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IMPACT ON GROUNDWATER FROM CLOSURE OF AN UNDERGROUND ZINC–LEAD MINE IN SOUTHWEST WISCONSIN

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IMPACT ON GROUNDWATER FROM CLOSURE OF AN UNDERGROUND ZINC-LEAD MINE IN SOUTHWEST WISCONSIN

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ABSTRACT

Following closure of the Shullsburg Mine, an underground zinc-lead mine in southwestern Wisconsin, water quality in nearby private water-supply wells deteriorated. Affected wells were located within the cone of depression created by the large pumps used to keep the underground mine dewatered. Following mine closure, groundwater from these wells showed increased levels of sulfate, iron, calcium, magnesium, and total dissolved solids. The mechanism for increasing the concentrations of these materials in the groundwater is postulated to be the following sequence: (1) oxidation of sulfide minerals, (2) formation of soluble sulfate mineral phases, (3) breakdown of carbonate host rock by acid produced during sulfide oxidation, and (4) dissolution of soluble materials by groundwater within rock strata that was previously dewatered during active mining.

INTRODUCTION

The Shullsburg Mine in Lafayette County, Wisconsin, is a complex of zinc-lead ore bodies ranging up to 350 ft below the land surface within dominantly dolomitic host rocks (fig. 1). The mine, operated as a single mining unit accessible initially through a vertical shaft and later through an incline, was opened in 1949 and was operated almost continuously until the mine closed in 1979. A second mine (known as the Blackstone Mine) was opened in 1950. The two mines were joined by mine drifts in 1970. Cones of depression developed as a result of pumping necessary to dewater both mines. Because of the mines close proximity and similar location about 300 ft. below the pre-mining water table, these areas of water-level decline coalesced shortly after 1950.

Within one year following cessation of mining operations, private water-supply wells in the immediate vicinity of the Shullsburg Mine began to produce water with elevated concentrations of sulfate which ranged from 700 mg/l to 3500 mg/l (fig. 2). The laxative effect of sulfate in drinking water is well-documented (Environmental Protection Agency, 1976). The adverse impact of these sulfate-laden waters on both humans and livestock prompted citizen complaints to the Wisconsin Department of Natural Resources (WDNR). In addition to diarrhea and related gastric distress in humans, some local farmers noted pronounced declines in milk production from dairy cattle.

The Wisconsin Geological and Natural History Survey (WGNHS) initiated an investigation in 1980 to determine the extent of groundwater quality decline in the area, to identify the probable cause of the poor water quality, and to suggest mitigation measures for affected landowners (Evans and others, 1983). The results of this investigation indicate that there is a close spatial and temporal relationship between mine dewatering and subsequent recovery of water levels and the development of adverse water quality. The role of water-well construction in the presence or absence of poor-quality groundwater in private wells near the mine complex was also evaluated. In cooperation with the WDNR, the WGNHS formulated guidelines for new well construction to mitigate the local water-supply problems.

