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A Paired-catchment Approach for Characterizing Hydrologic Response to Mountaintop Mining

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A PAIRED-CATCHMENT APPROACH FOR CHARACTERIZING HYDROLOGIC RESPONSE TO MOUNTAINTOP MINING

by

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Under the Direction of Richard Milligan, PhD

ABSTRACT

This study examined six large-scale watersheds divided into three pairs (mined and unmined), leveraging streamflow and mining permit datasets from the U.S. Geological Survey (USGS) and West Virginia Department of Environmental Protection (WVDEP), to develop a novel high-resolution time series of five decades of surface mining and valley fill activity for each watershed. Streamflow metrics were evaluated for trends and any correlation with mining permit history. Both mined and unmined watersheds experienced little or no change in annual flow. Mined watersheds exhibited significant decreasing trends in maximum flow and significant increasing trends in minimum flow, and these metrics were significantly correlated with mining permit history. No effect of mining cover on runoff ratio (Q/P) was found for any watershed. Future work should differentiate mining from other land-use/land-change disturbances in each watershed and expand on the mining permit histories developed in this study.

INDEX WORDS: Hydrology, Streamflow, SFM/VF, Paired watershed, Trend analysis, Land use change

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DEDICATION

This is dedicated to the Kalapooia River and Michael. This would never have happened without either of you.

ACKNOWLEDGEMENTS

Thank you to everyone that supported me through this, many of whom will never see this but are appreciated. Thanks to my adviser, Dr. Milligan, for endless patience and guidance, and my committee, Dr. Diem and Dr. Pangle, for helping me to get better at writing science and doing science. Thank you to Dr. Price for pointing me at hydrology.

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LIST OF ABBREVIATIONS

MTM – Mountaintop Mining

SFM – Surface Mining

VF – Valley Fill

AOC – Approximate original contour

WVDEP – West Virginia Department of Environmental Protection

USGS – United States Geological Survey

NOAA – National Oceanic and Atmospheric Administration

1 INTRODUCTION

1.1 Surface mining and valley fill

Surface mining (SFM) and valley fill (VF) are dramatic and complex drivers of environmental change, creating a cascade of disturbances at every spatial and temporal level, from the headwaters to beyond the watershed outlet, impacting flora, fauna and human communities. SFM is a form of mountaintop mining that involves the removal of forest cover, soil, and bedrock to access underlying coal seams in mountainous landscapes. SFM creates excess soil and rock, or overburden, which is typically either backfilled into the mined-out area to create an approximate original contour (AOC) or placed in adjacent valleys or hollows as VF, thus burying headwater streams (G.A.O, 2010).

The full impact of surface mining on hydrology has yet to be understood. SFM/VF practices lead to multiple levels of environmental disturbance including the fragmentation of forest, a loss of biodiversity, and harm to biotic communities downstream (Holzman, 2011; Wickham *et al.*, 2013). Additionally, post-reclamation mined sites may not resemble reference sites even decades later, and short-term reclamation efforts may negatively impact long-term recovery (Holl, 2002). For these reasons, long term and large-scale SFM and VF research remain needed in the Appalachian region of the United States (Palmer *et al.*, 2010).

SFM/VF has an enormous spatial extent across the Appalachians, giving greater importance to large-scale studies. As early as 2001 conservative estimates of mine impacted land for West Virginia stood at 244,000 acres and eight years later this increased to 352,000 acres (E.P.A, 2003; Yuill, 2003; Geredien, 2009). According to the West Virginia Department of Environmental Protection (WVDEP) as of 2017, around 500,000 acres across West Virginia had been permitted for surface mining, not counting valley fill permits or any permit overlap. More than 100,000 acres of watershed area were approved for valley fill between 1985 and 2001 in West Virginia with a projected loss of 30.72 square kilometers of riparian habitat from mining activities (E.P.A, 2011). Mining permitted landscapes can undergo “on-off-on” use, having periods of no activity. The rising popularity of fracking in the United States has also played a part in the inconsistent usage of SFM/VF for coal mining in West Virginia (Frondel *et al.*, 2019).

SFM/VF is known to impact hydrologic response in multiple ways. Both valley fill and mined sites increase the impermeability of the watershed through compaction, slowing infiltration and creating more overland flow (Chong *et al.*, 1997). Valley fill also leads to voids beneath the surface of the fill, creating storage spaces that are slow to release flow, and increase risk of flooding (Wunsch *et al.*, 1999). This sluggish release of flow from the voids in valley fill leads to increased baseflow (Nippgen *et al.*, 2017). Valley fill has also been suggested as playing a role in the presence of significantly decreased maximum flow (Messinger *et al.*, 2003; Zégre *et al.*, 2014). While SFM/VF has not been found to impact annual flow, mined sites have been shown to experience high levels of peak flow during storm events, which may be attributed to preferential flow paths within valley fill (Messinger, 2003; Negley *et al.*, 2006; Ferrari *et al.*, 2009; Evans *et al.*, 2015).

The purpose of this study was to explore the impact of SFM/VF on streamflow at large spatial scales. Therefore, this study examined six large-scale watersheds divided into three pairs of watersheds (mined and unmined). To seek out a high-resolution method of characterizing mining at the large-scale, mining datasets from the WVDEP were leveraged to develop a novel high-resolution time series of five decades of SFM/VF. Five decades of streamflow acquired from the United States Geological Survey (USGS) were evaluated for any significant trends over time, and any significant correlation with mining permit data. This study found significant correlation between SFM/VF permit history and both reduction in maximum annual flow as well as increasing annual minimum flow. Results of this study suggest valley fill impacted headwaters begin altering downstream flow regimes upon approaching as little as 1% SFM/VF mining.

1.2 Long-term hydrological impacts of land use conversion

Multi-decadal hydrologic flow data is necessary for any examination of disturbance thresholds that can support accurately forecasting watershed behaviors. Forecasting watershed behavior is important for the management of mined lands, improving upon our uncertain understanding of threshold behavior in watersheds, and insight into long-term hydrologic response to mining. Additionally, understanding how a watershed responds to change in the long-term is important for management of mined lands at each stage, from pre-mining, during the mining process, to management of the post-mining condition (Botter, 2014). Research evaluating hydrologic flow response typically focuses on event (peak) flow rather than long-term response. The study of a mined landscape response to stormflow events is important for management of the mined lands; however, evaluating the multidecadal response of mined lands is equally important for long-term management (Messinger, 2003; Wiley *et al.*, 2003; Du *et al.*, 2012; Hopkinson *et al.*, 2016).

Post-mining reclamation processes are inadequate. One reason for the inadequacy of current reclamation processes is that reclaimed sites are no longer able to behave as a mature landscape, but a young one. The use of long-term hydrologic flow data furthers understanding of how to better mimic more mature landscapes. Improving the ability to mimic mature landscapes in reclaimed sites will reduce negative impact on watershed flow response to mining disturbance in both the short and long term (Eckels *et al.*, 2010; DePriest *et al.*, 2015). Beyond the need for mimicking mature landscapes, current reclamation practices do not appear to restore mined sites in any meaningful sense. Alongside the challenge of a newly immature landscape, reclamation practices do not bring mined land to a pre-mined state but rather to what approaches an urbanized state (Bonta *et al.*, 1997; Ferrari *et al.*, 2009). Urbanized behavior in reclaimed watersheds, along with a lack of economic development, adds importance to defining the “end-point” for post-mined land in a reclamation sense, of which the end point is generally a “replacement ecosystem” (Geredien, 2009; Lima *et al.*, 2016). Mining regulations rely on mitigation post-mining rather than putting plans into place at the time a permit is granted (Allen, 2014). The reliance of mining regulations on short term mitigation in mining disturbed sites is insufficient, as post-restoration vegetation can substantially differ from the pre-mined state for several decades (Holl, 2002).

Studies that use multi-decadal hydrologic flow data are important for the management of mined lands, improving on the reclamation process, and providing insight into long-term hydrologic response to mining. Thresholds for watershed response to mining remain unclear. Thresholds have been studied for the long-term impact of forest reduction on hydrology and biota downstream but there are no known comprehensive studies for thresholds of mining impact on streamflow response (Zégre *et al.*, 2014). Studies of thresholds for mining impact on streams are generally conflicted and have focused mainly on changes in water quality rather than overall streamflow behavior (Hartman *et al.*, 2005; Petty *et al.*, 2010; Merriam, 2015). A range of 10% to 30% disturbance of total watershed area by mining appears to be a threshold for biological impairment of streams, while as little as 1 to 5% mining activity has been found to begin negatively impacting local ecology (Petty *et al.*, 2010; Merriam *et al.*, 2011). Bernhardt *et al.* (2012) found catchments expressed biological impairment when more than 2.2% of a catchment’s surface area had undergone surface mining. A minimum of 20% deforestation has been suggested to detect measurable increases in annual streamflow (Bosch *et al.*, 1982). In a study of catchments that were deforested and converted to pasture in Australia, New Zealand, and South Africa, Brown *et al.* (2013) found that catchments needed between 8 and 25 years to reach a new equilibrium after loss of forest cover.

1.3 Inconsistent quality of available SFM/VF data

A fully comprehensive mining dataset is indispensable to assessing the relationship between long-term hydrologic metrics and mining disturbance. While all-inclusive mining data is essential for developing insights into the connections between mining and watershed response, there are no known comprehensive mining datasets available for the southern Appalachian coalfields (Wu *et al.*, 2017). A full data-driven story of the region requires cross-referencing several patchwork datasets to create a single comprehensive whole (Geredien, 2009; Soulard *et al.*, 2016). Identifying the full extent of mining disturbance is typically accomplished through analysis of single 'snapshots' of remote sensing imagery such as Landsat 5 TM imagery (USGS) that occur close to a specific time-slice and using leaf-off for better resolution of the hillshape (Lechner *et al.*, 2016). Satellite images are typically chosen to reflect a moment in time every three or five years or even once a decade with varying time gaps between images (Zégre *et al.*, 2013; Hendrychová *et al.*, 2016). Number of years between satellite images used for analysis and degree of variation in years between images generally speak to the overall quality of the available data (Townsend *et al.*, 2009; Ross *et al.*, 2016). Analysis of remote sensing imagery with an often-variable period of years between images is a commonplace style of mining characterization, but mining is a process that is in flux and can be discontinuous for an area. Lacking high resolution mining data that would allow studies to accurately track the dynamic landscape changes within a mining site leaves open the possibility of making incorrect assumptions regarding landscape changes over time.

Characterization of mining disturbance may also vary depending on the study. A study may not consider underground mining or may differentiate between reclaimed and active mining. Another study may use ‘total mining disturbance’ or annual mine production values (Zégre *et al.*, 2013; Zégre *et al.*, 2014; Ross *et al.*, 2016). Mining permit data may be used to correlate with classification of remote sensing data. There can be disadvantages to correlating mining permit data with remote sensing data such as computational requirements and increasing complexity when leveraging data (Redondo-Vega *et al.*, 2017).

1.4 Large-scale watersheds

The impact of surface mining and valley fill goes beyond the changes in topography, requiring examination at larger scales (1 km^2 - 10,000 km^2). More than 6,400 square kilometers of overburden, what makes up valley fill, have been conservatively estimated across 11,500 square kilometers of southern West Virginia, which is a volume that has been compared to the 1991 Mount Pinatubo eruption in equivalent volume of displaced material (Umbal *et al.*, 1996; Ross *et al.*, 2016). The ability to comprehensively scale watershed modeling upwards to the large-scale has been studied extensively for decades and remains not yet fully realized (Beven, 2006). Large-scale studies are difficult to pursue due to the increasing complexity of variables and mechanisms involved in the watershed at increasing scale (Blöschl *et al.*, 1995). Studying the mechanisms of watershed behavior at the microscale is the easiest path for research due to the cost and labor prohibitive nature of large-scale studies. Microscale studies are informative for studying small-scale interactions with land use change (Hewlett *et al.*, 1967; Alvarenga *et al.*, 2016). Small catchments are likely to have a more variable hydrologic response than larger catchments to any changes in dynamical systems, which adds value to scaling our understanding to larger watersheds (Pilgrim *et al.*, 1982).

