Electrical earth resistivity surveys near brine holding ponds in Illinois

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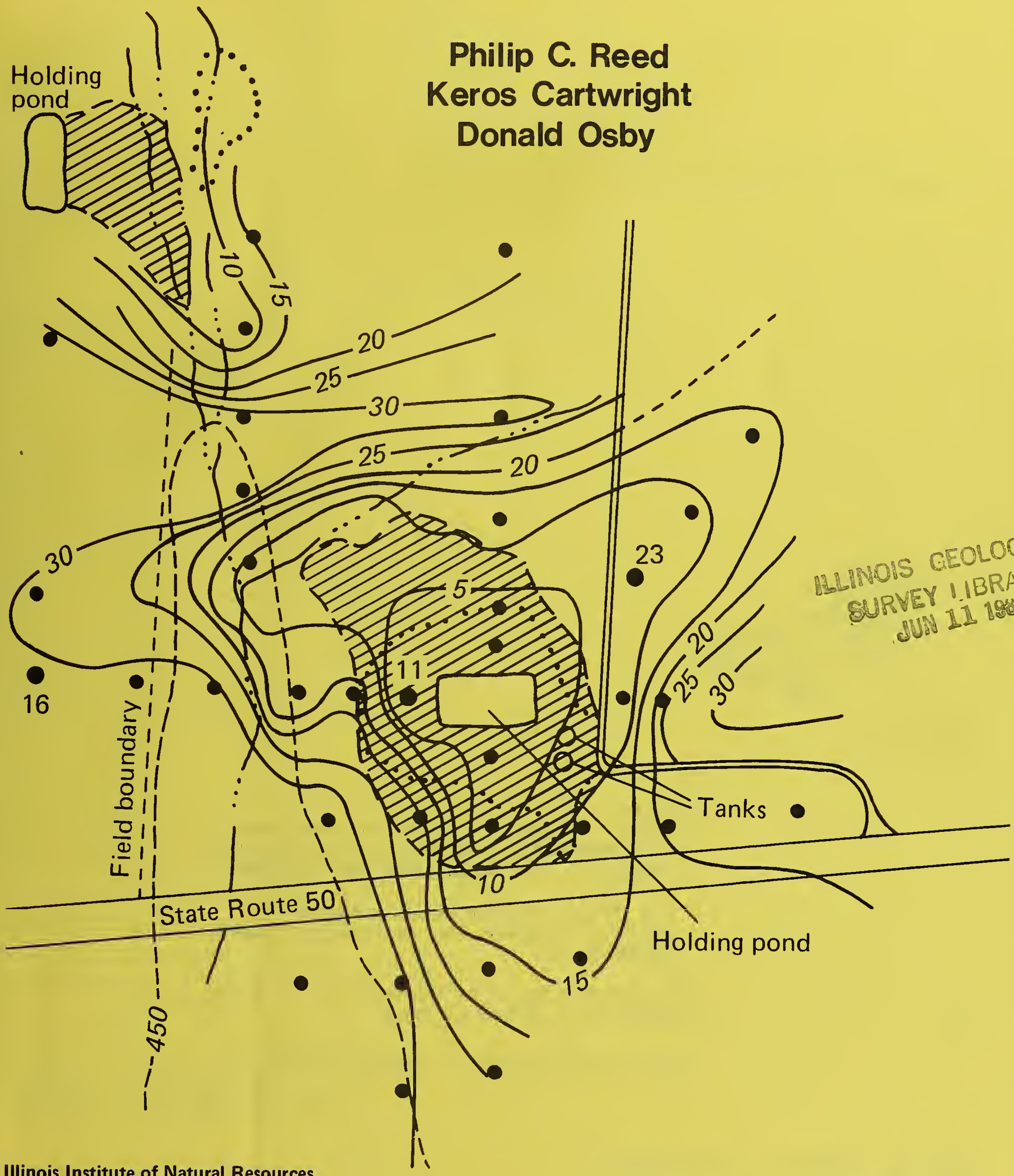

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ABSTRACT

Electrical earth resistivity surveys were conducted in the vicinity of five oil field brine holding ponds to develop a methodology for identifying elevated levels of soluble salts near oil fields. The five sites, all in similar hydrogeologic environments, were distributed across the main oil-producing region of Illinois. Four of these sites were selected for detailed study of a possible relationship between changes in apparent electrical earth resistivities and changes in water quality.

The resistivity surveys clearly indicate the direction and extent of salt water migration around the holding ponds. Apparent resistivity measurements can be used to approximate quality of the ground water because there is a direct relationship between the resistivity and water quality. This relationship can be used to indicate relative salinities; however, the relationship should be used with caution in making estimates of water salinity.

Brine migration has not affected the regional water quality, and appears to be of limited regional significance. Studies of water chemistry from observation wells at the selected holding pond sites indicated that some attenuation of the brine is occurring.

INTRODUCTION

Salt-water brines from oil fields in Illinois, characterized by high chloride, bromide, potassium, and sulfate content (Reed, 1978; Meents et al., 1952), have been disposed of in various ways since large commercial production in southern Illinois began in the 1930s. At first, most of the brines were simply discharged in creeks. In the 1940s, wells were designed to reinject the brine associated with oil production into compatible underground reservoirs; but it was common practice to put the brine into a pond because it was thought that the brine would evaporate into the atmosphere. Now most brine is either reinjected in the producing formation as a part of the secondary recovery effort or disposed of by injection through nonproducing wells called salt-water disposal wells. In Illinois, where precipitation exceeds lake evaporation (Roberts and Stall, 1967), a brine holding pond may actually become an infiltration pond: brine discharged into the pond along with a part of the associated precipitation may slowly enter the ground-water system and eventually be discharged into nearby streams. The effect on the stream depends on the relative volumes of water from contributing sources; although the surface-water problem was greatly improved through the use of holding ponds, local ground-water contamination is now present in some Illinois oil fields.

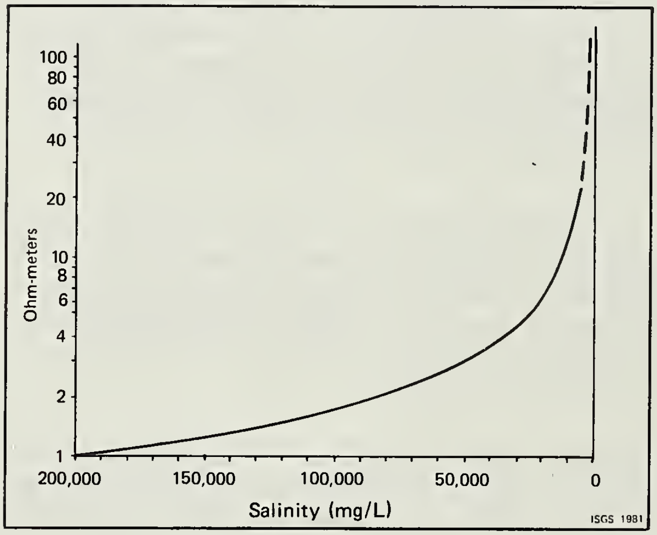


FIGURE 1. Relationship of resistance and connate water salinity (after Guyod, 1952).

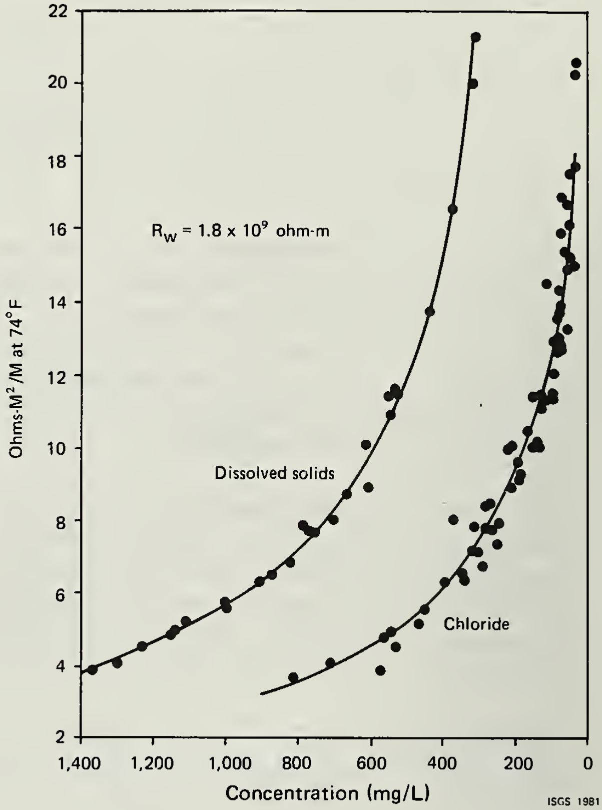


FIGURE 2. Relationship of resistivity, chloride, and dissolved solid content (after Whitman).

Vegetation kills, generally limited to a small area surrounding the ponds, are often the most visible effect of the brine holding ponds. These vegetation kills can be seen from the ground and from aerial photographs. False-color infrared, black and white infrared, and black and white photographs of the holding ponds in the area were examined. Brown and, to a smaller extent, a light bluish-green coloration on the false-color infrared photographs depict stressed or dead vegetation due in part to high mineral concentrations in the soil. Older black and white aerial photographs were used to estimate the areal extent of vegetative cover around the ponds at earlier periods.

Earth resistivity studies using the standard Wenner electrode configuration have been used to monitor the deterioration of water quality and the extent of leachate migration near landfills and other waste sites (Cartwright and McComas, 1968; Warner, 1969; Hackbarth, 1971; and Cartwright and Sherman, 1972). Since the apparent resistivity of earth materials is controlled by both the lithologic character of the materials and the quality of the pore water, differences in apparent resistivity at and near brine holding ponds should be partly related to differences in mineralization of the ground water. This study was initiated to develop methodology for relating the mineralization of shallow ground water to surface electrical earth resistivity measurements (apparent resistivity) near salt-water holding ponds. The basic data are included in a report to the IEPA (Reed, 1978).

RESISTIVITY THEORY

The electrical earth resistivity survey is based on the principle that compact glacial till, clay, and shale present less resistance to the passage of an electrical current than do unconsolidated sand and gravel, or sandstone and limestone. However, the resistance to the passage of electricity through earth materials containing pore water with high concentrations of soluble salts will be much less than that for similar materials with relatively fresh pore water.

In Illinois, experience with making vertical electrical soundings with the Wenner electrode configuration (Van Nostrand and Cook, 1966) in ground-water exploration in glacial materials (Buhle and Brueckmann, 1964) has shown that the assumption that a given "a" spacing is equal to the depth of examination is generally reliable. Experience has also shown, however, that the layering of earth materials of greatly different resistivities distorts the electrical field, and the presence of saline pore water in shallow sediments severely limits the depth of electrical penetration. Thus, depth profiles extended to an "a" spacing of 80 feet may measure the apparent resistivity of all materials to approximately 80 feet in an area not affected by salt water; but in sections measured with highly saline pore water, maximum penetration appears to range between 5 and 20 feet. This approximation was made by comparing analyses of vertical profiles and core resistivity measurements made in the field.

The change in resistivity with water salinity is shown in figure 1 as adapted from Guyod (1952). The greatest change in resistivity occurs at the lower salinity end of the curve from 30,000 mg/L downward. Measurements of residue on evaporation and chloride concentrations in holding pond water at three of the sites studied ranged from about 2,000 to 93,000 mg/L dissolved solids and from 1,000 to 55,000 mg/L chloride. In figure 2 (modified from Whitman, 1965) the general relationship is shown between chloride, dissolved solids, and resistivity in the lower ranges of salinity.

LOCATION AND STUDY OF SITES

Four sites were selected for study on the basis of results of the field reconnaissance. The sites shown on the map in figure 3 are located in active oil fields in Bond, Christian, Clay, and Effingham Counties, in areas where salt water migrating from disposal ponds has caused vegetation kills. The selected sites were at places where there appeared to be a reasonable chance of obtaining basic data from which a methodology could be developed for studying brine migration.

Prior to this study, electrical earth surveys were conducted near several other brine holding ponds in the state of Illinois. The results of one of these studies is included in this report (the Bond-Clinton County Holding Site).

The following criteria were developed for selection of the four salt water disposal ponds in this study:

- The site should have uniform, easily determinable geology and simple hydrogeology, preferably with one main water transmission zone.

