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Research Article

Mine Flooding History of a Regional Below-Drainage Coalfield Dominated by Barrier Leakage (1970–2014)

Joseph J. Donovan and Eric F. Perry

Department of Geology and Geography, West Virginia University, 330 Brooks Hall, P.O. Box 6300, Morgantown, WV 26506-6300, USA

Correspondence should be addressed to Joseph J. Donovan; jdonovan@wvu.edu

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A 44-year record of water level fluctuations in a series of adjacent closed underground mines documents the history of closure and mine flooding in the Fairmont Coalfield, one of the oldest coal mining districts in the Pittsburgh coal basin, West Virginia, USA. As closures proceeded and mines began to flood, US environmental regulations were first enacted mandating mine water control and treatment, rendering uncontrolled surface discharges unacceptable. The purpose of this study is to present this flooding history and to identify critical events that determined how mine pools evolved in this case. Also examined is the strategy developed to control and treat water from these mines. Flooding is visualized using both water level hydrographs and mine flooding maps with the latter constructed assuming mine water hydraulic continuity between one or more mines. The earliest flooding formed small pools within near-surface mines closed prior to 1962 yet still pumped following closure to minimize leaking into adjacent still-active workings. These subpools gradually enlarged and merged as more closures occurred and the need for protective pumping was removed, forming what is today referred to as the unconfined Fairmont Pool. Later, deeper mines, separated by intact updip barriers from the Fairmont Pool, were closed and flooded more gradually, supplied in large part by leakage from the Fairmont Pool. By 1985, all mines except 2 had closed and by 1994 all had fully flooded, with the Fairmont Pool interconnected to deeper single mine pools via barrier leakage. As protective pumping ceased, the Fairmont Pool rose to a water level 3 m higher than surface drainage elevation and in 1997 discharged from an undermined section of Buffalo Creek near the Monongahela River. The principal mine operator in the basin then designed a pumping system to transfer water from the Fairmont Pool to their existing treatment facilities to the north, thus terminating the discharge. It may be concluded that the progress of mine flooding was influenced by mining history and design, by the timing of closures, by barrier leakage conditions, and by geologic structure. A key element in how flooding proceeded was the presence of a series of intact barriers separating deep from shallow mines. The shallow mines closed and flooded early, but then lost sufficient water by barrier leakage into the deeper mines to delay the completion of flooding until after the deep mines had all closed and flooded as well. Intensive mine water control has continued from the 1997 breakout to the present. The final water control scheme was likely unanticipated and serendipitous; future district-wide mining efforts should be advised to consider in advance closeout strategies to control mine water postmining.

1. Introduction

Following underground mining of gently dipping below-drainage near-surface coal, groundwater will rebound following closure in one or more mines within a given district [1–3]. This process is colloquially referred to as "mine flooding." Flooded mines derive water from adjacent and/or overlying flooded mines, by vertical infiltration from overlying freshwater aquifers and/or from surface water sources [4]. Flooded mines can become aquifers with substantial water storage. Donovan and Leavitt [5] estimated that all of the Pittsburgh seam coal mines in West Virginia and Pennsylvania, USA, contained 5×10^{12} liters of water as of 2004. Water in active below-drainage mines must be pumped to keep working sections dry [6]. Without pumping, flooded or flooding below-drainage mines form "pools" that may eventually discharge at the surface through portals, boreholes, or fractures. A mine pool is a volume of water filling *hydraulically interconnected* mine workings [7], which may include one or more mine property. Normally, pool development is most common in mines below surface drainage elevations.

The flooding phenomenon has been observed to proceed in quite different sequences and rates within different mining districts. This has been ascribed to factors including local hydrogeology, closure timing, and pumping history [7, 8]. Prior to about 1970 in the USA, the flooding process was generally unregulated and postclosure impacts or future management of closed flooded mines received little attention. Today, after observations of recent coal mine closures, postclosure mine water management has become a critical element in mine permitting and design. Realistic prediction of the duration and timing of postclosure mine flooding and the locations of potential future surface discharge(s) are considered critical information for mine design and planning [7, 9, 10]. However, such predictions are hampered by uncertainties related to the same factors that have caused flooding to proceed differently within different mines.

One of the key problems associated with prediction uncertainty is that robust long-term datasets documenting past flooding histories are, in general, not broadly available. The records that do exist are often only partially complete. In the USA, the coal industry is not required to record postclosure flooding observations nor are such data routinely measured by state or federal agencies. Any available flooding observations are frequently archived in nonpublic coal operator files or buried in agency mine permit files. Regulatory efforts to predict probable hydrologic consequences of mine closures do consider that mine pools may develop, but the accuracy of such predictions still depends on having access to long-term flooding data from past cases within similar settings. It may be that, in regional mine flooding, the past holds some of the keys to predicting the future.

The purpose of this investigation is to compile, present, and interpret such a long-term (>40 years) dataset of coal mine flooding observations. Data from multiple sources were collected for a series of about 12 contiguous large underground coal mines in the Pittsburgh coal basin of northern West Virginia (WV), USA. These 12 mines contain on the order of 40,000 hectares of workings. Underground mines in this district, originally called the Fairmont Coalfield, date back to 1880, when mining was done strictly by handloading methods. By 1901, the Fairmont Coal Company had incorporated, later to become part of the Consolidation Coal Company. Technology by that time was mechanizing, with common use of shuttle cars, long trains, conveyor belts, and different kinds of large mining machinery. By the 1940s, room and pillar methods were in widespread use, and by the 1970s, the mines of that age and depth were using longwall technology for the first time. Closure of a small number of shallow mines in this coalfield first occurred in the mid-1940s; in the 1970s, the rate of closures dramatically accelerated. While two longwall mines continue to operate at substantial depth in this coalfield today, the closure of all other mines in the former Fairmont Coalfield was completed by 1985. This is one of the first of the major coalfields in the Appalachian Basin to close in response to the decline of the eastern US steel industry from 1975 to 1985.

1.1. Objectives. This paper recounts the history of closures and ensuing mine flooding in the former Fairmont Coalfield from about 1970 to 2014. It was our priority to collect data from as close in time to the initial mine closures as possible. Objectives include the following:

(i) To examine the chronology for mine closure and the historical expansion of mine pools (flooding) over this period

(ii) To identify contributing events that led to the first breakout of mine water from this district in 1977

(iii) To examine how long-term hydraulic control of the flooded basin was subsequently achieved by one of the coal operators

(iv) To interpret why flooding in this coalfield occurred as it did

1.2. Study Area. The Fairmont Coalfield is a series of predominantly closed mines along the Monongahela River north and south of Fairmont, WV (Figure 1). It is the southeasternmost extent of mining in the synclinal Pittsburgh coal basin within the Monongahela and Ohio River drainages, whose full extent is shown in Figure 1. Most were drift- or slope-entry mines, originating at or near outcrops along the Monongahela River and its tributaries. Mine development proceeded in a downdip direction to the west-northwest from the outcrop, with overburden thickening and the coal deepening in that direction. The only seam mined underground here was the Pittsburgh coal, which occupies the base of the Monongahela Group ([11]; Figure 2). This coal has been extensively mined in parts of West Virginia, Pennsylvania, Ohio, and Maryland and was sought for its continuity and relatively uniform thickness (ca 2.0 m) as well as its bituminous grade. A negative aspect is its high (4–6%) sulfur content, and mine water from this coal commonly contains dissolved iron, sulfate, dissolved solids, and acidity in concentrations considered unacceptable for most uses [9, 12–14]. It has been used, both historically and today, as both metallurgical and steam coal. Until the mid to late 20th century, coke ovens along the river and at mine mouths were fed by mines like these. Approximately 30 communities in Marion County were coal camps surrounding portals into these mines (http://www.coalcampusa.com/nowv/fairmont/fairmont.htm). The approximate center of the Fairmont Coalfield lies at the confluence of the West Fork and Tygart Rivers, which merge at Fairmont to form the Monongahela River. The Pittsburgh coal outcrop is commonly found in proximity to either the Monongahela or West Fork drainages. Some coal extended east of the Monongahela or West Fork, but in general, the coal lays west of these rivers.

The coal that has been mined to date extends from elevations of 240 to 290 m MSL along the Monongahela-West Fork drainage down to an elevation of 60 to 90 m MSL in

