

Characterization of Groundwater in the Coal-Mine Aquifers of Indiana

Indiana Geological Survey Special Report 73



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Cover: Mine workings map of the Submarine Coal Mine, Vigo County, Indiana, which operated from 1919 to 1930.

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ABSTRACT

More than 194,000 acres (79,000 hectares) of Indiana are underlain by underground coal mines, most of which are abandoned room-and-pillar mines. The amount of groundwater that fills the voids of these abandoned mines may be as much as 172 billion gallons (6.5×10^{11} L). All the mines are less than 506 ft (154.2 m) in depth. Data regarding the physical hydrology of flooded underground coal mines and the chemistry of groundwater within them are available for only a few localities that have been investigated by the Indiana Geological Survey. Estimated storativities for three flooded mines range from 0.0003 to 0.0068, while calculated barometric efficiencies for four mines range from 0.17 to 0.83. Thus, some flooded mines are high-yield aquifers with potentially large storage capacities. At six mines, water levels were continuously recorded for periods ranging from 17 months to 9 years, and each mine exhibited unique water-level behaviors. Eighteen different sampling wells were installed by the Indiana Geological Survey into six flooded mines, and 209 samples of groundwater were collected. The water in shallow flooded mines (less than 150 ft [45.7 m] deep) is typically calcium-magnesium-sulfate water, with chloride becoming more important at greater depths. Despite high values of acidity, alkalinity is also often present in the flooded mines, so that values of pH are sometimes moderate or high. Many underground mines in Indiana were abandoned more than 50 years ago, so that significant volumes of water of relatively good quality may exist in places. In the future, as greater demands are placed on water resources, mine pools may see development for a variety of purposes, including geothermal heat-pump systems, energy storage, and cooling water.

INTRODUCTION

Large areas of southwestern Indiana are underlain by abandoned underground coal mines. Since the nineteenth century more than 900 million short tons (816 million metric tons) of coal have been removed from these mines, and many of the void spaces created by this mining are now filled with groundwater. For the purposes of this report, the water-filled voids and associated features such as shafts, boreholes, and subsidence fractures will be referred to as “coal-mine aquifers” or “mine pools” (discrete volumes of water within inter-

connected mine workings). In the future, these potentially high-yielding aquifers may represent resources of significant public and commercial value for a variety of purposes, but little is known about the quality of water within flooded mines, the mechanisms of recharge and discharge, or the hydrodynamics of individual mine pools. The purpose of this report is to summarize the limited data that are currently available and that are specific to Indiana and to suggest lines of research that might promote the future use—and remediation, where necessary—of this potentially valuable resource.

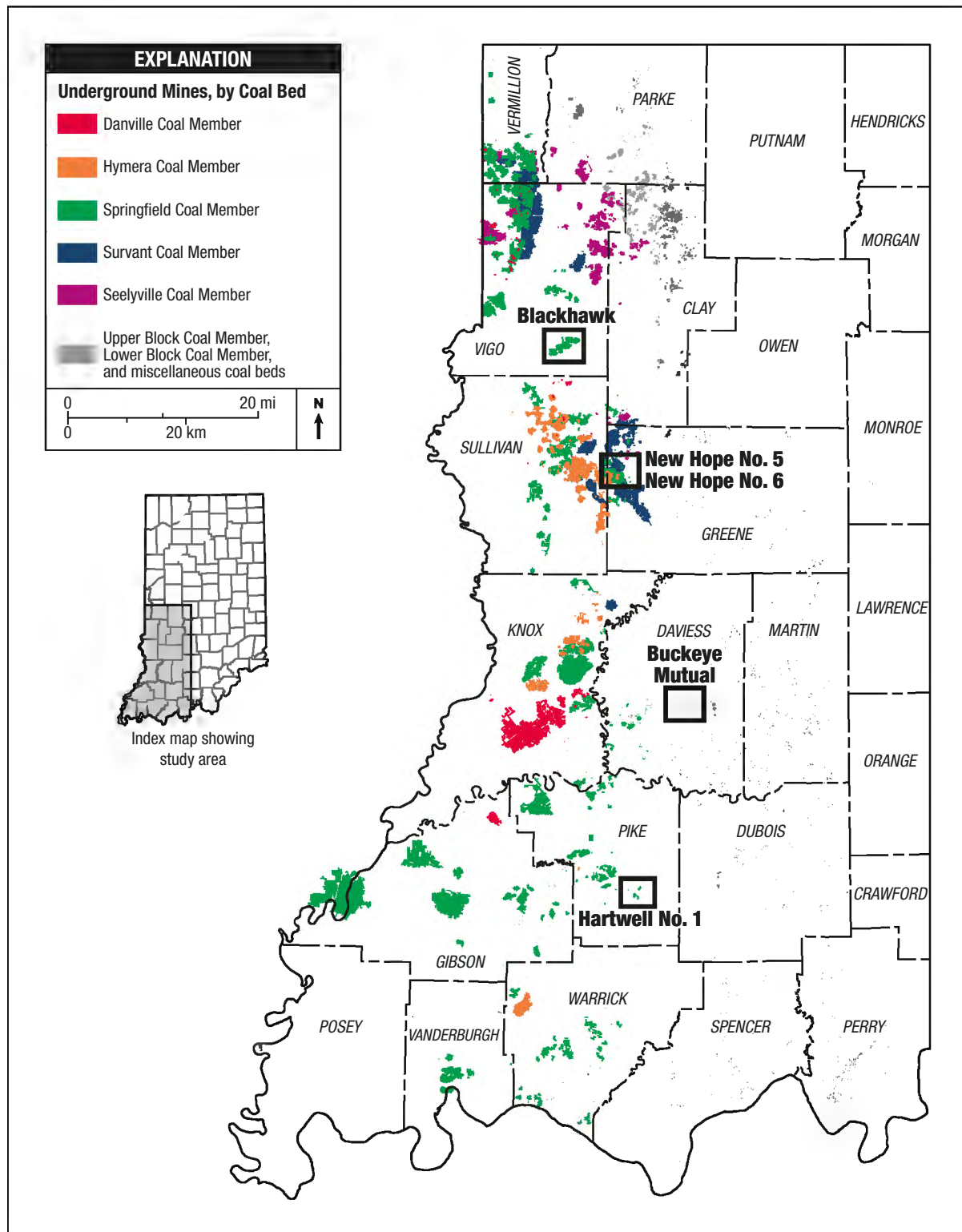


Figure 1. Map of southwestern Indiana showing the distribution of underground coal mines, by coal bed. The locations of selected underground mines that are discussed in this report are labeled. Source: IGS (2010a).

ACCESSIBILITY

More than 194,000 acres (79,000 hectares [ha]) of Indiana are underlain by underground coal mines, most of which are abandoned (fig. 1). Because underground mining of as many as three different seams occurred on a significant scale in several mining districts of Indiana (referred to as “multiseam mining”), the total extent of underground mines is even greater, exceeding 201,000 acres (81,341 ha). Of this, more than 88 percent is distributed among the Seelyville, Survant, Springfield, and Hymera Coal Members (fig. 2 and Table 1).

Differences in the average thicknesses of the principal coal beds in underground mines (Table 1) are related to the overall quality of each coal bed, so that mining of thinner coal was economically feasible wherever the quality of the coal was above average (Harper and Olyphant, 1992). For the purposes of this report, we will make the conservative assumption that mines in the Danville, Upper Block, and Lower Block Coal Members, as well as mines in other coal beds, have average thicknesses that are comparable to that of the Survant Coal Member, which is of relatively good quality. Using such assumptions, the total volume of the underground mines (including both pillars and voids) is approximately 1.06×10^6 acre-feet ($1.3 \times 10^9 \text{ m}^3$).

		Series	Group	Formation	Coal Bed
P E N N S Y L V A N I A N	Middle	Desmoinesian	Carbondale	Dugger	Danville Coal Member Hymera Coal Member
				Petersburg	Springfield Coal Member Houchin Creek Coal Member
				Linton	Survant Coal Member Colchester Coal Member Seelyville Coal Member
		Atokan	Raccoon Creek	Staunton	
				Brazil	Minshall Coal Member Upper Block Coal Member Lower Block Coal Member
				Mansfield	Mariah Hill Coal Member
	Lower	Morrowan			

Figure 2. Simplified stratigraphic column showing the principal coal beds in Indiana. Modified from Mastalerz and Harper (1998).

Table 1. Estimated acreage and volume of underground mines, by coal bed

Coal bed	Undermined area* (acres)	Average thickness of mined coal bed (ft)	Total volume of voids and pillars (acre-ft)
Hymera	22,000	5.1 [†]	112,000
Springfield	96,000	5.4 [†]	518,000
Survant	37,000	4.7 [†]	174,000
Seelyville	23,000	6.1 [†]	140,000
Others	23,800	4.7 [‡]	112,000

* IGS (2010a).

[†] Harper and Olyphant (1991, p. 277).

[‡] Assumed to be equal to the value for the Survant Coal.

The underground coal mines of Indiana are all room-and-pillar mines, and, while some operations practiced full recovery with pillar removal, most practiced partial mining. Consequently, 20 to 50 percent of the coal on a property was left as pillars. Assuming an extremely conservative recovery rate of only 50 percent, the approximate volume of voids left by underground coal mines in Indiana is approximately 530,000 acre-feet, or 23 billion cubic ft ($6.5 \times 10^8 \text{ m}^3$). If we are to assume that all the voids are intact and completely flooded, this represents a total volume of more than 172 billion gallons ($6.5 \times 10^{11} \text{ L}$) of water. By comparison, it has been estimated that abandoned underground mines of the Pittsburgh Coal of Pennsylvania and West Virginia, which is probably the most extensively mined mineral deposit in North America, will be filled with 1.4 trillion gallons ($5.3 \times 10^{12} \text{ L}$) by the year 2015 (Donovan and Leavitt, 2004).

Many of Indiana's underground mines are very shallow, so that the groundwater within them is readily accessible. Among 756 hoist shafts for which depths are recorded, 190 are less than 50 ft (15.2 m) deep, and 651 (86 percent) are less than 200 ft (60.9 m); the maximum recorded depth is only 506 ft (154.2 m) (IGS, 2010a). Among the underground mines in the Springfield Coal Member for which depth information is readily available, more than 38 percent of the workings (more than 31,000 acres [12,545 ha]) are less than 200 ft (60.9 m) deep (Table 2).

POTENTIAL USES

Groundwater is a very important resource in Indiana. In 2000, the statewide rate of use was 656 million gallons ($2.5 \times 10^9 \text{ L}$) per day, of which 71 percent was used for public water supplies and individual household use, 13 percent for irrigation and livestock, and 16 percent for industry, mining, and electric power generation (Indiana Ground Water Association, 2009). But ground-water supplies in southwestern Indiana—particularly from bedrock aquifers—are very limited. If the water within the flooded voids of abandoned underground coal mines was of good quality, the mines would represent an important high-yield aquifer of potentially great commercial value.

Table 2. Approximate depths of underground workings in the Springfield Coal, based on recorded depths of shafts and slopes*

Depth range (ft)	Total area (acres)
50–100	8,600
100–150	9,600
150–200	13,500
200–500	46,500
> 500	4,800

* IGS (2010a).

As discussed below, most of the water in many of the underground mines is probably not presently suitable for human consumption. Nevertheless, there is evidence that the quality of water varies greatly from place to place, and other suitable uses besides drinking water might be found in some areas. Also, it is possible that the water quality may improve in the future, both by long-term natural processes and by the shorter-term implementation of remedial actions, perhaps involving managed aquifer recharge.

Geothermal

In the United States, Watzlaf and Ackman (2006) discussed the potential application to geothermal heat-pump systems of water from abandoned mines in the Pittsburgh Coal Bed of Pennsylvania, West Virginia, and Ohio. They noted that open-loop systems could be employed, and that potential problems with scaling and corrosion caused by the chemistry of the mine water could be prevented by using an air-tight loop that would isolate the mine water from the heat pump, or by using an isolation plate heat exchanger, together with incorporating corrosion-resistant materials into the piping system. They estimated that about 30 percent of the mine water could be annually extracted and returned to the mines without concern for long-term heat-transfer effects ("heat contamination"). Perhaps most importantly, however, they observed that "[p]rior to investigating the thermodynamic and hydrologic settings of underground mine pools, broad-based public acceptance and support of this concept of mine water as a renewable energy source is needed" (Watzlaf and Ackman, 2006, p. 7). In the United States, certain legal issues might also require clarification, such as ownership of the mine water and the need for injection well permits.

In 2009, a demonstration project was funded by the U.S. Department of Energy, as part of their Geothermal Technologies Program, to promote the use of mine waters for ground-source heat-pump systems (GSHP). The project involved retrofitting the National Guard State Headquarter's building in Illinois with a GSHP that uses water in a flooded underground coal mine that is 200 ft (60.9 m) deep (U.S. Department of Energy, 2010).

Outside the United States, efforts to use water from abandoned underground coal mines for geothermal heating and air conditioning have been undertaken in Canada, Scotland, the Netherlands, Germany, Poland, and Slovakia. Banks and others (2009) described in detail the operation of two geothermal systems in Scotland that had operated successfully since 1999. They noted that ground-source heat pumps can be used to extract heat from contaminated groundwater, and the lack of contact between the mine waters and the atmosphere is a critical factor in the success of the Scottish systems:

"The British reluctance to use minewater in open-loop ground source heat systems can, to some extent, be ascribed to the belief that there is a risk of iron and manganese oxyhydroxides precipitating out in heat exchange elements (or in a recharge well) necessitating regular replacement or maintenance... (p. 352) [But]...if pumping does not result in dewatering of the flooded mine horizon and admixture of oxygen, if the pipework and heat exchanger are sealed units, if recharge takes place well below the water level in the recharge well and if pressures are regulated in the system (e.g., by regulation valves on the discharge main in the recharge well), the potential for precipitation of ferric and manganese oxyhydroxides and of calcite should be minimized. These conclusions wholly support the operational experiences from [Scotland].... Although the findings of this study cannot automatically be extrapolated to other mine systems and water chemistries, they offer grounds for optimism that, by careful management of system pressures and minimizing exposure to atmospheric conditions, minewater-based GSHP schemes can function reliably and with minimal maintenance requirements." (Banks and others, 2009, p. 356)

Power plants

Ziemkiewicz and others (2005) discussed the potential use of water from abandoned mines of the Pittsburgh Coal Bed as cooling water for power plants. They showed that water quality varies from net alkaline with low metal concentrations to strongly acidic having high concentrations of metals, calcium, magnesium, and sulfate, and that nearly all the water would require treatment. Nevertheless, they estimated the water requirements for power plants of various types (600-megawatt pulverized coal, and 80-megawatt fluidized bed combustion) and noted that the estimated amount of water available from flooded mines in the Pittsburgh Coal Bed (95,000 gallons per minute [359,614 Lpm]) would theoretically support power plants at as many as eight potential sites, would be feasible using existing technology, and would be economically competitive with river water.

Zick (2010) noted that six power plants in northeastern Pennsylvania use water from mine pools as makeup water to cooling towers, and that others are investigating the use of such water as boiler feed. He noted that both types of uses require treatment.

In Indiana, it has been proposed that storage of energy generated by power plants during off-peak hours could be achieved by pumping water between flooded underground mines and overlying inactive surface mines (Purdue University, 2010).

Other uses

Bukowski and others (2007) discussed a variety of projects that were being evaluated in Poland for the possible use of voids in abandoned mines. In addition to their possible use as water and geothermal reservoirs, other projects that were considered include use of voids for disposal of fine-grained wastes from mines and power plants and as reservoirs for gas, liquid fuels, and brines. However, they noted that "so far, mainly due to economic reasons, none of these projects have been fully accomplished."

In the United States, flooded underground coal mines have been used on a limited basis for the disposal of fine-grained waste from coal-preparation plants ("slurry" or "tailings") and of by-

products from coal-burning power plants (ash). In Indiana, disposal of slurry has occurred at several sites, and disposal of ash at one site. Use of flooded underground mines for such purposes has been somewhat inhibited by environmental concerns, including disposal of decanted water and potentially adverse effects on groundwater.

Our current work suggests that controlled artesian outflows of mine water might be useful for diluting surface discharges of acid mine drainage (AMD) prior to their introduction into passive treatment systems such as wetlands or sulfate-reducing bioreactors. In the immediate future, however, the use of such outflows may be inhibited by technical and regulatory uncertainties associated with the use of methods whose efficacy has not previously been demonstrated.

CONCEPTUALIZING A COAL-MINE AQUIFER

Ultimately, the responsible and reliable use of the groundwater resources within coal-mine aquifers will require the development of hydrologic models that describe, and hopefully predict, their behavior. Harper and Olyphant (1992) discussed the requirements and limitations of mathematical models needed to quantitatively predict the hydrologic effects of human activities. Such models would involve time-dependent responses in the form of a continuity equation, in which changes of head are related to inflows and outflows of water. An example of such an equation might be:

$$\Delta h/\Delta t = \sum Q_i/(SA_T) - \beta(\Delta P_a/\Delta t) + \sum(\epsilon_i \Delta P_i/\Delta t) \quad (1)$$

where the terms of equation 1 are defined as follows:

$\Delta h/\Delta t$ = rate of change of water level in a well installed in a flooded mine void;
 Q_i = various horizontal and vertical fluxes into (positive) or out of (negative) the mine aquifer;
 S = storativity of the mine aquifer;
 A_T = area of the mine aquifer;
 β = barometric efficiency;
 $\Delta P_a/\Delta t$ = rate of change of atmospheric pressure (in units of water depth);
 ϵ_i = other pressure coefficients that are analogous to barometric efficiency;
 $\Delta P_i/\Delta t$ = other time-dependent pressure effects (in units of water depth), such as those resulting from overburden loading, earth tides, methane migration, and others.

Some of these variables are amenable to easy measurement with great accuracy (such as h , β , P_a , and P_i). Good estimates of the areas of mine aquifers (A_T) are possible because maps of most of the mines in Indiana are available in the form of georeferenced GIS layers, although uncertainties can be introduced where undetected connections (boreholes or isolated tunnels) might exist between mines that would otherwise be isolated from each other. Storativity (S) can be estimated through experiments, and several such experiments conducted at mines in Indiana are described below. Unfortunately, the various inflows and outflows (Q_i), which are presumed to be the primary cause of changes in hydraulic head, are usually difficult or impossible to determine. Many springs that are believed to issue from flooded underground mines were mapped, but long-term monitoring of their outflows has never been conducted in Indiana. Such springs typically occur in the topographically lowest areas that overlie the mines, and many are associated with man-made features such as boreholes (see discussion below, p. 11), but an even larger number of undetected springs, seeps, and subsurface outflows from mines (into overlying alluvium and other unconsolidated deposits) probably exist. For some deeper mines, even ones that were abandoned several decades ago, surface discharges may not currently exist, but such discharges may yet develop in the future.

Because of the many uncertainties regarding critical boundary conditions and the hydrologic character of geologic media, Harper and Olyphant (1992) saw serious limitations to traditional theoretical and numerical approaches; they recommended the use of more empirical approaches, using detailed observations and changes in potentiometric levels of mines and associated strata to infer pathways and calibrate statistical equations for predicting hydrologic conditions.

In summary, the chief characteristics of mine aquifers that are of interest in the development of models, whether they be theoretical or empirical, include:

1. Mechanisms of recharge and discharge of mine pools;
2. The extents of individual mine pools, including those in districts with multiseam mining;
3. Current potentiometric levels of mine pools and long-term variations in those levels; and

4. Values of storativity and barometric efficiency for various mine pools.

These characteristics will be discussed in detail below.

Inflows and outflows

Systematic investigations of recharge and discharge from mine pools in Indiana are entirely lacking. For flooded underground coal mines, we can conceive of a great variety of possible recharge and discharge mechanisms, both lateral and vertical (fig. 3).

In their natural state, the coal beds of Indiana were typically interbedded with aquitards such as shales and underclays of low permeability. But in the past 100 years, these confining layers have been breached by intensive mining and drilling activity. Many underground mines are bordered or overlain by surface mines. In addition, thousands of holes, many of which were never properly plugged or sealed, now penetrate the mines' overburden.

And finally, vertical percolation through the overburden may occur in places where the bedrock has been fractured by the collapse of roof strata into a mine's voids (mine subsidence).