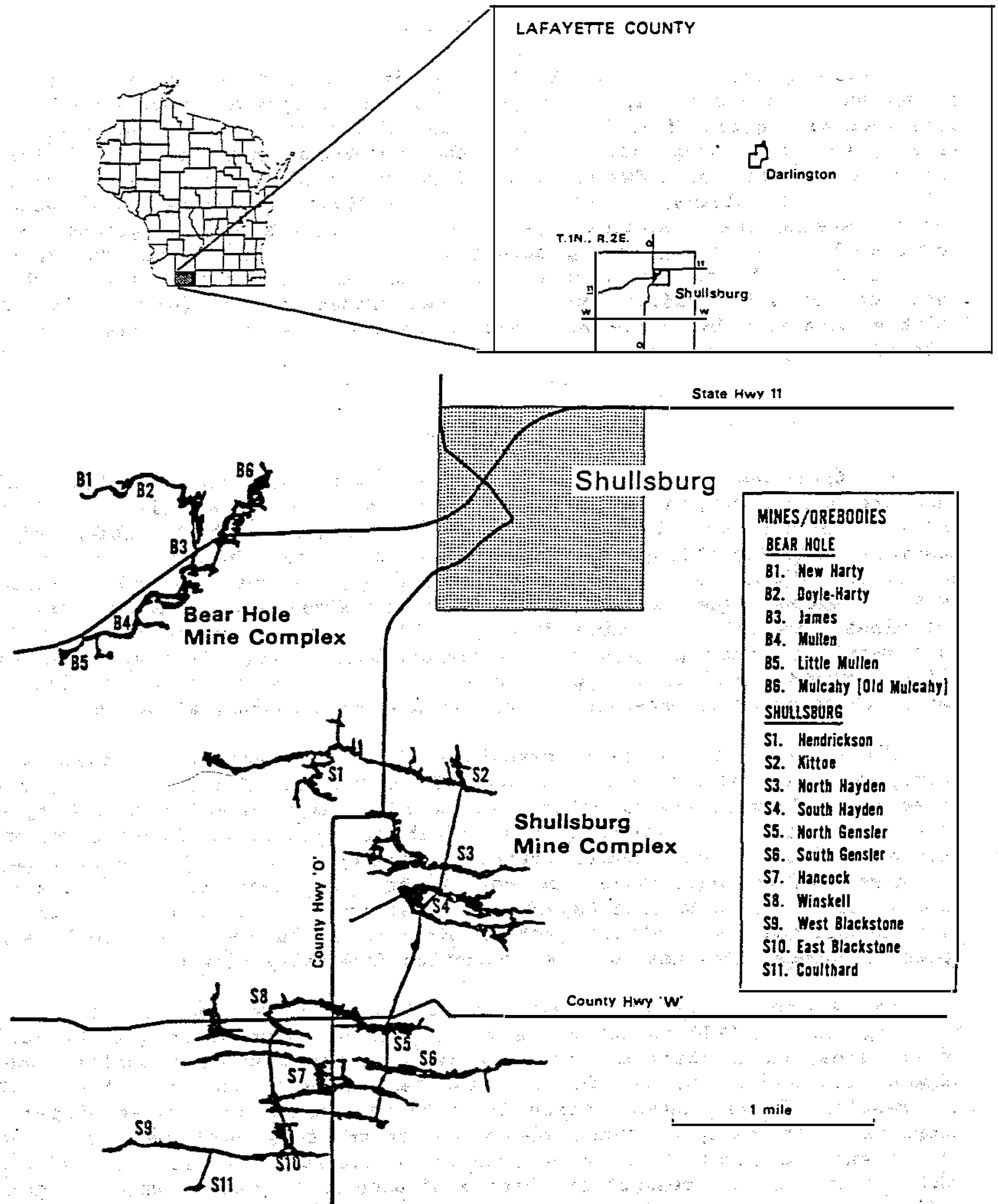

FIGURE 1.-- Map of the Shullsburg Area, Lafayette County, Wisconsin, showing location of the Shullsburg (including Blackstone) and Bear Hole Mine complexes. Each complex represents a group of ore bodies or separate mines that were interconnected by underground mine drifts (tunnels). The Bear Hole Mine complex is discussed by Evans and others (1983).

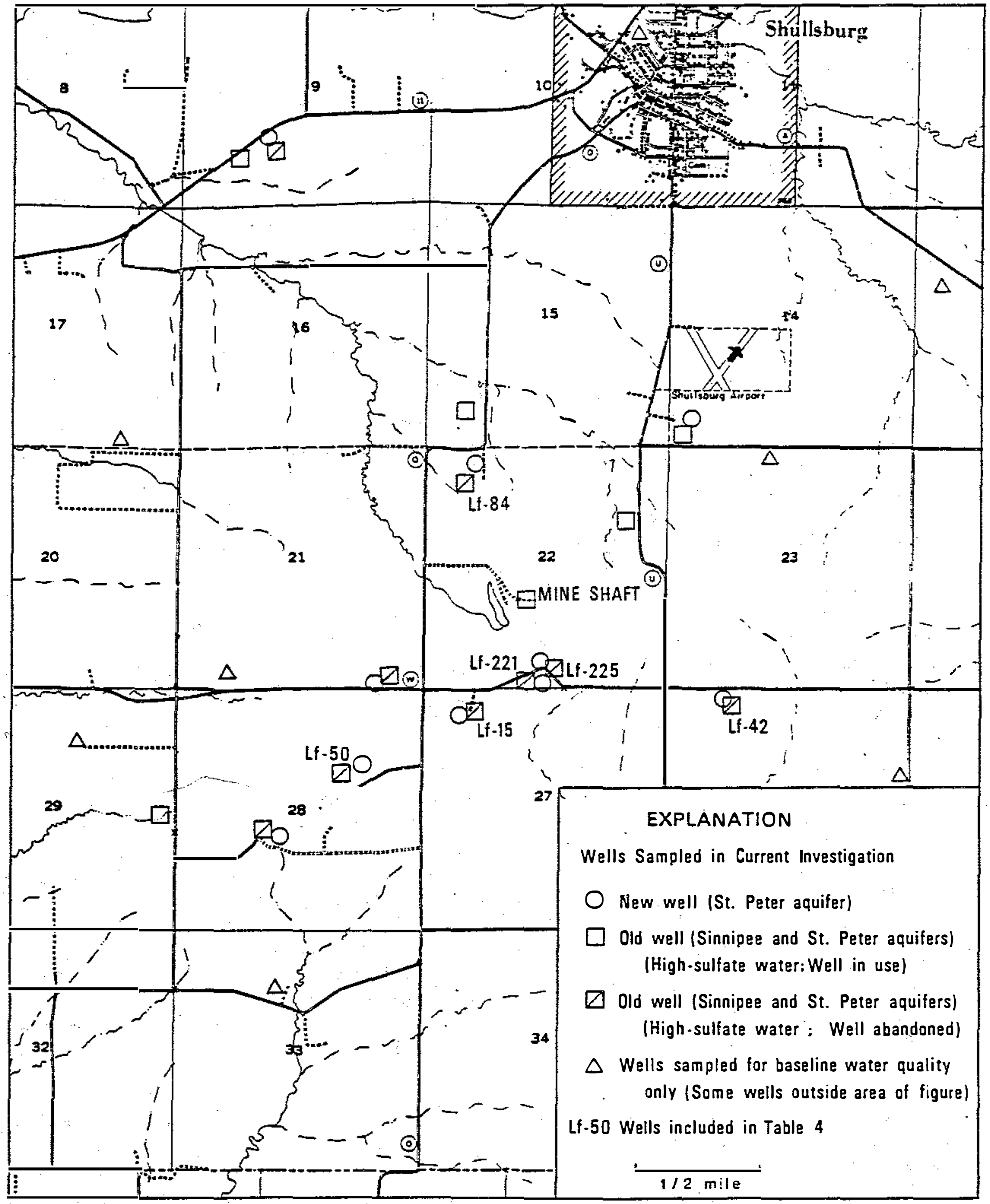

FIGURE 2.-- Location of wells sampled during investigation of the Shullsburg groundwater-quality problem. Triangles (Δ) represent wells sampled to obtain information on water quality within the Sinnipee and St. Peter aquifers unaffected by mining. Squares (□, ☒) represent wells with high concentrates of sulfate. Circles (O) represent new wells constructed during the course of this investigation.

ACKNOWLEDGMENTS

The contribution of C.L.R. Holt, Jr., formerly with the U.S. Geological Survey Water Resources Division, to the understanding of Shullsburg mine hydrology has been invaluable to the present investigation.

