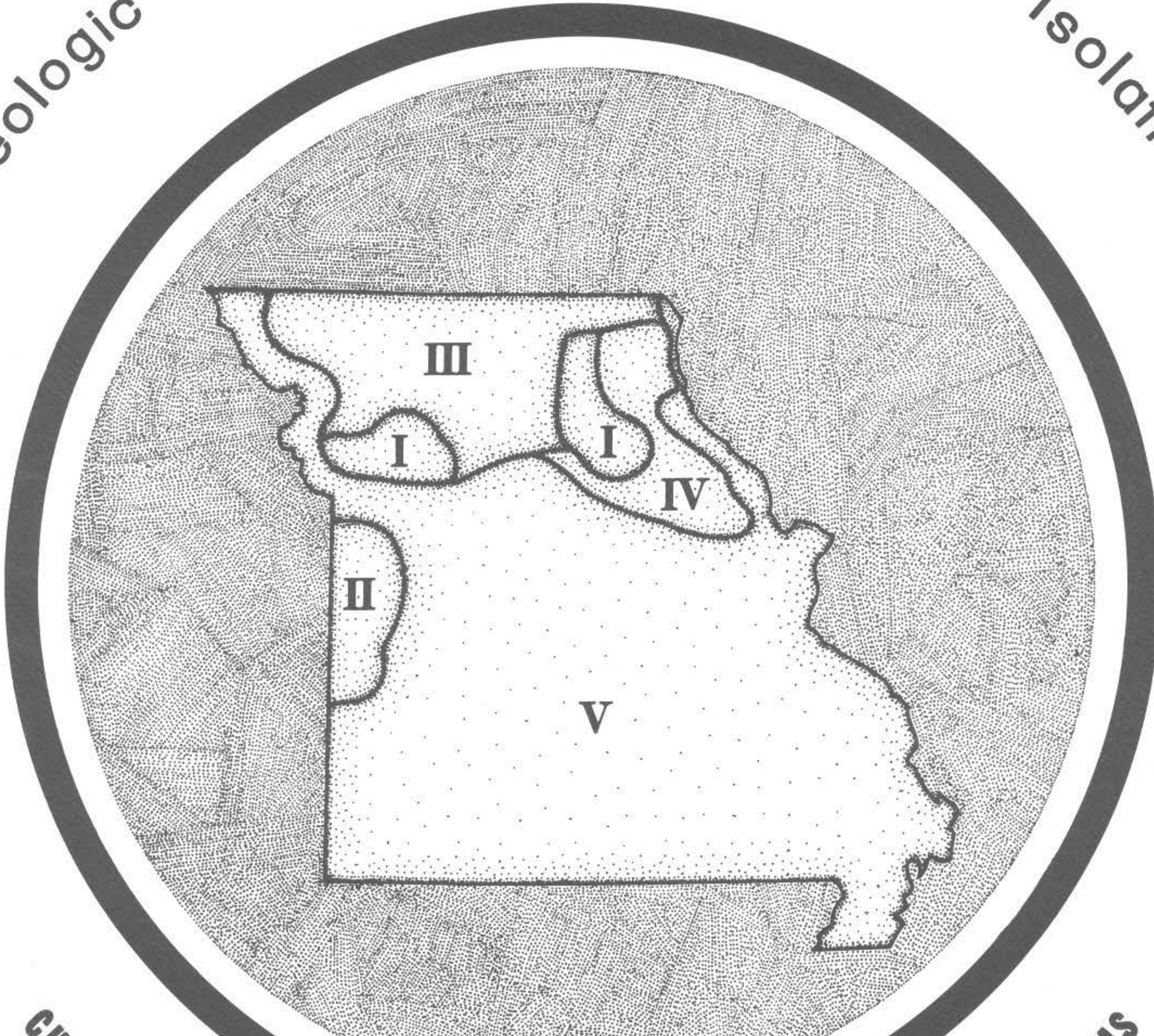
Geologic Aspects of Hazardous-Waste Isolation in Missouri



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GEOLOGIC ASPECTS OF HAZARDOUS-WASTE ISOLATION IN MISSOURI

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INTRODUCTION

Before adoption of The Solid Waste Disposal Act (Public Law 89-272) in 1965, little public attention was given to properly planned and carried out waste disposal practices. Wastes were commonly placed in dumps, sinkholes, road ditches, and creek beds. The isolation of what are now referred to as hazardous wastes is the subject of conjecture, investigation, and controversy. Regrettably, ignorance, poor planning, and lack of attention by the public and industry have resulted in severe environmental problems in several areas.

Congress passed the Resource Conservation and Recovery Act (Public Law 94-580) in 1975, which requires "cradle-to-grave" management of materials identified as hazardous. The law requires that all nonradioactive hazardous wastes be accounted for and disposed of in an approved manner.

The Missouri Geological Survey developed and applied a philosophy of assessment of limitations to the siting of waste isolation facilities in the widely varied geologic conditions throughout the state. The purpose of this report is to provide regional geologic information and to recommend exploration procedures based on that philosophy. The report is an engineering geology guide to aid in siting of hazardous-waste isolation facilities. Geologic conditions are described by physiographic provinces (fig. 1). The information about surficial materials, bedrock, and groundwater conditions can also be applied to the isolation of other types of nonradioactive wastes.

GEOLOGIC LIMITATIONS

The initial approach in statewide geologic evaluation of potential hazardous-waste sites is to consider degrees of geologic limitations (see plate 5). The greater the limitations, the more complex will be exploration, development, monitoring, and operation. The concept of limitations precludes premature designations such as "favorable" or "unfavorable." Site suitability can only be determined after detailed exploration, which should proceed in accordance with standardized geologic and engineering techniques. These are described in other publications and will not be discussed in this report.

The function of a hazardous-waste landfill is to isolate wastes. Geology, engineering design, and operational procedures are interrelated, and therefore it is essential that geologists and engineers cooperate throughout exploration, design, construction, operational, and postoperational phases.

The purpose of geological evaluation is to determine site characteristics that may influence movement of potential contaminants in surface water and groundwater. To accomplish this, many geologic factors must be considered. These include the following:

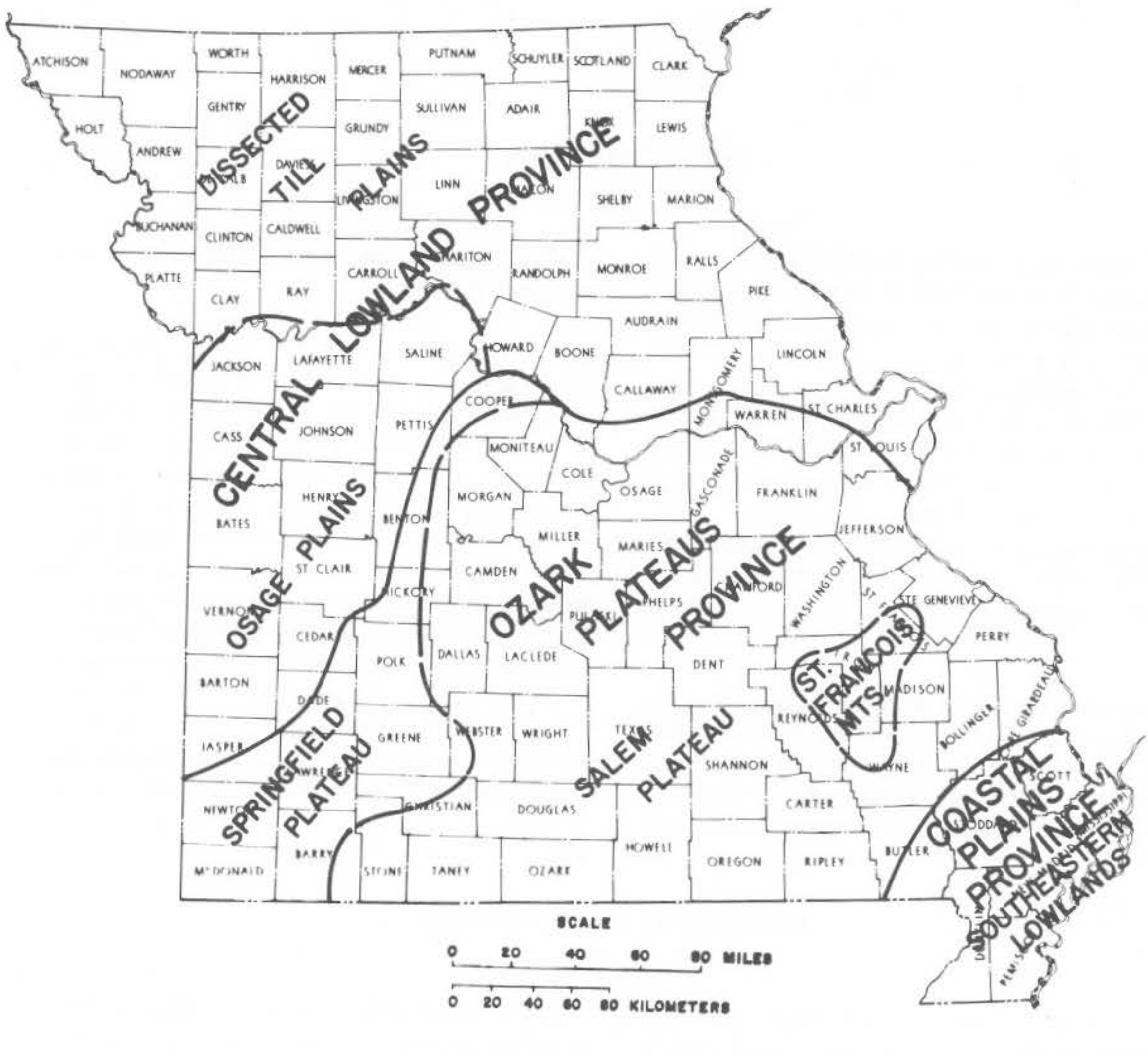

Figure 1. Physiographic Provinces of Missouri

1. surficial-material thickness and properties
2. bedrock type
3. topography
4. geologic history of the landscape
5. surface water and groundwater relationships

The geologic characteristics of an area impose varying degrees of limitations on activities that may safely be carried out. A classification system based on geologic conditions that limit the usefulness of an area for hazardous-waste isolation is helpful in the initial selection of sites for more detailed study.

Where geologic conditions are least limiting, landfills for management and/or treatment of hazardous wastes may be operated in such a way that they will not endanger surrounding areas. However, there are no "safe" sites if one ignores geologic limitations or fails to inspect and monitor operational procedures and postoperational changes.

In areas judged to have slight limitations, regional geologic conditions may be such that there are favorable prospects of locating suitable hazardous-waste isolation sites. This is not to imply that only minimal procedures will suffice; the natural resources of such an area and in the vicinity of a site must be protected by application of proven exploration, design, operational, and monitoring procedures.

Where geologic conditions indicate moderate limitations, the likelihood of finding suitable hazardous-waste sites is less favorable than in areas of slight limitations. Nevertheless, numerous potentially suitable hazardous-waste isolation sites do exist in areas of moderate limitiations. Important factors may justify the additional expense necessary to explore such areas, but the geologic conditions at a site in such an area must be such that the natural resources of the region and in the vicinity of the site would be protected by strict adherence to proven exploration, design, operational, and monitoring procedures.

Regions or areas defined as having severe limitations are most likely to have few potentially suitable hazardous-waste isolation sites. In such regions, the geologic exploration necessary to find suitable sites would be prolonged, costly, and probably futile. For sites to be suitable for detailed exploration, the geologic conditions in their vicinity should be similar to those that characterize areas of slight limitations. The probability of these circumstances existing in areas of severe limitations is remote; nevertheless, detailed studies may identify potentially suitable sites for isolation of certain types of hazardous materials in regions of severe limitations, because the work required to prepare statewide maps of the type included in this report serve only to show broad areas where conditions seem to be consistently similar. Site-specific studies may identify anomalous areas with fewer limitations.

Many geologic conditions must be evaluated in exploring for hazardous-waste sites. However, no individual site, regardless of how suitable in other respects, will have all the geologic conditions considered least limiting for site suitability. Examples of geologic conditions that define limiting factors relative to exploration, development, and operation of hazardous-waste isolation facilities include the following:

Slight limitations

1. gently rolling topography with moderate slopes (3 to 10 percent)
2. stable landscape conditions
3. artesian groundwater conditions
4. groundwater of insufficient quantity or quality for use by the general public
5. discharge rather than recharge conditions
6. minimal surface recharge of groundwater
7. clay-rich glacial drift 40 to 100 ft (12 to 31 m) thick
8. predominantly shale bedrock below surficial material

Even in a region with slight geologic limitations, some individual sites may have so many limiting geologic conditions that they should not be further considered for development.

Moderate limitations

1. very flat uplands with slopes less than 3 percent
2. moderately steep slopes (10 to 15 percent)
3. leaky artesian conditions
4. glacial drift greater than 100 ft (31 m) thick
5. loess of moderate or greater thickness, modified by weathering
6. limestone or sandstone bedrock overlain by thick to very thick glacial drift
7. groundwater of sufficient quantity and quality for use by the public

Severe limitations

1. steep slopes (greater than 15 percent)
2. landscape instability
3. regional recharge of groundwater
4. water tables deep below ground surface
5. widespread water-bearing sand deposits with lateral continuity
6. aquifers at shallow depth and currently used for public water supply
7. residual soil over carbonate bedrock
8. loess unmodified by weathering
9. extensive areas of limestone or sandstone bedrock at shallow depths
10. karst (sinkhole) topography
11. flood plains

Regions with severe limitations may also have many features defined as moderately limiting. Usually there is no distinct boundary between the two.

Five regions in Missouri have been defined and classified according to their limitations for isolation of hazardous wastes. Such ranking refers only to regional or area-wide investigations and merely implies that fewer potentially suitable sites might be rejected in a region of slight to moderate limitations than in one of severe limitations.

NORTH-CENTRAL MISSOURI AND NORTHERN WEST-CENTRAL MISSOURI

This region has slight to moderate limitations. Glacial drift 40 to 100 ft (12 to 31 m) thick is underlain predominantly by shale bedrock. Other areas with these properties exist in northwestern Missouri and, to a limited extent, in the eastern part of northern Missouri.

WESTERN MISSOURI

This region, south of Kansas City in west-central Missouri, has slight to moderate limitations. Exploration for hazardous-waste isolation sites is recommended where shale bedrock underlies a predominantly clay soil cover. A particularly important limiting factor is the general thinness of surficial materials. Where there are limestone outcrops, groundwater is quite likely to be shallow, and there are quite likely to be springs, at least some of them used locally by homeowners and farmers.

NORTHWESTERN MISSOURI

In this region there is glacial drift 100 ft (31 m) or more in thickness underlain predominantly by shale bedrock. A major reason for judging this a region of moderate limitations is the increased possibility of widespread deposits of water-bearing sand and gravel in very thick drift. These conditions exist in and near buried stream channels of northwestern Missouri, and in extreme north-central and northeastern Missouri.

EASTERN MISSOURI AND THE COLUMBIA-ST. LOUIS CORRIDOR

This region includes areas where glacial drift overlies thick limestone. In some places drift deposits are thick and clay rich, thus reducing site limitations. However, extensive water-bearing sand deposits may also exist. Locally, there are areas where shales overlie a thick limestone sequence, thus reducing site limitations.

SOUTHERN MISSOURI

This severely limited region includes the Ozark Plateaus, the Southeastern Lowlands (Mississippi Alluvial Plain), the loess hills adjoining major rivers, flood plains, and extensive bedrock outcrops in eastern Missouri. Nevertheless, there are potentially suitable areas for the isolation of certain types of hazardous wastes: 1) portions of the St. Francois Mountains where specially designed underground excavations could be constructed, and 2) areas underlain by shale and/or thick clays.

Regulatory procedures are necessary to implement laws governing hazardous-waste isolation. In the interest of protecting the public, one must make professional judgments that extend beyond "cookbook" procedures. For example, in portions of the Ozark Plateaus remote from sinkholes, faults, or unstable terrain, there are clay deposits more than 40 ft (12 m) thick, with laboratory permeabilities in the range of 10^{-8} cm/s. As determined by laboratory tests, the engineering properties of these soils indicate a clay content of 50 percent or more and high plasticity. In this setting the water table is generally deep, perhaps 100 ft (31 m) or more below the surface. Because of the soil structure, which cannot be accurately described by current laboratory or field tests, groundwater — and contaminants — may move rapidly downward through materials that, from laboratory tests alone, may appear to be impermeable. Conversely, some soils in northern Missouri consist of sandy clay 40 ft (12 m) or more thick, with laboratory permeabilities in the range of 10^{-8} cm/s. This sandy clay is classified as having low plasticity and may have only 30 to 40 percent clay. In this area the water table is usually near the surface. However, deep surface-water infiltration, hence, flushing of contaminants into the subsurface, essentially does not occur because groundwater moves laterally rather than downward. Thus, the general risk of groundwater pollution may be less in areas judged solely on the basis of "cookbook" laboratory tests prescribed by regulatory guidelines.

Permeability values are an example of an overworked regulatory criterion. A commonly listed minimum permeability is 10^{-8} cm/s, which normally refers to fine-grained materials such as silt and clay. At present, there is no test that accurately measures permeabilities of clayey soils or soils having silt as the principal constituent. Measurement of permeability in fine-grained materials is not accurate within less than about an order of magnitude, e.g., 10^{-7} cm/s compared to 10^{-8} cm/s. For example, it is possible to differentiate between a suite of samples with permeabilities in the range of 10^{-7} cm/s and one with permeabilities in the range of 10^{-8} cm/s. Experience and a knowledge of sampling and testing procedures are essential.

In some instances additional investigations are necessary beyond those outlined in the regulatory guidelines. This can be vexing to some applicants who plan to operate a waste isolation facility and believe they have followed all prescribed guidelines. However, because of the variability of geologic conditions in Missouri and the difficulties of quantifying soil and bedrock data, professional judgment should be allowed in the final interpretation of data.

