Task 3-3 Final Report, MISTII GEO-27

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principal components of the PCS.

1 INTRODUCTION

1.1 Interaction between mine voids and gas wells

The intersection of underground coal mines by natural gas wells creates the potential for a variety of safety, environmental, and economic concerns. Gas wells can intersect either closed or active underground mines, or alternately become mined around in future coal operations. In this task, we will be concerned primarily with closed mines, as mine-safety related to gas wells in active operations is well codified in federal and state mine-safety regulations (e.g., MSHA regulations in 30 CFR § 75.1700 for oil and gas wells). The recent boom in drilling of Devonian shale-gas wells has accentuated both safety- and environmentally-related risks associated with intersecting old mines.

Problems related to natural gas wells passing through closed coal mines include:

- lost circulation of drilling fluids and other drilling-related difficulties
- coal bed methane (CBM) explosion risk, and
- contamination of shallow aquifers.

The current best-management approach to drilling through a mine opening is to drill without fluids to at least 20 feet below the base of the mine opening, then to case and cement the opening up to no less than 20 feet above the mine roof. When drilling through multiple coal beds, casing is typically cemented in no less than 20 feet below the deepest bed and no less than 20 feet above the shallowest coal (e.g., W.Va. Code §22-6-20 for "protective devices"). On the other hand, longwall mining of coal can result in fractures extending as much as 40 times the height of the workings (Singh and Kendorski, 1981; Peng, 1986; Palchik, 2003). It is therefore conceivable that drilling fluids or gases could enter the mine via a compromised or circumvented seal via subsidence fractures. CBM from mines also has the potential for hazard to drilling operations and/or surface explosion, as occurred on a Marcellus drill site intersecting the closed Alexander mine on June 7, 2010 in Moundsville, WV (Tognerie and Puko, 2010). This incident resulted in injury to seven contract workers.

In addition to such problems, shale gas extraction poses other environmental risks. Reservoir stimulation by hydraulic fracturing, a.k.a. “fracking”, places large demands on local water resources, especially if horizontal drilling is performed. Fracking of a single horizontal shale-gas well can require 3 million gallons of water or more (Harper, 2008). In contrast, drilling a conventional gas well without fracking uses only on the order of 100,000 to 300,000 gallons of water (Hopey, 2011). The chemical makeup of return-flow fluids is also of potential concern, as this represents original frack water and additives mixed with highly-saline or briny formation water (Hayes, 2009). Prudent disposal of flowback fluids should not include discharge to surface waters or into underground mines, whose groundwater ultimately reports back to the surface via various flowpaths.

1.2 Purpose and objectives

The purpose of this task is to gain an understanding of how and where shale-gas operations may influence or interact with local underground mine-water resources of the Appalachian region. The drilling of conventional natural gas wells has taken place since the 1900s. In 2004, Range Resources drilled and completed the first Marcellus well in Pennsylvania using fracking. The years immediately after were characterized by land acquisition and permitting, followed by widespread drilling of shale-gas wells ion 2006-2012. In portions of this shale-gas district, there are extensive flooded underground mines, not seen in other shale-gas fields. To date, little is known about how the technologies and completion practices employed in shale-gas drilling may affect or interact with these mine pools.

To examine potential interactions between underground mines and shale gas drilling, we must first locate areas where they co-exist. To accomplish this, the following will be performed:

- compilation of geospatial data regarding mines and gas wells
- 2-D and 3-D visual representations of subsurface mining
- analysis of results

In addition, we will provide a baseline estimate of water chemistry in selected underground mines of the region. Mine-water discharges in large volume from mining districts of this area, in excess of 100,000 gallons per minute in the Pittsburgh seam alone (Donovan and Leavitt, 2004). The water chemistry of these discharges vary from place to place, and to date there have been few samples documenting the current chemistry. To provide an index of water chemistry prior to alteration by gas-well activity, sampling and analysis of these discharges would be required.

1.3 Study area

The study area is the Appalachian Basin within all of West Virginia and parts of Maryland, Ohio, Pennsylvania and Virginia (Figure 1). The study area was chosen because it has numerous recent shale gas wells drilled through underground mines. Most of these wells are either horizontal or vertical completions and used fracking techniques. The study area covers 38,200 square miles (61,500 square kilometers) within the Appalachian Highlands region. It lies mainly in the Allegheny Plateau physiographic province (Fenneman, 1938; Figure 2) and includes the Appalachian Coal Basin, a broad regional syncline in which many coal beds are found in the subsurface. Thrust faults and folds of the Valley and Ridge Province abut this basin to the east, forming a boundary the Allegheny Plateau at the Allegheny Front. The surface geology within the study area ranges from late Precambrian- to Permian-age rocks, with the oldest rocks in the Valley and Ridge. Within the plateau itself, most rocks range from Mississippian to Permian in age.

The geologic history of this area is that of the Paleozoic. From late Precambrian to late Ordovician time, the region was periodically covered by a shallow sea, which resulted in the deposition of sequences of clastic and carbonate marine rocks. The Taconic Orogeny at the end of the Ordovician created uplift to the east of the region which provided sediment to the newly created western foreland basin during the Silurian and Devonian periods. Near the end of the Silurian, evaporites were deposited over much of the area; these salts (mainly halite) are the source of the aqueous brines that saturate the deep basin today. Further uplift from the Acadian Orogeny in the middle and late Devonian provided terrigenous predominantly clastic marine sediments, including the Marcellus Shale. By the end of the late Devonian, the sea receded in many areas and erosion dominated, and the last significant marine deposit was laid down during a middle Mississippian marine intrusion. During the Pennsylvanian, the sea receded exposing a coastal platform which continued to subside at approximately the same rate of deposition, resulting in thick cyclothems of sandstone, shale, and coal upon which this study focuses.

The Marcellus Formation (Oliver and others, 1967) is black, organic-rich shale of middle Devonian age with considerable natural gas content. Estimates by Engelder and Lash (2008) put the total gas in place at 500 trillion cubic feet (141.6 trillion cubic meters), about 50 trillion cubic feet (14.2 trillion cubic meters) of which is roughly estimated to be recoverable. Figure 3 shows the study area in relation to the extent of the Marcellus shale. The shale exhibits natural vertical fractures resulting from tectonic forces that have prevailed in the region (Engelder and Lash, 2008). Historically, only low-producing gas wells have been completed in the Marcellus due to its low intrinsic permeability. Rarely, a conventional Marcellus well has produced high volumes of gas attributed to intersecting vertical fractures. In the period since 2004, new horizontal-drilling and fracking technologies have increased the fracture density within the shale and made high gas yields not only possible but commonplace. The purpose of hydraulic fracturing is both to intersect more of the vertical fractures and to create new fractures between the newly-formed reservoir and the well.

All of the economically-minable coals in the study area are bituminous and of Pennsylvanian age. The geology may be generalized as, from youngest to oldest (Figure 4), the Monongahela, Conemaugh, Allegheny, and Pottsville groups, based on terminology of Ruppert et al. (2001) and Tewalt et al. (2001). These units consist of multiple sequences of flat-lying sedimentary strata, including sandstone, conglomerate, siltstone, shale, claystone, limestone and coal (Miller, 1968). The bituminous coal deposits within the basin are folded into a few hundred small-scale synclines and anticlines, which trend in a northeast direction parallel to the Appalachian Mountains (Arndt and Averitt, 1968). The depositional environments of these Pennsylvanian strata were thought to be deltaic or marginal marine (Ruppert et al., 2001).

Mining has been carried out largely in the last 150 years. Due to recent environmental regulations limiting sulfur dioxide emissions from coal-fired power plants, there has been some shift to low-sulfur coals in the western United Sates, leading to a decline in Appalachian production (Ruppert, 2001). While some large mines are still active in the study area, vast areas are now underlain by closed coal mines.

1.3.1 Northern Appalachian underground coal mines aquifers

The Northern coal fields in SW Pennsylvania, Western Maryland, northern West Virginia, and SE Ohio consist mainly of strata in the Allegheny (Kittanning, Clarion, Mercer, Freeport coals) and Monongahela Groups (Pittsburgh, Sewickley, Redstone, Waynesburg, and Washington coals). The Monongahela Group includes the basal Pittsburgh coal, the Sewickley and Redstone within about 100 feet above it, and the Waynesburg and Washington coals near the top of the group. The Conemaugh Group has only one major coal, the Bakerstown near its base. The Upper Freeport coal is the upper member of the Allegheny Group, just below the contact with the Conemaugh. Beneath the Upper Freeport are the Clarion, Mercer, and Upper and Lower Kittanning, which overlies the Fire Clay coal zone, at the top of the Pottsville Group (Ruppert et al., 2001). The Allegheny Group is relatively thin (maximum of about 250 feet) compared to the other Pennsylvanian-age groups within West Virginia (Arkle et al., 1979).

The Freeport and Kittanning coals are mined in portions of the northern region, extending south into central WV.

By far the most extensive and continuous mining in the northern coalfields occur in the Pittsburgh coal, which is widely mined in both surface and underground in SW Pennsylvania, NW West Virginia, and SE Ohio. Mine discharges emit from a large number of these workings. Donovan et al. (2003) delineated a vast nearly-continuous reservoir of mine water extending from Pittsburgh on the north to the vicinity of Clarksburg, WV on the south. This mined area includes 379,000 hectares (0.94 million acres) in Pennsylvania and West Virginia, of which about 159,000 (0.39 million acres) hectares were as of that time flooded. This represents approximately 1.2 billion m^3 (42.4 billion ft^3) of water in storage. The total discharge based on “one time” measurement census in 2002 was estimated at >171 million cubic meters/year (>86,000 gpm), an estimate that the authors considered too low due to undersampling. In excess of 70% of this water is not currently treated. Once still-flooding mines in the basin fully resaturate, additional discharge, water storage, and flooded mine area will be added to this total.

The water chemistry of the Pittsburgh mine aquifer is general above regulatory standards for metals in many locations, but shows substantial variability based on time since discharge began, hydrologic conditions, and other factors. New discharges since 1979 have been being treated for metals removal (Casner, 1994). Iron values of current discharges range from <1 to >1,000 mg/L, and acidity ranges from net alkaline water to >2,000 mg/L as $CaCO_3$ (Donovan et al., 2003). However, the occurrence of strongly acidic waters is relatively uncommon, and over a period of several years, deep below-drainage flooded mines that initially produced acid water tend to become net alkaline with pH>6.5 and gradually diminishing iron concentrations (Donovan and others, 2003; Lambert and others, 2004). At present, there are several discharges in compliance with CWA discharge limits on iron and aluminum.

Water chemistry of acidic (pH 2-4) mine water is generally elevated in iron and/or aluminum, calcium, magnesium, sodium, and sulfate, and is often found in above-drainage (up-dip), as opposed to below-drainage (down-dip) mines (Mentz and Wang, 1975; Morris et al., 2008). Under net-alkaline conditions (pH 6-7), only iron and manganese occur in significant concentrations, and water can have extremely high alkalinity, to >500 mg/L as $CaCO_3$, in addition to sulfate (McDonough et al., 2005). In either acidic or alkaline forms, mine water from the Pittsburgh seam is geochemically distinctive from that of Appalachian basin formation waters, which are in the majority of cases Na- and Cl-dominant. Formation waters can also have detectable concentrations of Br and Ba, which are generally below detection in Pittsburgh seam mine water.

1.3.2 Southern Appalachian coal mine aquifers

There are also numerous closed mines and, in some locations, mine water is the southern Appalachian coalfields of West Virginia, Kentucky, and Virginia. The coals of this area are Middle to Lower Pennsylvanian in age (Allegheny Group and Pottsville Group). In addition to the Allegheny Group coals as described above, the Pottsville coals include the Pocahontas, New River, and Kanawha formations or local equivalents. The coal seams in this region are more numerous than those in Northern coalfields, with >30 minable seams in southern West Virginia and adjacent states (Rehbein and others, 1981; Blake and others, 1994; Figure 5). In general, these are substantially lower in sulfur than coals in the Northern basin (Englund and others, 1986). Some of these southern coals are more continuous than others, but only a few (the Pocahontas #3 seam; the Eagle, locally called Pond Creek, seam; and the No. 2 Gas seam) tend to be correlated over long distances. Others either split into multiple seams, or pinch out, from location to location, making correlation difficult (Blake and others, 1994). The terminology for coals in different states diverges. Mining in most portions of the southern coal fields occurs in "stacks" of seams, with from 1 to 6 different seams mined in nearby locations by either surface or underground techniques, or both, depending on depth of cover. However, for the Pocahontas seams, nearly all of the mining is underground.

2 METHODOLOGY

2.1 Data Sources

Spatial and descriptive data were collected from the WV Geologic and Economic Survey, Ohio Geological Survey, WV Department of Environmental Protection, PA Department of Environmental Protection, and US Geological Survey. Following is a partial list:

Coal data by seam

- Mine outlines by coal seam
- Structure contours and grids
- Extent of coal (outcrop)

Shale-gas wells and geology

- wells as of year 2012 (target formation, type of completion, completion length, spud date and/or completion date)
- Formation extent
- Structure contours and grid

Water data

- Watershed boundaries
- Rivers and streams
- Water treatment facilities

Base map data

- Elevation
- Roads
- Towns , County, and State boundaries

QA/QC were applying to compile data from different sources and to generalize the geology of the coal beds. Coal beds were combined at the formation level in most cases, excluding coal beds for which minor underground mining takes place.

2.2 3-dimensional visual representation of subsurface geology

A 3-dimensional visualization of the geology and well/mine locations was performed using the ESRI ArcScene application to realistically depict gas wells intersecting mine beds. Raster datasets of coal bed elevation are here used to depict coal extent and underground mine outlines. Coal mine outlines are superimposed and colored based on their status as open or closed operations. An approximate 30x vertical exaggeration was employed.

The point dataset for natural gas wells was laid on the 30-meter digital elevation model and extrapolated down to their target formations. The wells are classified by spud date, completion type/length, and water usage.

3 RESULTS

3.1 Distribution of underground mines and shale gas wells

Distribution of underground mines in the region are shown in Figure 6, classified by geologic formation, from the Monongahela Group (youngest) to the Pocahontas Formation (oldest). The mining in Ohio includes both Monongahela and Allegheny group coals in close proximity and are not differentiated in this view. Mining was not included for Maryland or Virginia as no Marcellus wells have yet been drilled in these states.

Figure 6 also shows the distribution of shale gas wells. All wells in PA and WV are in the Marcellus, while those in Ohio include both Utica and Marcellus completions. The files were updated to include wells completed or spudded from 2006 to June 2012 (PA), to September 2012 (WV), and to July 2011 (Ohio), as well as wells that are at present shut in. A credible up-to-date source for wells in Kentucky could not be located and so no wells were plotted, and few unconventional gas wells are thought to occur there at present. In counties of the study areas shown in Figure 6 that have underground mining, there are 1681 wells in PA (only Fayette, Greene, Washington, Westmoreland, and Allegheny counties, not other portions of the state), 75 in Ohio, and 1061 in West Virginia.