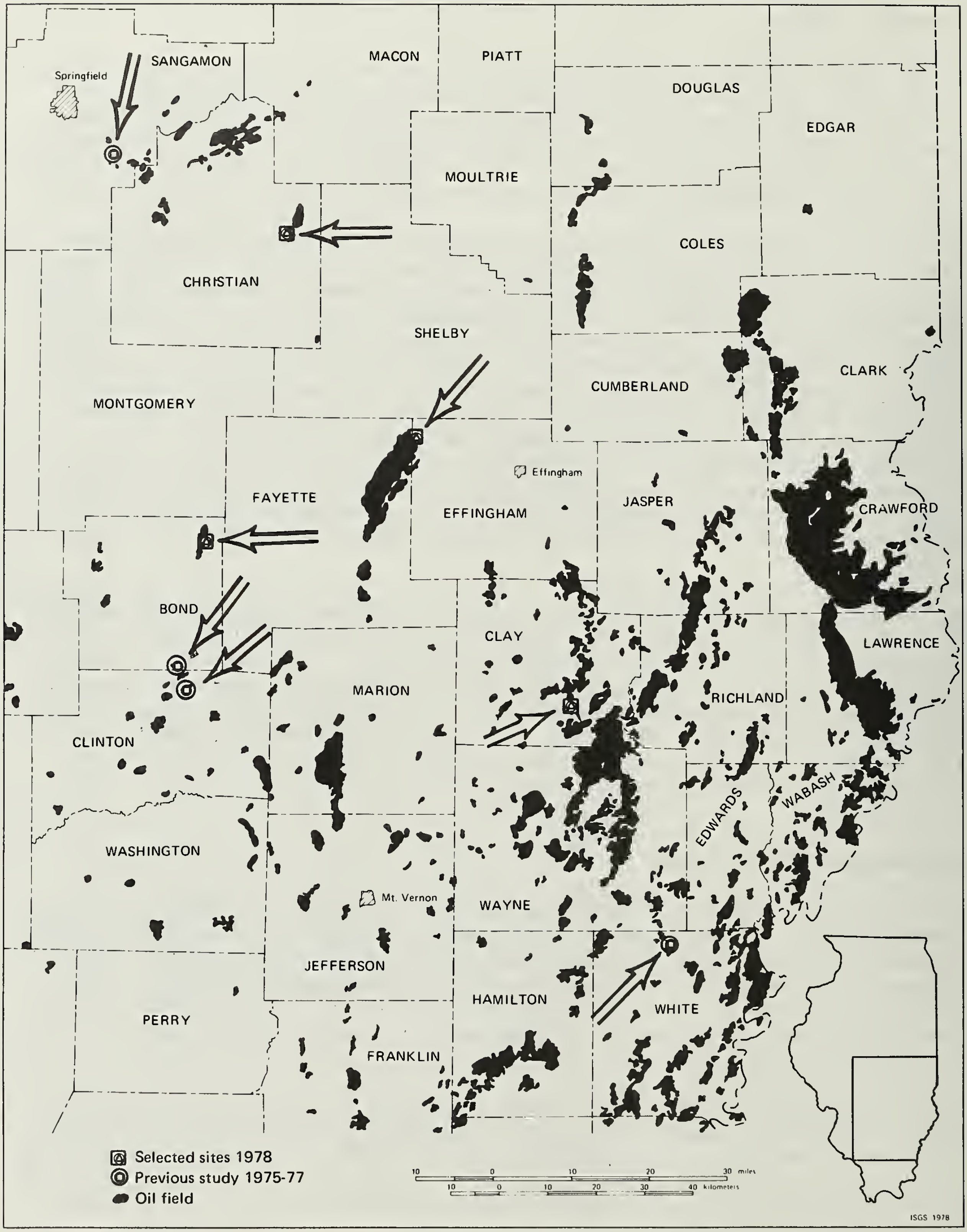


FIGURE 3. Locations of electrical earth resistivity studies in Illinois oil fields.

- The site should be sufficiently isolated from other sources of chloride contamination, including other brine ponds.

- The site should have been in operation for a sufficient length of time so that salt water has had a chance to migrate.

- The site and observation wells should be accessible for a period of one year, if possible.

- The layout of the site should be such that the observation wells can be located with a minimum of interference with existing property use.

- The site should have as few pipes and other metallic objects as possible which could interfere with resistivity measurements.

- The sites should be geographically distributed across the oil-producing region of the state and be representative of hydrogeologic environments of the oil fields.

- The land owner, tenant, and lessee of the site should be cooperative.

- The sites should be free of any ongoing or pending litigation or regulatory action.

The procedures used for studying the sites included: (1) making electrical earth resistivity soundings at systematic intervals near the salt water disposal ponds to ascertain apparent resistivity of earth materials; (2) constructing maps depicting the apparent resistivities at various "a" spacings around the disposing ponds; (3) conducting auger and split-spoon sampling of the earth materials, generally every five feet, at the observation well sites; (4) measuring the resistivity of the cores of the earth materials obtained by split-spoon method; (5) making gamma logs through the augers to further verify the characteristics of earth materials near the ponds so that slotted pipe could be placed opposite the most favorable water yielding zones; (6) obtaining water samples for comparative analysis with resistivity data; (7) comparing elevations of water in the ponds and wells; and (8) analyzing selected samples for grain size, clay mineralogy, and hydraulic properties.

Deposits of Illinoian till consisting primarily of the Hagarstown Member and the Vandalian Till Member of the Glasford Formation—some of the most widespread glacial deposits in Illinois—outcrop and immediately underlie relatively thin deposits (1 to 6 ft) of Wisconsinan loess in much of the oil field area studied. Hagarstown deposits consist of four types of compact to noncompact sediments: gravelly till, poorly sorted gravel, well sorted gravel, and sand and silt, often occurring with mixtures and blocks of underlying till (Jacobs and Lineback, 1969). The Hagarstown averages 15 to 20 feet in thickness in many broad, flat till plain areas of south-central Illinois, but may also occur as linear elongate ridges and kames up to 100 feet thick. Where the Hagarstown is permeable it serves as a source of small to moderate supplies of ground water. Most of the holding ponds studied were excavated within 5 to 20 feet of Hagarstown materials, consisting chiefly of sand and silt with minor amounts of gravel. The deposits were generally uniform in texture and thickness at sites where drilling was undertaken and had low to moderate hydraulic conductivities (3×10^{-4} to 1×10^{-5} cm/sec). The Hagarstown Member

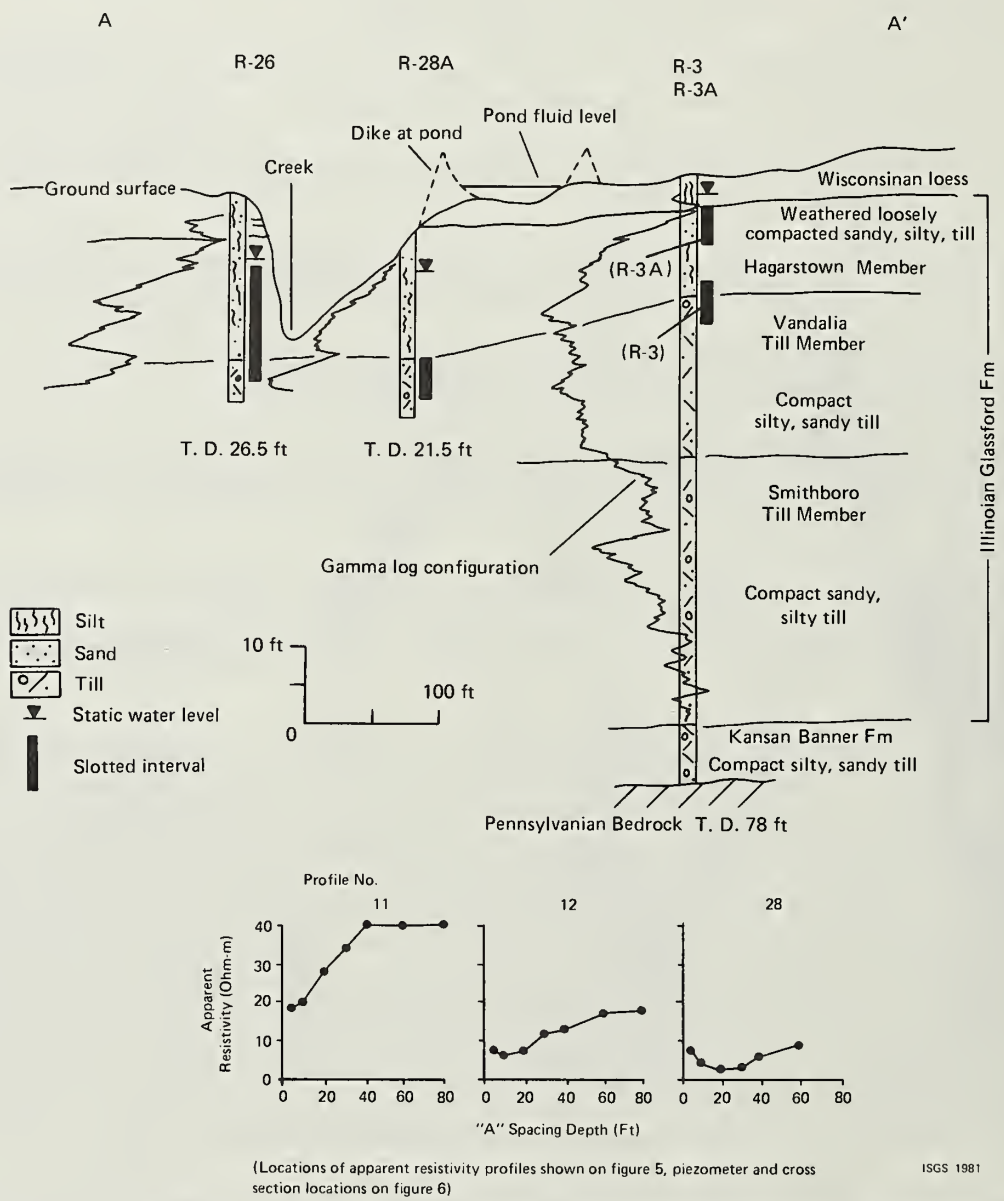


FIGURE 4. Geologic cross section, Woburn consolidated oil field (Section 10, T. 6 N., R. 2 W., Bond County, Illinois), and apparent resistivity profiles.

is underlain by the Vandalia Till Member, a compact, sandy, silty, clayey till with a much lower hydraulic conductivity.

The hydraulic conductivity differences between the Hagarstown Member and Vandalia Till Member suggest that the principal control on chloride migrations of the holding pond brines is related to lithologic characteristics and distribution of the Hagarstown or other shallow, permeable materials above the Vandalia Till Member. The distribution of chlorides and other soluble salts within the permeable materials is considered to be the result of dilution by rainfall and aquifer water, and the gradient and direction of ground-water flow. The field studies verify this simple model. The resistivity measurements and penetrometer measurements of split-spoon samples show higher resistivity and greater density of the till underlying the Hagarstown Member, indicating that mineralized water has moved laterally rather than downward. Lateral migration of mineralized water is also reflected in the apparent resistivity values calculated from vertical electrical soundings.

FIELD STUDIES

Bond County holding pond

The Bond County holding pond is located in Section 10, T. 6 N., R. 2 W., Bond County, Illinois, in the Woburn Consolidated Oil Field. The land elevation is between 565 and 580 feet above mean sea level. The pond reportedly receives an average of 20 barrels of brine per day. Drainage is generally westward from the pond toward a north-flowing tributary of Gilham Creek. The study site is part of a relatively flat and featureless drift plain underlain by Illinoian glacial deposits. The unconsolidated glacial drift and overlying deposits of loess consist of about 80 feet of till, sand, and clayey silt. Beneath the glacial deposits is bedrock of Pennsylvanian age. The stratigraphy at the pond is illustrated by the cross section (fig. 4).

The surface materials at the site consist of 2 to 5 feet of Wisconsinan loessial silt and sand which form part of the soil in the region. Below the loess, exposed along unvegetated drainageways west and south of the pond, is the Hagarstown Member of the Illinoian Glasford Formation. An abandoned pond has been breached by erosion to a depth of 6 to 7 feet, exposing infilled spoil materials above the Hagarstown. The Hagarstown extends to about 20 feet below the land surface and consists primarily of sandy silt with minor amounts of sandy ablation till.

The silt, sand, and sandy till of the Hagarstown Member contain greater amounts of coarse clastic material, are less compact, and are relatively more permeable than the remaining tills of the Glasford Formation. The best exposure of Hagarstown is on the west side of the active holding pond where about 8 feet of continually moist, unvegetated silt extends downward from the diked part of the pond, ending abruptly at the waterway. The silt of the Hagarstown is differentially weathered, having undergone two periods of soil genesis. The Hagarstown Member is underlain by about 20 feet of the Vandalia Till Member of the Glasford Formation, a sandy, silty, clayey till with a few thin sand lenses. Underlying the Vandalia Member is about 30 feet of silty, clayey, smooth textured till of the Smithboro Till Member of the Glasford Formation. The lowermost 8 feet of glacial drift consists of compact Kansan till which overlies the Bond Formation of Pennsylvanian age.

Forty-three vertical electrical soundings were measured at the Bond County site (fig. 5). Most profiles were extended to an "a" spacing of 80 feet. Three representative profiles are illustrated in figure 4. Profile 28 illustrates a profile in an area severely affected by mineralized water. The most severely affected zone of the apparent resistivity profile is reflected in the 10- or 20-foot "a" spacing in all cases. It appears that the 50-foot "a" spacing is beginning to reflect effects of the lower till.

Profile 12 illustrates an area moderately affected by mineralized water in the Hagarstown. Profile 11, an area which has not been affected at all, reflects

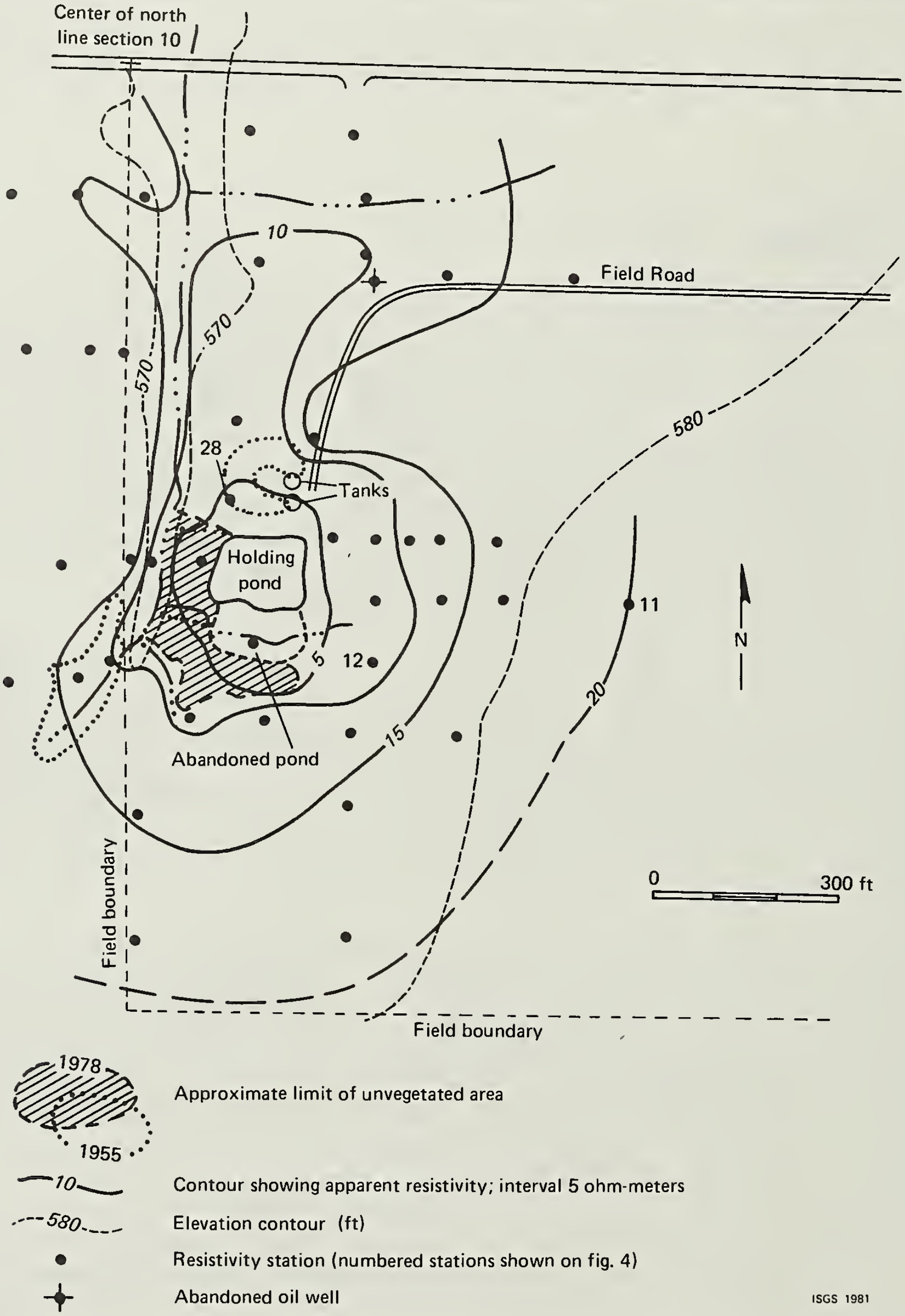


FIGURE 5. Apparent resistivity at 10-foot "a" spacing, Woburn consolidated oil field.

background to which other stations can be compared. The isoresistivity map (fig. 5) for an "a" spacing of 10 feet seems to indicate the maximum extent of mineralized water. The limit of mineralized water effects probably is near the 15 ohm-meter contour line or slightly beyond.

