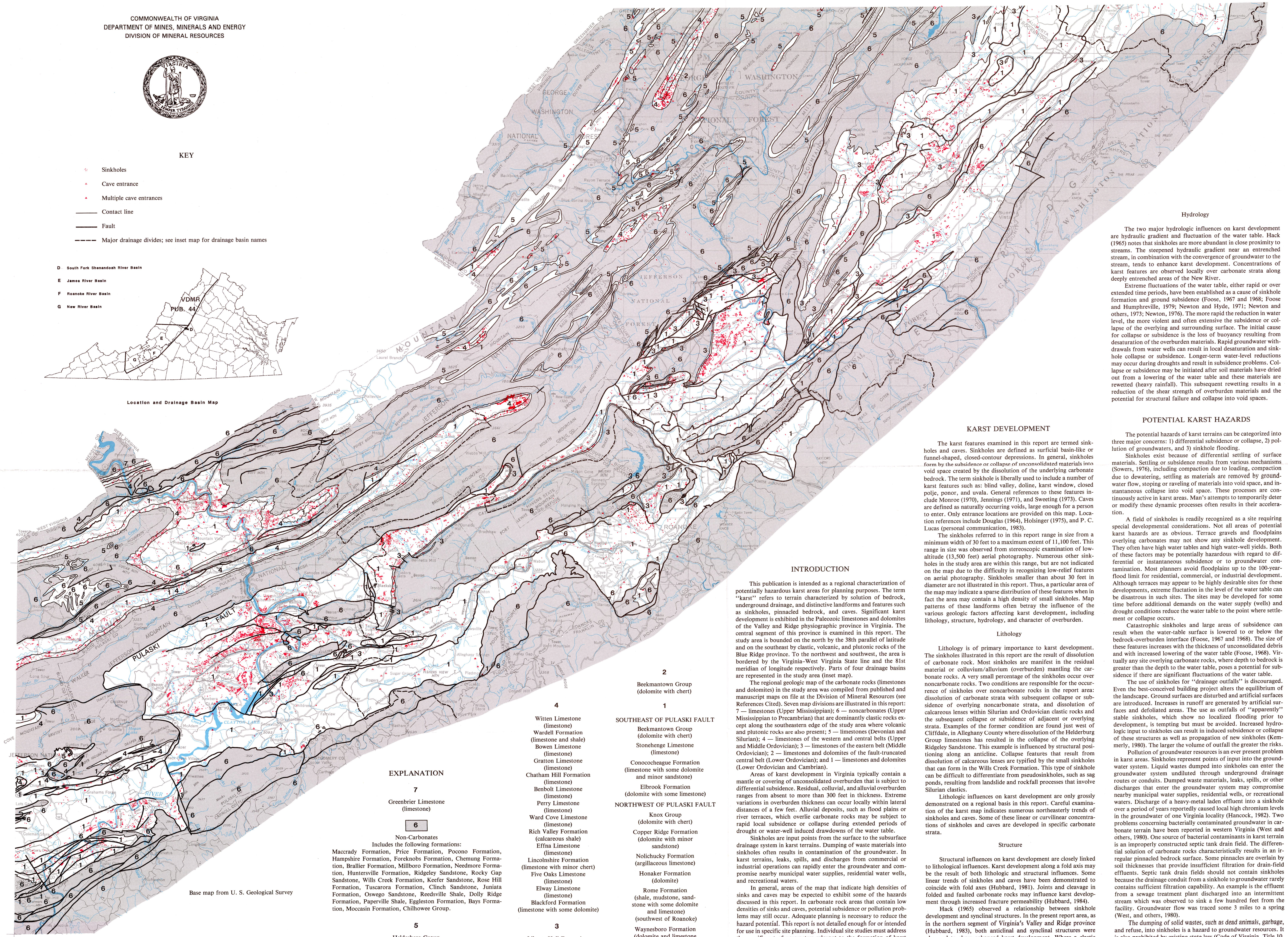
SELECTED KARST FEATURES OF THE CENTRAL VALLEY AND RIDGE PROVINCE, VIRGINIA

David A. Hubbard, Jr.