1.5 Paired-catchment studies

Pairing watersheds and streams to have a reference watershed is a common practice when studying catchment response to mining. Paired-catchment studies are useful for evaluating watershed response to land use/land change and provide a control sample of undisturbed watershed behavior. Similar characteristics such as size and physical features are essential when using a paired catchment method (Collier *et al.*, 1964; Hibbert, 1967; Minear *et al.*, 1976; Negley *et al.*, 2006). One challenge when studying watersheds at a large-scale (1 km^2 - 10,000 km^2) and using a paired catchment method is that a reference watershed may possess trellis drainage patterns while mined watersheds in the Appalachians typically have dendritic drainage patterns (Wiley *et al.*, 2013). Because of the potential value of using a reference watershed, any drainage pattern differences must be considered during any analysis involving hydrologic flow.

1.6 Research questions and objectives

As has been noted, multiple research gaps exist in understanding the relationship between SFM/VF and hydrologic flow response within Appalachian watersheds. The impact of surface mining processes is extensive and complex, both within and beyond the watershed. Additionally, mitigation responses to surface mining have been inadequate, and scaling watershed studies up to large-scale watersheds remains a task made difficult by the nature of watershed systems.

The goal of this study was to evaluate for any long-term trends in hydrologic response within large-scale watersheds and evaluate for any significant correlation between hydrologic response and mining permit data. In order to meet the previously stated goal, this study evaluated three pairs of mined and unmined watersheds using a novel method of mining permit history characterization to assess for any statistically significant trends within long-term hydrologic metrics and any significant correlation between hydrologic metrics and corresponding watershed mining permit history. Watersheds located within West Virginia, a state in north-eastern United States, were chosen due to the extensive surface mining activity across the southern region of the state.

To answer major research gaps noted in previous sections, the overarching research question was as follows: What is the impact of SFM/VF on both large-scale watersheds and long-term hydrologic flow? Building from this question, four research objectives were undertaken: (1) Build comprehensive mining permit datasets for three sets of paired watersheds, (2) Evaluate long-term hydrologic metrics, (3) Identify significant trends within each flow metric, and (4) Identify significant correlations between flow metrics and mining permit history.

2 STUDY REGIONS

This section consists of the six selected watersheds from Section 4.2. West Virginia, located in the Appalachian region of the United States, is shown in Figure 1 and gives a top-level view of the watersheds being studied and their locations relative to each other. Each figure in the study region section (e.g. Figure 2) shows the cumulative mining in the watershed that was used for analysis in this study. Each of the 6 watersheds are discussed in detail in the following subsections, 2.1 to 2.6.

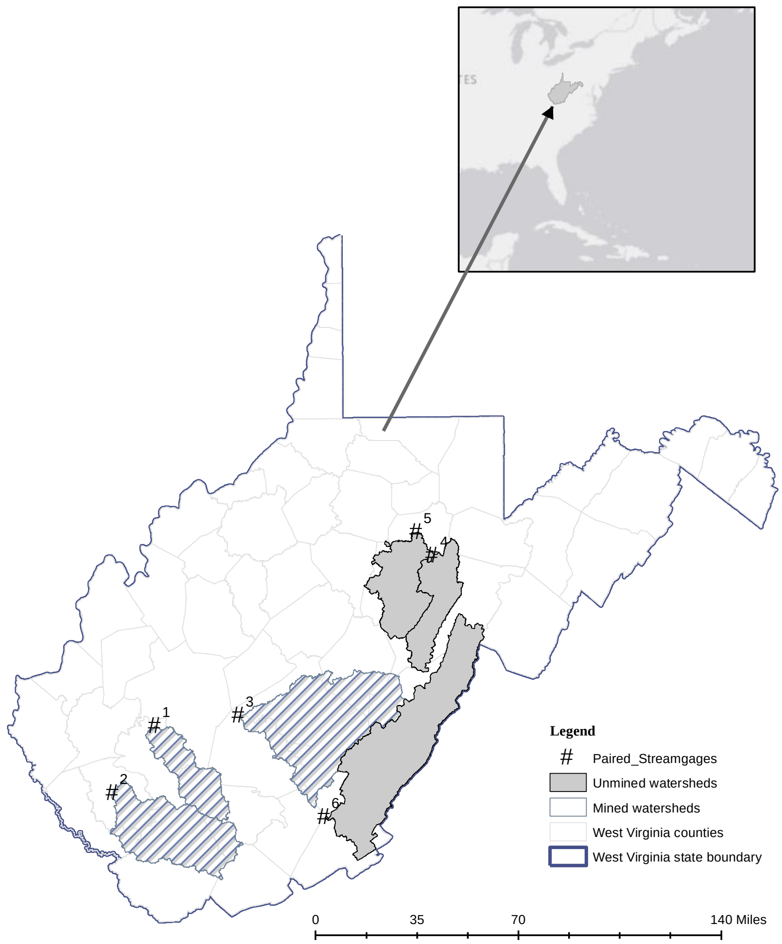

Figure 1 West Virginia and paired watersheds: Mined; (1) Big Coal River at Ashford; (2) Guyandotte River at Logan; (3) Gauley River Above Belva; Unmined; (4) Tygart Valley River at Belington; (5) Tygart Valley River at Philippi; (6) Greenbrier River at Alderson.

2.1 USGS 3198500 Big Coal River at Ashford, WV

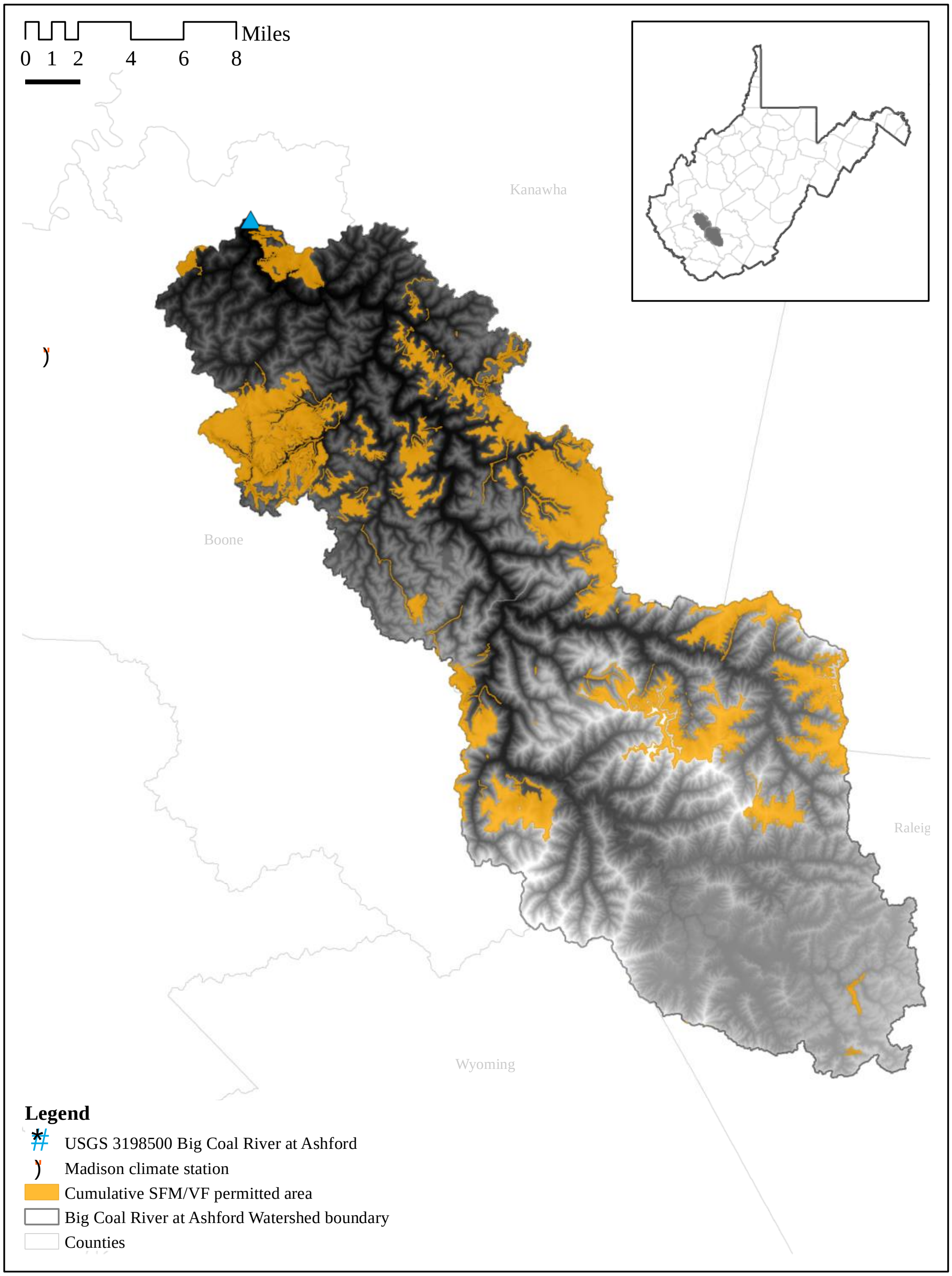

Figure 2 USGS 3198500 Big Coal River at Ashford, WV

Located in the far south-western region of West Virginia, Big Coal River watershed covers an area of 390 square miles, draining south to north, with an elevation ranging from 620 ft to 3556 ft and an average elevation of 1736 ft. This study calculated that a cumulative 14.88% of Big Coal River has been legally permitted for SFM/VF as of 2018. Big Coal River watershed is underlain by sedimentary sandstone (Cardwell *et al.*, 1968). The headwaters of the Big Coal River watershed are primarily flood plains that turn into steep, mountainous terrain with narrow valley floors that become mountainous plateaus in the northern half of the watershed. The southern flood plains have a moderately deep soil with poor drainage and permeability (8). The rest of the watershed is generally deep and well drained. Big Coal River is humid subtropical with no dry season but may have warm summers in the southern headwaters (11).

2.2 USGS 3203600 Guyandotte River at Logan, WV

Guyandotte River Watershed is located in the far south-western region of West Virginia and covers an area of 833 square miles, draining from east to west. This study found a cumulative 7.74% of Guyandotte River watershed has been legally permitted for SFM/VF as of 2018. Guyandotte River watershed is primarily humid subtropical with no dry season and a temperate oceanic climate along the easternmost headwaters of the watershed (16). Guyandotte River watershed has largely mountainous terrain with steep slopes and narrow valley floors, and an elevation ranging from 607 ft to 3560 ft with an average elevation of 1880 ft. The watershed consists of sedimentary sandstone, along with siltstone and coal (Cardwell *et al.*, 1968). Higher elevation soils are generally shallow and poorly drained, and generally acidic alluvium is found on the flood plains and valley floors (Ehlke *et al.*, 1983).