Water levels from the piezometers and the holding pond show a small ground-water mound (superimposed on the local flow system) beneath and around the pond. The ground water discharges into the small stream west of the pond (fig. 6). There is an apparent increase in gradient toward the drainageway.

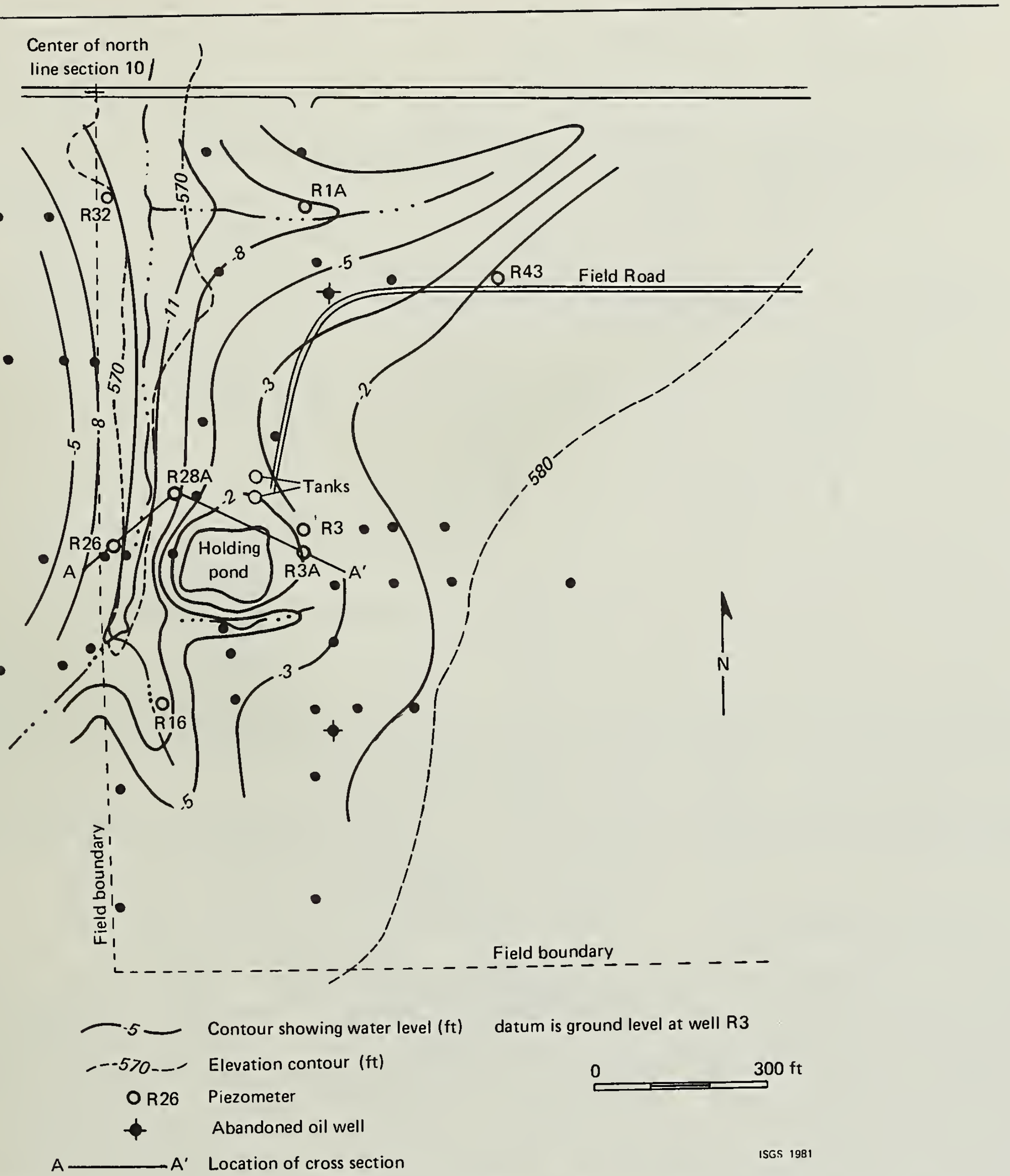


FIGURE 6. Water level contours, Woburn consolidated oil field (Sec. 10, T. 6 N., R. 2 W., Bond County, Illinois).

Water from the mound seeps from the west side of the active pond into the waterway. The extent of unvegetated areas surrounding the holding pond in 1978 is similar or slightly smaller than the area shown on the 1955 aerial photographs. The unvegetated area stops sharply at the waterway, as is expected from the change of the flow pattern in the area.

The distribution of apparent resistivity at the 10-foot "a" spacings (fig. 5) indicates the greatest migration of chlorides northward and westward toward drainageways. The distribution pattern also indicates more migration to the east than indicated by the piezometric map (fig. 6) suggesting that greater volumes of brine were introduced in the system in the past. The apparent resistivity values of the vertical electrical sounding curves and generally higher resistivity values from split-spoon samples of the till below the

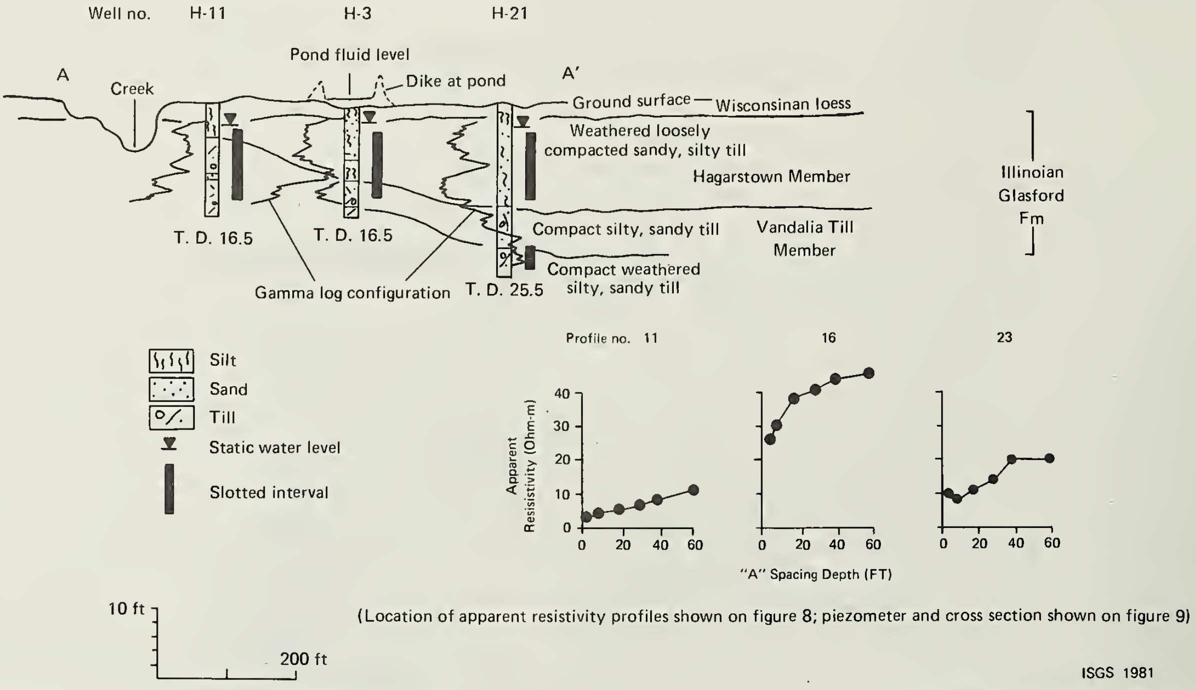


FIGURE 7. Geologic cross section, Sailor Springs consolidated oil field (Sec. 21, T. 3 N., R. 7 E., Clay County, Illinois), and apparent resistivity profiles.

Hagarstown indicate that the mineralized pond water has not migrated downward into the underlying till.

Clay County holding pond

The Clay County site is located in Sections 21 and 28, T. 3 N., R. 7 E., within the Sailor Springs Consolidated Oil Field. The pond reportedly receives four barrels of brine per day at the present time. The land elevation ranges between 445 and 455 feet above sea level, and drainage is westward toward a tributary of Elm River. The unconsolidated Illinoian glacial drift and overlying loess consist of about 25 feet of silt, sand, and clayey sandy till. These units overlie the Mattoon Formation of Pennsylvanian age. The stratigraphy of the site is illustrated by the cross section (fig. 7).

The site is overlain to the west and north with up to 3 feet of loose, often moist, fairly clean sand with granules, probably spoil derived from the pond excavation. This surficial material is porous and permeable and appears to transmit pond fluid rapidly. The remainder of the site is overlain by about 4 feet of Wisconsinan Loess. Beneath the spoil and loess there is about 10 to 15 feet of loosely compacted soil, sand, silt and deeply weathered till of the Hagarstown Member of the Glasford Formation. Underlying the Hagarstown is 10 to 20 feet of compacted, relatively impermeable Vandalia Till Member which probably extends to the bedrock.

Thirty-nine vertical electrical sounding profiles were measured at the Clay County site (fig. 8). Most of the profiles were extended to an "a" spacing of 60 feet. Three representative profiles are shown on figure 7. Profile

11 represents an area severely affected by mineralized water, profile 23 a moderately affected area, and profile 16 an unaffected area. Some of the stations appear to have variable resistivities due to differences in the lithology of the earth materials. "Background" stations also appear to be somewhat variable. Part of the variability may be due to a high resistivity surface layer encountered at some stations; however, not all differences can be accounted for in this way.

The isoresistivity map of the 10-foot "a" spacing appears to show the maximum extent of mineralization (fig. 8). The limit of mineralized water appears to be within the 20 ohm-meter line over most of the site except southwest of the pond, where a highly resistive surficial layer raises the apparent resistivity values for the entire vertical electrical sounding profile.

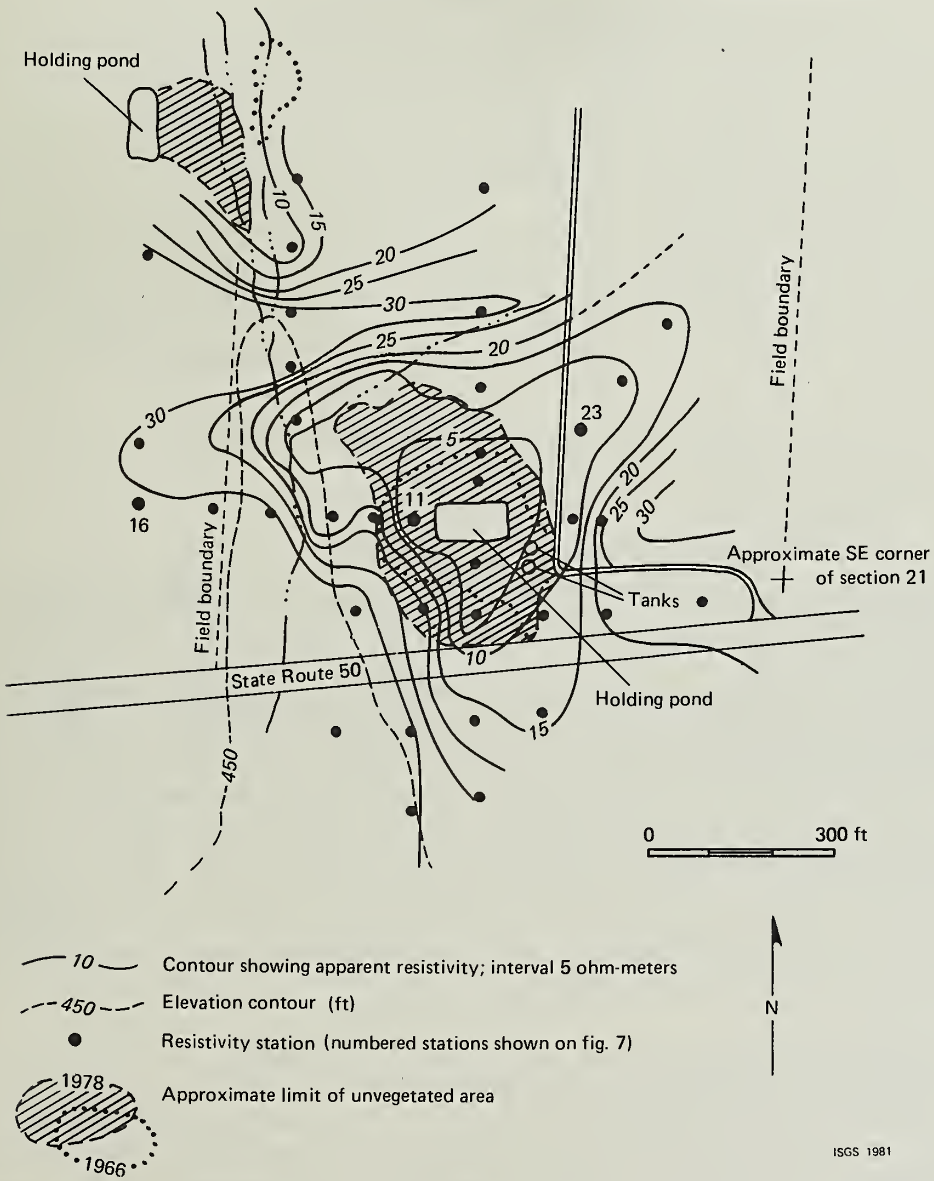


FIGURE 8. Apparent resistivity at 10-foot "a" spacing, Sailor Springs consolidated oil field.