1988

COMMONWEALTH OF VIRGINIA
DEPARTMENT OF MINES, MINERALS AND ENERGY
DIVISION OF MINERAL RESOURCES

PUBLICATION 83
SELECTED KARST FEATURES OF THE CENTRAL
VALLEY AND RIDGE PROVINCE, VIRGINIA



KEY

Sinkholes

Cave entrance

Multiple cave entrances

Contact line

Fault

Major drainage divides; see inset map for drainage basin names

D South Fork Shenandoah River Basin

E James River Basin

F Roanoke River Basin

G New River Basin

Location and Drainage Basin Map

EXPLANATION

7

Greenbrier Limestone
(limestone)

6

Non-Carbonates
Includes the following formations:
Maccrady Formation, Price Formation, Pocono Formation, Hampshire Formation, Foreknobs Formation, Chemung Formation, Brallier Formation, Millboro Formation, Needmore Formation, Huntersville Formation, Ridgeley Sandstone, Rocky Gap Sandstone, Wills Creek Formation, Keefer Sandstone, Rose Hill Formation, Tuscarora Formation, Clinch Sandstone, Juniata Formation, Oswego Sandstone, Reedsville Shale, Dolly Ridge Formation, Paperville Shale, Eggleston Formation, Bays Formation, Moccasin Formation, Chilhowee Group.

5

Helderberg Group
(limestone with thin beds of sandstone, chert, and shale; sandstone south and southwest of New Castle, Craig County and included in unit 6)
Tonoloway Limestone
(limestone)

4

Witten Limestone
(limestone)
Wardell Formation
(limestone and shale)
Bowen Limestone
(limestone)
Gratton Limestone
(limestone)
Chatham Hill Formation
(limestone)
Benbolt Limestone
(limestone)
Perry Limestone
(limestone)
Ward Cove Limestone
(limestone)
Rich Valley Formation
(calcareous shale)
Effna Limestone
(limestone)
Lincolnshire Formation
(limestone with minor chert)
Five Oaks Limestone
(limestone)
Elway Limestone
(limestone)
Blackford Formation
(limestone with some dolomite)

3

Liberty Hall Formation
(limestone with some shale)
Lincolnshire Limestone
(limestone with minor chert)
New Market Limestone
(limestone)

2

Beekmantown Group
(dolomite with chert)

1

SOUTHEAST OF PULASKI FAULT

Beekmantown Group
(dolomite with chert)
Stonehenge Limestone
(limestone)
Conococheague Formation
(limestone with some dolomite and minor sandstone)
Elbrook Formation
(dolomite with some limestone)

NORTHWEST OF PULASKI FAULT

Knox Group
(dolomite with chert)
Copper Ridge Formation
(dolomite with minor sandstone)
Nolichucky Formation
(argillaceous limestone)
Honaker Formation
(dolomite)
Rome Formation
(shale, mudstone, sandstone with some dolomite and limestone)
(southwest of Roanoke)
Waynesboro Formation
(dolomite and limestone with shale, mudstone, and sandstone)
(northeast of Roanoke)
Shady Dolomite
(dolomite)

Base map from U. S. Geological Survey

Scale 1:250,000

INTRODUCTION

This publication is intended as a regional characterization of potentially hazardous karst areas for planning purposes. The term "karst" refers to terrain characterized by solution of bedrock, underground drainage, and distinctive landforms and features such as sinkholes, pinnacled bedrock, and caves. Significant karst development is exhibited in the Paleozoic limestones and dolomites of the Valley and Ridge physiographic province in Virginia. The central segment of this province is examined in this report. The study area is bounded on the north by the 38th parallel of latitude and on the southeast by clastic, volcanic, and plutonic rocks of the Blue Ridge province. To the northwest and southwest, the area is bordered by the Virginia-West Virginia State line and the 81st meridian of longitude respectively. Parts of four drainage basins are represented in the study area (inset map).

The regional geologic map of the carbonate rocks (limestones and dolomites) in the study area was compiled from published and manuscript maps on file at the Division of Mineral Resources (see References Cited). Seven map divisions are illustrated in this report: 7 — limestones (Upper Mississippian); 6 — noncarbonates (Upper Mississippian to Precambrian) that are dominantly clastic rocks except along the southeastern edge of the study area where volcanic and plutonic rocks are also present; 5 — limestones (Devonian and Silurian); 4 — limestones of the western and central belts (Upper and Middle Ordovician); 3 — limestones of the eastern belt (Middle Ordovician); 2 — limestones and dolomites of the fault-truncated central belt (Lower Ordovician); and 1 — limestones and dolomites (Lower Ordovician and Cambrian).