Surface mines

In Indiana, many shallow underground mines are immediately adjacent to spoil deposits and high-wall lakes left by surface mines that operated in the same coal bed. Spoil deposits are the disturbed and displaced overburden from surface mining. Composed of fine-grained to very coarse grained materials, spoil is extremely heterogeneous, and estimates of its hydraulic conductivity may range over four orders of magnitude (from 10^{-6} to 10^{-2} m sec⁻¹) (Maher and Donovan, 1997). In addition to being flanked by surface mines, many underground mines are directly overlain by surface mines that operated in overlying coal beds. For the Springfield Coal Member alone, as much as half of the underground-mined areas may either be flanked or directly overlain by spoil deposits and highwall lakes.

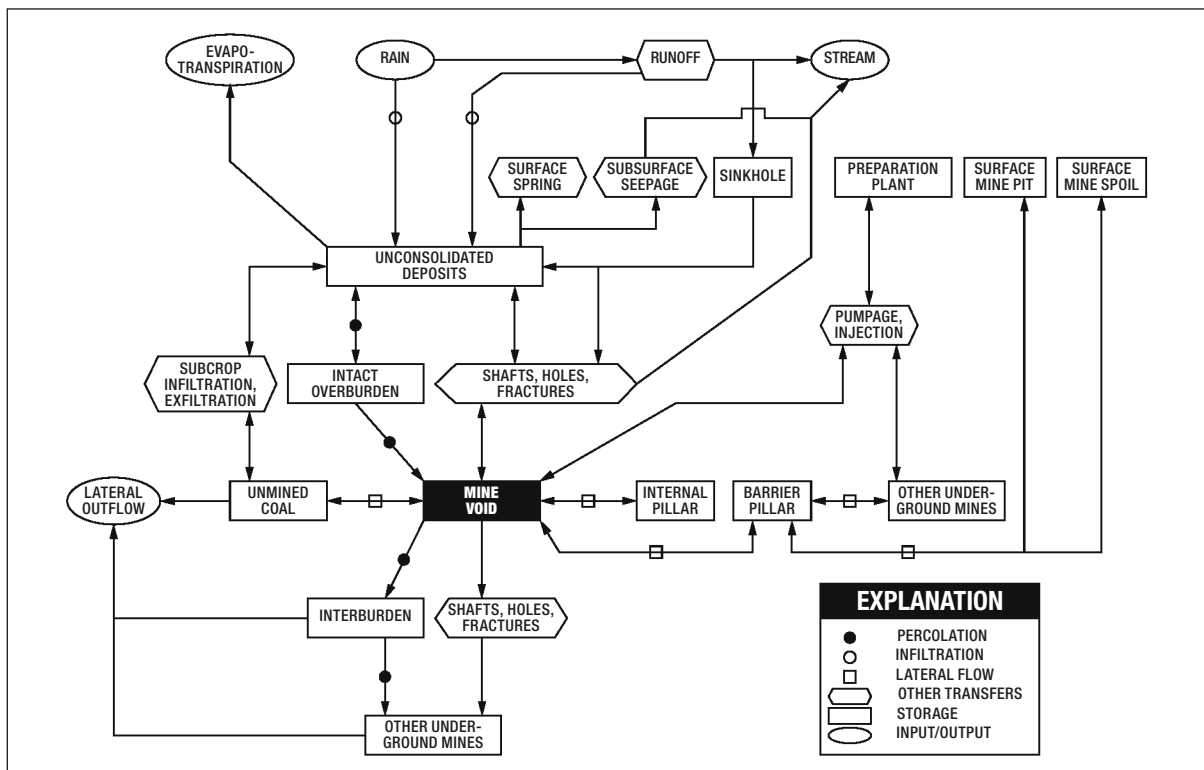


Figure 3. Schematic diagram showing potential flowpaths of groundwater within and around flooded underground coal mines.

In Indiana, as discussed by Cocroft (1984, p. 47):
 “Strip-mined portions of the study area provide excellent recharge capabilities to shallow aquifers ... [because] the disturbed area contains a mixture of rubble that is highly porous and permeable. The adjacent high-wall areas are fractured due to the ... mining activities. These abandoned strip mine areas store water ... and release water.”

Nevertheless, quantitative data regarding the contribution of spoil deposits and highwall lakes to the recharge of nearby underground mines are almost entirely lacking.

Fractured overburden

Because they are so shallow, many of the underground mines in Indiana experienced problems with roof collapse and inflows of water, even when they were active. For example, although the Dresser Mine (Vigo County) was at a depth of 200 ft (60.9 m), much of the overburden consisted of sands and gravels of the Wabash River, and it was necessary to build thick (and expensive) concrete bulkheads to hold back the water in certain areas:

“... at Dresser the water usually breaks through if there is less than 65 ft. of solid material protecting the coal from the water-saturated gravel above... [P]illars in abandoned areas squeeze down and allow the top to break. In many cases, these breaks extend up to the water-bearing deposit. With the Wabash River in flood... some bulkheads have been called upon to withstand 90 lb. per square inch.” (Coal Age, 1938)

Collapse of roof strata can continue long after the cessation of underground mining, and the overlying land is subject to development of both sinkhole-type and sag-type subsidence (Harper, 1982) (fig. 4). In Indiana, sinkholes may exceed 25 ft (7.6 m) in depth and involve the downward movement of as much as 500 yards³ (382 m³) of unconsolidated sediments. Sinkholes generally occur where mines are less than 150 ft (45.7 m) deep, but shallow sag-type subsidence can occur over mines at depths down to and exceeding 450 ft (137.1 m).

Some subsidence features in Indiana have been mapped (fig. 5), but many additional features probably exist that have never been mapped, including

sinkholes in forested areas that cannot be observed from aerial photographs and subtle sags in farm fields whose origins are not easily determined. Some subsidence features may become more evident after heavy rainfall because they may hold standing water.

In West Virginia, it was determined that subsidence fractures caused by room-and-pillar mines increased hydraulic conductivity, which caused increased infiltration of precipitation and surface water, so that both gaining and losing streams were found in mined areas (Hobba, 1993). In Ohio, it was shown that water was preferentially recharged to an abandoned underground coal mine through subsidence features, and that a stream draining an overlying watershed was captured by a subsidence feature, contributing 60 to 80 percent of the mine's outflow (Pigati and Lopez, 1999).

In Indiana, only anecdotal reports exist regarding the role of subsidence features in the capture of surface drainage. At several sites, sinkholes are known to have developed along the axes of small upland streams, and capture of surface drainage has occurred in places. For example, in southeastern Boonville (Warrick County), much subsidence occurred along a tributary of Cypress Creek, just downstream of a large stream-capturing sinkhole. In a few places, such as along an upland tributary of Lagoon Creek, east of Jasonville (Greene County), some sinkholes along a streambed were plugged as part of the Abandoned Mine Lands (AML) Program of the Indiana Department of Natural Resources, Division of Reclamation. However, no attempt has been made in Indiana to systematically map such stream-capturing features or to determine their effects on subsidence or discharges of AMD.

In addition to providing potential connections between the land surface and underlying mines, collapse of roof strata can potentially create flow paths between subjacent mines in multiseam mining districts. In such districts, the rock strata between mines sometimes collapsed, disrupting active operations. For example, as indicated by notations on a mine map (“No. 5 Seam Caved”), eastward mining in the New Hope No. 6 Mine (Hymera Coal Member) (Greene County) might have been limited by disturbance of the coal bed caused by collapse of strata in the underlying New Hope No. 5 Mine (Springfield Coal Member). It is unknown whether such fracturing of interburden

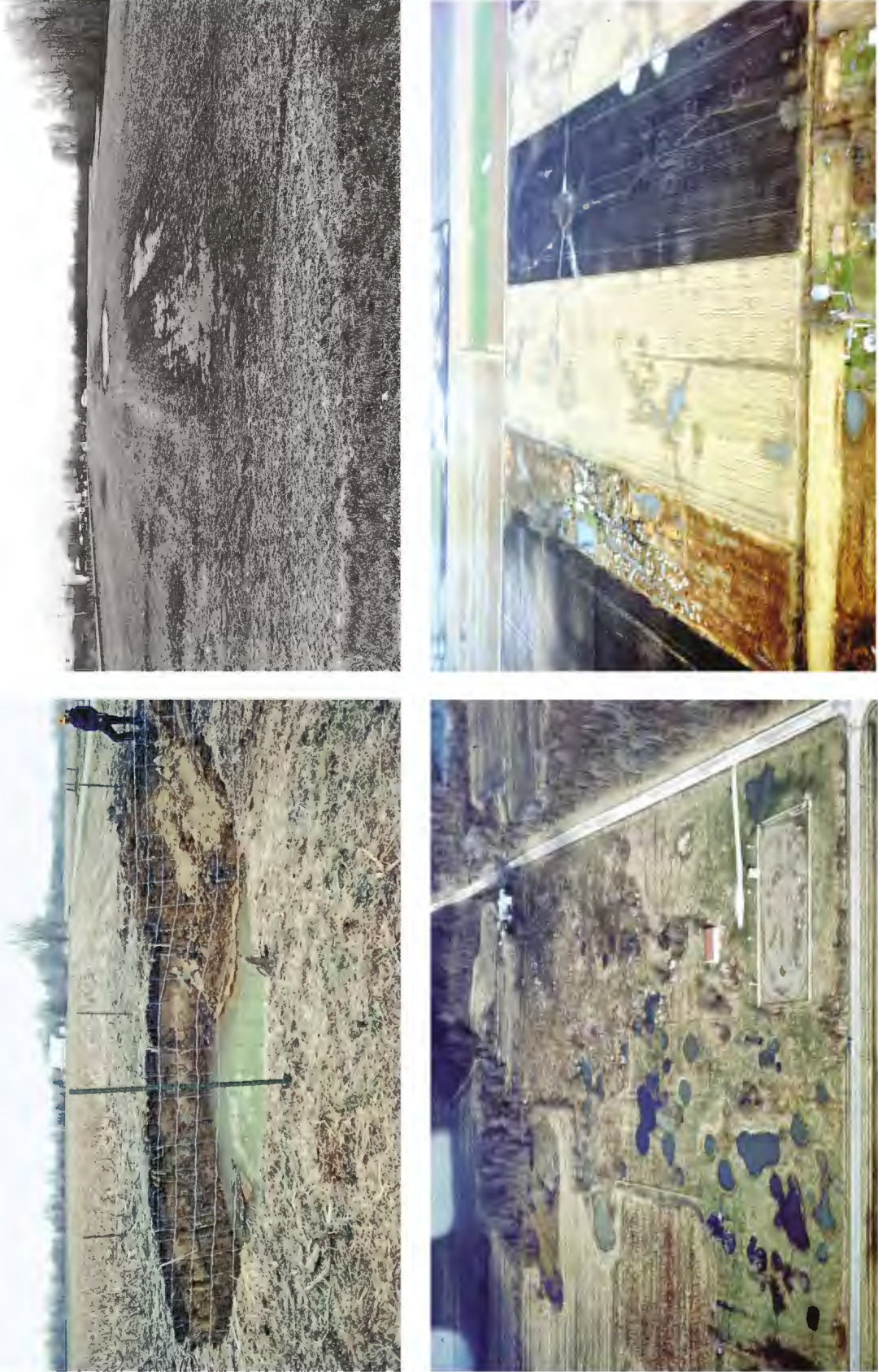


Figure 4. Photographs showing examples of sinkhole-type subsidence (left) and sag-type subsidence (right) in Indiana.

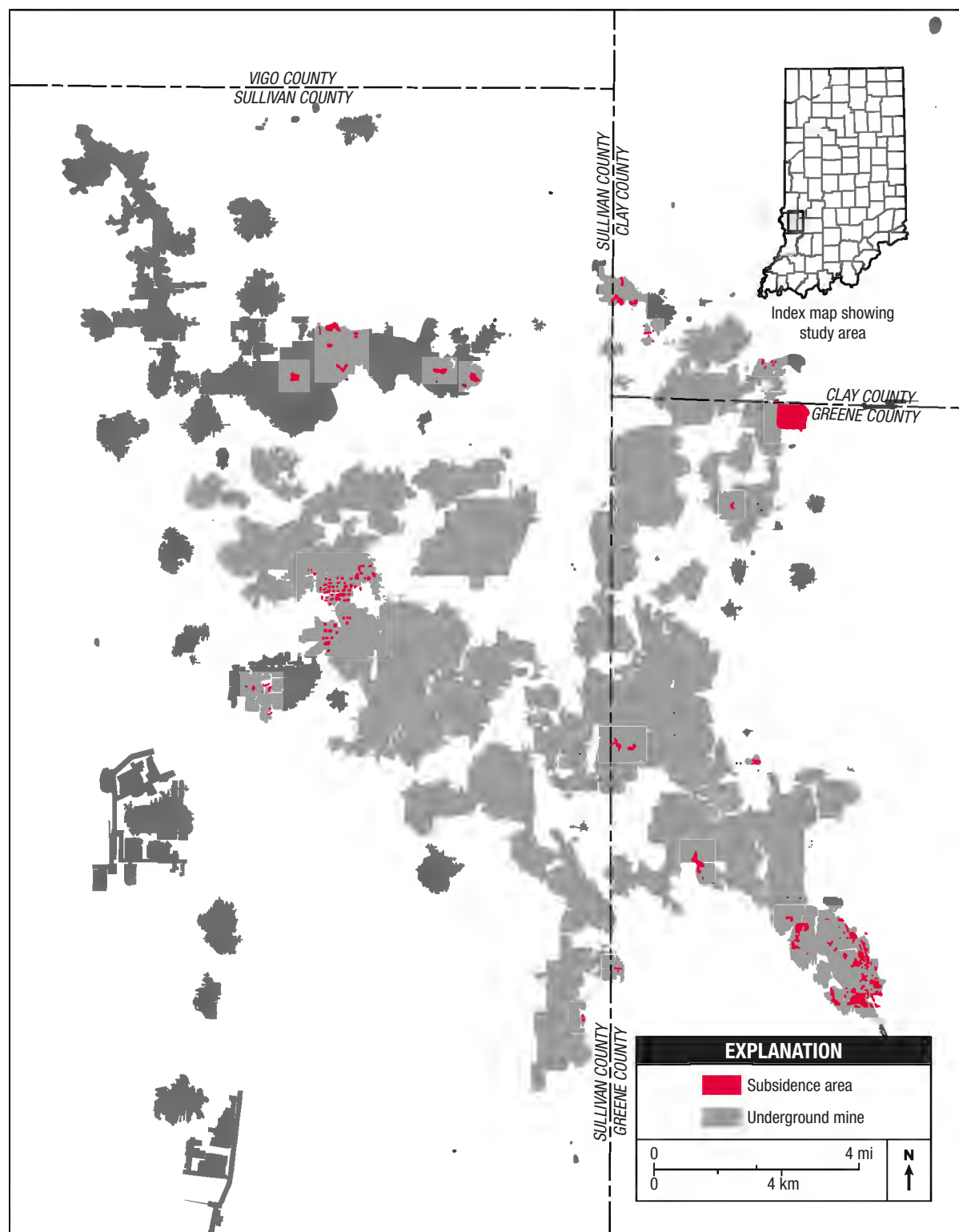


Figure 5. Map showing the locations of subsidence features that have been mapped in parts of Greene, Sullivan, Vigo, and Clay Counties, Indiana. Source: IGS (2010a).

might represent hydrologic pathways of relatively low resistance between mines.

Finally, it should be recognized that roof collapse affects the horizontal flow of water through flooded workings. Void spaces may migrate upward, so that flow paths are diverted upward into the overburden. Within the mine passages themselves, the presence of rock rubble may increase the resistance to flow.

Mine entries

The large underground mines of Indiana were accessed through thousands of vertical shafts and oblique slopes. In addition, hundreds of small mines were accessed through horizontal adits into hillsides (fig. 6 and Table 3).

To avoid flooding and minimize leakage during active mining, the mine entries were often placed in topographically higher portions of a mining property. Shafts and slopes had diameters that typically ranged from 10 to 25 ft (3 to 7.6 m). Larger shafts were often compartmentalized for the transport of men and coal and for utility lines. Smaller shafts were sometimes emplaced for ventilation or coal removal. Most were lined with wood or concrete.

Through most of Indiana's mining history, many operators plugged and sealed their shafts and slopes at the time of a mine's abandonment. The objective, however, was to prevent human entry or later collapse of the shafts, and no consideration was given to hydrologically sealing these very large-diameter features. Materials and procedures for sealing shafts were not standardized nor specified in detail by either state or federal laws. Collapse of old shafts has occurred intermittently, such as the collapse in the 1980s of a shaft into the Green Valley Mine (Vigo County), which was abandoned in 1963 (fig. 7).

Of the 1,098 underground mines in Indiana for which dates of abandonment are known, 1,037 (94 percent) were abandoned before 1977, when the federal Surface Mining Control and Reclamation Act (SMCRA) was enacted. As recently as 2009, the Coal Mining Law of Indiana simply stated:

"All entrances to an abandoned mine shall be filled by the operator last engaged in the operation of the mine immediately following aban-

donment of the mine. Vertical openings shall be filled and maintained from the bottom to the surface. All other mine openings shall be filled and sealed in a manner prescribed by the director." –Indiana Code, Title 22, Article 10 (Indiana Department of Labor, 2009)

The Indiana Department of Natural Resources, Division of Reclamation, has an ongoing program to identify and fix open shafts, collapsed shafts, or shafts that present a danger of collapsing. Nevertheless, there remain several thousand shafts and slopes, many of which may be poorly sealed, that represent potential hydrologic pathways for the movement of water from the surface and from surficial deposits into underground workings, as well as the exchange of water between subjacent underground mines in districts where multiseam mining was practiced.

Mine utility holes

While they are active, many underground mines must be dewatered constantly to remove groundwater that enters through the coal bed and the roof strata. When mines are small, water may be collected in a sump near the bottom of the shaft, from which it is pumped to the surface. But when mines grow large, it may become more efficient to collect water at various points within the mine, and then pump the water directly to the surface through boreholes that are drilled down into the mine from the surface. The holes were typically 6 to 18 inches (15.2 to 45.7 cm) in diameter and cased with steel. The locations of such holes were often plotted on mine maps, where they are referred to as "pump holes" or "discharge holes." For example, nine discharge holes are shown on the map of the New Hope No. 5 Mine (Indiana Geological Survey Coal Mine Information System [CMIS] Mine #342132) (Greene County), where the spacing between holes was as little as 870 ft (265.1 m), and two such holes are shown on the map of the smaller, overlying New Hope No. 6 Mine (CMIS Mine #342130), where the spacing between holes was only 700 ft (213.3 m).