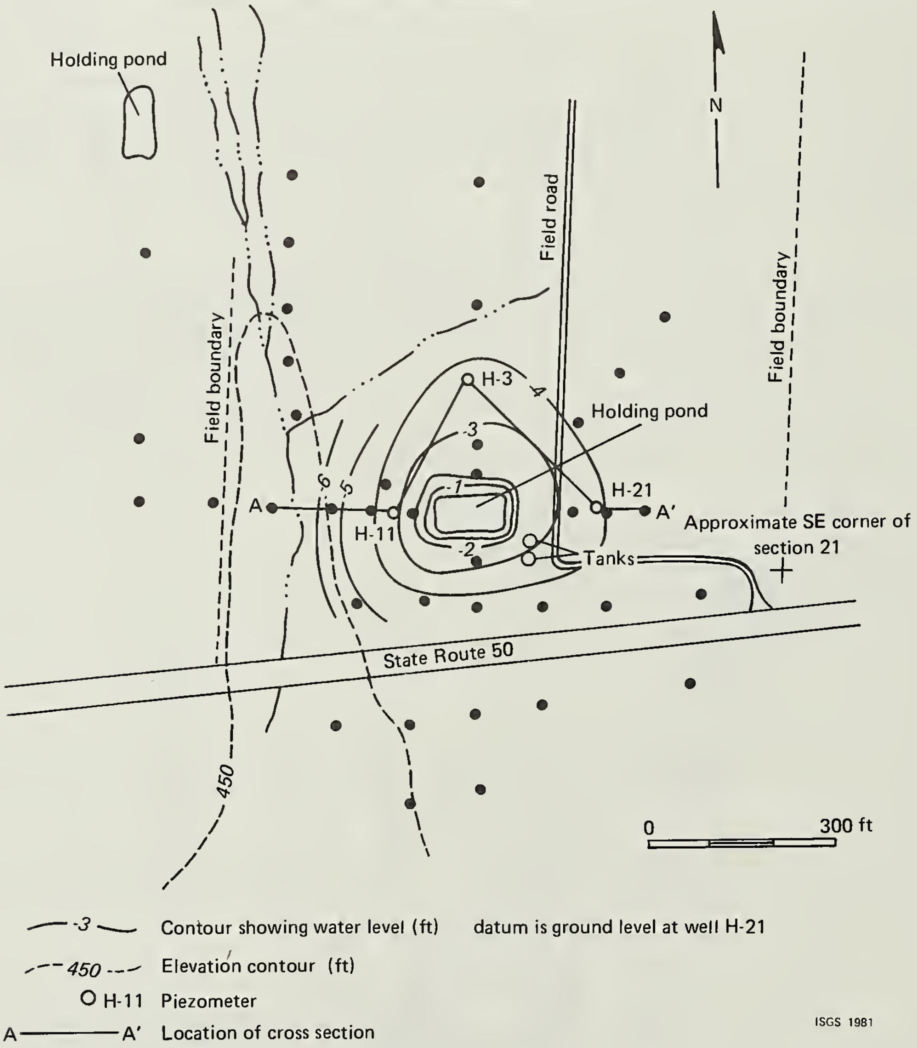


FIGURE 9. Water level contours, Sailor Springs consolidated oil field.

Water levels from the piezometers and holding pond (fig. 9) indicate that a ground-water mound has developed beneath the pond. Although no local flow direction was determined because of insufficient data, the gradient westward toward the creek is steeper, suggesting greater flow in that direction. A comparison of present vegetation patterns with aerial photographs taken in 1966 indicates that the construction of State Route 50 in the early 1970s may have interrupted a part of the southeastward migration of the unvegetated area around the pit. To the northwest, the unvegetated area has extended outward 200 feet in a broad eliptical pattern to a field waterway, documenting the chloride migration since 1966 near the pit.

The distribution of apparent resistivity at the 10-foot "a" spacing (fig. 8) indicates a general outward migration of brine from the holding pond with the main directions of movement to the south, northwest, and northeast. There is probably additional migration to the southwest, where the high-resistivity surficial materials "mask" deeper low-resistivity materials. The relationship is not directly indicated by the general water level record but is corroborated by the water quality data.

■ **Christian County holding pond**

The Christian County site is located on an Illinoian till plain in Section 20, T. 13 N., R. 1 E., within the Assumption Consolidated Oil Field. The pond reportedly received as much as 100 barrels of brine per day prior to abandonment in 1977. The land elevation ranges between 610 to 620 feet above mean sea level, and drainage is southeastward toward a tributary of Oak Branch Creek. A shallow depression north of the pond diverts part of the surface water to the north. The unconsolidated Illinoian glacial drift and the more recent deposits of loess consist of sand, silt, and glacial till about 80 feet thick and form a broad, flat plain in this area. Beneath these deposits is bedrock of the Pennsylvanian Bond Formation. The general stratigraphy of the site is illustrated by the cross section (fig. 10).

The surficial material at the site consists of about 5 feet of loessial silt and sand which form part of the surface spoil materials around the unvegetated areas of the pit. Beneath the loess is about 15 feet of silt and very fine- to fine-grained sand of the Hagarstown Member of the Illinoian Glasford Formation. Below the Hagarstown, in descending order, are the Vandalia and Smithboro Till Members of the Glasford Formation. These units consist of compact sandy, silty, clayey till and may extend to the underlying bedrock.

Thirty-six vertical electrical sounding profiles were measured at the Christian County site (fig. 11). Most profiles were extended to an "a" spacing of 80 feet. Three representative profiles are shown in figure 10. Profile 12

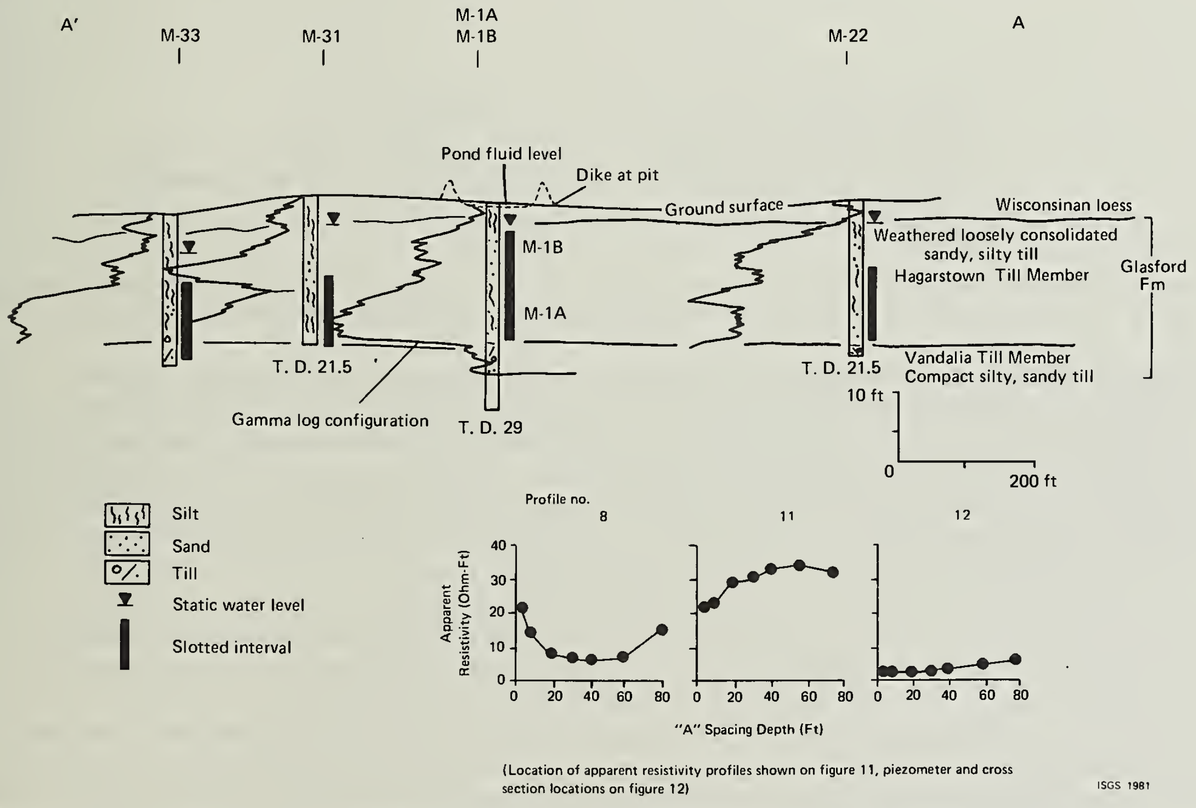


FIGURE 10. Geologic cross section, Assumption consolidated oil field (Sec. 20, T. 13 N., R. 1 E., Christian County, Illinois), and apparent resistivity profiles.

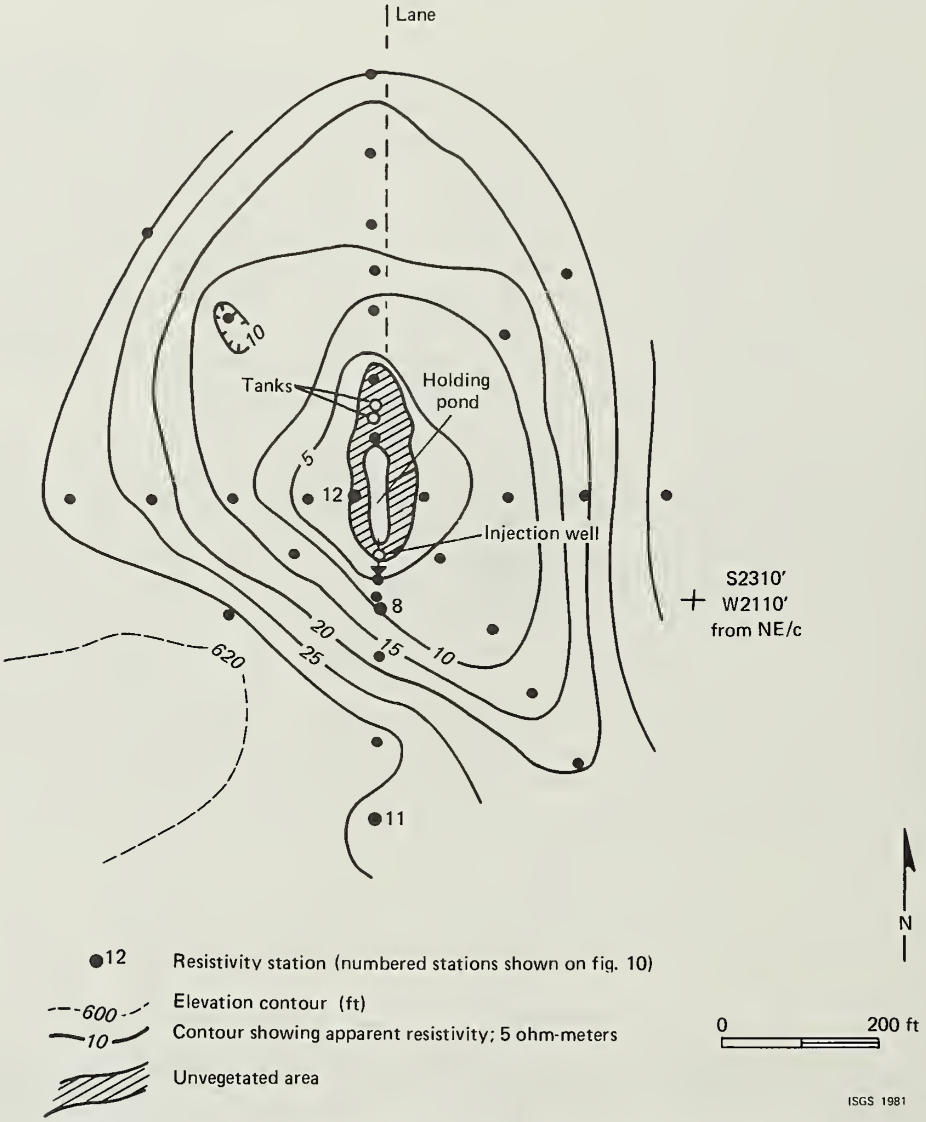


FIGURE 11. Apparent resistivity at 20-foot "a" spacing, Assumption consolidated oil field.

represents an area severely affected by mineralized water, profile 8 a moderately affected area, and profile 11 an unaffected area. The isoresistivity map at the 20-foot "a" spacing appears to best show the extent of mineralized water, possibly reflecting the stratification of water within the aquifer that extends to almost 20 feet below the land surface. The 10 to 15 feet of silt and sand is the deepest and thickest aquifer studied. The limit of mineralization is near the 25 ohm-meter contour.