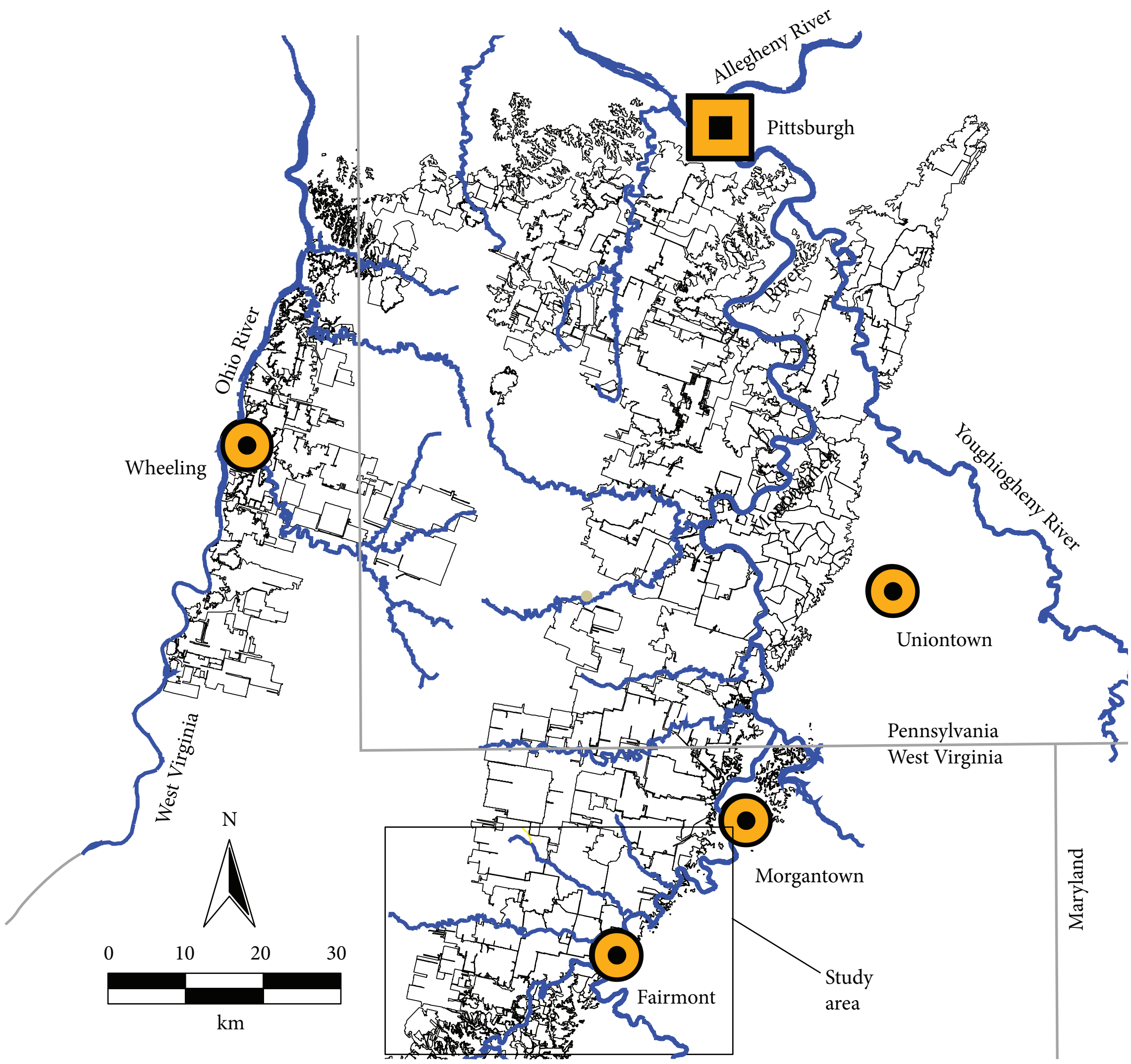

FIGURE 1: Location of study area in Pittsburgh coal bituminous basin, WV-PA-OH, USA.

the deepest mining (Figure 3). As is generally the case, age of workings is inversely related to mine depth. In some locations close to the Monongahela and West Fork Rivers, the coal is above drainage but elsewhere mines are below drainage. Areas where overburden is shallower than about 60 m have been observed in this region to show enhanced vertical infiltration, with the highest rates of recharge associated with subsidence-induced fracturing [15]. With some exceptions, rivers and streams were not undermined and adequate barriers were left in place to prevent surface discharge of mine water except at portal locations. The elevation of the river system is about 262 m at the Monongahela-West Fork-Tygart confluence. Excepting a small number of minor synclines and anticlines, the coal forms a monocline striking about 30°NE dipping to the NW (Figure 3). The dip angle is in fact quite gentle, from 0.5 to 3.0 degrees.

There was little environmental regulation of coal mining over most of the history of this mining district. However, mine water discharge of poor water quality is a well-known impact of mining underground coal with high pyrite content, such as the Pittsburgh seam [16]. The Surface Mining Control and Reclamation Act of 1977 (SMCRA) established the first comprehensive U.S. environmental standards for underground coal mines. This law was enacted only 8 years before closure of the final mine in this study area. Before SMCRA, active mines generally had few requirements in handling or disposal of mine water nor were they legally responsible for water in closed workings they had once operated. After 1977, operating mines became responsible for water in both active and closed (post-1977) operations. SMCRA and water discharge permits were employed to exert a major influence in water management by underground mine operators. They may have also played some role in forcing mine closures in this district.

Figure 4 shows all below-drainage underground mines that were closed between about 1944 and 1985, as well as wells and treatment plants referred to in this study. Shallow closed mines shown as "updip," primarily across the West Fork and Monongahela Rivers from the main coalfield, are older, generally unflooded, and not the focus of this study; they are shown in white outlines without labels. The outcrop of the coal (in red) is generally close to the major rivers and

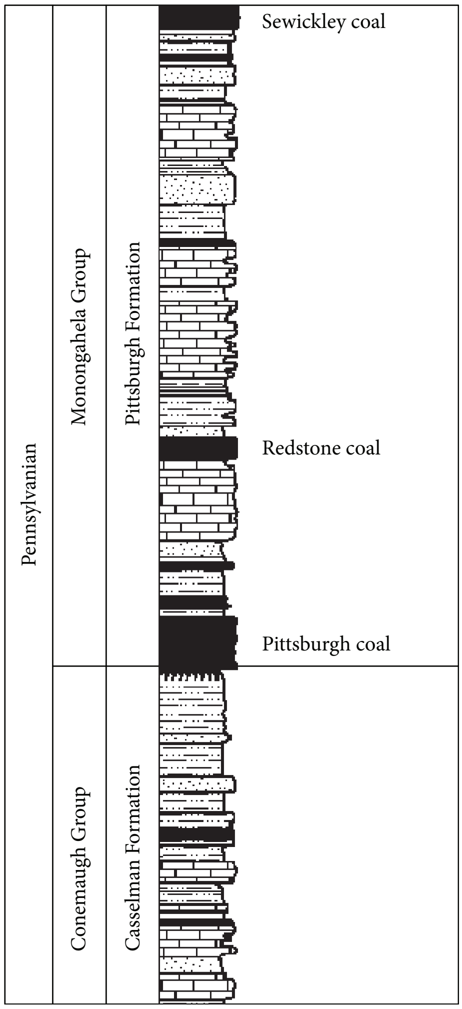

Figure 2: Stratigraphy of Upper Pennsylvanian age coal in the northern Appalachian region, USA. After Cecil et al. [26].

also follows their tributaries. The names are attached to these mines (see Table 1) in some cases to correspond "mine pools" (*sensu* [7]). For example, mines Beth 8 and Beth 41 were mined independently by the same operator, but at closure, entries were left open between them, so after flooding, they formed a single pool. Two deep mines, in yellow in Figure 4, are still currently active but are hydrogeologically isolated from adjacent shallower closed mines that have flooded.

1.3. Monitoring and Pumping Wells. The yellow circular symbols of Figure 4 represent monitoring wells whose data were used in this study. They are unlabeled in mines in which they are the sole monitoring well. In mines with more than one well, each well within that mine is designated "A," "B," etc. Table 2 shows local names for these wells cross referenced to the map identification of Figure 4. These monitoring locations are either cased boreholes/shafts installed during mining by the operator or wells installed for research purposes after 1997. Some were also used for intermittent pumping of mine water before and/or after closure. Pump wells are shown as red squares; some of these were also used for monitoring as designated in Table 2. Active mine water treatment plants (Table 3) are shown as red triangles; all of these generally have one or more pump wells nearby, not explicitly shown on this figure. Two pumps at the north end of the district produce water from Jordan mine that is diverted by pipeline (arrows) to treatment plants over Arkwright mine to the north. In all of these mines, water is high in dissolved iron and pumped discharges have required treatment to meet modern discharge standards.

1.4. Closure History. Figure 5 shows the mines of Figure 4, grouped by closure dates. Letters refer to mine names in Table 1. Only three adjacent mines (Dakota = I, Mine 38 = H, and Mine 56 = G) were closed in the 1940s. The next closure was Mine 63 (F) to their southwest in 1962. Excepting currently active mines (A and N) and Arkwright (O, closed in 1994 and not part of the Fairmont Coalfield), all other below-drainage mines in this figure closed between 1971 and 1985.

2. Methods

2.1. Data Sources. Principal datasets for the investigation include the following:

(i) Water levels in monitoring wells and mining boreholes measured over time and referenced to mean sea level by engineering level surveying

(ii) A GIS dataset developed for this area, consisting of mine outlines, internal and perimeter barrier pillars, monitoring and pump locations, treatment plants, outcrop location, and depths/elevations of the base of coal [17, 18]

(iii) The chronology of mine operations/closures and, if available, pump operations

These data were derived from multiple sources, including regulatory file data, research project measurements, and data communicated from mining company staff. Much information was gleaned from a 2017 regulatory report for Arkwright mine that included considerable basic data collected within the Fairmont Coalfield [19]. Additional relevant data were extracted from a recent regulatory agency research report [20]. Under current (2018) water management, all water originating from Fairmont District mines is treated at two large treatment plants (Dogwood Lakes and Flaggy Meadows) built over Arkwright Mine in the mid-1980s and early 2000s, respectively. Smaller treatment plants occur over Williams, O'Donnell, and Jamison mines; all are shown in Figure 4. The black arrows in the vicinity of Jordan and Arkwright mines indicate pipelines conveying water from pumps to treatment locations.