The shaded area represents the subcrop for the Marcellus east) and Utica/Marcellus (west) shale gas fairway. Well locations are based on factors including depth to target formations, lease ownership, pipeline and gatherer distributions, gas composition (wet or dry), and economics.

Figure 7 shows a 3-dimensional view of surface topography, underground mine geometry, and depths of completed Marcellus wells through June 2011. These views demonstrate the substantial depth contrast between the shale gas producing zones and the underground mines, the deepest of which are still above sea level. The likelihood of direct interaction between gas well fluids and those in mines is restricted to drilling activities, catastrophic failure of multiple casings and/or cement jobs, and surface or near-surface disposal activities involving drilling and flowback wastes. The potential for fracture flow from Devonian formations up into the mined Pennsylvanian coals has nowhere been demonstrated and would require pronounced fracturing and modification to natural hydrogeologic conditions to be feasible. It will not be considered further in this report. Therefore, the only risk considered will be near-surface disposal activities.

3.2 Areas of current potential interaction between gas wells and coal mines

Table 1 lists counties in which shale gas wells are found as well as counts of wells intersecting coal mines. Of 2784 gas wells in the three states that were drilled in coal-producing counties, 709 (25.5%) are drilled through closed underground mines (Table 2). The large majority of these (532) are completed through mines in the Monongahela Group in the Northern coalfields, most of these in the Pittsburgh seam. The highest densities by far are in the four southwestern Pennsylvania counties (Greene, Washington, Fayette, and Westmoreland) with somewhat lower numbers in Harrison and Marion counties in West Virginia. Greene County, PA, alone has 171 gas wells over closed mines. Lower densities of wells over mines occur in Preston, Barbour, and Upshur counties, WV, principally in Allegheny Group coals, and in Kanawha, Boone, Logan, Mingo, Lincoln, and McDowell counties, WV, principally in Pottsville Group coals.

By this assessment, the potential for interactions between mines and gas well operations seems greatest in the Northern coalfields and, specifically, within the Pittsburgh seam (Monongahela Group) mines. The current hotbed of this type of development is in southwestern Pennsylvania and in the Monongahela and Ohio river drainages.

3.3 Mine water chemistry in the Pittsburgh seam during 2012

In March through August 2012, 72 discharges from closed mines in the Pittsburgh Seam were sampled for water chemistry in southwestern Pennsylvania and northern West Virginia. The West Virginia counties that were the focus of this sampling are Marshall, Ohio, Monongalia, Marion, and Harrison. The Pennsylvania counties are Allegheny, Washington, Westmoreland, Greene, and Fayette. All these are among the highest in Marcellus well density shown in Table 1. This area was selected because of the numerous mine water discharges from underground mine pools of this area as well as because of locally intense shale gas activity.

Figure 8 shows the sample sites, distributed over the area from Pittsburgh to Wheeling to Clarksburg, WV. Discharges were sampled in several categories:

- closed pre-SMCRA discharges, from portals or flowing wells of long-closed mines
- post-SMCRA closures, whose raw water now reports to treatment plants supplied by pumping wells
- transfer pumps moving water from one mine to another for water management

Sites were screened for those with discharge >100 gallons/minute and with landowner or plant operator access. Water was either grab-sampled at the closest point of emergence from the subsurface or pumped through a sealed acrylic flow-through cell using a portable peristaltic pump and tygon tubing. Under steady flow, pH and oxidation-reduction potential (ORP) were measured with Hanna HI 9025 meters and dissolved oxygen (DO) with a Hanna HI 9142 meter. A YSI EC300 meter was used to measure electrical conductivity (in microsiemens/cm at 25^o C). The ORP was converted into an Eh value by calibration to a fresh Zobell solution:

$$Eh = E_{obs} + Eh_{zobell} - Eh_{zobell\ observed}$$

Where E_{obs} is the field measured electrode ORP value in mV, Eh_{zobell} is 428-0.22 (t-25^{o} C), and $Eh_{zobell-observed}$ is the lab -measured electrode ORP of the Zobell solution in mV. All meters were calibrated daily, using two-point (4 and 7) calibration of pH and one-point calibration of electrical conductivity with 1413 S/cm solution (0.01M KCl). Two-point calibration of DO was performed at100% (air) and 0% saturation (sodium metabisulfate solution).

Measurement of alkalinity was performed by field titration of 100 ml of sample with 1.6N sulfuric acid in a 250mL Erlenmeyer flask to endpoint 4.5. Measurement of discharge was performed where feasible with a USGS wading rod will be conducted using the 0.6d method.

Samples were drawn in 2 aliquots from a single flow and filtered through a 0.45 micron filter into a 100 mL polyethylene bottles, of which one was acidified using trace metal grade nitric acid. Both were be stored on ice in the field and refrigerated at 5o C until lab analysis at the National Research Center for Coal and Energy (NRCCE) Analytical Laboratory at West Virginia University.

Lab analysis was performed by inductively coupled plasma optical emission spectroscopy (ICP-OES) for total Al, Fe, Mn, Na, K, Mg, Ca, Ba, S and Se. Sulfate concentrations were calculated from the ICP total sulfur. Anions (Cl, F, Br, NO3) were analyzed by ion chromatography (IC). Analyzed samples underwent standard quality control measures including blind and blank samples, duplicate samples, and charge balances of all samples. Analytes occurring below instrumental detection limits were reported as non-detects.

Appendix A shows location coordinates, water chemistry, field parameters, estimated flows, and other data for these sites. They are given a 3 or 4 character abbreviation based on the name of the mine from which they discharge. suffixes “a”, “b”, “c” etc are attached to these for multiple discharges from a single mine, although the majority of mines have only a single discharge. Appendix B shows laboratory water chemistry according to the 4-character site code.

Figure 9 shows categories of water discharges of underground mines in the Northern Appalachians. Mines fall into one of three categories: abandoned mine land (AML) discharges; mine-drainage treatment plants supplied by pumps; and transfer pumps moving waters between mines across coal barriers, also by pumping. In general, most AML discharges date to prior to 1977, while AMD plants and transfer pumps are part of treatment schemes installed for mines that have flooded and began to discharge in the years since 1977. As a result, most AML sites are “old” mine discharges that have been active for many years, while the pumped discharges represent younger mine-water discharges under industry or state control.

3.4 Spatial patterns in water chemistry

Figures 10 through 16 show spatial concentration plots of water chemistry in mine discharges. They are classed into groups based on interval concentrations

Figure 10 shows pH. While mine drainage in this region used to be acidic, today most discharges are somewhat alkaline (pH>4.5) and only a few discharges remain acidic (pH<4.5). Acidic sites tend to be clustered in areas of shallow mining and well-aerated mine workings near the coal outcrops. Some discharges (large circles) are highly alkaline and show pH of 7 or higher. These are normally mines with full flooding to near the coal outcrop.

Figure 11 (alkalinity) underscores the trends suggested by pH. In general, the highest alkalinities exceed 500 mg/L and tend to be found in the deep-pool locations of mines, where discharge occurs from pumping or flowing wells. A good example of these are in the Masontown, PA area, where several discharges arise from flowing wells near the deepest parts of mines on the east side of the Monongahela River, where the west-dipping coal outcrop lies close to river elevation well east of the river. The non-alkaline discharges (triangles) occur in unsaturated portions of mines, while the alkaline discharges are in locations within mine pools. In general, the most alkaline samples are derived from deep within mine pools.

Figure 12 shows conductivity, a somewhat-linear surrogate for total dissolved solids. The most mineralized samples appear to occur in the area of West Virginia mines west of Morgantown, an area of recent (2004) completion of mine flooding. These large conductivities are interpreted to reflect relative young or "juvenile" (Younger, 1997) mine water. The other area of higher TDS values is in the Wheeling area, although these mines are not recently flooded. Figure 13 shows sulfate in discharges. The patterns for sulfate closely mirror conductivity.

Figure 14 shows the pattern for chloride ion. The highest chloride values occur in deep mines of Marion and Monongalia county, WV (Loveridge, Blacksville #1, Jamison #9), which are very deep in the basin and thought to be encountering more saline basin waters. Additionally, Blacksville #1 was at one time legally permitted to accept injection of coal-bed-methane condensate wastes, which are saline. The highest chloride concentrations were 1475 mg/L from the Loveridge treatment plants. Additionally, moderately elevated Cl concentrations are found in the NE part of the basin along the Irwin Syncline, and in discharges along the Monongahela, Youghiogheny, and Chartiers Creek watercourses. These Cl values ranged from 100 to 466 mg/L. “Normal” low Cl concentrations is shallow mine workings near the outcrop are on the order of <100 mg/L.

Figure 15 and 16 show results for bromide and barium, respectively. These patterns are quite different than those for either pH/alkalinity or conductivity/sulfate. Discharges with high Ba/Br occur in Pennsylvania near Masontown, on the east side of the Monongahela; in discharges along the Youghiogheny River, Chartiers Creek, and Raccoon Creek, and in West Virginia near Wheeling. In contrast, the WV mines with juvenile mine water show below-detection of extremely low values.

3.5 Principal component analysis

Results of a principal component analysis (PCA) on 14 variables (pH, Conductivity, Eh, HCO3, Fe, Al, Mn, Na, K, Ca, Mg, Ba, SO4, Br, and Cl) are shown Figures 17 to 19. The dataset is a slight condensation of Appendix B, with NO3, F, and Be being removed because of low variability and/or a high proportion of non-detects. A number of values for Ba, Br, Fe, Mn, and Al also were below instrumental detection, but in a number of other samples, they were significantly abundant. Therefore, as PCA requires values for all individuals and variables, ND values for these variables were converted to 50% of that variable’s detection limit itself, a common approach with censored data of this type.

Figure 17 shows a scree plot of eigenvalues for the 14 principal components, which is interpreted to indicate that only the first three eigenvectors contain more variance than an original variable. The total variance of these three is 73.2% of the total variance. Figures 18 shows component loadings on eigenvectors 1 and 2 (top) and 1 and 3 (bottom). Figure 19 shows a 3-dimensional plot of component scores of individual waters on the first 3 eigenvectors, plotted in component space along with the vectors of the component loadings for each original variable.

These results may be interpreted as follows. Figure 17 indicates that the first 2 eigenvectors are predominant, with the third being barely significant. As can be resolved from the variable loading projections in Figures 18 and 19, Eigenvector 1 has high positive loadings from Ca, SO4, conductivity, Mg, Fe, Mn, Na, and K, and to a lesser degree from HCO3 and pH, and a negative loading from Eh. Eigenvector 1, therefore has high loadings from the concentrations of virtually all common constituents and is clearly a vector related to salinity, e.g. TDS. Eigenvector 2 in contrast has high positive loadings from pH and alkalinity, and negative ones from Eh and aluminum. vector 2 is an expression of degree of alkalinity, and sites scoring highly on it will tend to be net alkaline mine waters. Conversely, negative scores would be free-draining acidic mine waters. Eigenvector 3 has positive loadings from Br, Ba, and to a lesser degree aluminum. This vector – the weakest of the three – is interpreted to be related with deep formation waters, elevated in Ba and Br, entering underground mines. Only a few sites tend to score highly on eigenvector 3 (especially Palmer, Gates, Drago, and Adah), which are sites from the east side of the Monongahela River in an area of intensive shale gas drilling.

It has long been identified that flooding occurs at various rates in underground mines but has outcomes that are predictable within uncertainty in parameters (Adams and Younger, 2001; Whitworth, 2002; Leavitt et al., 2003; McCoy et al., 2006). After flooding of mines has proceeded to its new hydrologic equilibrium, the partitioning of mines into alkaline vs. acidic long-term water quality categories has been previously identified by many authors (Wood et al., 1999; Stiles et al., 2004; Stoertz et al., 2004). However, the prominent TDS and Br-Ba contaminations in this dataset are unique and suggest that interaction between underground mine waters and formation fluids may represent a previously unanticipated trend in regional water quality. If so, the results of this study would suggest that they be tested and confirmed.

4 SUMMARY AND CONCLUSIONS

Analysis of 2784 Marcellus wells (about 78% of all wells drilled in the study area) drilled since 2006 in coal-producing counties of PA, WV, and OH were examined geospatially with respect to the known location of closed and active underground coal mines. The following conclusions may be drawn from their spatial distribution:

1. about 25.5% of these wells intersect closed or active underground mines
2. of these, the majority (75%) occur in the Monongahela Group of northern WV, southwestern PA, and eastern OH.
3. The highest concentration of shale gas wells is in southwestern PA (Green, Washington, Fayette, and Westmoreland counties.
4. the geometry of the mines with respect to the depth of the shale gas wells suggests there is limited risk of contamination of the mines, provided well casing and cement grout integrity is fully maintained.
5. however, the extensive distribution of near-surface underground mines in the vicinity of intensive shale-gas development suggests that there is tangible risk of contamination of mine water by shale-gas drilling and waste fluids.

To examine this possibility, 71 samples of mine water were collected from the full extent of the Pittsburgh seam mine aquifer. Results indicate the following:

1. There are fundamental variations in TDS between areas of the mine aquifer, thought to be related to age of mine flooding (juvenile vs. fully-flushed underground mines
2. there are also variations in alkaline vs. acidic character of mine waters, with acidic waters of low pH and alkaline waters of circumneutral pH and elevated bicarbonate alkalinity. This is thought to be related to hydrologic condition of each mine, either fully-, partially, or non-flooded.
3. A small number of sites in the Monongahela, Youghiogheny, and Ohio valleys indicate elevated values of Br (up to 3.28 mg/L) and/or Ba (up to 0.076 mg/L). While these are low concentrations and represent no toxicity threat, they are thought to likely be related to disposal or leakage of gas-well or formation fluids into underground mine waters. There is coincidence between the mines in which gas wells occur and mine water discharge locations.

Much of the evidence for contamination of mine waters by Marcellus formation fluids is based upon relatively low concentrations of bromide ion. Produced waters from Marcellus Shale gas wells, after injection of low-TDS hydraulic fracturing fluids and subsequent flowback, are highly saline (14 to 248 g/L TDS) brines dominated by Na-Ca-Cl and containing elevated Br concentrations and Br/Cl ratios (McIntosh, 2012). These conditions indicate evaporation of paleoseawater past halite saturation and further modification by diagenetic reactions. Variable solute concentrations with relatively constant solute to bromide ratios suggest later brine dilution by freshwater. Marcellus Shale formation waters have similar major ion chemistry and stable isotope compositions to adjacent Upper Devonian shales and sandstone formation waters, yet are distinct from brines in underlying Silurian formations and dilute groundwater in shallow aquifers. Warner et al. (2012) have outlined likely contamination of shallow groundwater by mixing relationships involving Br, Cl, Na, Ba, Sr, and Li, as well as strontium and radium isotopes. Dresel and Rose (2012) calculated a molar Cl/Br ratio is western Pennsylvania brines from 136 to 401 (average 236).

This water chemical sample can be used as a 2012 baseline for assessing future changes in mine-water chemistry. It appears that some impacts, while minor in magnitude, have already begun. What is not clear is how the subsurface contamination has taken place and how little or much it will grow in the future.

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Figure 1. Location of the study area in West Virginia, Pennsylvania, Ohio, Virginia, and Kentucky.