Similarly, so long as mines were small in extent, high-voltage electrical cables were typically passed through the shaft. But as the mines grew in size, running such cables through long mine passages was both inefficient and unsafe, so holes were drilled at intervals on the surface. These steel-cased holes, similar to the pump holes, were

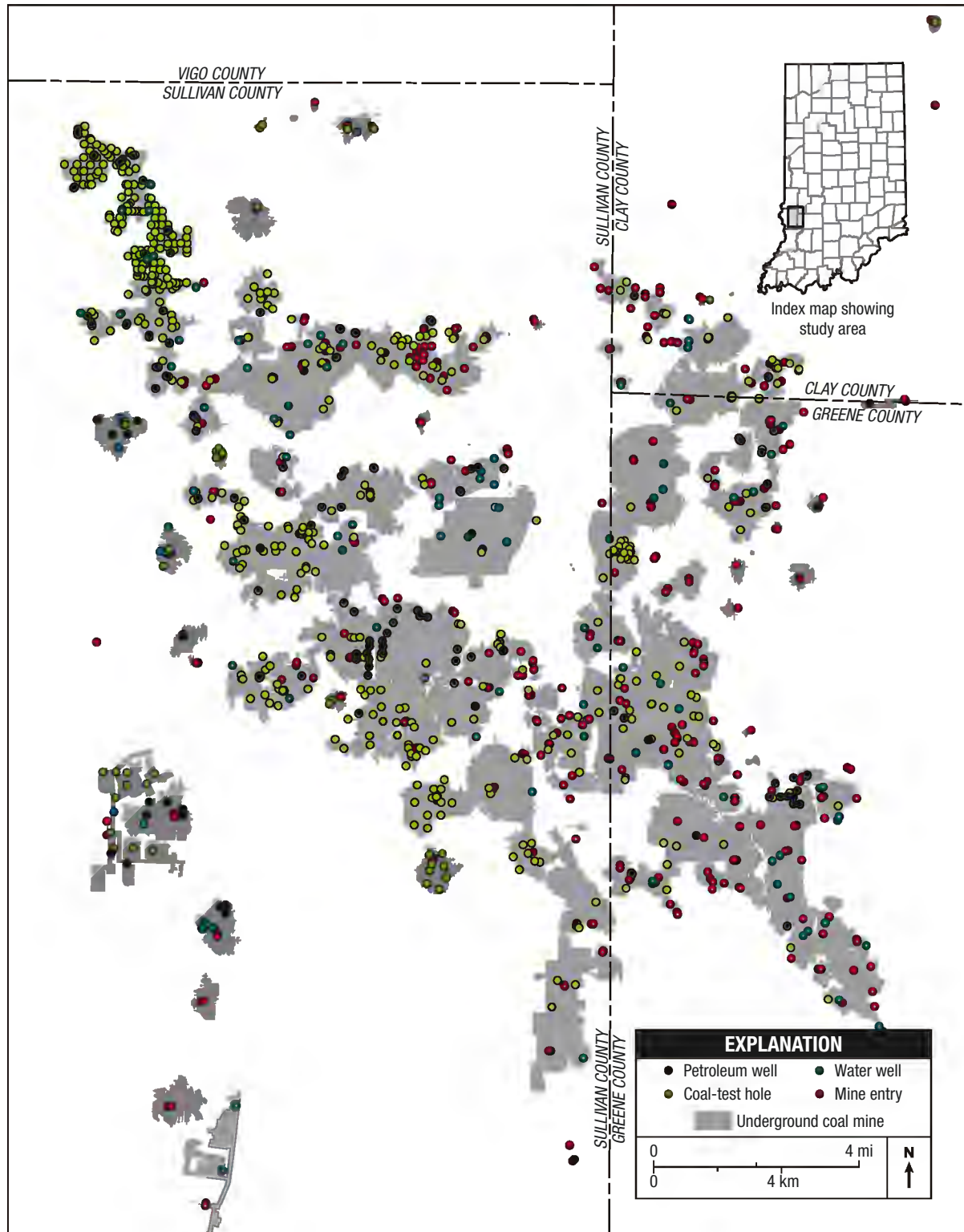


Figure 6. Map showing mine entries, coal-test holes, oil and gas wells, and water wells that are located within the boundaries of underground coal mines in parts of Greene, Sullivan, Vigo, and Clay Counties, Indiana. Sources: Coal Mine Information System and Petroleum Database Management System of the Indiana Geological Survey, and the water-well-record database of the Indiana Department of Natural Resources, Division of Water.

Table 3. Number of mine entries in Indiana*

Category	Number
Vertical mine shafts	1,131
Mine slopes	1,971
Other mine entries	577

* IGS (2010a).

often plotted on mine maps, where they are referred to as “convertor holes,” “cable holes,” or “power holes.” On the map of the New Hope No. 5 Mine, for example, several convertor holes were paired with pump holes at distances of as little as 40 ft (12.1 m) apart.

Some of these holes happened to have been installed where the elevation of the overlying land is relatively low, and at least as late as the 1980s, some were sources of artesian outflows of mine water (fig. 7). The locations of all such holes in southwestern Indiana have never been systematically mapped, but at least several hundred probably were emplaced. For most of Indiana’s mining history, there were no regulations regarding the abandonment of pump holes and power holes, and many may still be extant.

Drill holes

Both recharge and discharge may occur by leakage around or through some of the thousands of oil and gas wells and water wells that pass through the internal pillars and unmined blocks of coal that remain within abandoned underground coal mines (Table 4).

Within the coal-mined area of Indiana, the oldest petroleum well for which records are available was drilled in 1897, and at least 80 were drilled before 1930, some of which were not plugged until 2008 (IGS, 2010b). Several hundred were drilled during the 1930s and 1940s. Before the 1930s, shallow oil and gas wells were often abandoned without installing a cement plug. From the 1930s to 1952, wells typically had a cement plug, and, after 1952, modern methods of plugging (including the use of additives that inhibit the degradation of cement) became widespread. Nevertheless, it has been noted that “a potential for leakage exists in a wide variety of inactive wells, even from those that are properly sealed with cement” (Ide and others, 2006, p. 5). Also, many wells were left unplugged when petroleum companies became insolvent, such as occurred widely in 1986. Most oil and gas wells presumably penetrate pillars and unmined blocks of coal within the mines, but, as discussed above, such pillars are subject to failure, thereby exposing concrete plugs and steel casings to corrosive waters. Shedlock (1980) concluded that saline waters had moved from the open sections of boreholes of abandoned oil wells into fractures in sandstone bedrock, and from there into a shallow glacial outwash aquifer near the municipal well field of Vincennes (Knox County). Stumpf (1982, p. 79) suggested that a shallow well in Pike County containing sodium-chloride water (285 ppm and 391 ppm, respectively) might be receiving upwelling brines associated with oil and gas production in the area. Thus, the potential exists for the entry of brines, petroleum, and petroleum-associated gases into the mine workings.



Figure 7. Photographs showing the collapsed shaft of the Green Valley Mine (left), and an artesian outflow of acid mine drainage from an abandoned, unplugged pump hole (right). The photographs were taken in the early 1980s.

Table 4. Number of wells that penetrate underground coal mines of Indiana

Category	Number
Exploratory coal-test holes	1,294*
Petroleum test wells	1,180†
Water wells	1,082‡
Mine utility holes	unknown
Waste disposal holes	unknown

* Indiana Geological Survey (2010a).

† Harper and Olyphant (1991, p. 277).

‡ Assumed to be equal to the value for the Survant Coal.

Abandoned oil and gas wells can also serve as conduits for the emergence of AMD from underground mines onto the surface. Originally thought to have been brines from gas-producing sands, at least 20 artesian outflows in Pennsylvania were determined to be AMD derived by downward flow from coal mines: “AMD formed in the coal mines is infiltrating into lower aquifers, moving outside the lateral limits of mining, and using abandoned gas wells as conduits to the surface” (Hedin and others, 2005).

In addition to petroleum test wells, more than 1,000 water wells pass through the underground mines of Indiana (Table 4). Although most of these wells presumably penetrate pillars and unmined blocks of coal within the underground mines, such pillars are subject to crushing and fracturing, so that any water wells with steel casings could become exposed to chemically corrosive waters within the mines (primarily chloride-rich waters). Failure of the casings could then result in entry of AMD into either overlying or underlying aquifers. The authors are personally aware of an incident where the failure of a residential water well penetrating the Blackhawk Mine in southeastern Vigo County resulted in contamination of the residence’s water supply by AMD.

Finally, more than a thousand coal-test holes were drilled within the boundaries of mines and in immediately surrounding areas (Table 4). These exploratory coal-test holes were drilled by coal companies and others in the exploration and development of coal properties. The National Coal Resource Data System (NCRDS) shows the locations of almost 1,300 such holes within the boundaries of underground mines alone, and

hundreds or thousands more are indicated on maps of abandoned mines.

These exploratory coal-test holes were typically of small diameter (1.5 inches [3.8 cm]) and were never cased. Most were probably never plugged using modern hole-plugging methods. It is possible that some of these exploratory holes later became sites of artesian outflows of mine water; inspection of a mine map indicates that a major artesian outflow of AMD from the New Hope No. 5 Mine, about 1.3 miles (2.1 km) northeast of Dugger (Greene County), may be associated with such a feature (Harper and others, 1992, p. 36).

Waste-disposal holes

Several anecdotal reports exist regarding the disposal of septic wastes into shallow underground mines, but there are no published reports regarding the possible use of abandoned underground coal mines for disposal of septic, industrial, or other wastes. In 1984, at a site near Linton (Greene County), a hydrologic investigation was conducted by personnel of the Indiana Geological Survey (IGS) and the U.S. Geological Survey in association with a subsidence event. As part of the investigation, a water sample was collected from a well about 60 ft (18.2 m) deep into an unnamed mine into the Survant Coal Member and submitted for bacterial analysis. Although no *Escherichia coli* were detected, species of *Pseudomonas* and *Proteus* were detected in moderate abundances (Smith and others, 1985). It was known that septic waste from a mobile home about 300 ft (91.4 m) from the sampling well was being disposed of into the mine.

By April 16, 2010, the Indiana Department of Environmental Management had identified a number of waste-disposal sites that directly overlie or are in close proximity to underground coal mines, including 6 open dumps that are not regulated and may be illegal dump sites of solid waste; 11 old landfills that never received permits under current regulations; 21 industrial waste sites that generate or manage hazardous waste, nonhazardous industrial waste, and solid waste; and 10 cleanup sites that require mitigation of risk to human health and the environment through investigation, remediation, or institutional controls. Whether there are any adverse environmental effects of such sites on groundwater in underlying mines is largely

unknown. However, any contaminants that enter the groundwater at such sites could potentially be disseminated widely through flooded workings.

Flow within mine pools

The Coal Mine Information System (IGS.indiana.edu/CMIS) of the IGS contains a very large archive of mine maps and other data relating to the underground coal mines of Indiana. The digitized and spatially georeferenced maps allow very detailed and accurate calculations of the areas of the original void spaces within the mines. For some mines, notations on the maps provide data regarding small-scale variations in the thickness of the coal bed, as well as indications of potential hydrologic interconnections between mines.

Most older room-and-pillar mines used some variety of panel mining. That is, the property was exploited by creating interconnected networks of development entries used for transporting men, materials, and coal; these were necessary for mine-wide ventilation, drainage, haulage, and electrical systems. Because these development entries were essential for the long-term functioning of mining systems, mine operators usually tried to protect them from roof collapse by driving them narrowly (typically 12 to 15 ft [3.7 to 4.6 m]) and leaving adjacent pillars that were as wide, or wider, than the entries (Coal Age, 1938). In the absence of any other evidence, we can speculate that flow within flooded underground mines might be concentrated within these development entries.

In contrast to the development entries, most of a mine's coal production came from sets of production entries, which were often made as wide as possible (typically 21 to 30 ft [6.4 to 9.1 m]) and having narrow (8 to 18 ft [2.4 to 5.5 m]) intervening pillars. Consequently, the production entries were highly subject to roof collapse, and many failed during mining or shortly after the cessation of mining. On mine maps, sets (or panels) of production entries often appear as cul-de-sacs, so that we might expect to find slow flow or stagnation within such areas. Often, however, miners broke through from one set of production entries to another or the narrow intervening pillars were crushed, so that direct hydrologic connections between panels may have been created, in which case flow rates might be greater than would otherwise be expected.

Our understanding of the flow dynamics within mine pools would be greatly enhanced if it were possible to conduct dye-trace experiments within flooded mines. But difficulties occur using dyes and other tracers to investigate the nature and directions of groundwater flow within abandoned underground coal mines (Aldous and Smart, 1988). These include the chemical effects of acidity on fluorescence, the chemical interaction of dyes with ferric hydroxide deposits, and the complexity of mine workings, including the presence of unmapped roof collapses and breaches in barrier pillars.

To our knowledge, only one attempt has ever been made to directly measure flow rates or flow directions in abandoned underground coal mines of Indiana. In May 1984, a subsidence event destroyed a house that was located south of Linton (Greene County). As part of the subsidence investigation, several holes were drilled by the U.S. Office of Surface Mining, and these holes were subsequently used by personnel of the U.S. Geological Survey and the IGS to conduct a dye-tracing experiment. Rhodamine-WT dye was injected on two occasions using different injection wells. Flow through the underground mine was determined to be northerly at a rate of 0.3 to 22 ft per day (9 cm to 6.7 m per day) (Smith and others, 1985). It was inferred that the observed variation in flow rates was related to aspects of the mine plan, with the slower flow occurring within an isolated room and the faster flow occurring within intact entries. It was also inferred that flow through the underground mine was driven by the difference in hydraulic head between a lake in a final-cut pit at a surface mine located about 400 ft (121.9 m) southeast of the study area and a final-cut lake located about 1,300 ft (396.2 m) to the northeast, both of which probably directly abutted underground workings.

In addition to understanding flow paths within a particular flooded mine, the development of useful hydrologic models requires knowledge regarding the barriers and connections between neighboring mines. In the Appalachian Coal Basin, attempts were made to develop methods for producing chronological flooding maps and predicting future discharge locations for selected mine pools (Leavitt and others, 2003; Morris and others, 2008). In such efforts, the importance of intact barrier pillars that were sometimes left between mines was noted:

"Where these barrier pillars exist they form a significant restriction to mine flooding. Heads in excess of 280 feet have been observed across mine barrier pillars. Despite this restriction, water leakage from mine to mine through the barrier pillars can have a significant effect on mine flooding rate." (Leavitt and others, 2003, p. 1,068)

Where barrier pillars between mines remain intact, values of hydraulic conductivity in the Pittsburgh Coal Basin are estimated to range from 0.12 ft day⁻¹ to 0.32 ft day⁻¹ (3.7 to 9.8 cm day⁻¹) (McCoy and others, 2006). In the absence of direct measurements, a similar range of values may be assumed to exist for coal beds in Indiana.

Some of the greatest disasters in the history of coal mining occurred when miners were drowned or trapped after unintentionally breaking into the flooded workings of neighboring abandoned mines. Modern mining laws specify that operators of underground mines must conduct exploratory drilling in advance of mining whenever they approach within 200 ft (60.9 m) of abandoned mines. But many older underground mines of Indiana came in very close proximity to neighboring mines, and, in some places, physical connections were purposely made between mines. Places where barriers between mines were penetrated are sometimes indicated by notations on mine maps, even though the actual connections may not be shown. For example, along the southern boundary of the New Hope No. 6 Mine (CMIS Mine #342130) (Greene County), there are notations ("Drilled Thru," "Cut Thru," and "Holed") indicating that connections were made with the neighboring Sunflower No. 6 Mine.

Long-term changes in water levels

For confined or semiconfined aquifers such as flooded underground mines, the level to which water will rise in wells installed in the aquifer is referred to as the aquifer's "potentiometric surface." Because water can typically flow freely through the interconnected tunnels of underground mines, the potentiometric surface may be perfectly flat across the entire extent of a mine or interconnected group of mines, even those underlying several square miles. Changes in the potentiometric level of a mine pool indicate that changes occurred either in the balance between inflows and out-

flows, or that changes occurred in the volume of available storage.

Between 1985 and 1997, as part of a series of reclamation-related projects, personnel of the IGS installed monitoring wells into the voids and pillars of six flooded underground mines of different sizes and depths. At each site, water levels were recorded at regular intervals for periods ranging from 17 months to 9 years (fig. 8).

As discussed below in a series of case studies, each long-term water-level record was found to have unique characteristics, so there are few similarities from one site to another. Although several records may show some evidence of a drought in 1988, the water-level records at any given site often changed unpredictably, and we can only speculate about the causes of these changes.

Blackhawk Mine

The Blackhawk Mine (CMIS Mine #800514) in southeastern Vigo County is a flooded underground mine that operated in the Springfield Coal Member between 1919 and 1951. The depth of the mine ranges from 83 ft to 260 ft (25.2–79.2 m). At its deepest point, it is separated from a neighboring mine, the Dixie Bee Mine (CMIS Mine #800515), by a barrier pillar that is approximately 250 ft (76.2 m) wide (fig. 9).

Together, the two mines exploited relatively thick coal that is associated with a structural trough in the Springfield Coal Member. Total production from the Blackhawk and Dixie Bee Mines was 6.2 and 2.1 million short tons (5.6 and 1.9 million metric tons), respectively (Wier, 1952), and the areas underlain by the two mines are 1,661 and 449 acres (672 and 182 ha), respectively. Assuming an average recovery rate of 0.5 and an average thickness of 5.5 ft (1.7 m), the storage capacities of the two mines when fully flooded would be 1.5 billion and 0.9 billion gallons (5.7 billion and 3.4 billion L), respectively.

Between 1949 and 1952, an unnamed surface mine (CMIS Mine #200506) was active in the Springfield Coal Member, just updip from the Blackhawk Mine (fig. 9), approaching as closely as 500 ft (152.4 m). Today, this surface-mined area is characterized by ungraded spoil deposits and by ponds and lakes, the largest of which, French Lake, is about 60 acres (24.2 ha) in extent. The lake may

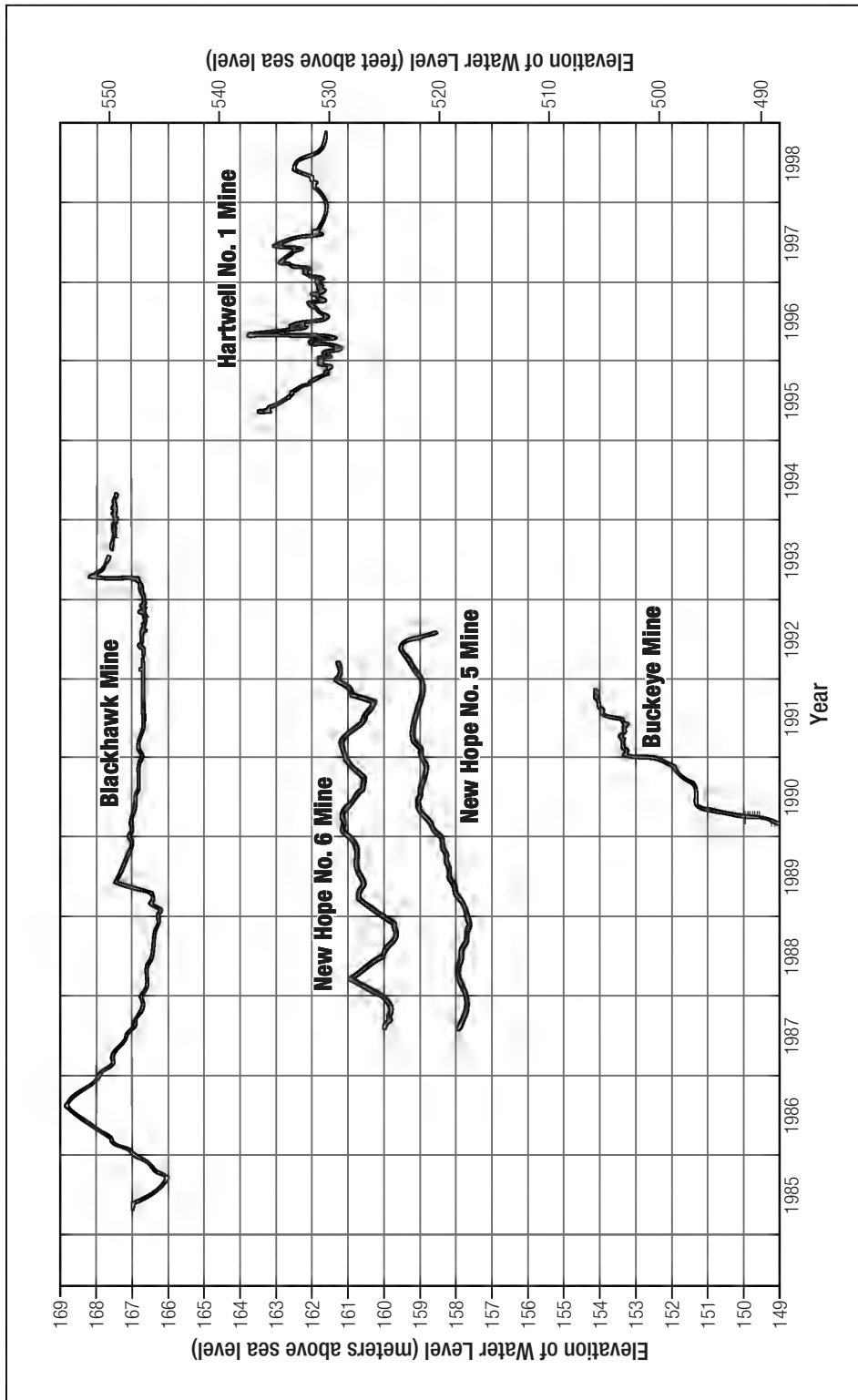


Figure 8. Graph showing the elevation of water in monitoring wells installed in voids of the Blackhawk, New Hope No. 6, New Hope No. 5, Buckeye, and Hartwell No. 1 Mines. Data from the Mutual Mine is not included. See Figure 1 for locations.