In summary, the concept of geologic limitations is that no region is simply "favorable" or "unfavorable." There are too many geological variables that affect exploration, operation, monitoring, and other related matters to make such simple judgments.

PHYSIOGRAPHIC PROVINCES

OZARK PLATEAUS

The Ozark Plateaus province is divided into three subprovinces in Missouri: the Salem Plateau, the Springfield Plateau, and the St. Francois Mountains. The Salem Plateau surrounds the St. Francois Mountains and is an area of regional groundwater recharge to important aquifers. The Springfield Plateau to the southwest also is a major recharge region. The province extends south and southwest into Arkansas and Oklahoma. It is bounded on the west, north, and east by the Central Lowland; on the southeast, by the Coastal Plains (fig. 1).

SALEM PLATEAU

BOUNDARIES

The largest subprovince is the Salem Plateau, the northern and eastern boundaries of which are the Missouri and Mississippi Rivers. The Ozark escarpment to the southeast and the Eureka Springs escarpment to the west are also prominent features that outline the boundaries of the plateau in Missouri.

TOPOGRAPHY

The Salem Plateau is characterized by rolling to rugged topography underlain by dolomite and sandstone. There are areas of high relief in the vicinity of the St. Francois Mountains and the southwestern and southern parts of the state. There are broad prairie-plateau areas in the north and central portions. Narrow stream valleys with angular, joint-controlled drainage patterns are common.

The western part drains to the Osage River; the northern part, to the Missouri River. In the east and south, drainage is to the Mississippi River; in the southwest, to the White River. Large lakes and reservoirs include Lake Wappapello, Clearwater Lake, Lake of the Ozarks, and Table Rock Lake.

STRUCTURAL GEOLOGY

The regional structural geology of the Salem Plateau consists of unusual features and numerous faults and folds resulting from episodes of uplift. Sedimentary rocks surrounding the asymmetrical dome of the St. Francois Mountains dip most steeply to the east and south, into the Illinois Basin and the Coastal Plains, respectively.

The predominant structural trends are northwest-southeast and northeast-southwest. Most folding and faulting is gentle and is north of the St. Francois Mountains. There are several systems of faults throughout the region. In the vicinity of Cape Girardeau, faulting is reported to have displaced residual surficial materials and loess, suggesting geologically recent activity.

Unusual features in the Salem Plateau include the Decaturville and Crooked Creek structures, which may be the result of meteorite impact or explosive volcanic events. They are two of a series of various features that are interpreted by some as defining a structural lineament approximately along the 38th parallel (Snyder and Gerdemann, 1965; Heyl, 1972). Other features are presumably caused by collapse in bedrock weakened by solution.

BEDROCK

Dolomite, cherty dolomite, and sandstone constitute the principal bedrock of the Salem Plateau. Cambrian and Ordovician sedimentary rocks ring igneous knobs of the St. Francois Mountains. The Cambrian Lamotte Sandstone, Bonneterre and Davis Formations, and Derby-Doerun Dolomite, all described below in the section on the St. Francois Mountains, are of limited areal extent in the Salem Plateau.

The Cambrian Potosi and Eminence Dolomites and the Ordovician Gasconade Dolomite and Roubidoux Formation, are composed of massively bedded dolomite, cherty dolomite, and sandstone. The Roubidoux Formation, though generally referred to as a sandstone, has much dolomite and chert.

The overlying Ordovician Jefferson City, Cotter, and Powell Dolomites are composed of thin- to medium-bedded dolomite and cherty dolomite. The Ordovician St. Peter Sandstone and Everton Formation, principally sandstone and sandy dolomite, are present in the eastern portion of the region.

Pennsylvanian shale, sandstone, and dolomite occur in the northeastern Salem Plateau. Fireclay deposits have accumulated in pre-Pennsylvanian sinkholes in the underlying Jefferson City Dolomite.

Isolated deposits of Cretaceous and Tertiary shale and clay occur in the southeastern portion of the plateau. They resemble shale and clay in portions of Crowleys Ridge, in the Coastal Plains.

SURFICIAL MATERIALS

Stony red clay, characteristic of the Ozarks, is the dominant surficial material of the Salem Plateau. Surficial material properties vary, depending on parent material and landform position. Thickness varies from a few feet to several hundred feet (1 to 100 m).

Surficial material on the gently to steeply rolling terrain is residuum developed from carbonate and sandstone bedrock. It ranges from stone-free red clay to gravel. Characteristically, the red clay has low density; is flocculated, permeable, and angular and blocky in structure; and usually is only moderately plastic. The residuum tends to be moderately to poorly sorted and highly permeable where boulders, gravel, and small chert fragments are the principal components.

Landscape relief is a very important factor in site evaluation. For example, where residuum is not significantly affected by gravity it retains the relict structure of the parent bedrock, a condition that forewarns of catastrophic sinkhole collapse and high infiltration of surface water into the subsurface.

Surficial materials on the relatively flat portions of the Salem Plateau are developed in loess overlying residuum derived from Pennsylvanian shale or from Ordovician formations. The loess, 2 to 4 ft (1 m) thick, has a fragipan that impedes shallow moisture infiltration. Loess occurs on other landforms, but it is best preserved on the flatter uplands.

In losing streams where flow escapes into permeable residuum and cavernous bedrock, valley gradients are relatively low. Losing streams generally have highly permeable, poorly sorted flood plain deposits, usually of moderate thickness.

Gaining streams deposit materials similar to those of losing streams in size and composition, but sorted by stream flow. The valley floors slope gently in gaining tributaries. Stream flow is from surface runoff and from discharges of springs from bedrock. Deposits of alluvium interfinger with colluvial talus and slope wash. Soil profiles may include fragipan development.

Thickness of surficial materials varies widely, from very thin soil on the glades of southwestern Missouri to residuum more than 200 ft (60 m) thick. The thickest surficial materials are in the southeastern part of the plateau. Much of the central portion of the plateau has surficial materials 30 to 100 ft (10 to 31 m) thick. However, there is a large area of very thin surficial materials, mostly silt loam and silty clay, along the western boundary of the Salem Plateau.

GROUNDWATER

Virtually all bedrock units are aquifers, although some formations produce very low yields. Karst development, with large springs and caves, is extensive in the southern portion. Sinkholes, caves, springs, and solution-enlarged joints are well developed in some areas; other karst areas are identified primarily by losing streams, subdued topography, and low-density stream drainages.

Groundwater generally is pumped untreated for private, municipal, and industrial uses. Few areas draw water from streams or impoundments. Karst development in the bedrock has produced complex local groundwater conditions. Karst features and permeable residuum allow rapid recharge of meteoric water and rapid entry and diffusion of surface pollutants.

Meteoric waters, and liquids from waste materials on the relatively flat uplands percolate through modern soil to the fragipan, whence some flow is diverted laterally to adjoining hillslopes. Some of this flow may percolate slowly through the fragipan. Where there is permeable residuum below the fragipan, water flows virtually unrestricted downward into bedrock.

Surface-drainage divides do not necessarily coincide with groundwater-drainage divides. Losing and gaining streams occur randomly in some watersheds. Other watersheds, especially on young landscapes, generally have gaining streams. Surface and subsurface stream piracy occur along solution-enlarged joints and fault traces (Aley and others, 1972; Dean and others, 1976).

Detailed information on groundwater conditions includes water-well, water-chemistry, temperature, static-water-level, and production data, and records of drilling conditions. This information is available in published reports.

ENGINEERING GEOLOGY

Factors to be considered in the location and construction of engineered structures, factors of particular importance in siting waste isolation facilities, are karst development, permeable surficial materials, pinnacled and permeable bedrock, and a complex groundwater regime.

Important karst features include collapse sinkholes (Aley and others, 1972; Williams and Vineyard, 1976), sinkholes, springs, and caverns (Bretz, 1956, 1965), solution-enlarged

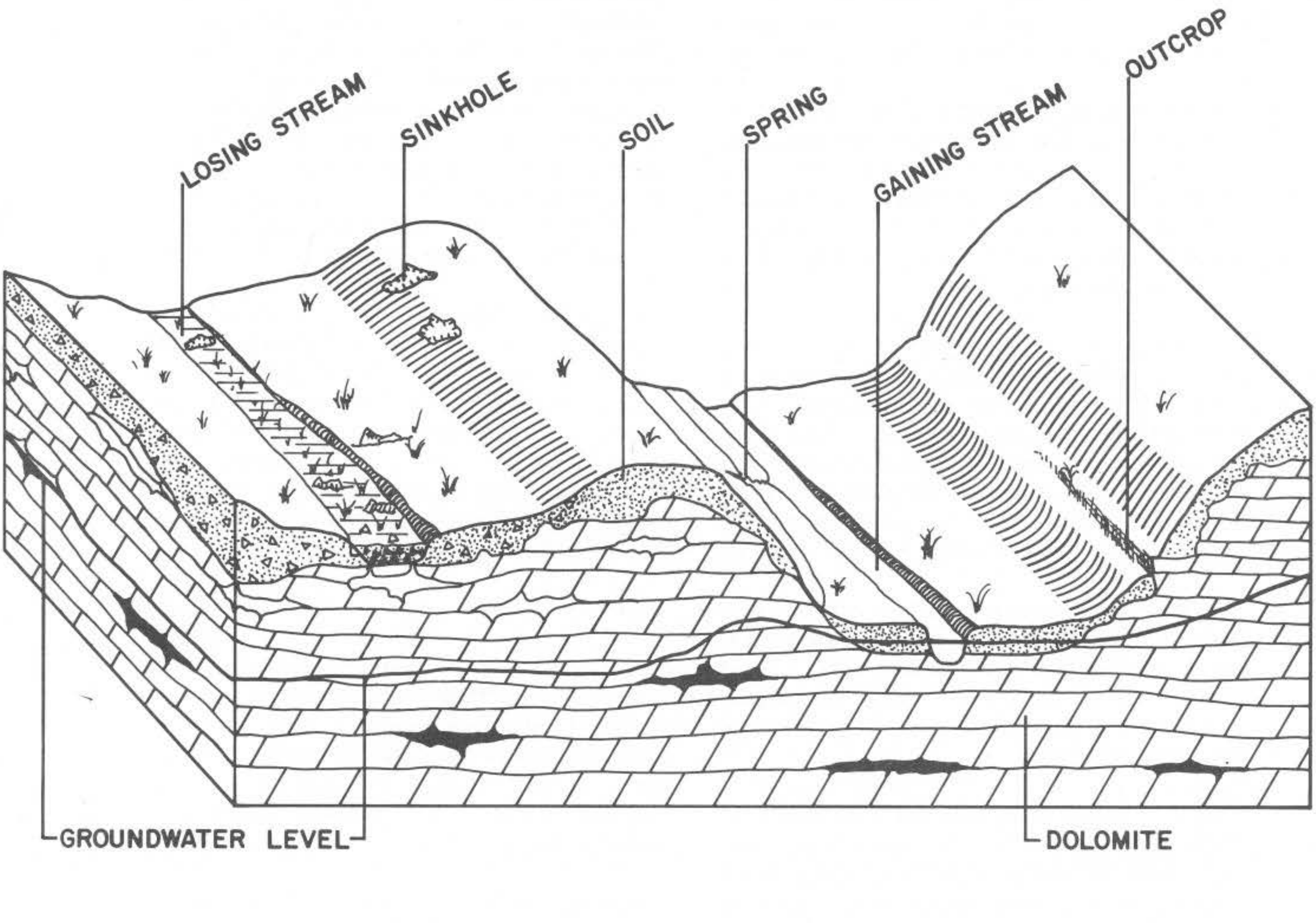

Figure 2. Generalized profile of groundwater regime of losing and gaining streams typical of the Ozark Plateaus

joints, and gain or loss of water flow in streams (Harvey and others, 1977). A thorough investigation of a potential site or area should include drilling for detailed soil and bedrock samples, an inventory of karst features, and detailed hydrogeologic studies. Landscape age and setting provide excellent clues to recharge or discharge conditions. Topography downslope from retreating escarpments is younger than the adjoining plains and has surficial material and bedrock of low permeability because there has been less opportunity for solution. However, surficial materials may be very thin.

The Salem Plateau has few areas suitable for exploration for hazardous-waste isolation sites. Those underlain by Cretaceous or Tertiary clays and Pennsylvanian shales offer the best possibilities. In this region, limitations are less severe for nonhazardous-waste isolation facilities.

EXPLORATION CONSIDERATIONS

Chert beds and sandstone boulders in the residuum impede drilling and make sampling difficult. Chert beds also frequently make excavation extremely difficult, particularly in trenches or pits. Backhoe excavation is the preferred first step in exploration. Examination of exposed subsoil in trenches or pits in residuum can provide more useful data for initial site exploration than borings. Mode of origin of surficial materials can be determined by examining the features of relatively undisturbed subsoil on the sides of backhoe pits. Knowing the mode of origin of the surficial material assists in determining if more detailed, more costly exploration is warranted. If a site is considered suitable for detailed investigation, deeper borings will be necessary. If boring is difficult, geophysical exploration can be used to supplement information from borings.

Collapse sinkholes are most likely to occur in residuum 40 ft (12 m) or more in thickness. Collapses occur in upland areas and stream valleys, and where there is a history of cave development and previous collapses (Williams and Vineyard, 1976; Aley and others, 1972). Close spacing of boreholes or seismic-profile lines can help identify existing or developing collapse sinkholes. Resistivity methods are also useful, provided the residual materials are not excessively dry.

Solution-enlarged joints and caves are often found during exploration. Cave information can be obtained from the Missouri Department of Natural Resources, Division of Geology and Land Survey, the Missouri Speleological Survey, and local caving groups. Such information includes location, cave conditions, physical size of cave openings, and status of mapping of individual caves. In some cases, because of landowner request, these data are confidential.

SPRINGFIELD PLATEAU

BOUNDARIES

The Springfield Plateau, in the southwestern corner of the state and extending into Arkansas, Oklahoma, and Kansas, is that portion of the Ozark Plateaus west of the Eureka Springs escarpment (the "Burlington escarpment" of Marbut (1896)), which abruptly separates the Springfield and Salem Plateaus. The escarpment is essentially the eastern boundary of the outcrop area of Mississippian rocks.

TOPOGRAPHY

There are three general landforms: the Eureka Springs escarpment, the rugged hills near it, and the relatively level uplands of broad prairies and sinkhole plains. Except for the escarpment and adjoining rugged hills, the Springfield Plateau is not extensively dissected.

Karst features such as caves, springs, and solution-enlarged joints are common, but generally they are not as large as those of the Salem Plateau.

The northern portion of the region drains into the Osage River; the western portion, to the Neosho River and Lake of the Cherokees. The White River receives drainage from the southern portion of the Springfield Plateau.

Large lakes and reservoirs include Stockton Lake, Harry S Truman Reservoir, Pomme de Terre Lake, Fellows Lake, and Lake Springfield.

STRUCTURAL GEOLOGY

The Mississippian and older sediments dip gently away from the St. Francois Mountains. The bedrock forms a structural plain, the surface of which is reflected to some extent in the topography of the region.

The Bolivar-Mansfield and Chesapeake faults, northwest-trending, high-angle gravity faults, with throws of up to 300 ft (91 m) (McCracken, 1971), are prominent structures of the Springfield Plateau. In the southwestern portion of the plateau, the Seneca fault system has a westerly trend.

Gentle folds, generally several miles long, with dips of a few degrees, parallel the fault systems. Some asymmetrical folding has displaced beds several hundred feet and produced steeper dips (McCracken, 1967, 1971).

BEDROCK

Bedrock is principally Mississippian limestone and cherty limestone, the latter being the most prevalent rock type in the southern and eastern portions of the plateau. To the north, there is limestone with less chert and more shale. In the central portion, there are Pennsylvanian channel sandstones, remnants of which form discontinuous narrow deposits that trend roughly north-south. Siltstone, shale, cherty limestone, and dolomite crop out on the Eureka Springs escarpment.

SURFICIAL MATERIALS

Thickness of surficial materials varies from thin soil cover to more than 40 ft (12 m) and increases, northeast to southwest, to maximum thickness south of Joplin and in Lawrence and Barry Counties. The areas where these materials are thinnest, approaching glade conditions, are in the White River and Sac River watersheds and along the Eureka Springs escarpment.

Surficial materials on the uplands are of two general types: loess over residuum, and residuum only. The former is preserved only on broad ridgetops and relatively undissected prairies; the latter, on slopes and eroded narrow ridges.

Uplands composed solely of residuum exist where the older loess-capped landforms have been removed by erosion. Erosion, accelerated in part by sinkhole development, strips the loess. Consequently, silts are deposited in sinkholes and on some valley flood plains.

Surficial materials on the plateau can be partly differentiated by color: loess-derived material is generally brown; residual material, generally red or, locally, yellowish brown. Engineering properties of loess (CL-ML), residuum (CH-MH), colluvium (CL, ML-CL), and alluvium (ML-CH) can also help distinguish surficial materials. All surficial materials, except loess, contain angular chert fragments that range up to boulder size. In some areas the chert-fragment content of soil samples exceeds 50 percent. The chert becomes soft and tripolitic in southwestern portions of the plateau.

The loess is a brown silt loam or silty clay, usually with a fragipan (hardpan) developed in the soil. Loess thickness seldom exceeds 2 or 3 ft (1 m).

Residuum typically grades from almost chert-free red clay to chert boulders with minor amounts of red clay. The material, commonly a cherty red clay that dries to form angular, blocky soil fragments, drains rapidly. However, samples of red clay tested under laboratory conditions usually show low permeability. The low density of the red clay is attributed to the iron-bonded, flocculated nature of the material (Whitfield, 1978). The residual soils also develop fragipans on the uplands of this region.

