

# THE OHIO JOURNAL OF SCIENCE

Vol. 71

SEPTEMBER, 1971

No. 5

## WATER POLLUTION BY OIL-FIELD BRINES AND RELATED INDUSTRIAL WASTES IN OHIO<sup>1</sup>

WAYNE A. PETTYJOHN

*Department of Geology, The Ohio State University, Columbus, Ohio 43210*

### ABSTRACT

Contamination of surface- and ground-water resources, owing to the disposal of oil-field brines and other industrial high-chloride waste waters, has long been a major problem in many areas in Ohio. A major cause of pollution is the use of brine "evaporation" pits. Although the chloride content in many contaminated areas has decreased with time by several orders of magnitude due to natural cleansing, concentrations in other areas have increased. The time at which a contaminated area will return to its original condition can not be accurately determined, because natural flushing depends on several hydro-geologic factors as well as the amount and rate of infiltration of rain.

### INTRODUCTION

Since drilling of the first oil well at Titusville, Pennsylvania, in 1859, pollution problems related to the disposal of oil-field brines have confronted both the petroleum industry and the general public as well. Practically every oil-producing state has enacted laws that regulate the drilling and plugging of wells and the disposal of brines. Many of these laws are the direct result of ground-water or surface-water contamination.

It is with deep regret that the *Journal* reports the death, on July 30, 1971, of Miss Margaret Foust, Secretary of The Spahr and Glenn Company, printers of the *Journal*, and the main person there with whom the *Journal* staff dealt. Her consistent competence, dependability, and concern throughout the years have been a real help to me, and to those that came before me.

The Spahr and Glenn Company has printed the *Journal* ever since 1901 (beginning with volume 1, number 2), cooperating with and outlasting a whole sequence of 12 editors; I am pleased to take advantage of this opportunity to acknowledge our great debt to The Spahr and Glenn printers. And I and the rest of the *Journal* staff join this company in mourning the passing of Margaret Foust; she will be sorely missed by all of us.

JANE L. FORSYTH

<sup>1</sup>Manuscript received January 27, 1971.

The serious and widespread effects of brine pollution are rarely recognized by most individuals, including those in state legislatures who formulate and pass into law the regulatory procedures. Unfortunately ground-water resources may be seriously and perhaps irreparably contaminated long before landowners are even aware that a problem exists. The water-bearing strata contaminated by brines may remain unusable, depending on the degree of contamination and on hydrologic conditions, for years, decades, or even millennia. In Texas, Alabama, Ohio, and probably many other oil-producing states, especially before enactment of protective controls, utilization of salt-water disposal pits caused the ground water to become so severely contaminated locally that in many instances the chloride concentration in the ground water was greater than that of the brines discharged into the disposal pits.

#### CONTAMINATED AREAS

An oil discovery well completed in Morrow County, Ohio, in 1961, excited a flurry of wildcatting and speculation throughout several areas in the central part of the State (fig. 1). About one of each three tests drilled for the next four years was a producer. The wells, which tapped porous reservoirs in the Copper Ridge Dolomite of Cambrian age, generally ranged in depth from 3000 to 3500 feet. Produced with the crude oil were large volumes of brine. Chloride concentrations of some of the brines ranged from 35,000 to 150,000 mg/l (milligrams per liter).

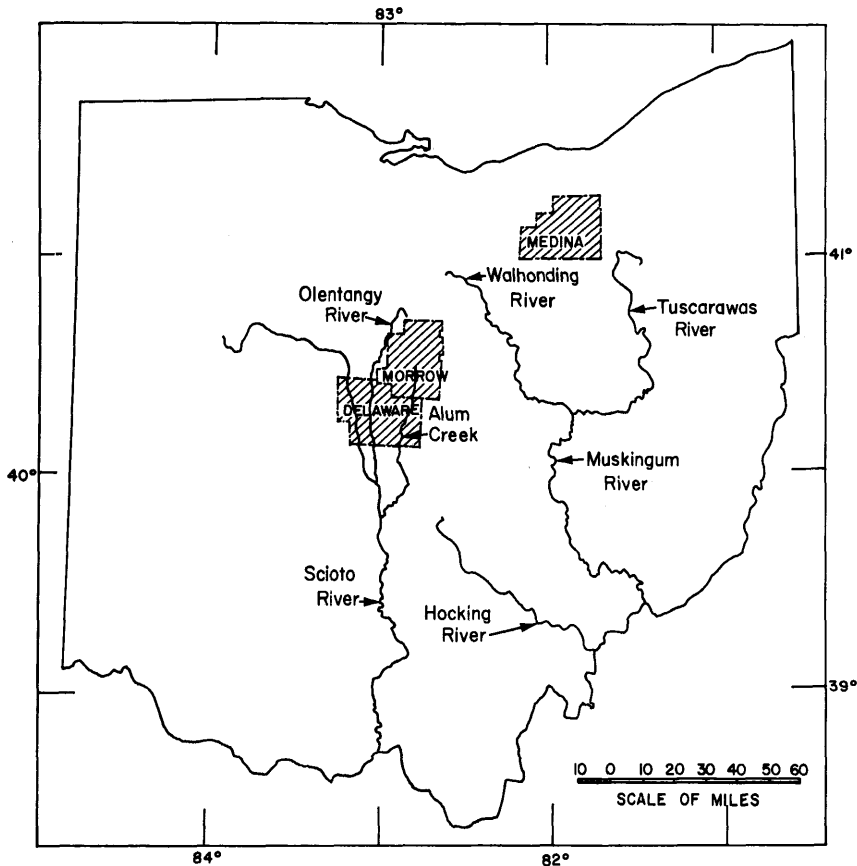


FIGURE 1. Location of brine contaminated areas in Ohio.