The cooperation of the personnel of the Wisconsin Department of Natural Resources is gratefully acknowledged as are the comments and assistance of Ron Hennings, Head of the Water Resources Section, Wisconsin Geological and Natural History Survey. Harold Haman, formerly with Eagle-Picher Industries, Inc., supplied water-level data and other useful information on the Shullsburg Mine complex.

GEOLOGIC AND HYDROGEOLOGIC SETTING

The Shullsburg Mine is located in southwestern Wisconsin in the Upper Mississippi Valley Zinc-Lead district (Hyle and others, 1959). Numerous, small zinc-lead ore bodies occur as mineralized zones associated with (1) vertical joints (gash-vein deposits), (2) inclined fractures (pitches), (3) bedding-plane fractures (flats), and (4) as disseminated occurrences of sulfide minerals. The Shullsburg Mine includes principally ore bodies of the gash-vein and pitch-and-flat types, but disseminated sulfide mineralization is also common within the carbonate host rocks.

Mineralized zones include sphalerite (ZnS) and galena (PbS) as ore minerals. Common gangue minerals include marcasite and pyrite (FeS_2), calcite ($CaCO_3$), and minor amounts of barite ($BaSO_4$). Sulfide mineralization extends into country rock strata from mineralized fractures as a replacement phenomena for distances up to 400 ft (122 m) (Mullens, 1964).

The host rock for zinc-lead ore bodies at the Shullsburg Mine is the Middle Ordovician Sinnipee Group (Platteville, Decorah, and Galena Formations), a more than 300 ft sequence of dolomite with lesser amounts of limestone and shale (table 1). The Sinnipee Group is overlain to the southeast in the immediate area by the Upper Ordovician Maquoketa Formation, a shale unit that increases in thickness from 0 ft at the Shullsburg Mine to over 100 ft towards the southeast. The Middle Ordovician St. Peter Formation underlying the Sinnipee Group is a very fine to coarse-grained quartz sandstone that varies from less than 40 ft to more than 100 ft thick within the immediate Shullsburg area. A 1-ft to 3-ft shale interval (Middle Ordovician Glenwood Formation) overlies the sandstone of the St. Peter Formation, but is not present everywhere. The St. Peter and Glenwood Formations are known collectively as the Ancell Group.

From a hydrogeologic perspective, the Sinnipee Group and the St. Peter sandstone of the Ancell Group are aquifers (table 1, fig. 3). The Maquoketa Formation and the Glenwood Formation of the Ancell Group (where present) are aquitards. The Sinnipee aquifer is characterized by fracture flow within the fractured and cavernous dolomite and limestone. To the northwest, where the Sinnipee Group crops out and the Maquoketa Formation is absent, the Sinnipee aquifer is unconfined. To the southeast the Sinnipee aquifer is located below the Maquoketa aquitard and may behave as a confined aquifer, but hydrogeologic

Table 1. Principal Geologic Units in the Shullsburg Area

Stratigraphic Unit Group	Formation	Dominant Lithology (thickness in ft)	Hydrogeologic Function
	Maquoketa	shale (0-100+)	aquitard
Sinnipee	Galena	dolomite (300-340)	aquifer
	Decorah		
	Platteville		
Ancell	Glenwood	shale (0-3)	aquitard
	St. Peter	sandstone (40+)	aquifer

data are lacking in that region. The St. Peter aquifer is confined, with the potentiometric surface, as measured in area wills open only in the St. Peter aquifer, being approximately 100 ft (30 m) above the top of the St. Peter Formation.

GROUND-WATER QUALITY AND QUANTITY NEAR THE SHULLSBURG MINE

Prior to Mine Development

The construction of the Shullsburg Mine began in late 1948 with shaft sinking completed in 1949 to 765 ft above mean sea level (m.s.l.) for a total depth of 330 ft. Prior to mine construction the shape of the water table generally reflected land-surface topography. The potentiometric surface of the Sinnipee aquifer for January 1947 is shown in Figure 4A (data from C.L.R. Holt, Jr. in an unpublished manuscript on Shullsburg Mine hydrology prepared in the early 1960s).

Groundwater quality data for the pre-mining period in the Shullsburg area are lacking. Construction reports prepared for private water-supply wells indicate that water quality in the Sinnipee aquifer was acceptable for domestic use. Hindall and Skinner (1973) characterize water quality from the Sinnipee aquifer in the region as "good" with the following averages for selected chemical constituents: total dissolved solids, 375 mg/l; sulfate, 40 mg/l; and total alkalinity as $CaCO_3$, 320 mg/l.

During Active Mine Development

Figure 4B shows the potentiometric surface of water in the unconfined Sinnipee aquifer as of June 1958, about nine years after Shullsburg Mine development and dewatering of the Sinnipee host rock had been initiated. (Water-level data after June 1958 and before mine closure are not available.) The maximum decline in water level within the Sinnipee between 1947 and 1958 is in excess of 280 ft (fig. 4C). According to Holt (undated), rates of groundwater pumping for mine dewatering ranged from 4 to 17 million gallons per day. Higher rates of water removal were necessary when mining activity involved development of a new area of mineralization. The increased rate of water inflow as mining reached a new ore body reflected the fractured nature