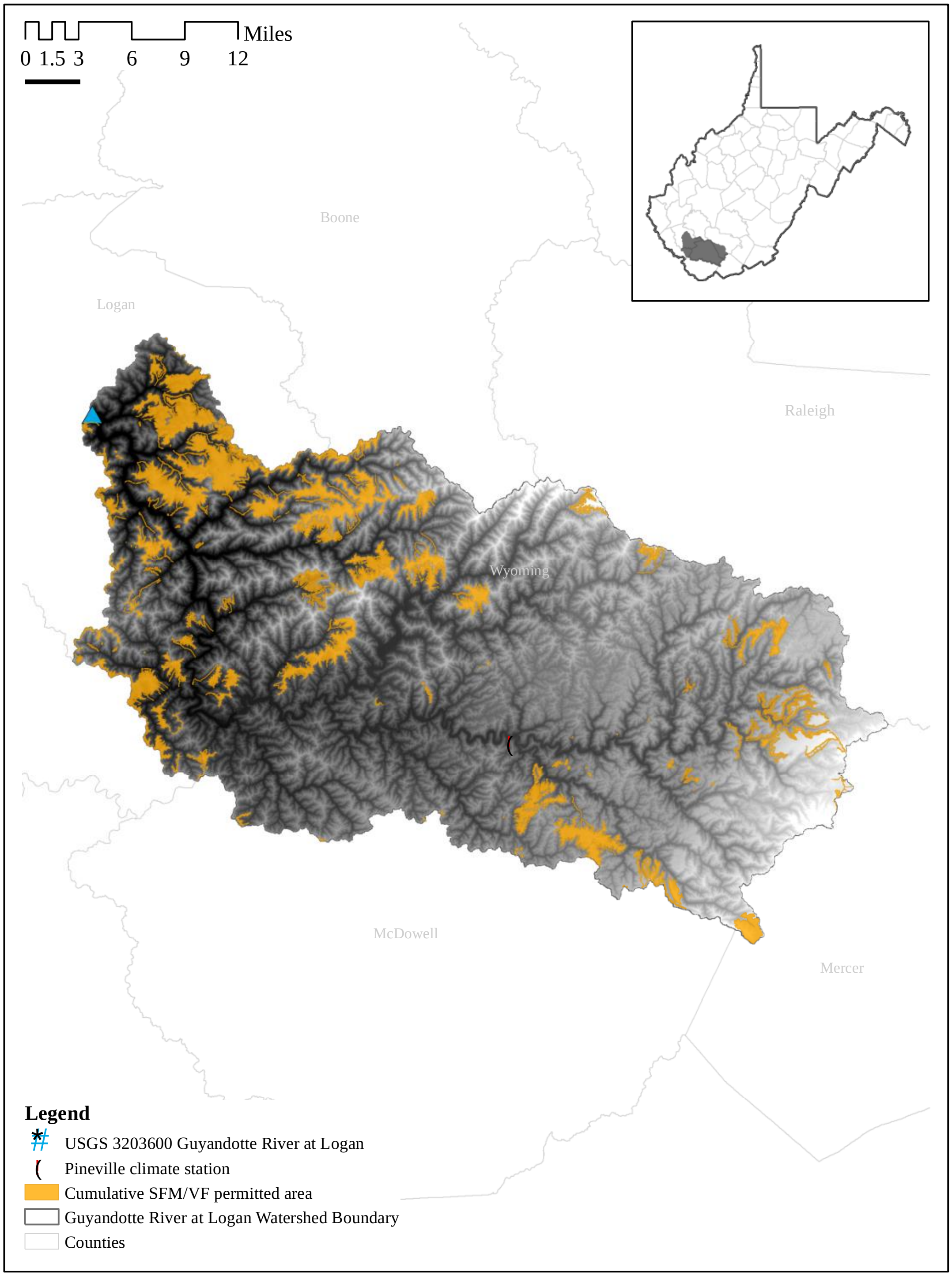

Figure 3 USGS 3203600 Guyandotte River at Logan, WV

2.3 USGS 3192000 Gauley River Above Belva, WV

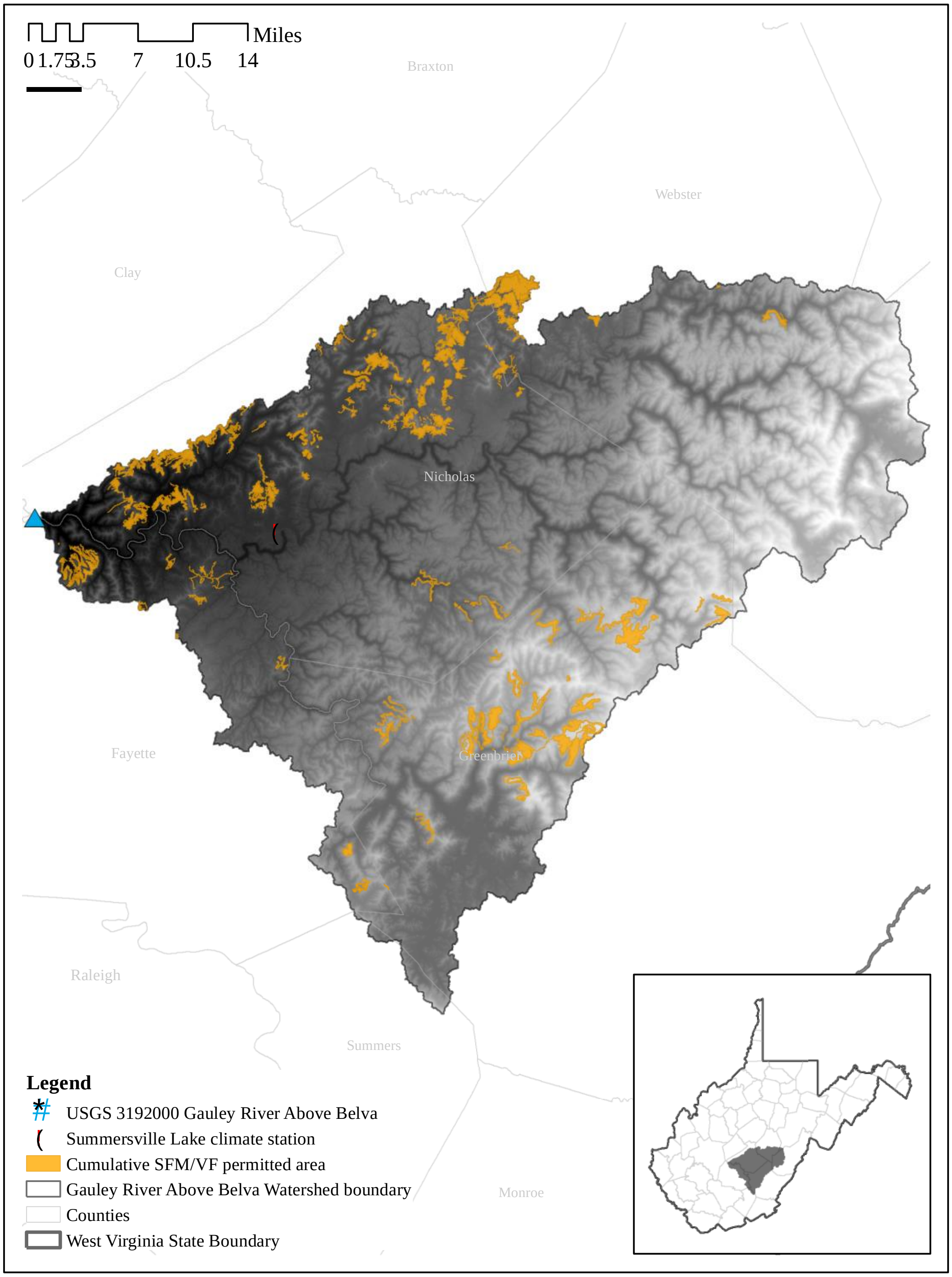

Figure 4 USGS 3192000 Gauley River Above Belva, WV

Gauley River Watershed is located in the south-eastern region of West Virginia and drains an area of 1315 square miles. Elevation ranges from 673 ft to 4708 ft with an average elevation of 2720 ft. Streamflow drains from the high, mountainous eastern region and less mountainous low plains of the southern region, into the north-west. This study calculated that a cumulative 3.19% of the watershed has been legally permitted for SFM/VF as of 2018. Gauley River watershed primarily consists of steep slopes and poorly drained, shallow soils with high potential for erosion (Ehlke *et al.*, 1982). Gauley River Watershed is humid continental with warm summers and cold winters (2).

2.4 USGS 3051000 Tygart Valley River at Belington

The watershed draining into USGS 3051000 will be referred to as the Belington watershed and is located in the mid north-east region of West Virginia in the Appalachian Plateaus. The Belington watershed covers an area of 415 square miles, draining south to north. The Belington watershed has an elevation ranging from 1690 ft to 4764 ft with an average elevation of 2552 ft. This study found the Belington watershed to have a cumulative 0.19% area that has been legally permitted for SFM/VF as of 2018. The Belington watershed consists of sedimentary bedrock and is defined by a distinctive floodplain bisecting almost the full length of the watershed. Soils range from well drained, moderately deep soil in the uplands and slopes, to poorly drained flood plains, and moderately well drained silt loam in river valleys (8). Tygart Valley watershed is humid continental with warm summers (9).