2.2. Hydraulic Head Measurements in Wells and Mining Boreholes. Groundwater level datasets in this study are of two types: (a) manual operator measurements, generally at intervals of 1–4 weeks or more, and (b) after 1998, measurements by the authors' research groups, commonly using high-frequency datalogger-coupled transducers and resampled to intervals of 1–2 weeks for this study. All data pre-1998 were from measurements by mine operators in

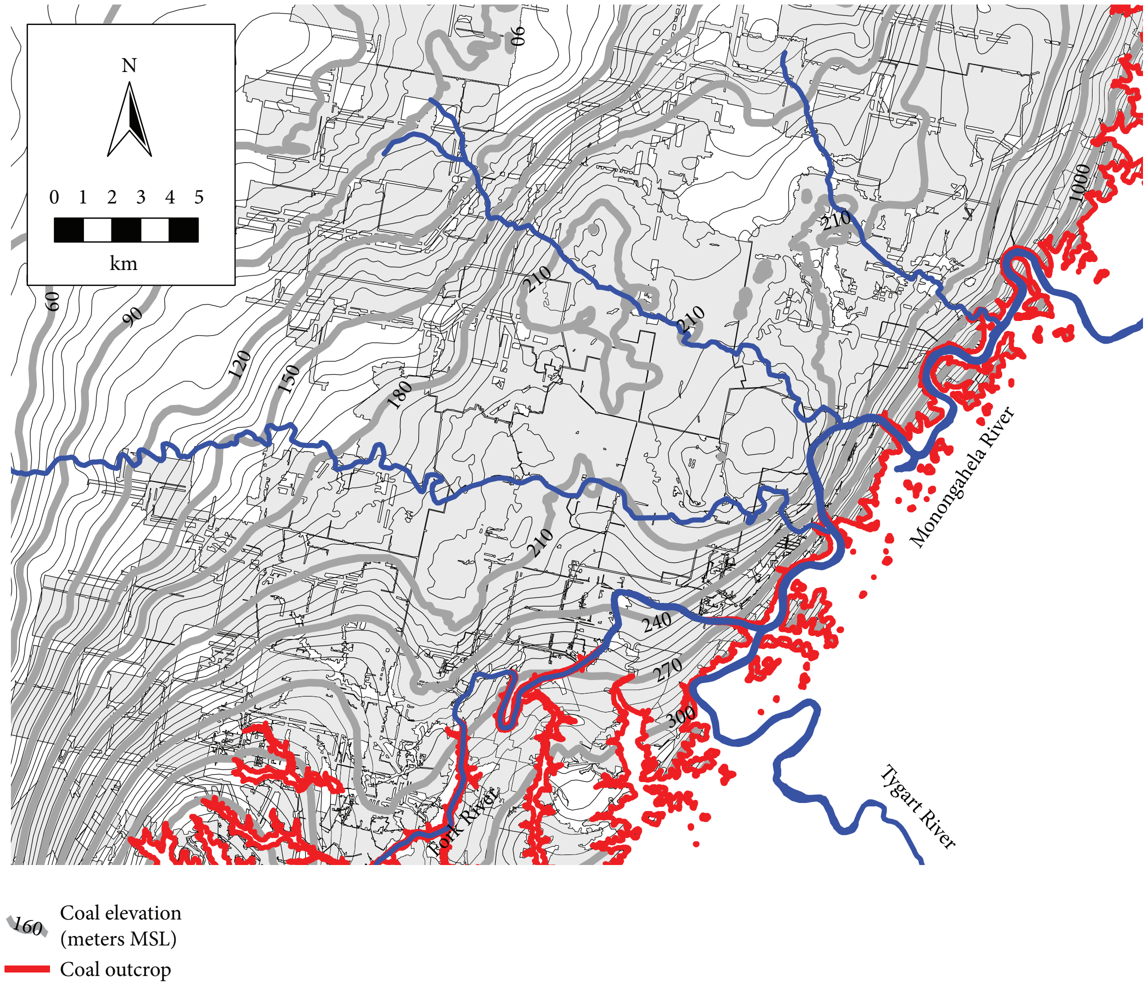

Figure 3: Structure contours of the base of the Pittsburgh coal, in meters MSL. Contour interval 6 m. Bold red line indicates coal outcrop.

the basin. Recorded data included date, measured depth to well water level, accurately surveyed measuring point elevation, and calculated water level elevation above mean sea level (MSL). Accuracy of individual measurements is likely variable, depending on depth of measurement, instrumental accuracy, deviation from vertical of the wells employed, survey error, and human error. While no statistically rigorous estimate can be made, error is roughly estimated at ±0.5 m. Many of these mine water aquifers are confined and their water levels display high barometric efficiency, with fluctuations of up to 0.5 m over hours to days in response to air pressure changes.

2.3. Mine Mapping. The mine and barrier polygons shown in Figures 2–5 and others were digitized from original mine maps, georeferenced to a common base. Details of this process are discussed in Leavitt et al. (2004). Particularly for older mining, georeferencing accuracy is subject to uncertainties in locations of features on the original maps. Polygon mapping was performed at an approximate scale of 1 : 24,000 and was aimed at maximizing the accuracy of barrier pillar thickness and geometry. The pillars separating mines are usually shown clearly on the original mine maps and can be significant hydrogeological features during and after mine flooding [21, 22]. These too are subject to survey errors. Internal coal pillars greater than 3 hectares in area were mapped, including unmined blocks of coal, rib supports for main entries, and some other features. Individual pillars in room-and-pillar or handloaded sections were not mapped. Mine extent shown in Figure 4 is at time of closure for all currently closed mines and as of year 2004 for the two active mines. Therefore, in maps of historic flooding we present, the extent of mining shown in figures for then-active operations may be slightly greater than the actual extent at any particular time preclosure.

Structure contours of the coal bottom were prepared at a 6 m contour interval from mine map contours as well as industry and agency data sources. Using these and mine water levels at specific times of interest, maps of mine flooding extent within closed or active workings were extrapolated from monitoring well water levels. To create these areas, it was assumed that the measured borehole water level at the end of calendar years extended across the entire mine or mine pool in a horizontal plane corresponding to that elevation. In flooding mines without ongoing pumping or injection of water, this assumption has generally proven well-founded in mines with multiple wells [23]. The horizontal plane assumption would be unjustified where (a) more than

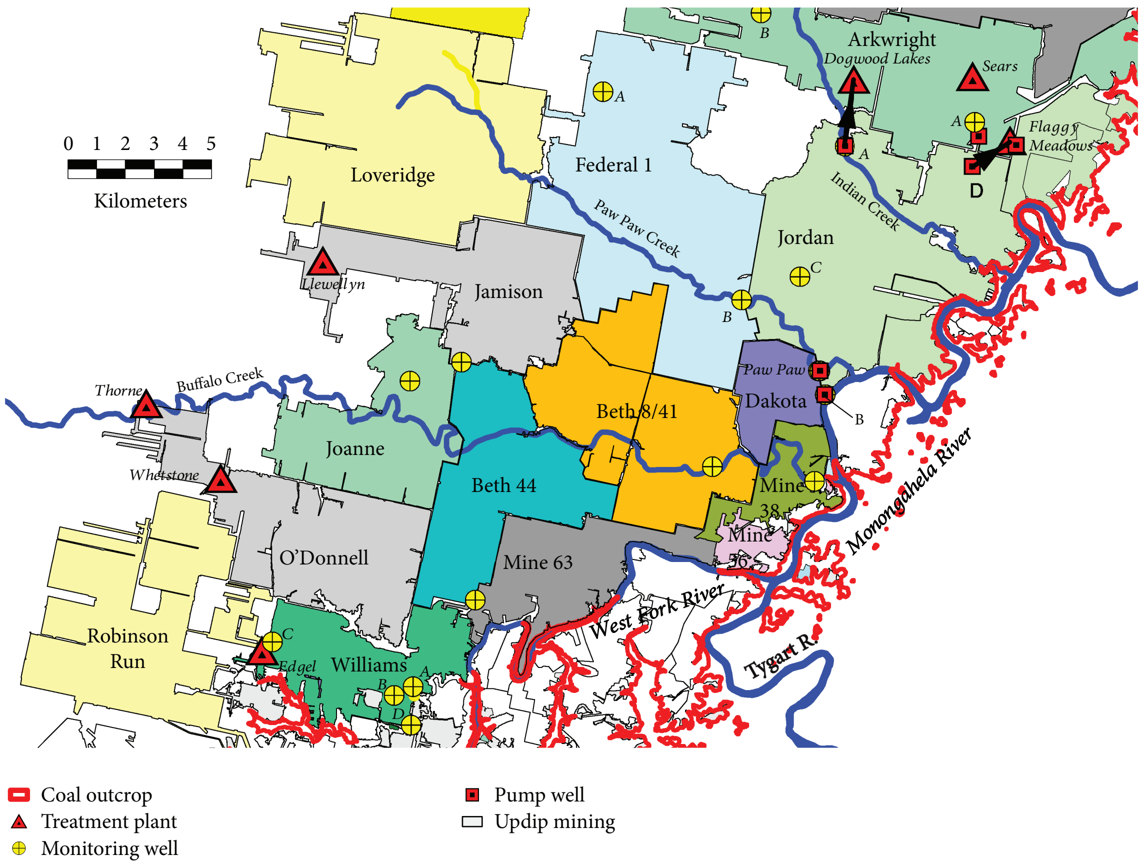

FIGURE 4: Underground mines, monitoring wells, pumping wells, and treatment plants mentioned in or relevant to the text. Currently active mines are shown in yellow.

TABLE 1: Mines in the Fairmont Coalfield and nearby areas. See Figure 4 for locations.