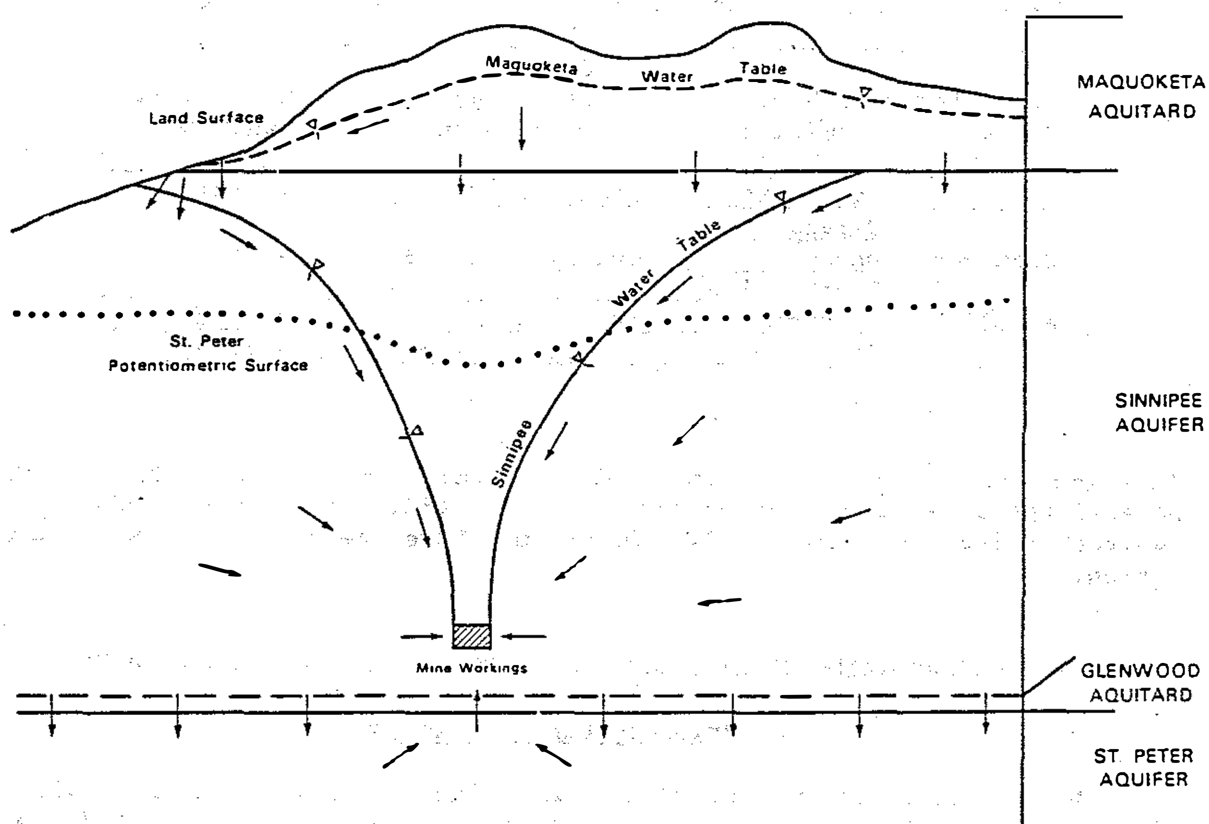

FIGURE 3.-- Schematic illustration of groundwater conditions during active mining in the Shullsburg Mine (modified from Holt, undated). Arrows show inferred directions of ground-water flow. Dashed line at top of Glenwood aquitard indicates the irregular occurrence of the Glenwood in this area.

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of the Sinnipee host rock associated with zinc-lead mineralization. The areal extent of the cone of depression resulting from mine dewatering had reached over 12 mi² by 1958 (fig. 4C).

Investigations during active mine development in the late 1950s (Holt, undated) and within three years of mine closure (Eagle-Picher Industries, 1977) indicate that groundwater quality changed as a result of mine-related activity. Increases in total dissolved solids, zinc, sulfate, calcium, and magnesium are apparent (Table 2). Holt (undated) suggested that the change in water quality from groundwater collected in wells near the mine and from water collected as it entered the mine along fractures, solution channels, bedding planes, and open drill holes was the result of dissolution of oxidized sulfide (now, sulfate) mineral phases. These more-soluble sulfate mineral phases were dissolved by groundwater moving through the dewatered bedrock in the vicinity of mine workings. Alternatively, data in Table 2 could also be explained by assuming that the chemical quality of groundwater near mineralized zones differs from groundwater present some distance away from these zones even before