Gaining and losing stream valleys have alluvial deposits similar in size and composition, but they vary in sorting and channel development. Gaining streams characteristically have thin to moderately thick, well-sorted, moderately permeable materials, and terraces of moderately thick, silty and sandy clay. Flood plain and terrace soil profiles of gaining streams may contain fragipans. Losing streams contain moderately to highly permeable, poorly sorted materials of moderate thickness in poorly developed channels, and few terraces. Flood plains of large losing streams have modern soils of very silty clay to silt loam overlying gravelly materials.

GROUNDWATER

The groundwater regime is best characterized as a leaky artesian system, comprising a minor (shallow) and a major (deeper) aquifer separated by a shale layer that partially impedes downward movement of water. The shale, part of the Mississippian Northview Formation, is not persistent across the Springfield Plateau.

The minor and major aquifers are distinguished by rock type and the chemical quality of the water. Water from the minor aquifer, Mississippian limestone, has characteristics of direct meteoric recharge; i.e., low total dissolved solids and may show contamination from urban and agricultural sources. The major, or deeper, aquifer comprises Cambrian and Ordovician dolomite and sandstone. It is recharged regionally by infiltration of meteoric waters and migration downdip from outcrop areas in the Salem Plateau. The water has calcium-magnesium bicarbonates in solution (Feder and others, 1969; Emmett and others, 1978).

In contrast to conditions in the Salem Plateau, water in the subsurface is usually confined to the surface watersheds of major drainages. However, surface flows in small watersheds may be diverted to subsurface flow paths that follow solution-enlarged joints and bedding planes to other minor surface drainages.

Streams can be classified as *gaining* or *losing*. A gaining stream cumulatively increases in flow downstream; a losing stream decreases. During periods of prolonged, intense rainfall, both stream types will sustain flow because of the temporary rise of the water table. A good discussion of field determination of gaining and losing streams is found in Dean and others (1976).

Fragipan development in a soil profile does not have a regional effect on the overall water regime, but it does affect local water movement in the shallow subsoil.

Groundwater is the principal source of public and private water supplies in this region. Such supplies are usually untreated prior to use. Poor waste isolation and well-construction practices have caused local contamination of shallow aquifers. Poor well construction has also contributed to pollution of the deep aquifer.

ENGINEERING GEOLOGY

Because of karst development, permeable surficial materials, and a complex water regime, it is extremely difficult to find suitable waste isolation sites in the Springfield Plateau. There are few places where engineering design could overcome severe geologic problems for hazardous-waste sites. Lakes, ponds, lagoons, and landfills can leak through surficial materials and bedrock, becoming loci of intense local recharge. Small catastrophic sinkhole collapses may be induced when water or other liquids are impounded (Whitfield, 1978; Aley and others, 1972). Thorough foundation investigations should be made by geologists and engineers experienced in working in karst terrain.

EXPLORATION CONSIDERATIONS

All karst features should be considered during exploration. Particular attention should be given to surficial materials, bedrock, and groundwater conditions.

Because of the relatively uniform properties of residuum and thinness of overburden, trenches and backhoe or bulldozer pits afford quick, inexpensive means of preliminary investigation.

The presence of relict bedding in surficial material causes some problems in sampling and in interpretation of the standard penetration test. The blow count may be misleading if the split-spoon sampler is driven through layers of clay and then through layers of gravel- to bounder-size chert fragments.

In the Springfield Plateau, geomorphic history has resulted in surficial materials that are well drained and preconsolidated. Relict bedding and soil structure are important factors that increase permeability. Soil conditioning and compaction somewhat reduce permeability.

Permeability measurements tend to be misleading in red clay of the Springfield Plateau. Experience has demonstrated that excavated exposures of this red clay, when allowed to dry, show a marked increase in permeability. Even artificial sealants perform poorly under these conditions. The preferred sealant is soda ash, because of the dispersing effect of the sodium ion.

Monitoring wells can be constructed in surficial materials and cavernous rock. Sealing casings may be difficult, however. Another problem is the raveling or enlargement of boreholes, caused by drilling through cherty residuum and cherty limestone.

Climatological conditions are important in field determinations of losing or gaining streams, both of which will sustain flow for a time after a rainstorm or major snow melt. Flow is more likely to occur in losing streams in the Springfield Plateau than in the Salem Plateau, because of the relatively low storage capacity of smaller solution-enlarged openings in bedrock in the Springfield Plateau. In field inspections, recent weather and hydrogeologic conditions of the watershed above and below a site must be considered in order to avoid misidentification of losing streams. In addition, streams may be classified as losing in certain reaches but gaining in adjacent ones. Characteristics of local flora aid considerably in identifying gaining and losing streams. For example, willows and other phreatophytes are indicators of gaining streams, whereas losing streams have fewer phreatophytes (Harvey and others, 1977).

ST. FRANCOIS MOUNTAINS

BOUNDARIES

The St. Francois Mountains are knobs and ridges of Precambrian igneous rocks. Physiographic boundaries enclose a roughly circular area of rugged terrain formed mostly in rhyolite and granite. Broad valleys underlain by dolomite, primarily Cambrian in age, lie among these rugged hills. The region is distinguished from the Salem Plateau by its rugged terrain, higher relief, thinner soils, and widespread exposures of barren igneous rock.

TOPOGRAPHY

The St. Francois Mountains are the highest structural and topographic region in the state. They are characterized by rugged terrain and local relief exceeding 600 ft (180 m).

Drainage is complex. Stream valleys are usually wide where underlain by dolomite, but have narrow, steep profiles in igneous rocks. Severely constricted stream valley segments are called "shut-ins" (Beveridge, 1978).

Major lakes include Lake Killarney, Iron Mountain Lake, and the upper and lower reservoirs of the Taum Sauk pumped-storage power plant on Proffit Mountain. Other large lakes are associated with mining. Council Bluffs Lake in Mark Twain National Forest is under construction.

STRUCTURAL GEOLOGY

Structurally the St. Francois Mountains are a domal uplift, with fault systems, minor folds, and other structures. This region of uplift was a major influence on the geomorphic and geologic history of southern Missouri and adjacent areas.

The igneous rocks of the St. Francois Mountains are at the center of the asymmetrical dome of the Ozark uplift, from which the sedimentary rocks of the Ozark Plateaus dip away radially (McCracken, 1967, 1971). The resulting concentric outcrop pattern of sedimentary rocks, however, is not reflected in the surface drainage pattern (Bretz, 1965). The Simms Mountain fault system is a major structural feature that crosses the northeastern portion of the St. Francois Mountains.

BEDROCK

Bedrock comprises Precambrian igneous and Cambrian sedimentary rocks. The igneous rocks, which originated in several volcanic and intrusive episodes, form the basement below the sedimentary rocks. The volcanic rocks are mainly rhyolites; the intrusive rocks, mainly granite. Jointing varies in spacing, direction, and parting width, according to rock type, weathering, and other geologic factors (Pratt and others, 1979; Kisvarsanyi, 1976; Hayes, 1961).

The Cambrian Lamotte Sandstone, which laps upon the Precambrian igneous knobs, is widespread and of variable thickness, depending upon the character of the Precambrian surface.

Bonneterre Dolomite overlies the sandstone and igneous rocks, exhibits several facies and lithologic changes, and contains caves and solution-enlarged joints. It also contains the lead deposits of Missouri.

The Davis Formation, a shale and dolomite sequence, overlies the Bonneterre. Although vertical joints in the Davis permit some water movement, the unit impedes downward movement.

The Derby-Doerun Dolomite, a medium to massively bedded dolomite, is a moderately permeable, bluff-forming unit overlying the Davis Formation.

Younger bedrock formations are described above in connection with the Salem Plateau.

SURFICIAL MATERIALS

Surficial materials are mostly residual, their thickness depending on landform position, parent materials, and depth of weathering. Generally the soil cover is thin and sparse, and rock exposures are widespread. The thinnest soils are on mountain tops; the thickest, between the St. Francois Mountains and the enclave of igneous peaks and ridges near Eminence, in Shannon County. Irregularity of the bedrock surface, particularly where igneous rocks are exposed, causes local variations in thickness. Colluvial deposits have attained appreciable thickness through erosion of higher peaks.

Surficial materials formed on fine-grained igneous rocks, principally rhyolite, constitute a very thin veneer of loess-derived silty loam. Typically, rhyolite is exposed as barren rock glades. The coarse-grained igneous rocks, principally granite, are mantled by a sandy clay residuum of variable thickness. Landscapes of lower relief form on the Lamotte Sandstone and Bonneterre Dolomite. Thin sandy loam to sandy clay forms on the Lamotte, whereas the Bonneterre Dolomite develops a red clay of moderate permeability, low to moderate plasticity, low density, and angular, blocky structure. The Davis Formation generally has a thin cover of surficial material, typically a veneer of loess-derived silt loam over thin silty clay. The Derby-Doerun Dolomite, exposed in numerous bluffs and other outcrops, has a very thin cover of silt loam to silty clay.

GROUNDWATER

Public and private water supplies are from surface-water reservoirs and from aquifers. The Precambrian igneous rocks provide extremely limited yields through joints and fractures. Lack of storage and poorly integrated, closed joints, except in outcrops, severely limit the availability of groundwater.

The groundwater regime is either water table or leaky artesian. Water table conditions exist where sedimentary rock aquifers are partially or totally isolated by surrounding igneous bedrock. Such areas are of limited areal extent and yield variable quantities of groundwater.

The major aquifers in the St. Francois Mountains are Cambrian sandstones and dolomites. Because of the irregular igneous rock surface, recharge of these aquifers is local and storage capacity varies. Solution activity in the dolomites allows rapid recharge through joints and fractures in the bedrock.

ENGINEERING GEOLOGY

Karst development, permeability of surficial materials and bedrock, bedrock topography, seismic activity, and the variable thickness of surficial materials are factors of particular concern in siting waste isolation facilities.

Residuum generally is permeable in the St. Francois Mountains. In some areas, open joints and karst features in sedimentary rocks cause rapid recharge of groundwater aquifers.

Shaly dolomite and associated residuum provide natural impedence to percolating liquids. Because of lateral changes in bedrock type, the influence of the shale and residuum is variable.

Nuttli (1979) reports that the St. Francois Mountains region is subject to considerable microearthquake activity. Although there are many epicenters, they do not seem to be concentrated along the major fault systems.

Development possibilities for waste isolation facilities in surficial materials are severely limited. Areas underlain by shale or igneous rock have few limitations; however, thickness of surficial materials will be inadequate in many of these settings. For certain types of waste, specially constructed underground excavations in rhyolite can be safe for isolation purposes. On the other hand, mines seldom can be adapted for waste isolation.

EXPLORATION CONSIDERATIONS

Thickness and type of surficial materials can be estimated visually in many areas. If necessary, exploration pits can be dug and drilling can be done with minimum problems. Results should be easy to interpret, because the relationship of surficial materials to bedrock is generally simple.

There are few caves, sinkholes, and losing streams, in the region.

Groundwater studies should include the relationship of local conditions to the regional groundwater regime. Groundwater data from one area cannot be interpolated between other areas.

The St. Francois Mountains, like all subprovinces of the Ozark Plateaus, have severe limitations that would affect exploration, development, and operation of hazardous-waste isolation facilities.

COASTAL PLAINS

The Coastal Plains extends from southeastern Missouri to the Gulf of Mexico. In Missouri, the upper part of the Coastal Plains is called the Southeastern Lowlands (Mississippi Alluvial Plain).

SOUTHEASTERN LOWLANDS (MISSISSIPPI ALLUVIAL PLAIN)

BOUNDARIES

The Southeastern Lowlands, a part of the Coastal Plains (Fenneman, 1938), occupy the southeastern corner of the state, "the Bootheel." They are bounded on the northwest by the Ozark escarpment, and extend into Illinois, Kentucky, Tennessee, and Arkansas as the Mississippi Alluvial Plain.

TOPOGRAPHY

Except for Crowleys Ridge, the Benton Hills, and stream terraces, the topography is essentially flat, but with a nearly imperceptible slope to the south. The only major lake in the area is a shallow impoundment in the Duck Creek Wildlife Area.

Crowleys Ridge and the Benton Hills rise abruptly from the generally featureless plain. The Benton Hills and Crowleys Ridge extend southwest and south from the Mississippi River, near Commerce, into Arkansas. They exhibit moderate relief, particularly on the northern, southern, and eastern slopes. The western slope is more gentle. Drainage from Crowleys Ridge flows away from the hills into the Mississippi Alluvial Plain, which drains mainly to the south and is modified by an extensive system of dredged drainage ditches.

STRUCTURAL GEOLOGY

The region, part of the Mississippi structural trough, is affected by both regional and local geologic structures. A northeast-trending fault zone, perhaps a graben or a rift zone, completely buried by thick sediments, parallels the line of epicenters of the New Madrid earthquakes of 1811 and 1812 and of subsequent, less severe events (McCracken, 1971). Nuttli (1979) reports continuing earthquake activity. Loess is faulted against Tertiary sediments, thus indicating recent surface faulting.

BEDROCK

Bedrock in this region includes consolidated and poorly consolidated sediments, exposures of which are limited to Crowleys Ridge and the Benton Hills. The oldest exposed bedrock units are Ordovician dolomite and sandstone. Younger exposed bedrock units are Cretaceous and Tertiary clays and sands, less consolidated than the Paleozoic rock, which unconformably overlie the Ordovician formations and are overlain by a thin, nonpersistent deposit of unconsolidated, rounded and polished gravel and by loess. The well-sorted gravel on the uplands of Crowleys Ridge resembles similar gravel in the Salem Plateau.

SURFICIAL MATERIALS

Surficial materials are loess, residuum, and alluvium, the alluvium having the greatest areal extent.

Uplands typically have a loess cover, the thickness of which increases toward the Mississippi River. Farrar and McManamy (1937) report that loess in Stoddard County is commonly 5 to 10 ft (2 to 3 m) thick but rarely exceeds 30 ft (9 m).

Loess is typically composed of silt, with minor fine sand and clay. It is of low to moderate plasticity, well sorted, moderately permeable, and is usually modified by slope movement, weathering, and clay enrichment. A clayey subsoil is commonly developed in the modern soil profile.

Gravel is the most common clastic material on the uplands of Crowleys Ridge and the Benton Hills. The overlying fine-grained loess generally winnows into the gravel to produce a clayey or silty, well-sorted gravel having little or no plasticity, which is highly permeable, unless there is an admixture of clay.

Residuum derived from the weathering of the Ordovician bedrock is of limited areal extent and moderately permeable. Coarse materials, consisting of angular chert and some sandstone fragments, are contained in a matrix of red clay.

The clays, shales, and the clayey residuum derived from them usually are covered by loess. The residuum has moderate to high plasticity and low permeability.

The alluvium of the minor drainges is primarily silt loam and silty clay, but gravelly material may be extensive where streams erode Ordovician bedrock. Thickness of the alluvium in the minor drainages is 10 to 40 ft (3 to 12 m).

Major streams in the Southeastern Lowlands have deposits of stratified gravel, sand, and silt. Clay-rich "gumbo" deposits are extensive west of Crowleys Ridge and in some areas near the Mississippi River. Fisk (1944) should be consulted for a detailed discussion of the development of the Mississippi Alluvial Plain. Thickness of alluvium varies; several well logs indicate thicknesses exceeding 200 ft (61 m). Locally borings have encountered boulder deposits at depths of 60 ft (18 m) in the predominantly sand and gravel material.

Because of the low relief and the low gradient of major rivers, many drainage ditches have been constructed into integrated drainage-district networks that allow intensive crop farming; however, the region remains susceptible to flooding.

GROUNDWATER

The aquifers in the Southeastern Lowlands are unconsolidated alluvium and poorly consolidated sand and gravel formations. The Ozark Plateaus and major streams draining into and through the region are important groundwater recharge sources.

Crowleys Ridge is important because of its local recharge to the surrounding alluvium; however, water supplies on Crowleys Ridge are limited and more costly to develop than on the alluvial plain. In fact, some individual water supplies on Crowleys Ridge are only cisterns.

The alluvial-plain deposits contain vast amounts of groundwater, relatively hard and high in iron and dissolved solids (Fuller, 1977), only 10 to 15 ft (3 to 5 m) below the surface. Shallow wells can obtain water at depths of 10 to 20 ft (3 to 6 m); however, to avoid pollution, many wells are at least 60 ft (18 m) deep.

The Eocene Wilcox Group is the upper bedrock aquifer underlying the alluvium. Yields are over 2000 gpm (7570 lpm), but may require treatment for iron (2 to 10 mg/l), and total dissolved solids (250 to 350 mg/l) (Fuller, 1977).

The Upper Cretaceous McNairy Formation is an artesian aquifer. Yields of 500 gpm (1892 lpm) can be obtained, producing water of high quality, with low iron (less than 0.3 mg/l) and total dissolved solids (15 to 25 mg/l). Water temperature, however, may exceed 100°F (37.8°C) (Fuller, 1977).

ENGINEERING GEOLOGY

Particularly important factors in siting hazardous-waste isolation facilities are seismicity, flooding, surficial-material properties, and local and regional groundwater conditions.

There is periodic flooding of the Southeastern Lowlands, but the Benton Hills and Crowleys Ridge usually are not affected.

Generally, surficial materials vary in composition vertically and exhibit lateral continuity. Clay materials are moderately to highly plastic, exhibit low permeability, and possess moderate to high shrink/swell characteristics. Sands tend to be very permeable. Channel meandering and subsequent cutoffs have resulted in oxbow lakes, which have been either filled or drained for agricultural purposes. Some are naturally filled with thick clay deposits. Thorough exploratory drilling and/or trenching is necessary to identify surficial-material profiles for site planning.