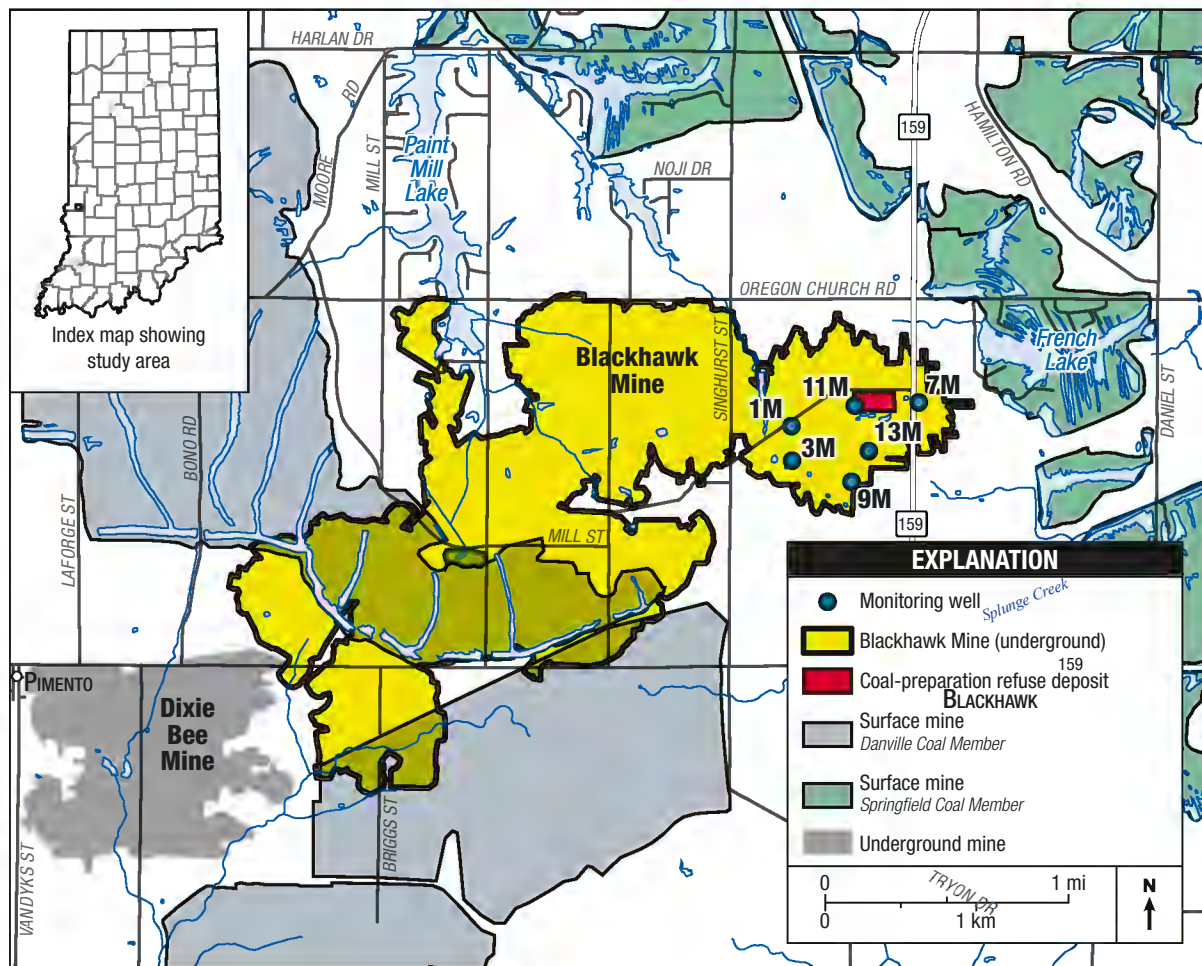


Figure 9. Map showing the Blackhawk Mine (Springfield Coal Member), the locations of monitoring wells installed in the mine, and the relationship of the mine to other surface and underground mines and to a deposit of pyritic coal-preparation refuse.

be a source of recharge to the underground mine (Funkhouser, 1983, p. 37); it is surrounded by houses and its water is of good quality. A surface mine in the Danville Coal Member (Chieftain No. 20 Mine, CMIS Mine #200487) that was active between 1958 and 1968 directly overlies 407 acres (164.7 ha) of the Blackhawk Mine. Within this area, more than 68 acres (27.5 ha) of highwall lakes directly overlie the underground mine. A surface mine in the Danville and Hymera Coal Members (Farmersburg Mine, CMIS Mine #203351) that was active between 1996 and 2008 directly overlies an additional 83 acres (33.5 ha) of the Blackhawk Mine. The pits extended down to depths of 70 ft (21 m) in areas where the Blackhawk Mine was as little as 200 ft (60.9 m) deep. Within those areas, more than 18 acres (7.3 ha) of highwall lakes directly overlie the underground mine. These may also represent areas of potential recharge to the underground mine.

The land surface above the shallowest part of the Blackhawk Mine experienced significant subsidence, manifest by dozens of broad sags that are visible on historical aerial photographs. Cores of the roof strata (black shale) exhibited fractures as much as 19 ft (5.7 m) above the Blackhawk Mine. In the area overlying the Blackhawk Mine, several anecdotal reports exist of gas emissions from water wells, a gas and water outburst in an open field, and a gas and water outburst while a water well was being drilled (Harper and others, 1990, p. 185).

Between July 16 and November 17, 1984, a 40-acre (16.1-ha) pile of coarse-grained refuse from a coal-preparation facility was reclaimed by burial in shallow pits (less than 30 ft [9.1 m] deep) that were excavated into unconsolidated surficial materials (Harper and others, 1990, p. 180). As part

of reclamation feasibility investigations, six wells were installed in voids and pillars of the Blackhawk Mine (fig. 9). Water-level measurements were made manually on a monthly basis between April 15, 1985, and August 14, 1991, and measurements were made electronically on a daily basis between February 8, 1992, and September 20, 1994 (fig. 8).

Among the wells installed in voids, water-level changes were essentially simultaneous and equal. During the 9-year period of monitoring, the water level in the voids was distinguished by three striking perturbations, each of which was characterized by a linear rise followed by a prolonged exponential decline (fig. 8 and Table 5).

If we make certain assumptions regarding the mine's storativity (S) (see discussion below) and extent (A_T), then we can estimate the volumes of water (V_w) and rates of inflow (V_w/t) that are represented by these linear rises (Δh), where:

$$V_w = S \cdot A_T \cdot \Delta h \quad (2)$$

The estimated inflows are summarized in Table 6. Each of the linear rises was followed by a prolonged exponential decline (fig. 8). These declines can be described by the standard recession equation:

$$h = h_0 e^{-bt} \quad (3)$$

Table 5. Linear rises of the potentiometric level of the Blackhawk Mine

Period	Duration (t) (days)	Rise (Δh) (ft)	Rate ($\Delta h/t$) (inches/day)
September 13, 1985–August 12, 1986	333	9.25	0.33
February 8, 1989–June 13, 1989	125	4.32	0.41
April 12, 1993–April 19, 1993	7	4.84	8.30

Table 6. Estimated inflows of water associated with linear rises of the potentiometric level of the Blackhawk Mine

Storativity (S)	Extent (A_T) (acres)	Volume of water (V_w) (gallons)	Rate of inflow (V_w/t) (gallons min ⁻¹)
September 13, 1985–August 12, 1986			
0.0002*	831 [‡]	501,000	1
0.002 [†]	1055 [§]	6,360,000	13
February 8–June 13, 1989			
0.0002*	831 [‡]	234,000	1
0.002 [†]	1055 [§]	2,970,000	17
April 12–April 19, 1993			
0.0002*	831 [‡]	262,000	26
0.002 [†]	1055 [§]	3,328,000	330

* Low estimate of storativity, consistent with a more confined aquifer such as that associated with the Mutual and Buckeye Mines (see discussion in text).

[†] High estimate of storativity, consistent with a less confined aquifer such as that associated with the New Hope No. 5 Mine (see discussion in text).

[‡] Area of voids of the Blackhawk Mine only, assuming that the mine's overall recovery rate was 0.5.

[§] Combined area of voids of the Blackhawk and Dixie Bee Mines, assuming that the recovery rate of both mines was about 0.5.

where h_0 is the initial potentiometric level and h is the potentiometric level t days later. The calculated values of the recession constants (b) are summarized in Table 7.

Although the recession constants (b) are very small, statistical analysis of the standard errors and T-ratios indicate that the differences between them are statistically significant. It should also be noted that the potentiometric level stabilized at a higher level (h) following each perturbation (Table 7).

Harper and others (1990) discussed possible causes of the first linear rise and subsequent exponential recession. They dismissed several potential causes of the linear rise, including water-level changes in French Lake, or the build-up and subsequent release of methane pockets within voids of the Blackhawk Mine. They speculated that the linear rise might have resulted from downward leakage of water from saturated surficial deposits through fractures associated with the collapse of roof strata or through poorly sealed annuli around monitoring wells. Vertical leakage through subsidence fractures from overlying highwall lakes in the Danville Coal Member is another possibility. The rises may have ended when the vertical pathways swelled shut or were filled with sediment. The subsequent exponential declines of water levels may have resulted from discharge through the unmined coal bed that is downdip from the mine. Indeed, the estimated values of the recession constants are consistent with a discharge medium of very low permeability. In summary, despite the striking mathematical simplicity of segments of the water-level record, we can still only speculate about causation.

If we apply a simple linear trend-line to the entire data set, we obtain the following equation:

$$h = 0.0012t + 507.8 \quad (4)$$

where h is the potentiometric level (in ft) on a given date and t is the number of elapsed days between January 1, 1900, and the specified date. Thus, the average rate of rise of the potentiometric level is 5.3 inches (13.5 cm) per year. By extrapolating backward in time, the potentiometric level in 1951, when the Blackhawk Mine was abandoned, would have been about 530 ft (161.5 m) above mean sea level. This is approximately the same elevation as the easternmost and highest portion of the underground mine. If such an extrapolation is valid, then the mine voids must have flooded very quickly following abandonment; however, the subsequent rise of the potentiometric level may be an ongoing process.

If the pattern of intermittent linear rises followed by exponential declines has continued to repeat itself since 1994, then the water level will stabilize at successively higher levels with each repetition. In this case, we can predict that the potentiometric level of the Blackhawk Mine may reach elevations as high as 560 to 570 ft (170.6 to 173.7 m) between the years of 2020 to 2040, after which contaminated water might emerge in the area of Paint Mill Lake, which, at an elevation of only 560 ft (170.6 m), is the topographically lowest area that overlies the abandoned workings. Such a prediction is not inconsistent with other investigations elsewhere. In a mining district in the United Kingdom, it was suggested that surface discharges from a mining district might develop over a period from 15 to more than 100 years following cessation of all mining and pumping activity (Gandy and Younger, 2007).

Mutual and Buckeye Mines

The Buckeye and Mutual Mines (CMIS Mines #801254 and #802379, respectively) in Daviess County are flooded underground mines that operated in the Mariah Hill Coal Member (Mansfield Formation) between 1870 and 1913. Operating at

Table 7. Exponential declines of the potentiometric level of the Blackhawk Mine

Period	Duration (t) (days)	Initial level (h_0) (ft)	Final level (h) (ft)	Recession constant (b)	Standard error of b
August 12, 1986–February 8, 1989	911	553.85	545.18	-1.541×10^{-5}	6.994×10^{-7}
June 13, 1989–April 12, 1993	1399	549.5	547.31	-2.611×10^{-6}	1.691×10^{-7}
April 19, 1993–May 14, 1994	390	552.15	549.78	-6.934×10^{-6}	2.838×10^{-7}

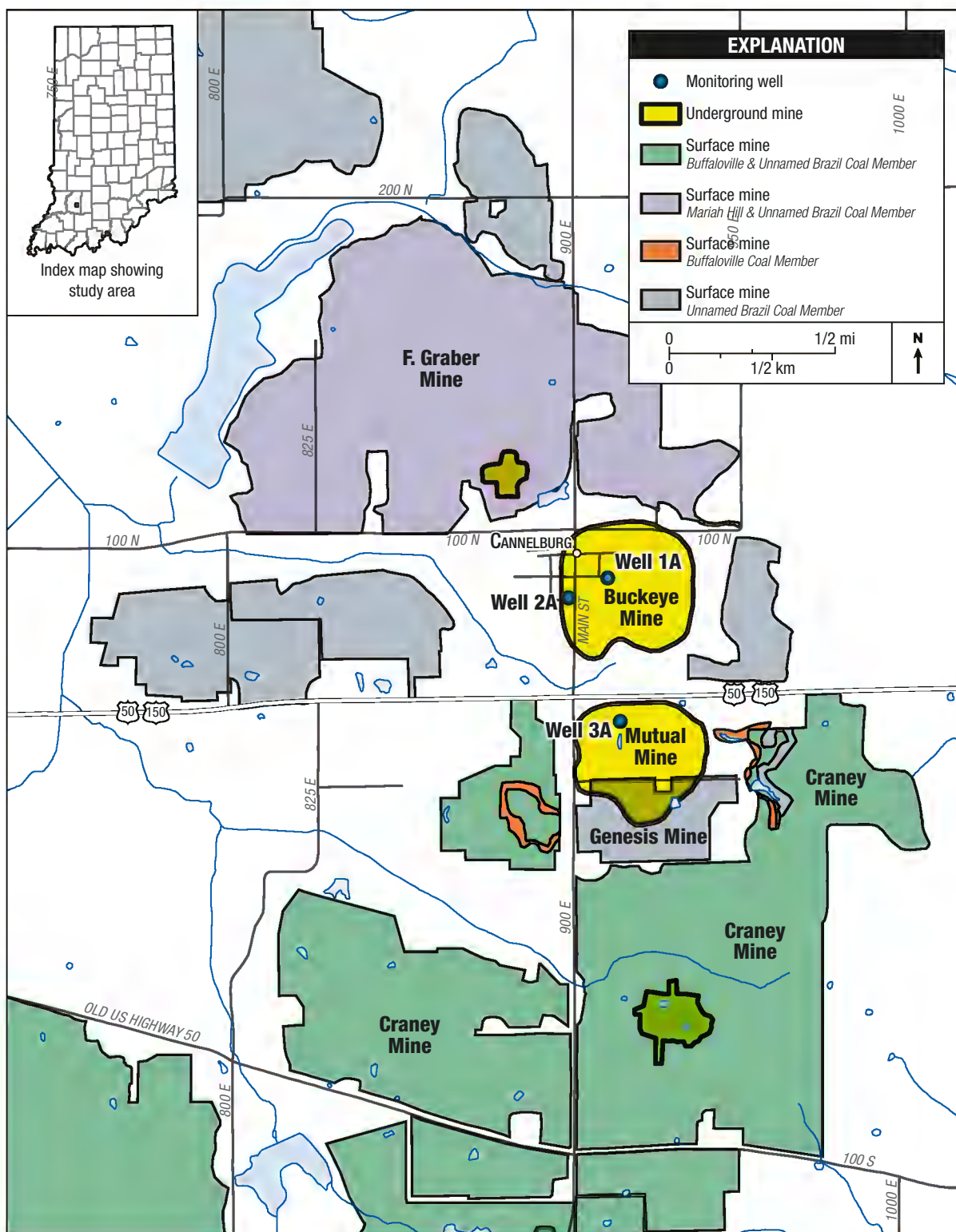


Figure 10. Map showing the Buckeye and Mutual Mines (Mariah Hill Coal Member), the locations of monitoring wells installed in the mines, and the relationship of the mines to other surface and underground mines.

depths of about 75 to 100 ft (22.8 to 30.4 m), they were presumably separated by a narrow barrier of unmined coal (fig. 10).

Within the mines, entries and rooms were typically 25 to 36 ft (7.6 to 10.9 m) wide, and pillars were as narrow as 8 to 20 ft (2.4 to 6.09 m) wide. Extraction ratios ranged from 55 to 85 percent (Harper and Olyphant, 1993, p. 50). Production from the Buckeye and Mutual Mines was 415,000 and 349,000 short tons (376,000 and 317,000 metric tons), respectively (Hutchison, 1971), and the areas underlain by the two mines are 90 and 74 acres (36.4 and 29.9 ha), respectively. Assuming an average recovery rate of 0.5 and an average thickness of 4 ft (1.2 m), the capacities of the two mines when fully flooded would be 110 million gallons (416 million liters).

Beginning in 1979, a series of surface mines operated in the Mariah Hill Coal Member, as well as in several overlying and underlying coal beds. In the early to mid-1980s, one of these surface mines (F. Graber Mine, CMIS Mine #200601) encountered the northernmost workings of the Buckeye Mine (fig. 10), which they partially dewatered by pumping. Another mine (Craney Mine, CMIS Mine #203073) was within less than 800 ft (243.8 m) of the southern boundary of the Mutual Mine. A third mine (Genesis Mine, CMIS Mine #200608) exploited shallow coal beds above the Mutual Mine.

As part of a subsidence investigation, monitoring wells were installed at various stratigraphic levels, including three wells in the flooded voids of the two underground mines (fig. 10) and five wells in unmined coal beds. Water-level measurements were recorded electronically on an hourly basis between April 1990 through December 1991. In contrast to short-term responses to precipitation, the long-term record of the Buckeye Mine was characterized by a series of steplike changes, with rapid rises during short periods followed by relatively stable levels during longer periods (fig. 8).

Harper and Olyphant (1993) statistically analyzed the records of water-level changes that occurred in the wells. Short-term changes in water levels associated with two neighboring underground mines were inferred to occur in response to three recharge mechanisms, including, in decreasing order of importance: 1) Precipitation that bypasses the mines' overburden through some unknown, possibly mine-related, pathway; 2) percolation

from overlying aquifers; and 3) lateral flow from the coal bed's subcrop.

As with the Blackhawk Mine, the possibility also exists that some waste materials have periodically been disposed of through boreholes installed into the mine. However, the average rate of change for the entire period (0.39 inch per day [0.98 cm per day] for a 502-day period), if extrapolated backward, indicated that the potentiometric level would have been at the elevation of the Buckeye Mine itself in June 1986, which was about when a neighboring surface mine (F. Graber Mine, CMIS Mine #200601) ceased active operations. From this, it was inferred that the long-term record represented the reestablishment of hydrologic conditions in the Buckeye Mine existing before the surface mine was active (Harper and Olyphant, 1993).

New Hope No. 5 and New Hope No. 6 Mines

The New Hope No. 5 and New Hope No. 6 Mines (CMIS Mine #800467) in Sullivan and Greene Counties are flooded underground mines that operated in the Springfield and Hymera Coal Members, respectively. The larger New Hope No. 5 Mine, at a depth of 85 to 100 ft (25.4 to 30.4 m), was active between 1932 and 1948. The smaller, overlying New Hope No. 6 Mine, at a depth of 30 to 60 ft (9.1 to 18.2 m), was active between 1933 and 1948 (fig. 11).

As discussed above, two neighboring mines in the Springfield Coal Member, the Twin Shaft No. 5 and Sunflower Mines, were within 25 ft (7.6 m) of the New Hope No. 5 Mine.

Production from the New Hope No. 5 and New Hope No. 6 Mines was 13.2 million short tons (12 million metric tons) (Hutchison and Hasenmueller, 1988), and the areas underlain by the two mines are 1,033 and 304 acres (418 and 123 ha), respectively. Assuming an average recovery rate of 0.5 and average thicknesses of 6.5 and 6 ft (1.9 and 1.8 m), respectively, the capacities of the two mines when fully flooded would be 1.1 billion and 0.3 billion gallons (4.2 billion and 1.1 billion L), respectively.