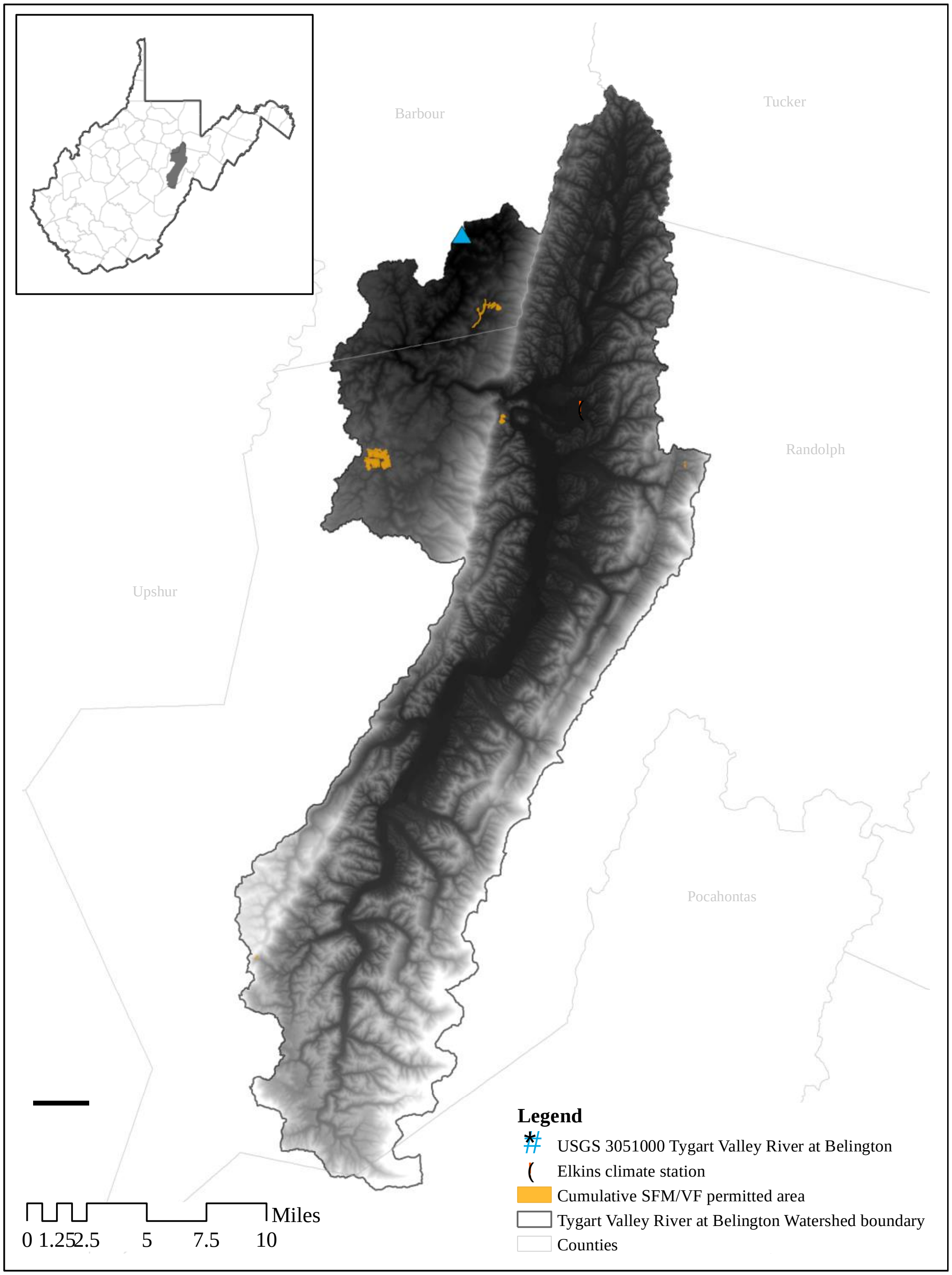

Figure 5 USGS 3051000 Tygart Valley River at Belington, WV

2.5 USGS 3054500 Tygart Valley River at Philippi, WV

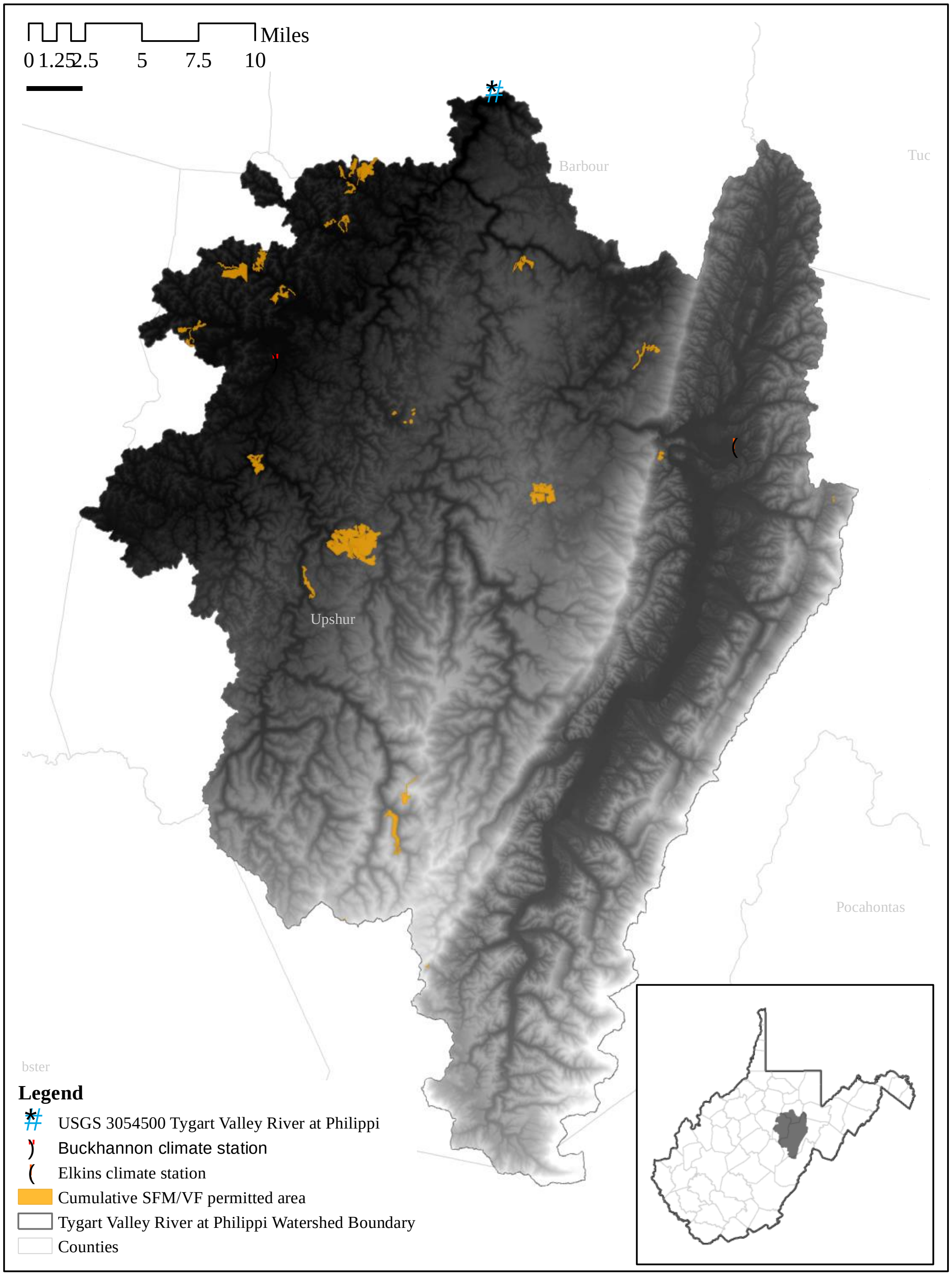

Figure 6 USGS 3054500 Tygart Valley River at Philippi, WV

The watershed draining into USGS 3054500 will be referred to as the Philippi watershed and is in the north-eastern region of West Virginia. The Philippi watershed includes the Belington watershed used in this study (USGS 3051000) and drains an area of 918 square miles. Watershed elevation ranges from 1286 ft to 4767 ft with an average elevation of 2326 ft. In this study a cumulative 0.61% of the Philippi watershed was calculated to have been legally permitted for SFM/VF as of 2018. Philippi watershed is located in the Appalachian Plateaus province. The western half of Philippi is primarily sandstone and shale, while the eastern side consists of shale, alluvium, and sandstone (Cardwell *et al.*, 1968). Soils generally range from moderately deep to deep, and are well drained (8). The Philippi watershed climate is generally temperate and becomes more humid as the elevation lowers into floodplains in the west (9; 18).

2.6 USGS 3183500 Greenbrier River at Alderson, WV

Greenbrier River Watershed is located along the south-eastern edge of West Virginia, draining from north to south an area of 1384 square miles. Watershed elevation ranges from 1532 ft to 4852 ft with an average elevation of 2733 ft. This study calculated that a cumulative 0.01% of the Greenbrier River watershed has been legally permitted for SFM/VF as of 2018. The Greenbrier Watershed is divided by the Valley and Ridge province, consisting mostly of shale and limestone (Cardwell *et al.*, 1968). The oldest regions such as along mountain ridges and side slopes tend towards well-drained stony soils, surrounded by more shallow but well-drained soil, with a range of permeability across the watershed (8). The Greenbrier watershed is primarily humid continental with warm summers and cold winters (1; 14).

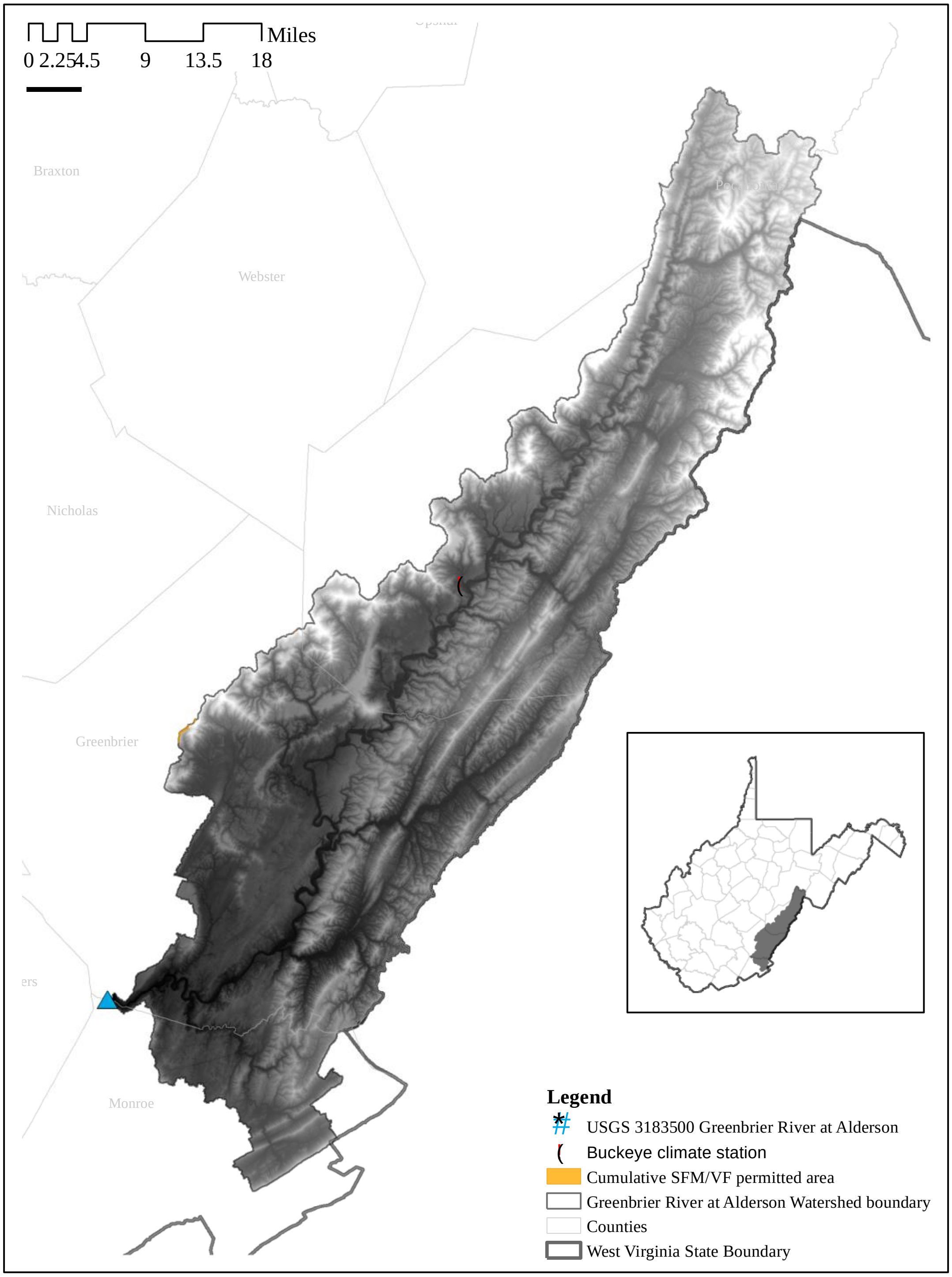

Figure 7 USGS 3183500 Greenbrier River at Alderson, WV

3 METHODS

3.1 Preliminary characterization of streamgages for pairing

A broad initial query was made of the USGS database for streamgages located within West Virginia based on having a minimum and consistent 30-year daily flow period of record. This quantity of daily flow data was chosen for the initial query to obtain streamgage data with daily flow observations occurring pre-mining, during mining and post-mining. Further constraints were then applied to reduce the number of candidate gages for hydrologic analysis and to refine the quality of potential streamflow data: (1) Minimum of 10000 observations of daily flow, (2) Daily flow must fall into a date range of January 1st, 1970 and November 1st, 2018, and (3) Daily flow must have no more than a maximum 30 consecutive days missing from the observations. Once the first constraint was applied, streamgages were evaluated using the second and third constraint for daily flow data listed above.

3.2 Refinement of characterization

Digital Elevation Models (DEMs) covering the West Virginia Appalachians were acquired for the remaining streamgage candidates to delineate catchment basins using streamgages as the pour point (https://viewer.nationalmap.gov/basic/). These DEM derived watersheds along with mining and valley fill permit boundaries were used to determine percent of legally permitted mining and valley fill for each watershed (WVDEP, http://tagis.dep.wv.gov/home/Downloads).

3.3 Calculating watershed permit areas

The mining layers shown in Section 2 Study Regions are derived from mining and valley fill permits acquired from the West Virginia Department of Environmental Protection (WVDEP) after having undergone the steps that will be described in this section, and these layers depict cumulative legally permitted SFM/VF as of the end of 2018. Mining permits and valley fill permits provided by the WVDEP were used to calculate the cumulative legally permitted mining area for each watershed. Mining permits are vulnerable to human error and do not accurately describe the true beginning and end period of mining activity, only the legally permissible time period they may occur. Permits may be explicitly identified as surface mining based on the permit identification (S at the beginning of the PERMIT_ID; S301496), but surface mining may occur within an area permitted under a different permit identification code (e.g. O504293). Additionally, Valley Fill permits may have permit identifiers beginning with a U (e.g. U002685), which is understood to denote an underground mine. After careful consideration of permit records and comparing the landscape over time in watersheds, it was concluded that valley fill permits with 'U' in the permit identifier would still be considered valley fill as this study focused on the VF itself rather than the source of VF material.