	Area (ha)	Mining methods (s)	Date of closure	Treatment plants	Operator at closure	Designation Figure 4
Arkwright	5508	Room/pillar, longwall	1994	3	Consol	O
Beth 44	2900	Room/pillar	1971	0	Bethlehem Steel	E
Beth 8/41	3740	Room/pillar	1982	0	Bethlehem Steel	J
Dakota	896	Room/pillar	1944	0	Consol	I
Federal 1	6233	Room/pillar, longwall	1985	0	Eastern Associated	M
Jamison	3000	Room/pillar	1978	0	Consol	K
Joanne	2542	Room/pillar	1983	0	Consol	D
Jordan	5350	Room/pillar	1978	0	Consol	N
Loveridge	6090	Longwall	—	1	Consol	L
Mine 38	806	Room/pillar	1946	0	Consol	H
Mine 56	315	Room/pillar	1947	0	Consol	G
Mine 63	1892	Room/pillar	1962	0	Consol	F
O'Donnell	3370	Room/pillar	1982	2	Consol	C
Robinson Run	4039	Longwall	—	0	Consol	A
Williams	1970	Room/pillar	1979	0	Consol	B

After Perry [20]

one pool exists in a specific mine as evidenced by well data or (b) mine water is being injected into or pumped out of a specific mine. Any such situations are highlighted in Results.

2.4. Pumping History. Mine closure estimates were obtained from regulatory files and maps, considered to be reasonably accurate post-1970. Pumping history, however, is more

Table 2: Monitoring and pumping wells in the study area. See Figure 4 for locations.

Mine name	Designation	Borehole name	Primary use	Secondary use	Dates of WL record From	To
Arkwright	A	Flaggy	Monitoring		2001	2014
Arkwright	B	Shaw shaft	Monitoring		2005	2016
Arkwright	C	Flaggy pump 1	Pump		—	—
Arkwright	D	Flaggy pump 2	Pump		—	—
Arkwright	E	Sears pump 2	Pump		—	—
Arkwright	F	Sears borehole	Monitoring		2005	2014
Beth 44	A	Carberry	Monitoring		1972	2017
Beth 8/41	A	Barrackville	Monitoring		1994	2017
Dakota	A	Paw Paw	Pump		1969	2004
Federal 1	A	8 North	Monitoring		1987	1995
Federal 1	B	Grantown	Monitoring		1999	2013
Jamison	A	Llewellyn	Pump		—	—
Joanne	A	Rachel	Monitoring		1999	2013
Jordan	A	Hagans	Pump	Monitoring	1978	2017
Jordan	B	Baxter	Pump	Monitoring	1978	1988
Jordan	C	Ministers Run	Pump	Monitoring	1978	1996
Jordan	D	Ball Park	Pump		—	—
Mine 38	A	Penn overall	Monitoring		1997	2017
Mine 63	A	Pump Station #7	Monitoring	Pump	1961	2013
O'Donnell	A	Thorn	Pump		—	—
O'Donnell	B	Whetstone	Pump		—	—
Williams	A	Pump Station #6	Monitoring	Pump	2002	2013
Williams	B	Nutter Run	Monitoring		1979	1995
Williams	C	Hawks Nest	Monitoring		1968	1979
Williams	D	Shinnston	Monitoring		2002	2008

Table 3: Currently active treatment plants handling Fairmont Coalfield mine water. See Figure 4 for locations.

Mine name	Plant name	First operated	Notes
Jamison	Llewellyn	1978	Protective pumping for Loveridge
O'Donnell	Thorn	1982	Protective pumping for Robinson Run
O'Donnell	Whetstone	1982	Protective pumping for Robinson Run
Williams	Edgell	1978	
Dakota	Paw Paw pump	1997	Barrier transfer Dakota-Jordan following 1997
Arkwright	Flaggy Meadows	2001	Water from Arkwright and Jordan (Booth, Ballpark pumps)
Arkwright	Sears	1990	Water from Arkwright and Brock #4 (Sewickley)
Arkwright	Dogwood Lakes	1979	Water from Jordan (Hagans pump)

difficult to determine. The best evidence for pump operation is the mine water level data themselves; when pumps operate, they often maintain a uniform or declining water level, and when pumps are turned off, water levels generally rise until either a discharge or control elevation is attained. Thus, changes in pump operation manifest themselves as changes in slope on a hydrograph, adding to the utility of water level measurements for interpreting mine hydrology (e.g., [24]). Some records of pumps being either turned off or turned on were available from operators.

3. Results

Figures 6–9 constitute hydrograph and flooding map results that will be referred to frequently. Figure 6 shows maps of flooded pool areas in the Fairmont Coalfield at the end of (from top to bottom) years 1970, 1975, and 1980. Figure 7 shows similar maps of reconstructed flooded pool extent in (from top to bottom) late 1985, 1990, and 1994. Figure 8 (1969–1998) and Figure 9 (1995–2014) are water level hydrographs for monitoring wells in these figures, corresponding

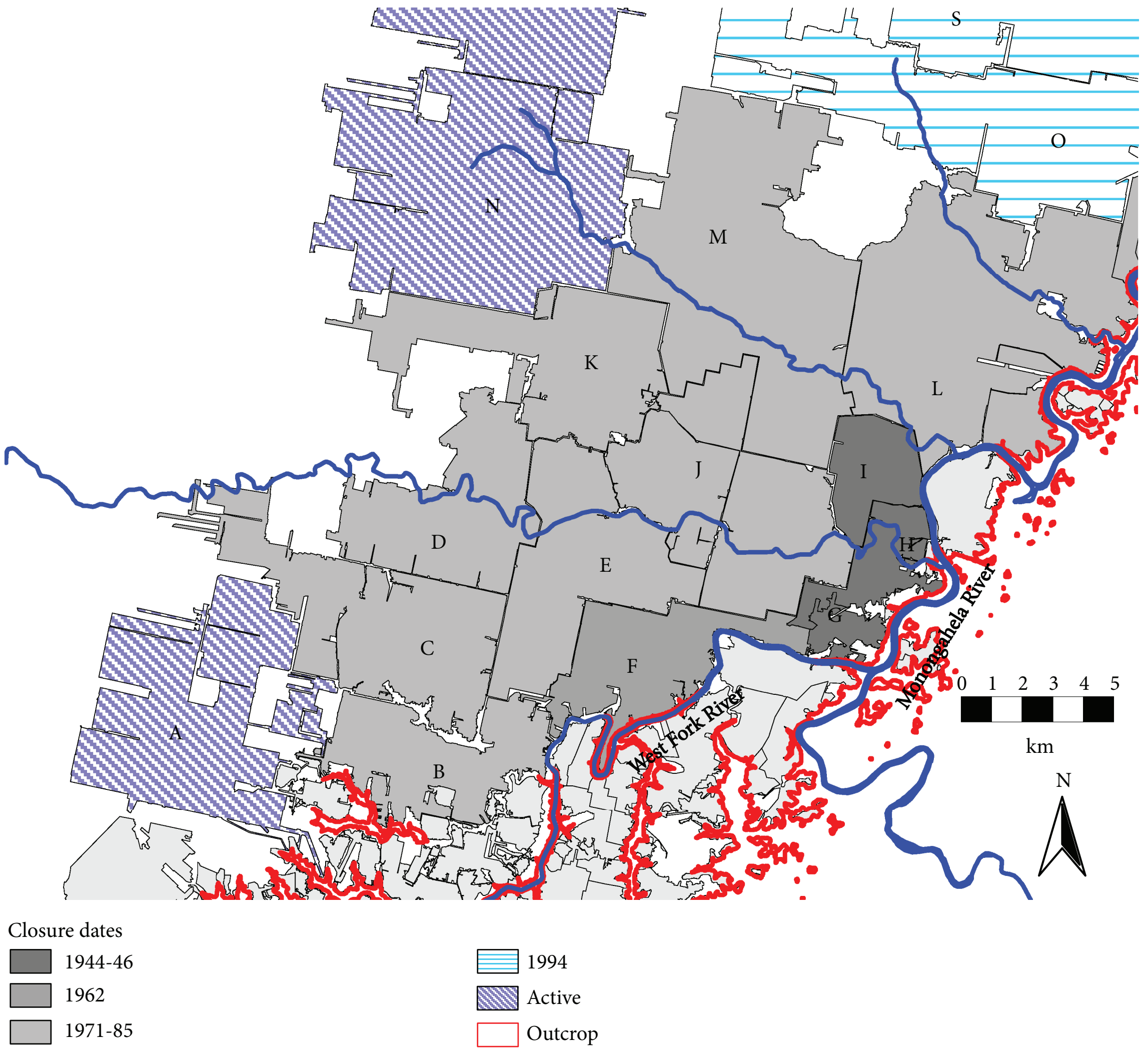

FIGURE 5: Mine closure chronology showing approximate dates of mine closures. Pale grey polygons north and south of the West Fork River are updip mines in shallow cover near the outcrop.

to the flooding maps of Figures 6 and 7. These were constructed using (a) mine closure dates from Table 1 and (b) water level data available to that time as outlined in Table 2. These maps show active mines in light red, for which any flooded areas are not shown as they would generally be small (exception: Williams mine, which had two large pools prior to closure). Superimposed on the hydrographs of Figures 8 and 9 are arrows indicating (a) closure dates of specific mines, (b) the onset of SMCRA in August 1977, and (c) pumping and siphon operational changes at the Paw Paw borehole in Dakota mine.