Areas of karst development in Virginia typically contain a mantle or covering of unconsolidated overburden that is subject to differential subsidence. Residual, colluvial, and alluvial overburden ranges from absent to more than 300 feet in thickness. Extreme variations in overburden thickness can occur locally within lateral distances of a few feet. Alluvial deposits, such as flood plains or river terraces, which overlie carbonate rocks may be subject to rapid local subsidence or collapse during extended periods of drought or water-well induced drawdowns of the water table.

Sinkholes are input points from the surface to the subsurface drainage system in karst terrains. Dumping of wastes materials into sinkholes often results in contamination of the groundwater. In karst terrains, leaks, spills, and discharges from commercial or industrial operations can rapidly enter the groundwater and compromise nearby municipal water supplies, residential water wells, and recreational waters.

In general, areas of the map that indicate high densities of sinks and caves may be expected to exhibit some of the hazards discussed in this report. In carbonate rock areas that contain low densities of sinks and caves, potential subsidence or pollution problems may still occur. Adequate planning is necessary to reduce the hazard potential. This report is not detailed enough for or intended for use in specific site planning. Individual site studies must address the specific set of parameters relevant to the formation of karst features and the possible hazards at each location. This report is intended to indicate, on a regional basis, areas where special site planning and engineering considerations are necessary to avoid potential subsidence or collapse, groundwater pollution, and sinkhole flooding hazards. Previous report done by Hubbard (1983).

KARST DEVELOPMENT

The karst features examined in this report are termed sinkholes and caves. Sinkholes are defined as surficial basin-like or funnel-shaped, closed-contour depressions. In general, sinkholes form by the subsidence or collapse of unconsolidated materials into void space created by the dissolution of the underlying carbonate bedrock. The term sinkhole is liberally used to include a number of karst features such as: blind valley, doline, karst window, closed polje, ponor, and uvala. General references to these features include Monroe (1970), Jennings (1971), and Sweeting (1973). Caves are defined as naturally occurring voids, large enough for a person to enter. Only entrance locations are provided on this map. Location references include Douglas (1964), Holsinger (1975), and P. C. Lucas (personal communication, 1983).

The sinkholes referred to in this report range in size from a minimum width of 30 feet to a maximum extent of 11,100 feet. This range in size was observed from stereoscopic examination of low-altitude (13,500 feet) aerial photography. Numerous other sinkholes in the study area are within this range, but are not indicated on the map due to the difficulty in recognizing low-relief features on aerial photography. Sinkholes smaller than about 30 feet in diameter are not illustrated in this report. Thus, a particular area of the map may indicate a sparse distribution of these features when in fact the area may contain a high density of small sinkholes. Map patterns of these landforms often betray the influence of the various geologic factors affecting karst development, including lithology, structure, hydrology, and character of overburden.

Lithology

Lithology is of primary importance to karst development. The sinkholes illustrated in this report are the result of dissolution of carbonate rock. Most sinkholes are manifest in the residual material or colluvium/alluvium (overburden) mantling the carbonate rocks. A very small percentage of the sinkholes occur over noncarbonate rocks. Two conditions are responsible for the occurrence of sinkholes over noncarbonate rocks in the report area: dissolution of carbonate strata with subsequent collapse or subsidence of overlying noncarbonate strata, and dissolution of calcareous lenses within Silurian and Ordovician clastic rocks and the subsequent collapse or subsidence of adjacent or overlying strata. Examples of the former condition are found just west of Cliffdale, in Alleghany County where dissolution of the Helderberg Group limestones has resulted in the collapse of the overlying Ridgeley Sandstone. This example is influenced by structural positioning along an anticline. Collapse features that result from dissolution of calcareous lenses are typified by the small sinkholes that can form in the Wills Creek Formation. This type of sinkhole can be difficult to differentiate from pseudosinkholes, such as sag ponds, resulting from landslide and rockfall processes that involve Silurian clastics.

Lithologic influences on karst development are only grossly demonstrated on a regional basis in this report. Careful examination of the karst map indicates numerous northeasterly trends of sinkholes and caves. Some of these linear or curvilinear concentrations of sinkholes and caves are confined to specific carbonate strata.