To address the complexity of mining permits a set of four distinct permutations of mining permits were devised to describe maximum to minimum possible legally permitted mining area over time within each watershed. These four permutations of mining permits allow us to approximate those permits not specifically evaluated for this study. The following four permutations were calculated for each of the watersheds:

1. Area of all mining permits and valley fill permits.
2. Area of all mining permits including valley fill, but not including 'not started'/'NS'.
3. Area of all surface mining permits, including valley fill permits.
4. Area of all surface mining permits and valley fill permits, not including 'not started'/'NS'.

As this study focused on surface mining and valley fill, Permutation 4 was converted into a percentage of area for each watershed to provide a method of ranking SFM/VF permitted area for the eventual pairing of watersheds. All four permutations of permits were then averaged, and this average turned into a percent of the amount of area legally permitted to be disturbed by any given permit within each catchment basin. The Permutation 4 percentage value of SFM/VF disturbance and percentage value of the average of Permutations 1-4 were then statistically compared using Spearman's *rho*. Only SFM and VF permits active to the end of 2018 were evaluated for the purposes of this study.

3.4 Creating paired watersheds

If cumulative legally permitted area for SFM/VF in a watershed was greater than 3% of watershed area, then this watershed was considered a candidate for being a mined watershed to pair with an unmined watershed. Watersheds that crossed over the West Virginia border were removed as an option for pairing due to lack of available permit data for outside states. Once watersheds considered highly disturbed were chosen, the drainage area of these watersheds was then ranked for pairing highly disturbed catchments with those of similar size but with less than 1% mining disturbance.

3.5 Compiling mining history timeseries

A comprehensive time series of mining permit history was developed for each watershed based on the results of Section 3.3. Mining permit history time series analysis used each year of recorded permits within each watershed by considering the time period from issue date to expiration date for each surface mine permit and the epoch of each VF permit.

VF permits are treated differently from MTM permits as they are not issued in the same way as other mining permits. VF permits are issued without distinct issue-and-expiration dates that can be marked as clear periods of activity. VF permits consider the VF within an 'epoch' and permits are given a specific set of epochs; 1984; 1990; 1996; 2003; 2009; 2011; 2012. For this study if a valley fill permit epoch was 1984 the area of the permit was considered active from 1984 to the next listed epoch year. If a surface mine permit was issued and/or active before December 31st of a given year then the area was used for that year. Evaluating SFM and VF permits cumulatively would not have considered remediation work or potential recovery over time. Annual mining permit time series for each watershed was then transformed from square miles into a percentage of the area of the watershed for each year for each watershed.

3.6 Annual metrics and statistical analysis

The annual hydrologic metrics used for analysis were a) average annual streamflow (Q_{avg}), b) annual minimum daily streamflow (Q_{min}), c) annual maximum daily streamflow (Q_{max}), d) annual 25th percentile (Q_{25}), e) annual 75th percentile (Q_{75}) and f) annual interquartile range (Q_{IQR}). If any observation days were missing data, an average of the previous day and the next day was used in its place. These six hydrologic flow metrics were chosen to more closely replicate results of Zégre *et al.* (2014). In order to use complete years of recorded hydrologic flow data the following constraints were applied to each streamgage in addition to the previously mentioned constraints from Section 3.1:

1. Only hydrologic flow data starting on the first of the year was used
2. When hydrologic flow data does not begin at the beginning of the year, we start at the beginning of the first full year

Each of the 6 watersheds were evaluated for: 1) trends in clear directionality in flow over time, 2) differences or similarities in flow metrics between each pair, 3) any significant correlation between hydrologic metric and mining permit history. Precipitation for the 1963-2018 period was acquired from the National Oceanic and Atmospheric Administration (NOAA) and used to create simple runoff ratios (Q/P) for annual total flow in each watershed. These annual runoff ratios were compared with cumulative annual mining permits for each watershed.

The Mann-Whitney U test was performed on annual hydrologic metrics to evaluate the hydrologic metrics between each watershed pair using the null hypothesis that distribution of metrics would be equal between pairs using a significance level of $p \geq 0.05$. The Mann-Whitney U test allowed for any differences in normality between metrics of each pair as some metrics could be normally distributed for one watershed in the pair but not the other. Kendall′s tau-b was used to test annual values for trends over time for hydrologic metrics within each watershed using a significance level of $p \geq 0.05$. Kendall′s tau-b was also used to test for any significant trends over time for the runoff ratio noted previous. Pearson r correlation test using a significance level of $p \geq 0.05$ was performed on annual hydrologic metrics and mining permit history for each watershed to test for any significant correlation between both metrics.

4 RESULTS

4.1 Characterization of streamgages and watersheds

The initial query of streamgages in West Virginia for a minimum of 10000 daily flow observations resulted in 101 streamgages. Further constraints as described in Section 3.1 were then applied to both reduce the number of candidates and refine the quality of the potential streamflow for analysis. The data constraints described in 3.1 as well as the data limitations described in Section 3.2 resulted in 20 streamgages, illustrated in Figure 8. The four permutations of SFM/VF permit area were then developed to characterize the mining history of each of the 20 watersheds (Table 1). Using Spearman′s *rho* to test for correlation between Permutation 4 as a percentage and an average of Permutations 1 through 4 transformed into a percentage found a significant correlation at *r* = 0.952 respectively with a p value of 0.00. Permutation 4 (all surface mine and valley fill permits minus those marked as not yet begun) was deemed appropriately representative of mining disturbance in each watershed, while maintaining an approximation of permits not within the scope of the study and so was used for the rest of the study.

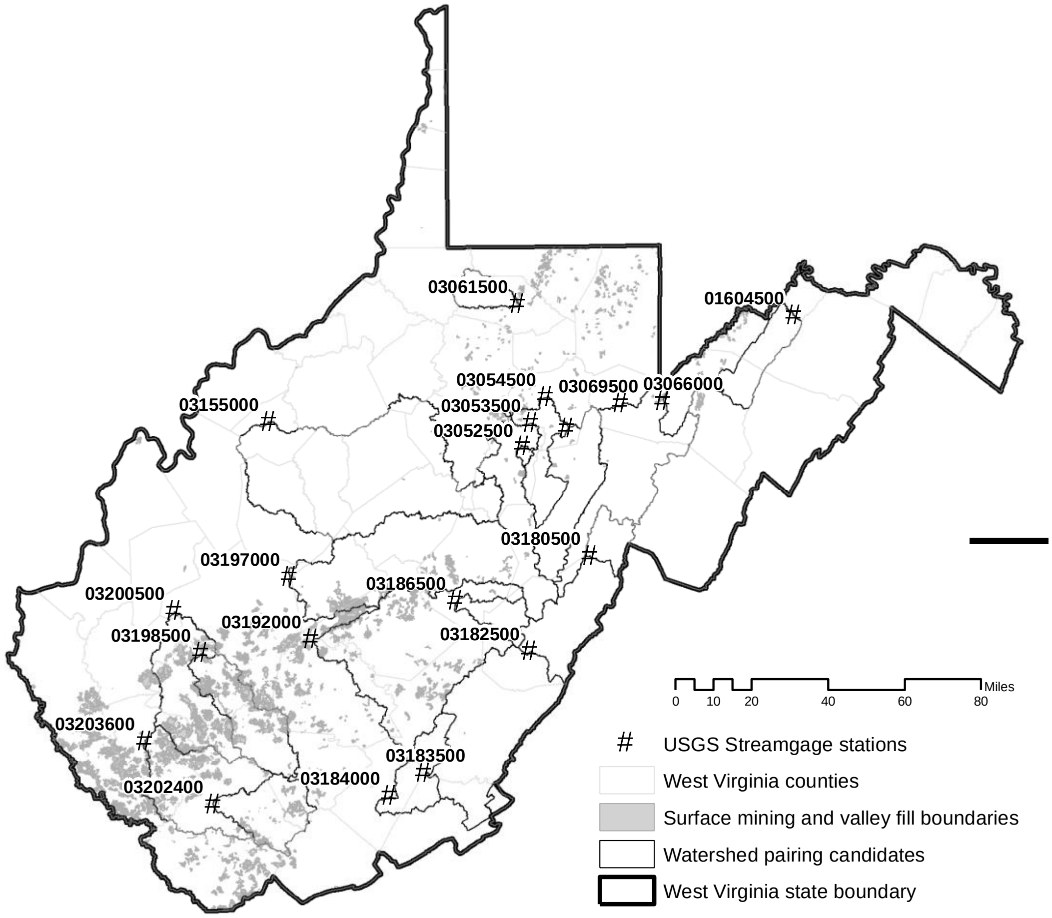

Figure 8 West Virginia and pairing candidates (20 streamgage/watersheds).

Table 1 Final streamgage/watershed pairing candidates. Permutation 1 - All mining and valley fill permits; Permutation 2 - All mining and valley fill permits not started as of 2018 are removed from Permutation 1; Permutation 3 - All surface mine and valley fill permits; Permutation 4 - All surface mine and valley fill permits not started as of 2018 are removed from Permutation 3

USGS Number	STREAM GAGE NAME	Watershed Area (mi²)	Permutation 1 (mi²)	Permutation 2 (mi²)	Permutation 3 (mi²)	Permutation 4 (mi²)	Mining % (Perm. 4)
1604500	PATTERSON CREEK NEAR HEADSVILLE, WV	221.11	0.68	0.68	0.00	0.00	0.00
3051000	TYGART VALLEY RIVER AT BELINGTON, WV	414.68	2.58	2.19	1.06	0.79	0.19
3052500	SAND RUN NEAR BUCKHANNON, WV	14.26	0.05	0.05	0.04	0.04	0.28
3053500	BUCKHANNON RIVER AT HALL, WV	276.76	5.77	5.76	3.74	3.74	1.35
3054500	TYGART VALLEY RIVER AT PHILIPPI, WV	917.84	10.95	10.54	5.88	5.56	0.61
3061500	BUFFALO CREEK AT BARRACKVILLE, WV	115.74	2.83	2.83	0.19	0.19	0.16
3066000	BLACKWATER RIVER AT DAVIS, WV	85.75	1.56	1.32	0.62	0.62	0.73
3069500	CHEAT RIVER NEAR PARSONS, WV	717.46	4.19	3.95	1.93	1.90	0.26
3155000	LITTLE KANAWHA RIVER AT PALESTINE, WV	1514.15	0.21	0.21	0.13	0.13	0.01
3180500	GREENBRIER RIVER AT DURBIN, WV	133.03	0.00	0.00	0.00	0.00	0.00
3182500	GREENBRIER RIVER AT BUCKEYE, WV	539.31	0.04	0.04	0.00	0.00	0.00
3183500	GREENBRIER RIVER AT ALDERSON, WV	1384.45	1.53	1.53	0.21	0.17	0.01
3184000	GREENBRIER RIVER AT HILLDALE, WV	1619.58	2.00	2.00	0.21	0.17	0.01
3186500	WILLIAMS RIVER AT DYER, WV	127.49	0.00	0.00	0.00	0.00	0.00
3192000	GAULEY RIVER ABOVE BELVA, WV	1314.90	53.00	50.70	44.16	41.98	3.19
3197000	ELK RIVER AT QUEEN SHOALS, WV	1143.68	39.97	37.97	33.41	32.53	2.84
3198500	BIG COAL RIVER AT ASHFORD, WV	390.44	70.90	70.45	59.10	58.12	14.88
3200500	COAL RIVER AT TORNADO, WV	858.07	170.04	163.72	143.86	137.95	16.08
3202400	GUYANDOTTE RIVER NEAR BAILEYSVILLE, WV	307.10	13.18	12.07	13.18	12.07	3.93
3203600	GUYANDOTTE RIVER AT LOGAN, WV	832.82	86.30	82.10	67.56	64.50	7.74

4.2 Pairing of watersheds

Five watersheds experienced greater than 3% cumulative mining permitted area and therefore were considered mined for this study. Of these five watersheds, three were successfully paired with watersheds that met two requirements: The watershed 1) had less than 1% cumulative mining permitted area and 2) was of reasonably similar size. This pairing resulted in 6 watersheds divided into 3 pairs (mined versus unmined) (Table 2, Figure 1).