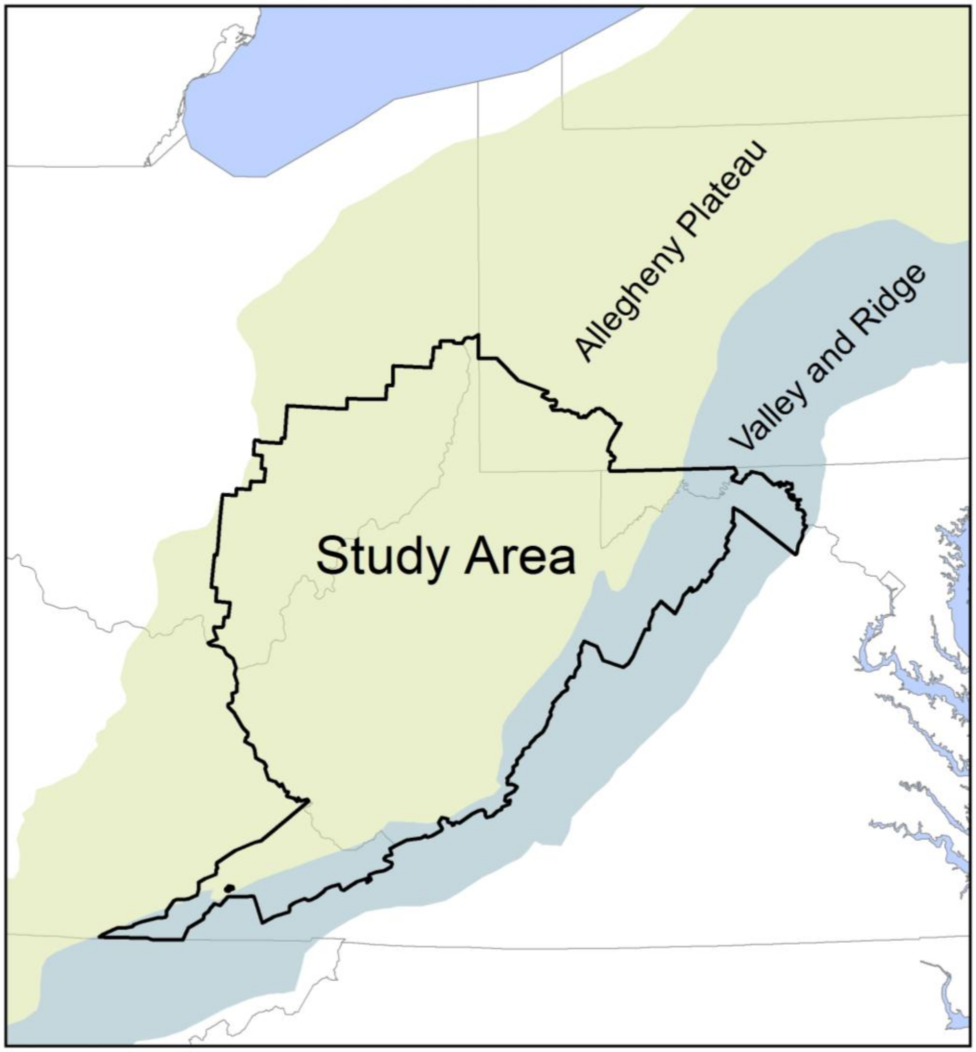


Figure 2. Physiographic provinces of the study area.

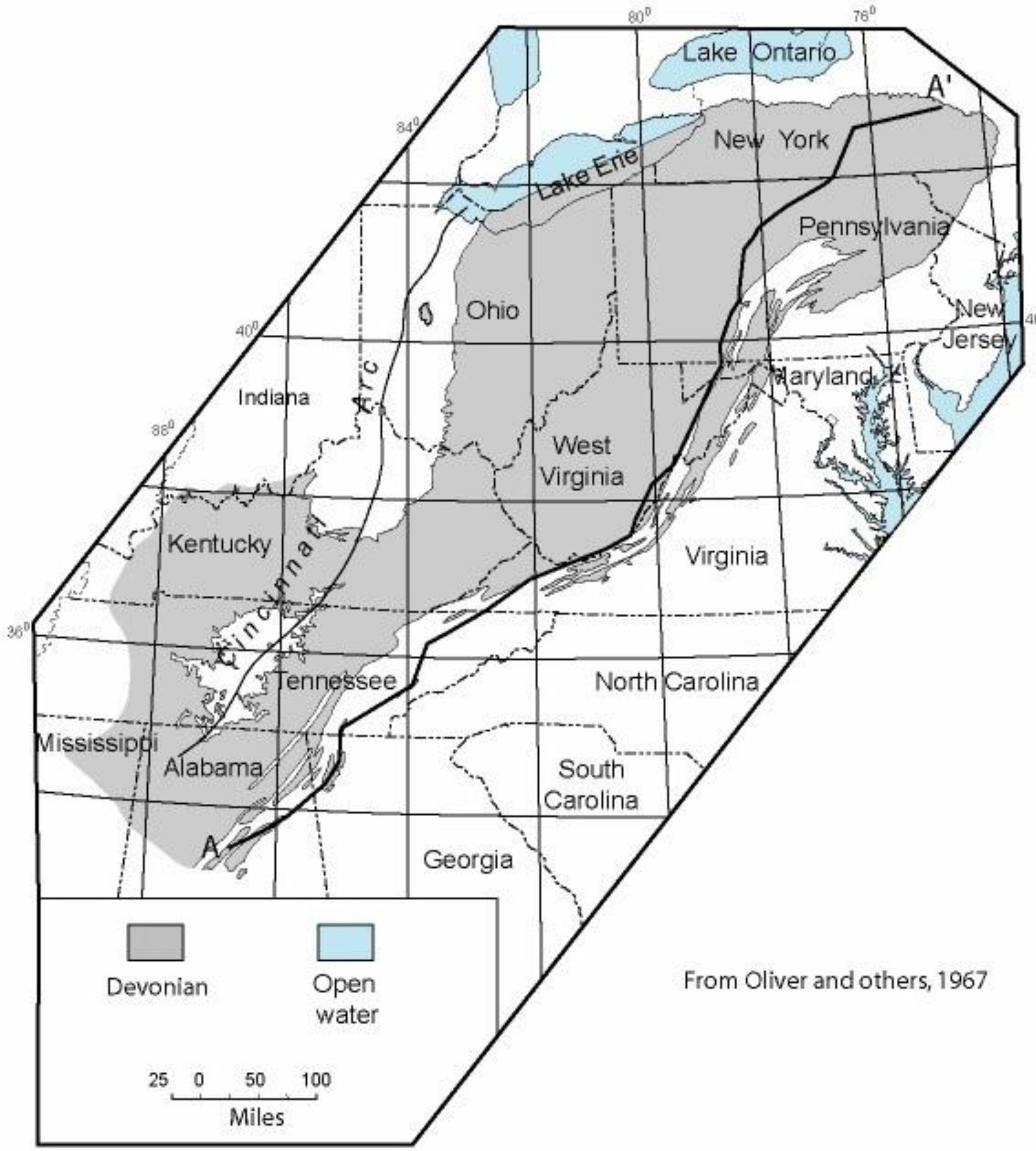
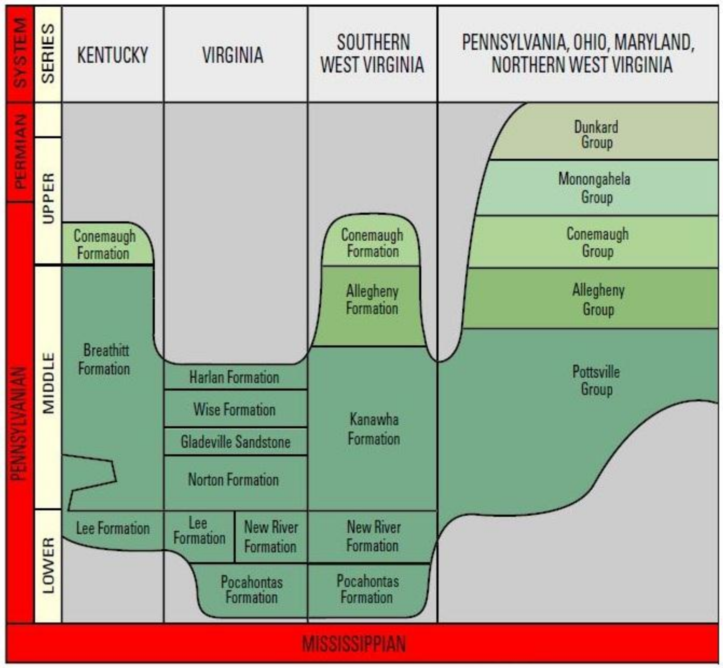


Figure 3. Extent of Devonian marin shales in the Appalachian basin. After Oliver and others, 1967.



SYSTEM	SERIES	GROUP	COAL STRATIGRAPHY
PENNSYLVANIAN	UPPER	Monongahela Group	Pittsburgh coal bed
		Conemaugh Group	Bakerstown coal bed
	MIDDLE	Allegheny Group	Upper Freeport coal bed Lower Kittanning coal bed
	MIDDLE / LOWER	Pottsville Group	Fire Clay coal zone Pond Creek coal zone Pocahontas No. 3 coal bed

Figure 4. Non-coal and coal stratigraphy of Pennsylvanian coal-bearing strata in areas of the Appalachian basin. After Ruppert, 2001.

Allegheny Gp	lower	No. 6 Block
		No. 5 Block
		Little No. 5 Block
		Stockton "A"
Kanawha (Pottsville) Group	upper	Stockton
		Coalburg
		Winifrede
		Lower Winifrede
	middle	Chilton "A"
		Chilton
		Fire Clay
		Hernshaw
		Williamson
		Cedar Grove
		Alma
		Peerless
		No. 2 Gas
		Powellton
		Eagle "A"
		Eagle (Pond Creek)
		Little Eagle
	lower	Beckley
		Fire Creek
		Little Creek
		Pocahontas No. 7
		Pocahontas No. 6
		Pocahontas No. 5
		Pocahontas No. 4
		Pocahontas No. 3 rider
		Pocahontas No. 3
		Pocahontas No. 2A
		Pocahontas No. 2
		Pocahontas No. 1
		Landgraf
		Keystone
		Simmons
		Squire Jim

Figure 5. Coal seam stratigraphy in the Middle Pennsylvanian strata of Southern West Virginia. Compiled from Rehbein and others (1981), Blake and others (1994), Milici and others (2000), Ruppert and others (2001), and Tewalt and others (2000).

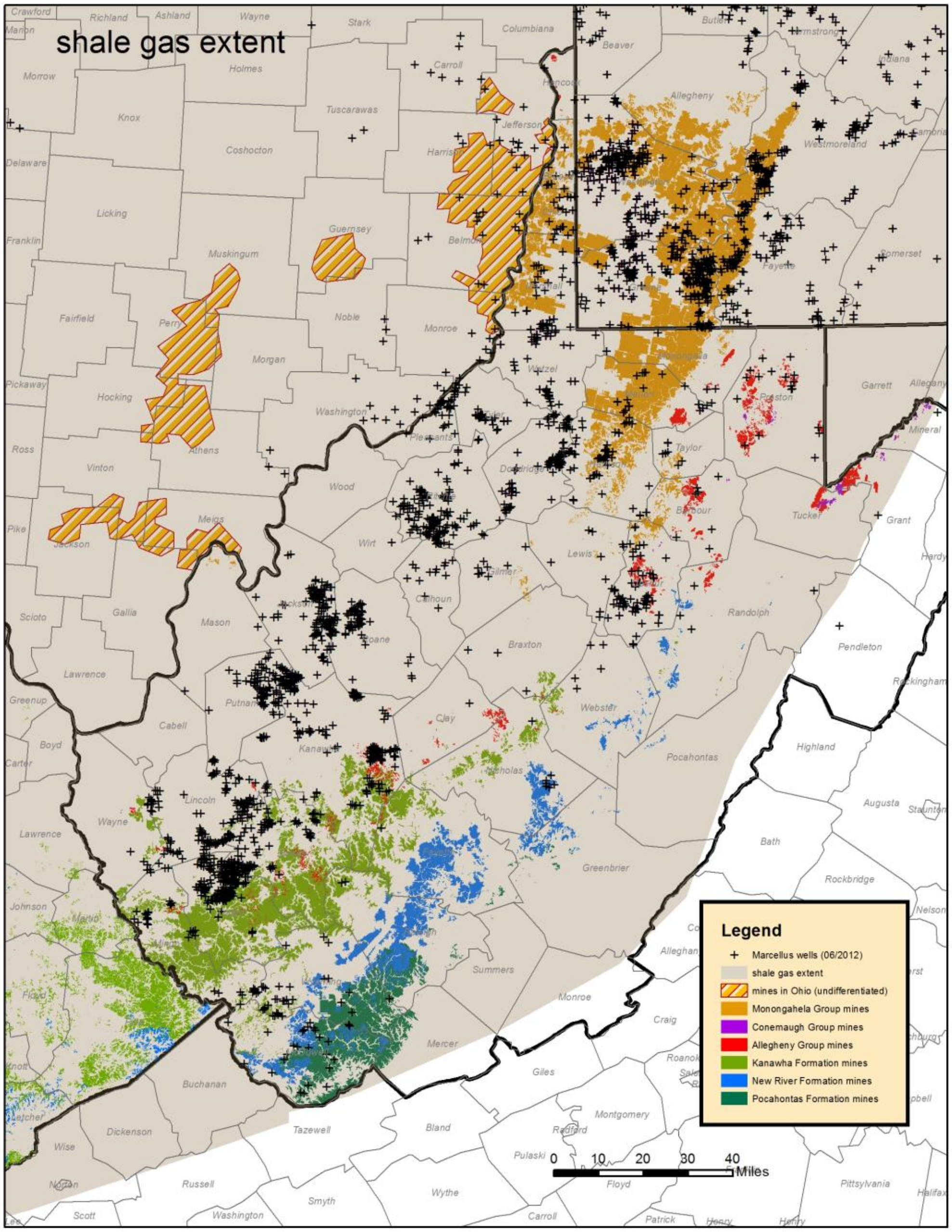


Figure 6. Underground mines and shale gas wells since 2006 in the Appalachian basin.