Both the New Hope No. 5 and New Hope No. 6 Mines are overlain by or in close proximity to several large lakes that occupy final-cut pits of abandoned surface mines in the Hymera Coal Member. In addition, another final-cut pit is filled with a reclaimed deposit of fine-grained refuse

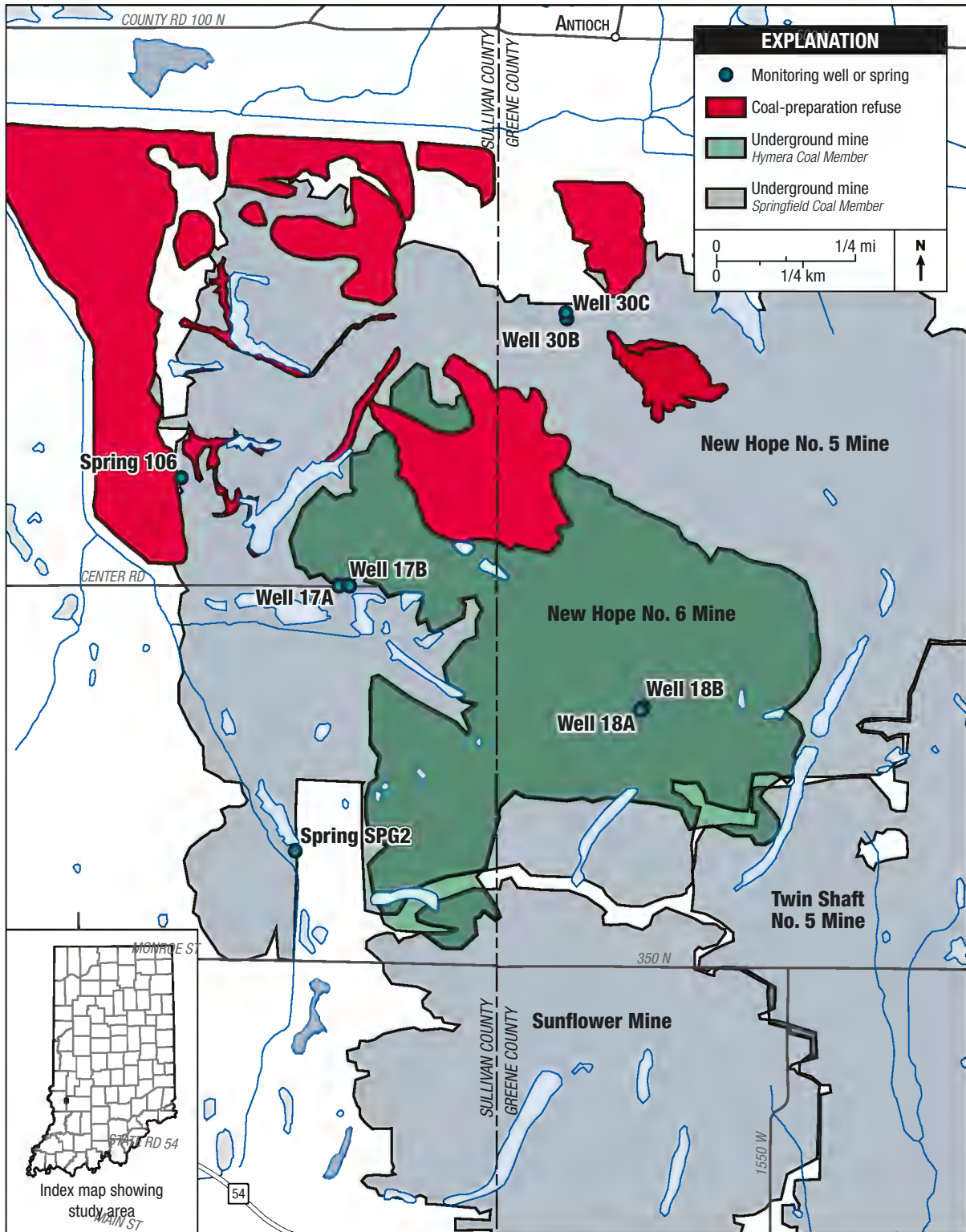


Figure 11. Map showing the New Hope No. 5 Mine (Springfield Coal Member) and New Hope No. 6 Mine (Hymera Coal Member), the locations of monitoring wells installed in the mines, and the relationship of the mines to other underground mines, and to deposits of pyritic coal-preparation refuse.

("slurry") from a preparation plant. The slurry deposit, in turn, is situated to receive drainage from a reclaimed deposit of coarse-grained refuse ("gob"). Prior to their reclamation in 1993, both the slurry and gob deposits were discharging highly contaminated drainage, having pH values less than 3, and acidity and sulfate concentrations that exceeded 2,000 and 4,000 mg/L, respectively. The New Hope No. 6 Mine may be receiving recharge from one or several of these features. Several springs are known to be discharging from the workings of the New Hope No. 5 Mine (fig. 11).

As part of a reclamation feasibility investigation, monitoring wells were installed in voids and pillars of the New Hope No. 5 and New Hope No. 6 Mines. Water levels were measured monthly between August 1987 and October 1991 from two wells installed in voids of the New Hope No. 5 Mine (Wells 17A and 18A) and two wells installed in a pillar and a void of the New Hope No. 6 Mine (Wells 18A and 18B) (fig. 11). From October 1991 to August 1992, water levels in wells installed in voids of the New Hope No. 5 Mine were recorded electronically on an hourly basis. Shorter-term records are available from three other wells installed in voids and pillars of the New Hope No. 5 Mine (fig. 8) and its neighboring Twin Shaft No. 5 Mine.

For most of the period of investigation, water levels rose irregularly from an elevation of about 517 ft (157.5 m) above mean sea level to almost 523 ft (159.4 m). The peak level in the wells installed in the voids of the New Hope No. 5 Mine was achieved on May 29, 1992, at 16:00 (4 p.m.) Eastern Standard Time, after which levels began falling rapidly at a rate of 0.84 inch (2.1 cm) per day (Harper and others, 1992). Using a value of storativity that had been estimated for the mine (see discussion above), this rate of decline indicated either an increase of outflow or a reduction of inflow of 120 gpm (454 Lpm).

Harper and others (1992) speculated about possible causes of the rapid decline, including: 1) increased flow through existing springs and seeps, as a result of decreased resistance to flow, 2) development of new springs or seeps in response to the high pressure-head that was achieved in May 1992, or 3) human activities that involved pumping from the New Hope No 5 Mine or its neighboring mines.

The latter hypothesis seems most likely, given that water from the neighboring Twin Shaft

No. 5 Mine was being used by a mining company that was active in the area. Water was being intermittently pumped from the mine, as well as from the Templeton No. 2 Mine in the underlying Survant Coal Member, to supply a coal-preparation facility. Water that had passed through the preparation plant had formerly been returned directly to the Twin Shaft No. 5 Mine by gravity drainage through disposal wells (Coal, Inc., 1983), but by September 1992, other disposal sites, such as surface-mine pits and sealed-off panels within an active underground mine in the Survant Coal Member, were apparently being used (Coal, Inc., 1991). Unfortunately, no quantitative data regarding these withdrawals and injections were available from the coal company.

Hartwell No. 1 Mine

The Hartwell No. 1 Mine and a neighboring unnamed mine (CMIS Mine #800003 and #800957, respectively) in Pike County are flooded underground mines that operated in the Springfield Coal Member between 1895 and 1908. Operating at depths of about 50 to 100 ft (15.2 to 30.4 m), they were presumably separated by a narrow barrier of unmined coal (fig. 12). Production from the Hartwell No. 1 Mine was 238,500 short tons (216,000 metric tons) (Wier and Stanley, 1953), and the areas underlain by the two mines are 45 and 34 acres (18.2 and 13.7 ha), respectively. Assuming an average recovery rate of 0.5 and an average thickness of 4 ft (1.2 m), the capacities of the two mines when fully flooded would be 51 million gallons (193 million liters).

The water level in a monitoring well installed in voids of the Hartwell No. 1 Mine was electronically recorded between May 1995 and September 1998 (fig. 8). The flow of a spring that was known to issue from the mine workings was also recorded. Between January 11 and October 7, 1996, reclamation of the overlying surface involving extensive earth-moving activity was conducted as part of the Abandoned Mine Lands Program of the Indiana Department of Natural Resources, Division of Reclamation. Prior to reclamation, the mine workings were hydrologically well connected to several nearby surface-mine ponds, as demonstrated by a pump test (see discussion below), and water levels in the monitoring well, like water levels in the ponds, declined steadily from May 1995 to the commencement of reclamation in January 1996. While reclamation was being conducted, the

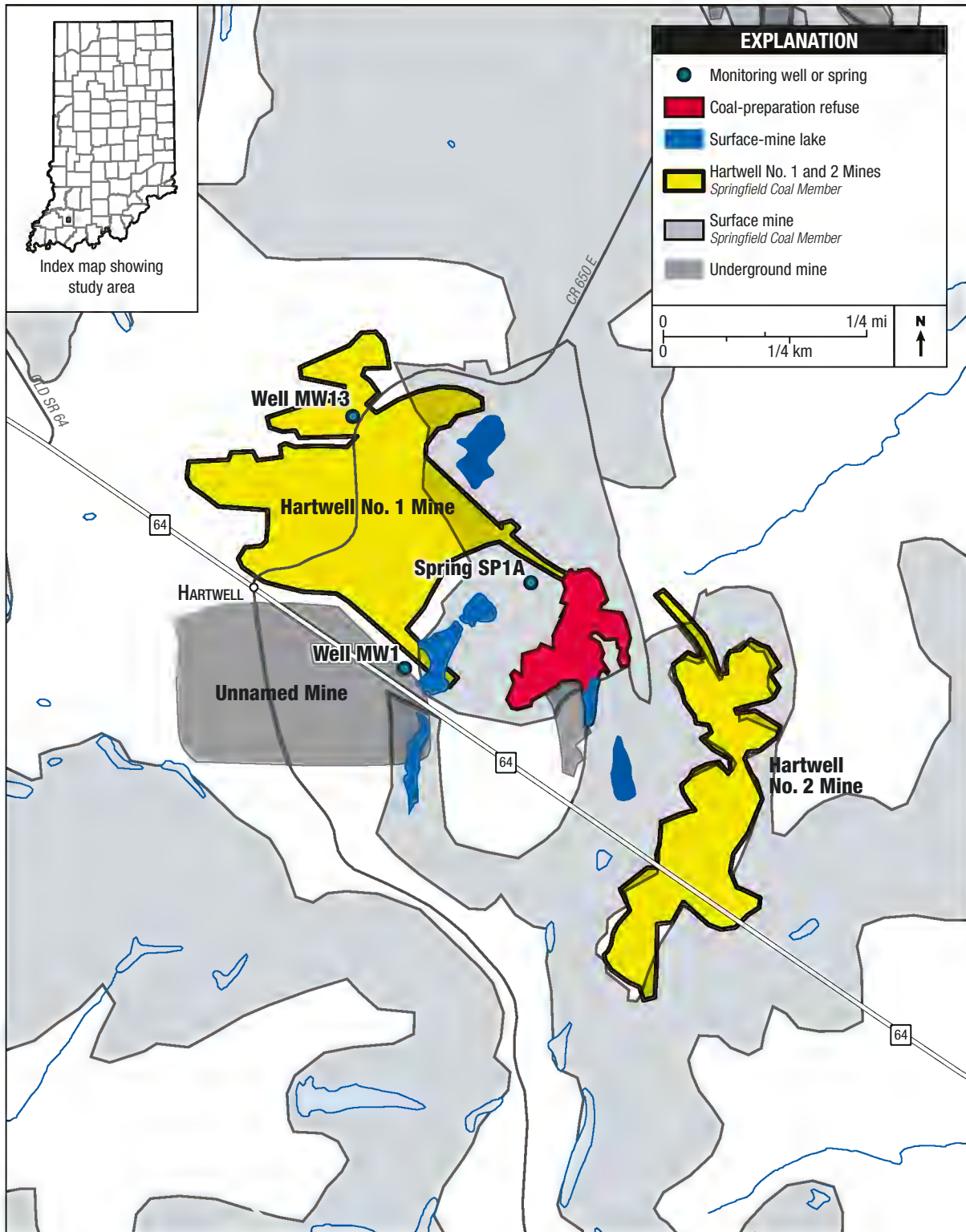


Figure 12. Map showing the Hartwell No. 1 Mine (Springfield Coal Member), the locations of monitoring wells installed in the mine, and the relationship of the mine to other surface and underground mines, and to a deposit of pyritic coal-preparation refuse.

water level fluctuated over a range of more than 8.2 ft (2.4 m). After reclamation, the water level in the monitoring well and the water level in a remaining surface-mine pond appeared to remain coupled but no longer exhibited identical elevations. The level of the surface-mine pond rose much higher and faster in response to precipitation than did the potentiometric level of the mine. In association with this change, an increase occurred in the range of discharge of the spring that issues from the underground mine: maximum discharges became higher and minimum discharges became lower than previously observed. There was no obvious explanation for these observed changes (IGS, 1999); presumably, they resulted from changes in connections between the surface drainage and flooded underground workings. Such changes might have included the plugging by reclamation activities of direct connections between the mine workings and the surface-mine ponds, or changes in the resistance of the spring's flow related to the presence of a passive anoxic limestone drain installed to treat the spring's discharge.

Measures of aquifer confinement

In the future, the development of beneficial uses for the groundwater stored in the coal-mine aquifer may involve either recirculation of the water or net withdrawals of water. For example, use of the water for geothermal heat pumps may principally involve recirculation of the water, so that the use of heat pumps should not greatly affect the amount of water in the system and, therefore, should not cause large short- or long-term changes in potenti-

ometric levels. But net withdrawals of water, such as might be required for reclamation of abandoned mine lands, would require careful management of the water budget to avoid depletion of the resource or dewatering of mine voids. It is desirable to keep voids fully flooded, because the introduction of air into abandoned workings could increase the dissolution of sulfate minerals and the oxidation of pyrite, resulting in increased discharges of AMD.

In situations involving net withdrawals, estimates of storativity would be useful in planning a project's overall water budget. Barometric efficiency is the ratio of water-level changes in a well to changes in barometric pressure; it is related to storativity and is a measure of the competence of an aquifer's confining overburden. Between 1990 and 1995, the IGS conducted a series of experiments at several flooded underground mines. The results of these experiments were used to estimate values of storativity for several flooded underground mines. Highly accurate values of barometric efficiency were also calculated.

Storativity

Storativity (S) is the volume of water that is taken into storage (V_w) per unit area of aquifer (A_T) per unit rise of hydraulic head (Δh):

$$S = V_w / (A_T \Delta h). \quad (5)$$

The experiments by the Indiana Geological Survey involved the injection or withdrawal of known volumes of water (V_w), while simultaneously measuring changes of water levels in observation wells (Δh) (Equation 2) (Table 8).

Table 8. Measurements taken during storativity experiments

Mine	Method	Date	Volume (V_w) (gallons)	Duration (hrs)	Level change (Δh) (ft)
New Hope No. 5	withdrawal*	April 13, 1992	239,000	25	0.106
		August 12, 1992	386,000	45	0.181
		August 26, 1992	487,000	50	0.217
Hartwell No. 1	withdrawal†	October 4, 1995	396,000	19.5	0.12
Buckeye	injection‡	October 30, 1990	2,000	0.55	0.19

* Controlled withdrawal through an artesian well.

† Withdrawal by pumping from a highwall lake that was hydraulically connected to the flooded underground mine.

‡ Gravity injection from a tanker truck.

While measurements of water-level changes (Δh) and the volumes of water that are injected or withdrawn (V_w) are straightforward, certain assumptions are required regarding the nature and extent (A_p) of each aquifer. Good maps exist for most of the underground mines in Indiana, so that the areal extents of the mines can be accurately determined. But Indiana's underground mines are room-and-pillar mines, so should the total area of a mine be used in the calculation or only the area of the interconnected voids, excluding the pillars? For the purposes of this report, the total area of each mine was used, which should tend to underestimate storativity values.

Pump tests were conducted on the New Hope No. 5 Mine by making controlled artesian withdrawals on April 13, August 12, and August 26, 1992, from a well installed in a mine void (Well

30C, fig. 11). Measurements of water-level responses were made in three observation wells, including two wells installed in other voids of the mine (Wells 17A and 18A), and one well installed in a pillar (Well 30B). Well 18A was located more than 3,800 ft (1,158.2 m) from the withdrawal well (Well 30C). The responses of the three observation wells were simultaneous and identical (as determined by using electronic water-level loggers with measurement intervals of 5 minutes) (fig. 13).

Inspection of maps of the New Hope No. 5 Mine and its two neighboring mines (the Twin Shaft No. 5 and Sunflower Mines) indicates that a barrier of about 50 ft (15 m) was generally maintained between the mines, although, in places, the separation was as narrow as 25 ft (7.6 m). While the area of the New Hope No. 5 Mine is about 45 million ft² (4.2 million m²) (including both pillars and voids),

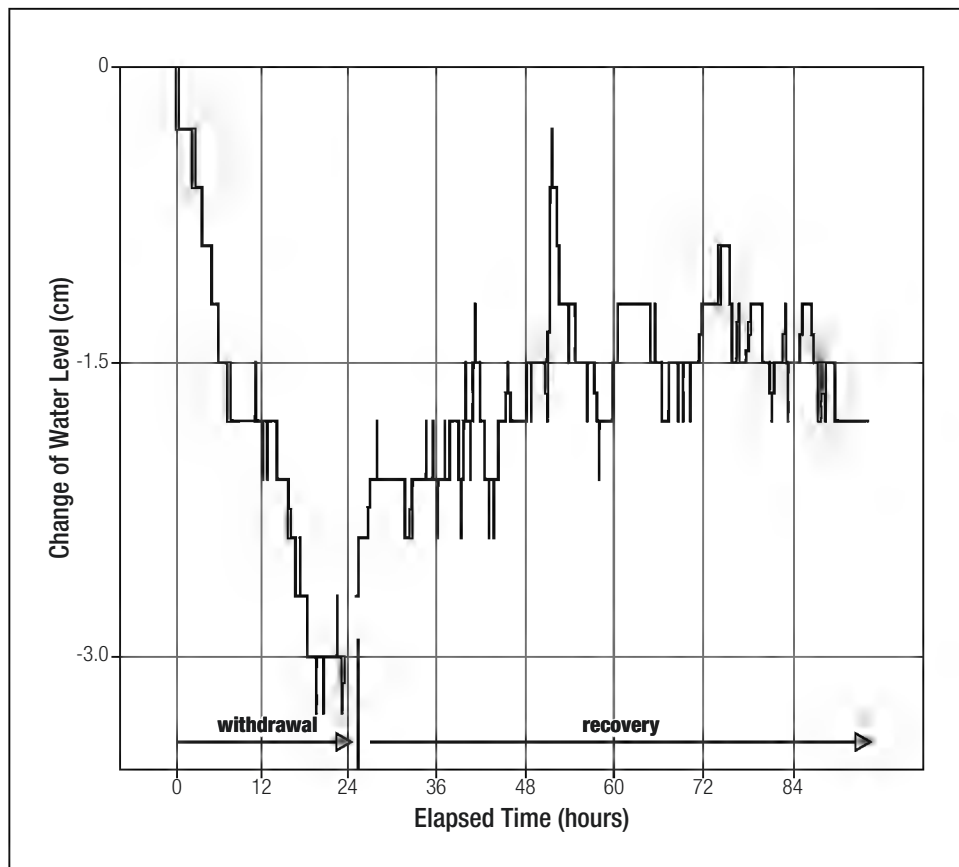


Figure 13. Graph showing the results of a controlled withdrawal of water from the New Hope No. 5 Mine through Well 30C, conducted on April 13, 1992. Water levels were recorded in Well 30B. Using a valve, the artesian outflow was maintained for 25 hours, and the total outflow was 239,000 gallons (904.7 L). Similar responses (not shown) were recorded in Wells 17A and 18A. Source: Harper and others (1992, p. 37).

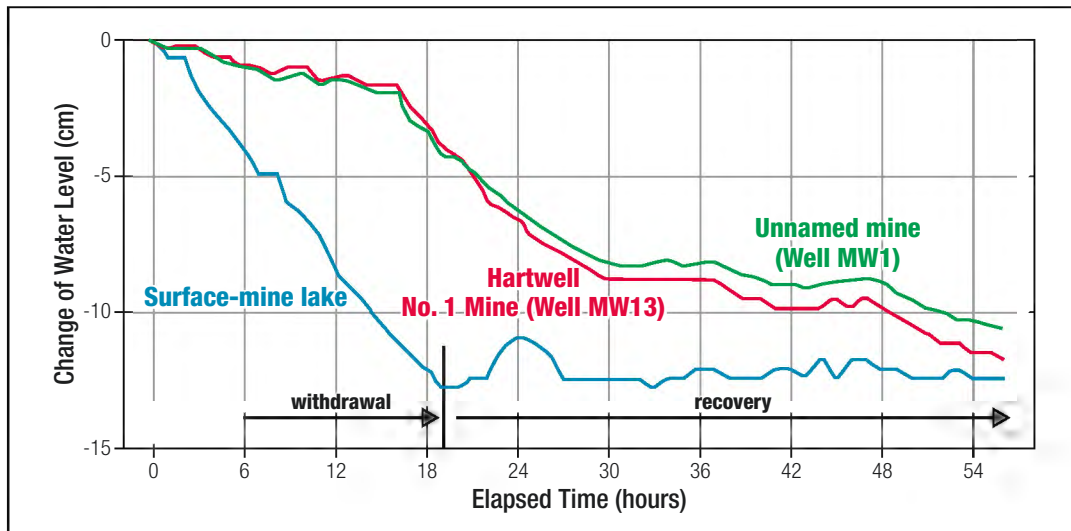


Figure 14. Graph showing the results of a pump test on a surface-mine highwall lake, conducted on October 4 and 5, 1995. The highwall lake had a good hydrologic connection to the adjacent underground Hartwell No. 1 Mine (Well MW13), as well as a barrier pillar between the Hartwell No. 1 Mine and a neighboring unnamed mine (Well MW1). The total volume of water removed by pumping during a period of 19.5 hours was 390,000 gallons (1,476,310 L). Source: IGS (1999).