The uplands and slopes of the Benton Hills and Crowleys Ridge ordinarily do not exhibit rapid changes in their surficial-material profiles. Most upland soils have developed a clayey subsoil. Thick sequences of loess can result in severe erosion and slope creep. Permeability characteristics of the loess limit its suitability for waste isolation.

There are karst features near Scott City, in the Benton Hills, but elsewhere in the region they are not developed in the carbonate bedrock to any significant degree. The rapid recharge of all aquifers seriously limits the siting of hazardous-waste isolation facilities. Accidental release of contaminants can rapidly affect wells and aquifers over a large area. Suitable locations for hazardous-waste isolation can be identified only by extensive investigation and exploration. The most likely locations are the clay and shale formations on Crowleys Ridge, or clay-rich soils in the Sharkey soil series on the alluvial plain.

EXPLORATION CONSIDERATIONS

Soil surveys published by the U.S. Department of Agriculture Soil Conservation Service provide excellent preliminary information on surficial materials. Remote sensing data and soil surveys can aid in identifying meander scars which have not been eroded by flooding or river-channel changes.

Exploration pits and trenches can be useful in identification of surficial materials, in sampling, and in observing water table conditions. Because of saturated unconsolidated and poorly consolidated materials, water-quality testing requires that boreholes be carefully cored and sealed. Drilling is less difficult on Crowleys Ridge and the Benton Hills.

Flood-prone areas can be identified by examination of aerial photographs, and from information obtained from the U.S. Corps of Engineers, the U.S. Geological Survey, and the Missouri Department of Natural Resources, Division of Geology and Land Survey. Interviews with long-time local residents can also be helpful. Dikes and areas designated as floodways should be identified.

Regionally, the Mississippi Alluvial Plain has severe limitations for siting hazardous-waste isolation facilities.

CENTRAL LOWLAND

The Central Lowland province includes that part of Missouri north of the Missouri River and a large western portion south of it (fig. 1). The area is divided into two subprovinces: the Osage Plains and the Dissected Till Plains

OSAGE PLAINS

BOUNDARIES

The Osage Plains, part of the Central Lowland as defined by Fenneman (1938), occupy the west-central part of the state. They are bounded on the north by the Missouri River. The eastern edge can be defined by a line extending southwestward from Cooper County to Jasper County (fig. 1), a boundary that in part roughly corresponds to the contact of Mississippian and younger rocks of the Osage Plains with the older bedrock of the Ozark Plateaus to the east. The Osage Plains extend westward into Kansas and Oklahoma.

TOPOGRAPHY

The Osage Plains exhibit major and minor topographic features amid the overall low relief of the region. Prominent escarpments are caused by thick, erosion-resistant limestone 10 to 30 ft (3 to 9 m) thick. Only thin soils are developed on the escarpments; the plains between them have thicker surficial materials.

Drainage is primarily into the Osage River. Drainage ditches are broad, maturely dissected uplands, which gradually yield to somewhat steeper valley slopes, particularly along the major drainages.

Underfit streams occur in broad valleys. The filled valleys and reduced stream gradients result in somewhat poorly drained alluvium. Construction of drainage ditches has improved the drainage systems of some flood plains.

STRUCTURAL GEOLOGY

The geologic structure includes folding and minor faulting. Individual structures, such as domes and folds, have produced gas, oil, or both, in limited quantities.

Extensions of the Bolivar-Mansfield and Chesapeake fault systems cross the southern part of the area in a northwesterly direction. Large block faults at depth are thought to be responsible for the folding in this region (Gentile, 1968).

BEDROCK

Rocks of the Pennsylvanian Cherokee, Marmaton, Pleasanton, and Kansas City Groups are present in the Osage Plains. The development of escarpments, plains, and other topographic features has been largely controlled by the rock types within these groups and formations (fig. 3).

The Nevada Lowlands, the easternmost portion of this region, is developed on less resistant shales and sandstones of the Cherokee Group. These deposits are cyclic sequences (cyclothems) of limestone, shale, sandstone, underclay, coal, and siltstone.

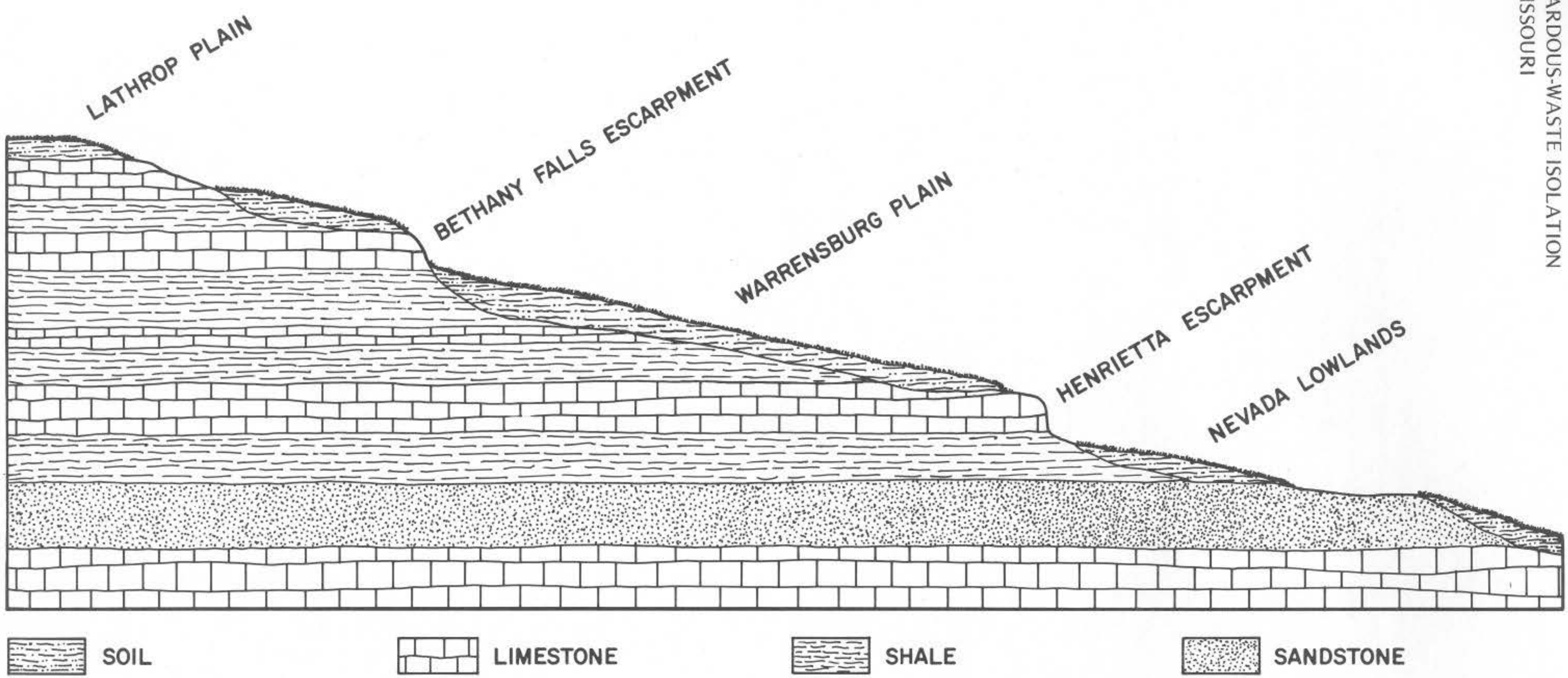

Figure 3. Cross section, northwest to southeast, across Osage Plains

The Henrietta escarpment, formed by a relatively thick limestone, the Higginsville Formation, is the boundary between the Warrensburg Plain and the Nevada Lowlands to the south and east, respectively. The gently rolling Warrensburg Plain is developed on the soft shales and sandstones of the Marmaton and Pleasanton Groups. The discontinuous Warrensburg Sandstone Member of the Pleasanton Group is a cross-bedded, channel-fill sandstone, possibly as much as 150 ft (46 m) thick.

The Lathrop Plain is underlain by limestones and shales of the Kansas City Group. The topographic effects of resistant limestone are more noticeable on the Lathrop Plain than on the Warrensburg Plain and, to some extent, on the Nevada Lowlands. The escarpment of the Lathrop Plain is formed by resistant limestones of the Swope Formation, particularly the Bethany Falls Limestone Member.

Coal has been mined primarily by surface strip mining in the Cherokee and Marmaton Groups. The scarcity of coal in the Kansas City Group precludes mining on the Lathrop Plain.

Limestone has been mined underground and at the surface, particularly in and near Kansas City. Subsidence has occurred where poor mining practices were followed.

Natural gas and crude oil have been produced from many wells, particularly near Kansas City, and in Bates and Vernon Counties.

SURFICIAL MATERIALS

The surficial materials of the region include loess, residuum, and alluvium, their composition and properties varying with the associated landforms. Thickness also varies with landforms, but there is regional uniformity.

Upland surficial-material profiles have very thin loess over residuum on bedrock. The residuum is derived from parent bedrock, including thick sandstones and limestones and thin cyclic deposits (cyclothems) of sandstone, shale, coal, limestone, siltstone, and clay.

Loess, which constitutes the upper part of many soil profiles, increases in thickness northward. The soil developed on it has low to moderate plasticity, is moderately to highly erodible, and frequently develops a claypan subsoil of low permeability.

Residuum developed on sandstone has granular structure, low to moderate plasticity, and moderate permeability. Sandstone-supported uplands and slopes are common in the southern part of the region, where the soil cover is thin and sandstone outcrops are numerous.

Residuum developed on shale has high plasticity and low permeability.

The soil on limestone-supported uplands is developed from very thin loess over thin, residual, reddish-brown silt loam to silty clay and has moderate plasticity and permeability.

The present wide flood plains, low stream gradients, and preserved stream terraces suggest that current stream gradients and patterns have changed little since the Pleistocene. The composition of surficial material on the terraces is similar to that of the valley deposits. The alluvium comprises silt loam and silty clay of moderate permeability and low to moderate plasticity. It is thin on minor tributaries, but is moderately thick to thick in larger stream valleys.

Surficial materials average 20 ft (6 m) thick and almost never exceed 40 ft (12 m), except for major valleys, in which alluvial thickness may reach 50 ft (15 m). Thickness of surficial materials varies considerably with the associated landforms: limestone escarpments have thin cover; the low, broad, intervening landforms have thicknesses of 15 to 30 ft (5 to 9 m); and valleys generally have the thickest surficial materials.

GROUNDWATER

Groundwater in the Osage Plains is limited in quantity and of poor quality. Water is mostly supplied from surface impoundments and stream-intake pipes.

Surficial materials of the uplands and slopes produce low yields from water perched on claypans and fragipans and in residuum at the surficial material-bedrock contact. These perched water zones are seasonal, locally recharged by precipitation, and vary with local conditions and permeability.

Wells in terrace deposits and alluvium in the upper Osage River drainage produce low yields; however, higher yields are obtainable from the alluvial aquifers in the lower Osage Valley (Gann and others, 1974). Alluvial aquifers are recharged by precipitation and are probably also recharged during periods of high-stream discharge and flooding. Recharge to alluvial aquifers is greater than recharge to bedrock aquifers. Groundwater in the alluvium tends to be high in iron, bicarbonates, and other dissolved solids. Because of subdued relief and shallow stream gradients, groundwater movement is slow, although some streams have been modified by drainage ditches (Miller, 1966; Gentile, 1976).

Mississippian and Pennsylvanian formations are the bedrock aquifers in this region. The Pennsylvanian aquifers are characterized by water table conditions; however, because of geologic structure, artesian conditions may exist locally in shallow wells. Artesian conditions exist in deeper wells drilled to Ordovician bedrock. Yields are low, 1 to 15 gpm (4 to 57 lpm), and the water is high in chlorides, sodium, iron, bicarbonates, and other dissolved solids. Yields increase in deeper wells, but quality decreases significantly with depth (Miller, 1966).

The Warrensburg Sandstone Member of the Pleasanton Group may yield up to 50 gpm (190 lpm), but dissolved solids may exceed 1000 mg/l. The channel-fill sandstone is locally recharged by precipitation; recharge may also occur through upper reaches of the old channel.

Mississippian and older bedrock aquifers exhibit leaky artesian conditions; however, water table conditions exist near the border of the Ozark Plateaus. Yields vary from 25 to a few hundred gpm (95+ lpm). Water quality is highest near the eastern border of the Osage Plains and decreases toward the northwest, with increasing concentrations of chlorides, sodium, and other dissolved solids (see plate 4). Recharge is by regional water movement from the Ozark Plateaus and by limited infiltration of precipitation.

ENGINEERING GEOLOGY

The plasticity and permeability of residual surficial materials vary with rock type. The least permeable, thickest surficial materials are developed on the uplands and are underlain primarily by shale. Conversely, the most permeable, thinnest surficial materials are developed along the limestone escarpments. The limestone bedrock has solution-developed features, allowing rapid transmission of water.

Sandstone and sandy residuum are very permeable, and the thin, sandy soil affects many engineering-related projects.

Isolation of wastes, particularly in landfills, has some limitations. Shale-derived surficial materials and shale bedrock offer the most suitable locations, particularly where the water from bedrock aquifers is highly mineralized. Surficial-material thickness should be investigated very early in planning. The low permeability of the surficial materials and underlying shale bedrock restrict downward and, to some extent, lateral movement of water.

Because of permeable alluvium, high water tables, and flood risks, flood plains are severely limited as hazardous-waste sites. Stream terraces, however, may be unaffected by flooding, and some are formed of less permeable material than those of the adjoining flood plains. Water table depths in the alluvium and terraces of the flood plains are 20 to 30 ft (6 to 9 m).

EXPLORATION CONSIDERATIONS

There has been considerable geologic mapping in the Osage Plains, mostly in connection with mineral resources. Groundwater studies have been completed in adjoining counties in Kansas. Soil surveys published by the U.S. Department of Agriculture Soil Conservation Service can provide good preliminary information on surficial materials.

Limestone ledges can be identified by low-altitude aerial photographs. Landforms in the Osage Plains reflect the bedrock better than do the landforms in the other provinces and subprovinces in Missouri. The isolated hilltops and the escarpments have been formed by more resistant sandstone and limestone. The softer, more subdued landforms are underlain predominantly by shale. Soil cover is thicker in the areas of shale bedrock. In some ways, exploration can be done more easily, more rapidly, and more reliably in the Osage Plains than in the other provinces and subprovinces.

Trenching by backhoe or bulldozer can provide useful preliminary information on surficial materials and can often reach bedrock. Trenching permits examination of seeps or perched water tables in surficial materials, and provides means to determine relationships of surficial materials and bedrock.

Exploration procedures are not complex. Basically the questions to answer are the following: (1) Is there sufficient thickness of surficial material? (2) Is there an abundance or general absence of groundwater? (3) Can near-surface perched water tables be controlled?

In summary, the Osage Plains have slight to moderate limitations for potential hazardous-waste sites. Inadequate thickness of surficial materials is the most serious limitation.

DISSECTED TILL PLAINS

BOUNDARIES

The Dissected Till Plains, within the Central Lowland, as described by Fenneman (1938), include essentially all glaciated areas of the state, and loess-covered bedrock adjoining the Mississippi River from Pike County to St. Louis County. The southern boundary of the plains is approximately defined by the Missouri River.

TOPOGRAPHY

The topography of the Dissected Till Plains ranges from the prairies of east-central and northeastern Missouri to steep, bedrock-formed hills and ravines near the Mississippi River. The western two-thirds drains southward into the Missouri River; the eastern third, southeastward to the Mississippi River. The streams in eastern Missouri generally have straight courses that trend southeastward toward the Mississippi River.

Rolling hills characterize the northwestern area, and there are rugged hills in the north-central portion. The broad upland prairies are almost classically developed in the eastern part of the region, near Mexico and Centralia. Similar prairies exist in the northeast near Lewistown, Williamstown, and Kahoka. Flat topography and clay-rich subsoils cause these prairies to be poorly drained.

Topography is rugged along the loess-capped valley walls of the Missouri and Mississippi Rivers. Mature, rugged topgraphy, with short, steep valleys draining into large streams, also exists along the Chariton River and in the Thousand Hills region.

The Dissected Till Plains are distinctive in stream development, with broad flood plains and underfit stream channels. For portions of their lengths, some streams roughly parallel buried preglacial channels. The flat flood plains are interrupted only by terraces and drainage ditches.

STRUCTURAL GEOLOGY

The structural geology is primarily defined by a system of gentle folds bounded on the east by the Lincoln fold and Cap au Gres fault, and on the west by the Forest City basin. There are small local structures throughout the western half of the region.

The Lincoln fold lies along the eastern edge of Missouri and extends eastward into Illinois near the town of Elsberry, Missouri. This northwest-southeast-aligned structure is a complex uplift comprising structural anticlines, synclines, domes, and faults (Krey, 1924). The Cap au Gres fault has displaced the Lincoln fold and the Dupo-Waterloo anticline of Illinois, left-laterally about 30 mi (48 km) (Cole, 1961).

The Forest City basin is a broad, structural, depositional basin centering around Forest City, Missouri. It is apparently well-defined on all but the eastern side (McCracken, 1971). Some oil and gas has been produced from the basin for many years.

BEDROCK

Shale is the most common bedrock throughout the region, although limestone is widespread in the eastern portion. In eastern and northeastern Missouri, there are many large landslides in areas underlain by Ordovician and Mississippian shales. Ordovician and Mississippian limestone and sandstone occur along the southern and southeastern portions; however, Pennsylvanian rocks dominate the bedrock sequence in the plains.

Lower Pennsylvanian and older formations are described elsewhere in this report. Middle and Upper Pennsylvanian rocks range from the Lansing to the Wabaunsee Groups. The Lansing and Pedee Groups are composed principally of shale, limestone, and minor sandstone. The limestone units are from 1 to 20 ft (0.5 to 6 m) thick, but tend to the lower end of this range.