Unregulated disposal of these brines grossly contaminated several local shallow ground-water reservoirs. Before the enactment of specific legislation prohibiting such practices, much of the brine was removed from the well site by contract hauling. Contract tank truckers spread the waste on roads or indiscriminately dumped it into ditches, streams, swamps, quarries, or onto open or wooded fields. At other sites the brine waste was put into "evaporation" pits. A third and by far the most acceptable method was by means of a deep disposal well that returned the waste to the producing zone.

The most common disposal technique was by means of "evaporation pits"—a bulldozed hole in the ground in the vicinity of the well or separator. The pits, ranging from about 20 to 35 feet square, are three to 10 feet deep. Liquid wastes were, and in many places still are, dumped or pumped into the "evaporation" or, hydrologically speaking, "infiltration" pits. There the brine supposedly evaporates, but actually much infiltrates. These pits, of which perhaps hundreds still exist in Ohio, are now called "holding ponds"—but the change in nomenclature does not modify the way the procedure works nor the effects of this procedure on the ground water, that is, infiltration of brine from the pit into the ground. The pit-disposal technique has been one of the major causes of ground-water con-

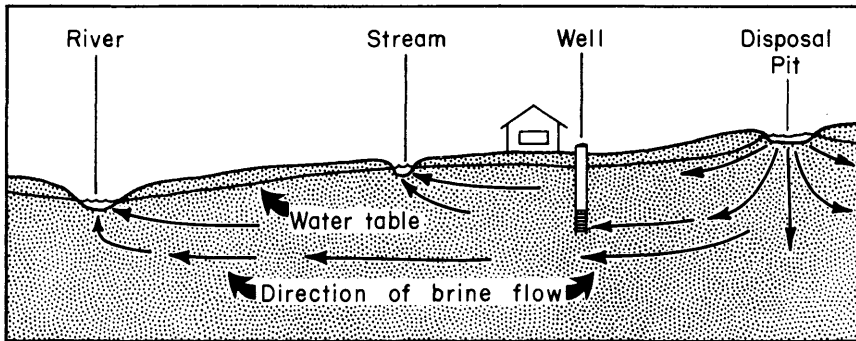


FIGURE 2. Schematic diagram illustrating contamination of surface water and ground water by pit disposal of oil-field brine.

tamination in central Ohio. Moreover, abnormally high concentrations of chloride in many streams and rivers in the State, which are especially noticeable during periods of low flow, result from the natural discharge of highly contaminated ground water into the streams. A few "holding ponds" are conveniently drained by buried pipelines extending from the pond to a nearby stream. On the other hand, many of the ponds in areas of more permeable substrata are lined and permit only a minimal amount of leakage. Practices and the degree of compliance with the recently enacted regulations and rules (Ohio Revised Code) vary over a wide range. A few examples of local contamination, taken from a lengthy personal surveillance of the Morrow County area, will illustrate.

In the spring of 1967, a landowner in Peru Township, southeastern Morrow County, noticed that water from his well, which is 47 feet deep, had a strong salty taste (fig. 2). When it was used to water the garden, much of the produce died; the water began to corrode the plumbing, and even the family dog found it unpalatable. A water sample collected from the well in May 1967 contained 2800 mg/l of chloride, or more than 10 times the U.S. Public Health Service recommended limit of 250 mg/l for drinking water (1962). In September a second analysis showed a chloride content of 3300 mg/l, an increase of about 12 percent in only four months. The oil company that owned several producing wells surrounding the property apparently became alarmed, and pumped the water well for about three days "to clear it up". In May 1968 a sample from the well con-

tained 5650 mg/l of chloride and in September another sample contained 7600 mg/l. In November 1969 the chloride concentration was 7700 mg/l.

Several "evaporation" pits formerly existed in the vicinity of the contaminated well, one only about 600 feet away, in 1964 and part of 1965. Reportedly, these pits were all abandoned and filled by late 1965. Thus, it required one and a half to two years after the pits were abandoned for the brine to infiltrate through the ground and reach the well.

The well was not all that was affected by the brine from these pits. A small intermittent stream, a foot or two wide, which crosses the property, contained 40 to 61 mg/l of chloride in November 1969, and a major water course, nearly a mile away, contained more than 80 mg/l. In this part of Ohio, normal surface-water concentrations of chloride average less than 15 mg/l. These water courses were reflecting the chemical quality of the shallow underground water (fig. 2).

In early 1964, oil-drilling activities included an area in and around the village of Cardington in Morrow County. Several producing wells were drilled in the vicinity of the four shallow (30 feet) municipal water wells. Brines were discharged into pits or into an excavated ditch within 50 feet of these wells. Later in the year, village officials began to show some concern about the possibility of well-field contamination, and by January 1965 two of the village wells, which had formerly contained less than 10 mg/l of chloride, were contaminated with as much as 3750 mg/l. Eventually the entire well field had to be abandoned.

Elsewhere throughout at least 60 square miles in Morrow County, the effects of brine disposal began to appear, especially during 1964 and 1965. Several dozen areas, generally less than one square mile each, began to produce water containing, in some cases, several thousand milligrams per liter of chloride. Each area contained one or more producing oil wells and brine-disposal pits. Many domestic and stock wells had to be abandoned, and water was either hauled in or pumped from new and deeper wells at considerable cost. In many areas since 1967, however, the chloride concentration has decreased substantially; in other areas concentrations remain about the same or are higher.