Figures 9, 10 and 11 illustrate the contextual relationship between mining permit permutations 1 through 4 as calculated in Section 4.1 for each of the six final paired watersheds. Figure 11 illustrates the potential unaccounted mining permitted area within each of the final six watersheds.

Table 2 Final 6 streamgages chosen for pairing.

Study Number	USGS Number	Streamgage name	Mining Percent	Watershed Area (mi²)	Streamflow date range
1	3198500	BIG COAL RIVER AT ASHFORD, WV	14.88	390.44	1931-2018
4	3051000	TYGART VALLEY RIVER AT BELINGTON, WV	0.19	414.68	1908-2018
2	3203600	GUYANDOTTE RIVER AT LOGAN, WV	7.74	832.82	1963-2018
5	1608500	TYGART VALLEY RIVER AT PHILIPPI, WV	0.61	917.84	1941-2018
3	3192000	GAULEY RIVER ABOVE BELVA, WV	3.19	1314.90	1929-2018
6	3183500	GREENBRIER RIVER AT ALDERSON, WV	0.01	1384.45	1896-2018

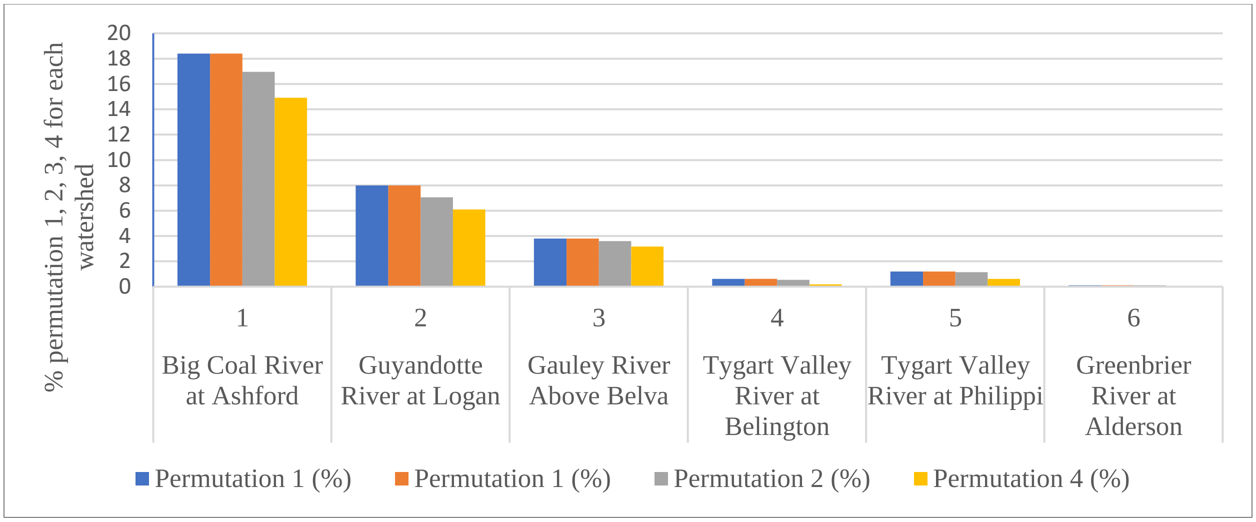

Figure 9 Watershed mining permit permutations 1, 2, 3 and 4 for each paired watershed. Mined 1 - Big Coal River at Ashford, Mined 2 - Guyandotte River at Logan, Mined 3 - Gauley River Above Belva, Unmined 1 - Tygart Valley River at Belington, Unmined 2 – Tygart Valley River at Philippi; Unmined 3 – Greenbrier River at Alderson.

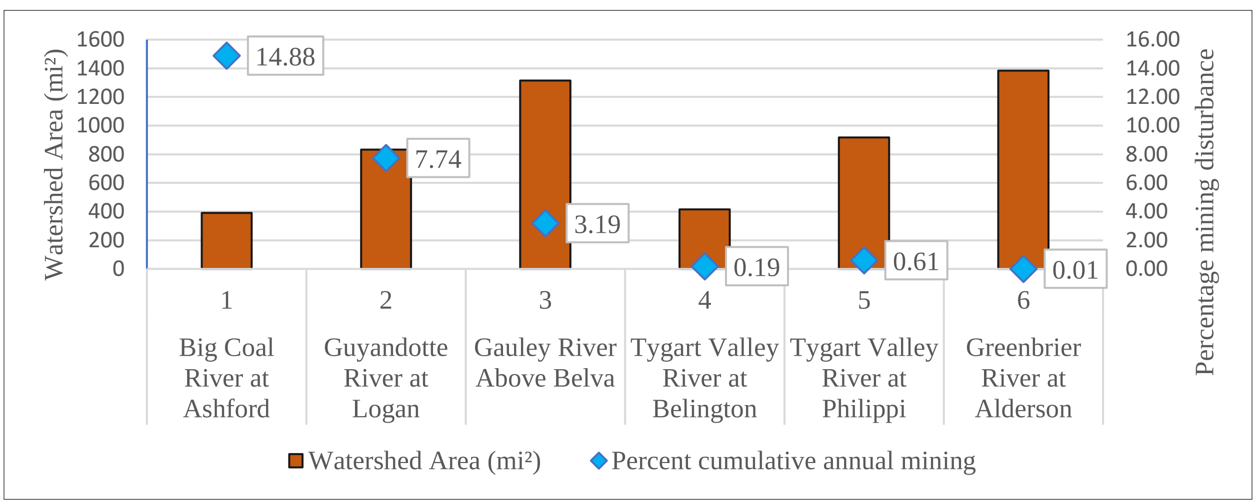

Figure 10 Mining percentage versus watershed area (square miles).

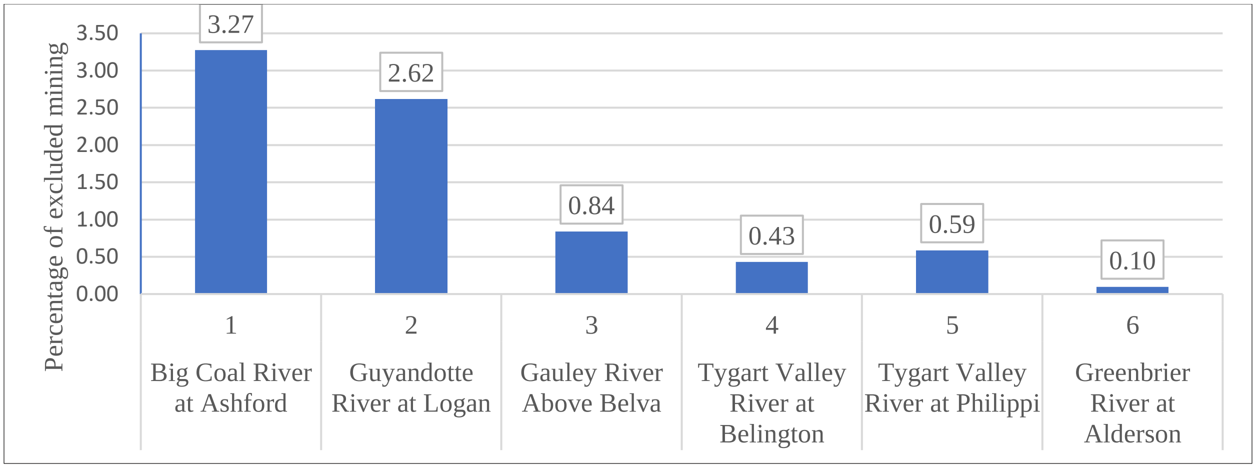

Figure 11 Unaccounted cumulative mining permitted area within each paired watershed (percentage).

4.3 Mining permit history timeseries

As can be seen in Figure 12, the mined watersheds experienced similar growth in area permitted for mining beginning in the early 1970's until diverging in the early 1990's. Big Coal River experienced a dramatic increase in mining permitted area in the 1990's and continued to increase with small reductions in mining in 2002 and 2011, until seeing a sharp drop in mining between 2017 and 2018. Guyandotte River experienced around half as much active mining permitted area as Big Coal River, reaching around 5% mining in 2001 and remaining steady until gradually decreasing down to around 4% in 2018. Annual area permitted for mining remained under 1% for Gauley River save for 1986-1997 and 2012-2017 and rose to a high of 1.8% in 1991.

Unmined watersheds remained consistently very low in mining permit area throughout their time series at less than 1% among all three watersheds, which can be seen in their study figures in Section 2 (2.1-2.6).

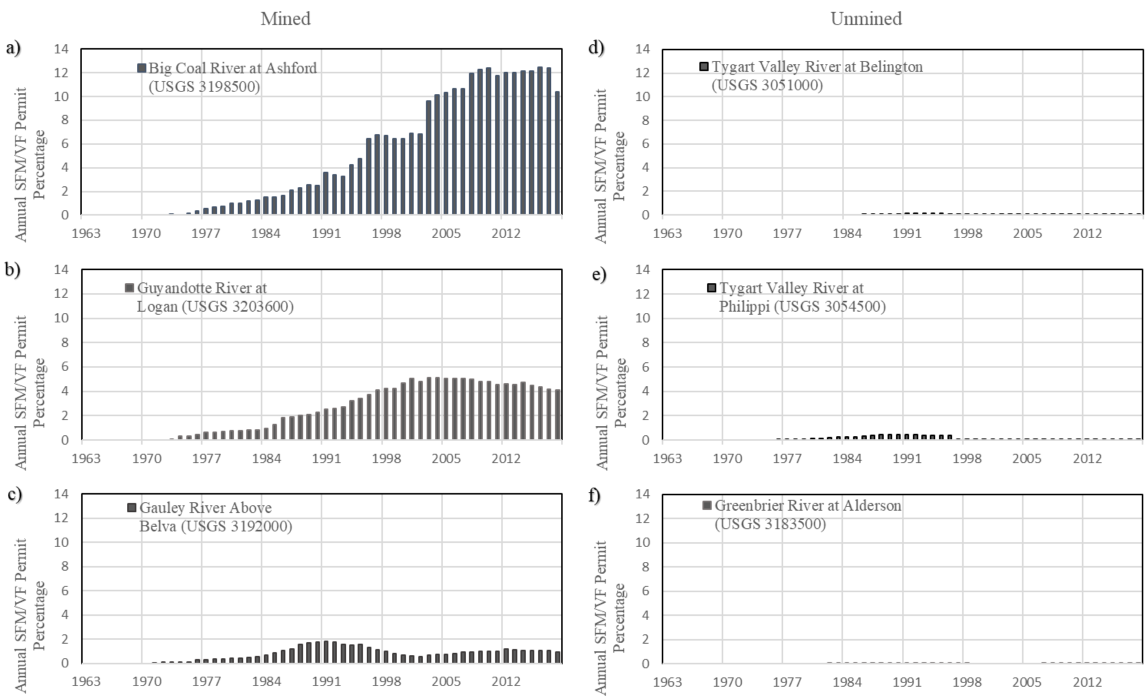

Figure 12 Time-series of mining permit history for mined and unmined watersheds. X axis is years 1963-2018, y axis is percentage of area permitted for mining in watershed. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington, e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4 Annual hydrologic metrics for paired watersheds

The full time series data for Guyandotte River is unavailable and due to this the scope of the data for the five other watersheds was clipped to just the available data for Guyandotte River (1963-2018). This restraint of data by only analyzing hydrologic flow from 1963 to 2018 for each watershed was done to maintain consistency in analysis across watersheds. The complete results without this clipping are available in Appendix A. Six hydrologic flow metrics were created based on the time period restraint of 1963-2018 for each streamgage belonging to each watershed.