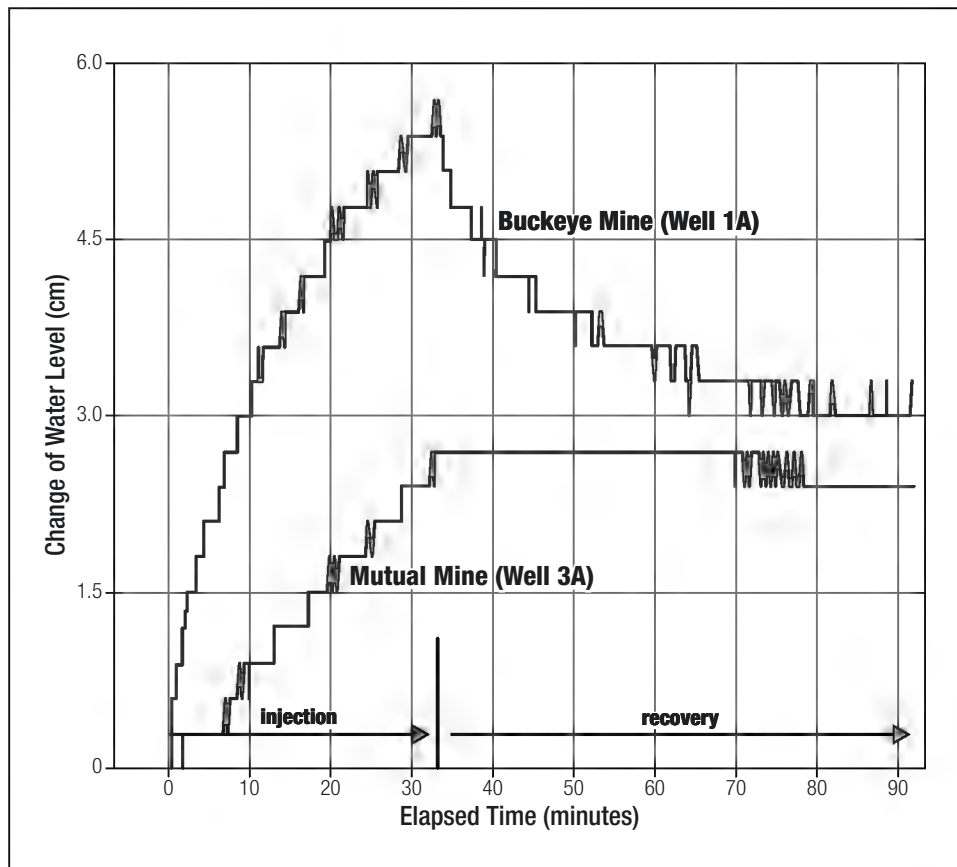


Figure 15. Graph showing the results of a controlled injection of water by gravity flow through a well installed in voids of the Buckeye Mine (Well 2A), conducted on October 30, 1990. The total volume of water that was introduced during a period of 33 minutes was 2,000 gallons (7,570 L). Water levels in observation wells installed in voids of the Buckeye Mine (Well 1A) and the neighboring Mutual Mine (Well 3A) were measured every 10 seconds. Source: Harper and others (1991, p. 25).

Table 9. Estimates of storativity

Mine	Date	Storativity	
		minimum	maximum
New Hope No. 5	April 13, 1992	0.0030	0.0068
	August 12, 1992	0.0028	0.0064
	August 26, 1992	0.0030	0.0068
Hartwell	October 4, 1992	0.002	
Buckeye	October 30, 1990	0.0003	

the total area of the mine and its two neighboring mines is more than 100 million ft² (9.3 million m²). Consequently, for the New Hope Mine No. 5, a range of values for storativity were calculated, based on the smaller and larger areas.

In the case of the Hartwell No. 1 Mine, a neighboring unnamed mine exists. But when water was pumped from a surface-mine highwall lake on October 4, 1995, an observation well installed in a narrow barrier pillar between the Hartwell No. 1 Mine and a neighboring unnamed mine (Well MW1) responded identically to an observation well installed in voids of the Hartwell No. 1 Mine itself (Well MW13), demonstrating that a good hydraulic connection existed between the two mines (fig. 14). Consequently, the total area of the two mines (3.4 million ft² [316,000 m²]) was used in the storativity calculation.

In the case of the Buckeye Mine, which has an area of approximately 3.9 million ft² (362,000 m²), an observation well also existed in the neighboring Mutual Mine, whose area is approximately 3.2 million ft² (297,000 m²). During the injection conducted on October 30, 1990, the water level in the observation well in the Mutual Mine (Well 3A) rose steadily, but at a slower rate than the observation well in the Buckeye Mine (Well 1A) (fig. 15). This demonstrated that a hydraulic connection existed, but that the connection was not perfect. Consequently, for the Buckeye Mine, the storativity calculation was modified, as follows:

$$S = V_w / ([A_T \Delta h]_{\text{BUCKEYE}} + [A_T \Delta h]_{\text{MUTUAL}}) \quad (6)$$

Finally, because the withdrawals from the New Hope Mine took as long as 50 hours, it was necessary to adjust calculations for background trends in water-level changes within the observation wells.

Table 10. Barometric efficiencies of flooded underground mines*

Mine	Barometric efficiency	Mine depth (ft)
Blackhawk	0.83	83–260
Buckeye	0.67	75–100
New Hope No. 5	0.27	85–100
New Hope No. 6	0.17	30–60

* Harper and Olyphant (1992, p. 6).

After making the various assumptions and adjustments discussed above, values of storativity were calculated (Table 9). For confined aquifers, storativity values typically range from 5×10^{-5} to 5×10^{-3} (Freeze and Cherry, 1979, p. 60), so that the estimates for the three mines in Indiana are in the middle to upper part of that range.

Barometric efficiency

Based on measurements made by personnel of the IGS, values of barometric efficiency for four flooded underground mines are summarized in Table 10. For confined aquifers, values of barometric efficiency typically range from 0.2 to 0.75 (Freeze and Cherry, 1979, p. 234), so that the New Hope No. 5 and New Hope No. 6 Mines appear to be poorly confined. Such an inference is in accord with the estimate of high storativity for the New Hope No. 5 Mine. In contrast, the barometric efficiencies of the Buckeye and Blackhawk Mine indicate that they are relatively well confined, which, in the case of the Buckeye Mine, accords with the estimate of a moderate value of storativity.

Electronic monitoring of water levels in wells installed in confined flooded underground mines may be characterized by short-term spikes, diurnal sinusoidal cycles, and biweekly sinusoidal cycles associated with external loads such as the passage of railroad trains, daily barometric variations, and biweekly earth tides. See Harper and others (1991) for examples of such phenomena from the Buckeye Mine (Davies County).

The role of methane pockets

Finally, in our attempts to conceptualize the physical hydrology of coal-mine aquifers, we must keep in mind that water is not the only fluid that is pres-

ent in coal beds. Methane gas accumulates in abandoned underground mines, and in a few places, homeowners and farmers used mine gas locally for drying grain or to supplement home heating. Attempts are also being made in Vigo County to produce such mine gas for the generation of electricity (Marketwire, 2010).

In addition to controlled releases, the authors are aware of several anecdotal reports of sudden, uncontrolled outbursts of methane from abandoned underground coal mines of Indiana. These include a report by a farmer of a sudden outburst in a cultivated field that overlies the Blackhawk Mine (Vigo County). Also, on September 3, 2003, a gas outburst occurred near U.S. Route 41 near Sullivan (Sullivan County). It was determined that the outburst, which happened a few days after a heavy rain, was from the abandoned Buck Creek Mine, at a depth of about 250 ft (76.2 m). The outburst, which was apparently associated with a borehole, was capped, diverted, and burned at an estimated cost of \$100,000 (Terre Haute Tribune Star, 2003).

The hydrologic effects, if any, of the buildup and release of such methane pockets in abandoned underground coal mines is unknown. Presumably, the gradual buildup of methane within traps formed in structurally high areas of the mine might cause the potentiometric level within monitoring wells to rise. Conversely, the sudden release of such gas, perhaps by roof collapse or drilling, might be reflected by a sudden decline in potentiometric levels.

CHARACTERIZATION OF WATER CHEMISTRY

Past investigations in Indiana

In 1960, Gluskoter (p. 614) stated: "there was a complete lack of analytical data [from both Indiana and Illinois] on uncontaminated groundwater from coal at depths from 100 to 800 feet." In the 1970s, a series of reports by the Indiana Department of Natural Resources, Division of Water (IDNR-DOW) included chemical analyses of water samples from wells, some of which penetrated coal beds (for example, Cable and others, 1971; Cable and Robison, 1973; Cable and Wolf, 1977) (fig. 16).

Reports that included chemical data were also produced by the U.S. Geological Survey (Bobo and Eikenberry, 1982). Banaszak (1980) discussed the possible role of coal beds as aquifers in many domestic water wells.

During the 1980s, a series of graduate student theses at Indiana University included analytical data (Glore, 1970; Reifenstein, 1980; Stumpf, 1982; Smith, 1983; Funkhouser, 1983; Cocroft, 1984; and Giles, 1987) (fig. 16). These investigations were funded, in part, by the U.S. Office of Surface Mining Reclamation and Enforcement, as part of an effort to establish baseline conditions that could be used to evaluate applications for mining permits that were being issued under the Surface Mining Control and Reclamation Act of 1977 (Cocroft, 1984). Most of the data reported in these and other early investigations were analyses of water samples from preexisting domestic and agricultural water wells containing long uncased intervals (fig. 17).

Of the 258 sites that were sampled, 184 included waters that were possibly derived from two or more coal beds, and only 74 sites could be associated with waters from a single coal bed (Table 11). Consequently, attempts were made in the student theses to characterize the chemistry of the waters using statistical methods (such as analysis of mean values or weighted averages, or factor analysis). Emphasis was placed on relationships of overall water chemistry with depth. Several students used the same water wells, so that two or three samples were collected from some wells.

Between 1985 and 1995, IGS personnel installed monitoring wells into the voids and pillars of six flooded underground mines (discussed previously). Between 1985 and 2008, 209 samples were collected from 18 different wells (Harper and others, 1987; Harper and others, 1991; Branam and Harper, 1994; IGS, 1999) (Table 11). In addition, they collected 30 samples from five observation wells in unmined coal beds. In contrast with many earlier investigations, these samples can be related to specific, individual coal beds. Also, in 1992, 11 samples were collected from within the active Buck Creek Mine. In addition to water samples collected from wells, 57 samples were collected from 9 different springs that are believed to issue from underground mines (Branam and Harper, 1994; IGS, 1999) (Table 11).

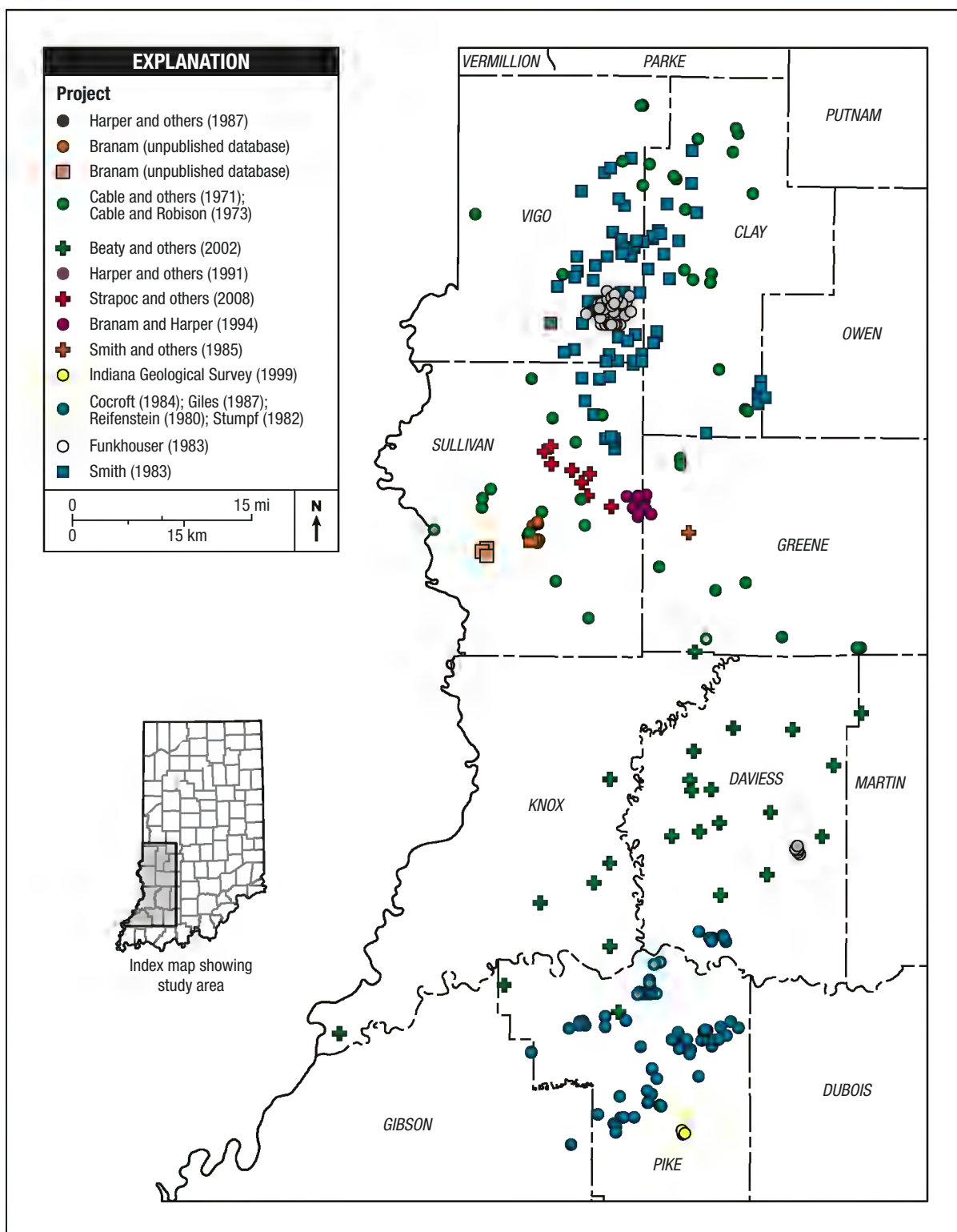


Figure 16. Map of southwestern Indiana showing locations where water samples related to coal beds were obtained for analysis. The legend indicates the cited source of analytical data.

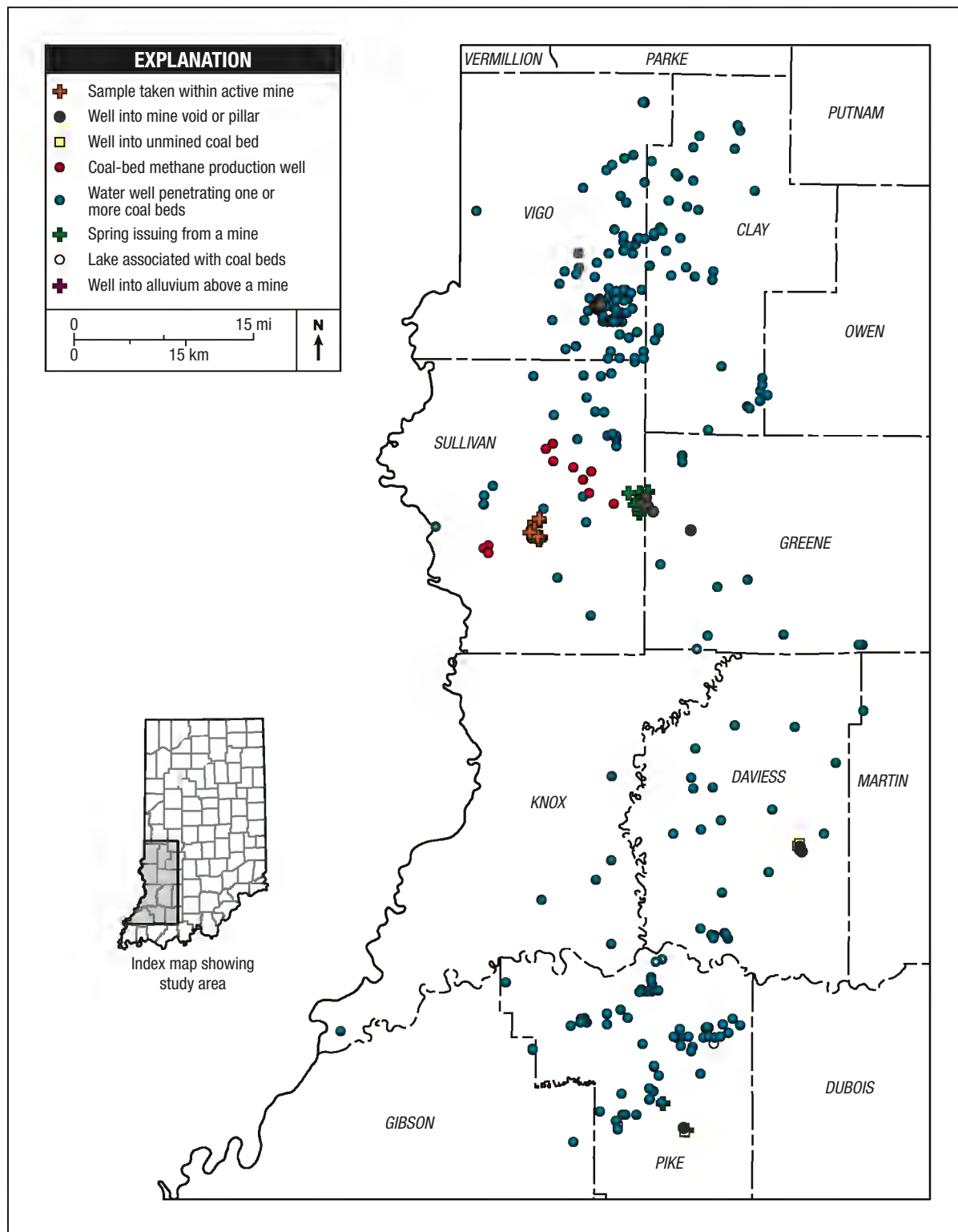


Figure 17. Map of southwestern Indiana showing locations where water samples related to coal beds were obtained for analysis. The legend indicates the type of feature (for example, well, spring) from which the samples were obtained.

More recently, Strapoc and others (2007, 2008) reported chemical and isotopic (deuterium and oxygen) analyses for water samples from eight wells producing methane gas from the Seelyville and Springfield coal beds at depths ranging down to 460 ft (140 m). In 2010, three additional samples were collected by the IGS from coal-bed-methane production wells (Table 11), and a sample was obtained from the then-flooded Buck Creek Mine, which closed in 1994.

The largest numbers of sites that are associated with a single coal bed are related to the Springfield and Seelyville coal beds, and the greatest number of samples are associated with the Springfield (Table 12).

Many data were collected from the various projects described above have been summarized in data products available upon request from the IGS.

Variations in prevalent chemical character

Based on analysis of the prevalent chemical character of samples from water wells in southwestern Indiana, the investigations by students of Indiana University in the 1980s discussed three general types of water—shallow (less than 125 ft [38.1 m]), intermediate (125 to 200 ft [38.1–60.9 m]), and deep (greater than 200 ft [60.9 m]) (Cocroft,

1984). The waters of intermediate depth were believed to represent relatively unaltered waters that ranged in character from calcium-magnesium-bicarbonate to sodium-bicarbonate waters. By comparison, shallow waters (primarily calcium-sulfate to calcium-bicarbonate waters) were characterized by higher values of total dissolved solids, specific conductance, bicarbonate, sulfate, chloride, and iron than intermediate waters.

When all water samples from wells installed in a single unmined coal bed are plotted on a trilinear diagram, there is very broad overlap among samples from shallow and intermediate depths, although there is also some suggestion of the greater abundance of sulfate and chloride in the shallow samples (fig. 18).

Cocroft (1984) attributed the greater contamination of the shallow waters to the percolation of meteoric waters through materials left by surface mining. As stated by Funkhouser (1983), “coal mining [presumably surface mining] has had very little effect on water chemistries of wells drilled to the depths of 150 feet or greater.”

