). Base-flow measurements were used to estimate a recharge rate of 1.52 in/yr, which is about 4% of the total precipitation (D'Lugosz and others, 1986). Wells commonly yield 25-150 gpm, and locally yield as much as 300 gpm (OSDH, 1983).

Washita Igneous

The Washita Igneous hydrogeolgic basin consists of the Cambrian-age igneous rocks exposed in the Washita Mountains and scattered outcrops to the west. The basin encompasses parts of Comanche, Greer, Jackson, Kiowa, and Tillman counties in southwestern Oklahoma.

The Washita Mountains consists of a block of igneous rocks bounded by steep faults. The igneous rocks include rhyolite flows, tuffs, conglomerate beds, and diabase sills of the Carton Rhyolite Group; granites in the Wichita Granite Group; and gabbros, anorthosites, and dirorites in the Raggedy Mountain Gabbro Group (Havens, 1977).

No wells are known to obtain water from the igneous rocks. Barclay and Burton (1953) observed the granite outcrops to be intricately jointed and speculated that wells intersecting the joints below the water table might yield moderate quantities of water.

Table A-1. Names, ages, and codes for geologic units, as cited in the hydrologic atlases (HAs), by hydrogeologic basin

Hydrogeologic Basin	**Age**	**Geologic Units**	**Code**	**HA**
Alluvium and Terrace Deposits	Quaternary	Dune Sand	Qds, Qd	5, 6, 250, 373, 450
		Alluvium	Qal, Qa	1-9, 250, 373, 450
		Terrace Deposits	Qt	1-9
Antlers	Lower Cretaceous	Antlers Sandstone	Ka	3, 9
		DeQueen Limestone	Kdq	9
		Holly Creek Formation	Kh	9
Arbuckle-Simpson	Devonian and Silurian	Woodford Shale	Dw	3
		Hunton Group	Dsh	3
	Upper and Middle Ordovician	Simpson Group:		
		Sylvan Shale, Fernvale Limestone, and Viola Limestone	Osfv	3
		Bromide, Tulip Creek, and McLish Formations	Obm	3
		Oil Creek and Joins Formations	Ooj	3
	Upper Cambrian-Lower Ordovician	Arbuckle Group:		
		West Spring Creek Formation	Owk, Ows	3
		Kindblade Formation	Ok	3
		Cool Creek and McKenzie Hill Formations	Ocm	3
		Butterly Dolomite, Signal Mountain Limestone, Royer Dolomite, and Fort Sill Limestone	Cbf	3
		Timbered Hills Group	Cth	3
Arbuckle-Timbered Hills	Cambrian-Ordovician	Viola Limestone and Bromide Formation	Ovb	6
		Upper Part of Arbuckle Group:		
		undifferentiated	Oua	6
		West Spring Creek and Kindblade Formations	Owk	6
		Cool Creek and McKenzie Hill Formations	Ocm	6
		Lower Part of Arbuckle Group and Timbered Hills Group	Cat	6

Hydrogeologic Basin	**Age**	**Geologic Units**	**Code**	**HA**
Arkansas Novaculite	Mississippian, Devonian, and Silurian	Arkansas Novaculite	MDSa	9
	Silurian	Missouri Mountain Shale Blaylock Sandstone	Sm, SmOp Sb	9 9
	Ordovician	Polk Creek Shale Bigfork Chert Womble Formation Blakely Sandstone Mazarn Shale Crystal Mountain Sandstone Collier Shale	Op Obf Ow Ob Om Ocm Oc	9 9 9 9 9 9 9
Blaine	Permian	Dog Creek Shale Blaine Formation: Van Vacter Member Elm Fork Member	Pdc Pb Pbv Pbe	6 6 6 6
Boone	Mississippian	undifferentiated Pitkin, Fayetteville, Batesville, Hindsville, and Moorefield Formations Keokuk Formation, Reeds Spring Formation, and St. Joe Group	Mu Mp, Mpfh Mkr	1 1, 2 1, 2
	Mississippian, Devonian, Silurian, and Ordovician	Chattanooga Shale, Sallisaw Formation, Frisco Formation, Quarry Mountain Formation, Tenkiller Formation, Blackgum Formation, Sylvan Shale, Fernvale Limestone, Fite Limestone, Tyner Formation, Burgen Sandstone, and Cotter Dolomite	MDSO, MDO	1, 2