3.1. Mine Pool Evolution

3.1.1. Phase 1: Early Flooding of Shallow Mines. In 1970, (Figure 6 top) virtually all mines north of the Monongahela/West Fork Rivers were actively producing coal except for Mines 63, 56, 38, and Dakota. Figure 10 shows the interpreted 1970 pool configuration in this shallowest portion of the coalfield at larger scale. These are beneath shallow overburden cover, close to both the West Fork and the coal outcrop. They had closed between 8 and >25 years earlier (Table 1) and by 1970 would have had sufficient time to full resaturate with water. However, available data from Dakota mine, today known to be hydraulically interconnected with Mine 38, suggests that water level in both mines was relatively low (209 m). This lies well below the inferred 1970 pool levels in Mine 63 (about 240 m) and Mine 56 (about 232 m), derived from spill elevations interpreted from mine map and barrier geometry ("spill A" and "spill B," respectively, in Figure 10). Industry records indicate that water in Dakota/Mine 38 was under control of a 1500 l/min pump at the Paw Paw location (Figure 10), operated presumably to minimize water pressure on the Dakota barrier with Jordan Mine, still active in 1970 by the same operator. Adjacent Beth 8/41 and 44 mines were also active and would have lower water pressure on their barrier as a result of the Paw Paw pumping. This interpretation implies that water updip of the Beth 44 and Beth 8/41 barriers would have spilled from Mine 63 into Mine 56 and from there into Mine 38, forming three separate "stair-step" pools all controlled by pumping at Paw Paw in Dakota. It is possible that other pumps may have been

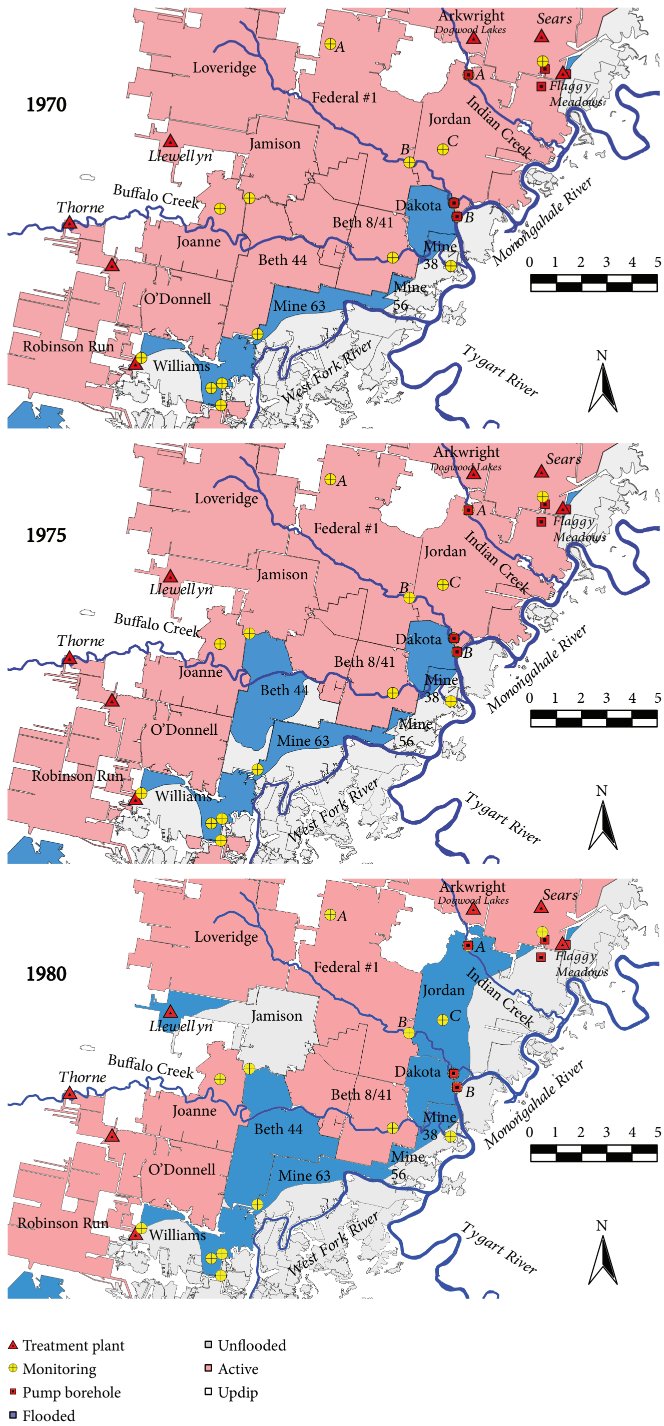

FIGURE 6: Flooding extent in closed mines, 1970–1980. Interior coal pillars are omitted for clarity.

operating in these mines, but no operator records indicate this and there was no apparent need to pump elsewhere, as the flow in the shallow pools would have operated by gravity alone. No treatment facilities were ever built at the Paw Paw pump location, and thus, its pumpage was likely discharged directly into Paw Paw Creek, within 50 m of the pump. This Dakota (Paw Paw) pumpage was discontinued in 1978 after SMCRA was enacted into law, following which the water levels in Dakota began to rise (Figure 8).

Southwest of Mine 63, Williams mine is interpreted to have had two large distinct, but interconnected, pools as early as 1970. Wells with water level measurements on the east pool were Williams B (Nutter Run) and on the west pool Williams C (Hawks Nest). Water levels in different locations within Williams were observed to range between 262 and 275 m from 1970 to 2013, much higher than those in Mine 63 or the other shallow subpools (Figures 8 and 10). Williams closed in 1979, but its water levels did not greatly change at or

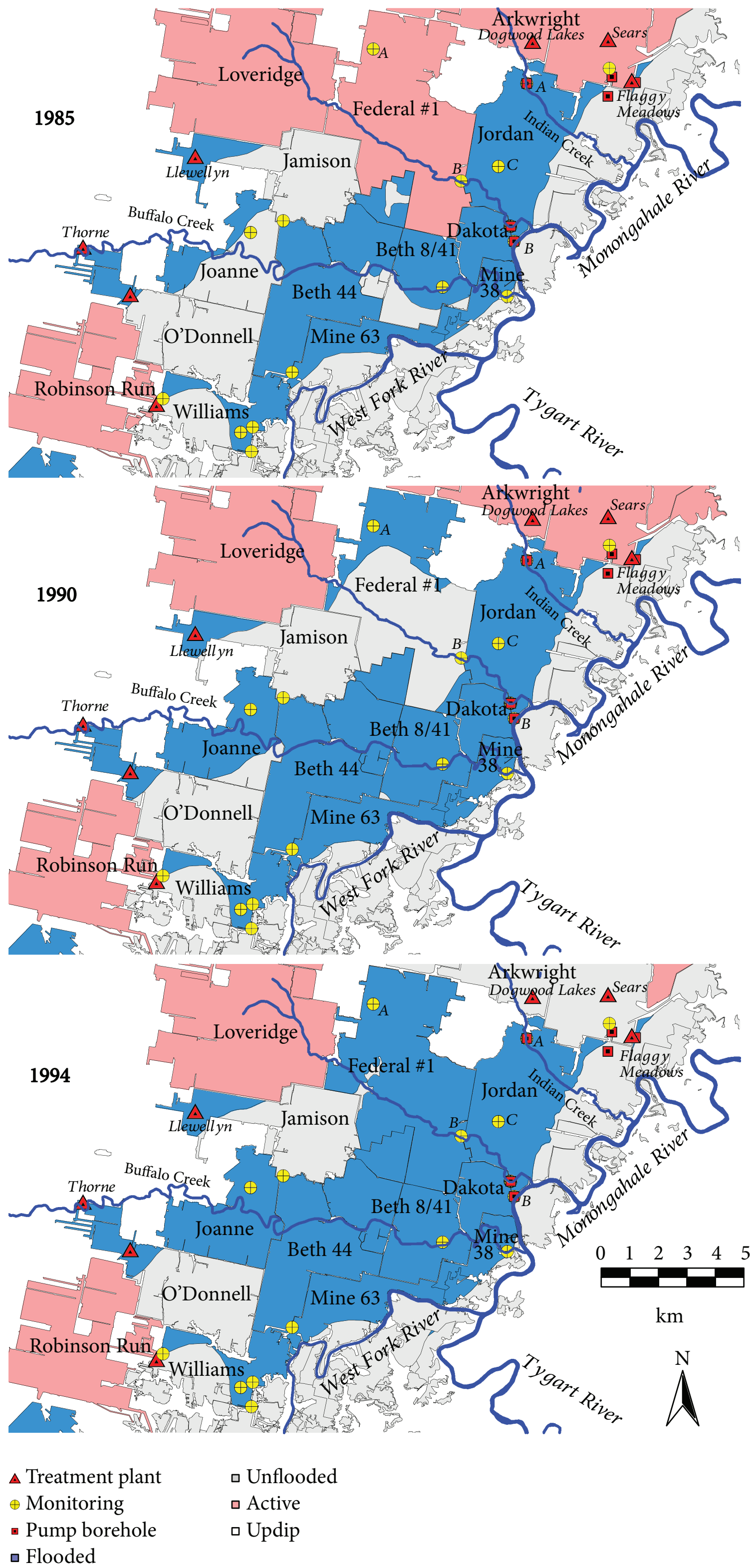

FIGURE 7: Flooding extent in closed mines, 1985–1994. Interior coal pillars are omitted for clarity.

following that time. The only postclosure pumping has been at Edgell treatment plant, near Hawks Nest borehole on the west pool, which still operates today. These two pools are interpreted to be interconnected at a spill over the axis of an anticline bisecting Williams that intersects its north barrier at an estimated 272 m. Hence, the west pool, where Edgell pumps, is slightly lower in water level elevation than the east pool (Williams A, B). It is interpreted that Edgell controls both pools and therefore pumps all infiltration into Williams that does not leak across its northern barrier into

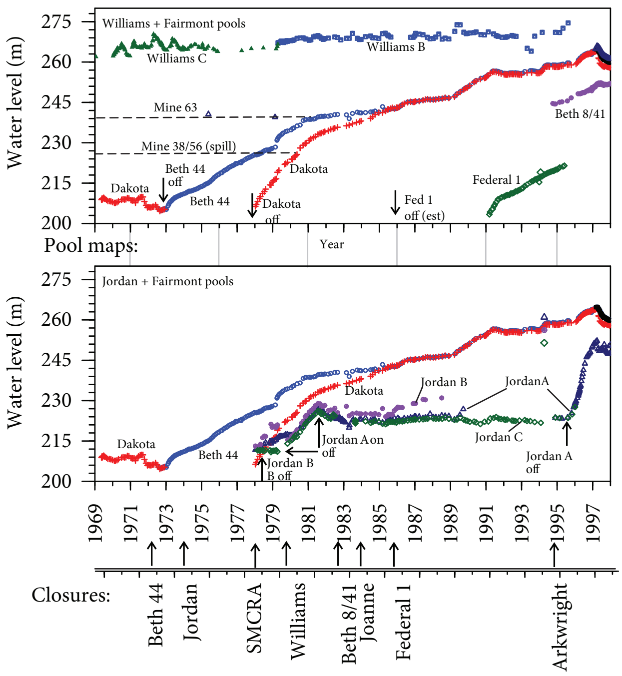

Figure 8: Water level hydrographs in Williams, Fairmont, and Jordan pools, 1969–1998. Labels and symbols refer to water levels at individual monitoring wells within the specified mines (see Tables 1 and 2). Grey bars between plots refer to dates of flooding maps, Figures 6 and 7.