Surface-water resources in Morrow County were also affected, generally to a lesser degree, due to three major causes: (1) dumping of brine directly into water courses, (2) intentional draining of evaporation pits into streams, and (3) natural discharge of polluted ground water into stream channels. In view of the stream pollution, the Ohio Department of Health began a surface-water surveillance program during the period April 1964–April 1966. Determination of chloride in samples collected weekly in Shaw and Whetstone Creeks showed chloride concentrations ranging from four to as much as 1350 mg/l. Concentrations were highest during August–December 1964, decreased until May 1965 (a very dry year), and then began to increase again. Even in mid-April 1966, when the surveillance program was terminated, concentrations at two of the three sites exceeded 110 mg/l, which is less than Public Health Service limits but still more than seven times the normal background concentration. Surface-water samples taken at time of low flow in Whetstone, Alum, and Blacklick Creeks as late as 1967 still contained above-normal concentrations of chloride. Elsewhere in the basin, samples collected directly upstream from local ground-water contamination areas contained the least chloride; concentrations increased to a maximum in the contaminated areas and then slowly decreased downstream, due to dilution. Situations such as these existed as late as 1970. Unquestionably, however, the overall chloride content in both surface water and ground water in most of the areas contaminated during the early 1960's has decreased by several orders of magnitude.

In southeasterly parts of Ohio, such as the Hocking River basin, oil-field brines are heavily mineralized and may contain more than 320,000 mg/l of total dissolved solids. At places in this area, brines reportedly are stored in holding

ponds to await some natural disaster. Commonly, heavy spring rains cause the pits to overflow, eroding the dirt retaining walls, which in turn allows the pit to empty on the ground or into a nearby water course. This effectively takes care of the waste through "an act of God", but it places a severe load on the streams' capacity to dilute contaminants. During midsummer 1962, the Ohio Water Pollution Control Board cited four Hocking County oil producers for brine contamination. In one case, an overflow stream from an "evaporation" pit killed all the vegetation for more than 350 feet from the pit. In another case, water samples collected from a stream above and below a pit contained 26,101 and 30,102 mg/l of chloride respectively, whereas, near another well, surface water samples contained 3,104 to 7,891 mg/l of chloride; a third pit polluted a stream with as much as 16,892 mg/l of chloride.

#### DELAWARE AREA

The overall effects of surface- and ground-water contamination due to disposal of oil-field brines is readily evident from the preceding examples, but a more detailed examination of cause and effect indicates that the problem of contamination and natural cleaning is highly complex. A contaminated area in Delaware County, Ohio, has been described in considerable detail by Shaw (1966), Boster (1967), and Hulman (1969). Their work, techniques, and conclusions are summarized here in order to show not only the complexities of the problem, but also the considerable differences of opinions. Shaw, in his work, described the fluctuations in specific conductance, chloride concentration, and water level in a small area (about 20 acres) adjacent to the Olentangy River, near Delaware. Data were collected from 15 observation wells ranging in depth from five to 22 feet from July 1965 to December 1966. Boster had eight new observation wells constructed in the contaminated area, in which he measured the fluctuations in water level, chloride concentration, and specific conductivity, and attempted to determine the limits and degrees of contamination by means of electrical resistivity techniques. Hulman reinvestigated the Delaware area during the period January–October 1969 and found the chloride concentration greatly reduced, but still excessive at many times and in many wells.

The contaminated area lies northeast of Delaware on the flood plain of the Olentangy River. Here the floodplain, which is half a mile wide, is underlain by about 15 to 35 feet of alluvial and glacial gravels interbedded with sand, silt, and clay. The underlying bedrock, the Delaware Limestone of Devonian age, does not crop out in the area, but is exposed below the water surface in the present channel of the Olentangy River. However, shale has been reported by drillers; this shale, which is probably the Olentangy Shale of Devonian age, overlies the limestone and also crops out nearby. The land surface slopes gently toward the river, with an abrupt topographic break at the eastern margin of the floodplain. The southern part of the floodplain is slightly dissected by a small intermittent stream, Saunders Creek (fig. 3).

Precipitation in the Delaware area averages 38 inches per year. Flow in the Olentangy River is somewhat flashy, owing to controlled releases from nearby Delaware Reservoir and to peak periods of surface runoff. Much of the discharge of the river during later summer, fall, and winter is the result of effluent ground-water seepage.

During the period of major oil production in 1964–65, three oil wells were drilled in this area and four brine evaporation pits were created. Three of the pits were dug into the floodplain deposits and the fourth was excavated into the clayey till of the higher till plain to the east. The Skiles pit, which still exists, is adjacent to the Skiles No. 1 Hough oil well (fig. 3). About 300 feet to the south, across a section-line road and adjacent to the now-abandoned and plugged Slatzer No. 1 Ross well, were two of the pits, both of which are now filled (fig. 3). About 1100

feet to the east is the fourth pit, the Slatzer No. 2, which lies near the abandoned Slatzer No. 2 Ross oil well, and which is the only pit dug in till. This pit, like the Skiles pit, still exists. Shaw (1966, p. 71) reported that the Skiles pit was used during the period July 1, 1964, to July 30, 1965. The adjacent well produced about 126,000 barrels of brine during that interval and all of it was discharged into the pit. The brine averaged about 34,500 mg/l of chloride. The Slatzer No. 1 pit was used for at least 15 months and at least 110,000 barrels of brine containing 35,000 mg/l of chloride were pumped to it. Shaw calculated that the total amount of brine discharged in this area was equivalent to 1313 tons of chloride, or nearly 65 tons per acre throughout this salt-contaminated area.