The Douglas Group comprises sandstone, shale, and thin limestone. The Shawnee and Wabaunsee Groups are cyclical deposits of shale, limestone, and minor sandstone units. These groups are distinguished by many thin limestone units, mostly 2 or 3 ft (1 m) thick.

SURFICIAL MATERIALS

Continental glaciation was the most important source of surficial materials in the Dissected Till Plains. Basic terms in descriptions of glacial and glaciofluvial deposits are *glacial drift (or drift)*, a general term applied to all stratified and unstratified materials deposited by or derived from glaciers, and *glacial till (or till)*, which refers to unsorted, unstratified, generally unconsolidated materials deposited by glaciers and not reworked by glacial meltwater, and consisting of clay, sand, gravel, and boulders of widely varying size. Drift can be composed of till and stratified gravel, sand, and silt. Loess, a silt or silty clay commonly believed to have originated as windblown dust of Pleistocene age, is present as a thin cover over much of the glacial drift.

The first episode of glaciation, the Nebraskan, modified the topography and drainage to an undetermined extent and may have extended southward approximately halfway to the Missouri River, and as far east as Linn County (Heim and Howe, 1963). Holmes (1942) suggested that Nebraskan till and glaciofluvial deposits filled many of the preglacial channels and valleys.

Kansan till and drift cover almost all the state north of the Missouri River, and extend south of the river in some areas. The till is moderately plastic, averaging 30 percent or less sand, 40 to 45 percent silt, and 30 to 50 percent clay-size materials. Stratified sand and silt occur throughout the drift as channel and blanket deposits.

The Ferrelview Formation, provisionally assigned to the late Kansan, and Yarmouth, and possibly extending into the early or middle Illinoian (Howe and Heim, 1968), is an accretion-gley, often called "gumbotil," developed on poorly drained till surfaces. The complex origin of this material involves lacustrine and accretionary processes. Typically, it is a persistent thin unit, 7 to 10 ft (2 to 3 m) thick, and is best preserved on the prairies. Postdepositional erosion has destroyed it on rolling and rugged upland topography.

The Ferrelview Formation is a tenacious, moderately to highly plastic clay, highly impermeable and stone-free, usually with less than 20 percent sand, 40 to 50 percent silt, and 30 to 40 percent clay-size material. Howe and Heim (1968) report that the material contains the clay minerals illite and montmorillonite.

Illinoian surficial materials are predominantly loess, but Illinoian till and terrace alluvium are present (Goodfield, 1965). Perhaps the most striking of the post-Illinoian features is the Sangamon Paleosol, usually reddish-brown and 2 to 3 ft (1 m) thick, developed during the last (Sangamon) interglacial stage.

Wisconsinan loess mantles most older surficial materials in northern Missouri and is the principal source of several modern soils. Thicknesses may exceed 80 ft (24 m) locally, whereas many areas no more than 20 to 30 mi (50 km) from the rivers have only 3 to 7 ft (1 to 2 m) of loess. It is thickest on the uplands adjoining the Missouri and Mississippi Rivers.

Some distance from the major rivers, most loess is altered, i.e., modified or weathered, whereas essentially unaltered or unweathered loess occurs near the major rivers.

Loess is moderately to highly permeable, of low pasticity, composed of 15 percent or less fine sand, 60 to 80 percent silt, and 15 percent or less clay-size material; size distribution of particles varies. There has been little or no clay enrichment or soil profile development.

Modified loess is moderately to highly plastic, contains less than 10 percent sand, about 50 to 70 percent silt, and about 15 to 45 percent clay-size material. Clay-rich subsoils are well developed, relatively impermeable, and cause widespread shallow perched water tables.

In general, the glacial drift of northern Missouri is composed of relatively impermeable sandy clay till. In extreme northern north-central and northeastern Missouri, the drift has conspicuously more sand and more water-bearing channel-fill sand deposits; however, buried valleys and sand and gravel deposits are more numerous and better developed in northwestern Missouri. Sand-and-gravel-filled valleys, and outwash sand are present along the southern limits of glacial drift, between Columbia and St. Louis.

A typical profile of surficial materials in northern Missouri is a 15-ft (4-m)-thick modified loess cover, with a claypan modern soil. A tenacious gray clay, the Ferrelview Formation, 7 to 10 ft (2 to 3 m) thick, lies beneath the weathered loess; the contact is relatively distinct. Perched water tables can develop at this contact, as well as on the modern claypan soil developed on the modified loess cover. Glacial till, a yellowish-brown, oxidized, leached, sandy clay, underlies the Ferrelview; the contact is relatively distinct. The leached interval of the till is 7 to 15 ft (2 to 5 m) thick. Beneath the leached interval, the yellowish-brown till is oxidized but unleached for 20 to 40 ft (6 to 12 m) and gradually changes downward to a dark-gray, unleached, unoxidized till. Throughout this vertical profile the till is well jointed.

Variations in this typical profile occur on steeper slopes where the modified loess cover has been removed by erosion, and a modern soil developed directly on the till. The Sangamon Paleosol, a distinct red or reddish-brown to brown, well-developed paleosol, is present on some of the more gently eroded upper slopes. Another variation may exist where the till is less than 40 to 60 ft (12 to 18 m) thick. In such places, the lowest unit, the dark-gray clay, may be absent, and the entire till sequence may be a yellowish-brown sandy clay.

Residual surficial materials are present in the extreme southeastern corner of the Dissected Till Plains. The residuum, comprising a red clay and a stony red clay, both with blocky structure and having moderate plasticity and permeability, is derived from limestone and dolomite.

Terrace and alluvial deposits are derived from loess, drift, and residuum. Typically, well-sorted alluvium includes clay, silty clay, silt, sand, and gravel. The fine-grained materials range from low to moderate plasticity and moderate to high permeability.

GROUNDWATER

Groundwater occurs in unconsolidated and consolidated aquifers. Unconsolidated aquifers include alluvial and terrace deposits and some of the sand and gravel channel fills in the lower portion of glacial-drift deposits. Because of the fine-grained nature of the surficial materials, including alluvium, well yields are low, except where there are extensive layers of permeable materials or buried channel deposits. Water-bearing sand lenses are more likely to occur where the thickness of the drift exceeds 100 ft (31 m). Some recharge to glacial drift is thought to ascend from buried channels and from portions of underlying consolidated aquifers.

Water from the glacial drift is hard, and high in sulfates and iron (Gann and others, 1971, 1973). Dissolved solids vary considerably in the drift but appear to increase to levels above 1000 mg/l to the north (see plate 4). Water yields commonly are low, thus water from supplemental sources may be needed. Mainly because of their storage capacity, and the lack of alternative sources, shallow wells and cisterns are commonly used for domestic supplies.

Except for Missouri-Mississippi River alluvium, buried preglacial channels provide the best quality water and best yields among unconsolidated aquifers. The sources of water in these buried channels include recharge from modern drainages, infiltration through surficial materials, and recharge ascending from consolidated aquifers. Because groundwater in the buried channels has a moderate iron, calcium bicarbonate, and sodium sulfate content, it must be treated before use. Yields vary, generally ranging from 20 to 500 gpm (75 to 1892 lpm). Artesian conditions exist in deeper wells in the glacial drift. Deposits in major river valleys, such as those of the Missouri River, produce hard water with high iron and calcium bicarbonate content. Yields from wells in the Missouri River alluvium may exceed 1000 gpm (3800 lpm) (Gann and others, 1973).

To some extent, the modern drainage system of northern Missouri "mimics" the preglacial drainage system, i.e., some modern streams more or less parallel buried preglacial channels. Inasmuch as the smaller modern streams have highly silty alluvial deposits, the groundwater supplies are limited.

Surface water infiltrating into the upland soils, particularly in more level areas, tends to perch on clay subsoils, whence most of it seeps laterally until it reaches shallow upland drainages. Shallow soil moisture also recharges the modified loess; hence, perched water tables can be found on the clayey Ferrelview Formation. Little water is available from the soil or from the Ferrelview Formation and recharge is from local sources.

Water quality of consolidated aquifers varies considerably. It decreases toward three centers: St. Louis, Hannibal, and Jackson County (see plate 4). Dissolved solids increase with depth in these areas, exceeding 10,000 mg/l. Elsewhere, wells penetrating Pennsylvanian bedrock are known to produce water of higher quality.

In general, consolidated aquifers produce 3 to 30 gpm (11 to 114 lpm) of water, high in hardness and dissolved solids, including iron, bicarbonates, sulfates, and sodium (Gann and others, 1971, 1973). Yields are generally low.

Higher quality water, containing less than 1000 mg/l of total dissolved solids, is obtained from Mississippian and Ordovician aquifers in the southeastern part of the Dissected Till Plains.

ENGINEERING GEOLOGY

Factors to be considered in the design and construction of structures in the Dissected Till Plains are the surficial material characteristics, groundwater conditions, local water supplies, and flooding. These are particularly important in siting waste isolation facilities.

Both unaltered and altered loess affect waste isolation. Unaltered loess is of particular concern because of its high permeability, particularly along vertical joints. Spalling occurs along columnar joints. Buried ancient soil profiles (paleosols) tend to make vertical slopes unstable (Davis, 1955). Unaltered loess is highly erodable and susceptible to piping.

Altered loess has been weathered to the extent that soil profile development with clay enrichment affects the engineering properties. Perched water tables are caused by relatively impermeable claypan subsoils. The clay-rich subsoils are subject to change in volume, because they have high shrink-swell properties. Shrinkage cracks and frost heaving are serious problems in northern Missouri.

Continuity of till and stratified deposits is difficult to establish without detailed subsurface investigations. Sand may occur as isolated lenses, persistent channel sands, or laterally continuous layers. Bedrock topography is irregular and cannot be determined without extensive exploration.

In northwestern Missouri, the physical character of the major preglacial channels is generally well known and the channels have been accurately delineated, but the locations of tributary channels are not as well known. These major channels are principal water sources in some areas. Preglacial channels in north-central and northeastern Missouri are less well developed and defined; they have not been significant sources of groundwater.

Local water supplies come from various sources. Shallow wells store water that seeps slowly into them from perched water tables. Water from Pennsylvanian bedrock is locally of usable quantity. Cisterns store water from roofs or water haulers when other sources are undesirable or inadequate. Reservoirs and streams provide water for many communities.

In some areas, flash flooding is a hazard to which poor soil permeability and inadequate channel capacities are contributing factors.

Exploration limitations are fewest in the Dissected Till Plains, but extensive subsurface investigation is needed because of the variability of glacial drift deposits. Some surficial materials, such as accretion-gley and till, have low permeability. However, lateral permeability along contacts between different strata in the till and channel sands may allow leachate movement away from landfills or other waste isolation or spill sites.

Poor surface drainage on upland prairies can cause significant operational limitations. Gently rolling upland topography on moderately thick glacial till underlain by predominantly shale bedrock presents the fewest explorational and operational problems for waste isolation sites.

EXPLORATION CONSIDERATIONS

In the Dissected Till Plains, surficial materials vary laterally and vertically; hence, landform features, surface exposures, and exploration drilling should be thoroughly documented.

It is not always possible or practical to core or sample boreholes continuously during preliminary or early site-selection stages. However, preliminary exploration boreholes can serve as detailed exploration holes if they can be electrically logged, thus providing "continuous" information that can be related to later holes. Electric and gamma-ray logging can also provide critical supplemental stratigraphic and physical data during detailed site exploration.

Although bedrock geology is usually uniform over short distances, local features may require additonal or more closely spaced boreholes. Determination of bedrock depth is particularly important because of the possible presence of preglacial channels.

Mining records of nearby coal mines should be examined carefully, although it is unlikely that reliable data, such as mine maps, can be located. In some cases there have been both surface and underground operations. If possible, mining methods used should be determined. Generally, mines were of limited extent and their tunnels were barely large enough to permit access. After mining ceased several decades ago, many mines "squeezed" (collapsed) shut. Problems are now mainly associated with locating abandoned shafts, rather than with concern about surface settling. In northern Missouri, there are limestone mines, the physical conditions of which are easier to determine than those of the coal mines (Whitfield, 1981).

Several shallow perched water tables occur in the modified-loess/glacial-till sequence. Water also occurs in the glacial drift, in buried channels, and locally in the underlying bedrock. The relationship between shallow water and water at depth within the glacial drift and bedrock must be determined; hence, piezometers or monitoring wells should be installed at various depths in the glacial drift and bedrock. The piezometers or wells should be properly cased and sealed, so that the piezometric surfaces of the following may be measured:

1. perched water tables on modern clay subsoil
2. perched water tables above the Ferrelview Formation or other paleosols
3. glacial drift
4. buried channel deposits
5. shallow bedrock aquifers
6. deep bedrock aquifers

Data from previously drilled wells may be sufficient for item 6.

The importance of proper well construction cannot be overemphasized. Serious problems have been caused by improper grouting or sealing of exploration wells.

The hydraulic connection, or lack thereof, between water-bearing zones, and the movement of groundwater are especially important in considering waste isolation sites. Other procedures for identifying relationships between surface water, shallow perched water tables, and groundwater include chemical analyses and age dating.

In summary, the Dissected Till Plains have fewer seriously limiting geologic conditions that may affect hazardous-waste siting than other provinces or subprovinces in Missouri. However, one should recognize that sites may initially appear to have few limitations, but detailed geologic study and exploration may reveal severe limitations.

CONCLUSIONS

Systematic geologic investigations involving considerable planning are needed to evaluate existing and proposed hazardous-waste isolation sites. Area studies, including reconnaissance field investigations, are necessary to identify possible sites. Specific studies of several potential sites, including preliminary exploration, sampling, and testing, may be necessary before final site selection. Land costs should not be a factor in initial site selection. Too often, exploration and development costs and the extra professional time needed to complete site investigations can exceed any savings in land acquisition.

Determination of groundwater movement is the most important aspect of site exploration. Data on surficial materials, bedrock, landforms, and topography are ancillary to it but are necessary to site evaluation.

Sampling and testing should be well documented and all literature cited. Geologic investigation reports will be read by technical and nontechnical personnel representing various professions, occupations, interests, and backgrounds. Consequently, it is important to define technical terms as clearly and succinctly as possible.

Details of sampling and testing should be described thoroughly. For each test, why it was chosen, how it was conducted, and how it aids in interpretation should be discussed thoroughly. It is important to show how exploration sampling procedures can affect the results of field or laboratory testing. Deviations from standard practice in sampling and testing should be noted.

Classifications of broad areas as potentially safe, unsafe, poor, or excellent are not appropriate. Rather, classifications should be based on limitations in exploration, design, construction, and operation imposed by geologic conditions. Regions with fewer complex problems have fewer limitations to overcome; hence, there would be less overall expense to the public and to the private sector, and potentially fewer delays in processing of permits.

Regions with fewest limitations include geologic settings having predominantly shale bedrock, clay-rich glacial drift 40 to 100 ft (12 to 31 m) thick, discharge rather than recharge conditions, moderately sloping topography, and lacking major water-bearing deposits.

It cannot be overemphasized that sites with few limiting geologic conditions can be found in regions that are described as moderately limited. Conversely, there are sites in regions with slight limitations that could pose complex problems in exploration, design, and operation.

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Table A

GENERALIZED GEOLOGIC SECTION OF THE SALEM PLATEAU

SYSTEM	GROUP OR FORMATION	THICKNESS	PHYSICAL CHARACTERISTICS	HYDROLOGIC CHARACTERISTICS	ENGINEERING GEOLOGIC CHARACTERISTICS OF SURFICIAL MATERIALS AND BEDROCK
Quaternary	Alluvium	0-50 ft 0-15 m	Gravel, sand, silt, and clay.	Highly permeable. Small valleys not important as aquifers; larger valleys, such as Osage River valley, have significant amounts of groundwater in the alluvium.	Combination of colluvium, sorted and unsorted boulders, gravel, silt, and clay; variable, but generally high permeability. Sinkholes may form in some valleys; flood prone.
	Loess	0-20 ft 0-6 m	Silt, fine sand.	Not important as an aquifer; causes local perched water table.	Thin, brown silt and silty clay; moderate permeability. May develop fragipan. If fragipan exists, excavation may be difficult; may have drainage problems.
Pennsylvanian	Undifferentiated	0-80 ft 0-24 m	Cyclic deposits of shale, sandstone. Fire clay and other deposits in paleosinks developed in Ordovician formations.	Confining layer; retards downward movement of water into major aquifer.	Residual material from shale and sandstone; has low permeability, except along fractures in sandstone. Classification difficult because material varies from sandstone boulders to weathered shale.
Devonian & Silurian	Undifferentiated	0-800 ft 0-244 m	Cherty limestone, sandstone, and limestone of limited areal extent.	Sequence is not important as an aquifer.	Usually thin residual soils; very cherty in some areas. Shaly limestone acts as confining layer. Cherty limestone difficult to drill.
Ordovician	Maquoketa Shale	0-60 ft 0-18 m	Shale and sandstone.	Confining layer; retards downward movement of water into major aquifer.	Thin soil; gray silty clay; moderate to low permeability. Prone to sliding.
	Kimmswick Formation Plattin Formation	0-700 ft 0-214 m	Limestone and dolomite, coarse and fine-grained; minor shale beds.		Thin, red stony clay or red clay; angular blocky structure; high permeability. Colluvium has lower permeability. Solution-enlarged joints intricately connected with sinkholes. Pinnacled bedrock affects excavations.
	Joachim Dolomite Dutchtown Formation	0-300 ft 0-92 m	Massive dolomite and limestone; some shale beds.		Bedrock usually weathers readily; not prone to solution-enlarged joints.
	St. Peter Sandstone Everton Formation	10-100 ft 3-31 m	Sandstone and sandy dolomite.		Very thin, red to brown sandy loam; granular structure; high permeability; case-hardened when exposed; closed joints. Difficult to blast and excavate.
	Powell Dolomite Cotter Dolomite Jefferson City Dolomite	0-500 ft 0-153 m	Massive dolomite and cherty dolomite.	Major aquifer; sequence acts as a hydrologic unit; substantial yields possible.	Thin, stony silty clay; moderate plasticity; moderate to high permeability. Colluvium has moderate to low permeability and slightly more plasticity. Bedrock locally has solution-enlarged openings and pinnacles; generally weathers easily.
	Roubidoux Formation Gasconade Dolomite	0-250 ft 0-76 m 0-300 ft 0-92 m	Alternating sandstone and cherty dolomite. Cherty dolomite; prominent basal sandstone (Gunter Sandstone Member).		Soil usually thick, well-drained, preconsolidated. Red stony clay alternating with red sandy loam grading into sandy clay; low to moderate permeability. Colluvium alternates from red sandy loam to sandy clay. Cavernous; sinkholes form in portions of southern Missouri; solution-enlarged joints. Gasconade bedrock may have massive bluffs. Eminence is often highly pinnacled.
Cambrian	Eminence Dolomite	0-400 ft 0-122 m	Massive dolomite and cherty dolomite.		
	Potosi Dolomite				Same properties as above except characteristically drusy with quartz fragments. Soil is generally red clay with limited to no chert.