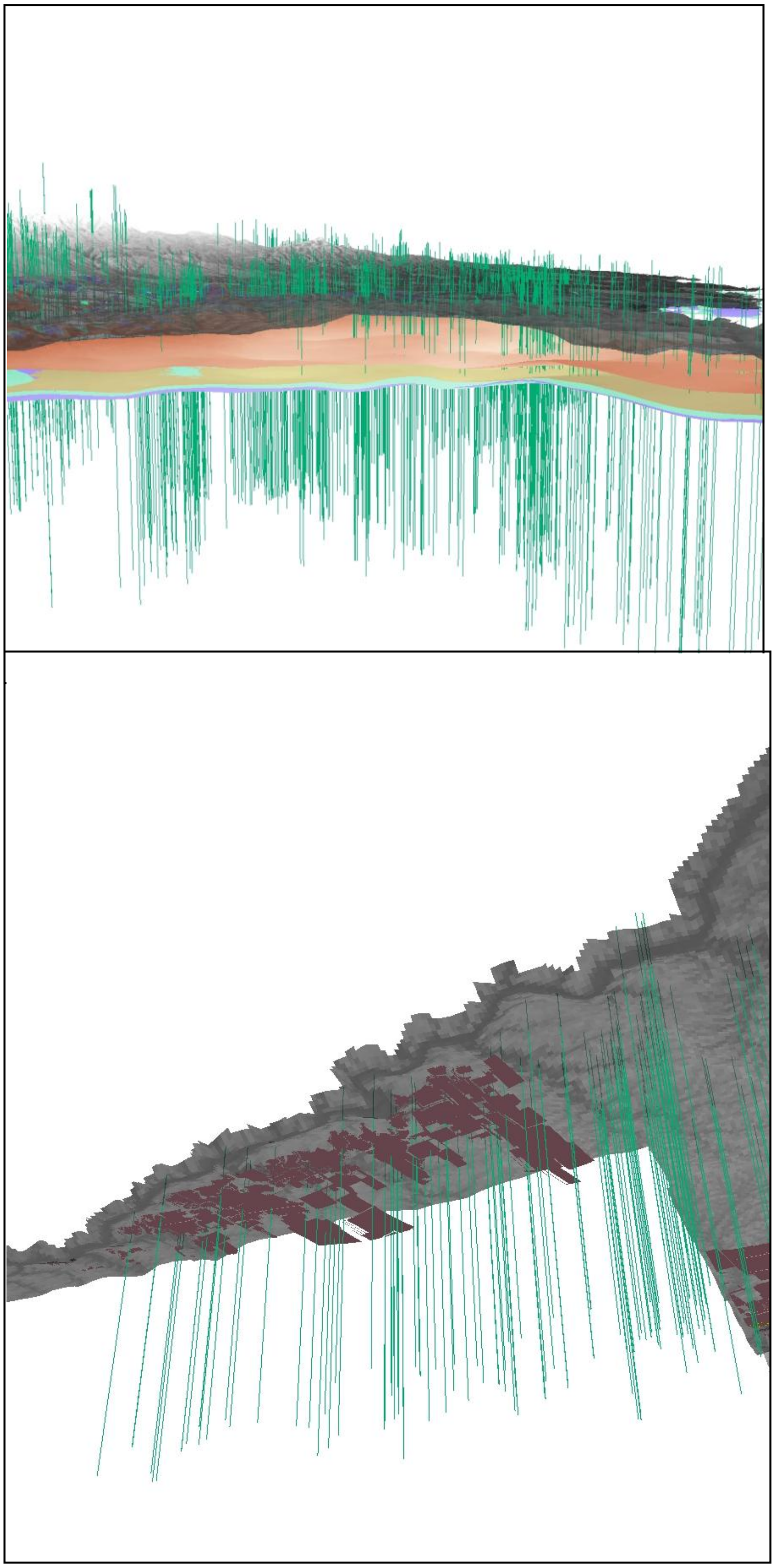


Figure 7. 3-dimensional perspective views of gas wells drilled through West Virginia coal mines: (top) looking west from Eastern Panhandle; (bottom) tooking up and northeast at Northern panhandle.

County	State	Marcellus wells	shale gas wells drilled through underground mines				
			Monongahela	Allegheny	Kanawha	New River	Pocahontas
Harrison	WV	99	45				
Marion	WV	33	17				
Ohio	WV	25	15				
Marshall	WV	57	11				
Brooke	WV	12	6				
Monongalia	WV	9	1				
Upshur	WV	87		11			
Preston	WV	21		8			
Barbour	WV	8		3			
Wayne	WV	15		3	5		
Taylor	WV	9		2			
Boone	WV	125			18		
Kanawha	WV	189			30		
Lewis	WV	11					
Lincoln	WV	107			3		
Logan	WV	188			67		
McDowell	WV	28				7	4
Mingo	WV	31			13		
Nicholas	WV	7			3		
Greene	PA	525	171				
Washington	PA	662	87				
Fayette	PA	222	86				
Westmoreland	PA	253	71				
Allegheny	PA	19	0				
Belmont	OH	13	11				
Jefferson	OH	16	8				
Monroe	OH	10	2				
Harrison	OH	3	1				
	Totals	**2784**	**532**	**27**	**139**	**7**	**4**

Table 1. Census of (a) Marcellus wells in counties with coal mines, (b) Marcellus wells drilled through closed or active underground coal mines.

	all Marcellus wells in counties with mines	Marcellus wells sited over mines
West Virginia	1061	272
Ohio	42	22
Pennsylvania	1681	415
Total	**2784**	**709**
		25.5%

Table 2. Summary of census results in Table 1.

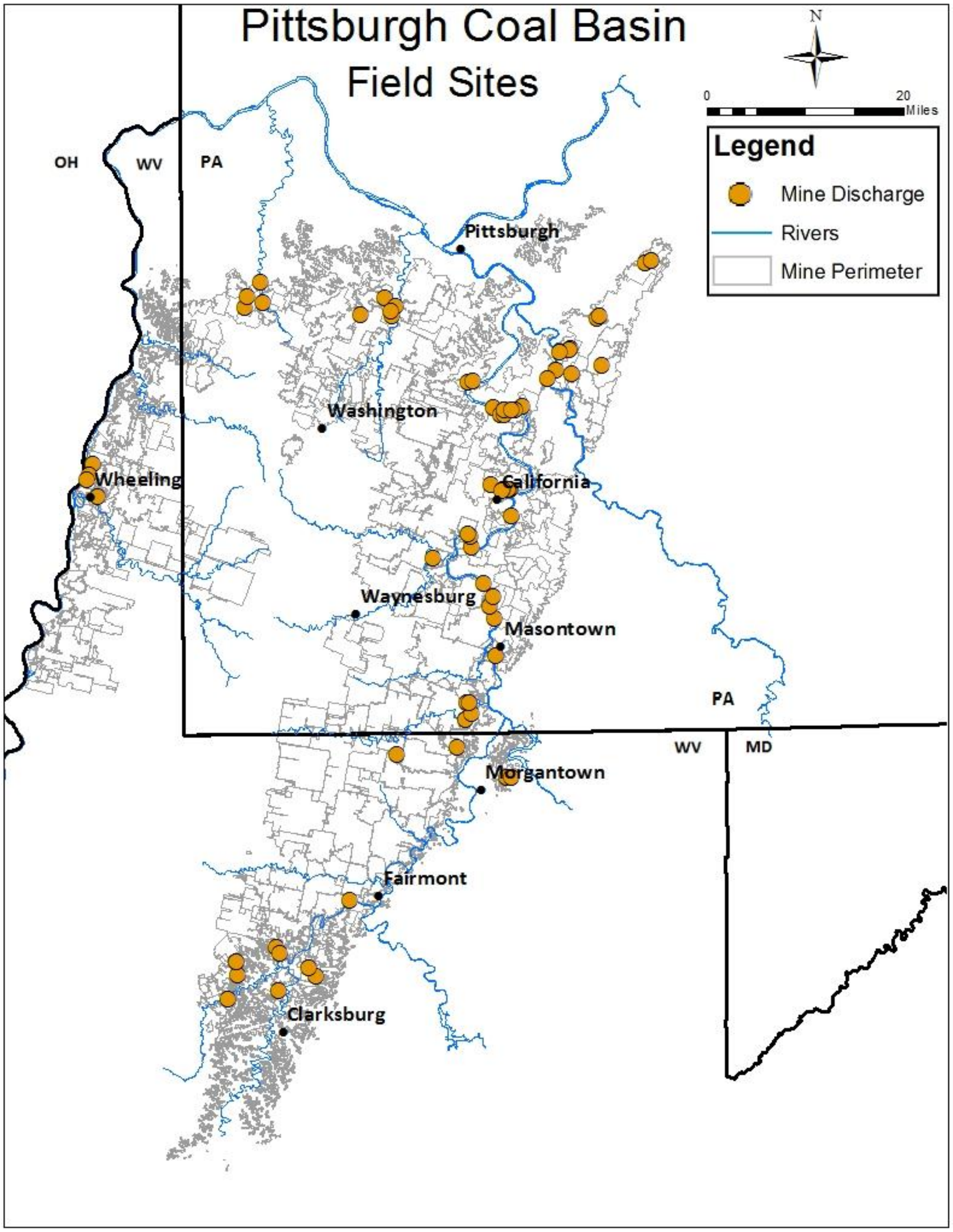


Figure 8. Distribution of water sampling locations for mine water in the Pittsburgh seam.

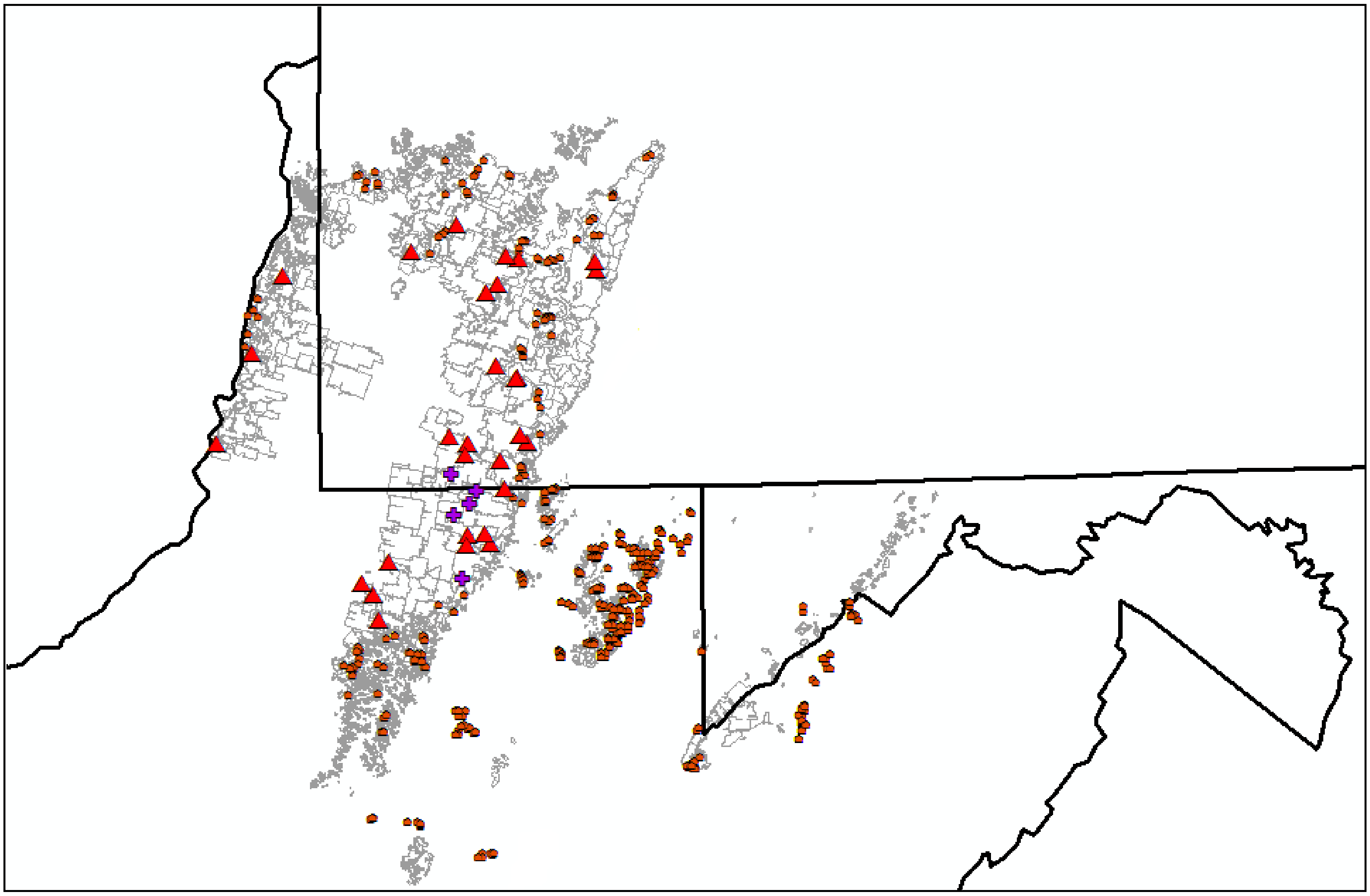


Figure 9. Distribution of different categories of mine water in the Northern Appalachian coal fields. Squares = AML mine discharges; triangles = pumps at AMD treatment plants; crosses = transfer pumps between mines.

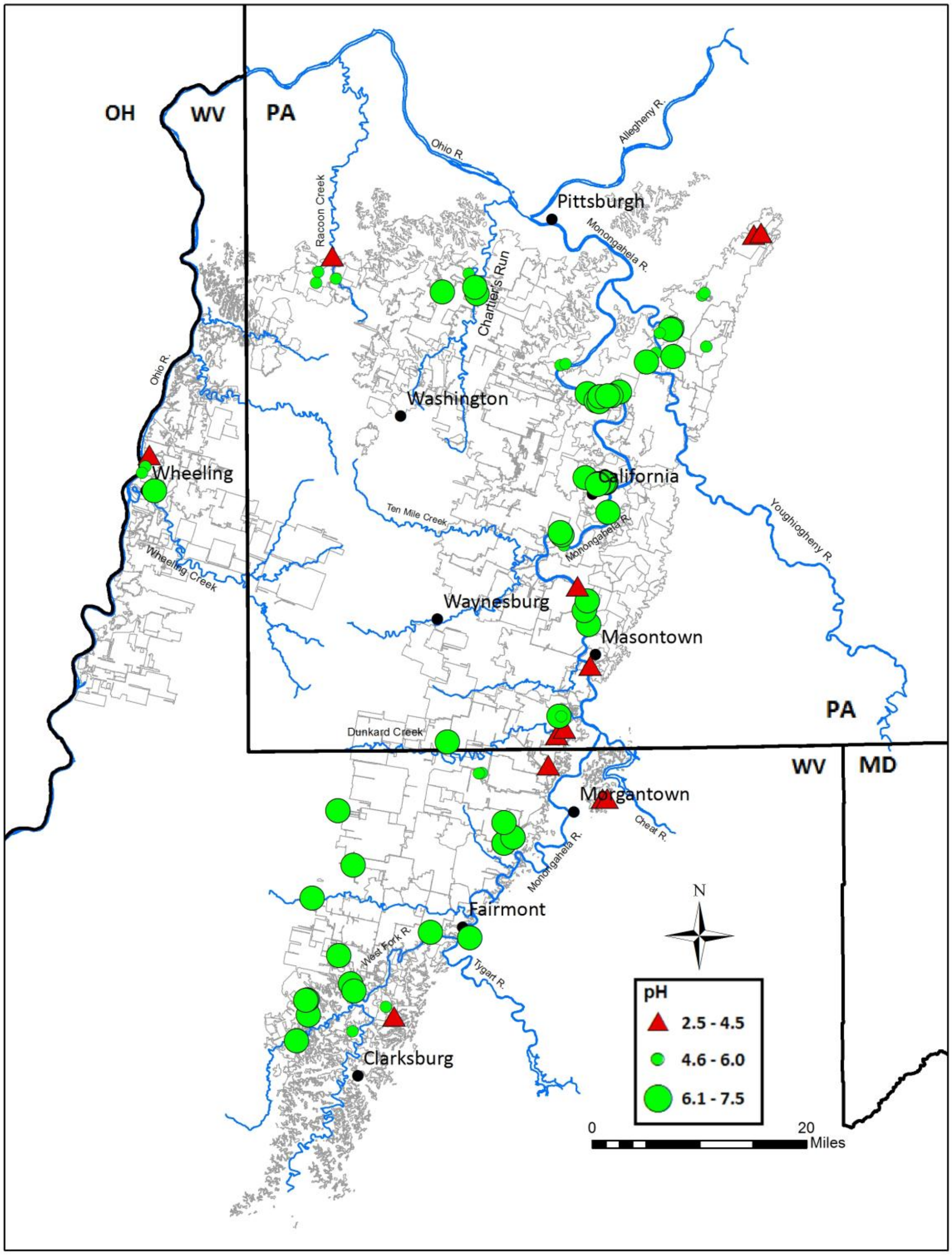


Figure 10. Distribution of pH groups in mine water discharges of the Pittsburgh seam.