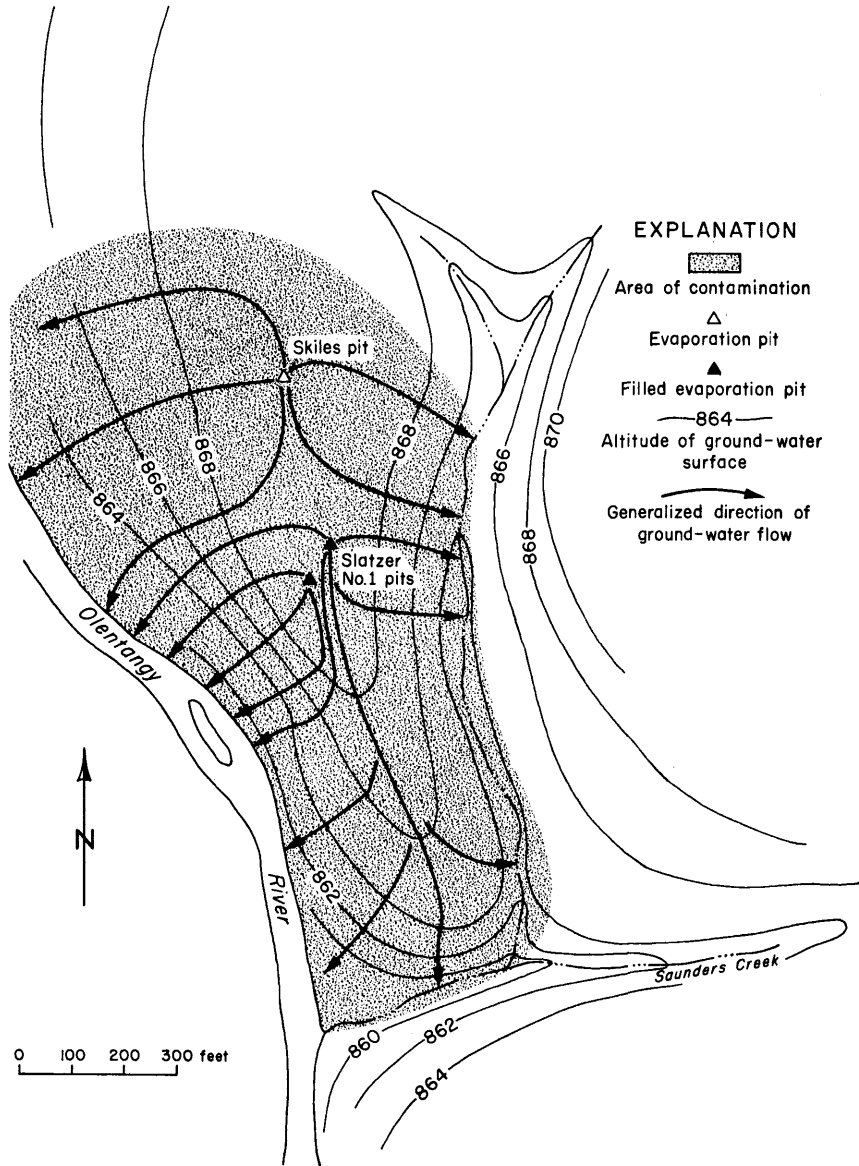


FIGURE 3. Water-level surface in the Delaware contaminated area in January 1966.

Twenty-three shallow observation wells were drilled by Shaw and Boster in the area, with well screens at different altitudes. Unfortunately, geologic logs of the test holes are not available. Some of the screens were gravel-packed and some were not.

The lack both of geologic logs of the test holes and of information on well completion presents certain difficulties when attempting to interpret water-level, chloride, and conductivity data. The slow migration of a concentrated mass of brine down the water-table gradient is probably much more complex than is described here, and involves some interchange of water between the bedrock and the unconsolidated deposits. However, the hydrologic properties of the floodplain deposits, where the observation wells are located, are sufficiently distinct from those of the underlying bedrock and of the adjacent till to be treated here as a separate hydrologic unit.

The configuration of the water table as it existed in 1965 (Shaw, 1966), 1966 (Boster, 1967), or 1969 (Hulman, 1969), provides much interesting information. The maps prepared by these three investigators are similar; a modified version of one of Boster's (1967) maps is shown as Figure 3. The small southward-trending intermittent stream acts as a ground-water drain, as do Saunders Creek and the Olentangy River also. Ground-water flowlines, originating at the three evaporation pits on the floodplain, indicate that most of the contaminated water was discharged directly down the relatively steep ground-water gradient into the Olentangy River at the west boundary of the area, while a smaller, although still considerable, amount was discharged into the intermittent stream channels forming the eastern and southern limits. The discharge of briny ground water into these surface courses was expected because of the closeness (about 300 feet) of the pits to the streams. Evidence of such discharge is still visible, as for example, the abundance of dead trees and other vegetation between the pits and the stream channels. In addition, even during 1969 and 1970, surface-water measurements showed an increase in stream discharge and chloride concentration in the Olentangy River near the contaminated area.

There has been considerable decrease in chloride concentration in the ground water since July 1965, when the pits were abandoned, as the contaminated ground water continued to move to zones of discharge, showing that the aquifer is slowly purging itself of the contaminants. During 1965 and 1966, chloride concentrations in many wells near the disposal pits, although variable, were in excess of 15,000 mg/l. In 1969, chloride concentrations in these wells, with one exception, were less than 2,000 mg/l and generally were less than 1,000 mg/l.