Structure

Structural influences on karst development are closely linked to lithological influences. Karst development along a fold axis may be the result of both lithologic and structural influences. Some linear trends of sinkholes and caves have been demonstrated to coincide with fold axes (Hubbard, 1981). Joints and cleavage in folded and faulted carbonate rocks may influence karst development through increased fracture permeability (Hubbard, 1984).

Hack (1965) observed a relationship between sinkhole development and synclinal structures. In the present report area, as in the northern segment of Virginia's Valley and Ridge province (Hubbard, 1983), both anticlinal and synclinal structures were observed to show enhanced karst development. Where a clastic core is exposed, the nose of a fold structure often demonstrates a concentration of solution features. In Giles County, the Bane dome and the Clover Hollow anticline have a fairly uniform distribution of sinkholes and caves developed in their limestone flanks. The dolomite cores of these folds contain fewer such features.

Hydrology

The two major hydrologic influences on karst development are hydraulic gradient and fluctuation of the water table. Hack (1965) notes that sinkholes are more abundant in close proximity to streams. The steepened hydraulic gradient near an entrenched stream, in combination with the convergence of groundwater to the stream, tends to enhance karst development. Concentrations of karst features are observed locally over carbonate strata along deeply entrenched areas of the New River.

Extreme fluctuations of the water table, either rapid or over extended time periods, have been established as a cause of sinkhole formation and ground subsidence (Foose, 1967 and 1968; Foose and Humphreville, 1979; Newton and Hyde, 1971; Newton and others, 1973; Newton, 1976). The more rapid the reduction in water level, the more violent and often extensive the subsidence or collapse of the overlying and surrounding surface. The initial cause for collapse or subsidence is the loss of buoyancy resulting from desaturation of the overburden materials. Rapid groundwater withdrawals from water wells can result in local desaturation and sinkhole collapse or subsidence. Longer-term water-level reductions may occur during droughts and result in subsidence problems. Collapse or subsidence may be initiated after soil materials have dried out from a lowering of the water table and these materials are rewetted (heavy rainfall). This subsequent rewetting results in a reduction of the shear strength of overburden materials and the potential for structural failure and collapse into void spaces.

POTENTIAL KARST HAZARDS

The potential hazards of karst terrains can be categorized into three major concerns: 1) differential subsidence or collapse, 2) pollution of groundwaters, and 3) sinkhole flooding.

Sinkholes exist because of differential settling of surface materials. Settling or subsidence results from various mechanisms (Sowers, 1976), including compaction due to loading, compaction due to dewatering, settling as materials are removed by groundwater flow, stoping or raveling of materials into void space, and instantaneous collapse into void space. These processes are continuously active in karst areas. Man's attempts to temporarily deter or modify these dynamic processes often results in their acceleration.

A field of sinkholes is readily recognized as a site requiring special developmental considerations. Not all areas of potential karst hazards are as obvious. Terrace gravels and floodplains overlying carbonates may not show any sinkhole development. They often have high water tables and high water-well yields. Both of these factors may be potentially hazardous with regard to differential or instantaneous subsidence or to groundwater contamination. Most planners avoid floodplains up to the 100-year-flood limit for residential, commercial, or industrial development. Although terraces may appear to be highly desirable sites for these developments, extreme fluctation in the level of the water table can be disastrous in such sites. The sites may be developed for some time before additional demands on the water supply (wells) and drought conditions reduce the water table to the point where settlement or collapse occurs.

Catastrophic sinkholes and large areas of subsidence can result when the water-table surface is lowered to or below the bedrock-overburden interface (Foose, 1967 and 1968). The size of these features increases with the thickness of unconsolidated debris and with increased lowering of the water table (Foose, 1968). Virtually any site overlying carbonate rocks, where depth to bedrock is greater than the depth to the water table, poses a potential for subsidence if there are significant fluctuations of the water table.

The use of sinkholes for "drainage outfalls" is discouraged. Even the best-conceived building project alters the equilibrium of the landscape. Ground surfaces are disturbed and artificial surfaces are introduced. Increases in runoff are generated by artificial surfaces and defoliated areas. The use as outfalls of "apparently" stable sinkholes, which show no localized flooding prior to development, is tempting but must be avoided. Increased hydrologic input to sinkholes can result in induced subsidence or collapse of these structures as well as propagation of new sinkholes (Kemmerly, 1980). The larger the volume of outfall the greater the risks.