1. Average annual streamflow (Q_{avg})
2. Annual Minimum daily streamflow (Q_{min})
3. Annual Maximum daily streamflow (Q_{max})
4. Lower 25th percentile (Q_{25})
5. Lower 75th percentile (Q_{75})
6. Interquartile Range (Q_{IQR})

4.4.1 Average annual daily flow

All six watersheds experienced no significant trends in average annual flow (Table 4).

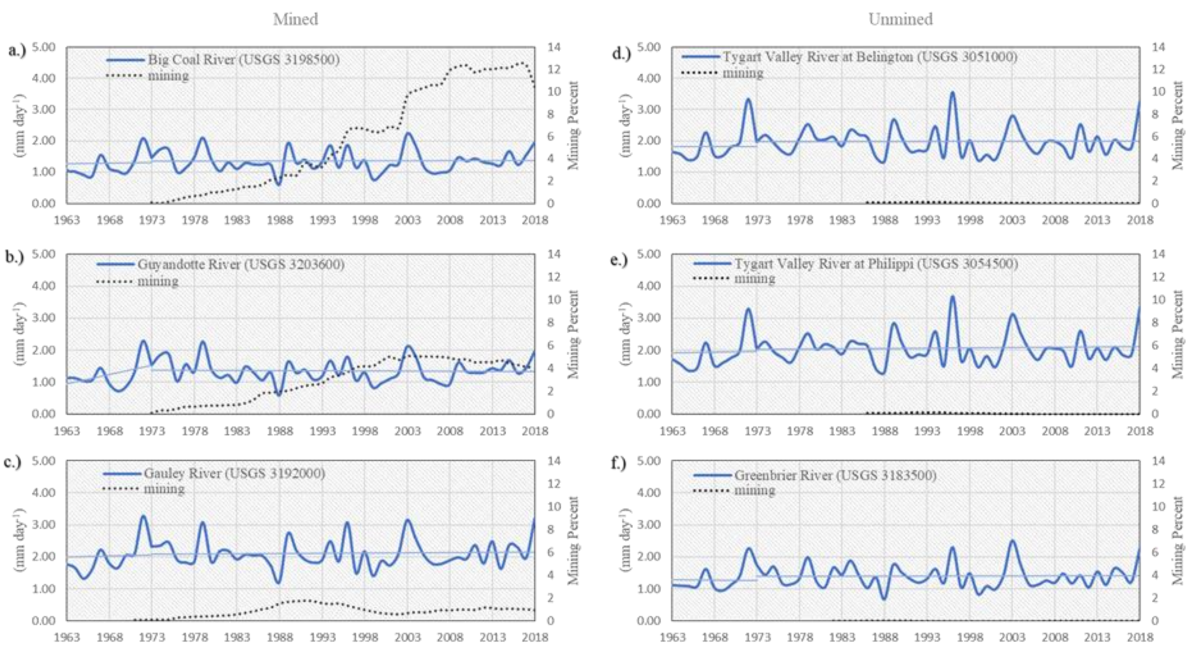

Figure 13 Mined and unmined watersheds average annual daily flow. First column is mined, second column is unmined. Left axis is (mm/day) and right axis shows mining percentage. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington,

e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4.2 Minimum daily flow

Two mined watersheds experienced significant increasing minimum flow (Table 4). Big Coal River experienced a significant increase in minimum flow that appears to have begun pre-1973 and this increasing trend appears to continue to the present (Figure 14, Table 4). Unmined watersheds had no significant trends in minimum flow.

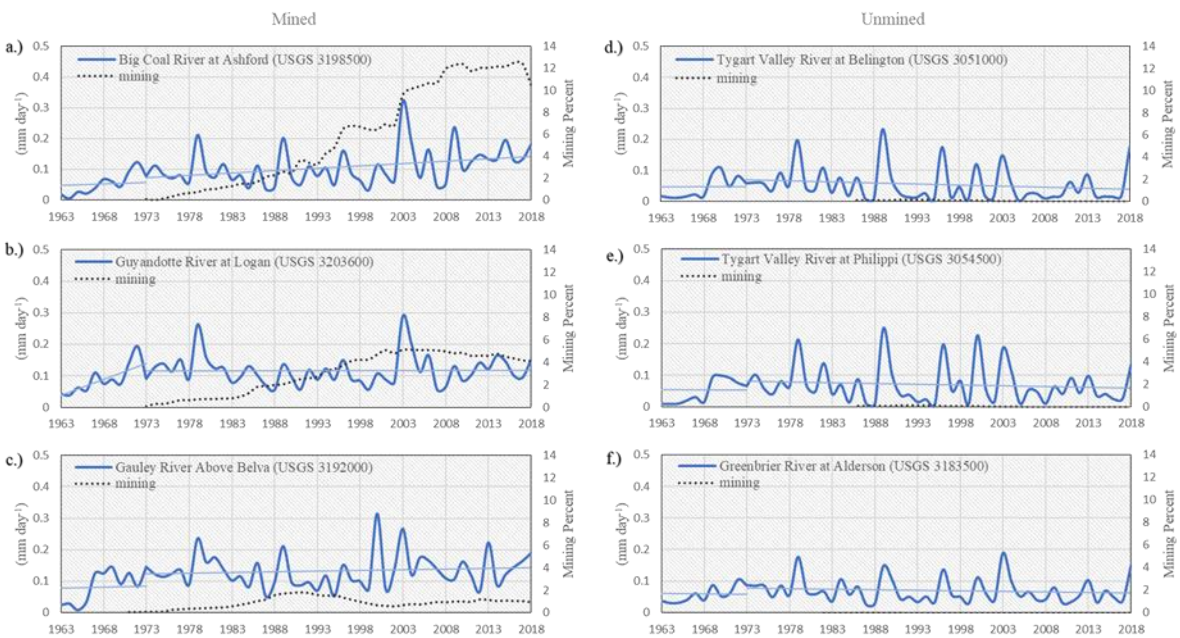

Figure 14 Mined and unmined watersheds annual minimum daily flow. First column is mined, second column is unmined. Left axis is (mm/day) and right axis shows mining percentage. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington, e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4.3 Maximum daily flow

Big Coal River showed significant decreasing maximum flow post-1973 and this appears to have begun in the late 1970's/early 1980's (Figure 15, Table 4). Guyandotte River experienced a significant decreasing maximum flow that begins in the early 1980's and after this change it does not return to pre-1980's levels. Gauley River did not present with any significant changes in maximum flow. Unmined watersheds showed no significant trends in maximum flow.

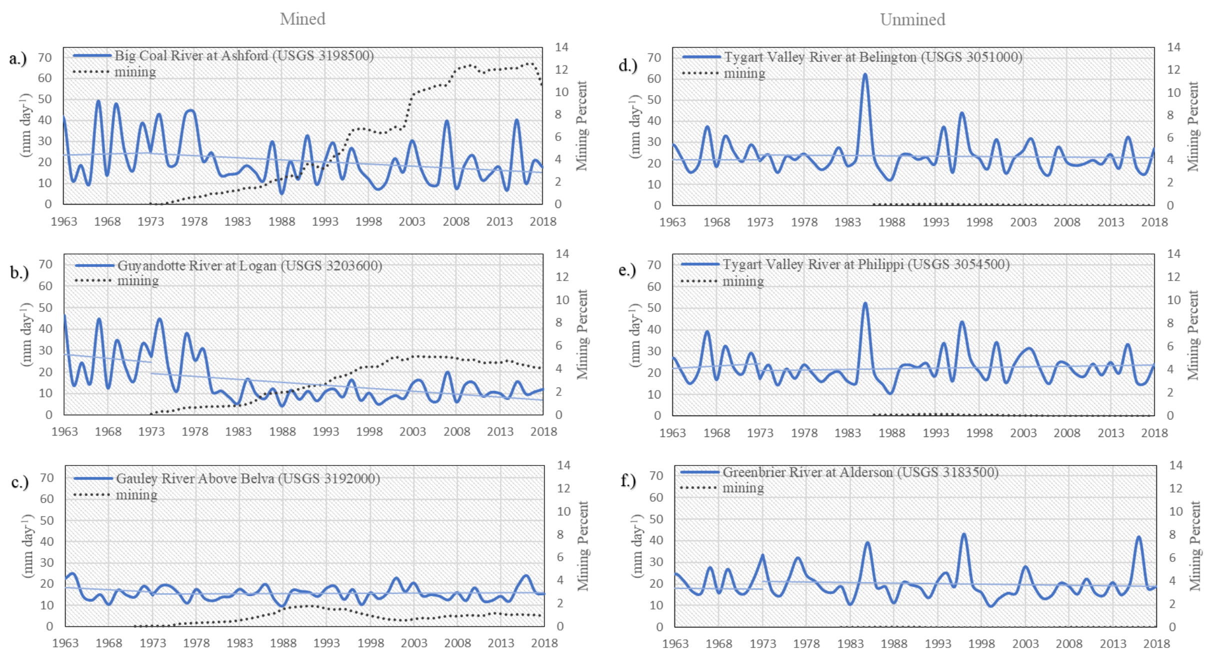

Figure 15 Mined and unmined watersheds annual maximum daily flow. First column is mined, second column is unmined. Left axis is (mm/day) and right axis shows mining percentage. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington, e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4.4 25th percentile

Big Coal River experienced a significant increasing trend in the 25th Percentile (Table 6) from 1963 to 1973, and then a slightly more positive trend from 1973 to 2018 but after 2008 these increasing values do not return to 2007 levels (Figure 16). Guyandotte River had a significant increasing trend in the 25th percentile (Table 4). Unmined watersheds had no significant trends in 25th percentile flow.

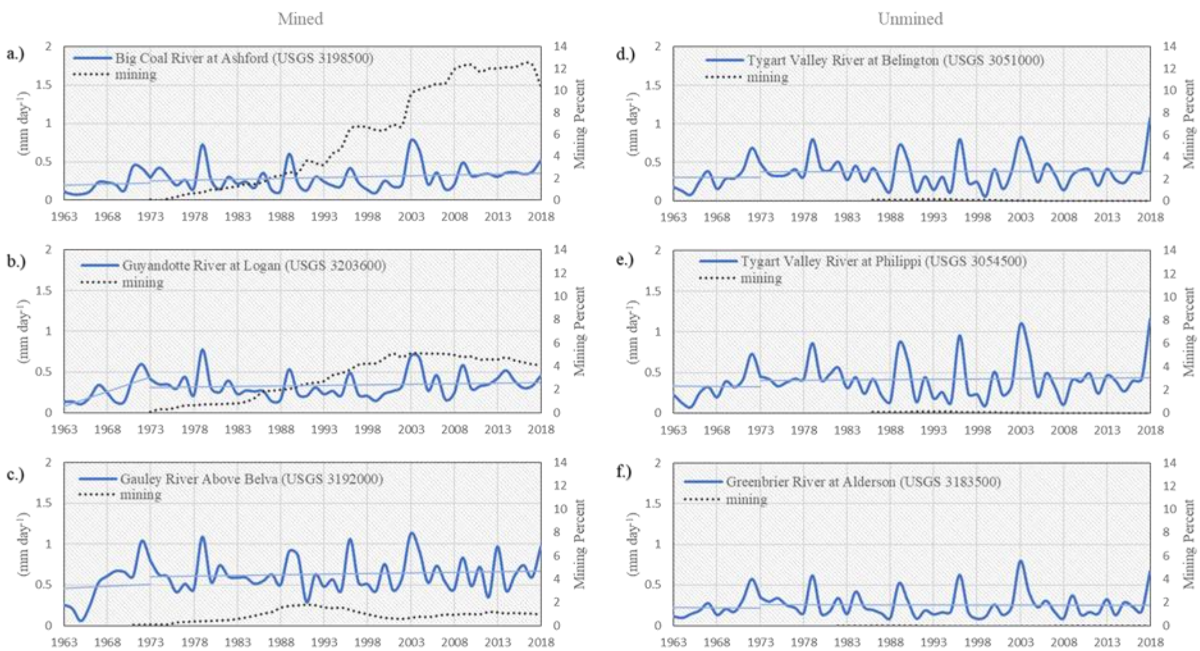

Figure 16 Mined and unmined watersheds annual 25th percentile daily flow. First column is mined, second column is unmined. Left axis is (mm/day) and right axis shows mining percentage. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington, e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4.5 75th percentile

Of the mined watersheds only Big Coal River was found to have a significant positive trend in 75th percentile flow (Table 4). Unmined watersheds had no significant trends in 75th percentile flow.