Shaw (1966) believed that the steep ground-water gradient, coupled with the highly permeable nature of the floodplain deposits, would permit rapid ground-water exchange throughout the area. His estimate of the average velocity of ground-water flow here was about 1.5 feet per day. A study of the deposits, however, reveals that they are considerably less permeable than Shaw assumed. Although highly permeable gravel occurs near Saunders Creek, the deposits in many parts of the area include several feet of silt and clay, together with fine- to medium-grained sand. In addition, the deposits are highly lenticular along this reach of the Olentangy River. The second method used by Shaw to determine the ground-water velocity was based on the average chloride content, the area between adjacent isochlors (a contour line connecting points of equal concentration), and an estimate of aquifer porosity and saturated thickness. On the basis of these estimates and of other data, he calculated that the 20-acre area would be free of contamination within 16 months, or sometime between August and October, 1967—a prediction that is now known to be considerably in error. Probably one of Shaw's most significant errors was the assumption that the freshwater front would move uniformly through the sediments.

Boster (1967) pointed out that, on the basis of monthly measurements, the

isochlors showed no appreciable change in configuration, but only in intensity. He recognized a gradual decline in chloride content throughout the area during his period of study, but believed that the decline was not linear with time. In fact, using some of Shaw's data, Boster calculated a chloride-free date of October, 1969. However, he also recognized the highly significant phenomenon of ion exchange, whereby sodium chloride is retained in soil owing to attachment of cations and anions to clay and silt. His final conclusion was that the floodplain deposits could return to their natural state by December, 1972.

Hulman (1969) began his study of the Delaware contaminated area during January, 1969. Whereas Shaw and Boster were more concerned with time of dissipation of the contaminant, Hulman was more interested in the reasons for the continuous fluctuations in chloride values throughout the area. He reported that changes in chloride could be correlated with precipitation, that is, infiltration following periods of rainfall resulted in increased dissolved mineral concentrations in the ground water. He believed that salt crystals existed in the zone of aeration, having been formed during the infiltration of highly concentrated brines in 1964 and 1965, which went into solution when water from infiltrated rainfall was available. He predicted that the area would remain contaminated until all of these salt crystals had been removed from the soil, and that complete removal might require decades.

A study of chloride fluctuations in specific wells compared with isochlor and precipitation data indicate the validity of Hulman's hypothesis. The positions of the 1,000-mg/l isochlor as it existed during selected months in 1965 and 1966 (traced directly from Shaw's maps) are shown in Figures 4, 5, and 6. It is interesting to note that the area enclosed by the 1,000-mg/l isochlor changes monthly and that the changes, even those from one month to the next, do not necessarily enclose smaller and smaller areas. This suggests that a linear relationship between chloride decrease and time does not exist. For example, the September 1965 1000-mg/l isochlor encloses a larger area than does the January 1966 isochlor (fig. 4), indicating a natural flushing effect on the reservoir during the four-month period, but when the position of the January 1966 1000-mg/l isochlor is compared with that of February 1966 (fig. 5), as well as with those of March and April (fig. 6), it is apparent that the contaminated area has increased in size. Significantly, both February and April were wetter than the previous months.

An examination of three similar maps presenting data for three specific months during 1969 shows similar phenomena (figs. 7, 8, and 9). The larger area enclosed by the March 500-mg/l isochlor was probably the result of 0.15 inches of rain that fell the day before the water samples were collected (fig. 7). A similar explanation (based on an antecedent rainfall) may account for the larger area enclosed by the September 500-mg/l isochlor (figs. 8 and 9). Monthly decreases in the area enclosed by the 500-mg/l isochlor are also readily explainable as resulting from less rainfall, as well as from natural cleansing of the floodplain deposits. It can be seen, then, that in this area, both the size of the contaminated area and the chloride concentrations are functions of precipitation.

Of all of the observation wells, a set of three, located about midway between the Skiles and Slatzer No. 1 pits, yielded the most useful data. None of these three wells, which are about two feet apart, were constructed alike (fig. 10). Well D-17s is shallow; the base of the gravel-packed screen is nine feet below the land surface. Observation well D-16s has a gravel-packed screen that bottoms 23 feet below the land surface, and the annular space above the gravel-packed screen was filled with clay to prevent vertical leakage along the pipe. Well D-3 is 23 feet deep, and the entire annular space from the screen to within two feet of the surface is gravel-packed. Well D-3 admits water from the entire saturated thickness; well D-17s admits water only from the upper part of the saturated zone; and well D-16s admits water only from the bottom part of the floodplain deposits. Graphs showing the variations through time of the chloride concen-