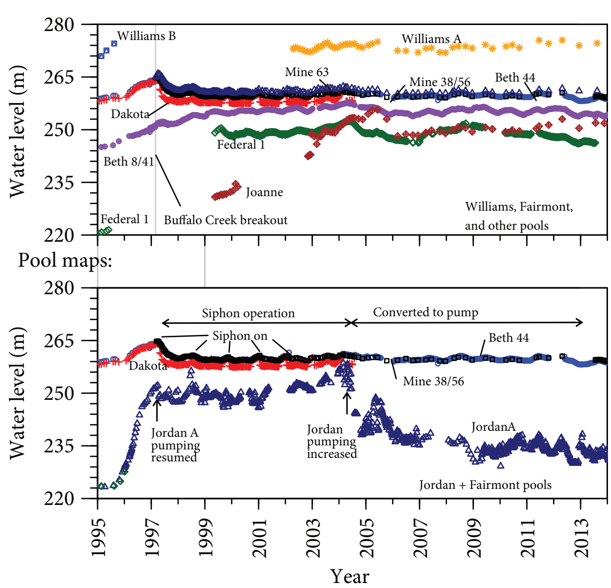

Figure 9: Water level hydrographs in (a) all pools and (b) Jordan and Fairmont pools, 1995–2014. Labels and symbols refer to water levels at individual monitoring wells within the specified mines (see Tables 1 and 2). Grey bars between plots refer to dates of flooding maps, Figure 7.

deeper mines, i.e., Mine 63, Beth 44, and O'Donnell. This keeps the Williams pools from forming a surface discharge.

The difference in pool elevations between Williams and the downdip mines is strong evidence this barrier has remained intact, although some leakage likely occurs. The head difference between pools in Mine 63 and Williams has decreased over time from 27 meters (1970–1984) to 10 meters (1997) as Mine 63 filled after cessation of Dakota pumping (Figures 8 and 9). Therefore, Williams is interpreted to be a leaky source of water for Mine 63 and others across its northern barrier, but this leakage rate would have declined over time as the head difference across the barrier decreased. The barrier sections are, furthermore, short, suggesting that total leakage may not be large.

Early flooding therefore created a series of six shallow, discontinuous pools (2 in Williams plus 4 in deeper mines) with no documented surface discharge except for pumping at the Paw Paw and Edgell locations. The Williams Mine contained a split pool divided by a small anticline and was itself contained by an intact barrier from discharge into the shallow Mines 63, 56, and 38 subpools. The Paw Paw pumping was apparently done to protect active operations in adjacent mines, but also controlled these shallow pools. The basin map (Figure 6 top) shows very limited mine pool development, largely restricted to these outcrop areas.

3.1.2. Phase 2: Flooding of Beth 44 to Form the Fairmont Pool. When Beth 44 closed in early 1972, it flooded from elevation 205 m at a rate of about 4 m/year (Figure 8), inundating over half of the mine in about three years (Figure 6 center). By 1980, it was nearly roofed (Figure 6 bottom). Thereafter (1980–1981), the Beth 44 pool was observed to merge with the 240 m pool of Mine 63 (Figure 8(a)), following which the two mines flooded together at a slower rate, demonstrating that the barrier between them is hydraulically open. However, Williams to the south maintained a separate, much higher pool level, indicating its barrier was intact and restricting flow into Mine 63/Beth 44.

By 1978, when SMCRA was enacted, all pumpage was discontinued in both Jordan and Dakota mines. The Paw Paw (Dakota) pump was turned off in 1978, initiating flooding in Dakota at a very rapid rate of 10–15 m/year. Jordan had closed in 1973 but still operated pumps until 1978 at 3 locations (Baxter, Minister Run, and Hagans; Jordan B, C, and A), ostensibly to minimize barrier leakage into adjacent active mines. Between April and June 1978, subpools in Jordan rose and quickly merged into a single pool (Figure 8(b)), flooding at a similar rate to Beth 44 until mid-1981 at water level 224 m. At that time, the pump at Jordan A was restarted, conveying water to a newly constructed post-SMCRA water treatment plant at Dogwood Lakes about 2 km from the pump location. Water level in Jordan pool was lowered and held at about 222 m (Figure 8(b)). Mine maps indicate a "cut-through" section in the Arkwright-Jordan barrier had been reached in 1981 by the rising Jordan pool near 223 m, causing leakage from Jordan into the operating Arkwright mine. Minimizing this leakage may likely have been the cause of renewed pumping at Jordan A (Figure 8).

There were small, but significant, changes in the configuration of the shallow pools (Mines 38/56/63 + Dakota) in this time period. As Beth 44 flooded, it merged with Mine 63 in early 1981; this merged pool continued to rise more slowly until it merged with Mines 38, 56, and Dakota in

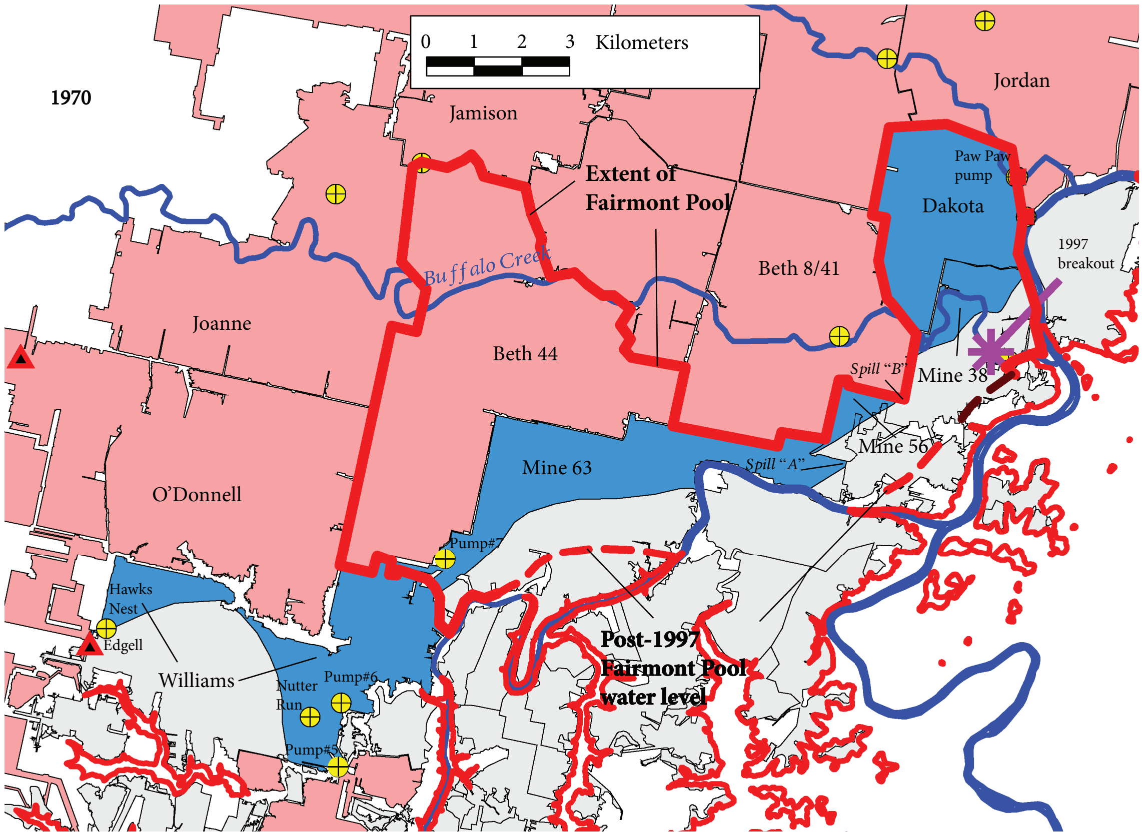

Figure 10: Closer view of phase 1 flooding progress in year 1970 showing Williams Pool and the three subpools (mines 63, 56, and 38) that later merged into the Fairmont Pool. Ultimate extent of the flooded Fairmont Pool is shown in thick red line, dashed along the "beach" location. Purple symbol represents location of Buffalo Creek mine water breakout in 1997.

early 1986. All these subpools from 5 different mines had now merged between Jordan and Williams/O'Donnell mines, a distance of some 25 km (Figure 8), and after 1986 continued to gradually rise at a single common water level elevation. This large merged pool has been termed the "Fairmont Pool" in earlier literature [20] and is shown outlined in solid red (perimeter barriers) and dashed red (1997 pool level) in Figure 10. Until about 1985, the flooding pattern in the Fairmont Pool resembled a "horseshoe" configuration (Figure 6 bottom), perched around and above the Beth 8/41 mine, still active until 1983. By 1990, after Beth 8/41 had roofed with mine water, the horseshoe pattern disappeared.