Table B

GENERALIZED GEOLOGIC SECTION OF THE SPRINGFIELD PLATEAU

SYSTEM	GROUP OR FORMATION	THICKNESS	PHYSICAL CHARACTERISTICS	HYDROLOGIC CHARACTERISTICS	ENGINEERING GEOLOGIC CHARACTERISTICS OF SURFICIAL MATERIALS AND BEDROCK
Quater- nary	Alluvium	0-30 ft 0-9 m	Sand, silt, clay, and angular chert gravel.	Not important as an aquifer.	Mixture of colluvium and sorted sand, gravel, and boulders; moderate to high permeability. Subject to flash flooding.
Pennsyl- vanian	Undifferentiated channel sands	0-100 ft 0-31 m	Shale and sandstone; irregular in distribution and thickness.	Yields little water in shallow dug wells; not important as an aquifer.	Thin silty and sandy clay; moderate permeability. Bedrock is dense, fractured, and has variable permeability; difficult to excavate.
Mississippian	Warsaw Formation	0-150 ft 0-46 m	Limestone, fine to coarsely crystalline; slightly cherty.	Yields are low in shallow wells.	Residual, red stony clay. Claypan may develop in upland soils. Residuum has moderate permeability; blocky; classified as MH. Colluvium developed from the residuum is less permeable; classified as MH, ML-CL, or CL. Solution-enlarged joints; cavernous, high permeability.
	Burlington-Keokuk Limestone	50-150 ft 15-46 m	Limestone, medium to coarsely crystalline; cherty, with nodular and bedded chert.	Interval yields small to moderate quantities of water in wells; springs are common; water draining from this aquifer maintains dry-weather flow of streams; water contains calcium bicarbonate in solution.	Same as above but with abundant chert in the soil.
	Elsey Formation	0-30 ft 0-9 m	Limestone, finely crystalline; abundant nodular and bedded chert.		
	Reeds Spring Formation	0-225 ft 0-69 m	Same as above; very cherty limestone.	Low yields.	
	Pierson Formation	5-35 ft 2-11 m	Dolomite, massively bedded, fine-grained.	Not important as an aquifer.	Thin soil cover. Bedrock forms ledges and minor escarpments.
	Northview Formation	2-80 ft 1-24 m	Siltstone and shale, brown to dark-gray.	Retards some downward movement of water from minor (limestone) aquifer to major (dolomite) aquifer.	Thin silty clay; low permeability. Soil cover can have shale admixture and poor engineering properties.
	Compton Formation		Limestone, finely crystalline, thin-bedded.	Numerous small springs, but not important as an aquifer.	Thin soil cover. Numerous solution-enlarged openings.
Devonian	Chattanooga Shale	0-30 ft 0-9 m	Shale, black, fissile; limited areal extent.	Limited retardation of downward movement of water from minor (limestone) aquifer to major (dolomite) aquifer.	Soil cover thin and can have poor engineering properties. Shale weathers to fragments.
Ordo- vician	Cotter and Jefferson City Dolomites		Dolomite, cherty dolomite, sandstone and bedded chert; medium to massive beds.	Sequence acts as a hydrologic unit; yields are low.	Thin soil cover of silt loam to silty clay mixed with chert fragments. Bedrock has distinctive joint and bedding planes, but is relatively impermeable.

TABLE C

GENERALIZED GEOLOGIC SECTION OF THE ST. FRANCOIS MOUNTAINS

SYSTEM	GROUP OR FORMATION	THICKNESS	PHYSICAL CHARACTERISTICS	HYDROLOGIC CHARACTERISTICS	ENGINEERING GEOLOGIC CHARACTERISTICS OF SURFICIAL MATERIALS AND BEDROCK
Quater-nary	Alluvium	0-30 ft 0-9 m	Silt, sand, gravelly clay.	Not important as an aquifer.	Well- to poorly sorted gravel; sand and clay; highly permeable; subject to frequent floods.
Cambrian	Derby-Doerun Dolomite	0-100 ft 0-31 m	Dolomite; medium to massive beds.	Retards water movement.	Thin, silt loam to silty clay; jointed bedrock; moderately permeable.
	Davis Formation	0-120 ft 0-37 m	Shale and shaly dolomite.		Loess-derived silt loam over thin silty clay. Relatively impermeable bedrock.
	Bonneterre Formation	0-400 ft 0-122 m	Dolomite; limestone locally.	Principal local aquifer; generally low to variable yields. Areas of high yields but low storage known.	Uplands consist of thin loess-derived silt loam over red clay of low to moderate plasticity. Slopes covered with similar materials, but with little loess and thinner profiles. Cavernous, solution-enlarged, jointed bedrock. Collapse sinkholes may develop in residuum. Surficial materials and bedrock have moderate to high permeability.
	Lamotte Sandstone	0-500 ft 0-153 m	Sandstone and conglomerate.		Thin sandy loam to sandy clay; moderate permeability. Bedrock has low to moderate permeability.
Precambrian	Undifferentiated Igneous rocks		Granite and rhyolite.	Retards the downward movement of water.	Uplands over rhyolite consist of thin loess-derived silty loam. Uplands over granite consist of thin loess-derived silty clay over residual sandy clay. Barren rock glades widespread. Rhyolite nearly impermeable; granite permeable along weathered joints.

Table D

GENERALIZED GEOLOGIC SECTION OF THE MISSISSIPPI ALLUVIAL PLAIN

SYSTEM	GROUP OR FORMATION	THICKNESS	PHYSICAL CHARACTERISTICS	HYDROLOGIC CHARACTERISTICS	ENGINEERING GEOLOGIC CHARACTERISTICS OF SURFICIAL MATERIALS AND BEDROCK
Quaternary	Alluvium	0-200 ft 0-61 m	Reworked sand and gravel, with deposits of blue and gray clay.	Principal regional water source, with substantial yields.	Poorly sorted materials in typical fluvial deposits. Clays in cutoff meanders and natural levees. Sand and gravel have high permeability. Flood-prone areas. High water table. Clay may exhibit shrink/swell characteristics. Unconsolidated, compressible materials may be encountered.
	Terrace Alluvium	0-30 ft 0-9 m	Sand and sandy clay in low ridges and terraces.	Not important as an aquifer.	
	Loess	5-40 ft 2-12 m	Silt and silty clay, yellowish-brown.	Small amounts of water may be perched on clay-rich subsoil in upland areas.	Silt and silty clay may have clay developed in soil profile on uplands. Sliding potential; irregular thickness; highly erodible; moderate permeability.
Tertiary	"Mounds" Gravel Equivalent	0-60 ft 0-18 m	Gravel, brown, with some black pebbles; reddish-brown sand and clay.	Locally important on Crowleys Ridge.	Limited to uplands; loess over unconsolidated gravel to sandy gravel. High permeability; poorly consolidated.
	Wilcox Group	0-250 ft 0-76 m	Sand, white, yellow, orange, and red; sandy clay to clay.	Upper portion is a principal water source; substantial yields possible. Water high in dissolved solids, particularly iron.	Uplands and slopes consist of thin to moderately thick loess over clay to sand. Clay has soft zones; sand poorly consolidated. Highly erodible.
	Porters Creek Clay	0-200 ft 0-61 m	Clay, light- to dark-gray, with minor beds of highly ferruginous clay.	Retards downward movement of water into the lower aquifer.	Uplands consist of thin loess over plastic clay. Slopes have thinner loess cover. Shale is jointed; has low regional permeability.
	Clayton Formation	0-10 ft 0-3 m	Sandy clay, green glauconitic.		
Cretaceous	Owl Creek Formation	0-400 ft 0-122 m	Sandy clay, dark, blue-gray.	Not important as an aquifer.	Of limited importance.
	McNairy Formation		Sand, yellow and white, fine to coarse, with local quartzite or gravel beds. Sandy clay and clay also present.	Minor water source; yields decrease to southeast. Water generally low in hardness, and in iron and other dissolved solids.	Sandy soil; sandstone beds form small bluffs. Firm to highly eroded unconsolidated sand.
Ordovician	Kimmswick Formation Decorah Formation Plattin Formation	0-450 ft 0-137 m	Dolomite and cherty dolomite, thin- to massively bedded (Decorah Formation is a shaly limestone).	Not important as an aquifer.	Uplands consist of thin to moderate thickness of loess over red clay or stony red clay. Residuum has moderate plasticity and permeability. Slopes have thinner loess cover than uplands. Intensely faulted bedrock; jointed; pinnacled; high permeability.
	Joachim Dolomite	0-175 ft 0-63 m	Dolomite and cherty dolomite, thin- to massively bedded.		
	Dutchtown Formation		Limestone and dolomite.		
	St. Peter Sandstone Everton Formation	0-450 ft 0-137 m	Massive sandstone and sandy dolomite.		Thin, sandy soil. Usually an uneven bedrock surface.
	Powell Dolomite Cotter Dolomite Jefferson City Dolomite	0-700 ft 0-214 m	Dolomite, well-bedded, cherty, with minor sandstone and shale.		Thin, stony soil; numerous rock outcrops. Bedrock surface usually even and firm.

Table E

GENERALIZED GEOLOGIC SECTION OF THE OSAGE PLAINS

SYSTEM	GROUP OR FORMATION	THICKNESS	PHYSICAL CHARACTERISTICS	HYDROLOGIC CHARACTERISTICS	ENGINEERING GEOLOGIC CHARACTERISTICS OF SURFICIAL MATERIALS AND BEDROCK
Quaternary	Alluvium	0-50 ft 0-15 m	Unconsolidated, stratified deposits of sand and gravel, silty clay, and silt loam.	Generally low yields but with isolated pockets of sand and gravel of higher yields. Water high in dissolved solids, particularly iron and bicarbonates.	Silt loam over silty clay; low to moderate plasticity and moderate permeability. Prone to flooding.
	Loess	0-20 ft 0-6 m	Silt loam, gray-brown.	Not an aquifer.	Clay-rich and relatively impermeable; low to moderate plasticity; highly erodible.
Pennsylvanian	Kansas City Group	120-135 ft 37-41 m	Alternating limestone and shale. Limestone formations form ledges.	Locally a minor water source; yields low. Water high in dissolved solids, particularly chlorides, iron, and bicarbonates. Higher quality water in the Warrensburg Sandstone Member.	Residual materials vary from thin cherty clay to silt loam. Limestones exhibit solution-enlarged joints; block slumping.
	Pleasanton Group	20-150 ft 6-46 m	Shale, siltstone, and sandstone.		Very thin loess over reddish-brown silt loam to silty clay; blocky structure; moderate plasticity and permeability. Sandstones generally have high permeability; siltstones and shales have low permeability.
	Marmaton Group	78-190 ft 23-58 m	Shale, sandstone, limestone, coal and clay. Limestone forms ledges.	Not an aquifer.	Shale-supported uplands and slopes; very thin loess over gray-brown silty clay; high plasticity; low permeability; low to moderate thickness. Clay has high shrink/swell potential.
	Cherokee Group	0-605 ft 0-185 m	Sandstone, shale, limestone, siltstone, coal and clay.		Very thin loess over gray-brown loam to silty clay; low to moderate plasticity; moderate permeability due to silty or sandy soil. Soil is usually very thin.

Table F

GENERALIZED GEOLOGIC SECTION OF THE DISSECTED TILL PLAINS

SYSTEM	GROUP OR FORMATION	THICKNESS	PHYSICAL CHARACTERISTICS	HYDROLOGIC CHARACTERISTICS	ENGINEERING GEOLOGIC CHARACTERISTICS OF SURFICIAL MATERIALS AND BEDROCK
Quaternary	Alluvium Terrace Alluvium	0-100 ft 0-31 m	Surface materials range from clay to loam; underlain by fine silt, silty clay, sand, and gravel.	Principal regional water supply source; low to moderate yields obtained; water quality variable.	Flood prone areas; well-sorted alluvial materials, clay may exhibit shrink/swell characteristics; compressible soils may be encountered; high water table.
	Peorian Loess (Primary)	0-40 ft 0-12 m	Silt loam, grayish-brown.	Not a hydrologic unit, but recharges underlying materials.	Stands in vertical cuts; little to no soil profile development. Primary loess changes in volume when wetted; sliding potential; jointed, highly erodible; susceptible to piping; moderate to high permeability.
	Sangamon Paleosol	0-3 ft 0-1 m	Clay and silty clay, reddish-brown; may have stone line.	Not important as an aquifer, but causes perched water tables.	Noticeable color and texture changes even for a thin unit; can be a principal slide plane.
	Loveland Loess (Secondary or modified)	0-20 ft 0-6 m	Silt loam with clay enriched subsoil in modern soil; underlain by yellowish-brown to brown silty clay.	Not important as an aquifer, but causes perched water tables.	Clay-enriched profile due to weathering; forms claypan subsoil in portions of eastern Missouri; swelling clay properties.
	Ferrelview Formation	0-10 ft 0-3 m	Clayey silt and clay; some sand of accretionary gley origin.	Not important as an aquifer; confining layer; retards downward movement of water.	Tenacious, firm, swelling clay; structureless and can be the cause of slides.
	Kansan Drift Nebraskan Drift	0-375 ft 0-114 m	Clay, sandy clay till; stratified sand and gravel, fluvial deposits.	Some areas have minor water sources; others have moderate supplies in channel-fill and sand and gravel deposits.	Till has moderate plasticity; jointed, firm, and preconsolidated; physical properties generally uniform. Nebraskan Drift is nonpersistent.
Pennsylvanian	Wabaunsee Group	0-340 ft 0-104 m	Shale, siltstone, sandstone, minor limestone, and coal.	Overall, units act as a confining layer; retards downward movement of water into lower aquifers.	Overlain by Quaternary deposits. Shales swell slightly when wetted; some sliding potential. Sandstone and limestone generally have high permeability due to jointing; shales have low permeability.
	Shawnee Group	0-250 ft 0-76 m	Cyclic deposits of limestone, shale, and sandstone.		
	Douglas Group	0-150 ft 0-46 m	Shale, limestone, and locally prominent sandstone channel-fill deposits.		
	Pedee Group	0-100 ft 0-31 m	Shale		
	Lansing Group	0-60 ft 0-18 m	Shale and minor limestone.		
	Kansas City Group	120-135 ft 37-41 m	Alternating limestone and shale; limestone formations form ledges.	Locally a minor water source; yields low. Water high in dissolved solids particularly chlorides, iron, and bicarbonates. Higher quality water in the Moberly Sandstone Member.	Limestone-supported uplands and slopes; thin loess over reddish-brown, stony, silty clay; blocky structure; moderate to high plasticity; moderate permeability; limestones exhibit solution-enlarged joints; difficult to excavate
	Pleasanton Group	20-150 ft 6-46 m	Siltstone, shale, and sandstone.		Generally covered by Kansan drift; locally siltstone- and sandstone-supported uplands and slopes with thin loess over grayish-brown silty clays. Sandstone and siltstone generally have low to moderate permeability; shale has low permeability.
	Marmaton Group	78-190 ft 23-58 m	Sandstone, shale, limestone, siltstone, coal, and clay.	Not an aquifer.	
	Cherokee Group	0-605 ft 0-185 m	Sandstone, shale, limestone, siltstone, coal, and clay.		
Mississippian and Ordovician	Undifferentiated		Described in other tables.	North of the 1000 mg/l TDS line. Not generally used as a water supply source. Low to moderate yields of mineralized water obtained. South of the 1000 mg/l TDS line, principal regional water supply source. High yields of high quality water available.	Described in other tables.

APPENDIX A

GEOLOGIC EXPLORATION USING PITS AND TRENCHES

Pit and trench exploration provides excellent three-dimensional profiles of surficial materials. Because geologists and engineers can thereby view materials in place and relatively undisturbed, these techniques are often preferable to drilling. For example, gross characteristics not always recognized in cores can be studied. Such features as joints, irregular contacts, dips, and faulting of surficial materials seldom are readily apparent in cores. Pits or trenches can be fitted with monitoring devices and backfilled and sealed to serve as shallow monitoring wells.

Pit and trench exploration is particularly useful in preliminary site investigations. Excavations in representative landforms, such as uplands, escarpments, or slopes can give detailed, low-cost information relatively quickly. The location of pits and trenches should be determined by the landforms and geologic materials in the area to be investigated, not rigidly determined by a simple grid pattern. Excavations should be indicated on a site base map and when completed should be surveyed for location and orientation. Orientation of pits and trenches is important if photographs are to be made; this is particularly important when narrow backhoe pits are excavated.

Trenches and pits should be logged and described. A summary profile resembles a boring log, indicating material type, physical character, and thickness. A sketch profile is a drawing of an excavation, with descriptions, depicting the areal extent of stratigraphic units in it.