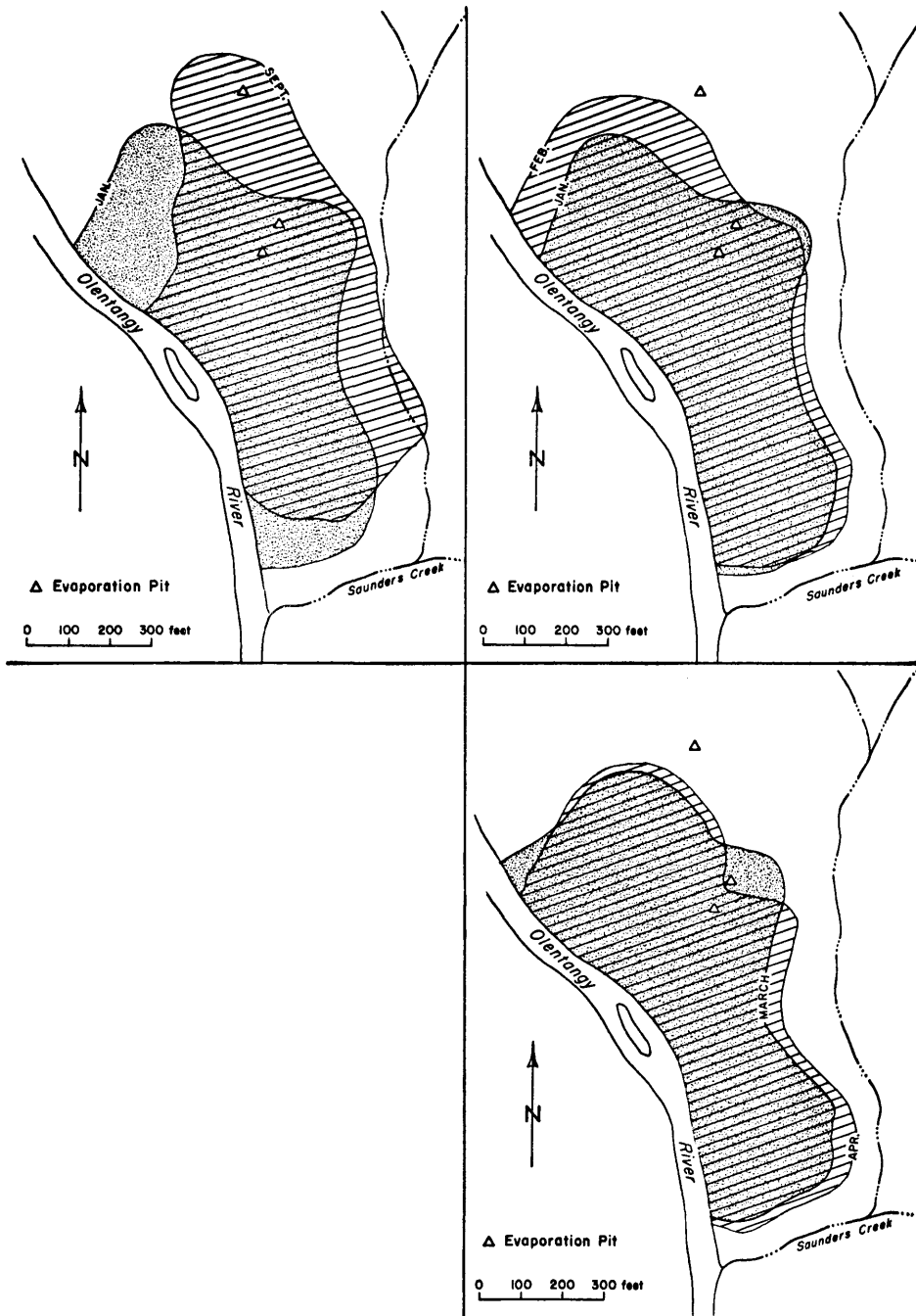


FIGURE 4. Areal extent of the contaminated area at Delaware enclosed by the 1000-mg/l isochlor during September 1965 and January 1966.

FIGURE 5. Areal extent of the contaminated area at Delaware enclosed by the 1000-mg/l isochlor during January and February 1966.

FIGURE 6. Areal extent of the contaminated area at Delaware enclosed by the 1000-mg/l isochlor during March and April 1966.

trations in these three wells is enlightening (fig. 11). In January, 1969, well D-16s, the deepest well, contained only 157 mg/l; well D-17s, which is shallow, contained 547 mg/l; and well D-3, which is open to the full thickness of the aquifer, con-