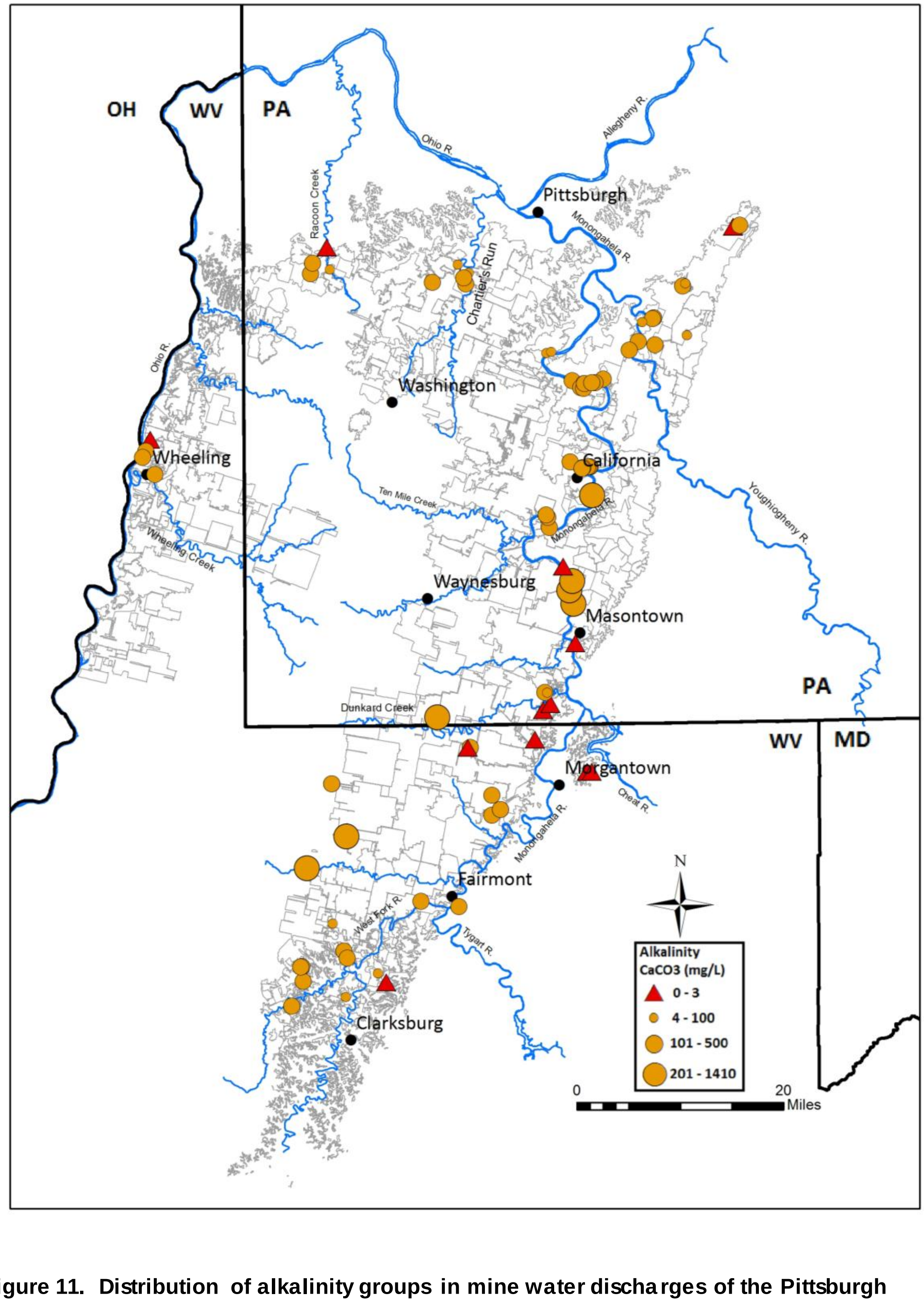


Figure 11. Distribution of alkalinity groups in mine water discharges of the Pittsburgh seam.

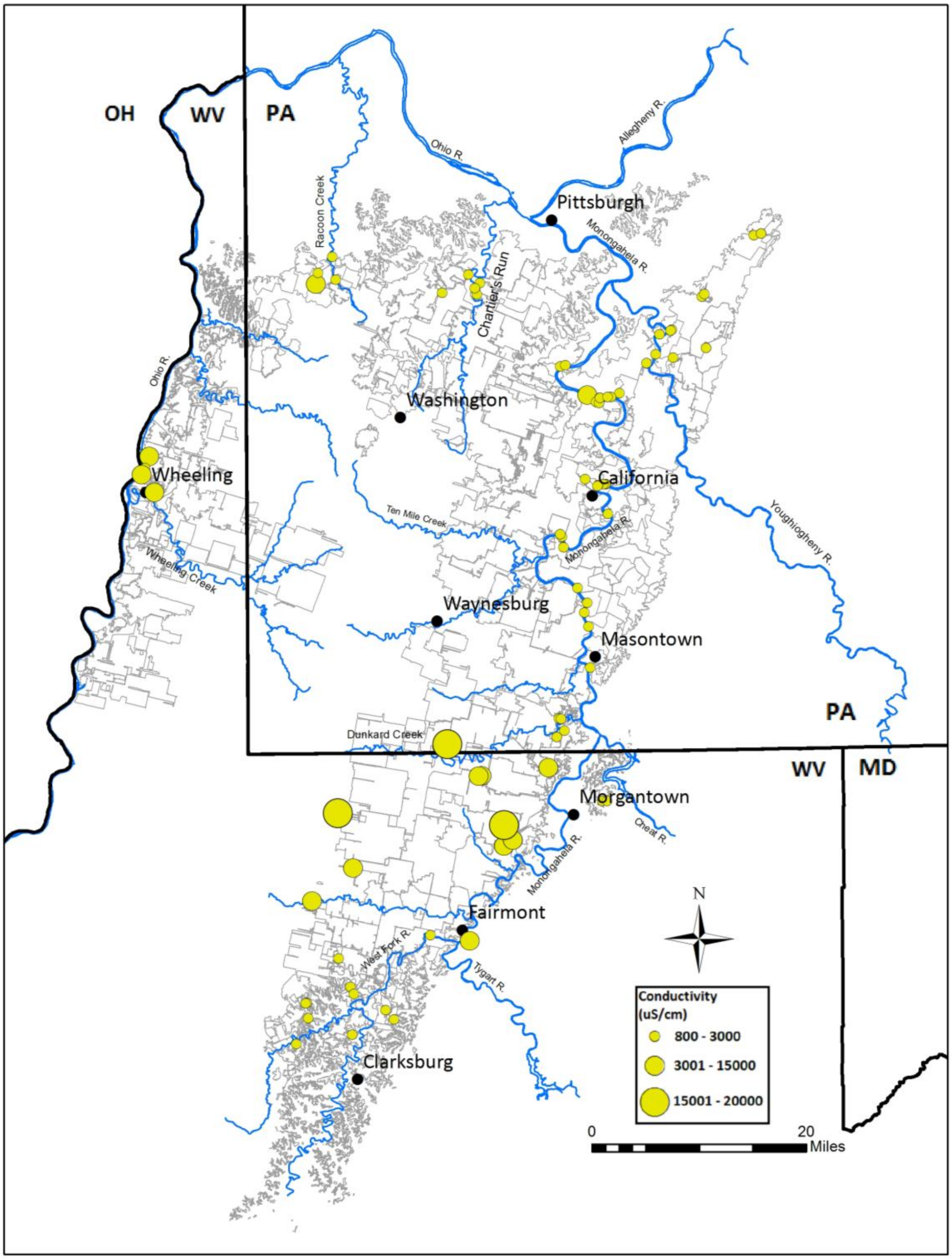


Figure 12. Distribution of conductivity groups in mine water discharges of the Pittsburgh seam.

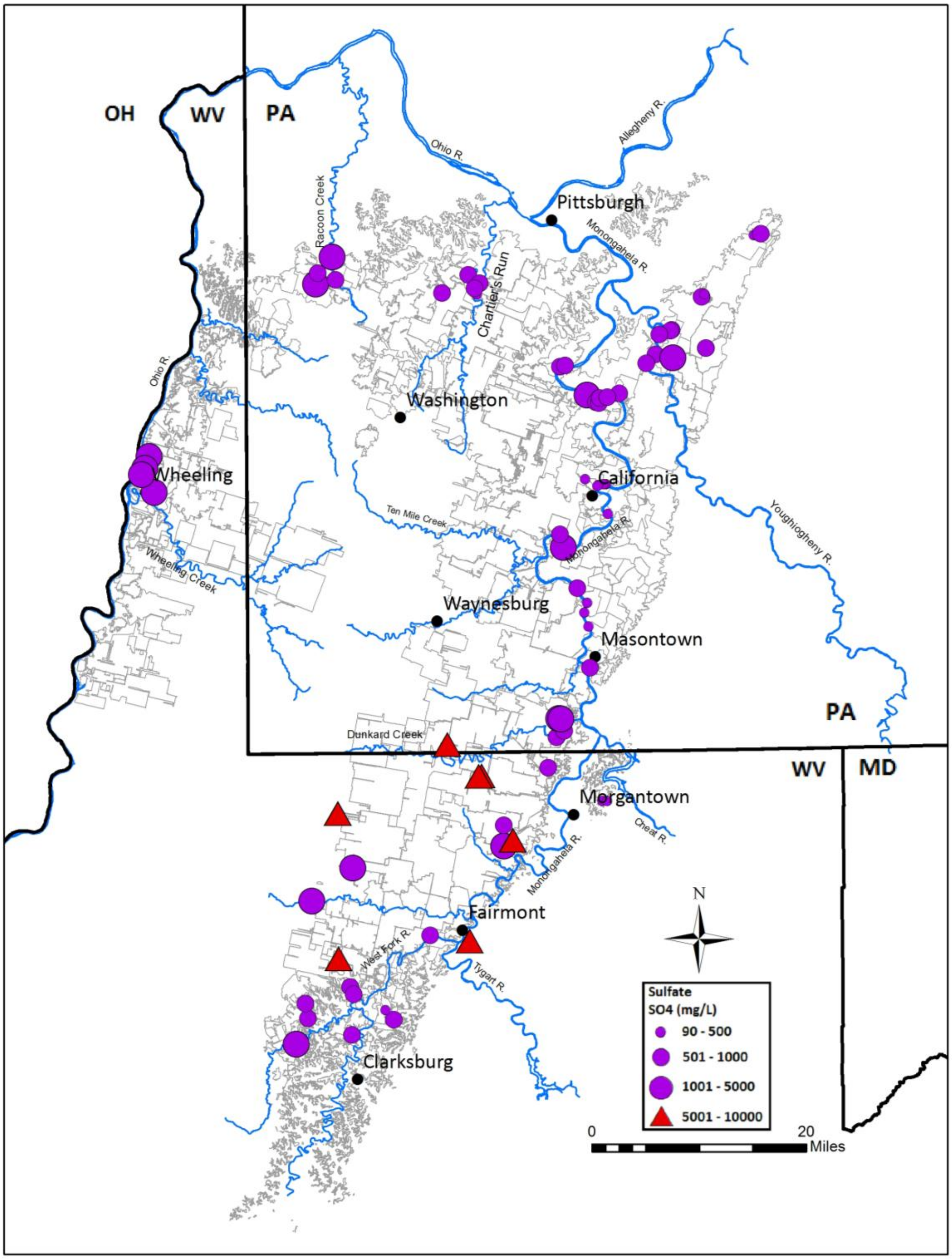


Figure 13. Distribution of sulfate groups in mine water discharges of the Pittsburgh seam.

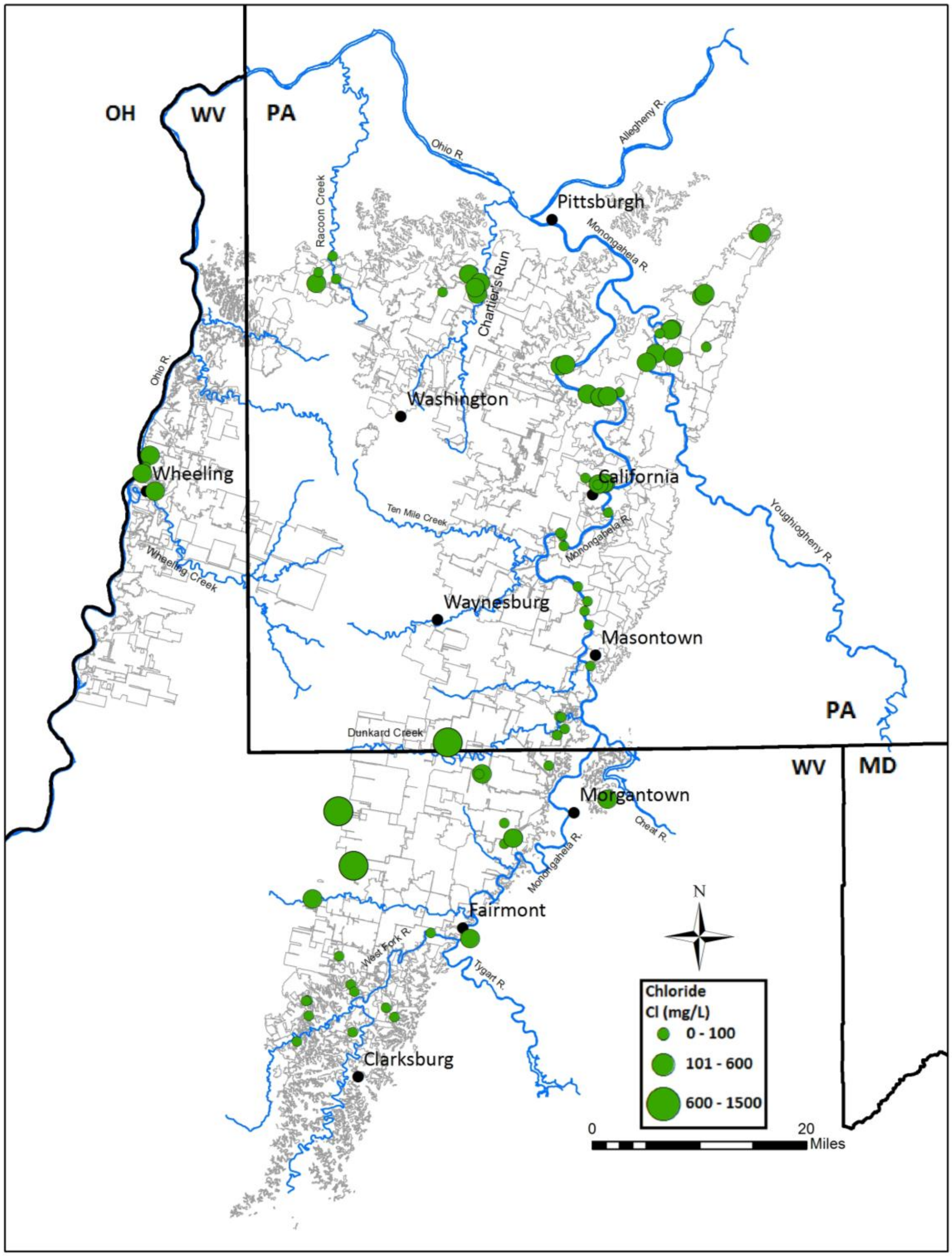


Figure 14. Distribution of chloride groups in mine water discharges of the Pittsburgh seam.