Hatheway and Leighton (1979) describe procedures for detailed subjective and objective profiles. A subjective log or profile is an interpretive drawing outlining units in a schematic fashion to indicate obvious relationships, such as those of faults. An objective log or profile is an unbiased descriptive drawing of physical characteristics.

When an excavation is to be logged or mapped, it is helpful to clean the walls with a broom, shovel, or scraping tool. Dousing or spraying the face of an excavation with water can make contacts more easily visible.

When a single pit or trench does not permit satisfactory analysis or description, a second excavation should be made. For example, a trench at right angles to the first may be necessary to provide adequate description or analysis.

Exploration by pits and trenches has limitations. Backhoes can excavate to a depth of 10 to 14 ft (3 to 4 m), except for large construction backhoes, which can reach greater depths. Bulldozers can excavate wider trenches more rapidly than a backhoe, but more ground is disturbed, and trenches cannot be excavated as deeply in the same length of time.

Slope stability may pose a hazard to workers in trenches; therefore, when excavating it is important to note seeps, side sloughing or spalling, unconsolidated sand, and loose materials around the top of an excavation (especially boulders in or on surficial materials). Shoring of unstable side slopes may be necessary. State and federal regulations may apply to this type of work; hence, exemptions and clearances may be necessary.

APPENDIX B

GENERAL RECOMMENDATIONS FOR MONITORING-WELL INSTALLATION

The primary purpose of a monitoring well is to sample a selected stratigraphic interval; therefore, the drilling or digging equipment should be selected for that purpose.

Monitoring wells must be sealed to exclude surface contaminants and to ensure that desired intervals are monitored. Installation and sealing of wells should be supervised directly by experienced professionals, preferably engineers or engineering geologists familiar with local soil, bedrock, and groundwater properties. Detailed records should be kept of installation procedures, including equipment and sealant used, method of installation, records of materials encountered in the drilling or digging, and results of sealing.

Minimum casing diameters of 2 to 4 in. (51 to 101 mm) usually are required when samples are to be collected from monitoring wells; diameters of 1 to 2 in. (25.5 to 51 mm) normally are sufficient when piezometers are to be installed for water-level measurements. The use of drilling muds or water should be avoided if possible. On a particular project, before the final monitoring well is drilled, it may be necessary to core and plug many test holes to obtain adequate descriptions of subsurface materials and necessary samples. A nonshrinking sealant, such as a bentonite-cement mixture, should be used for plugging.

The well screen in a monitoring well should be chemically inert with respect to the liquids to be sampled and should be placed on a filter pad at the bottom of the hole.

Well-screen installation procedures in monitoring wells will be the same regardless of well depth. Some monitoring wells can be constructed in relatively clean sand and gravel; in such cases, artifical gravel pack would not be necessary. In coarse materials, such as sand and gravel, it may be necessary to pump a well (as in development of a water supply well) in order to ensure that any fine materials in the deposit adjacent to the well are flushed. Otherwise, some plugging of the screen, and volume changes of samples could occur. In coarse material, drilling mud may be required. Care must be taken to reduce caking from mud buildup on the walls of the well bore; therefore, fresh water should be used to reduce adverse effects. Nylon-mesh netting or similar material can be used to screen fines when slotted PVC pipe is used in small-diameter installations (such as piezometers).

Cement slurry, cement-bentonite-mix slurrry, or possibly bentonite slurry, can be used to seal or grout shallow wells. Bentonite pellets should not be used, except as a cap or plug, to isolate grout from a gravel-packed well screen.

Shallow monitoring wells can be constructed by drilling or backhoe. Grout slurried into holes from the surface after casing is set is considered acceptable for shallow monitoring wells (25 ft (8 m) or less).

Backhoe monitoring trenches, usually less than 10 to 12 ft (3 to 4 m) deep, can be excavated with commonly available backhoe equipment, whereas deeper trenches require construction backhoes capable of digging to depths of 20 ft (6 m) or more. A widened surface excavation, subsequently backfilled and sealed, is required above the slit trench typical of a backhoe excavation to assure that no surface material from runoff enters the subsurface.

Bentonite or cement-bentonite slurry should be used to seal backhoe trenches used for leachate detection; cement slurry alone should not be used. A typical backhoe trench has a sand-gravel fill in the lower portion, surrounding a French drainpipe graded toward a sump on one end. A sampling riser should be installed in the sump. At least 6 in. (152 mm) of bentonite or cement-bentonite sealant should be spread across the sand and gravel fill. A greater thickness is required around and at the sampling riser, which should be constructed as a shallow well and sealed to within 4 ft (1 m) of the surface. It may be necessary to overexcavate, that is, widen the upper portion of the trench to assure that the sidewalls of the trench do not form vertical pathways for contaminants from the surface to move down into the collection system. It also is important to use compacting equipment to replace the dirt in the overexcavated portion. Established procedures in compaction control should be followed in placing dirt in the excavation, above the sealant. Hand-held compacting equipment may be necessary when compacting dirt adjacent to the sampling riser.

Moderate-depth monitoring wells, 25 to 80 ft (8 to 24 m) deep, should be grouted with a cement-bentonite slurry. Pressure grouting or tremie placement of grout materials at the bottoms of holes should be used. Positive grout return to the surface or confirmation of complete grout emplacement in the annular space between casing and hole should be established. Grout should be a nonshrinking cement-bentonite mix only; cement or bentonite grout alone is not suitable. To permit casing installation in moderate-depth wells, a minimum hole diameter of 6 in. (152 mm) from the surface to the bottom of the well would be required.

Installation of monitoring wells 80 ft (24 m) or more in depth generally should follow well-installation procedures required for public water supplies; this includes pressure grouting with positive surface return. Typically, this means the upper hole diameter may be 8 to 12 in. (203 to 305 mm) or 4 in. (101 mm) larger in diameter than the proposed casing. The bottom hole diameter must be of sufficient size for a gravel-packed well screen to be attached to a sampling riser at least 4 in. in diameter. The gravel pack must be protected from the effects of grouting. Such procedures, including grouting, should be the same as for wells of moderate depth. Holes of the depth indicated typically can sample both soil and bedrock.

A typical procedure in completing a hole is to pull back the casing to the top of the interval to be sampled, set a grout plug, and then grout. After the grout sets at least 72 hours, the hole is prepared for the well screen and gravel pack.

Sampling of soil moisture in the unsaturated zone is a technique for monitoring the migration of leachate from hazardous-waste isolation sites in fine-grained materials. A pressure vacuum lysimeter provides a means to sample in the unsaturated zone. Chemical analysis of water from the unsaturated zone can detect contamination prior to the introduction and spread of pollutants into the groundwater.

Lysimeters are inexpensive and relatively easy to install. Holes, each of which should be of sufficient diameter to accomodate instrument and sealant, are drilled or excavated to depths necessary for lysimeter installation. The porous ceramic cup at the tip of the lysimeter is set into 6 in. (152 mm) of silica sand placed in the bottom of a hole, which is then backfilled to the surface with a cement-bentonite grout. Equilibrium between soil moisture conditions and the lysimeter must be reached before measurements are valid. Background samples are extracted for chemical analysis. Thereafter, routine sampling and analysis can detect contaminants in the unsaturated zone escaping from isolation pits.

Tensiometers can be used to determine moisture changes in the unsaturated zone. A tensiometer is generally similar to a lysimeter, with a porous ceramic cup on the tip of a collecting tube. The difference is that a lysimeter is used to obtain samples, whereas a tensiometer is used to measure moisture in the unsaturated zone.

APPENDIX C

RESERVOIR AND STREAM INTAKES

Impoundment of surface water in reservoirs is a major source of public drinking water in western and northern Missouri. In these regions, inadequate supplies of groundwater and its generally poor quality restrict groundwater use for Public Drinking Water Supplies (PDWS) and for agriculture. Other regional sources of potable water are rivers and streams.

Plate 1 is a map, Public Water Supply Reservoirs and Drainage Areas in Missouri, which shows areas where surface-water contamination could affect public water supplies. Such contamination is of most concern where a liquid spill of a hazardous material, such as gasoline, occurs near a water intake on a stream or river. Because of dilution effects, pollution of lakes by spills is of less concern. Nonliquid spills are also of less concern, because the runoff can be controlled more easily.

Sources of the information shown on the map include the following divisions and sections of the Missouri Department of Natural Resources: regional offices of the Division of Environmental Quality, the Division of Geology and Land Survey, the Public Drinking Water Program, and the Dam Safety Program. Legal descriptions and topographic maps were used in determining locations of reservoirs, stream intake pipes, and their drainage areas.

Identification numbers of reservoirs used for PDWS are on file with the Missouri Department of Natural Resources, Division of Geology and Land Survey, Rolla. Specific information pertaining to reservoir size and drainage boundaries is contained in inspection reports completed between 1978 and 1980 by the U.S. Army Corps of Engineers, St. Louis District. Drainage areas of these reservoirs are outlined on the map when they are large enough for the map scale.

Drainage areas of major rivers, such as the Missouri and Mississippi, which have intake pipes for public water supplies, are not outlined. Larger reservoirs may have numerous intake pipes that serve several districts.

The map is current to September 1980. Revisions may be obtained from regional offices of the Missouri Department of Natural Resources, Division of Environmental Quality.

APPENDIX D

PUBLIC WATER SUPPLY DISTRICTS

Plate 2 is a map showing Public Water Supply Districts in Missouri. In areas served by PWSD's, water supplies are inspected and protected from sources of contamination that commonly affect private water supplies. Each PWSD is established by consensus vote of residents and provides water to individual customers. In areas where private water supplies are expensive or availability of potable water is limited, the PWSD is a valuable resource.

In Missouri, most PWSD's are north of the Missouri River, a region where scarcity of water in some areas of glacial-drift deposits, and high concentrations of dissolved solids in bedrock aquifers limit usable water. Sources of water are varied. Districts may have water supply reservoirs, stream intake pipes, wells and treatment facilities, or they may purchase water from municipal water systems or other sources. District boundaries change with population shifts or urban development. Many cities with populations above 5000 have independent water supplies. Increasingly, many PWSD's consolidate, resulting in larger areas serving many consumers. For example, a small district of 3 to 6 mi^2 may serve several dozen customers, whereas a large district may extend into several counties and serve thousands.

Typically, districts are smaller and fewer in southern Missouri, where private water supplies are more available and economical.

On legal establishment, PWSD's register with the Public Drinking Water Program of the Missouri Department of Natural Resources (MDNR). Listings of districts and members of their directive boards are on file with the MDNR.

For the map, county clerks of the counties containing PWSD's provided information concerning legal descriptions and boundaries. Revisions in district boundaries and district incorporation information may also be obtained from county clerks. Other information sources were engineering firms, Farmers Home Administration files, and individual district officers.

Individual districts are usually administered by a board of directors and auxiliary officers. Board membership is an elective position, planning and construction is contracted to an engineering firm, and legal matters are handled by a designated attorney.

The map is accurate to August 1, 1980. Periodically, new districts are established and district boundaries are revised. Final authority for boundary information rests with county clerks, district boards of directors, or district attorneys.

APPENDIX E

THICKNESS OF SURFICIAL MATERIALS

Surficial material is defined as all unconsolidated material, of whatever origin, overlying consolidated bedrock. Plate 3 is a map showing surficial material thickness throughout Missouri. Descriptions concerning mode of origin, classification, and engineering properties are in the text.

For this study, the primary sources of information concerning the thickness of surficial materials in Missouri were well logs filed at the Missouri Department of Natural Resources, Division of Geology and Land Survey. They contain information on location, well yield, stratigraphy of bedrock formations, and thicknesses of surficial materials and bedrock. On some logs, types of surficial materials are also identified. For areas of the state where such information is lacking, other sources were used: the Missouri State Highway Department, Whiteman Air Force Base, and the U.S. Army Corps of Engineers, Kansas City District.

On the map, surficial thicknesses of 100 ft (31 m) or less are indicated by 20-ft (6-m) contour intervals; above 100 ft, by 50-ft (15-m) intervals. In northern Missouri, the greatest thicknesses generally coincide with preglacial drainage channels, which in some areas are sources of usable water. Surficial materials 40 to 100 ft (12 to 21 m) thick present the fewest exploration limitations for investigating potential hazardous-waste isolation sites. Other factors, such as the type of underlying bedrock or the physical properties of the soil, may offset favorable thickness of surficial materials.

Areas enclosed on the map by lines (isopachs) drawn through points of equal thickness may have variations in surficial material thickness attributable to landform position. The uplands generally have thicker surficial material than the slopes and valleys. The map, however, is not intended as a substitute for specific site investigations.

APPENDIX F

TOTAL DISSOLVED SOLIDS IN CONSOLIDATED AND UNCONSOLIDATED AQUIFERS

Missouri is fortunate to have abundant high-quality groundwater, particularly in the southern half of the state, where the hydrologic characteristics of the bedrock and surficial materials allow rapid recharge and discharge of groundwater to bedrock aquifers. The low permeability of the thick layer of glacial drift in the northern half of Missouri restricts groundwater recharge and discharge in the bedrock aquifers. The bedrock units in this region also generally have low permeability. The high content of total dissolved solids (TDS) in the groundwater is characteristic of this low-permeability/low-recharge setting. Water from unconsolidated aquifers (glacial drift, sand, and gravel) contains lower TDS, but yields are small, except along some of the major river valleys and along buried preglacial channels in northwestern Missouri.

Plate 4 is a map showing total dissolved solids in consolidated and unconsolidated aquifers in Missouri. These data are from records and files of the Missouri Department of Natural Resources, Division of Geology and Land Survey and Division of Environmental Quality. Some water sampling and testing were conducted to modify or confirm existing data. The map is regional in concept, so local conditions can vary significantly with location.

Appendix G

PUBLIC WATER SUPPLY DAMS
(Alphabetically by County)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
Kirksville – Forest Lake Dam	MO10128	Adair	SESW	14	62N	16W	703
Savannah Lake Dam	10038	Andrew	NENE	7	59N	35W	17
Vandalia Community Lake Dam	10540	Audrain (See Pike County)					
Lamar Lake Dam	20002	Barton	SWNW	32	32N	30W	180
Adrian Lake Dam	20005*	Bates	NENW	3	41N	31W	26
Amoret	*	Bates	NWNW	5	40N	33W	
Bates County Public Water Supply District No. 2	20209*	Bates	SWNE	32	41N	33W	21
Appleton City Lake Dam	20047	Bates	NWNW	12	39N	29W	36
Butler Lake Dam	20015*	Bates	NWNE	14	40N	32W	67
Drexel Lake Dam No. 1	20213	Bates	SWNE	6	42N	33W	51
Drexel Lake Dam No. 2	20046	Cass	SWNE	6	42N	33W	28
Rockville	*	Bates		14	38N	29W	
Dearborn Reservoir	10426	Buchanan	NWSW	31	55N	34W	7
Breckenridge Lake Dam	10645	Caldwell	NESW	3	57N	26W	80
Hamilton Lake Dam	10261	Caldwell	SWSW	15	57N	28W	80
Archie	*	Cass	NESE	28	43N	31W	
Cleveland – Bartlett's Lake Dam	20310	Cass	NENE	4	44N	33W	7
Drexel Lake Dam No. 1	20213	Cass (See Bates County)					
Drexel Lake Dam No. 2	20046	Cass (See Bates County)					
Freeman Lake Dam	20056	Cass	SWSW	18	44N	32W	8
Garden City Lake Dam	20228	Cass	SWNW	31	44N	29W	22
Harrisonville Lake Dam	MO20078	Cass	SWSE	34	45N	31W	

* Indicates Stream Intake

Appendix G (continued)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
Harrisonville Lake Dam	MO20077	Cass	SESE	26	46N	31W	385
Peculiar Lake Dam	20305	Cass	SESW	22	45N	32W	10
Pleasant Hill Lake Dam	20004	Cass	SWSE	1	46N	31W	90
Pleasant Hill – Baldwin Lake Dam	20001	Cass	SESW	16	46N	30W	
Raymore Lake Dam	20051	Cass	SWSW	16	46N	32W	59
Marceline	12127	Chariton	SWSE	14	56N	19W	200
Wyaconda Lake Dam	10009*	Clark	NWNW	33	65N	9W	8
Smithville Reservoir	12084	Clay		13/24	53N	33W	7,190
Smithville – Helvely Park Lake Dam	10584*	Clay	NENE	26	53N	33W	13
Plattsburg – Smithville Lake	*	Clay		13/24	53N	33W	
Plattsburg Six Mile Lake Dam	10266	Clinton	SWSE	11	55N	32W	57
Plattsburg (Old)	10267	Clinton	SWNW	13	55N	32W	14
Cameron Lake Dam	10170	Clinton (See DeKalb County)					
Gower Lake Dam	10788*	Clinton	NESE	4	55N	33W	15
Jamesport Lake Dam	10559	Daviess	SESE	22	60N	26W	13
Lake Viking Dam	10414	Daviess	SENW	9	59N	28W	550
Cameron Lake Dam No. 1	10042	DeKalb	SWSW	10	57N	30W	25
Cameron Lake Dam No. 2	10169	DeKalb	NWNW	10	57N	30W	35
Cameron Lake Dam	10170	DeKalb	SENE	9	57N	30W	96
Maysville Lake Dam	10670	DeKalb	SESE	33	59N	31W	27
Maysville/Carl Redman Dam	12140	DeKalb	NWNE	3	58N	31W	12
King City Lake Dam	10078	Gentry	SWNE	28	61N	32W	12
King City Lake Dam	12093	Gentry	SWNE	28	61N	32W	34
Lake Springfield Dam	MO20023	Greene	SWSW	20	28N	21W	360