In phase 1, the area of flooding had been minor and restricted to 5 mines close to the outcrop with discontinuous pools. During phase 2, Beth 44 flooded and merged with phase 1 subpools to form the much larger Fairmont Pool, separated from both deeper (Beth 8/41, Joanne, O'Donnell) and shallower (Williams) mines by intact barriers. At the same time, pumps in Jordan were turned off by early 1978, but its flooding was interrupted by renewed pumping in 1981 to control barrier leakage into Arkwright mine to the north. Mines deeper than the Fairmont Pool and Jordan were still active as of 1978.

3.1.3. Phase 3: Deep Mine Closures and Completion of All Flooding. During phase 3, deep mines that closed between 1978 and 1986 included Beth 8/41, Joanne, Federal 1, Jamison, and O'Donnell. This represents all of the mining associated with the historic Fairmont Coalfield, except two deep longwall design mines (Robinson Run and Loveridge) that continue to operate to the present. Figure 7 shows the time series of flooding associated with these deep mine closures in 1985, 1990, and 1994.

These deeper mines differ from earlier closures in being shaft- rather than drift- or slope-entry designs. They do not extend to the outcrop and are separated from shallower updip mines by largely intact, but leaky, barriers. As they flooded, the phase 3 closures were at all times lower in head than the updip mines (Fairmont Pool, Williams, and, after 1996, Jordan), which served as a source of inflow to the deeper mines via barrier leakage. This was especially true during early flooding, when the downdip side of the updip barriers would have been dry and pressure gradients across barriers at their highest.

Two of these mines, Jamison (closed 1978) and O'Donnell (closed 1982), have never fully flooded, because their pools have been maintained at low levels by protective pumping at Thorne, Whetstone, and/or Llewellyn treatment plants (Figure 7). The purpose was to minimize barrier leakage into adjacent operating mines (Robinson Run and Loveridge). Jamison and O'Donnell will fill and fully flood once adjacent mining ceases and pumping is discontinued. These "protective pumping" mines receive barrier leakage from shallower mines updip, thought to be the primary source of their water

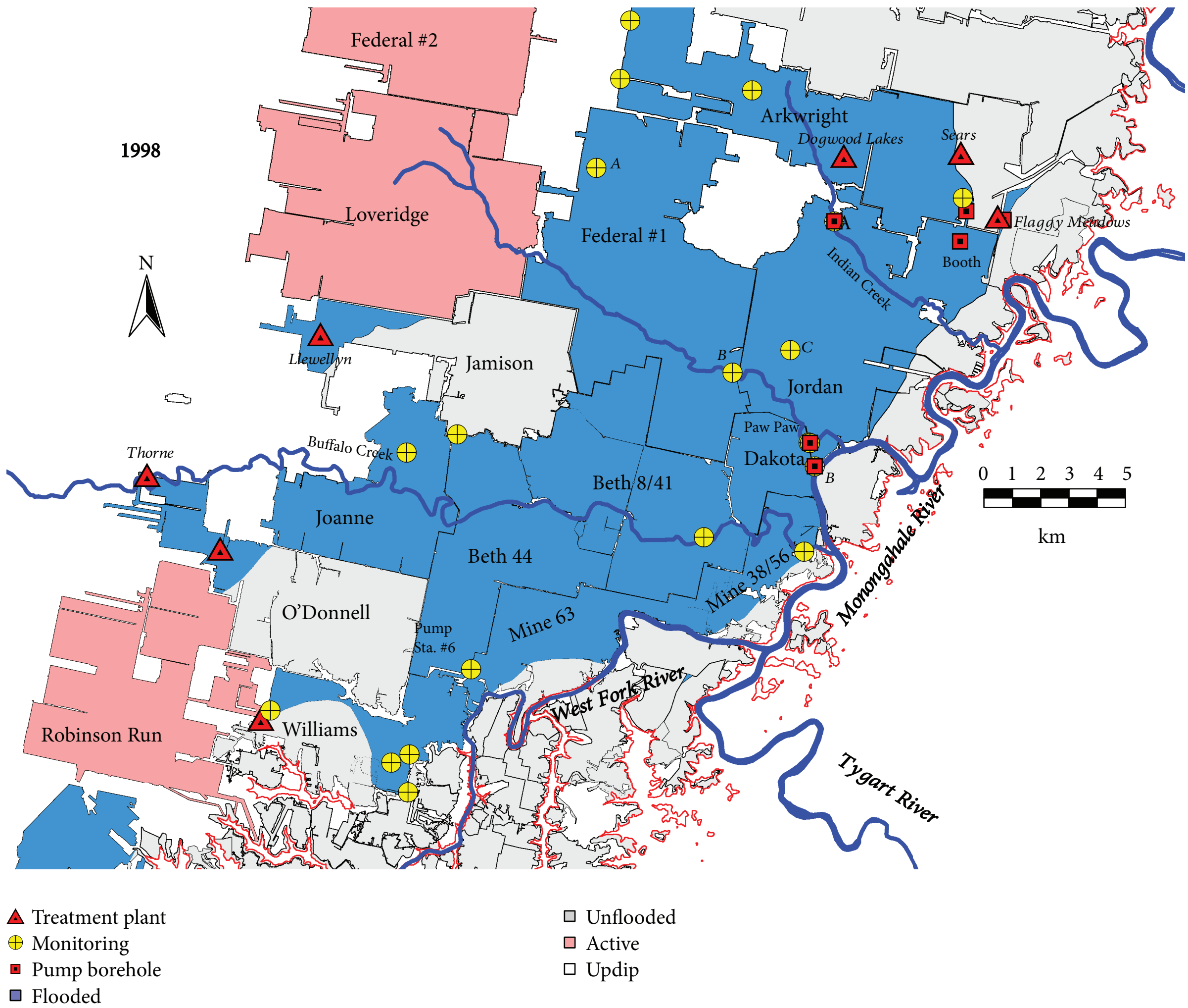

FIGURE 11: Flooding extent at maximum flooding following installation of Dakota-Jordan siphon at the Paw Paw site, 1998. Interior coal pillars are omitted for clarity. Yellow circle is Paw Paw pump; red circle is 1997 Buffalo Creek discharge.

at this relatively large depth. McCoy et al. [25] employed rates of pumping in Jamison and O'Donnell to estimate the average hydraulic conductivity of these updip barriers.

This third phase of flooding involved deeper mines without outcrop exposure. Flooding started immediately after closure and was complete within 10–15 years (Figures 7 and 9). Hydrographs indicate that the flooding rate was somewhat similar for the phase 3 deep mines (Federal 1, Beth 8/41, and Joanne). They roofed and gradually equilibrated to an annually stable water level by about 1999 (Figures 6–8). At this time, the hydraulic heads of their pools differed both from each other as well as from the shallower mines in the Fairmont Pool, which were higher in elevation. After 2000, a long-term steady-state condition ensued, with inflow both out of and between the phase 3 mines under control of barrier leakage rates. Their outflow was into either the pumped Jamison and O'Donnell pools or, for Federal 1 and Beth 8/41, into Jordan, with which they shared barriers at lower hydraulic head.

3.1.4. Phase 4: Breakout, Long-Term Pumping Control, and Equilibration. Figure 11 shows the pool configuration in 1998, at which time flooding of these mines had essentially been completed. It is barely distinguishable from the 1994 flooding map, with the major differences being (a) significant advance of flooding in Arkwright since its 1994 closure and (b) expansion in size and hydraulic head of the Jordan Pool, induced by turning off the Jordan A pump in 1995 after Arkwright closure (Figures 8 and 11). Following discontinuation of pumping, the flooding rate in Jordan was precipitous, with the pool rising about 25 m in only 18 months (Figure 8(b)). As Jordan rose, the head difference between Jordan and Dakota decreased from 36 m to only 12 m, undoubtedly causing a decrease in out leakage from Dakota and a backup (increase) in water level within the Fairmont Pool (Figure 8). At the beginning of 1997, the water level in the Paw Paw (Dakota) borehole was 263.8, an all-time high and approximately 3 m higher than the "normal" pool elevation (260.6 m) of the Monongahela River nearby. Under such circumstances, surface discharge was inevitable and, in fact, imminent.

In January 1997, a visible discharge of red metal-rich water was detected by an employee of the mine operator in the center of Buffalo Creek 1 km from the Monongahela and 4 km from the Paw Paw (Dakota) pump site along the Jordan-Dakota barrier (Figure 10). The source was mine water from the Fairmont Pool in a section of the creek undermined by Mine 38, connected to Dakota (i.e., the Fairmont Pool). Immediately, the Jordan-Arkwright operator initiated a plan to lower the water level in the Fairmont Pool mines by installing a large diameter siphon from Dakota to Jordan using the existing Paw Paw borehole. The siphon was plumbed to discharge into a new injection well drilled into Jordan across the Jordan-Dakota barrier approximately 30 m from the Paw Paw well. This was fully operational in late April 1997 at an approximate rate of 5700 l/min. The Fairmont Pool level, observed at Dakota, Beth 44, Mine 63, and Mine 38 boreholes, immediately responded to pumping and gradually declined 2 m by late 1997 (Figure 9), resulting in control and disappearance of the Buffalo Creek discharge. After the siphon began operation, water levels in most wells of the Fairmont pool were within 0.5 m of each other, with the Dakota monitoring well (e.g., the siphon intake) about 2 m lower, due to hydraulic losses either at the well intake or at the Dakota-Mine 38 barrier. The siphon needed to be operated only about 8 months per year to keep the Fairmont Pool water levels below 260.6 m and assure no surface discharge was possible. The annual winter/spring peaks in Fairmont Pool water levels between 1997 and 2003 (Figure 9) result from seasonal recharge as well as seasonal siphon operation in successive years.