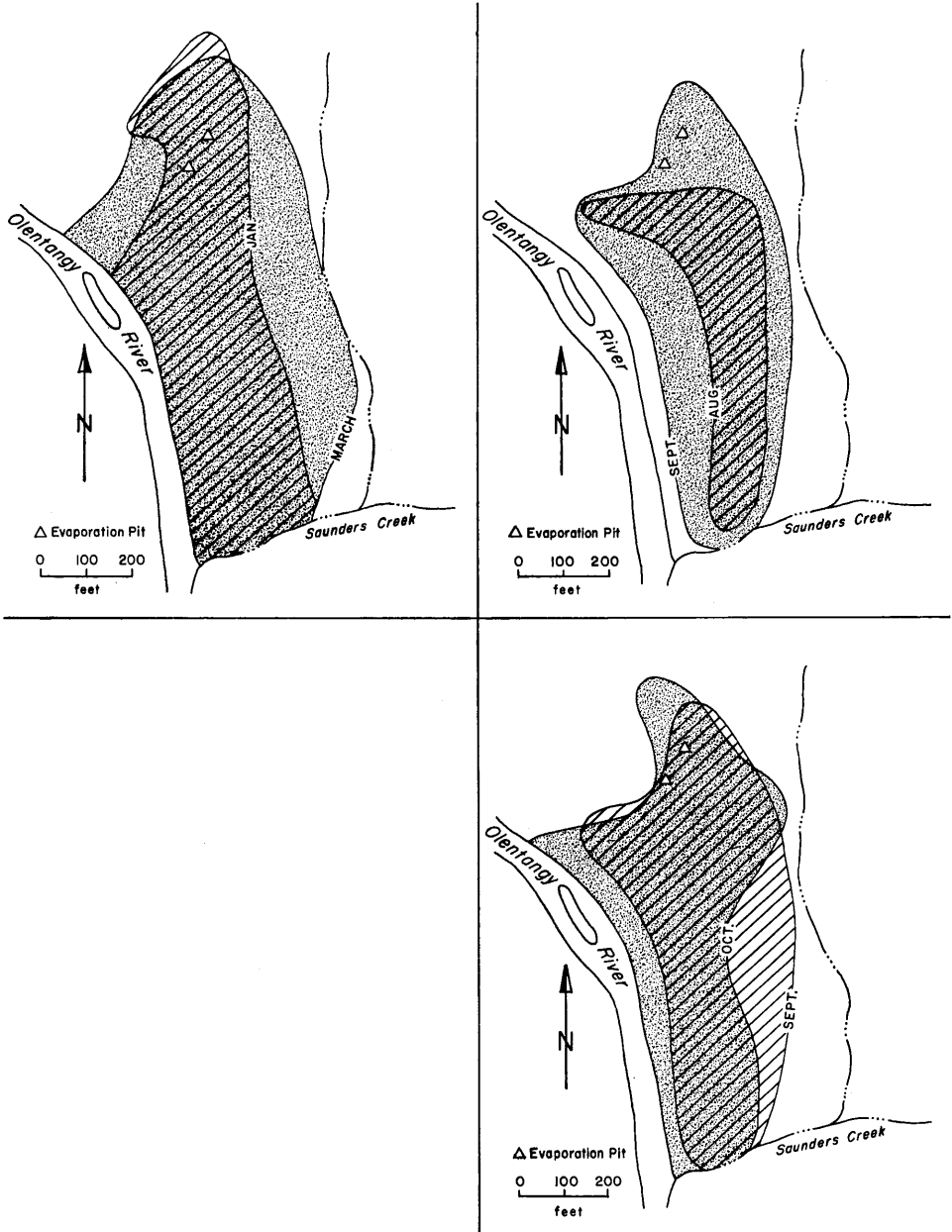


FIGURE 7. Areal extent of the contaminated area at Delaware enclosed by the 500-mg/l isochlor during January and March 1969.

FIGURE 8. Areal extent of the contaminated area at Delaware enclosed by the 500-mg/l isochlor during August and September 1969.

FIGURE 9. Areal extent of the contaminated area at Delaware enclosed by the 500-mg/l isochlor during September and October 1969.

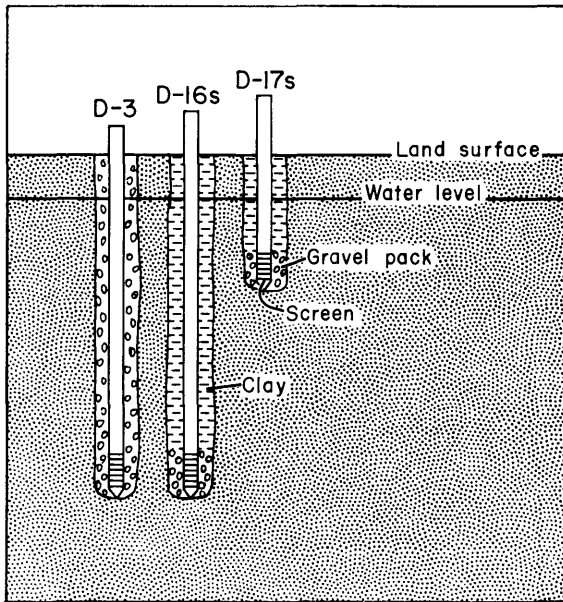


FIGURE 10. Completion details of observation wells D-3, D-16s, and D-17s.

tained 286 mg/l. By the following April 1969, which came during a rainy period, a complete inversion of values had occurred—the deepest well (D-16s) contained 1495 mg/l, the shallow well (D-17s) 837 mg/l, and the fully penetrating well (D-3), 1305 mg/l. Evidently the salt, which is apparently chemically attached,

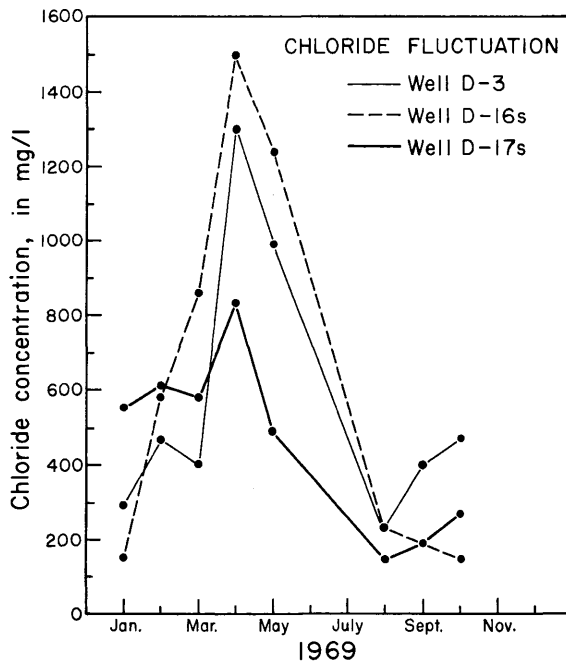


FIGURE 11. Fluctuation of chloride content in wells D-3, D-16s, and D-17s during January-October 1969.

in the form of crystals, to silt and clay held within pores in the upper part of the floodplain deposits, both in the zone of aeration and the zone of saturation, is dissolved and washed downward into the aquifer during periods of infiltration. If so, it is not possible to predict a time when the area will be completely clear of contamination, because it is entirely dependent upon the movement of soil moisture, and the rate, intensity, and duration of precipitation. Soil moisture, of course, too, depends not only upon the vagaries of nature, but also on the type of crops that might be planted in the contaminated area.