Water levels from the piezometers and the holding pond (fig. 12) indicate a ground-water mound beneath and around the pond superimposed on the local ground-water flow system. The general ground-water flow is from the northwest to the southeast, trending away from the upland toward the lowland area. The small rise in surface elevation southeast of the pond may also have some local influence restricted to a relatively small area around the pond and battery tanks.

The distribution of the apparent resistivity also indicates that the migration of chlorides is greatest southeastward in the main direction of ground-water

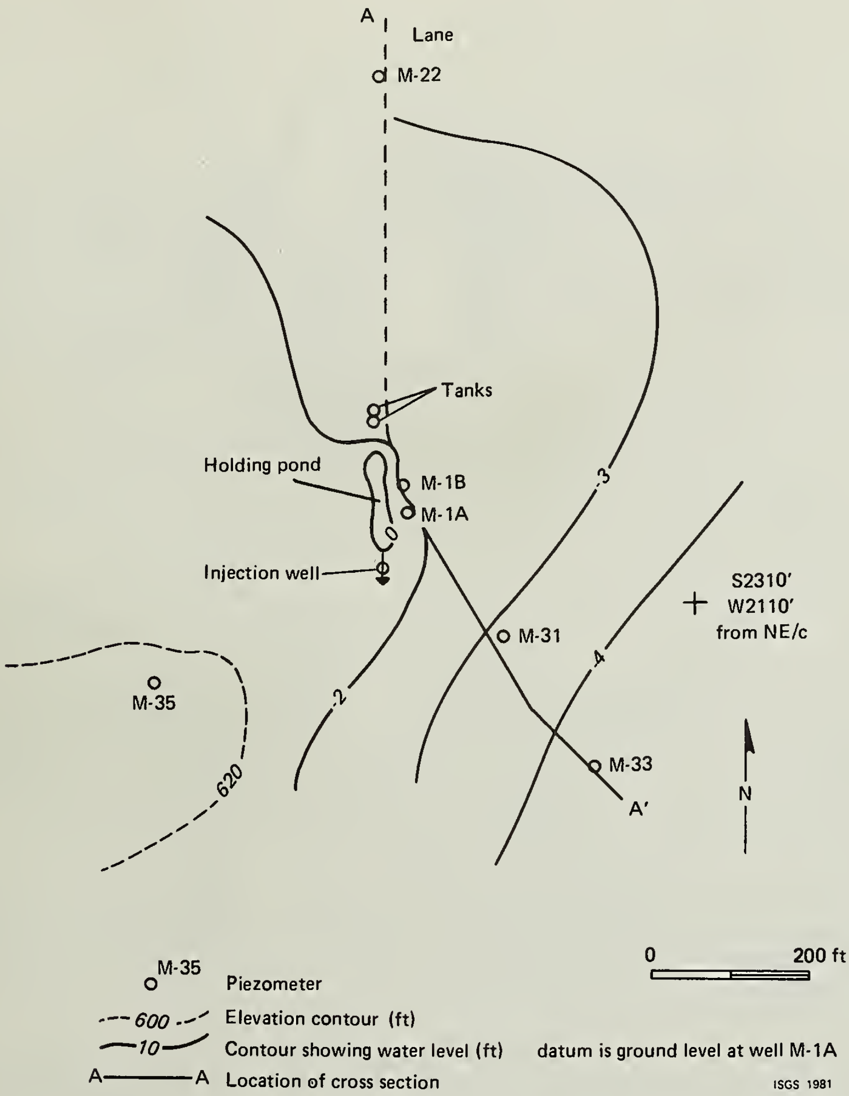


FIGURE 12. Water level contours, Assumption consolidated oil field.

flow. However, there is also a strong northward component of chloride migration not directly matched by the present ground-water flow. The northward component may be the result of a differing ground-water flow pattern during the period of use; it could also be the result of misinterpretation of the limited water level elevation data or of variations in the hydraulic conductivity of the Hagerstown Member. Apparent resitivity values from split-spoon samples were much higher in the Vandalia Till Member below the Hagarstown Member, indicating little downward movement of the highly mineralized water into underlying less permeable members.

■ Effingham County holding pond

The Effingham County site is located near the Fayette County line in Section 31, T. 9 N., R. 4 E., within the Louden Oil Field. The pond reportedly received 150 to 200 barrels of brine a day. The land elevation ranges between 595 and 630 feet above mean sea level. Drainage is partly eastward, but

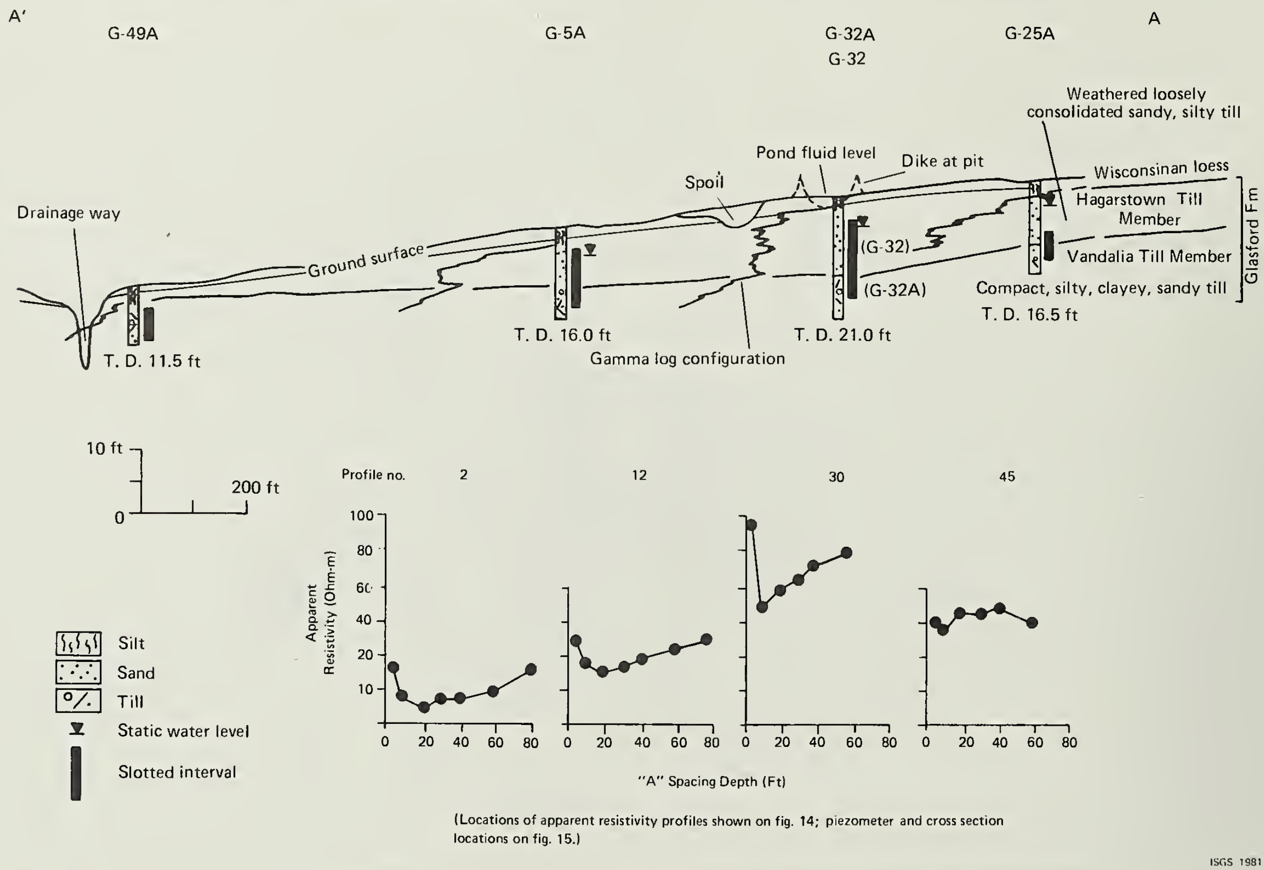


FIGURE 13. Geologic cross section, Louden Pool oil field (Sec. 31, T. 9 N., R. 4 E., Effingham County, Illinois, and Sec. 36, T. 9 N., R. 3 E., Fayette County, Illinois) and apparent resistivity profiles.

principally southward toward a tributary of Wolf Creek. The site is situated on the south flank of a southwest trending series of elongate Hagarstown mounds on the Illinoian till plain. The glacial drift is about 50 feet thick and overlies the Mattoon Formation of Pennsylvanian age. The general stratigraphy of the site is illustrated by the cross section (fig. 13).

The surficial material consists of loessial silt which forms the soil in this area. In places near back-filled abandoned ponds north, northeast, west, and immediately south of the pond, a sun-bleached, light brown sandy spoil cover is present to a depth of 3 to 4 feet. Underlying the spoil and the loessial soil is 5 to 18 feet of sand, silt, and sandy till of the Hagarstown Till Member of the Glasford Formation. The Hagarstown is deeply weathered with a uniform lithology in all parts of the study area except near well no. G-49A, where much of the till has been removed by stream erosion. Beneath the Hagarstown is a compact, silty, sandy till—the Vandalia Till Member of the Glasford Formation. The Vandalia Member contains more clay than the overlying Hagarstown, and consequently has much lower hydraulic conductivity. The Vandalia appears fractured in some of the split-spoon samples studied and therefore may be hydraulically connected to the overlying Hagarstown in places.

Sixty-four vertical electrical sounding profiles (fig. 14) were measured at the Effingham County site. Most profiles were extended to an "a" spacing of 60 feet; about 30 percent of the profiles were extended to an 80-foot "a"

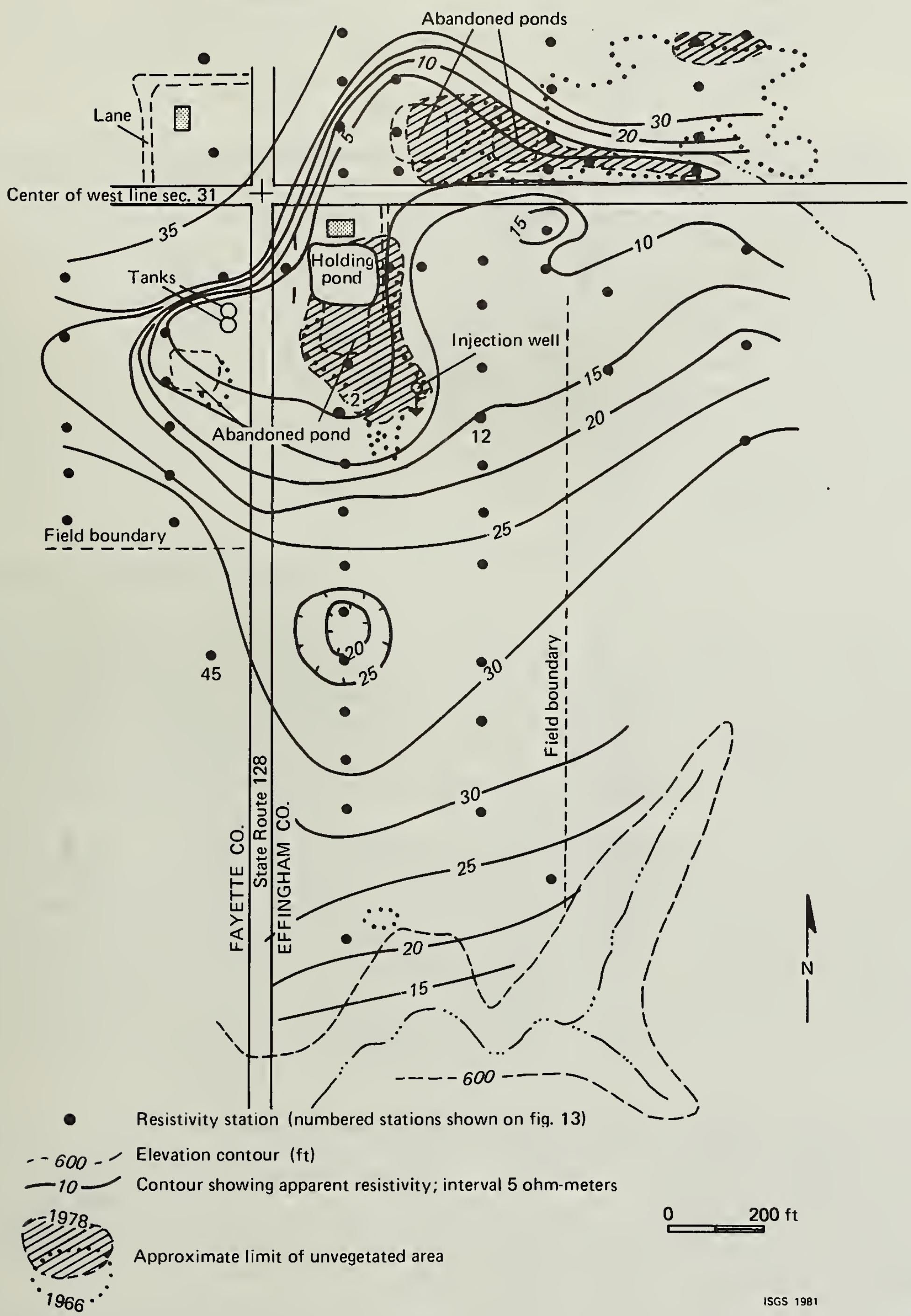


FIGURE 14. Apparent resistivity at 20-foot "a" spacing, Louden Pool oil field.

spacing. Four representative profiles are shown on figure 13. Profile 2 was made in an area with high brine concentration, profile 12 in a moderately affected area, and profiles 30 and 45 in unaffected areas. The determination of background is difficult at this site as very few resistivity stations appear to be in totally unaffected areas. The presence of abandoned and filled holding ponds makes this site somewhat more complex than the other sites.