Pollution of groundwater resources is an ever present problem in karst areas. Sinkholes represent points of input into the groundwater system. Liquid wastes dumped into sinkholes can enter the groundwater system undiluted through underground drainage routes or conduits. Dumped waste materials, leaks, spills, or other discharges that enter the groundwater system may compromise nearby municipal water supplies, residential wells, or recreational waters. Discharge of a heavy-metal laden effluent into a sinkhole over a period of years reportedly caused local high chromium levels in the groundwater of one Virginia locality (Hancock, 1982). Two problems concerning bacterially contaminated groundwater in carbonate terrain have been reported in western Virginia (West and others, 1980). One source of bacterial contaminants in karst terrain is an improperly constructed septic tank drain field. The differential solution of carbonate rocks characteristically results in an irregular pinnacled bedrock surface. Some pinnacles are overlain by soil thicknesses that provide insufficient filtration for drain-field effluents. Septic tank drain fields should not contain sinkholes because the drainage conduit from a sinkhole to groundwater rarely contains sufficient filtration capability. An example is the effluent from a sewage treatment plant discharged into an intermittent stream which was observed to sink a few hundred feet from the facility. Groundwater flow was traced some 3 miles to a spring (West, and others, 1980).

The dumping of solid wastes, such as dead animals, garbage, and refuse, into sinkholes is a hazard to groundwater resources. It is also prohibited by existing state law (Code of Virginia, Title 10, chapter 12.2, section 10-150.14). Researchers at Virginia Military Institute are attempting to determine the extent of sinkhole dumping in several Virginia counties including Botetourt County. A study in adjacent Rockbridge County located 20 sinkhole dumps (Slifer, 1987).

Flooding problems in karst terrain can result from two man-made conditions: the plugging of natural drains during construction and increases in runoff due to artificial surfaces. Inadequate silt control during construction can cause the plugging of sinkholes by sediment-laden runoff. The accompanying restriction of subsurface drainage results in decreased subsurface infiltration and increased surface runoff, ponding, or flooding. Flooding in karst terrains can also result from the increased runoff generated by residential, commercial, or industrial surfaces. The increased runoff from roads, parking lots, and structures is significant. Much precipitation that would have percolated directly into the ground surface is rapidly introduced into surface and subsurface (by increased drainage into sinkholes) drainage networks. Increases in runoff have been reported to range from 48 percent for areas of suburban housing to 153 percent or more for industrial or commercial areas (Aley and Thomson, 1981). Such increases in runoff can quickly exceed the drainage capacity of the inputs to the subsurface systems and result in ponding and flooding. Sinkhole flooding of this type has been reported in the Fairlawn area of Pulaski County (West and others, 1980). In severe cases, excessive runoff can overwhelm the capacity of natural subsurface drainage systems, causing water to back up and flood sinkholes up-system from the initial problem area (Crawford, 1981). At least one example of an overwhelmed natural subsurface drainage conduit is known from Virginia. A stream of water estimated with a peak flow of 50,000 gallons per minute was observed flowing from a normally dry sinkhole. Peak flow from the sinkhole occurred after surface-stream flow peaked from the November, 1985 major-storm event (D. W. Slifer, 1988, personal communication). Local residents reported similar phenomenon occurred during the 1969 Camile storm event. The input points to this natural conduit system are unknown, but do not appear to have been impacted by man.

PSEUDOKARST FEATURES

Two types of pseudokarst "sinkholes" have posed identification problems in this study area (Hubbard, 1984). Sinkhole-like features have been identified in landslides and rockfalls of Silurian sandstones in Giles and Montgomery counties (Schultz, personal communication, 1984 and Schultz, 1986). These features are sag ponds or the result of debris damming. One of these, Mountain Lake, is an impressive natural lake in Giles County. This lake, 0.54 × 0.2 miles in size, was apparently formed by debris-damming of a high stream valley (Sharp, 1933; Parker and others, 1975).

A second type of sinkhole-like feature is the result of the mining of lead-zinc ores in the later 1800s (Case, 1894) and iron ores (Watson, 1905) until about 1913. Residual ores from the Shady Dolomite were removed by an open-cut technique of mining whereby limestone pinnacles were exhumed. After years of erosion, these excavations in Wythe and Pulaski counties resemble sinkholes with exposed carbonate pinnacles.