#### OTHER CHLORIDE-CONTAMINATION AREAS

Other areas in Ohio contain surface or ground water having high chloride contents. In some cases it is caused by man-made pollution, but in others the salt water occurs naturally. A few cases will be briefly described.

During the late 1940's, a local contamination problem occurred in north-eastern Ohio, in Medina County, due to the use of water flooding in the secondary recovery of petroleum, according to Stanley Norris, of the U.S. Geological Survey (written communication, 1970). Several hundred injection wells were drilled in an area of about 15 square miles. Water was pumped into the Mississippian Berea Sandstone at pressures as high as 400 psi to flush out oil from depths of about 400 feet. This resulted initially in contamination of a few private water supplies by saline fluids, forced into the shallower strata through abandoned and unplugged wells.

Kuhlman (1968) investigated the effects of street salting during winter on the quality of water in the Olentangy River in the vicinity of Columbus. He found a considerable chloride increase in the river immediately downstream from each storm-drain outfall. The combined high flows of both the river and the storm drains, however, served to rapidly dilute the salt-rich meltwater so that in no case did the chloride concentration exceed 100 mg/l.

Industrial wastes have become important sources of salt-water contamination in some parts of the State, particularly in the Tuscarawas and Muskingum River basins. These basins are potentially one of the most productive ground-water regions in the entire Ohio River basin. The greatest potential for ground-water development lies along the courses of the Walhonding, Tuscarawas, and Muskingum Rivers. Individual wells in gravel deposits along the floodplains may yield as much as 2000 gallons per minute.

An example of this contamination occurs below Barberton, where large concentrations of chloride wastes dumped into the Tuscarawas River from a chemical complex present very serious water-quality problems. Because sand and gravel deposits along the valleys of the Tuscarawas and Muskingum Rivers form the most important aquifers in the drainage area, and heavy pumping induces recharge of river water, these aquifers will probably become more seriously contaminated, as development increases.

During low flow of the Tuscarawas River in September 1966, the content of dissolved solids (consisting largely of chloride) was 5,990 mg/l at Massilon, 2,800 mg/l below the Bolivar and Dover Reservoirs, and it was 2,360 mg/l even at Newcomerstown. The effect of the contamination persists at low flow in the Muskingum River, despite the dilution effects of the Walhonding River. Below Coshocton the content of dissolved solids in the Muskingum in 1966 was 1,500 mg/l, and even at McConnelsville dissolved solids were excessive at 1090 mg/l.

Because of poor industrial waste-disposal practices, wells in southeastern Barberton have had to be abandoned because of contamination by salt water containing as much as 20,000 mg/l of chloride (Norris, 1955). Farther downstream, at Coshocton, the city well-field has had to be abandoned due to chloride contamination. At Zanesville, municipal wells in the sand and gravel of the Muskingum River floodplain produced water containing as much as 222 mg/l of chlo-

ride as early as 1950. The city water supply at Marietta, which is pumped from wells in the Muskingum floodplain, also has shown a marked increase in chloride.

#### CONCLUSIONS

Local contamination by the disposal of oil-field brines can result in serious economic hardships where domestic, municipal, or industrial wells are affected. In many areas streams may also be affected by the discharge of contaminated ground water. In those areas where precipitation is high and the strata are relatively permeable and near a drain, whether it be a well, spring, or stream, the contaminated water may be rapidly discharged, as is evidently true at Delaware. On the other hand, where localized deposits of sand or gravel comprise one or several aquifers within an area of otherwise low permeability, and under low hydraulic gradients, the natural cleansing of the aquifer may require decades, hundreds, or even thousand of years to complete. Considerations such as these are of profound significance in legal actions and will have important ramifications in the awarding of damages in ground-water-contamination suits. On the other hand, high concentrations of chloride in surface- or ground-water supplies in some cases may not be produced by contamination by oil-field brines, but may reflect natural conditions or disposal of other industrial wastes.

#### ACKNOWLEDGMENTS

Appreciation for aid given during preparation of this manuscript is given to S.E. Norris, U.S. Geological Survey, and to R.L. Bates and Colin Bull, Department of Geology, The Ohio State University, all of whom read the report and offered several suggestions. Many data were obtained from reports of student research carried out in the Department of Geology, in particular reports by Jimmy Shaw, Ronald Boster, and Mark Kuhlman. Of special significance were the chemical analyses of water samples completed by Bruce Hulman, a graduate student at The Ohio State University.

#### REFERENCES CITED

- Boster, R. S.** 1967. A study of ground-water contamination due to oil-field brines in Morrow and Delaware Counties, Ohio, with emphasis on detection utilizing electrical resistivity techniques. Unpub. M.Sc. thesis, The Ohio State Univ. 191 p.
- Hulman, B. D.** 1969. A ground-water contamination study in the Delaware area, Ohio. Unpub. senior thesis, The Ohio State Univ. 34 p.
- Kuhlman, Mark.** 1968. A study of chloride contamination in the Olentangy River in the vicinity of Columbus, Ohio. Unpub. senior thesis, The Ohio State Univ. 26 p.
- Norris, S. E.** 1955. The encroachment of salt water into fresh. p. 628. *In* U.S. Department of Agriculture. Water, the Yearbook of Agriculture 1955. Govt. Print. Office.
- Shaw, J. E.** 1966. An investigation of ground-water contamination by oil-field brine disposal in Morrow and Delaware Counties, Ohio. Unpub. M.Sc. thesis, The Ohio State Univ. 127 p.
- U.S. Public Health Service.** 1962. Public Health drinking water standards. U.S. Public Health Service Pub. 956. 61 p.
-