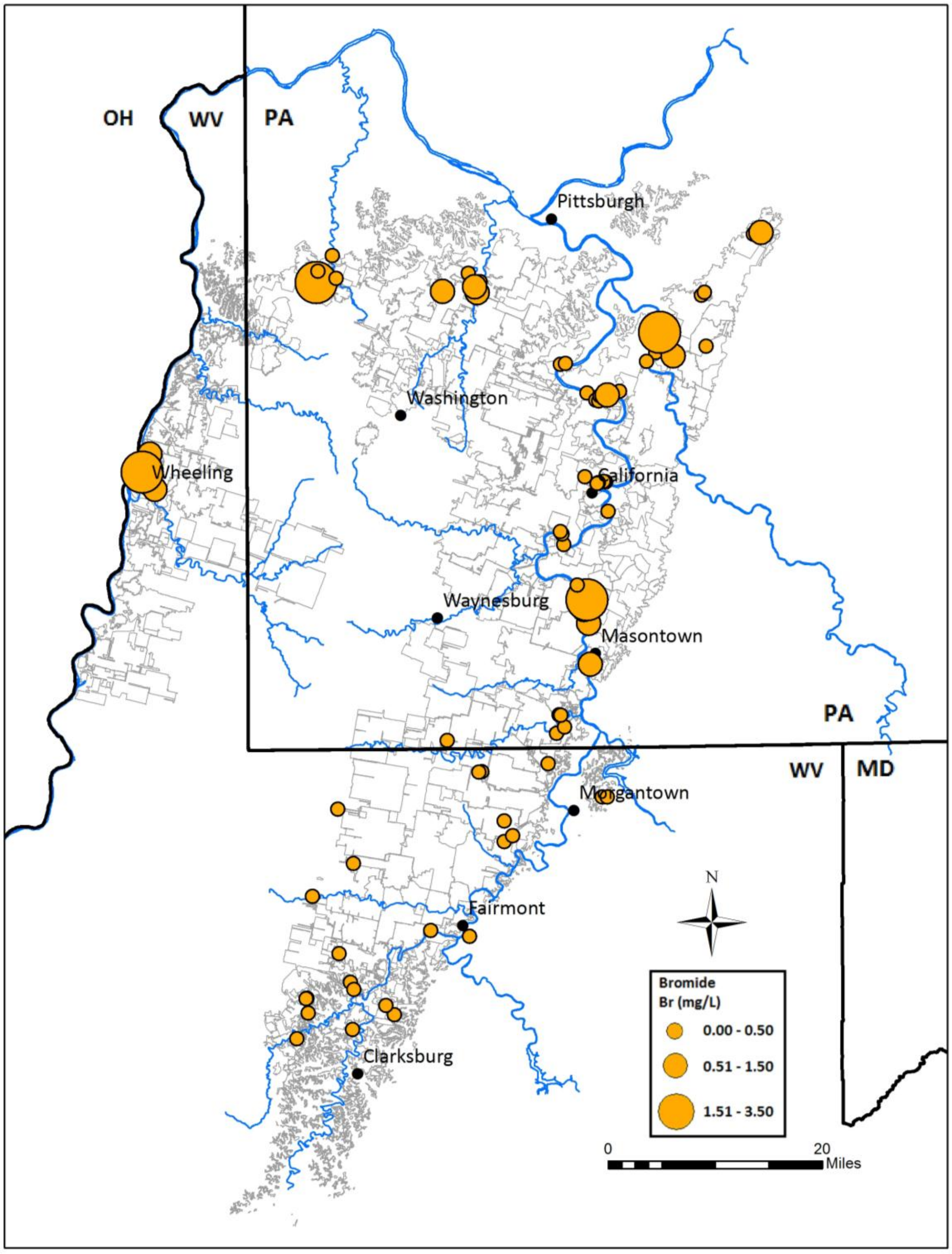


Figure 15. Distribution of bromide groups in mine water discharges of the Pittsburgh seam.

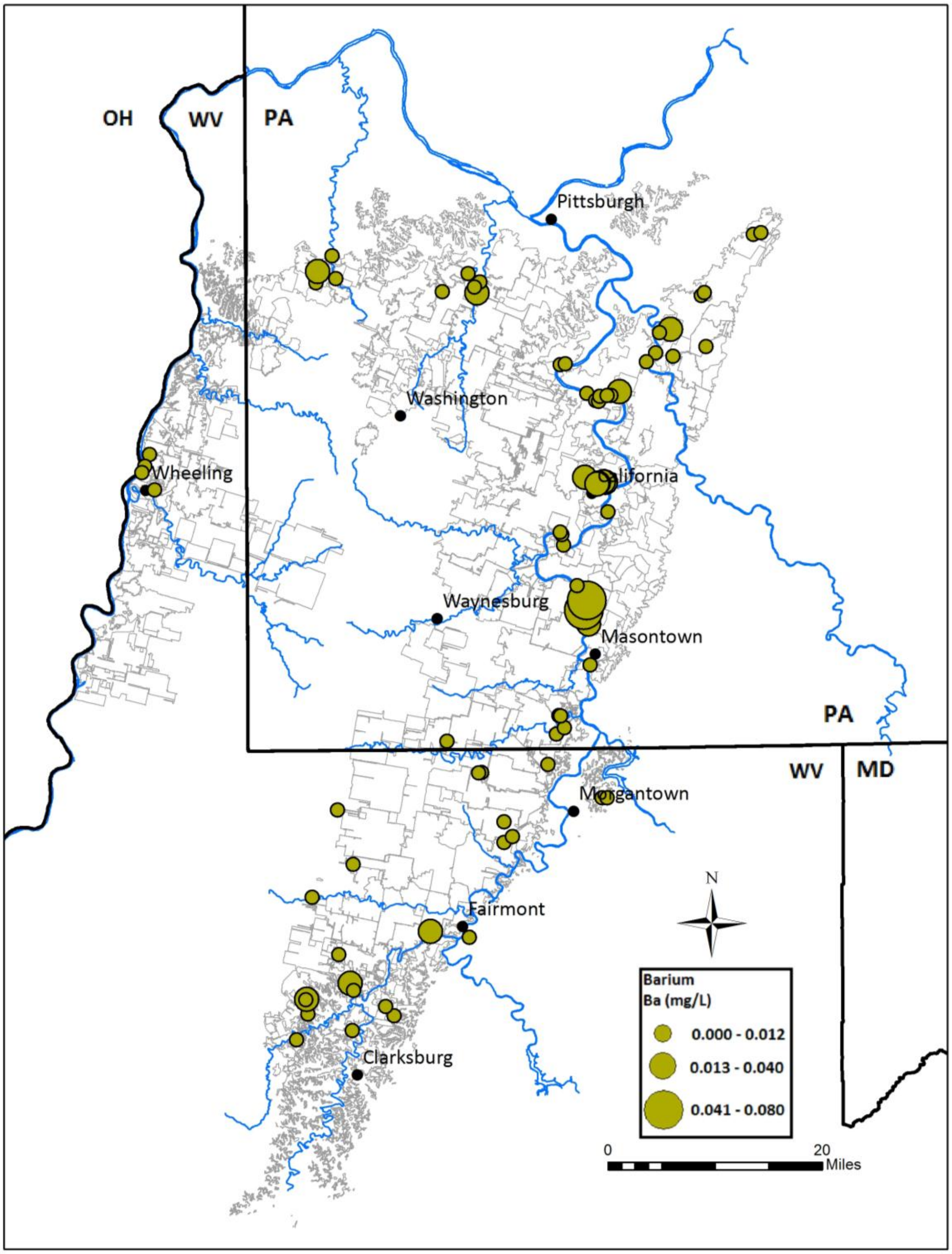


Figure 16. Distribution of barium groups in mine water discharges of the Pittsburgh seam.

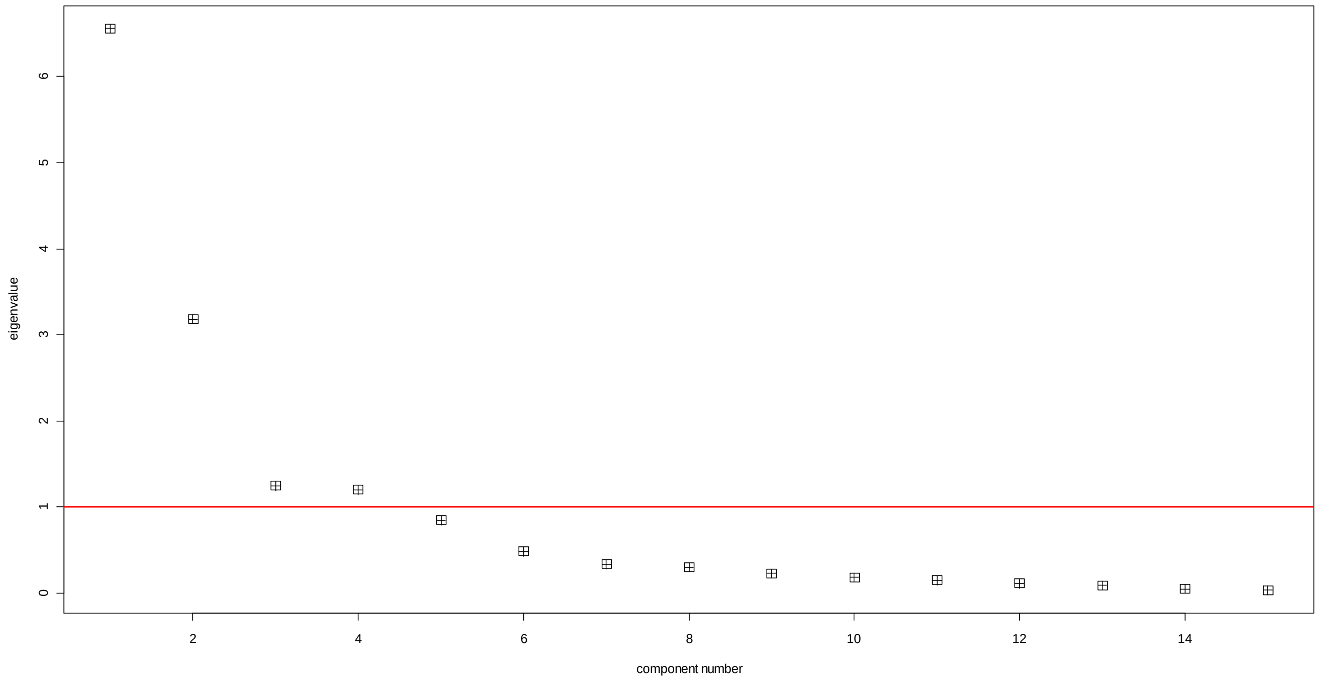


Figure 17. Scree plot of eigenvalues for PCA of mine-water chemistry. Red line = Kaiser cutoff criterion for significant eigenvectors.

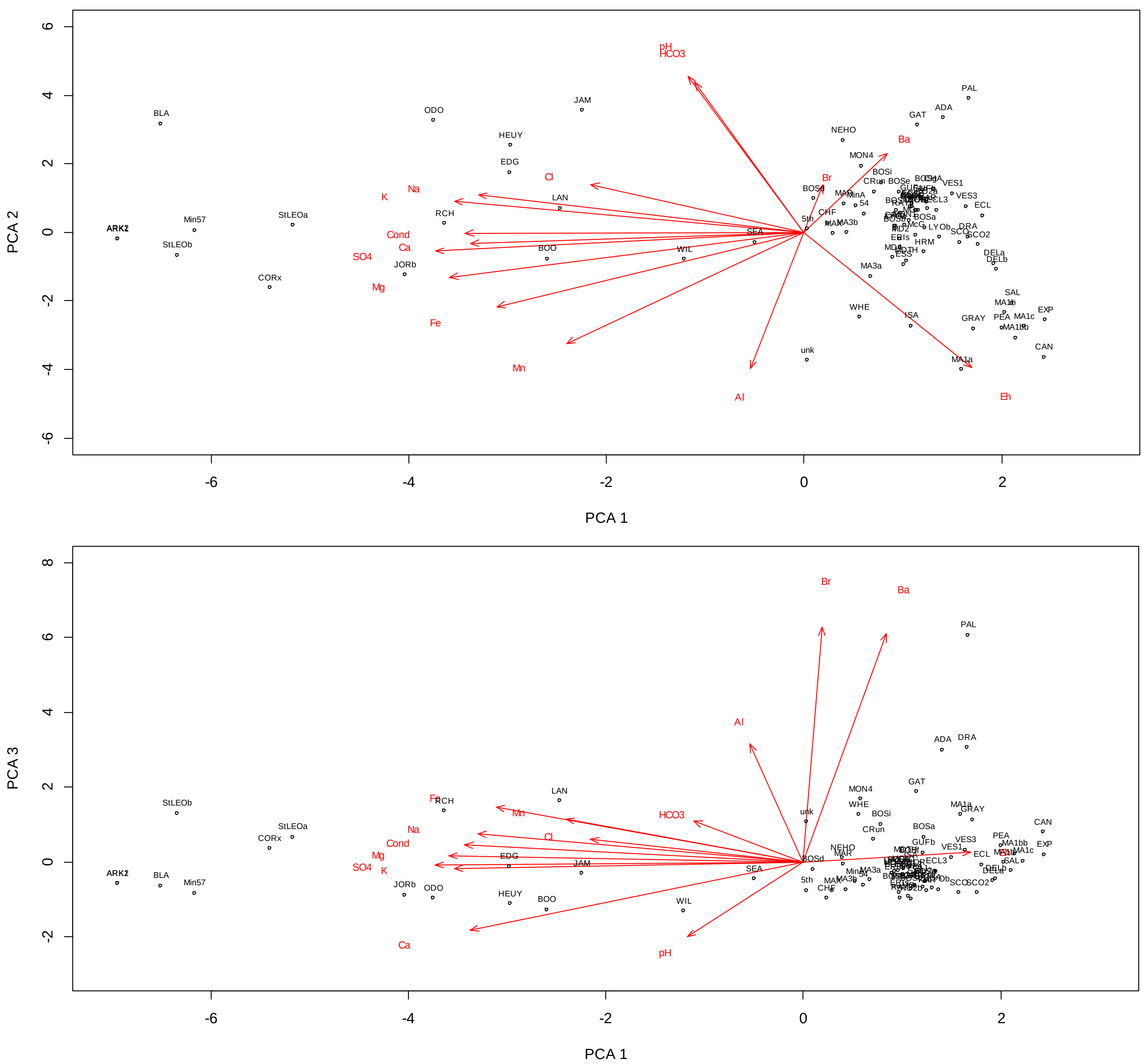


Figure 18. Score and vector bi-plots of (top) PCA 1 vs PCA 2, and (b) PCA1 vs PCA3. Red labels represent variables and black labels site names. See text for details.