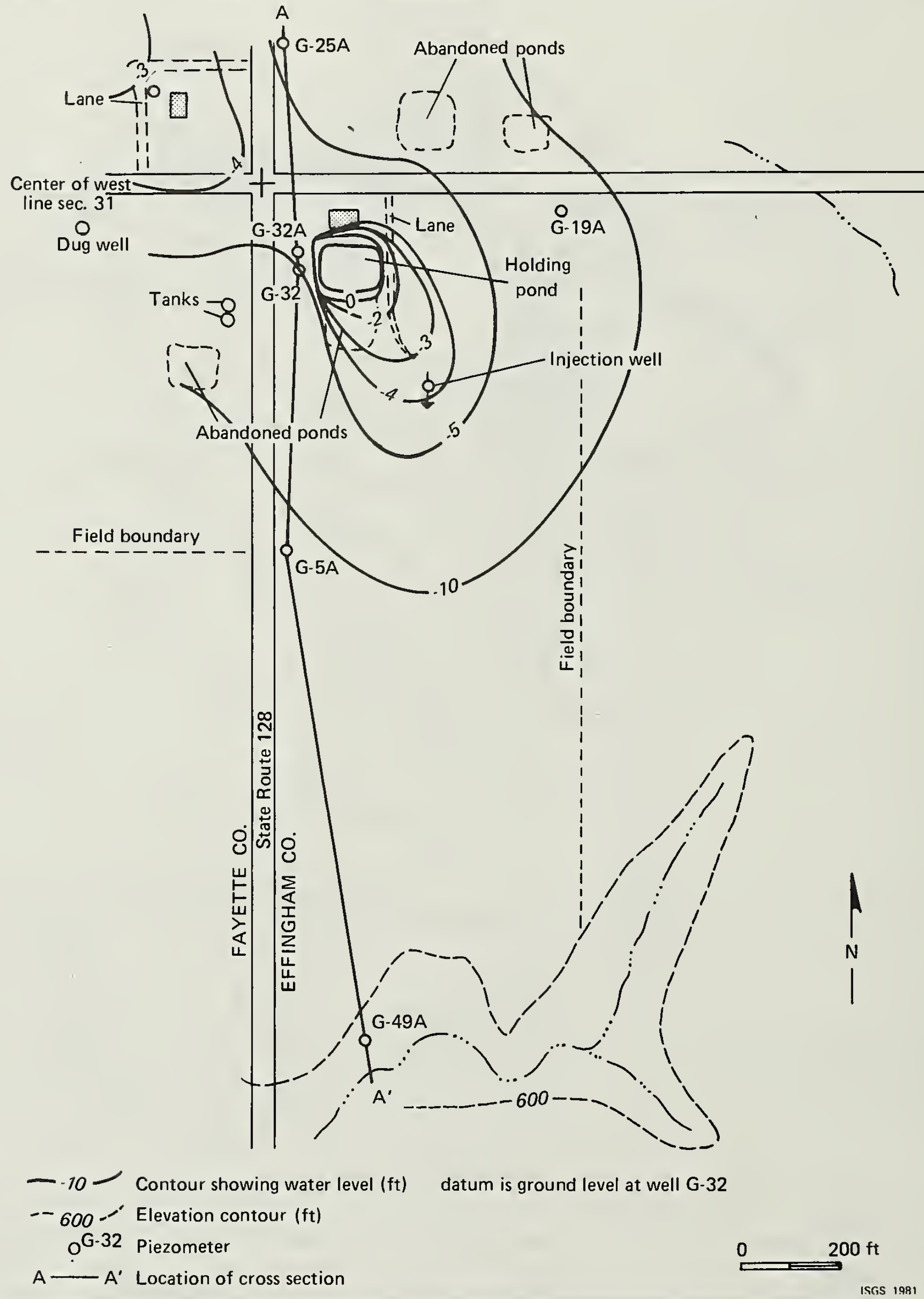


FIGURE 15. Water level contours, Louden Pool oil field.

Background values also appear to vary across the site, becoming slightly lower in the southern part of the study area. The 20-foot "a" spacing appears to best show the extent of mineralized water; the actual limit of mineralized water migration is near the 35 ohm-meter contour in most of the study area.

Water levels from the piezometers and the holding pond (fig. 15) indicate that there is a ground-water mound superimposed on the local ground-water flow system beneath and around the pond. There is a gradient southeastward or southward toward the creek. The limit of the unvegetated area has decreased considerably near the abandoned holding ponds, judging from comparisons with patterns shown on a 1966 aerial photograph, this decrease can be attributed largely to the infilling of the abandoned holding ponds since the unvegetated area around the existing pond is relatively unchanged.

The distribution of apparent resistivity reflects the coalescing and interaction of the chloride migration from the active pond and the inactive holding ponds, which do not affect the present ground-water flow. Thus, the distribution of chlorides shown on the isoresistivity map is not consistent with the present ground-water flow system. The greatest migration of brine is southward toward the creek and west, northeast and east outward from the vicinity of the abandoned holding ponds, as shown on the apparent resistivity map. Salt water appears to be returning to the surface and discharging into the creek at the south end of the study area near piezometer G-49A; this process is indicated by the decrease in apparent resistivity and quality of water in the piezometer, and is probably the result of migration from the pits; however, data are not available to definitely substantiate this assumption.

■ Bond-Clinton County holding pond

The site, located on a lease in the Beaver Creek Oil Field, Section 31, T. 4 N., R. 2 W., Bond County, was initially investigated on August 16, 1977 at the request of the Illinois Department of Mines and Minerals. The purpose of the study was: (1) to determine whether brine discharged in the pit on the lease was leaking into the ground-water reservoir and (2) to determine the distribution of the brine, if present, within the ground-water reservoir.

The brine pit is located in a region of gently sloping terrain of the Illinoian till plain between Greenville and Carlyle, Illinois. There are a number of oil well logs from the immediate area in the Geological Survey files, including two in the immediate vicinity of the pond; unfortunately, the description of the surficial material is very poor and often contradictory. The logs do suggest the presence of a sandy or gravelly zone (presumably the Hagarstown Member) at 10 to 15 feet below land surface. This interpretation is consistent with our regional stratigraphic information.

The site is geologically similar to the other holding pond sites cited in this report. There are two near-surface glacial tills in the region. The upper most till, the Hagarstown Member, consists mainly of sand and gravel and forms prominent hills and ridges in the region. Hills being quarried for sand and gravel just south of the brine pit contain thick Hagarstown sediments. In lowland areas away from the hills, the Hagarstown is found at depths of 10 to 20 feet below the land surface. The clayey, impermeable Vandalia Till Member forms a barrier for brine migration beneath the Hagarstown. Generally, the Hagarstown and overlying gleys and loessial sediments have undergone a complicated soil history, beginning with the formation of the Sangamon soil, continuing through two or more periods of soil genesis during the Wisconsinan and culminating with the modern soil formation. The Hagarstown and some sandy zones associated with the overlying loesses are relatively permeable.

Generalized observations of the hydrogeology can be made from analysis of the topography of the area near the brine pit. Brine entering the ground-water flow system from the holding pond flows north or northwest to a small,

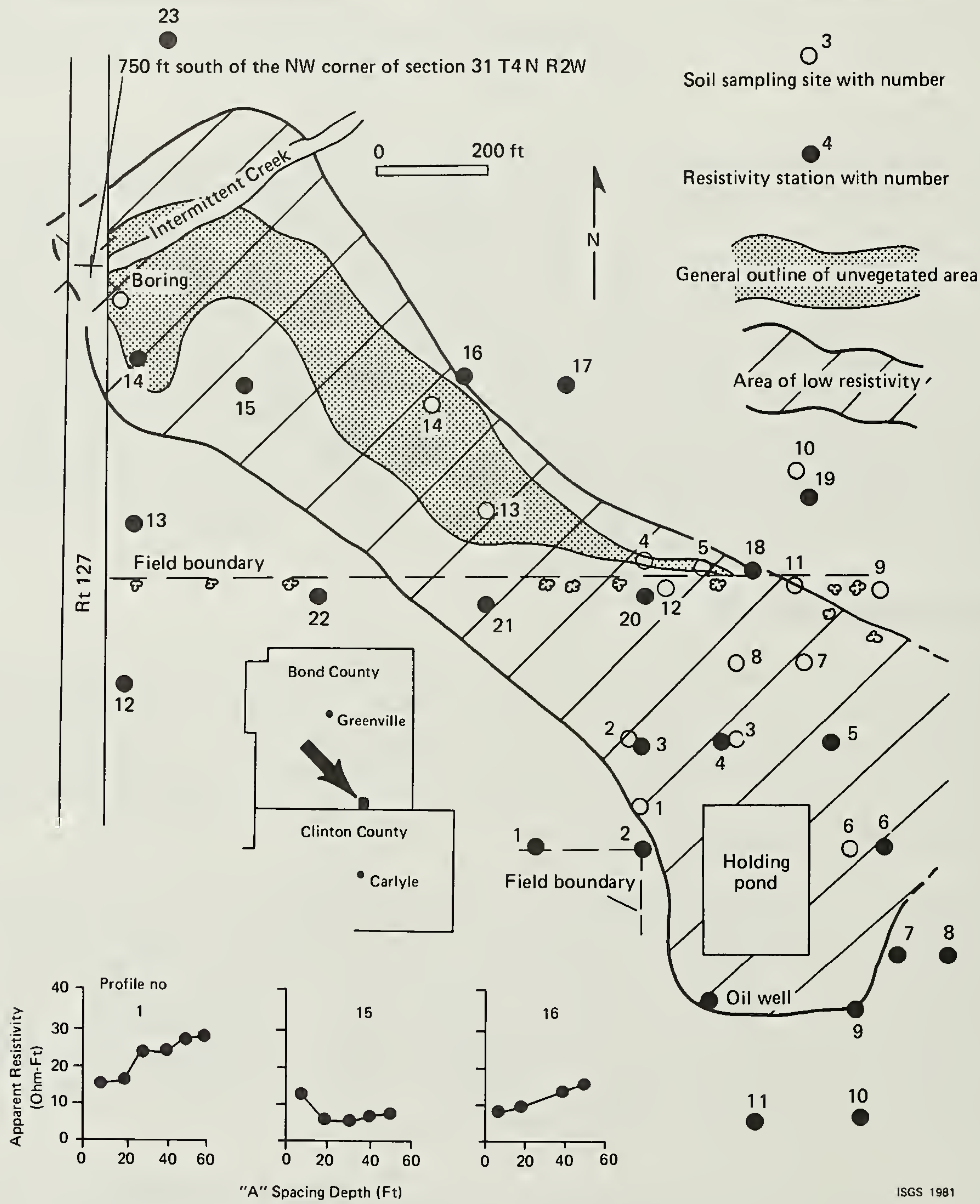


FIGURE 16. Bond County, Illinois study site, Beaver Creek oil field (Sec. 31, T. 4 N., R. 2 W., Bond County, Illinois), and apparent resistivity profiles.

unnamed tributary to Beaver Creek, which flows across the northwest corner of Section 31. Discharge of ground water would occur along the creek and possibly in the small drainage swale which transverses the field boundary, in a northeasterly direction, just north of the pit.

During the survey of the pit area, 23 vertical electrical sounding profiles were measured (fig. 16). Representative vertical electrical soundings are shown on figure 16; no profile could be obtained on station 14 because surface conductance distorted the electrical field preventing measurement of the electrical field. Isoresistivity slice maps were drawn for all "a" spacings from 10 to 50 feet. The slice maps show a region of greatly depressed apparent resistivity values (fig. 16) extending northwestward from the pit to the stream. Resistivity stations with normal profiles are 1, 10, 11, 12, 13, 17, 19 and 23. Stations 3, 4, 5, 6, 14, 15, 20 and 21 are strongly affected by highly conductive material. Stations 2, 7, 8, 9, 16, 18 and 22 are intermediate.

Vertical electrical sounding profiles in areas strongly affected by brine migration are of two types. The first type, best shown at station 15, shows a decline in resistivity values from the initial reading at a plus-10 feet, suggesting that the surface soils do not have significant accumulations of electrolytes. Stations showing this characteristic (3, 4, 5, 6, 9 and 15) are all in soil with good crop vegetative cover (except 15, a grassy part of a fallow field). The second type of depth sounding profile is illustrated at station 14, where no reading could be obtained because of the accumulation of electrolytes at the surface. Several attempts were made to obtain depth soundings in the unvegetated area between stations 14 and 16, but none could be obtained. Station 16 shows a similar low surface resistivity, but the decrease is much less severe.

The electrical earth resistivity data appear to verify the hydrogeologic evaluation based on topographic analysis and the regional geologic interpretations. These data show that an electroyte, almost certainly salt water brine from the pit, is entering the ground-water system and moving northwestward toward the small creek. The brine moves downward from the pit and then laterally in the permeable Hagarstown sediments above relatively impermeable Vandalia Till.

In order to travel from the pit to the creek (a distance of approximately 1500 feet) in 35 years, salty water from the brine pond would have to be moving in a zone more permeable than the Vandalia Till Member. The sandy Hagarstown sediments could provide such a zone of ground-water movement. The electrical earth resistivity survey strongly suggests that a wedge of salt water has extended northwest from the brine pit on the lease to the creek where the vegetation kill has occurred. This interpretation is supported by the electrical earth resistivity data and by a shallow borehole water sample near station 14 with a chloride concentration of 7060 ppm. The interpretation is consistent with the geology of the area and the generalized interpretation of the hydrogeology based on observations of the topographic relationships.