Hydrogeologic Basin	Age	Geologic Units	Code	HA
Cedar Hills	Permian	Cedar Hills Sandstone	Pch	6, 8, 5
Central Oklahoma	Permian	Garber Sandstone	Pg	3, 4
		Wellington Formation	Pw	3, 4
	(Pennsylvanian)	Oscar Group	lPo	3, 4
Cretaceous	Upper Cretaceous	Ozan Formation	Ko	9
		Brownstown Marl	Kbr	9
		Tokio Formation	Kto	9
		Eagle Ford Formation	Kef	3
		Woodbine Formation:	Kw	9
		Templeton Member	Kwt	3
		Lewisville Member	Kwl	3
		Red Branch Member	Kwr	3
		Dexter Member	Kwd	3
	Lower Cretaceous	Grayson Marl and Bennington Limestone	Kgb	3, 9
		Pawpaw Sandstone and McNutt Limestone	Kpm	9
		Weno Clay and Soper Limestone	Kws	9
		Denton Clay	Kd	9
		Bokchito Formation	Kb	3
		Caddo Formation	Kc	3, 9
		Kiamichi Formation	Kk	3, 9
		Goodland Limestone and Walnut Clay	Kgw	3, 9
Elk City	Permian	Elk City Sandstone	Pec	5

Hydrogeologic Basin	Age	Geologic Units	Code	HA
Mesozoic	Tertiary	Basalt	Tb	373
	Cretaceous	Colorado Group	Kc	
		Dakota Sandstone	Kd	
		Purgatoire Formation	Kp	
	Jurassic	Morrison Formation	Jm	373
		Exeter Sandstone	Je	
	Triassic	Dockum Group	TRd	373
Ouachita Mountains	Pennsylvanian	Atoka Formation	lPat	9
		Morrowan-Atokan undifferentiated	lPma	3
		Lynn Mountain Formation	lPlm	9
		Wapanucka Limestone and Chickachoc Chert	lPwc	9, 3
		Limestone Gap	lPlg	9
		Johns Valley Shale	lPjv	9, 3
		Morrowan undifferentiated	lPmo	3
		Jackfork Group	lPjf	9, 3
	Mississippian	Goddard Shale	Mg	9, 3
		Stanley Group	Mst	9, 3
		Delaware Creek Shale	Md	9, 3
Ogallala	Tertiary	Ogallala	To	373, 250, 450, 8, 5

Hydrogeologic Basin	**Age**	**Geologic Units**	**Code**	**HA**
Pennsylvanian	Pennsylvanian	Vanoss Group:	lPv	3, 4, 7
		Red Eagle Limestone	lPvre	7
		Long Creek Limestone	lPvlc	4, 7
		Americus Limestone	lPva, lPvam	4, 7
		Brownville Limestone	lPvb	4, 7
		Grayhorse Limestone	lPvg	4, 7
		Elmont Limestone	lPve	4, 7
		Ada Formation	lPa	3
		Vamoosa Formation	lPva	3
		Tallant Formation	lPt	4, 7
		Barnsdall Formation	lPbd	4, 7
		Vamoosa, Tallant, and Barnsdall Formations	lPbv	2
		Hilltop Formation	lPht	3, 4
		Belle City Limestone	lPb	3, 4
		Torpedo Formation	lPt	2
		Wann and Iola Formations	lPwi	4, 2, 7
		Chanute Formation	lPch	2, 4, 7
		Dewey Formation	lPd	2, 4, 7
		Nellie Bly Formation	lPnb, lPn	2, 3
		Hogshooter Formation	lPh	2
		Nellie Bly Formation and Hogshooter Limestone	lPnh	4, 7
		Coffeyville Formation and Checkerboard Limestone	lPcc	2, 4, 7
		Coffeyville or Grancis Formation	lPcf	3
		Seminole Formation	lPsl, lPs	1, 2, 3, 4
		Holdenville Shale	lPhd, lPh	1, 3, 4
		Holdenville and Lenapah Formations	lPhl	2