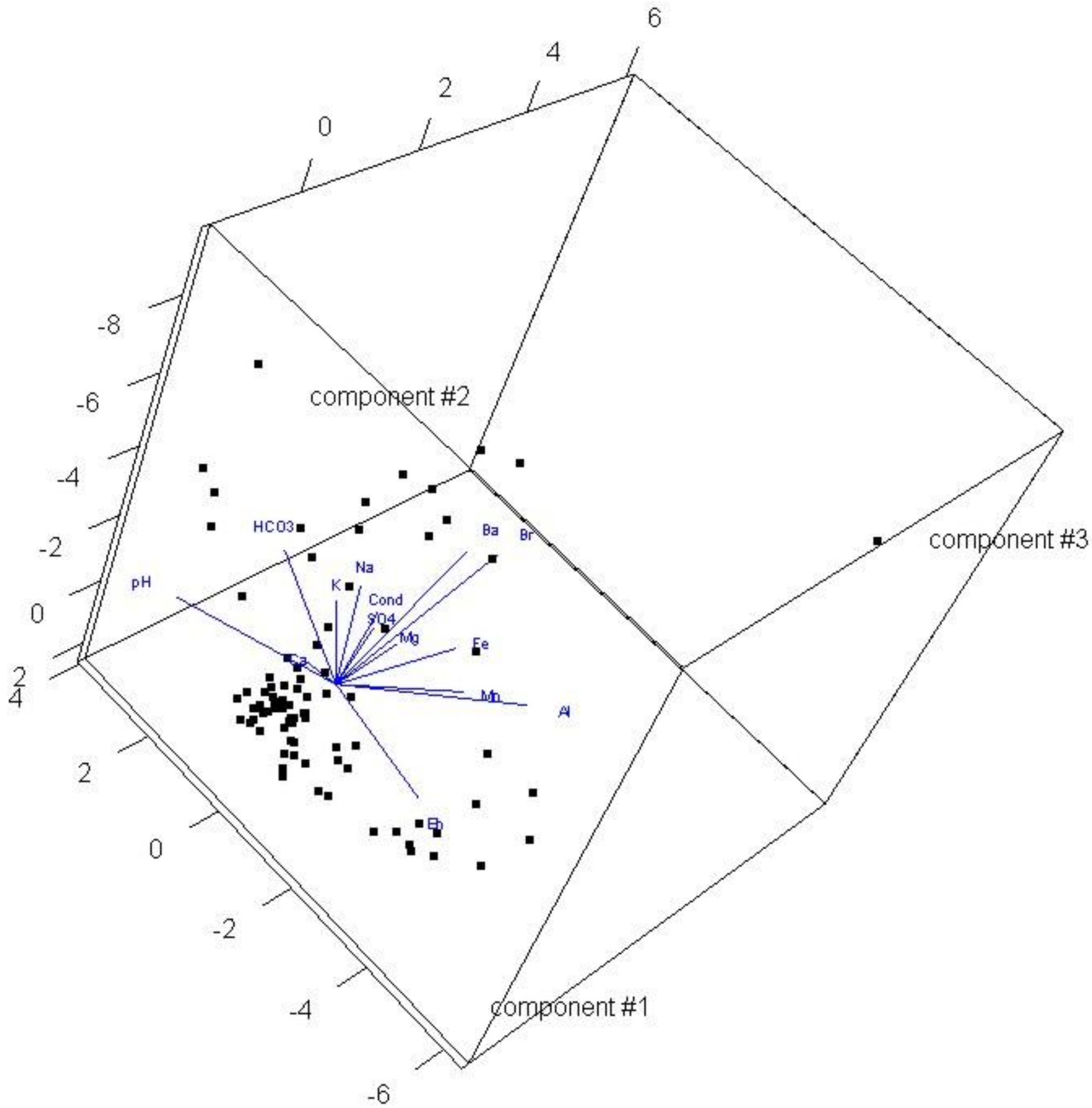


Figure 19. Tri-plot of scores (points) and variable loadings (blue vectors) on the first three principal components of the PCS.

Appendix A

Mine Name	ID	Sample ID	Opening	Easting	Northing	Temp (oC)	pH (field)	Cond (uS/cm)	Eh (elec.)	pe	O2 (mg/L)	Alk mg/L as CaCO3	Est. Flow gal/min
Chiefton	West Fork 2	1	Artesian Seep	548480	4353210	13.8	6.29	1958	0.229	3.865	0.46	245	200
Raybert	West Fork 5	2	Conduit	550219	4357062	13.0	6.41	1369	0.288	4.875	5.81	304	100
Ruby #2	Ruby 2d	3	Conduit	550030	4359322	12.1	6.73	1075	0.288	4.875	7.85	288	5
Ruby #2	Ruby 2c	4	Conduit	549889	4359255	13.5	6.62	1199	0.191	3.234	9.05	184	100
Gates	Gates	5	Artesian Seep	592371	4415810	16.3	6.41	2205	0.032	0.543	0.53	923	200
Palmer	Adah	6	Seep	591715	4417907	16.4	6.04	1917	0.014	0.235	0.66	853	123
Palmer	Palmer	7	Seep	592161	4419389	16.9	6.51	1993	0.193	3.259	0.74	853	600
Odonald 1 & 2	Grays Landing	8	Seep	592626	4409666	14.7	2.71	2965	0.538	9.088	High	0	400
Maiden #1	Maidsville	9	Conduit	586302	4394649	14.8	2.83	3885	0.623	10.538	High	0	150
Canyon Nester	Smith 06b	10	Seep	594433	4389665	11.7	2.57	2361	0.795	13.443	High	0	1
Peacock	Smith 03a	11	Seep	595171	4389630	14.3	2.84	2486	0.621	10.489	High	0	60
Export	Export	12	Conduit	617186	4474531	12.7	3.01	1072	0.663	11.208	4.38	0	500
Delmont	Borland2	13	Conduit	618303	4474784	12.4	4.80	864	0.432	7.297	0.65	13	100
Delmont	Borland1	14	Conduit	618283	4474777	12.5	4.49	892	0.444	7.497	0.67	0	100
Boston Gas & Coal	MD7x	15	Portal	595198	4450254	13.4	6.38	1940	0.231	3.897	0.99	394	150
Maiden #1	Taylorstown 2B SW	16	Portal	587573	4399239	16.4	3.70	1755	0.666	11.256	10.40	0	100
Maiden #1	Taylorstown 2B NE	17	Portal	587573	4399239	15.0	2.69	2442	0.787	13.303	11.40	0	200
Maiden #1	Taylorstown 2A	18	Portal	588739	4400200	13.6	2.74	2300	0.758	12.814	7.28	0	300
Maiden #3	Maiden 3B	19	Portal	587948	4402060	13.8	6.02	2147	0.259	4.372	1.15	202	300
Maiden #3	Maiden 3A	20	Portal	588220	4401997	14.3	4.92	2490	0.403	6.804	0.59	12.5	40
Maxwell	Luzerne	21	Seep	588623	4427676	13.8	5.99	2162	0.265	4.473	0.84	180	50
Chamoni	Brownsville	22	Seep	595283	4432723	12.8	6.62	1573	0.254	4.291	0.59	558	600
Karen	Karen	23	Portal	588386	4429296	13.6	6.40	1577	0.340	5.748	5.07	384	400
Maple Glenn	Maple Glenn	24	Portal	588135	4429694	11.4	6.91	1992	0.454	7.673	6.05	182	20
Boston Gas & Coal	Iron Falls	25	Portal	602485	4456682	13.2	5.95	1900	0.306	5.172	1.19	138	350
Boston Gas & Coal	Douglas Run	26	Conduit	601082	4455325	13.2	6.35	1650	0.218	3.684	5.68	308	350
Marchand	Marchand	27	Conduit	605094	4456131	14.4	6.12	2830	0.221	3.741	1.74	351	300
Lyons Run	Lyons Run	28	Conduit	609376	4465320	14.6	5.90	1748	0.260	4.393	3.45	137	1200
Lyons Run	Coal Run	29	Seep	609783	4465714	13.8	5.84	1320	0.394	6.654	0.75	56	5
Guffey	Guffey	30	Portal	604889	4460357	13.6	6.34	1920	0.214	3.619	0.51	341	400
Boston Gas & Coal	East Monongahela	31	Seep	592166	4450563	13.9	6.40	3250	0.211	3.574	0.49	358	5
Boston Gas & Coal	MD6 West (Rostosky)	32	Conduit	594041	4450132	13.7	6.37	2120	0.222	3.750	1.80	462	100
Guffey	Guffey Lower	33	Seep	604685	4460202	13.4	6.15	1921	0.235	3.964	0.42	224	150
Unknown	MD4 (Gilmore)	34	Seep	588136	4454851	14.3	4.90	2540	0.363	6.128	0.37	25	100
Unknown	MD2 or Coal Bluff	35	Seep	588876	4455011	13.5	5.47	1715	0.330	5.583	0.40	67	50
Catsburg	Catsburg	36	Conduit	593501	4449491	12.4	6.49	1604	0.258	4.356	2.80	219	120
Catsburg	Carroll	37	Seep	593924	4449365	12.8	6.41	1440	0.222	3.750	0.35	292	200
Boston Gas & Coal	MD10 Lower	38	Conduit	597015	4450803	13.8	6.59	1668	0.249	4.203	5.70	136	50
Boston Gas & Coal	MD9	39	Seep	595738	4450230	13.3	6.55	1370	0.096	1.618	1.24	313	80
Boston Gas & Coal	MD6 Original (Rostosky)	40	Conduit	594080	4450142	13.5	6.24	2030	0.295	4.992	4.80	288	100
Boston Gas & Coal	MD7 (Sunnyside)	41	Portal	595198	4450254	13.4	6.38	1940	0.231	3.897	0.99	394	150
Eclipse	Granville Hollow	42	Conduit	591828	4437914	12.8	6.65	937	0.504	8.517	6.39	246	80
Vesta #1 & #2	Vesta #1 & #2	43	Seep	594938	4437160	15.4	7.11	1450	0.479	8.099	5.20	449	40
Eclipse	Eclipse1	44	Seep	594823	4437179	13.6	7.00	1806	0.552	9.332	5.13	378	150
Eclipse	Eclipse2	45	Seep	594590	4437195	14.4	7.12	1840	0.501	8.474	5.81	366	100
Eclipse	Eclipse3	46	Conduit	593821	4437055	12.1	6.70	1510	0.496	8.390	3.70	323	170
Vesta #3	Vesta #3	47	Seep	593668	4436905	12.0	6.67	1216	0.496	8.377	5.83	291	100
Langloth	Langeloth	48	Conduit/Borehole	551417	4467191	13.2	5.78	5350	0.235	3.972	0.68	349	150
Erie_North	Erie_North	49	Conduit	551686	4468890	12.9	6.00	1560	0.309	5.217	5.90	181	200
Unknown	Surface Mine	50	Conduit	553844	4471255	13.6	3.55	2262	0.482	8.149	0.60	0	200

Pitts #3	MD1000gpm	51	Conduit	554405	4467849	13.6	4.66	1350	0.294	4.971	1.26	8	300
Montour #1	Gladden	52	Artesian Seep	570401	4465856	12.8	6.07	1720	0.307	5.187	0.55	141	1000
Essen #3	Presto-Sygan	53	Artesian Seep	574296	4468588	12.7	4.92	1740	0.399	6.745	0.78	24	600
Montour #4	Wingfield Pines	54	Conduit	575623	4465657	13.8	6.61	2790	0.215	3.628	2.77	405	1500
Unknown	McGlaughlin Run	55	Conduit	576057	4467315	13.1	5.67	1893	0.344	5.818	1.83	64	350
Unknown	Coal Run West	56	Artesian Seep	575270	4466551	13.4	6.32	2520	0.221	3.728	0.52	308	200
Nixon #5	Saltwell	57	Seep	563147	4356852	13.6	3.93	995	0.680	11.496	2.89	0	60
Scott #2	Owens 34b	58	Conduit	561897	4358251	13.0	5.57	830	0.439	7.427	6.90	66	150
Erie	Erie South	59	Conduit	556883	4354579	13.3	5.63	1353	0.368	6.216	2.00	82	100
Mine A	Prospect	60	Conduit	556594	4361743	12.6	6.52	1760	0.231	3.909	1.16	262	80
Mine #54 & #23	Backyard	61	Conduit	557103	4360665	12.6	6.33	1520	0.243	4.112	2.20	186	120
Pursglove/Osage	Core Pump	62	Valve	576321	4393481	18.5	5.28	11800	0.171	2.896	0.90	169	1200
Mine #26	Norway	63	Conduit	568617	4369531	13.5	6.25	1480	0.293	4.958	1.50	240	600
Dravo	Aluminum Falls	64	Seep	603045	4459675	12.4	4.66	1020	0.504	8.515	2.08	5	80
Unknown	Herminie	65	Portal	610051	4457628	12.9	5.50	1430	0.397	6.704	1.10	62	120
Scott #2	Owens 34bx	66	Conduit	561897	4358251	13.0	5.57	830	0.439	7.427	6.90	66	150
Unknown	Convent	67	Manhole	527154	4435988	13.9	6.85	5960	0.144	2.441	8.90	464	40
Wheeling Valley	Cherry Run	68	Conduit	526383	4441371	12.6	3.63	9500	0.560	9.471	9.05	0	50
5th Street	5th Street	69	Conduit	525725	4439561	12.2	5.94	2185	0.303	5.124	5.48	168	20
Richland	Richland	70	Manhole	525247	4438649	12.3	5.90	7550	0.264	4.461	6.56	121	20
Isabella	Isabella	71	Seep	590707	4421590	23.9	3.27	2971	0.621	10.504	3.41	0	15