DISCUSSION

The oil field brines are primarily chloride type waters (Meents et al., 1952); thus the specific conductance of the oil-field pond waters should have a direct relationship to both the chloride content and total dissolved minerals (as residue) of the water. Measurements of salinities and specific conductance of pond and ground water made in this study (fig. 17) show that this relationship is a straight line at salinities greater than 500 mg/L. At salinities less than 500 mg/L (i.e., as natural background water quality is approached) this relationship no longer holds; this occurs because the chloride ionic species no longer dominate the electrical properties of the water. Nevertheless, the characteristics of the pore water suggest that when the salinities of the water are somewhat above background levels, there should be predictable changes in electrical earth resistivity related to this change. Furthermore,

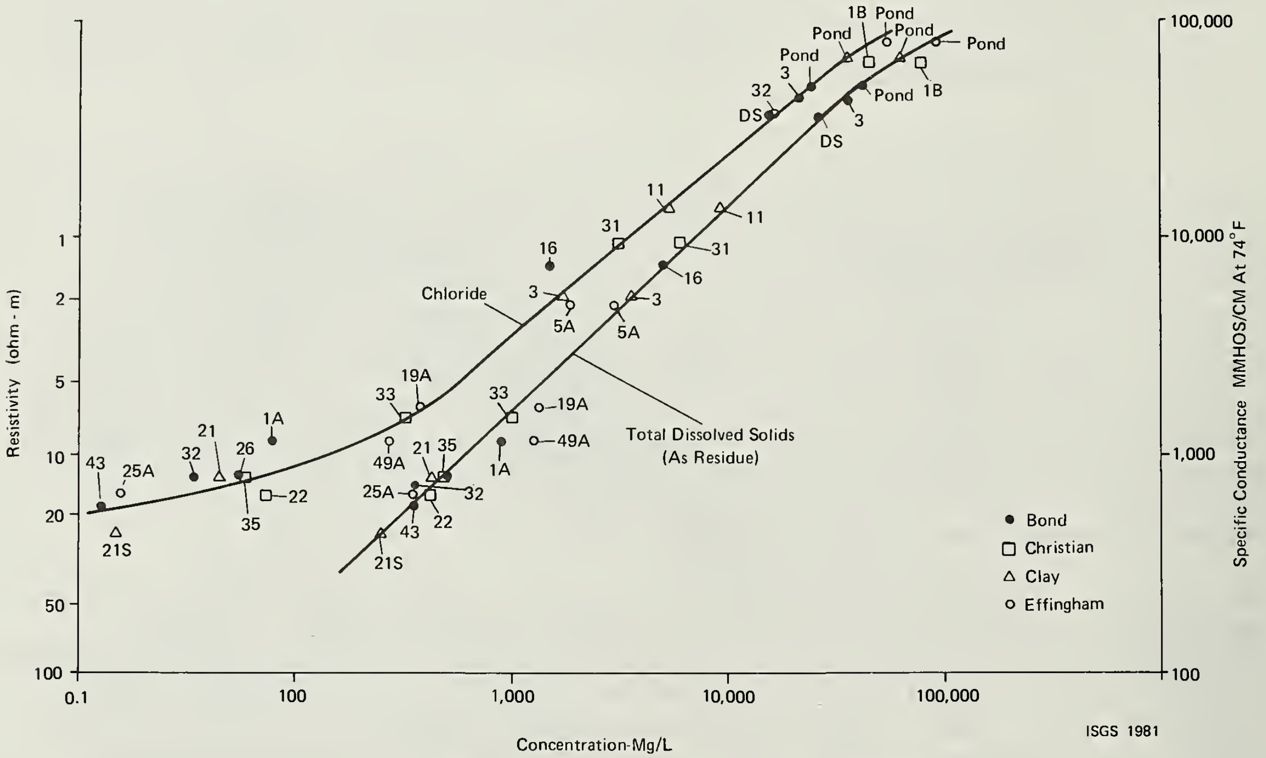


FIGURE 17. Relationship of resistivity and conductance to chloride content and residue on evaporation in water from Hagarstown Aquifer at study sites in Bond, Christian, Clay, and Effingham Counties, Illinois.

the change in salinity should be accompanied by a regular change in resistivity of earth materials. Since apparent resistivity—which takes into account the resistivities of all material within the region of electrical influence—was measured, rather than true resistivity, the earth material resistivity values will be variable.

The resistivity measured in saturated cores at the test sites shows a close relationship to the fluid resistance (salinity) from piezometers except in higher salinity ranges (fig. 18). The saturated core and fluid resistivity relationship form a straight line since the chloride ion represents the major anion in the brines. In the high salinity range the line curves downward, indicating little correlation between core and pore water resistivities; this suggests that the fluid resistivity dominates the core resistance at these high salinities.

The relationship between the salinity of formation waters obtained from the piezometers and the changes of apparent resistivity measured at the land surface is shown in figure 19. The least square fit of the data and the 90 and 95 percent confidence intervals indicate that for a given apparent resistivity value the values of chloride concentration contained with the 95 percent confidence limits span approximately an order of magnitude. At salinities below about 100 mg/L, variation in electrical properties of the earth material will mask the changes in water quality. Estimates of actual water quality can be made; however, precise values cannot be determined since the 95 percent confidence limits span is so large. Nevertheless, good relative values should be obtainable and the contaminant plume accurately defined. Actual salinities could be determined by a limited number of piezometers or wells if needed.

The direction in which ground-water flows from the study areas was generally predictable from analysis of the topographic relationships and considerations of ground-water flow theory. The electrical earth resistivity

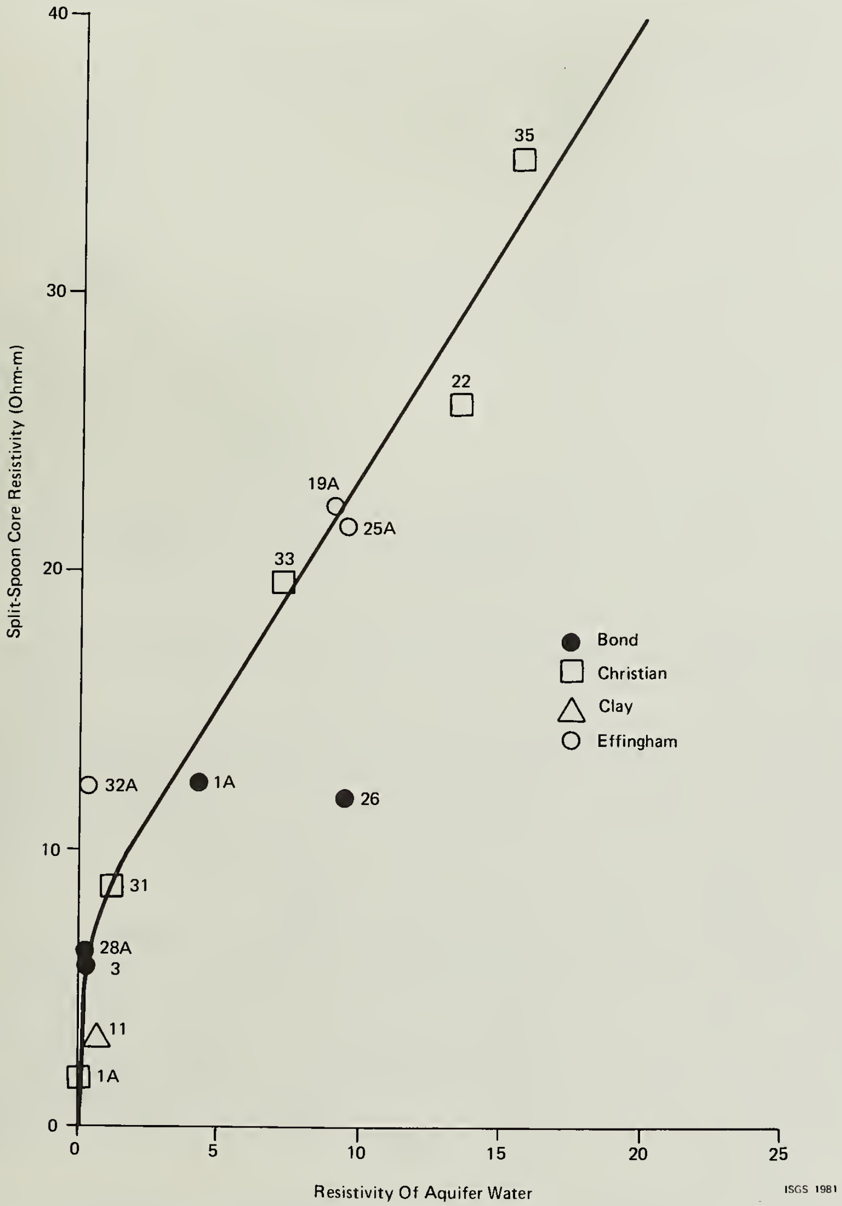


FIGURE 18. Relationship of split-spoon core and water resistivities from Hagarstown Aquifer at study sites in Bond, Christian, Clay, and Effingham Counties.

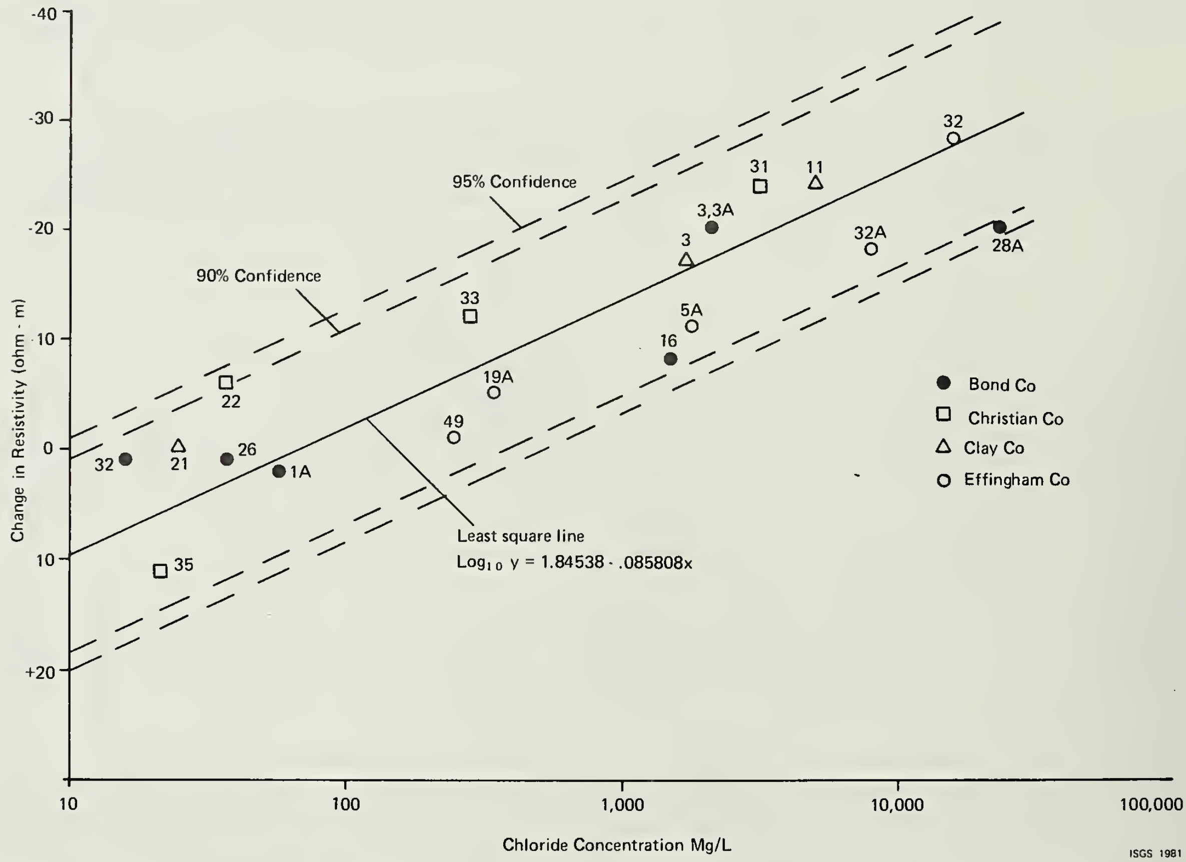


FIGURE 19. Relationship of apparent resistivity and chloride concentration, Hagarstown Aquifer, at study sites in Bond, Christian, Clay, and Effingham Counties.

surveys confirmed the flow direction and provided the details of the extent of the brine migration. Similar studies of the relationship of chloride ion concentrations and the apparent resistivity should be useful in estimated movement, location, and distribution of fresh-saline water interface in unconsolidated earth materials in other natural environments.

Analysis of water from the observation wells along the ground-water flow path shows that there is some attenuation of the brine. A hardness halo (Cartwright et al., 1977) has developed at each site (fig. 20), indicating that attenuation of the brine is occurring. This is significant when considering regional water quality problems related to brine disposal at the land surface. However, because of the high salinities and chemical character of the brines, the effects of this attenuation may be of limited significance at a site.