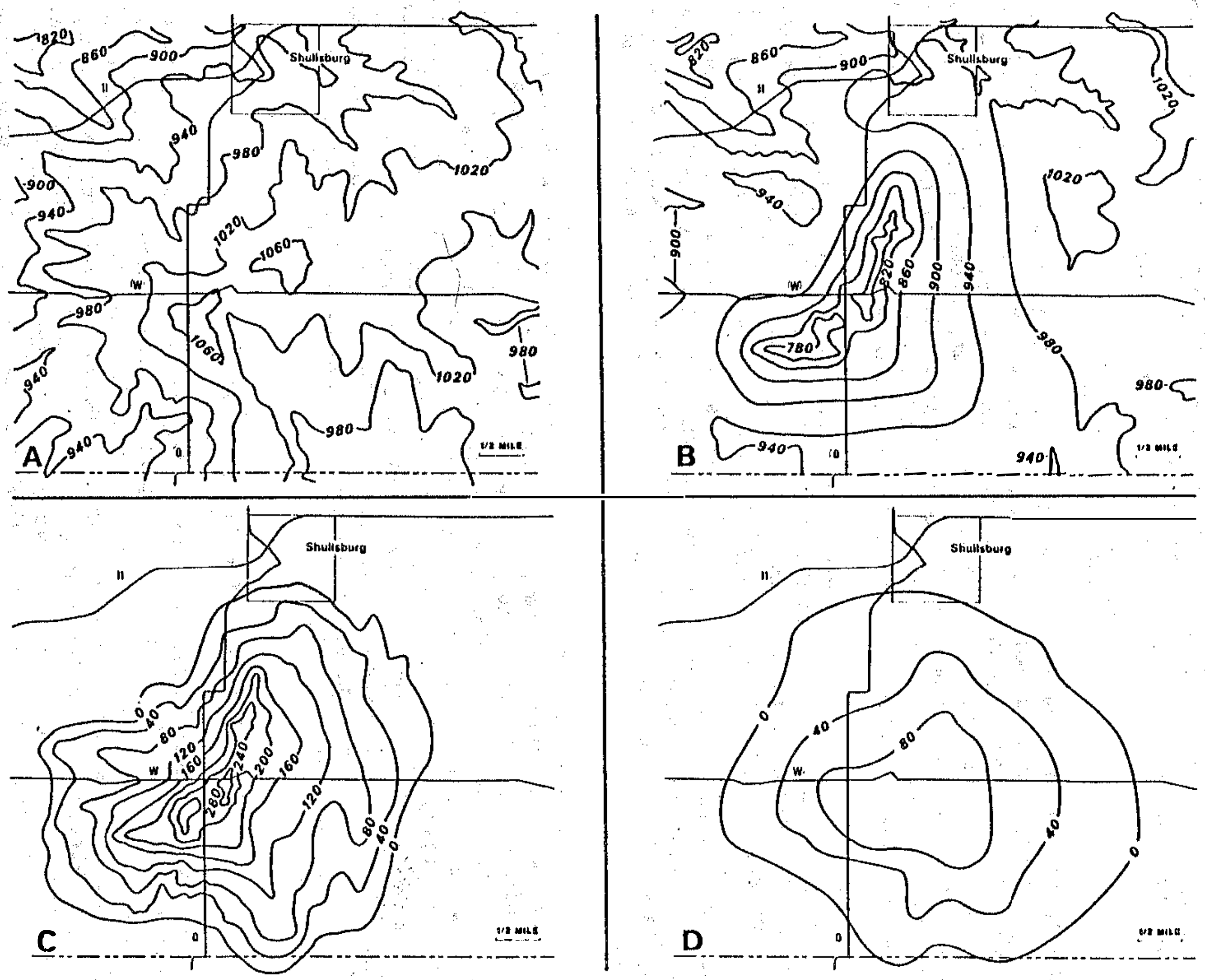

FIGURE 4.-- Groundwater levels in the Sinnipee Group aquifer.
A. Water levels in January 1947 (before-mining) from Holt (undated).
B. Water levels in June 1958 (during mining) from Holt (undated).
C. Water-level decline between 1947 and 1958 (Holt, undated).
D. Remaining water-level decline in June - September 1983 about four years after mine closure (Toran, 1984).

mining began. However, the presence of soluble sulfate mineral phases within the zone of saturation in the Sinnipee Group has not been observed (Heyl and others, 1959). The first explanation as proposed by Holt (undated) is the more likely hypothesis to explain the observed water quality.

Following Mine Closure

Pumping to dewater the Shullsburg Mine ceased in late September 1979. Water-level recovery, as measured in the main vertical shaft, was initially rapid with the rate of recovery declining over time (fig. 5). At present, water level in the main shaft at 945 ft above m.s.l. is approximately 180 ft (55 m) above the active-mining water level. The original (pre-mining) water table elevation at the main shaft was 1050 ft m.s.l. (Holt, undated). Thus, the current water level in the shaft remains 100 ft below the pre-mining level.

Figure 4D shows the cone of depression decline remaining in mid-1983 in the Sinnipee Group near the Shullsburg Mine. The cone of depression developed during mine dewatering is still present four years after mine closure, though less pronounced than during active mining (Toran, 1984). The areal extent of groundwater decline is over 14 mi^2 indicating the maximum development of the cone of depression during active mining must have exceeded 14 mi^2. This larger areal development of water-level decline as compared to that measured in June 1958 (fig. 4B) is the result of continuing mine development after 1958.

Groundwater quality in the vicinity of the mine following shutdown in September 1979 was determined by sampling private water-supply wells and water within the main shaft. Table 3 shows average values of selected chemical constituents in water sampled during the course of the present investigation. Table 4 shows groundwater quality during and after mining for specific wells sampled in the 1950s and in the early 1980s. Data collected to date indicate that groundwater that has moved through rock strata dewatered during the active phase of mine development shows increased levels of sulfate, calcium, magnesium, zinc, and total dissolved solids. Increases in iron concentration within this same water is suggested as well.

CAUSE OF WATER QUALITY CHANGES

Water-quality changes resulting from mining activity include increases in the concentrations of sulfate, calcium, magnesium, zinc, iron, and total dissolved solids. The cause of these changes is postulated to be the oxidation of sulfide minerals present within the Sinnipee Group. Field observations within the Upper Mississippi Valley zinc-lead district indicate oxidized mineral phases are common in areas above the water table. Examples of oxidized minerals encountered include hydrous magnesium sulfate (epsomite), hydrous iron sulfates (copiapite and melanterite), hydrous calcium sulfate (gypsum), and iron oxides, such as hematite and limonite (Heyl and others, 1959).

The oxidation of pyrite and marcasite is postulated to be the principal cause of observed water-quality changes within groundwaters passing through formerly dewatered rock strata in the vicinity of the Shullsburg Mine. Under

Table 2.-- Average values of selected chemical constituents in groundwater sampled during active mining. See Holt (undated) and Eagle-Picher Industries (1977) for sampling methodology, analytical laboratories, and analytical methods.

A. Private Water-Supply Wells Near Shullsburg Mine[a]

Aquifer	Constituent							
	Iron	Lead	Zinc	Calcium	Magnesium	Sulfate	Dissolved Solids	pH
Sinnipee Gp.	0.6 (5)[b]	--	--	--	--	33 (5)	400 (5)	7.4 (5)
Sinnipee and Ancell Gps. (St. Peter)	0.5 (13)	0.003 (5)	0.4 (5)	74 (3)	42 (3)	75 (13)	370 (5)	7.3 (13)
Ancell Gp. (St. Peter)	1.5 (7)	0.05 (7)	0.3 (7)	61 (4)	35 (4)	8 (7)	280 (7)	7.5 (7)