Appendix B

			Fe	Al	Mn	Na	K	Ca	Mg	Ba	Be	S	Se	Sr	SO4	NO3	Br	Cl	F
MINENAME	ID	Sample ID	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Chiefton	West Fork 2	1	52.24	<0.1	1.86	89.5	5.9	266.3	38.7	<0.012	<0.011	343	<0.045	3.18	1027	0.31	<0.129	4.7	0.8
Raybert	West Fork 5	2	17.37	<0.1	0.46	31.7	4.9	182.1	34.4	<0.012	<0.011	213	<0.045	2.05	637	<0.004	<0.129	2.0	0.2
Ruby #2	Ruby 2d	3	6.59	<0.1	0.30	39.0	5.3	138.8	31.8	0.014	<0.011	134	<0.045	2.08	400	0.03	<0.129	2.0	0.2
Ruby #2	Ruby 2c	4	24.38	<0.1	0.50	38.9	6.2	142.1	8.7	<0.012	<0.011	178	<0.045	1.87	534	<0.004	<0.129	2.4	0.1
Gates	Gates	5	0.71	<0.1	<0.1	594.1	3.3	24.0	8.7	0.038	<0.011	55	0.097	1.12	166	<0.004	0.53	7.0	0.6
Palmer	Adah	6	0.67	<0.1	<0.1	533.7	3.2	24.9	11.3	0.058	<0.011	39	<0.045	1.10	118	<0.004	0.51	5.7	0.6
Palmer	Palmer	7	0.92	<0.1	<0.1	504.9	3.1	30.6	28.3	0.076	<0.011	33	<0.045	1.28	99	<0.004	2.36	5.6	0.6
Odonald 1 & 2	Grays Landing	8	58.09	11.07	1.31	18.3	<0.1	96.2	35.3	<0.012	<0.011	243	<0.045	0.64	728	<0.004	0.58	5.6	0.6
Maiden #1	Maidsville	9	54.29	23.54	0.46	5.1	<0.1	117.0	35.3	<0.012	<0.011	287	<0.045	0.53	861	0.01	<0.129	1.3	<0.088
Canyon Nester	Smith 06b	10	37.53	13.32	1.17	1.9	<0.1	27.9	10.3	<0.012	<0.011	148	<0.045	0.07	444	0.45	<0.129	2.3	0.3
Peacock	Smith 03a	11	17.08	8.23	2.12	23.0	<0.1	49.7	17.0	<0.012	<0.011	131	<0.045	0.09	392	<0.004	<0.129	142.3	0.5
Export	Export	12	1.60	6.78	0.95	15.2	0.2	48.7	16.8	<0.012	<0.011	116	<0.045	0.37	347	0.17	<0.129	15.5	0.2
Delmont	Borland2	13	21.33	0.65	1.27	29.2	1.8	57.8	18.8	<0.012	<0.011	124	<0.045	0.49	371	<0.004	<0.129	29.7	0.2
Delmont	Borland1	14	23.30	0.80	1.28	28.6	1.7	59.6	19.5	<0.012	<0.011	125	<0.045	0.51	375	<0.004	<0.129	28.7	0.1
Boston Gas & Coal	MD7x	15	30.03	<0.1	0.32	442.4	3.0	79.5	21.7	<0.012	<0.011	242	<0.045	1.17	724	3.35	0.90	336.2	0.7
Maiden #1	Taylorstown 2B SW	16	2.35	6.19	1.03	22.3	0.3	92.9	40.8	<0.012	<0.011	208	<0.045	0.74	623	1.19	<0.129	5.8	0.4
Maiden #1	Taylorstown 2B NE	17	5.17	6.87	1.17	24.4	<0.1	96.5	40.4	<0.012	<0.011	224	<0.045	0.72	671	0.72	<0.129	5.6	0.4
Maiden #1	Taylorstown 2A	18	8.33	4.57	0.95	14.0	<0.1	106.7	27.0	<0.012	<0.011	201	<0.045	0.62	603	0.38	<0.129	5.7	0.8
Maiden #3	Maiden 3B	19	50.46	<0.1	2.16	181.5	5.0	159.0	59.1	<0.012	<0.011	373	<0.045	1.97	1116	<0.004	<0.129	7.1	0.4
Maiden #3	Maiden 3A	20	51.81	0.43	3.61	136.4	3.7	146.3	53.9	<0.012	<0.011	385	<0.045	1.40	1152	<0.004	<0.129	10.7	0.3
Maxwell	Luzerne	21	42.52	<0.1	2.29	213.0	6.0	189.5	50.9	<0.012	<0.011	406	<0.045	2.77	1217	0.01	<0.129	37.8	0.1
Chamoni	Brownsville	22	1.34	<0.1	0.11	332.7	2.7	50.5	18.2	<0.012	<0.011	114	<0.045	1.50	340	<0.004	<0.129	3.6	0.4
Karen	Karen	23	0.47	<0.1	0.19	256.4	3.8	91.1	27.8	<0.012	<0.011	166	0.08	2.11	496	0.41	<0.129	31.2	0.5
Maple Glenn	Maple Glenn	24	<0.1	<0.1	<0.1	322.4	4.5	101.4	45.1	<0.012	<0.011	325	<0.045	2.58	974	0.47	<0.129	70.8	0.2
Boston Gas & Coal	Iron Falls	25	59.37	<0.1	0.96	240.0	2.9	94.6	36.2	<0.012	<0.011	268	<0.045	1.44	803	5.32	<0.129	196.9	0.1
Boston Gas & Coal	Douglas Run	26	22.40	<0.1	0.47	251.6	2.4	77.4	27.2	<0.012	<0.011	168	<0.045	1.38	502	0.41	<0.129	147.1	0.3
Marchand	Marchand	27	48.43	<0.1	0.97	481.9	3.7	114.8	34.3	<0.012	<0.011	396	<0.045	1.79	1186	0.24	0.55	169.4	0.4
Lyons Run	Lyons Run	28	52.39	<0.1	1.55	184.6	3.1	101.3	30.0	<0.012	<0.011	245	<0.045	1.30	733	0.28	0.40	163.4	0.4
Lyons Run	Coal Run	29	6.05	<0.1	0.78	94.5	2.6	100.8	35.2	<0.012	<0.011	135	<0.045	1.42	404	0.27	<0.129	244.6	0.2
Guffey	Guffey	30	19.28	<0.1	0.44	390.4	2.3	49.8	16.3	<0.012	<0.011	197	<0.045	1.27	589	0.03	0.27	170.2	0.5
Boston Gas & Coal	East Monongahela	31	51.01	<0.1	0.72	614.8	4.5	130.3	41.5	<0.012	<0.011	517	<0.045	3.07	1549	<0.004	0.47	142.4	0.2
Boston Gas & Coal	MD6 West (Rostosky)	32	15.20	<0.1	0.41	405.1	3.1	72.1	23.6	<0.012	<0.011	208	<0.045	1.52	622	<0.004	0.43	90.5	0.4
Guffey	Guffey Lower	33	15.52	<0.1	0.51	390.1	3.0	52.0	17.9	0.017	<0.011	207	<0.045	1.31	619	1.87	0.30	161.9	0.4
Unknown	MD4 (Gilmore)	34	58.40	2.95	0.73	167.1	2.3	148.2	34.9	<0.012	<0.011	315	<0.045	1.36	945	<0.004	0.15	287.8	0.3
Unknown	MD2 or Coal Bluff	35	54.34	<0.1	0.75	174.4	4.0	118.0	38.5	<0.012	<0.011	269	<0.045	1.42	805	<0.004	<0.129	196.8	0.1
Catsburg	Catsburg	36	15.36	<0.1	0.50	251.6	2.6	90.8	29.8	<0.012	<0.011	233	<0.045	2.12	697	0.18	0.20	80.4	0.3
Catsburg	Carroll	37	14.32	<0.1	0.76	251.4	2.8	86.1	31.5	<0.012	<0.011	177	<0.045	2.07	531	<0.004	0.16	69.5	0.4
Boston Gas & Coal	MD10 Lower	38	33.76	<0.1	0.78	228.2	3.6	103.4	34.0	0.019	<0.011	320	<0.045	1.94	958	0.65	0.18	22.3	0.1
Boston Gas & Coal	MD9	39	24.27	<0.1	0.23	263.0	2.5	45.4	16.5	<0.012	<0.011	130	<0.045	0.89	391	<0.004	0.24	63.1	0.3
Boston Gas & Coal	MD6 Original (Rostosky)	40	11.27	<0.1	0.77	360.1	3.8	93.3	26.6	<0.012	<0.011	297	<0.045	1.28	890	0.19	0.37	107.4	0.2
Boston Gas & Coal	MD7 (Sunnyside)	41	30.21	<0.1	0.32	439.4	3.0	78.7	21.6	<0.012	<0.011	238	<0.045	1.20	713	1.72	1.48	329.9	0.9
Eclipse	Granville Hollow	42	<0.1	<0.1	<0.1	56.9	2.9	90.4	33.6	0.019	<0.011	84	<0.045	1.46	253	<0.065	0.11	31.7	0.2
Vesta #1 & #2	Vesta #1 & #2	43	<0.1	<0.1	<0.1	196.8	4.0	92.4	25.3	0.021	<0.011	86	<0.045	1.45	256	<0.065	0.17	71.9	0.3
Eclipse	Eclipse1	44	<0.1	<0.1	<0.1	215.4	4.7	136.5	38.8	0.012	<0.011	152	0.068	2.35	455	<0.065	0.16	173.7	0.3
Eclipse	Eclipse2	45	<0.1	<0.1	<0.1	207.7	4.9	138.3	39.9	0.015	<0.011	155	<0.045	2.46	464	<0.065	0.12	183.9	0.3
Eclipse	Eclipse3	46	<0.1	<0.1	<0.1	141.4	4.1	119.4	40.6	0.017	<0.011	105	<0.045	1.86	315	1.45	<0.088	180.4	0.2
Vesta #3	Vesta #3	47	<0.1	<0.1	<0.1	106.4	3.9	100.4	40.1	0.027	<0.011	102	<0.045	1.47	306	0.75	<0.088	69.2	0.2
Langloth	Langeloth	48	199.60	<0.1	2.82	692.9	18.2	331.5	82.1	<0.012	<0.011	916	<0.045	2.25	2742	6.13	1.96	466.3	<0.015
Erie_North	Erie_North	49	50.42	0.11	0.96	90.0	5.0	151.5	48.6	0.013	<0.011	267	0.052	1.22	799	21.15	<0.088	25.4	0.1
Unknown	Surface Mine	50	48.92	18.68	5.00	86.4	7.8	186.4	85.8	0.006	0.055	516	0.0225	1.29	1547	4.32	0.16	5.6	0.3
Pitts #3	MD1000gpm	51	53.32	3.49	1.31	54.3	8.3	107.2	35.7	0.006	0.055	247	0.0225	0.83	739	0.03	0.41	28.0	0.8
Montour #1	Gladden	52	73.01	0.15	0.71	186.9	6.3	84.0	31.2	<0.012	<0.011	255	<0.045	0.91	764	<0.065	0.51	12.1	0.0
Essen #3	Presto-Sygan	53	45.15	4.08	0.74	132.1	7.4	107.8	39.8	0.006	0.055	279	0.0225	0.70	836	0.03	0.04	143.2	0.5
Montour #4	Wingfield Pines	54	15.65	<0.1	0.34	423.4	7.7	103.4	28.5	0.021	<0.011	152	<0.045	2.43	456	<0.065	1.42	294.7	0.4
Unknown	McGlaughlin Run	55	38.22	0.84	0.42	166.8	4.4	82.7	30.7	<0.012	<0.011	172	<0.045	1.23	514	<0.065	<0.088	287.4	0.2
Unknown	Coal Run West	56	34.27	<0.1	0.40	434.4	6.3	77.0	24.1	<0.012	<0.011	206	<0.045	1.50	618	<0.065	1.17	185.0	0.4
Nixon #5	Saltwell	57	0.22	4.10	0.79	12.1	1.0	101.1	35.5	<0.012	<0.011	220	<0.045	0.62	658	<0.065	<0.088	2.0	0.2
Scott #2	Owens 34b	58	<0.1	<0.1	<0.1	18.3	2.7	107.9	39.3	<0.012	<0.011	152	<0.045	1.28	455	<0.065	<0.088	2.3	0.1
Erie	Erie South	59	12.42	<0.1	1.64	47.9	5.1	167.4	54.1	<0.012	<0.011	268	<0.045	1.43	803	<0.065	<0.088	7.3	0.2
Mine A	Prospect	60	37.38	<0.1	0.56	115.1	7.4	192.0	58.6	0.014	<0.011	314	<0.045	4.74	940	<0.065	<0.088	2.2	0.3
Mine #54 & #23	Backyard	61	48.69	<0.1	0.65	66.5	9.0	177.4	52.0	0.012	<0.011	269	<0.045	2.74	805	<0.065	<0.088	6.8	0.2
Pursglove/Osage	Core Pump	62	492.32	3.67	5.24	1615.9	12.3	286.0	216.6	0.006	0.055	2397	0.0225	0.90	7180	1.80	0.04	108.8	1.1
Mine #26	Norway	63	10.48	<0.1	0.53	152.5	5.4	123.4	37.7	0.016	<0.011	217	<0.045	1.84	649	<0.065	<0.088	9.1	0.3
Dravo	Aluminum Falls	64	0.05	0.85	0.34	35.2	8.2	108.6	35.5	0.006	0.055	213	0.065	1.08	639	1.76	3.28	43.0	0.2
Unknown	Herminie	65	29.57	0.27	1.74	82.1	3.5	111.6	35.3	<0.012	<0.011	251	<0.045	0.84	753	<0.065	<0.088	79.6	0.2
Scott #2	Owens 34bx	66	<0.1	<0.1	<0.1	13.2	3.4	115.4	46.1	<0.012	<0.011	182	<0.045	1.48	544	<0.065	<0.088	3.5	<0.015
Unknown	Convent	67	41.30	<0.1	0.49	1021.6	24.4	434.9	98.9	<0.012	<0.011	1141	<0.045	5.88	3416	0.29	0.98	212.6	0.3
Wheeling Valley	Cherry Run	68	137.84	13.05	0.44	230.1	6.3	60.4	22.0	<0.012	<0.011	387	<0.045	0.76	1158	<0.065	0.56	147.3	2.1
5th Street	5th Street	69	139.69	<0.1	0.47	144.3	14.0	194.6	46.0	<0.012	<0.011	368	<0.045	2.57	1101	<0.065	0.12	45.8	<0.015
Richland	Richland	70	409.99	<0.1	1.03	1067.4	23.3	295.8	117.5	<0.012	<0.011	1432	<0.045	3.86	4289	<0.065	1.63	440.6	<0.015
Isabella	Isabella	71	4.71	3.74	4.03	40.4	2.2	179.4	60.9	<0.012	<0.011	285	<0.045	0.68	853	<0.065	<0.088	5.3	0.8