CAVE RESOURCES

Ninety-six percent of Virginia's known caves are located on privately owned land and are not open to public use without permission of the owner. A number of these cases have further restrictions placed on visitation related to the protection of threatened and endangered species habitats, protection of water resources, and archaeological, biological, paleontological, and other scientific studies. Virginia's caves are protected by the Virginia Cave Protection Act (Code of Virginia 10-150.11 et seq.). For further information regarding cave resources, please contact the Virginia Division of Mineral Resources in Charlottesville, or the Virginia Cave Board, 1100 Washington Building, Capitol Square, Richmond, Virginia 23219.

REFERENCES CITED

Aley, T., and Thomson, K. C., 1981, Hydrogeologic mapping of unincorporated Greene County, Missouri, to identify areas where sinkhole flooding and serious groundwater contamination could result from land development: Project Summary prepared for Greene County Sewer District, by Ozark Underground Laboratory, Protem, Missouri, under contract with Missouri Department of Natural Resources, 11 p.

Case, W. H., 1894, The Bertha zinc-mines at Bertha, Virginia: American Institute Mining Engineering Transactions, v. 22, p. 511–536.

Crawford, N. C., 1981, Karst flooding in urban areas: Bowling Green, Kentucky, *in* B. F. Beck, ed., Proceedings of the Eighth International Congress of Speleology: National Speleological Society, Huntsville, Alabama, p. 763–765.

Douglas, H. H., 1964, Caves of Virginia: Falls Church, Virginia, Virginia Cave Survey, 761 p.

Foose, R. M., 1967, Sinkhole formation by groundwater withdrawals: Far West Rand, South Africa: Science, v. 157, n. 3792, p. 1045–1048.

——— 1968, Surface subsidence and collapse caused by groundwater withdrawal in carbonate rock areas: Proceedings of the 23rd International Geological Congress, Prague, v. 12, p. 155–166.

Foose, R. M., and Humphreville, J. A., 1979, Engineering geological approaches to foundations in the karst terrain of the Hershey Valley: Association Engineering Geologists Bulletin, v. 16, n. 3, p. 355–381.

Hack, J. T., 1965, Geomorphology of the Shenandoah Valley Virginia and West Virginia and origin of the residual ore deposits: U. S. Geological Survey Professional Paper 484, 84 p.

Hancock, Frank, 1982, EPA proposes water line to avoid chromium pollution: Roanoke Times, December 17, 1982, p. B1–2.

Holsinger, J. R., 1975, Descriptions of Virginia caves: Virginia Division of Mineral Resources Bulletin 85, 450 p.

Hubbard, D. A., Jr., 1981, Karst development in the Front Royal 7.5-minute quadrangle of Virginia, *in* B. F. Beck, ed., Proceedings of the Eighth International Congress of Speleology: National Speleological Society, Huntsville, Alabama, p. 511–514.

——— 1983, Selected karst features of the northern Valley and Ridge province, Virginia: Virginia Division of Mineral Resources Publication 44, map.

——— 1984, Sinkhole distribution in the central and northern Valley and Ridge province, Virginia, *in* Beck, B. F., ed., Sinkholes: their geology, engineering and environmental impact, proceedings of First Multidisciplinary Conference on Sinkholes: Florida Sinkhole Research Institute, University of Central Florida, Orlando, p. 75–78.

Jennings, J. N., 1971, Karst, an introduction to systematic geomorphology: Massachusetts Institute of Technology Press, v. 7, 252 p.

Kemmerly, P. R., 1980, Sinkhole collapse in Montgomery County, Tennessee: Tennessee Division of Geology, Environmental Geology Series No. 6, 42 p.

Monroe, W. H., 1970, A glossary of karst terminology: U. S. Geological Survey Water Supply Paper 1899-K, 26 p.

Newton, J. G., 1976, Induced and natural sinkholes in Alabama — a continuing problem along highway corridors, *in* Subsidence over mines and caverns, moisture and frost actions, and classification: Washington, D. C., Transportation Research Board Record 612, National Academy of Science, p. 9–16.

Newton, J. G., Copeland, C. W., and Scarborough, L. W., 1973, Sinkhole problem along proposed route of Interstate Highway 459, near Greenwood, Alabama: Geological Survey of Alabama Circular 83, 63 p.

Newton, J. G., and Hyde, L. W., 1971, Sinkhole problems in and near Roberts industrial subdivision, Birmingham, Alabama: Geological Survey of Alabama Circular 68, 42 p.