* Indicates Stream Intake

Appendix G (continued)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
Springfield – Fellows Lake Dam	MO20036	Greene	NWNE	22	30N	21W	820
Springfield – McDaniel Lake Dam	20038	Greene	NESE	26	30N	22W	300
Valley Water Mills Dam (Indirect Supply)	20035	Greene	NWNE	5	29N	21W	
Trenton Upper Reservoir	10509*	Grundy	NESE	18	61N	24W	68
Trenton Lower Reservoir	10508*	Grundy	NESE	18	61N	24W	103
Bethany Lake Dam	10051	Harrison	NWSW	2	63N	28W	18
Bethany New Lake Dam	10071	Harrison	NWSE	27	64N	28W	78
Harrison County Public Water Supply District No. 1 Lake Dam	10112	Harrison		33	66N	27W	
Ridgeway Lake Dam	12120*	Harrison	SWNE	32	65N	27W	
Armstrong Lake Dam	11520	Howard	NENE	28	52N	16W	12
Fayette Lake Dam No. 1	10131	Howard	NENW	15	50N	16W	10
Fayette Lake Dam No. 2	10130	Howard	NWNW	4	50N	16W	60
Fayette Lake Dam No. 3	10370	Howard	NWNW	10	50N	16W	185
Ironton-Sheppard Mountain Lake Dam	30324	Iron	NENE	1	33N	3E	21
Unity Village Lake Dam No. 1	20039	Jackson	SENE	25	48N	32W	15
Unity Village Lake Dam No. 2	20134	Jackson	NWSE	24	48N	32W	23
Holden Lake Dam	20194	Johnson	NESE	12	45N	28W	26
Holden Lake Dam	20221	Johnson	NWSW	7	45N	27W	30
Holden Lake Dam (New)	20532	Johnson	SESE	29	46N	28W	175
Baring Country Club Lake Dam	10010	Knox	SESE	26	63N	12W	81
Edina Lake Dam	10039	Knox	SESW	7	62N	11W	14
Edina Lake Dam	MO10040	Knox	SENE	12	62N	12W	42

*Indicates Stream Intake

Appendix G (continued)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
Concordia Lake Dam	MO20043	Lafayette	NWSE	20	48N	24W	245
Higginsville Lake Dam	10146*	Lafayette	NESW	4	49N	25W	40
Higginsville Lake Dam	11212*	Lafayette	SWNE	9	49N	25W	223
Odessa Lake Dam (Old)	20003	Lafayette	NWNW	14	48N	28W	19
Odessa Lake Dam (New)	20042	Lafayette	NWNE	15	48N	28W	90
LaBelle Lake Dam No. 1	10372	Lewis	NWNW	16	61N	9W	17
LaBelle Lake Dam No. 2	12118	Lewis	NWNE	16	61N	9W	162
Lewis County Public Water Supply District No. 1 Lake Dam	10218	Lewis	SWSE	6	60N	7W	60
Lewistown Lake Dam	10349	Lewis	NWSW	8	61N	8W	31
Brookfield Lake Dam	10181	Linn	SESE	33	58N	19W	120
Brookfield	10183*	Linn	NWNE	5	57N	19W	34
Bucklin Lake Dam	10056	Linn	SWNE	11	57N	18W	17
Linneus Lake Dam	10437	Linn	NESW	36	59N	21W	15
Marceline Lake Dam	10119*	Linn	NWSW	28	57N	18W	81
Marceline Lake Dam (New)	12127	Linn (See Chariton County)					
Atlanta Lake Dam	10330	Macon	SESW	29	59N	14W	14
Ethel Lake Dam	10055	Macon	NENW	36	59N	17W	23
LaPlata Lake Dam	10339	Macon	NESW	9	60N	14W	19
LaPlata Lake Dam (New)	12126	Macon	NENENW	14	60N	14W	
Macon Lake Dam	10153	Macon	SENW	17	57N	14W	200
Macon – Long Branch Lake	11176	Macon		8	57N	14W	
Macon County Public Water Supply District No. 1 – Thomas Hill	MO10134	Macon (See Randolph County)					

* Indicates Stream Intake

Appendix G (continued)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
New Cambria Lake Dam	MO10387	Macon	SWNE	7	57N	16W	7
Fredericktown Lake Dam	30489*	Madison	SESE	6	33N	7E	158
Mercer Lake Dam	10472	Mercer	NESW	30	66N	23W	21
Monroe City Lake Dam A	10539	Monroe	NWNW	13	56N	8W	20
Monroe City Lake Dam B	10538	Monroe	NWSW	30	56N	7W	43
Monroe City New Lake Dam	10542	Monroe (See Ralls County)					
Wellsville Lake Dam	10947	Montgomery	NWSE	33	50N	6W	
Wellsville (Quarry-Clay Pit)		Montgomery	SENE	4	49N	6W	16
Conception Abbey Lake Dam	10159	Nodaway	NWNW	25	63N	34W	10
Maryville	10997*	Nodaway	SWSW	15	64N	35W	
Maryville Reservoir	10998	Nodaway	SWSW	15	64N	35W	
Sedalia Lake Dam	30152*	Pettis	NESW	21	44N	21W	178
Bowling Green Lake Dam	10262	Pike	NWNW	29	53N	2W	45
Bowling Green Lake Dam (Old)	10263	Pike	NENE	30	53N	2W	20
Vandalia Lake Dam	10540	Pike	NENE	12	53N	5W	37
Dearborn Lake Dam	10426*	Platte	NWSW	31	55N	34W	12
Unionville Lake Dam (Old)	10152	Putnam	NESW	34	66N	19W	15
Unionville Lake Dam	10382	Putnam		27	66N	19W	70
Unionville – Thunderhead	10007	Putnam	NENE	15	66N	19W	1,150
Clarence Cannon Dam (Proposed)	12085*	Ralls	NWSE	14	55N	7W	
Monroe City Lake Dam	10542	Ralls	SWNE	34	56N	7W	131
Perry Lake No. 1	10980	Ralls	NWNW	34	54N	7W	15
Perry Lake No. 2	MO10675	Ralls	NWNW	34	54N	7W	7.4

* Indicates Stream Intake

Appendix G (continued)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
Ralls Public Water Supply District No. 1	*	Ralls	SESE	30	56N	4W	
Higbee Lake Dam	MO10660	Randolph	SESW	9	52N	14W	15
Moberly (Rothwell Lake Dam)	10006	Randolph	NESE	3	53N	14W	25
Moberly Park and Lake Dam	10004	Randolph	SENE	3	53N	14W	35
Moberly (Sugar Creek Lake Dam)	10005	Randolph	NESE	16	54N	14W	346
Thomas Hill Lake Dam	10134	Randolph	NESE	24	55N	16W	4,400
Sweet Springs Lake Dam A	20206*	Saline	SENE	15	48N	23W	4
Sweet Springs Lake Dam B	20205*	Saline	NWSE	10	48N	23W	7
Downing Lake Dam	10849	Schuyler	SWSE	17	66N	13W	18
Lancaster Lake Dam (New)	11198	Schuyler	SENW	23	66N	15W	
Lancaster Lake Dam (Old)	10851	Schuyler	SWNE	14	66N	15W	10
Schuyler Public Water Supply District No. 1 Lake Dam	10186	Schuyler	SESE	4	64N	15W	29
Memphis Lake No. 1	10163	Scotland	NENE	14	65N	12W	42.6
Memphis Lake No. 2	10217	Scotland	NESE	15	65N	12W	247.6
Memphis Reservoir	*	Scotland	SENE	12	65N	12W	2.06
Clarence Lake Dam	10609	Shelby	NWNE	15	57N	12W	18
Clarence Lake Dam	10608	Shelby	NWNW	15	57N	12W	31
Shelbina Lake Dam	10057*	Shelby	NESW	20	57N	10W	45
Shelbyville Lake Dam	10028	Shelby	SESE	19	58N	10W	29
Milan Lake Dam (Old)	10399	Sullivan	SESE	2	62N	20W	13
Milan Lake Dam (New)	MO10398	Sullivan	NENW	35	63N	20W	235

*Indicates Stream Intake

Appendix G (continued)

Dam	Reservoir Identification Number (MO)	County	Quarter Section	Section	Twp	Range	Surface Acres
Milan Lake Dam	MO10240	Sullivan	NENW	35	63N	20W	235
Green City Lake Dam	10155	Sullivan	SENE	16	63N	18W	6
Compton Hill Reservoir (City of St. Louis)	31696				45N	7E	
Stacy Park Reservoir (City of St. Louis)	MO31658				45N	6E	

*Indicates Stream Intake

Appendix H

PUBLIC WATER SUPPLY INTAKES ON MAJOR RIVERS

Supply	Stream	County	River Miles
St. Joseph	Missouri River	Buchanan	452.2
Kansas City	Missouri River	Clay	370.5
Lexington	Missouri River	Lafayette	322.5
Higginsville	Missouri River	Lafayette	306.0
Glasgow	Missouri River	Howard	227.0
Boonville	Missouri River	Cooper	197.0
Jefferson City	Missouri River	Cole	144.0
St. Louis (Howard Bend)	Missouri River	St. Louis	37.0
St. Louis County (Central Plant)	Missouri River	St. Louis	36.0
St. Charles	Missouri River	St. Charles	29.0
St. Louis County (North Plant)	Missouri River	St. Louis	20.5
Canton	Mississippi River	Lewis	342.3
Hannibal	Mississippi River	Marion	310.0
Louisiana	Mississippi River	Pike	282.8
St. Louis (Chain of Rocks)	Mississippi River	St. Louis	190.5
Cape Girardeau	Mississippi River	Cape Girardeau	54.3
Kirkwood	Meramec River	St. Louis	Approximately 1.2 mi. upstream from I-44 bridge
St. Louis County (South Plant)	Meramec River	St. Louis	Approximately 400 ft downstream from State Hwy. 30 bridge
St. Louis County (Meramec Plant)	Meramec River	St. Louis	Approximately 800 ft downstream from I-55

Appendix I

PUBLIC WATER SUPPLY INTAKES ON MINOR RIVERS AND STREAMS

Supply	Stream	County	Quarter Section	Section	Twp	Range
Bates County No. 2	Miami Creek	Bates	SESW	10	41N	33W
Adrian	South Grand River	Bates	SESE	34	43N	31W
Amoret	Marais DeCygnes	Bates	NWNW	5	40N	33W
Butler	Marais DeCygnes	Bates	SWSE	4	39N	32W
Butler	Miami Creek	Bates	SENE	24	40N	32W
Rockville	Osage River	Bates	SESE	22	38N	29W
Poplar Bluff	Black River	Butler	SWNW	2	24N	6E
Archie	South Grand River	Cass	NESE	28	43N	31W
Wyaconda	Wyaconda River	Clark	NENW	28	65N	9W
Plattsburg-Smithville Reservoir	Smithville Reservoir	Clay		13/24	53N	33W
Smithville	Little Platte River	Clay	SESE	23	53N	33W
Smithville-Helvely Park Lake Dam	Smithville Reservoir	Clay		13/24	53N	33W
Gower	Castile Creek	Clinton	SESW	10	55N	33W
Trenton	Thompson River	Grundy	NESW	18	61N	24W
Ridgeway	Big Creek	Harrison	SWNE	32	65N	27W
Clinton	South Grand River	Henry	SENE	7	41N	26W
Brookfield	Yellow Creek	Linn	NWNE	5	57N	19W
Marceline	Mussel Fork Creek	Linn	NESW	25	57N	18W
Chillicothe	Grand River	Livingston	SWNW	13	57N	24W
Fredericktown	Little St. Francis River	Madison	SESE	6	33N	7E
Paris	Middle Fork-Salt River	Monroe	NESW	10	54N	10W
Joplin	Shoal Creek	Newton	NENE	28	27N	33W

Appendix I (continued)

Supply	Stream	County	Quarter Section	Section	Twp	Range
Neosho	Shoal Creek	Newton	SWSW	7	25N	31W
Maryville	102 River	Nodaway	SWSW	15	64N	35W
Perryville	Saline River	Perry	NESW	15	35N	10E
Sedalia	Flat River	Pettis	NENW	22	45N	21W
Dearborn	Bee Creek	Platte	SESW	10	55N	35W
New London	Salt River	Ralls	NWNW	5	55N	4W
Ralls No. 1	Salt River	Ralls	SESE	30	56N	4W
Sweet Springs	Blackwater River	Saline	SESW	10	48N	23W
Memphis Reservoir	North Fabius River	Scotland	SENE	12	65N	12W
Shelbina	Salt River	Shelby	SWNE	17	57N	10W
Branson	Lake Taneycomo	Taney	NESE	5	22N	21W
Piedmont	Black River	Wayne	NWSE	9	28N	3E

APPENDIX J

SUGGESTED BASIC EXPLORATION PROCEDURES

I. Review of existing geologic and soil data; suggested sources are the following:
   - A. Missouri Department of Natural Resources, Division of Geology and Land Survey
   - B. Missouri Department of Transportation, Geology and Soils Section
   - C. U.S. Department of Agriculture, Soil Conservation Service
   - D. U.S. Geological Survey, especially the Water Resources Division
   - E. Libraries of various schools and universities, particularly published and unpublished graduate theses
   - F. U.S. Corps of Engineers District Offices

II. General field reconnaissance
   - A. Geology of surficial materials and bedrock
   - B. Examination of landforms, such as terraces, prairies, slopes, and escarpments
   - C. Evidence of local water use such as windmills, living wells, cisterns, well houses, ponds, water districts, and water haulers
   - D. Observation of receiving streams to determine flow conditions, including gaining or losing features
   - E. Initial exploration, e.g., by backhoe and drilling, to estimate surficial material thickness and type, groundwater conditions, and to determine depth to bedrock

III. Detailed exploration procedures
   - A. Continuous soil sampling of enough boreholes to determine stratigraphy and engineering properties, such as texture, Atterburg limits, pH, cation exchange, density, moisture *in situ* and after saturation, and permeability
   - B. Bedrock exploration to determine geologic and engineering properties, such as lithology, rock quality index, and permeability

     Information should be of sufficient detail to show subsurface conditons reliably. Geophysical exploration can provide useful supplementary data.
   - C. Surface Water and Groundwater
     1. Evaluation of local streams to determine recharge-discharge setting
     2. Determination of gradient(s), flow lines, and depth to water table(s)
     3. Determination of piezometric surface relative to the following:
        - a. The water table(s)
        - b. Depth of water in boreholes

          A water table above the piezometric surface indicates a downward hydraulic gradient, which would be shown during drilling by the lowering of water levels in boreholes. In such cases, there is great risk of downward movement of pollutants. Conversely, a piezometric surface above the water table indicates an upward hydraulic gradient. This positive-head environment need not be locally generated. The upward gradient indicates much less vertical movement of contaminants. Lateral movement can be more easily monitored and controlled. A positive hydraulic gradient is indicated by rising water level in boreholes.
     4. Search for perched water table(s) and, if found, determination of the following:
        - a. Whether perennial or non-perennial saturated soil exists below perched water tables
        - b. Soil stratigraphy and engineering properties to explain perched water tables
     5. Compilation of baseline ground-

water data, such as the following:

a. Direction and rate of groundwater movement
b. Temperature
c. Chemistry, including relevance to drinking water standards and reference to other properties or constituents, such as total dissolved solids, including iron, manganese, and sodium; pH; conductance; and possibly age dating

Groundwater chemistry and age dating studies should be directed toward determining the origin or source. Additional groundwater investigation might include background analysis for constituents that may be placed in the landfill. Analytical procedures should be consistent with current rules and regulations applicable to siting of hazardous-waste isolation facilities.

The procedures outlined above should be followed for each groundwater zone, including perched water tables and confined or unconfined groundwater. This means it is necessary to sample several levels and to ensure that each hole is properly sealed. A properly designed sampling program should provide much data on direction and movement of groundwater. In addition, it may be necessary to monitor a site through several seasons of the year or make projections for variations in water level changes. Exploration boreholes must be treated with care, because they can be avenues for groundwater contamination.

APPENDIX K

TERMINOLOGY

1. *Artesian:* refers to groundwater confined under hydrostatic pressure.

2. *Hydrogeologic investigation:* study of surface and groundwater conditions in relation to geologic setting.

3. *Permeability*: rate of transmission of a fluid through surficial materials. It is measured by the following scale:

High	greater than 10^{-5} cm/s
Moderate	10^{-5} to 10^{-7} cm/s
Low	less than 10^{-7} cm/s

4. *Piezometric surface:* an imaginary surface coinciding with the hydrostatic pressure level of the water in an artesian aquifer. The level to which water rises in a well is a particular example.

5. *Plasticity:* range in water content in which soil changes from liquid to semisolid. Described in the following terms:

High	CH
Moderate	CL, ML
Low	ML

6. *Preglacial drainage:* a drainage system that was active before glaciation, the channel(s) now completely or partially buried beneath drift.

7. *Residuum:* surficial material resulting from decomposition and weathering of bedrock. The terms *residuum* and *surficial material(s)* tend to be used interchangeably.

8. *Soil:* generally, the upper 3 to 5 ft (1 to 2 m) of surficial material, so modified and weathered that it will support rooted plants; a soil profile.

9. *Surficial material(s):* all unconsolidated

materials of whatever origin overlying bedrock. This material is considered soil by most engineers.

10. *Thickness:*

	Meters	Feet
Very thin	0-3	0-1
Thin	3-20	1-6
Moderate	20-40	6-12
Thick	40-100	12-31
Very thick	100+	31+

11. *Water table:* the upper surface of the zone of saturation where the hydrostatic pressure is equal to the atmospheric pressure.

12. Definitions of other pertinent terms are defined in Division 25, Chapter 3 of the Missouri State Code of Regulations. A copy of the code applicable to hazardous-waste isolation can be obtained by writing to Missouri Department of Natural Resources, Division of Environmental Quality, Solid Waste Program, P.O. Box 1368, Jefferson City, Missouri 65102.

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DIVISION OF GEOLOGY AND LAND SURVEY

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