Bromide is a common constituent of oil field brines and generally occurs at very low concentrations in shallow ground waters. Elevated bromide concentrations distinguish oil field brine from other contaminant sources such as landfill leachates and feed-lot liquors, and may be used as an indication of the

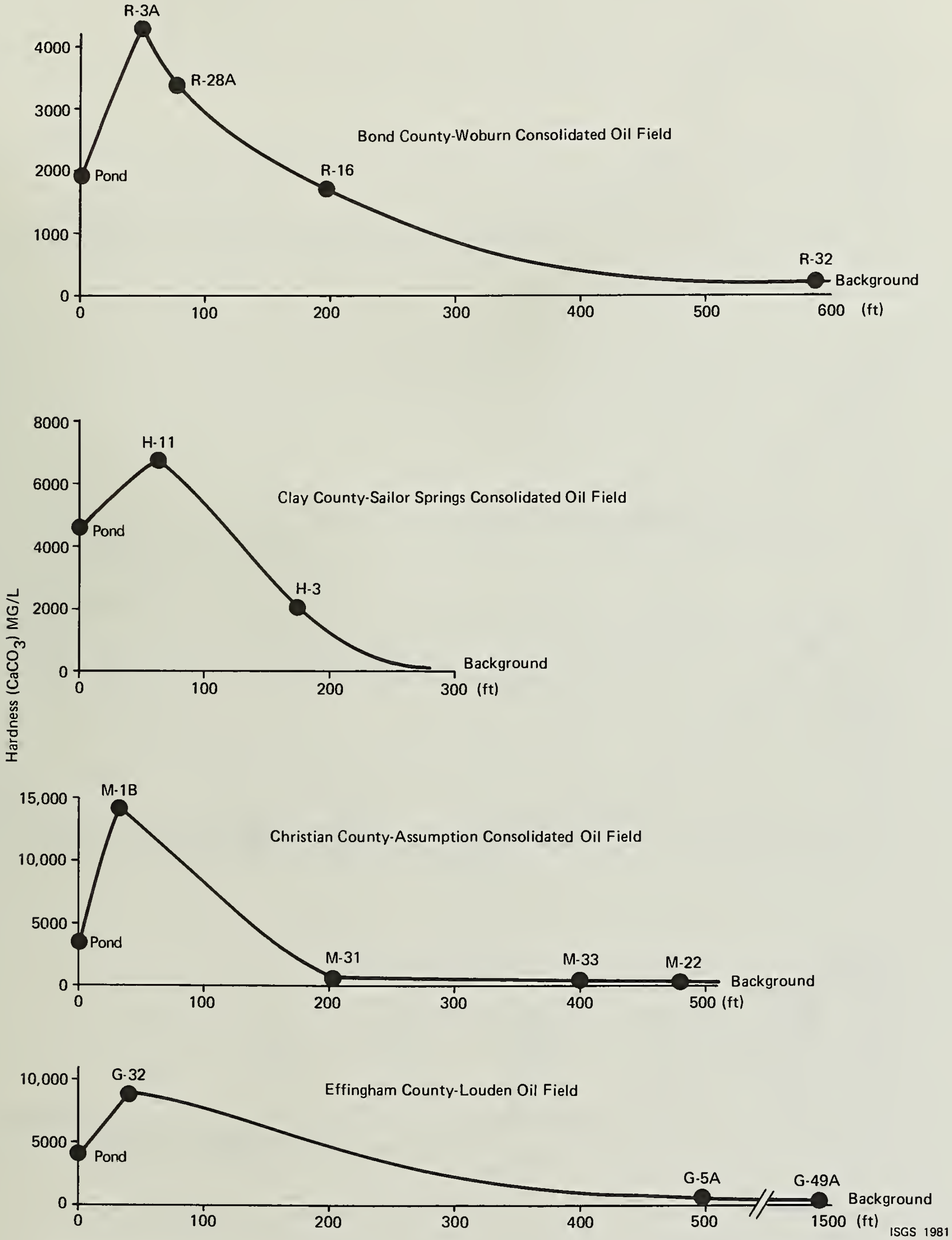


FIGURE 20. Hardness (as $CaCO_3$ ppm) as a function of distance at brine holding pond study sites in Bond, Clay, Christian, and Effingham Counties.

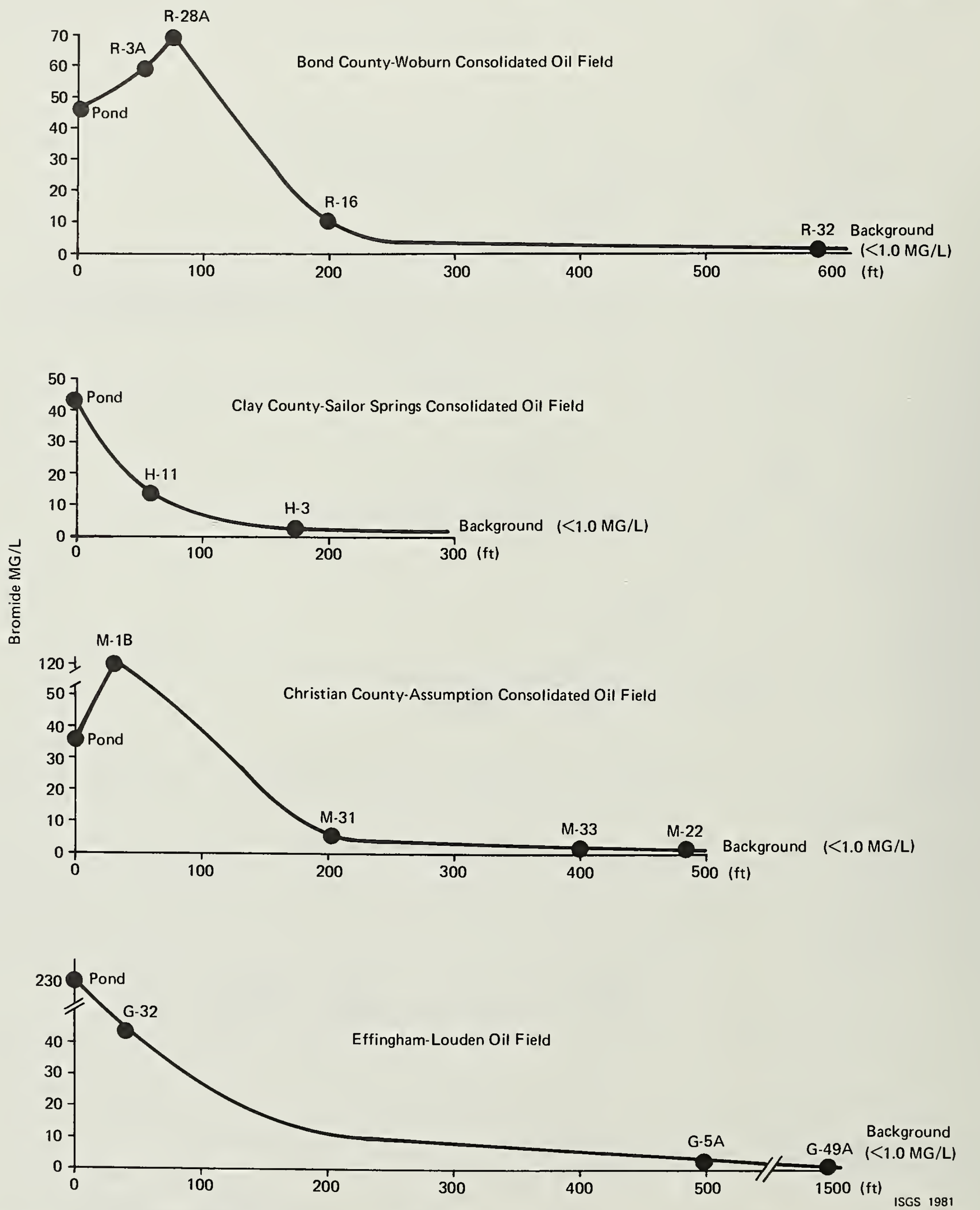
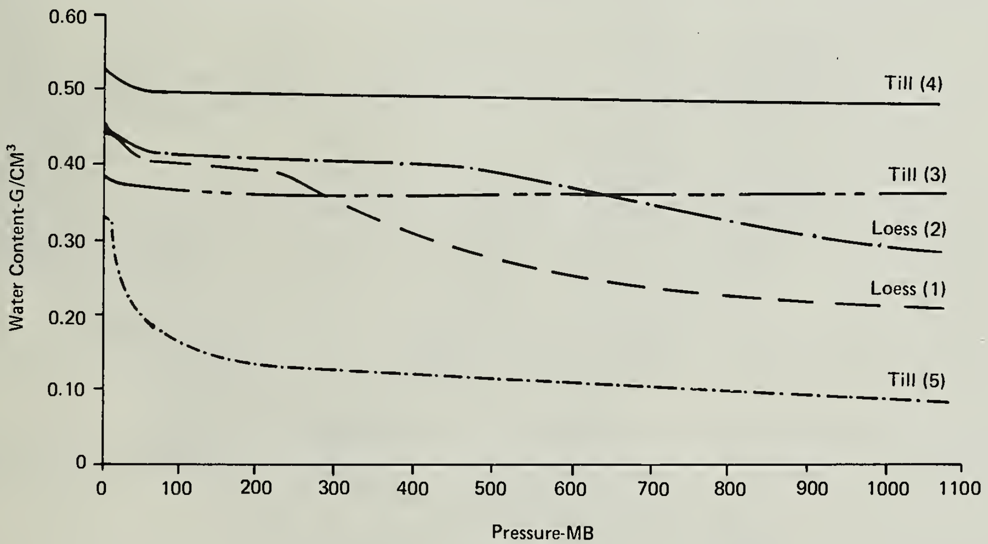


FIGURE 21. Bromide concentration as a function of distance at brine holding pond study sites in Bond, Clay, Christian, and Effingham Counties.

brine in the ground water. Analysis of bromide in the water from along the ground-water flow path shows decreasing concentrations, indicating that dilution is occurring (fig. 21). The Christian County site data appear to reflect the abandonment of the pond and removal of the source of bromide, indicating that natural renovation of the ground-water quality is proceeding.

Hydraulic conductivities and soil moisture characteristics in representative boring samples were measured in the laboratory (fig. 22). These data confirm that the Hagarstown Member is the principal water-transmitting unit and that the Vandalia Till Member has very low hydraulic conductivity. The soil moisture characteristic curves show generally high moisture contents at 15 bars suction for both the loess and till; more difference is noted in the Hagarstown materials. This suggests that (1) saturated flow predominates in these materials in almost all circumstances, and (2) if unsaturated flow were to take place, the veolocity of flow would be significantly less only in the Hagarstown materials. Since the Hagarstown is saturated in all the study sites, there would be no advantage in keeping the base of the ponds above the "water table."



Pressure plate test results

	Geologic material	Bulk density (G/cm³)	Total porosity (%)	Residual saturation (G/cm³)	Effective porosity (%)	Hydraulic conductivity cm/sec
1	Loess	1.55	44	0.28	17	3.0×10^{-6}
2	Loess	1.52	45	0.21	25	1.8×10^{-6}
3	Till (Hagarstown type)	1.75	36	0.08	28	1.8×10^{-4}
4	Till (Vandalia type)	1.58	53	0.48	5	2.0×10^{-7}
5	Till (Smithboro type)	1.76	38	0.36	2	2.5×10^{-8}

ISGS 1981

FIGURE 22. Hydrogeologic characteristics of representative geologic samples, central Illinois.

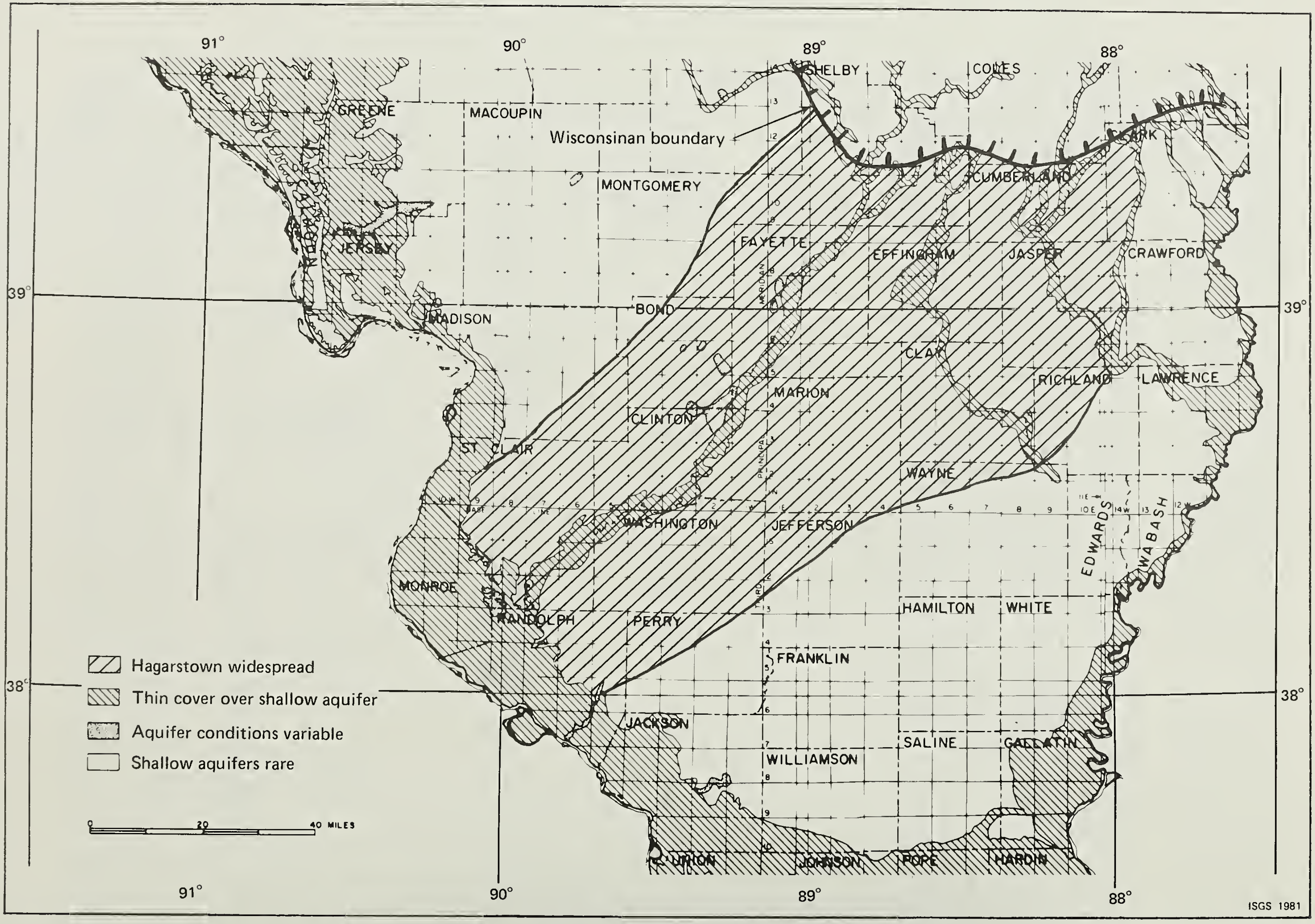


FIGURE 23. Generalized location of Hagarstown Till Member of the Glasford Formation.

We conclude from this study and previous field studies that the brine ponds in the oil fields do not pose a problem to the regional ground-water quality. However, brine ponds may pose severe local problems, producing vegetation kills and elevated salinities in nearby wells and streams. The most severe local problems will occur where shallow aquifers like the Hagarstown (fig. 23) are present, although other sand and gravel aquifers occur in the glacial drift and alluvium.

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