Parker, B. C., Wolfe, H. E., and Howard, R. V., 1975, On the origin and history of Mountain Lake, Virginia: Southeastern Geology, v. 16, n. 4, p. 213–226.

Schultz, A. P., 1986, Ancient, giant rockslides, Sinking Creek Mountain, southern Appalachians, Virginia: Geology, v. 14, p. 11–14.

Sharp, H. S., 1933, The origin of Mountain Lake, Virginia: Journal of Geology, v. 41, n. 6, p. 636–641.

Slifer, D. W., 1987, Rockbridge's illegal dumps: Blacksburg, Virginia, Virginia Water Resources Research Center, Focus on Water, n. 2, 8 p.

Sowers, G. F., 1976, Mechanisms of subsidence due to underground openings, *in* Subsidence over mines and caverns, moisture and frost actions, and classification: Washington, D. C., Transportation Research Board Record 612, National Academy of Science, p. 2–8.

Sweeting, M. M., 1973, Karst landforms: New York, New York, Columbia University Press, 362 p.

Watson, T. L., 1905, Lead and zinc deposits in Virginia: Geologic Survey of Virginia Bulletin 1, 156 p.

West, P. L., and others, 1980, Land capability analysis of the eastern portion of the Pulaski County growth corridor: New River Valley Planning District Commission, 31 p.

Geologic References Used in Compilation of the Map

Amato, R. V., 1974, Geology of the Salem quadrangle, Virginia: Virginia Division of Mineral Resources Report of Investigations 37, 40 p.

Bartholomew, M. J., 1977, Geology of the Greenfield and Sherando quadrangles, Virginia: Virginia Division of Mineral Resources Publication 4, 43 p.

——— 1981, Geology of the Roanoke and Stewartsville quadrangles, Virginia: Virginia Division of Mineral Resources Publication 34, 23 p.

Bartholomew, M. J., and Lowry, W. D., 1979, Geology of the Blacksburg quadrangle, Virginia: Virginia Division of Mineral Resources Publication 14, text and 1:24,000 scale map.

Bick, K. F., 1960, Geology of the Lexington quadrangle, Virginia: Virginia Division of Mineral Resources Report of Investigations 1, 40 p.

Bloomer, R. O., and Werner, H. J., 1955, The Blue Ridge region of central Virginia: Geologic Society of America Bulletin, v. 66, n. 5, p. 579–606.

Broughton, P. L., 1971, The Pulaski-Salem thrust sheet and the eastern part of the Christiansburg window, southwestern Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute and State University, 126 p.

Butts, Charles, 1933, Geologic map of Appalachian Valley of Virginia: Virginia Geologic Survey Bulletin 42, 56 p.

Chauvin, E. N., 1957, The Geology of the East River Mountain area, Giles County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 37 p.

Cooper, B. N., 1939, Geology of the Draper Mountain area, Virginia: Virginia Geologic Survey Bulletin 55, 98 p.

Currier, L. W., 1935, Zinc and lead region of southwestern Virginia: Virginia Geologic Survey Bulletin 43, 122 p.

Dietrich, R. V., 1954, Geology of the Pilot Mountain area, Virginia: Virginia Polytechnic Institute Engineering Experiment Station Series No. 91, 32 p.

——— 1959, Geology and mineral resources of Floyd County of the Blue Ridge upland, southwestern Virginia: Virginia Polytechnic Institute Engineering Experiment Station Series No. 134, 160 p.

Eckroade, W. M., 1962, Geology of the Butt Mountain area, Giles County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 63 p.

Edmundson, R. S., 1958, Industrial limestones and dolomites in Virginia: James River district west of the Blue Ridge: Virginia Division of Mineral Resources Bulletin 73, 137 p.

Eubank, R. T., 1967, Geology of the southeastern end of the Catawba syncline, Montgomery County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 91 p.

Glass, F. R., 1970, Structural geology of the Christiansburg area, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 80 p.

Hale, R. C., 1961, Geology of the Peters Mountain area, Giles County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 105 p.

Henika, W. S., 1981, Geology of the Villamont and Montvale quadrangles, Virginia: Virginia Division of Mineral Resources Publication 35, 18 p.

Hergenroder, J. D., 1957, Geology of the Radford area, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 84 p.

Hobbs, C. R. B., Jr., 1953, Structural geology of the Sinking Creek area, Giles County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 16 p.