Hydrogeologic Basin	**Age**	**Geologic Units**	**Code**	**HA**
Pennsylvanian	Pennsylvanian	Lenapah Formation	lPlp	2
		Nowata Formation	lPnw	2
		Oologah Formation	lPol	2
		Labette Formation	lPlb	2
		Fort Scott Limestone	lPfs	2
		Wewoka Formation	lPwk, lPw	1, 3, 4
		Wetumka Shale	lPwe, lPwt	1, 3, 4
		Calvin Sandstone	lPca, lPcv	1, 3, 4
		Senora Formation	lPse, lPsn	1, 2, 3, 4
		Stuart Shale	lPst	1, 3, 4, 9
		Thurman Sandstone	lPt	1, 3, 4, 9
		Boggy Formation	lPbo, lPbg	1, 2, 3, 9
		Bluejacket Sandstone	lPbj	3, 9
		Savanna Formation	lPsa, lPsv	1, 3, 9
		McAlester Formation	lPm	3, 9
		Hartshorne Sandstone	lPha	3, 9
		McAlester and Hartshorne Formations	lPmh	1, 2
		Savanna, McAlester, and Hartshorne Formations	lPsm	1, 2
		Savanna, McAlester, Hartshorne, and Atoka Formations	lPsma	2
		Atoka Formation	lPa, lPat	1, 2, 3, 9
		Bloyd and Hale Formations	lPbh	1, 2
		Atoka, Bloyd, and Hale Formations-undifferentiated	lPu	1
		Wapanucka Formation	lPwa, Pwal,	3
			lPwas	3
		Union Valley Formation	lPul, lPus	3
	Mississippian	Goddard Shale	Mg	3
		Delaware Creek Shale	Md	3
		Sycamore and Welden Limestone	Msw	3

Hydrogeologic Basin	Age	Geologic Units	Code	HA
Permian	Permian	Permian-undifferentiated	Pu	250, 450
		Doxey Shale	Pdy	5, 8
		Cloud Chief Formation	Pcc	5, 6, 8
		El Reno Group:	Per	5, 6
		Dog Creek Shale	Pdc	3, 4, 5, 6, 8
		Blaine Formation:	Pb	4, 5, 6, 8
		Van Vacter Member	Pbv	6
		Elm Fork Member	Pbe	6
		Flowerpot Shale	Pf	4, 5, 6, 8
		San Angelo Sandstone	Psa	6
		Chickasha Formation	Pc	3, 4, 5, 8
		Duncan Sandstone	Pd	3, 4, 5
		Post Oak Conglomerate	Ppo	6
		Hennessey Group:	Phy	5, 6
		Bison Formation (Shale)	Pbi	3, 4, 5, 7, 8
		Purcell Sandstone	Pp	3, 4
		Salt Plains Formation	Psp	4, 7, 8
		Kingman Siltstone	Pk	4, 7, 8
		Fairmont Shale	Pfa	3, 4, 7, 8
		Garber Sandstone	Pg	3, 4, 6, 7
		Wellington Formation	Pw	3, 4, 6, 7
	Pennsylvanian (assigned to Permian by Lindberg, 1987)	Oscar Group:	lPo	3, 4, 7
		Winfield Limestone	lPowi	3, 4, 7
		Fort Riley Limestone and Florence Flint	lPofr	3, 4, 7
		Wreford Limestone	lPowr	3, 4, 7
		Cottonwood Limestone	lPoc	3, 4, 7

Hydrogeologic Basin	**Age**	**Geologic Units**	**Code**	**HA**
Rush Springs	Permian	Whitehorse Group: Rush Springs Formation: Weatherford Gypsum Bed Marlow Formation: Doe Creek Lentil Verden Sandstone Lentil	Pwh Pr Prw Pm Pmd Pmv	5, 6 5, 6, 8 5, 6 5, 6 6 5
Tishomingo Granite	Cambrian Pre Cambrian	Colbert Porphyry Tishomingo and Troy Granites	Cp pCt	3 3
Vamoosa-Ada	Pennsylvanian	Ada Group: Wakarusa Limestone Bird Creek Limestone Turkey Run Limestone Vamoosa Group: Plattsmouth Limestone Leavenworth Limestone Labadie Limestone Bowring Limestone	lPa lPaw lPab lPat lPva lPvap lPvale lPval lPvab	7, 4 7, 4 7, 4 7, 4 7, 4 7 7 7 7
Washita Igneous	Cambrian	Carlton Rhyolite Group Wichita Granite Group Raggedy Mountain Gabbro Group	Ccr Cwg Cr	6 6 6