Starting in year 2002, water levels in shallow mines (Jordan, Fairmont Pool) as well as some deeper mines (especially Beth 8/41, Federal 1) abutting Jordan started to gradually increase (Figure 9). This increase is attributed to water levels in the deeper phase 3 mines finally "catching up" to those in the Fairmont Pool and Jordan and decreasing barrier leakage losses to these deeper mines. It also decreased head difference between Jordan and Dakota which reduced efficiency and flow rates of the siphon. Most significantly, the Fairmont Pool level had started to rise above its regulatory 260.6 m limit. To counteract, in early 2004, the operator replaced the Paw Paw siphon with a higher capacity pump that could be operated in all seasons, also adding a second pump at Jordan A (Hagans) to transfer more water out of and lower the Jordan pool. Additional pumpage was taken from 2 boreholes in the shallower part of Jordan, pumped as needed to the Flaggy Meadows plant. Under the new pumping scheme, Jordan was lowered to a fluctuating stage of about 225–240 m, similar to the 223 m level at which it was held prior to Arkwright closure. The Fairmont Pool mine water levels were returned to the range of 258–260 m and deeper pools have shown no additional rise since 2004, attaining a new apparent steady state.

For all mines of this study, there is a current near-steady-state hydraulic configuration, induced by pumping control. This means that all mine water from the Fairmont District, excepting Williams, is conveyed into Jordan by either barrier leakage or pumpage at the Paw Paw site or leaks into the two protective pumping mines. This water in Jordan, along with shallow recharge into Jordan itself, is pumped from 3 locations to treatment plants over Arkwright mine. Except for the 1997 Buffalo Creek event, no surface discharges of mine water from the below-drainage Fairmont Coalfield mines have occurred following enactment of SMCRA in 1978.

4. Summary and Conclusions

The sequence of mine flooding in the Fairmont District followed four distinct phases in the time period 1969–2014:

(1) Phase 1. Initial controlled flooding in shallow workings closed pre-1970 (the Fairmont and Williams subpools), with protective pumping maintained adjacent to active mines

(2) Phase 2. Relatively rapid flooding in Beth 44 and Dakota along the east and west sides of Beth 8/41 following Beth 44 and Jordan closures and resulting in full merger and development of the Fairmont Pool by 1986

(3) Phase 3. Closure and slow filling of deeper mines, supplied by barrier leakage from the Fairmont Pool and Jordan (1982–1995). At the end of phase 3, closure and discontinuation of pumping in Jordan and Arkwright mines caused acceleration of flooding (1995–1997)

(4) Phase 4. Breakout of Fairmont pool mine water in Buffalo Creek following by siphon/pump control of mine water at the Paw Paw site; water is either transferred into Jordan (from which it is pumped to treatment sites) or leaks across barriers into Jamison and O'Donnell. Long-term steady state was achieved in 2004, about 7 years after initial breakout

The progress of flooding was, of course, influenced by the sequence and timing of mine closures, and, in general, the shallowest mines closest to the outcrops had closed first. However, there were other factors also at play in the sequence of flooding events that were at least as important in this case as the closure timing.

(1) Protective Pumping of Active Operations. For a number of mines, flooding did not proceed immediately upon mine closure, because pumps in closed mines were kept operative to minimize pool levels and barrier leakage into still-active mines. This occurred in Dakota, Jordan, and the deep Jamison and O'Donnell mines. This held water levels in the Fairmont Pool far below flooding levels for decades after the first mines closed in the 1940s. As a result, it was less when mines close that dictated how quickly they flood, but when the last mines close and protective pumping is discontinued.

(2) Impact of Change of Regulations for Discharge of Mine Water under SMCRA. Protective pumping in both Dakota and Jordan was discontinued in 1978, well after both mines had closed, despite the fact that Arkwright, Beth 8/41, and other deeper mines were still active. It is very possible that this was due to the SMCRA requirement that discharges be treated, yet no treatment plants existed in these pumping locations. Thus, implementing SMCRA appears to have influenced discontinuation of protective pumping where treatment plants did not exist.

(3) The Existence of Intact Barriers between Shallow Mines of the Fairmont Pool and Deeper Mines. There are two different types of mines in the district: shallow slope- or drift-entry mines hydraulically open to the outcrop and deeper shaft-entry room-and-pillar mines with no direct outcrop connection. Separating the two are intact barriers which during flooding served to isolate the two from each other hydraulically except by barrier leakage. Therefore, the shallow pools flooded first (Fairmont Pool) and served as a source of slow leakage to the deeper mines as these later closed and gradually flooded. Once the deep mines roofed and approached the water levels of the shallow ones, the changes in barrier leakage that ensued required additional pumping capacity to control the Fairmont Pool, as occurred in 2004.

The shallow mines (Williams, the Fairmont Pool, and Jordan) have been, since steady state, unconfined in the vicinity of their flooding levels, i.e., had a narrow phreatic zone. On the other hand, the deeper flooded mines are completely confined. It was in the shallow pool areas that water control efforts needed to be focused, as this is where the greatest risk of surface discharge existed.

In summary, both the sequence of flooding and the method of pool control by pumping have been strongly influenced by whether the mines are confined or unconfined after flooding is complete. Unconfined pools will be supplied by recharge as well as barrier inflow/outflow and those that are most pivotal to effect long-term pumping control. Confined pools, on the other hand, will tend to have water balances dominated by barrier leakage. They will influence the water balance in shallower updip pools, but likely not be involved in pumping control schemes themselves, excepting deep mines like O'Donnell and Jamison used for protective pumping of active workings.

Data Availability

All water level data collected by the authors and used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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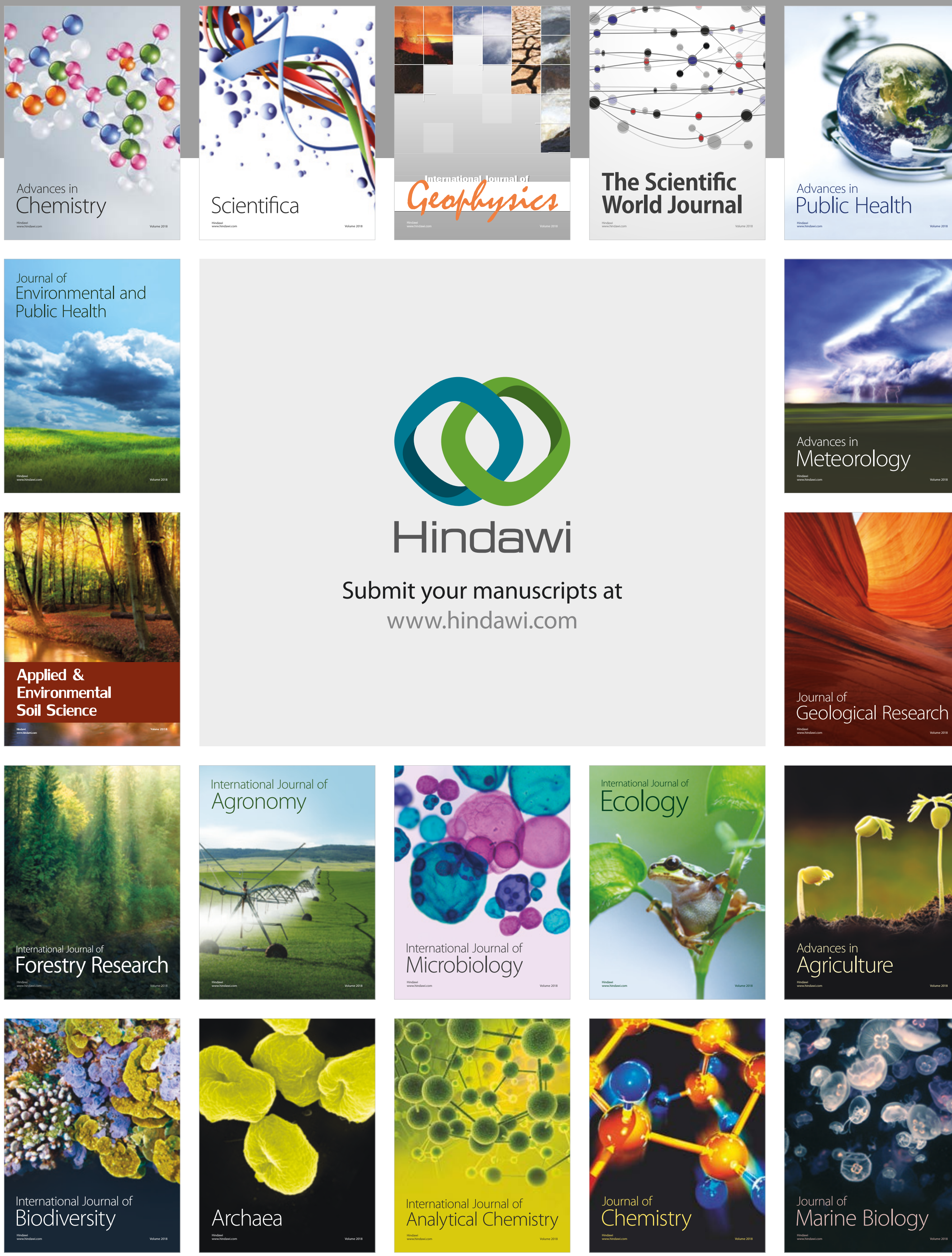
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