Cocroft (1984) found the deep waters (greater than 200 ft [60.9 m]) to be of poorer quality (dominantly sodium-bicarbonate waters) (fig. 18). They attributed this to long residence times and possible mixing with connate waters, including brines. The

Table 11. Water samples associated with coal beds of Indiana, by type of sample

Type of water sample	Number of sites	Number of samples
Water well penetrating a single coal bed	74	94
Water well penetrating two or more coal beds	184	251
Observation well in an abandoned underground mine	18	209
Observation well in an unmined coal bed	5	30
Coal-bed-methane production well	11	11
Samples collected in an active mine	11	11
Springs that issue from an underground mine	9	57

Table 12. Water samples associated with single coal beds of Indiana, by coal bed

Coal bed	Number of sites	Number of samples
Danville	5	7
Hymera	9	49
Springfield	41	268
Survant or Houchin Creek	12	26
Colchester	1	3
Seelyville	42	45
Minshall	1	1
Upper Block	1	1
Lower Block	8	8
Mariah Hill	3	3
Unnamed	3	3

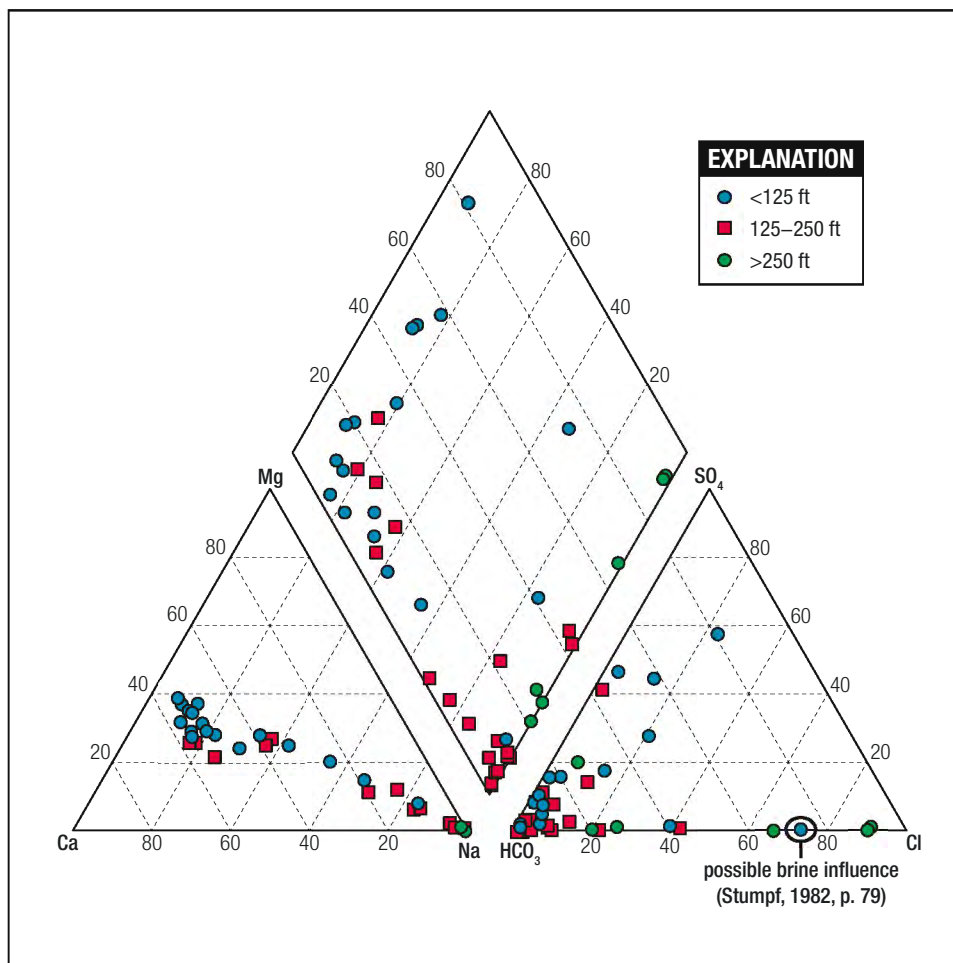


Figure 18. Piper trilinear diagram showing analyses of water samples from wells that were associated with only a single coal bed. Sources: Cable and Robison (1973), Cable and others (1971), Cocroft (1984), Funkhouser (1983), Giles (1987), Glore (1970), Reifenstein (1980), Smith (1983), Strapoc and others (2007), and Stumpf (1982).

relative importance of chloride is also evident in the trilinear diagram of all waters from unmined coal beds (fig. 18). However, the absence of chloride concentrations commensurate with sodium concentrations indicates that the sodium is primarily derived from cation exchange with clays, and that the influence of brines is minimal, so that shallow circulation systems predominate, at least to depths of 250 ft (76.2 m) (Funkhouser, 1983; Smith, 1983; Cocroft, 1984).

None of the investigations by the graduate students included any waters that were obtained directly from either active or flooded underground coal mines. Except for some samples obtained from the Buck Creek Mine (at a depth of 305 ft [92.9 m]),

all such samples later obtained by the IGS were from depths of less than 150 ft (45.7 m), and nearly all were characterized by generally high values of acidity and sulfate (Table 13).

The dominance of sulfate is evident on a trilinear diagram showing water samples from flooded underground mines (fig. 19). Despite the high values of acidity, alkalinity was also often present in the flooded mines, so that pH values were sometimes moderate or high, even in wells installed in such mines (fig. 20). The water samples that have the highest concentrations of acidity, sulfate, and iron are from the Blackhawk, New Hope No. 5, New Hope No. 6, and Twin Shaft No. 5 Mines (Table 14).

Table 13. Chemical analyses of water samples associated with single coal beds, by type of sample

[The upper number is the average value for all sites, calculated using the average value for each individual site. The lower numbers show the total range of values. The number of values used to calculate the average value is indicated by "n."]

Type of water sample	Number of sites	Total number of samples	Depth (ft)	pH	Acidity (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)	Chloride (mg/L)
Water wells penetrating a single coal bed*	73	93	135 50–280 n=73	— 6.2–9.4	not analyzed	378 190–1,352 n=40	58 0–900 n=65	121 3–3,400 n=73
Observation wells in flooded mines†	16	207	96 39–140 n=16	— 3.5–9.2	1,004 0–6,515 n=16	413 20–1,489 n=16	3,380 123– 15,594 n=16	21 0–152 n=16
Coal-bed-methane production well‡	6	6	359 325–394 n=3	— 7.47–8.8	not analyzed	1,230 788–1,761 n=6	621 0–3,494 n=6	1,663 55–4,741 n=6
Samples collected in an active mine§	11	11	305	— 7.8–8.8	not analyzed	1,767 1,650– 2,040 n=10	79 0–790 n=11	1,239 580–2,820 n=11

* Cable and others (1971), Cable and Robison (1973), Reifenstein (1980), Stumpf (1982), Smith (1983), Funkhouser (1983), Cocroft (1984), Giles (1987), Beaty and others (2002).

† Harper and others (1987), Harper and others (1991), Branam and Harper (1994), Indiana Geological Survey (1999).

‡ Strapoc and others (2008).

§ Branam (unpublished database).

The Blackhawk Mine is directly overlain by a gob deposit on the surface (fig. 9). Within the Blackhawk Mine, Well 1M was immediately downdip from the deposit of coal-preparation refuse (fig. 9), and it was water from that well that had the highest concentrations of sulfate (fig. 23). In contrast, Well 7M was farthest updip from the refuse deposit, and it had the lowest concentrations of sulfate.

The New Hope No. 5, New Hope No. 6, and Twin Shaft No. 5 Mines may all be hydrologically connected, and the New Hope No. 5 and New Hope No. 6 Mines are directly overlain by extensive deposits of gob and slurry (fig. 11). In contrast, the Hartwell No. 1 Mine is also in close proximity to a gob deposit, but it is not directly overlain by the deposit (fig. 12), and its chemistry is not characterized by high acidity, sulfate, or iron. There were no gob deposits in the vicinity of the Buckeye and Mutual Mines (fig. 10), and those mines have low concentrations of acidity and iron, although sulfate is moderately elevated.

Except in the Buck Creek Mine (at a depth of 305 ft [92.6 m]), chloride tended to be lower in the shallow flooded mines (at depths of less than 150 ft [45.7 m]) than in other types of waters associated with coal beds (Table 13). However, samples obtained from the active Buck Creek Mine (fig. 19) had relatively high concentrations of chloride and were similar to samples obtained from coal-bed-methane production wells, which were derived from similar depths. Thus, chloride generally increased from the shallow observation wells in mines (average depth = 96 ft [29 m]; average chloride = 21 mg/L) through water wells of intermediate depth (average depth = 135 ft [41 m]; chloride = 121 mg/L), to deeper samples from the Buck Creek Mine (depth = 305 ft [93 m]; average chloride = 1,239 mg/L) and coal-bed-methane production wells (average depth = 359 ft [109 m]; average chloride = 1,663 mg/L).

Regarding the waters from coal-bed-methane wells, Strapoc and others (2007, 2008) note that av-

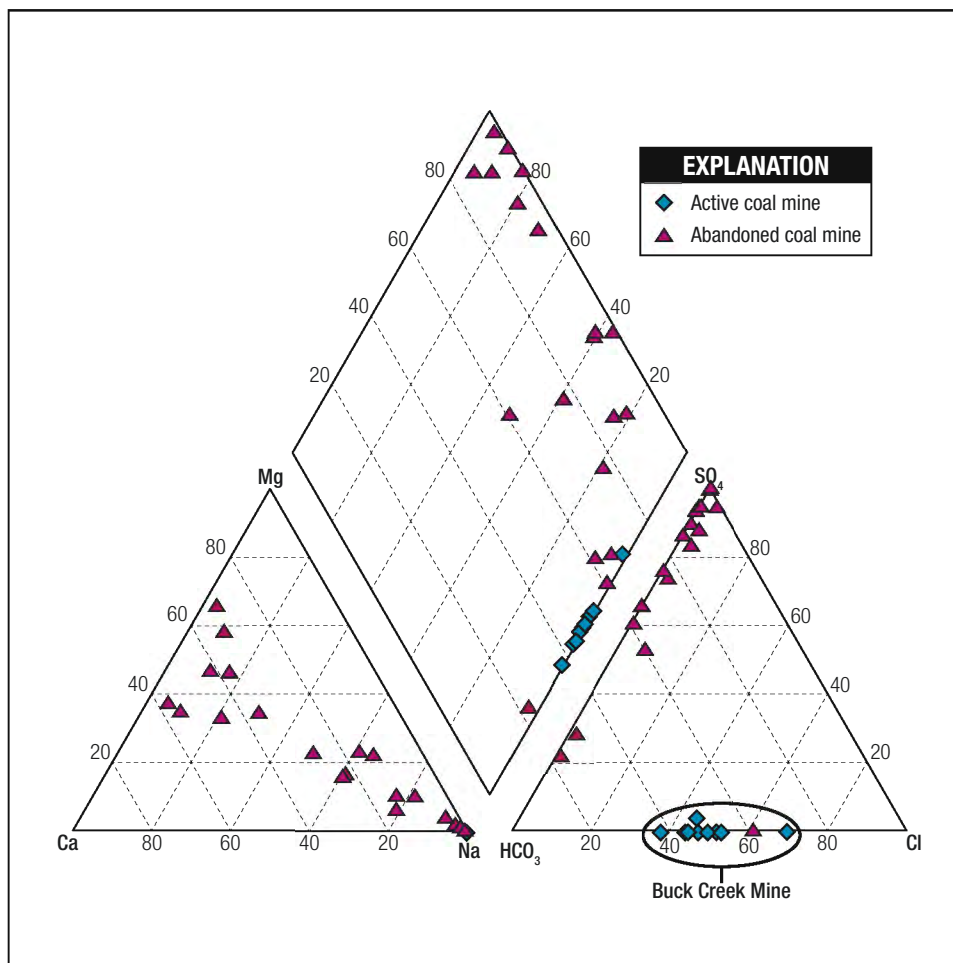


Figure 19. Piper trilinear diagram showing analyses of water samples from pillars and voids in flooded underground coal mines and water samples collected from within an active underground mine. Sources: Harper and others (1987), Harper and others (1991), Branam and Harper (1994), Branam (unpublished database), and Indiana Geological Survey (1999).

erage chloride concentrations associated with the Springfield and Seelyville coals (4,500 mg/L and 2,200 mg/L, respectively) are still 10 to 20 times lower than chloride concentrations in undiluted deep Illinois Basin brines, which indicates a high degree of hydrologic connectivity between coal beds and meteoric waters. They also note that oxygen isotope compositions resemble those of modern regional meteoric waters. They suggest that mean residence times are only a few thousand years or less, and that waters of glacial age have been completely flushed from the Springfield coal and partially flushed from the deeper Seelyville

coal within their study area (Strapoc and others, 2007, p. 281). Earlier investigations of oxygen isotopes and chloride concentrations from shallower wells had likewise indicated the predominance of meteoric waters in coal beds of southwestern Indiana (Funkhouser, 1983; Smith, 1983; Cocroft, 1984; Giles, 1987).

Natural changes in water chemistry

When operations cease at an underground coal mine, pumps are typically turned off and the mine

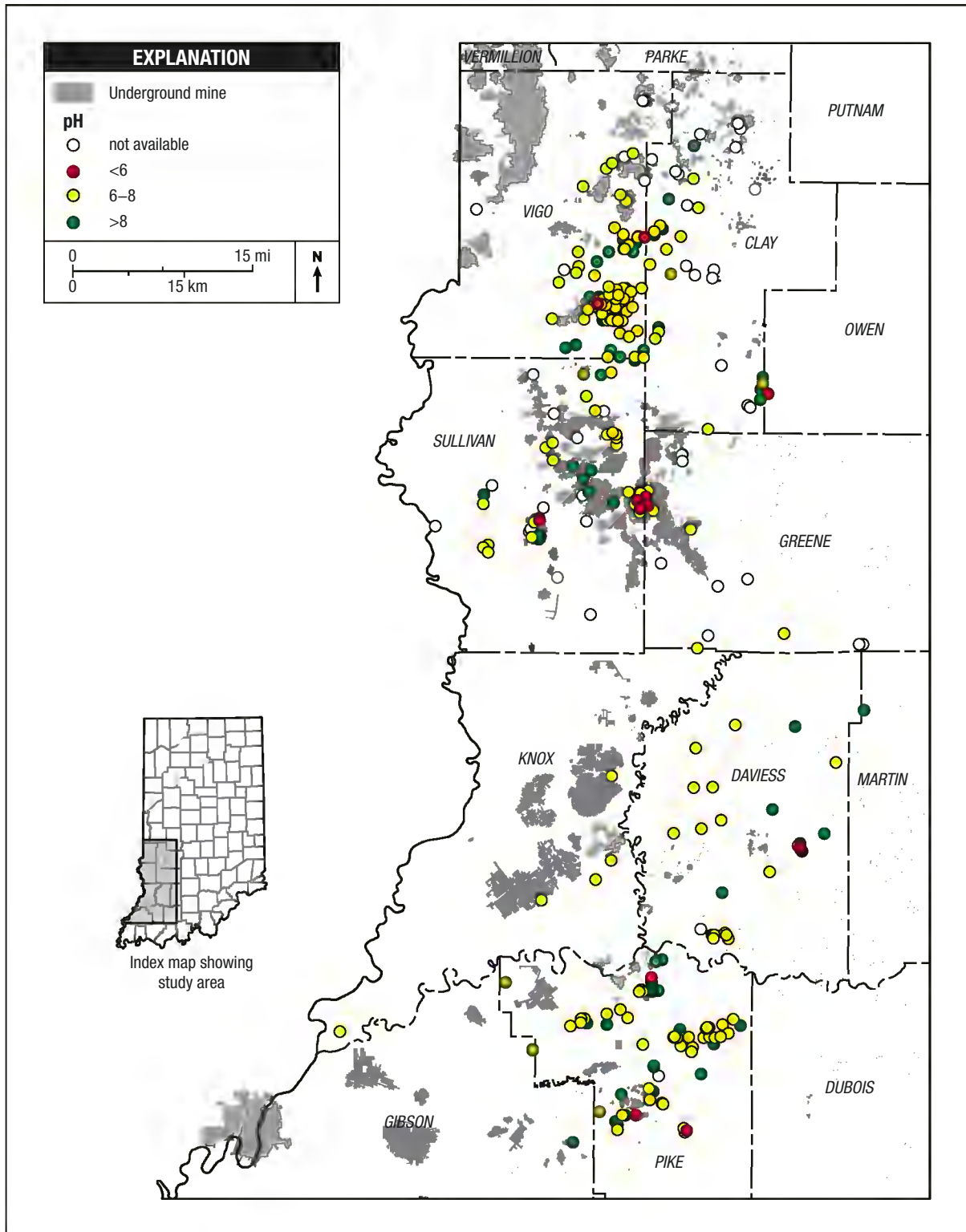


Figure 20. Map of southwestern Indiana showing the distribution of pH in water samples from wells associated with coal beds.

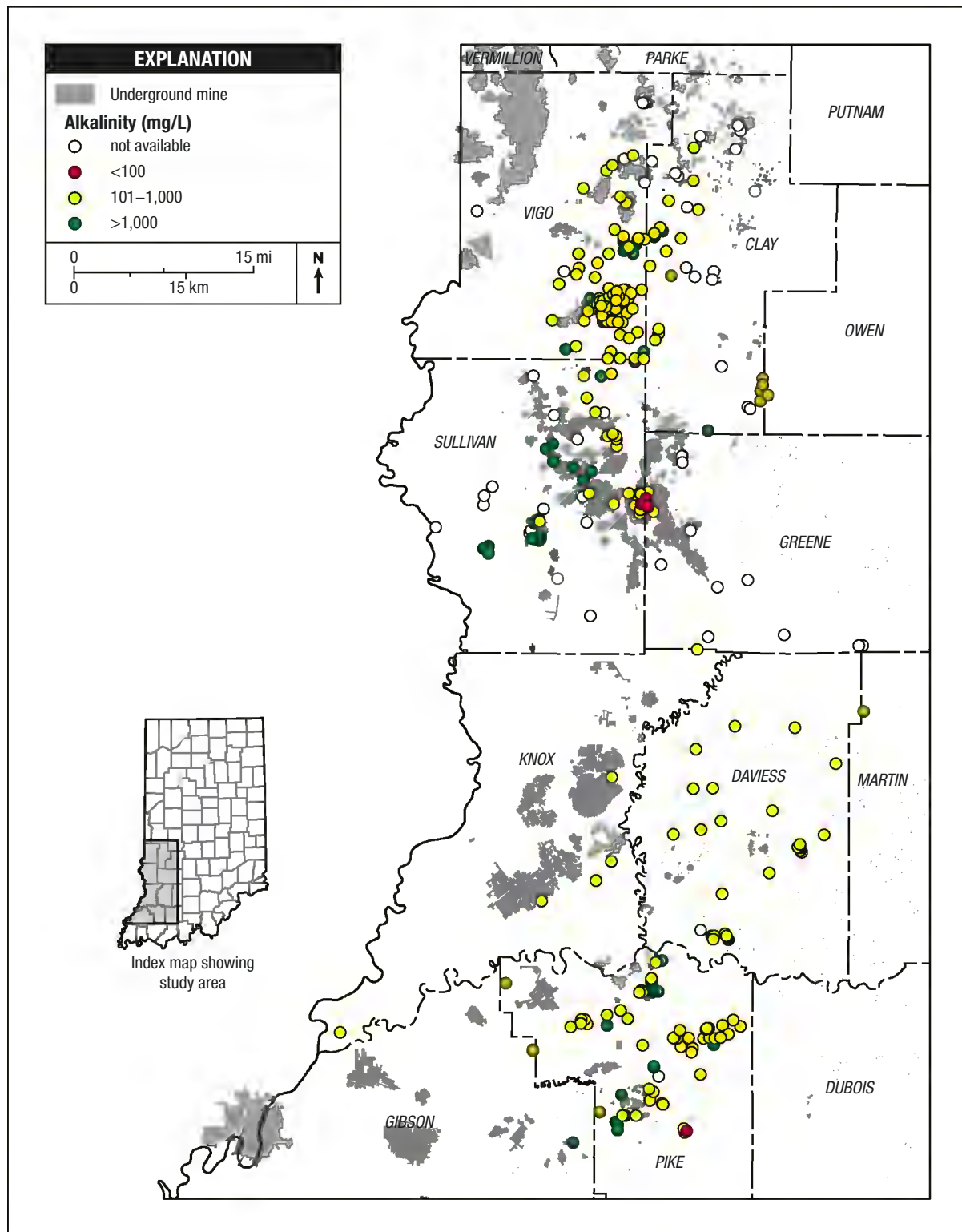


Figure 21. Map of southwestern Indiana showing the distribution of alkalinity in water samples from wells associated with coal beds.