Kozak, S. J., 1965, Geology of the Millboro quadrangle, Virginia: Virginia Division of Mineral Resources Report of Investigations 8, 19 p.

Ladd, H. S., and Stead, F. W., 1943, Manganese deposits of the Flattop and Round Mountain districts, Bland and Giles counties, Virginia: U. S. Geological Survey Bulletin 940-H, plate 37.

Lesure, F. G., 1957, Geology of the Clifton Forge iron district, Virginia: Virginia Polytechnic Institute Engineering Experiment Station Series No. 118, 130 p.

Lowry, W. D., 1971, Appalachian overthrust belt, Montgomery County, southwestern Virginia: Guidebook to Appalachian tectonics and sulfide mineralization of southwestern Virginia, Guidebook 5, Virginia Polytechnic Institute and State University, p. 143–178.

McDowell, R. C., 1968, Structural geology of Macks Mountain area, Virginia [Ph.D. dissert.]: Blacksburg, Virginia, Virginia Polytechnic Institute, 147 p.

McGuire, O. S., 1970, Geology of the Eagle Rock, Strom, Oriskany, and Salisbury quadrangles, Virginia: Virginia Division of Mineral Resources Report of Investigations 24, 39 p.

——— 1976, Geology of the Daleville quadrangle, Virginia: Virginia Division of Mineral Resources Report of Investigations 42, 43 p.

Marshall, F. C., 1959, Geology of the Kent window area, Wythe County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 21 p.

Moon, W. A., 1961, Geology of the Poplar Hill area, Giles County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 134 p.

Ovenshine, A. T., 1961, Geology of the Spruce Run Mountain area, Giles County, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 80 p.

Price, P. H., and Heck, E. T., 1937, Greenbrier County: West Virginia Geologic Survey, County Map, scale 1:62,500.

Rowland, R. A., 1934, Geology of the Angel's Rest area, Giles County, Virginia [M. S. thesis]: Cincinnati, Ohio, University of Cincinnati, 85 p.

Shufflebarger, T. E., 1953, Geology of Lower Cambrian metasediments in Poor Mountain area of Floyd, Montgomery, and Roanoke counties, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 68 p.

Spencer, E. W., 1968, Geology of the Natural Bridge, Sugarloaf Mountain, Buchanan, and Arnold Valley quadrangles, Virginia: Virginia Division of Mineral Resources Report of Investigations 13, 55 p.

Stead F. W., and Stose, G. W., 1943, Manganese and quartzite deposits in the Lick Mountain district, Wythe County, Virginia: Virginia Geologic Survey Bulletin 59, 16 p.

Stose, A. J., and Stose, G. W., 1957, Geology and mineral resources of the Gossan Lead district and adjacent areas in Virginia: Virginia Division of Mineral Resources Bulletin 72, 233 p.

Via, E. K., 1962, Geology of the Wolf Creek-Piney Ridge area [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 90 p.

Waesche, H. H., 1934, The areal geology of the Blacksburg region [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 68 p.

Webb, F., Jr., 1965, Geology of the Big Walker Mountain-Crockett Cove area, Bland, Pulaski, and Wythe counties, Virginia [Ph.D. dissert.]: Virginia Polytechnic Institute, 171 p.

Werner, H. J., 1966, Geology of the Vesuvius quadrangle, Virginia: Virginia Division of Mineral Resources Report of Investigations 7, 53 p.

Whitman, H. M., 1964, Geology of the Pearis Mountain area, Virginia [M. S. thesis]: Blacksburg, Virginia, Virginia Polytechnic Institute, 91 p.

Woodward, H. P., 1932, Geology and mineral resources of the Roanoke area, Virginia: Virginia Geologic Survey Bulletin 34, 172 p.

Virginia Division of Mineral Resources unpublished compilation interpretations: T. H. Biggs, T. M. Gathright, II, D. A. Hubbard, Jr., G. H. Liggon, H. M. Penley, E. K. Rader, A. P. Schultz, C. B. Stanley, and H. W. Webb.

Virginia Division of Mineral Resources manuscript maps: M. J. Bartholomew, H. J. Werner, Charles Butts, R. S. Edmundson, T. M. Gathright, II, S. E. Lewis, A. A. L. Mathews, E. K. Rader, A. P. Schultz, C. B. Stanley, and Charles Waag.