B. Groundwater Collected Within Shullsburg Mine

Source	Constituent							
	Iron	Lead	Zinc	Calcium	Magnesium	Sulfate	Dissolved Solids	pH
Mine[a] Workings	0.1 (12)	0.02 (10)	0.4 (10)	110 (10)	61 (10)	200 (13)	650 (13)	7.6 (13)
Shullsburg[c] Pump (24) (24)	--	0.01 (24)	1.1 (24)	390[d] (24)		480	740 (24)	6.8
Blackstone[c] Pump	--	0.01 (24)	2.2 (24)	340[d] (24)		230	740 (24)	6.8

a Data modified from Holt (undated). Samples collected and analyzed in late 1950s. Values rounded to reflect probable analytical precision. All values shown are in parts per million, except for pH.

b Numbers in parentheses are number of analyses included in the average value.

c Data from twice-monthly sampling in 1976 in support of Shullsburg Mine permit application (Eagle-Picher Industries, 1977). Samples collected at groundwater discharge points. All values shown are in milligrams per liter, except for pH.

d Values shown are for alkalinity as $CaCO_3$ in mg/l.

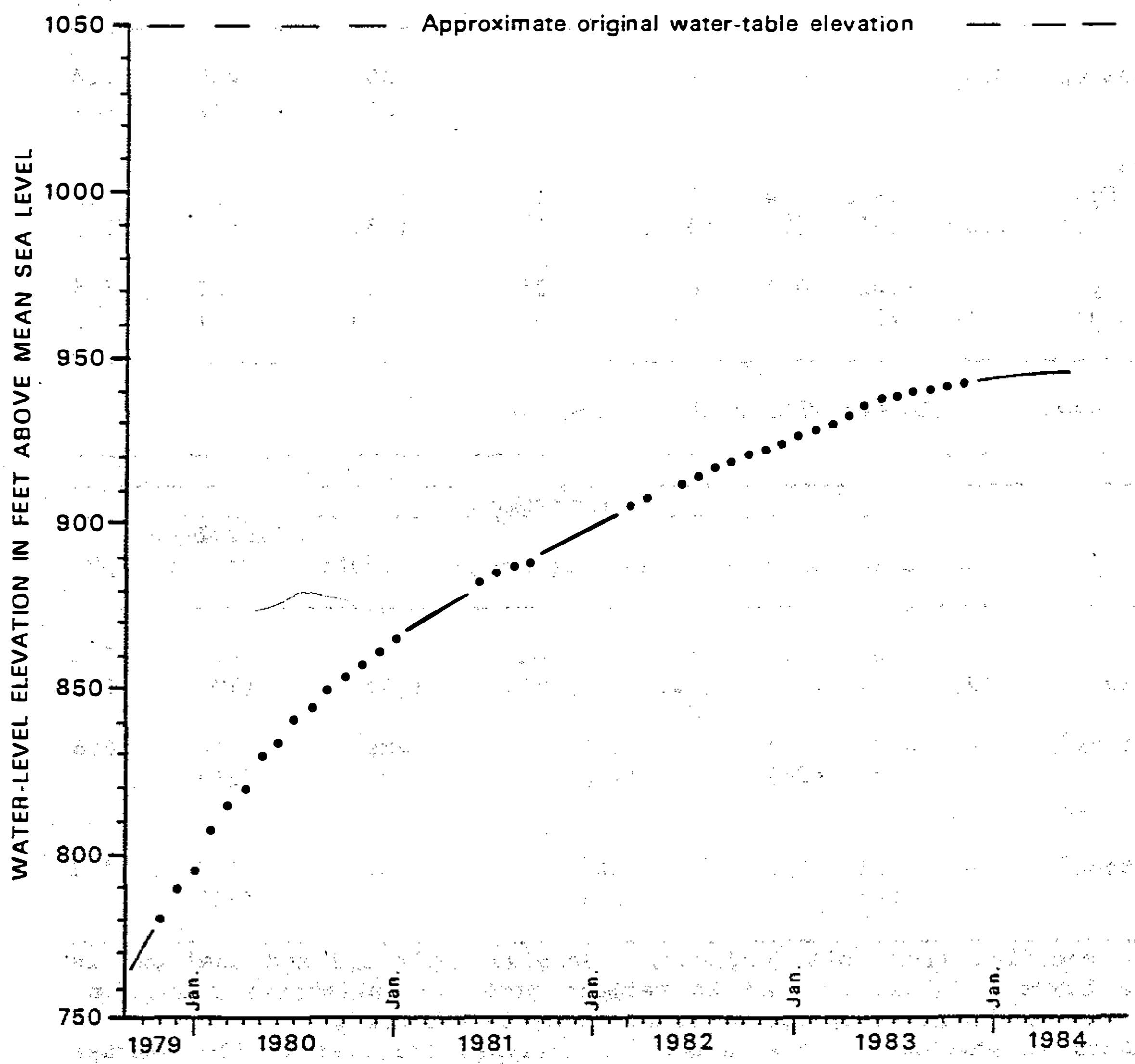

FIGURE 5.-- Water-level recovery in main shaft at Shullsburg Mine (data courtesy of Eagle-Picher Industries, Inc. and Inspiration Mines, Inc). Original (pre-mining) water level is about 1050 feet above mean sea level (Holt, undated). Dots indicate actual values; line indicates inferred values.

TABLE 3. Arithmetic averages of selected constituents in wells near Shullsburg Mine sampled after mine closure. See Evans and others (1983) for discussion of sampling methodology, analytical laboratory, and analytical methods.