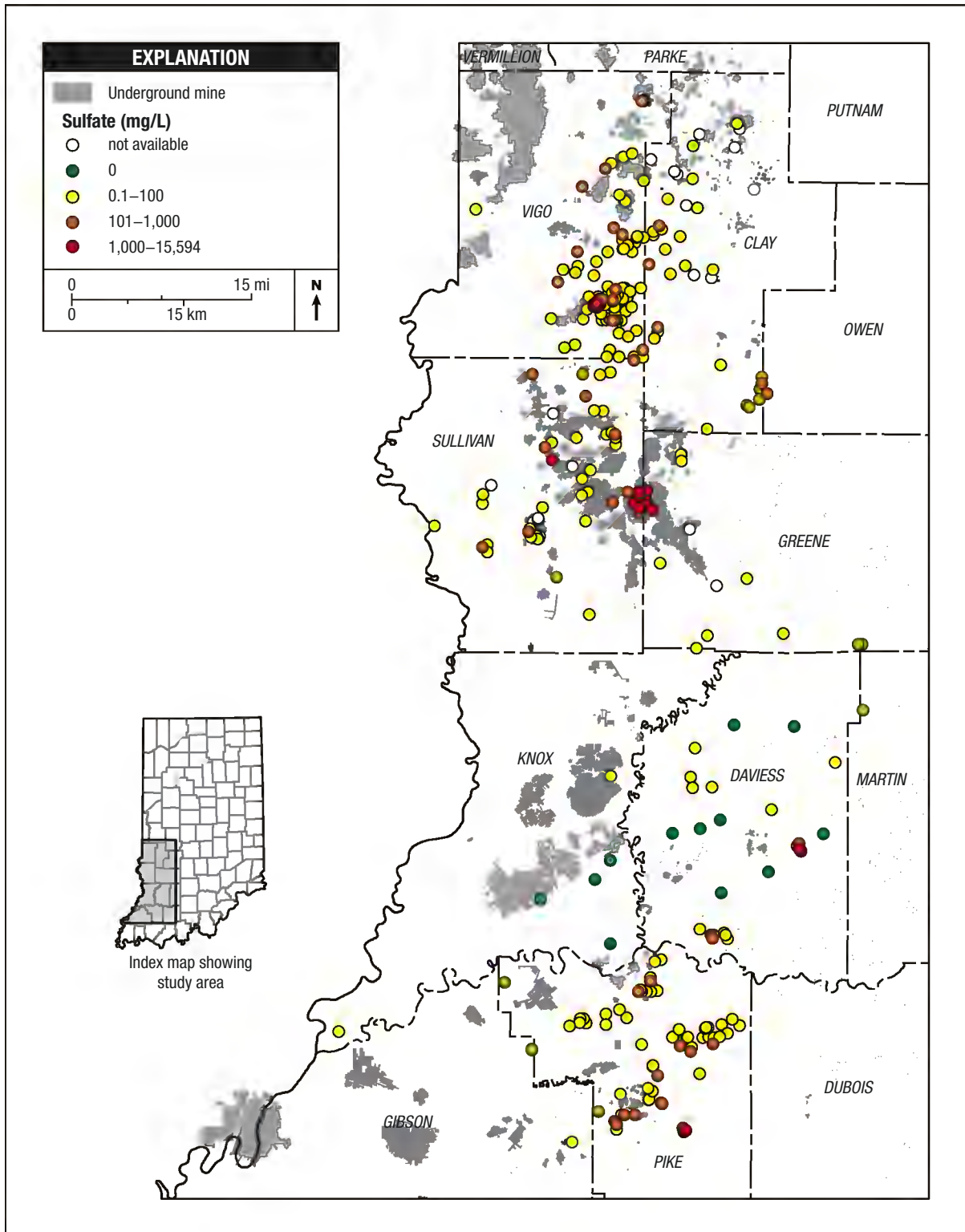


Figure 22. Map of southwestern Indiana showing the distribution of sulfate in water samples from wells associated with coal beds.

Table 14. Chemical analyses of water samples obtained from pillars and voids of flooded underground mines

[The upper number is the average value for all wells associated with each mine, calculated using the average value for each individual well. The lower numbers show the total range of values. The number of values used to calculate the average value is indicated by "n."]

Mine	Number of sites	Total number of samples	Depth (ft)	pH	Acidity (mg/L)	Alkalinity (mg/L)	Sulfate (mg/L)	Total iron (mg/L)
Blackhawk Mine	6	148	122 112–140 n=6	— 3.5–9.2	1,086 0–6,515 n=6	638 125–1,489 n=6	4,300 123–15,594 n=6	575 1–3,289 n=6
New Hope No. 5 Mine	4	26	75 44–107 n=4	— 5.3–7.0	1,829 265–6,160 n=4	359 20–647 n=4	4,532 2,673–6,156 n=4	348 25–870 n=4
New Hope No. 6 Mine	2	21	43 39–46 n=2	— 5.1–6.5	2,145 873–3,417 n=2	72 57–86 n=2	4,437 4,036–4,838 n=2	684 231–1,137 n=2
Twin Shaft No. 5 Mine	1	2	81 n=1	— 5.9–6.2	1,185 n=1	260 n=1	3,240 n=1	260 n=1
Buckeye and Mutual Mines	3	3	95 88–100 n=3	— 5.5–5.9 n=3	38 0–114 n=3	186 142–209 n=3	910 220–2,010 n=3	61 14–130
Hartwell No. 1 Mine	1	17	100 n=1	— 6.1–7.3	69 n=1	441 n=1	142 n=1	4 n=1

begins to fill with water. The chemistry of the groundwater that fills the mine depends upon a variety of local conditions, including:

1. Whether the mine is completely flooded with water or is only partially filled,
2. The length of time that the mine has been inactive, and
3. The character of the water that recharges the mine.

The water that initially fills a mine is referred to as the "first flush," and it may be highly contaminated with acidity, sulfate, and metals because of mixing with acidic pore waters and reactions with secondary products of pyrite oxidation (sulfate minerals) formed while the mine was active. Concentrations of sulfate during this period may be four or five times greater than concentrations in waters that were present while the mine was active (Gzyl and Banks, 2007).

Once flooding is complete, pH typically begins to increase linearly and conductivity begins to decrease. Concentrations of sulfate and iron begin

decreasing in a quasi-exponential rate (Younger, 2000; Gzyl and Banks, 2007). Water may continue to circulate through the fully inundated workings—although perhaps at a very slow rate—because surface outflows may develop, or the water may flow downdip into unmined portions of the coal bed. In such situations, concentrations of contaminants may decrease by 50 percent each time that the water within the mine is replaced (Varnell and others, 2004). (Chloride, however, may show no temporal trends [Gzyl and Banks, 2007].) Eventually, concentrations will stabilize at values that are related to the sulfur content of the coal bed, and pH may stabilize around 7 (Younger, 2000). In computer simulations, McDonough and others (2005) determined that simulated water quality in southwestern Pennsylvania should reach steady-state conditions about 25 to 30 years after mine pools flooded, and that water quality in flooded voids was governed by alkaline recharge water slowly replacing acidic water from the initial filling of the mine. Thus, flooded mines that are below surface drainage generally have the best-quality water (Ziemkiewicz and others, 2005).

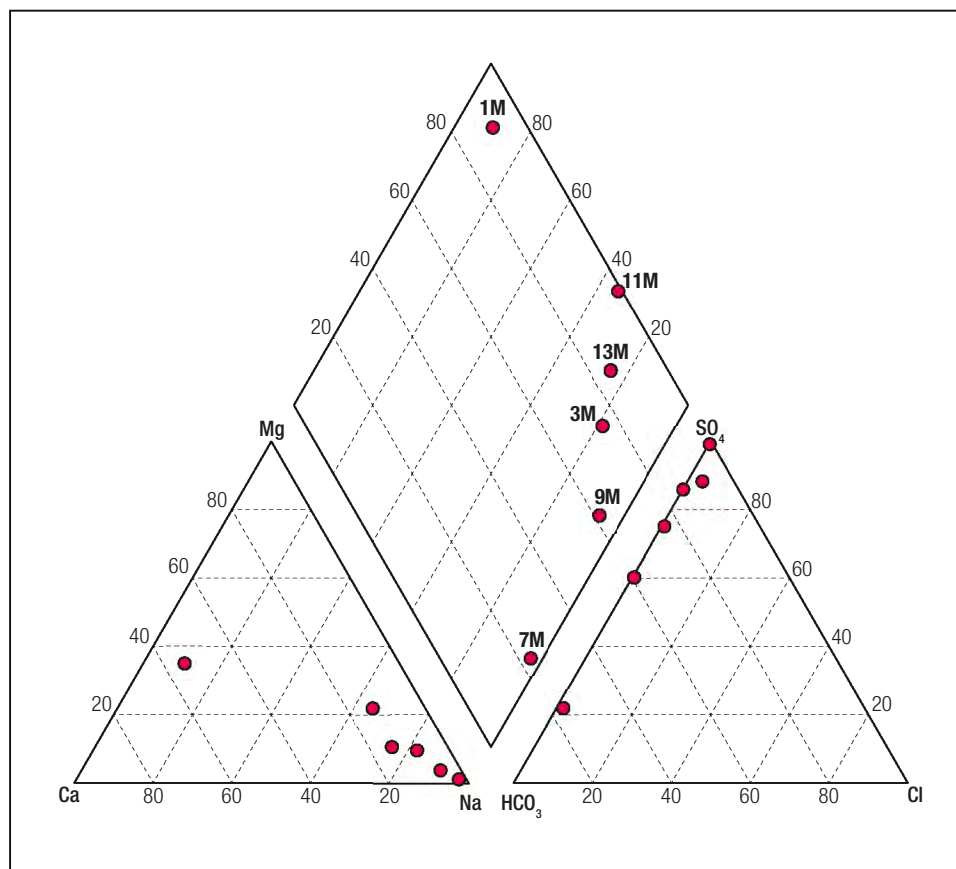


Figure 23. Piper trilinear diagram showing analyses of water samples from pillars and voids in the flooded Blackhawk Mine. Source: Harper and others (1987).

Across broad areas of Indiana, underground mining ceased more than 25 years ago, and many underground mines were abandoned more than 50 years ago (fig. 24). This gives us reason to expect that large volumes of water of relatively good quality may exist within those workings that are fully flooded. However, not all underground mines in Indiana are situated below surface drainage. Particularly where freely flowing springs have developed through poorly plugged shafts, boreholes, or mine-utility holes, the workings may drain rapidly enough that the most elevated portions of the mines remain partially filled with air or gas. Oxidation of pyrite and the generation of acidic water may continue indefinitely, so that such partially flooded mines are more likely to remain contaminated for longer periods (Varnell and others, 2004). Demchak and others (2004) compared water samples collected in 1968 from underground mine discharges in northern West Virginia with samples collected in 1999–2000, and they concluded that underground mines that are below

drainage improved rapidly (20 to 40 years) in quality, but that mines situated above drainage may or may not show any improvement with time. In some places, efforts have been made to seal abandoned underground mines to flood them more fully. Stoetz and others (2001) demonstrated that hydraulic sealing of a mine complex in southeastern Ohio in 1980, which resulted in 90 percent inundation of the workings, was associated with an increase of pH from 2.7 to 5.3 and a decrease of conductivity from 2,700 to 600 microSiemens cm^{-1} .

Another factor that may inhibit the natural remediation of groundwater within flooded workings is the character of the recharge water. It was noted above that the high concentrations of sulfate, acidity, and iron that occur in groundwater within flooded mines in Indiana may be derived from downward vertical leakage of AMD from pyritic refuse deposits (gob and slurry) on the surface. Currently available data are inadequate to quantitatively assess the role that such deposits

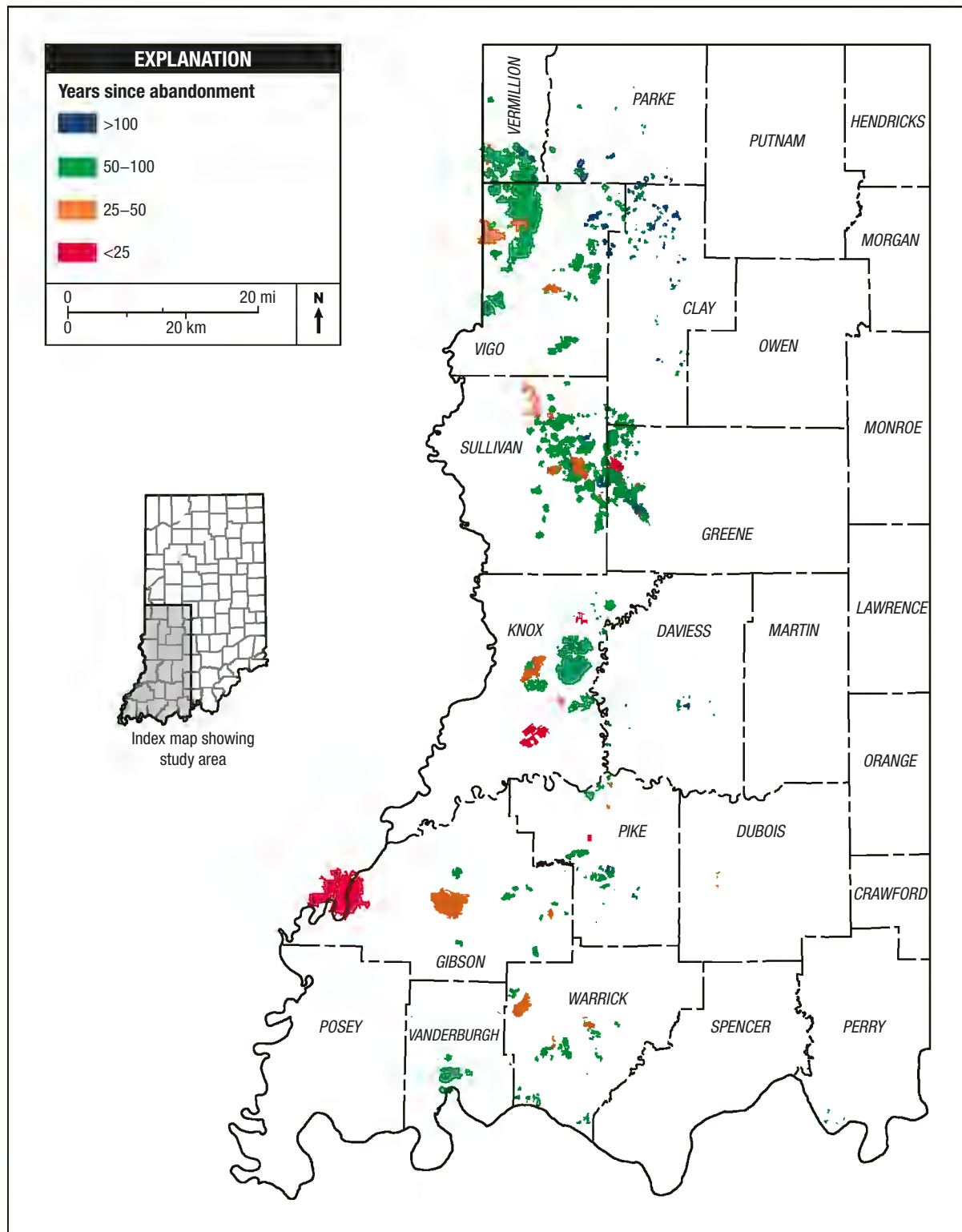


Figure 24. Map of southwestern Indiana showing the distribution of underground mines classified by the number of years since their abandonment. Source: Indiana Geological Survey (2010a).

play in the generation and maintenance of acidic conditions within the mines, but the possibility of such an influence has important implications for the remediation of coal-mine aquifers, causing the quality of water to remain degraded for decades or centuries.

Harper and others (2007) identified 75 coal-slurry deposits (covering 764 acres [309.1 ha]) that appeared to be emplaced in final-cut pits of surface mines, and an additional 49 deposits (covering 788 acres [318.8 ha]) that appear to be emplaced on ungraded spoil deposits. In such settings, AMD generated on the surface might easily find its way into nearby underground workings. Many of the gob and slurry deposits have been reclaimed by the IDNR-DOR under the provisions of the Abandoned Mine Lands Program, but most of the deposits were reclaimed in place. And while the reclamation efforts were highly successful in reducing erosion, stream siltation, and AMD in surface waters, only a few of the slurry deposits have been physically removed by re-mining. The effects, if any, of these efforts on the quality of groundwater at depth in neighboring underground mines are unknown. In such settings where contamination may be derived from the surface, rehabilitation of coal-mine aquifers might require the alteration of surface drainage to reduce or eliminate the infiltration of contaminated surface drainage into the mines.

SUMMARY AND CONCLUSIONS

As much as 170 billion gallons (643 billion L) of groundwater may reside within flooded underground coal mines of southwestern Indiana. Currently, little use is being made of the void spaces of such mines or the water within them. In the past, emphasis was placed on the hazards and environmental problems associated with abandoned mines, with little consideration given to the potential beneficial uses of these unique features. In the future, however, as even greater demands are placed on water resources, the high-yield aquifers represented by mine pools may see development for a variety of purposes, including geothermal heat-pump systems, energy storage, and cooling water.

In Indiana, detailed data regarding the physical hydrology of abandoned underground coal mines is available only for a few localities. Nevertheless,

even these very limited data indicate that our coal-mine aquifers vary greatly in character, ranging from essentially unconfined aquifers having relatively large storage capacities to well-confined aquifers with small storage capacities.

The water in unmined coal beds ranges in character from calcium-magnesium-bicarbonate and calcium-magnesium-sulfate waters at shallow depths (less than 125 ft [38.1 m]), through calcium-magnesium-bicarbonate waters at intermediate depths (125 to 250 ft [38.1 to 76.2 m]), to calcium-magnesium-chloride waters at greater depths (greater than 250 ft [76.2 m]). Surface mining in Indiana generally occurred where the overburden was less than 150 ft (45.7 m) thick, so the presence of sulfate in the shallow waters may be attributable to contact with surface-mine spoil, but such effects of surface mining may not penetrate into greater depths. In general, the presence of chloride at depths greater than 250 ft (76.2 m) is probably associated with cation exchange with clays, rather than the influence of brines, although contamination from brines, including oilfield brines, may occur in places.

In contrast to unmined coal beds, the water in shallow flooded mines (less than 150 ft [45.7 m] deep) is typically calcium-magnesium-sulfate water, with chloride becoming more important at greater depths. Many underground mines are overlain by deposits of pyritic refuse from coal-preparation facilities, and much of the acidity and sulfate within flooded mines may be derived from such deposits. Even after such deposits are reclaimed, they may continue to shed contaminated drainage into underlying mines, so long as the pyritic materials remain in place. However, where pyritic deposits do not exist on the surface or where they were removed by re-mining, the quality of water in flooded workings can be expected to improve naturally through time, so that some mines may contain water of relatively good quality. Thus, by considering a variety of factors, it may be possible to prospect for suitable groundwater. Factors influencing groundwater quality include the length of time since a mine was abandoned, its proximity of pyritic refuse deposits, its depth and relationship to surface drainage channels, and its elevation relative to the regional water table.

Even long after a mine's abandonment, its physical hydrology may be significantly affected by human

activities, such as nearby surface mining, mine reclamation, coal-preparation activities, exploratory drilling for oil, gas, or water, and possibly even construction activities on the surface. Natural phenomena, such as abnormally high precipitation or subsidence events, can also trigger changes in the hydrologic regime. Such changes, both natural and man-made, may be manifested by increased or decreased discharges of AMD from existing springs, the appearance of new AMD discharges, or methane emissions at the surface. Such manifestations may occur at considerable distances, as much as several miles, from the activities that trigger them, so that it may be difficult or impossible to associate cause and effect.

Subsidence is of particular concern. It is possible, indeed likely, that significant perturbations of the hydrologic regime within flooded underground mines can trigger subsidence events. As many as 20,000 housing units and 45,000 people may overlie abandoned underground mines in Indiana. Other infrastructure that is exposed to subsidence damage in Indiana include as much as 90 miles (144.8 km) of U.S. and state highways and 66 miles (106.2 km) of railroads, as well as dams, nursing homes, airports, a hospital, and a prison. Consequently, any deliberate attempt to re-engineer the hydrology of flooded underground mines should be preceded by an assessment of the potential exposure of infrastructure to subsidence damage.

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