Aquifer	Constituent								
	Iron	Manganese	Lead	Zinc	Calcium	Magnesium	Sulfate	Dissolved Solids	Alkalinity (HCO_3^-)
Sinnipee Gp.	0.16[a] (19)[b]	0.05 (19)	0.012 (19)	0.42 (19)	115 (19)	63 (19)	230 (20)	800 (19)	388 (18)
Sinnipee and Ancell Gps. (St. Peter)	3.2 (7)	0.05 (8)	0.044 (7)	0.54 (7)	106 (8)	61 (8)	210 (7)	730 (7)	386 (10)
Ancell Gp. (St. Peter)	0.60 (35)	0.05 (36)	0.003 (31)	0.45 (36)	68 (37)	40 (37)	57 (30)	490 (33)	357 (28)
Complaint-Investigation[c] [Open to both Sinippee and St. Peter Aquifer]	4.3 (31)	0.89 (29)	0.033 (34)	6.05 (31)	357 (31)	330 (30)	1,860 (28)	3,370 (29)	445 (24)

a All values shown are milligrams per liter.
b Numbers in parentheses indicate number of analyses included in average.
c Complaint-investigation wells are wells sampled as a result of a complaint concerning water quality.

aerobic conditions as would develop with dewatering, the iron sulfide is oxidized releasing hydrogen ions and sulfate, probably in the form of hydrous iron sulfates. The hydrogen ion would be available to attack associated sulfide minerals, such as sphalerite.

Therefore, groundwater that is in contact with oxidized, iron-sulfide-rich intervals, which include other sulfide minerals that are less-readily oxidized, should show an increase in the concentration of iron, sulfate, certain metal cations, total dissolved solids, and hydrogen ion. Increases in hydrogen ion concentration (lower pH) within groundwater sampled near the Shullsburg Mine have not been observed reflecting the buffering effect of the carbonate host rocks of the Sinnipee Group. Increases in the concentrations of calcium and magnesium indicate dissolution of dolomite. A more detailed investigation of the geochemical relationships responsible for the changes in water quality is currently in progress (Toran, 1984).

ROLE OF WELL CONSTRUCTION

Domestic water-supply wells in the Shullsburg area are typically constructed to depths of 100 to 200 ft into the Sinnipee Group and are cased to depths of 40 to 50 ft. In the vicinity of Shullsburg Mine the lowering of

Table 4. Arithmetic averages of selected constituents in groundwater sampled during active mining and after mine closure. See Holt (undated) and Evans and others (1983) for sampling methodology, analytical laboratory, and analytical methods.

Well Number		No. of Samples	Constituent							
			Iron	Lead	Zinc	Calcium	Magnesium	Sulfate	Dissolved Solids	Alkalinity (HCO_3^-)
Lf-15	During	2	0.6[a]	5	0.5	60	24	6.7	290	344
	Post	2	4.4	27	12	257	120	800	1540	383
Lf-42	During	2	0.5	10	0.07	89	54	107	484	403
	Post	3	0.6	4	6.9	355	369	2050	3650	414
Lf-50	During	2	0.7	< 3	1.5	66	35	74	312	380
	Post	3	3.7	61	8.5	448	395	2830	4080	524
Lf-84	During	1	1.3	<10	0.04	61	34	13	290	346
	Post	1	<.1	< 3	18	320	160	1260	2450	—
Lf-221	During	1	0.8	—	—	—	—	14	—	349
	Post	3	5.2	5	2.9	419	840	3450	6820	480
Lf-225	During	3	0.2	—	—	—	—	30	—	371
	Post	4	0.1	2	1.5	475	438	2970	4290	430

a All values shown are in milligrams per liter except for lead which is shown as micrograms per liter.

area groundwater levels due to dewatering required the deepening of several private wells, which was a common practice of the mining companies active at the Shullsburg Mine complex. Additional casing was generally not added. Because the amount of water-level decline was significant, deepened wells were completed into the underlying St. Peter aquifer. Due to the confined nature of the St. Peter aquifer, water levels within these deepened wells were generally 100 ft above the top of the St. Peter sandstone.

As long as the mine was operating and pumps maintained the lowered water level within the Sinnipee Group, the deepened wells, which were open to both the St. Peter and Sinnipee aquifers, produced water of acceptable quality. Upon cessation of mining and the ensuing recovery of water levels within the Sinnipee, contaminated groundwater (water containing increased levels of sulfate, calcium, magnesium, certain metal cations, and total dissolved solids) entered the open boreholes of wells. As water-level recovery continued and increasingly larger volumes of contaminated water became available, the quality of water pumped from the wells declined and complaints of poor water quality were made. The initial concern regarding declining water quality came to the attention of local officials about ten months following mine closure. To date, 14 wells have been affected by the sulfate-contaminated groundwater.

In a few cases wells had been constructed by the mining company for landowners near the operating mine that were cased into the St. Peter aquifer. All these wells have continued to produce water of acceptable quality. Thus, the importance of well construction to the mitigation of inferior water quality in the vicinity of the Shullsburg mine is clear (fig. 6). Since hauling water from some distant source was prohibitively expensive and construction of shallow wells was impractical due to slow water-level recovery, the only recourse to mitigate the water-supply problem was a new well drilled into the underlying St. Peter aquifer. New wells, cased and pressure-grouted into the St. Peter sandstone, have been completed for ten households, and at least one more well is scheduled for completion in the near future (Summer 1985). In all cases where the wells have been constructed properly (with one exception, see following paragraph), the wells have produced water of excellent quality.

A review of the head relationships between groundwater in the St. Peter aquifer and in the Sinnipee aquifer indicates that recovery of water levels within the Sinnipee to an elevation higher than the potentiometric surface of the St. Peter will result in a head reversal. The downward gradient resulting from the reversal of head across the Glenwood aquitard overlying the St. Peter aquifer poses a continuing threat to new wells constructed to alleviate existing water-supply problems. New wells cased and pressure-grouted into the St. Peter aquifer may produce water of inferior quality if some path allowing water movement between the Sinnipee and the St. Peter aquifers exists (Glenwood Formation absent or fracture opening between the two formations). To date, one new well constructed in accordance with official state guidelines to mitigate the Shullsburg water problem has been adversely affected by this head-reversal phenomenon.

Eventually, the Sinnipee water levels should recover sufficiently to allow movement of contaminated water away from zones having soluble sulfate minerals. With dilution and dispersion the impact of declining water quality in the Shullsburg area is expected to eventually dissipate. However, estimates of rates of water-level recovery and rates of infiltration of uncontaminated water into the Sinnipee aquifer in this area have not been made.

SUMMARY AND CONCLUSIONS

The dewatering between 1948 and 1979 necessary to develop the numerous zinc-lead ore bodies within the Sinnipee Group south of Shullsburg resulted in the formation of soluble oxidized mineral phases, principally hydrous sulfate minerals. Upon mine closure and cessation of pumping the formerly dewatered area in the vicinity of the Shullsburg Mine workings became newly saturated. Groundwater entering the formerly dewatered rock strata dissolved the oxidized mineral phases and promoted further dissolution of associated sulfide minerals. The quality of water in private water-supply wells open to either the

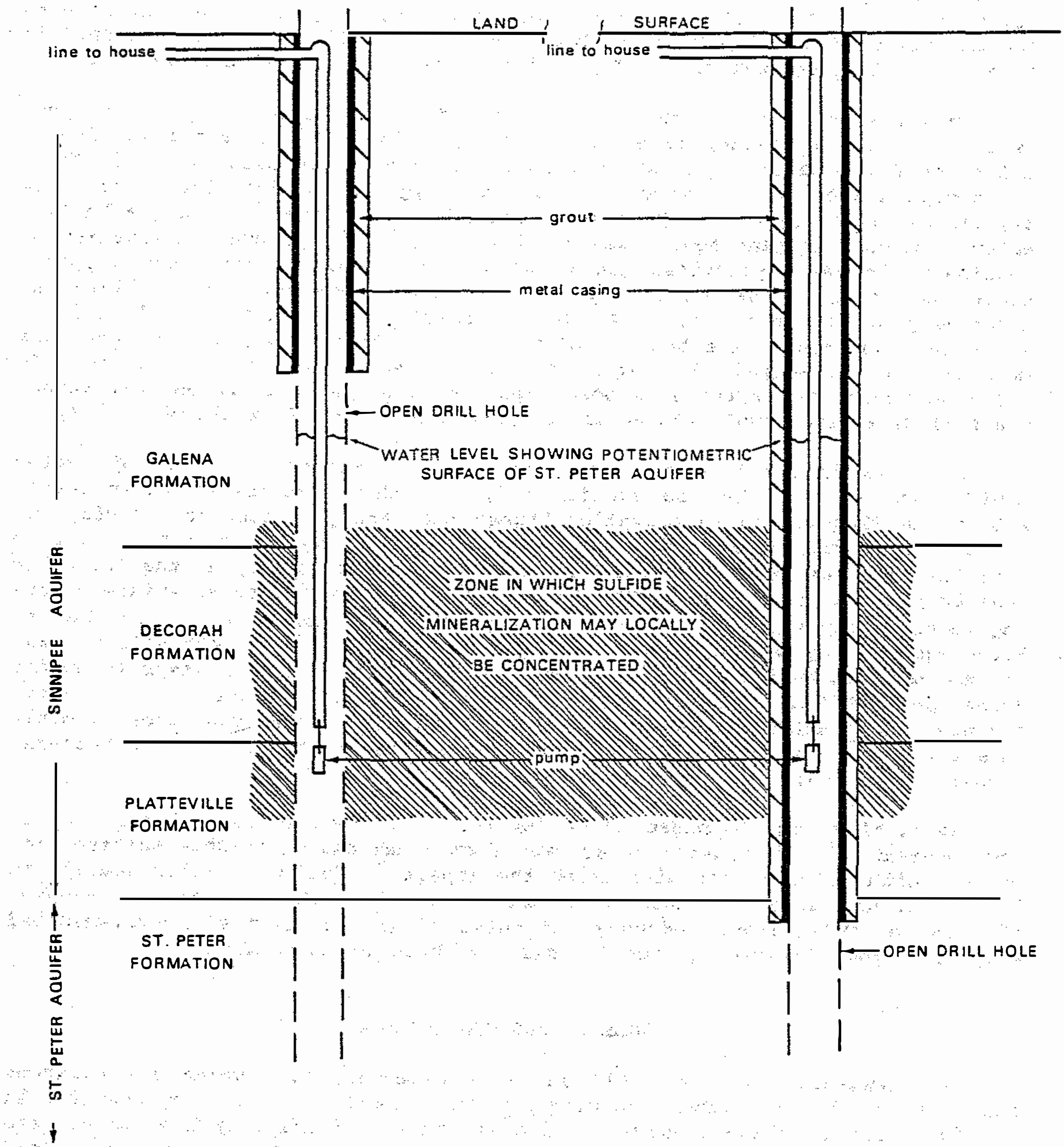

FIGURE 6.— Schematic illustration of the role of well construction in determining if groundwater that has been in contact with oxidized sulfide minerals (sulfates) will enter the well. Well on the left is open to water contaminated with sulfate; the well on the right is not. Movement of sulfate-laden groundwater down into the St. Peter Formation following a head reversal may permit contaminated water to affect newly constructed wells (right).

Sinnipee aquifer alone or to both the Sinnipee and St. Peter aquifers is characterized by increased concentrations of sulfate, iron, calcium, magnesium, zinc, and total dissolved solids as compared to water from these same aquifers in locations at some distance (more than one mile) away from the mine.

Sulfate levels in affected wells ranged from 700 mg/l to 3500 mg/l causing physical discomfort among humans using the water and serious economic losses for dairy operations having cattle affected by the water. Complaints to the WDNR and the WGNHS by affected individuals resulted in a program of investigation, recommendations for new well construction, and help in obtaining financial assistance for new well construction.

The eventual disposition of the Shullsburg water problem is not known at this time. Dilution and dispersion of contaminated groundwater in the Sinnipee Group is expected. However, no estimate is yet possible of when this severe impact of mining on groundwater near Shullsburg will actually disappear.

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