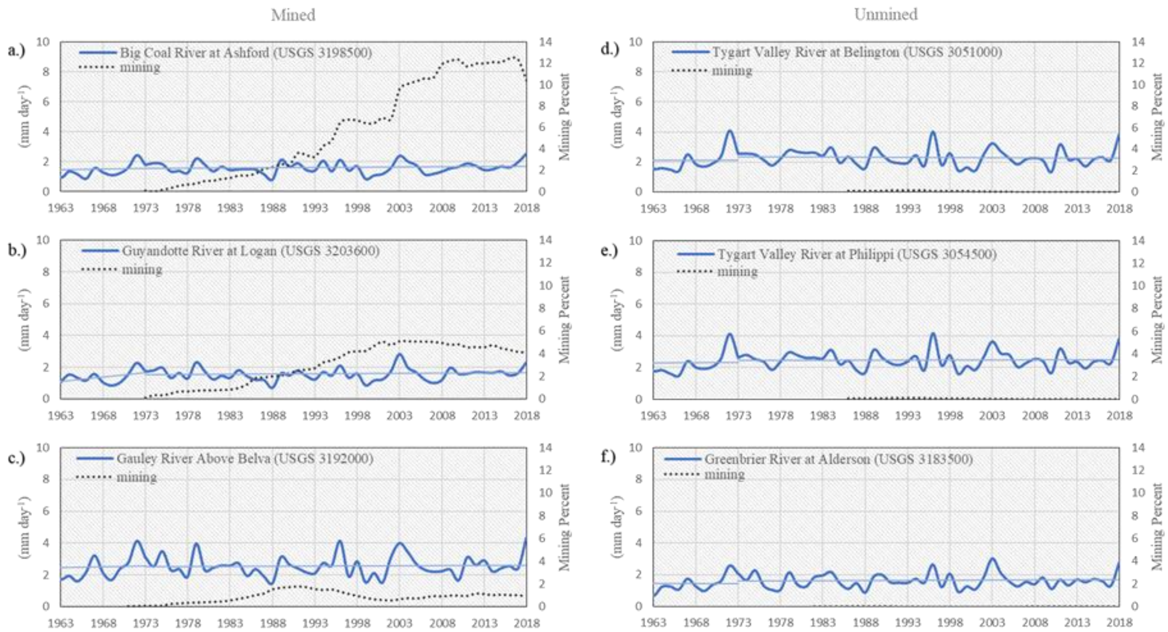

Figure 17 Mined and unmined watersheds annual 75th percentile daily flow. First column is mined, second column is unmined. Left axis is (mm/day) and right axis shows mining percentage. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington, e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4.6 Interquartile

No watershed was found to have a significant trend in interquartile (IQR) flow

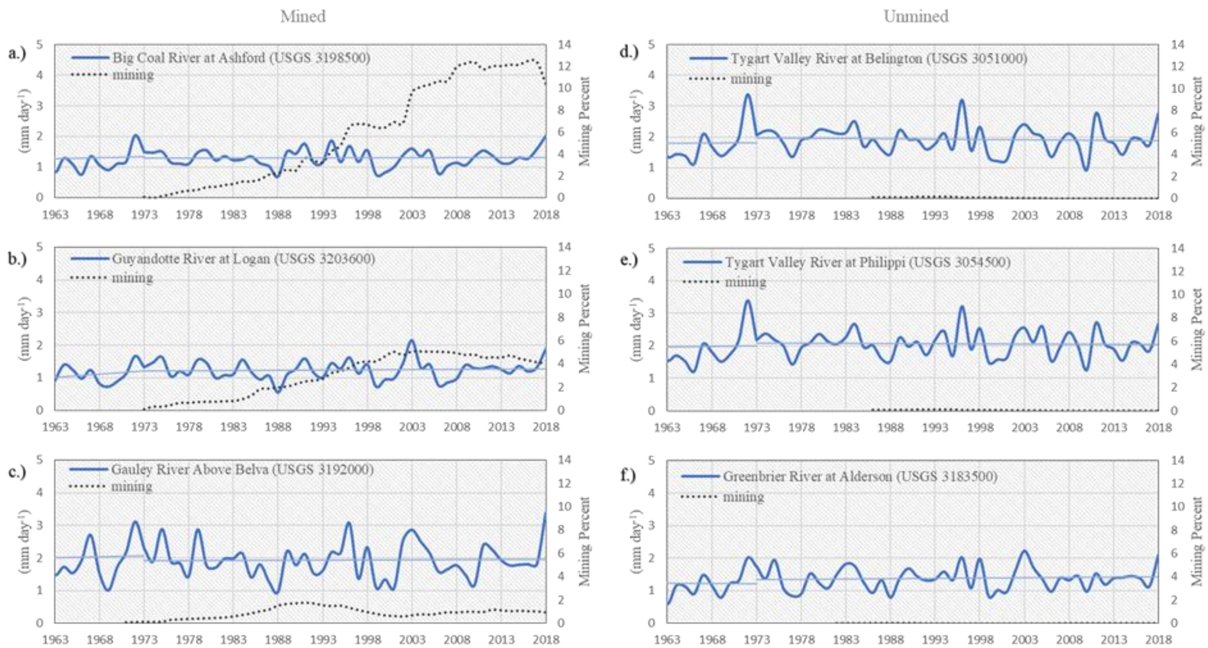

Figure 18 Mined and unmined watersheds annual Interquartile daily flow. First column is mined, second column is unmined. Left axis is (mm/day) and right axis shows mining percentage. a) USGS 3198500 Big Coal River at Ashford, b) USGS 3203600 Guyandotte River at Logan, c) USGS 3192000 Gauley River Above Belva, d) USGS 3051000 Tygart Valley River at Belington, e) USGS 3054500 Tygart Valley River at Philippi, f) USGS 3183500 Greenbrier River at Alderson.

4.4.7 Runoff ratios and mining permit history

The Pearson r correlation test found no significant correlation between Q/P and mining permit history for any watershed.

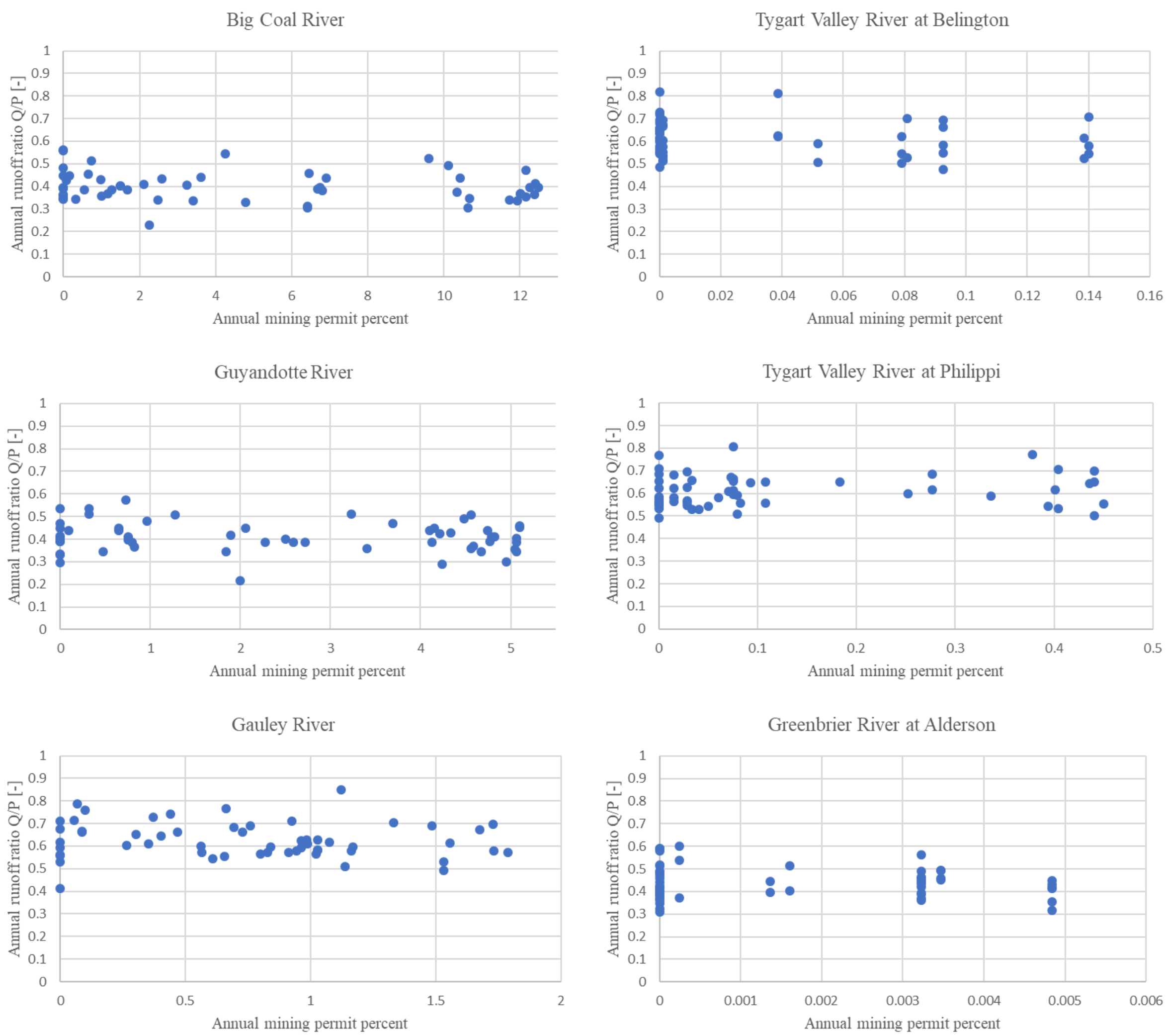

Figure 19 Runoff ratio (Q/P) vs. annual mining permit percentage in each watershed.

4.5 Statistical analysis of paired watersheds

The Mann-Whitney U test (2-tailed, significance at $p < 0.05$) showed both the watershed pair Big Coal River and Tygart Valley River (1&4) and the pair Gauley River and Greenbrier (3&6) had statistically different distributions across all metrics (Table 3). The medium sized pair Guyandotte River and Tygart Valley River at Philippi had a statistically similar distribution for the 25th Percentile at a p value of 0.11 (Table 3). Belington and Philippi both had higher total annual flow than their watershed counterpart, however Gauley had more total annual flow than its reference watershed, Greenbrier. To adjust for precipitation a simple runoff ratio was used for annual total flow in each watershed. Kendall's tau-b (1-tailed) found no statistically significant changes in the runoff ratio of any of the watersheds.

Kendall's tau-b non-parametric test of hydrologic metrics in each watershed for trends over time detected significant trends in flow metrics of several watersheds (Table 4). Big Coal River (Watershed 1) experienced a significant positive trend in minimum flow (r = 0.368), a slightly less significant negative trend in maximum flow (r = -0.19), and significant positive trends in the 25th and 75th percentiles (r = 0.257, r = 0.183). Guyandotte River (Watershed 2) had a significant negative trend in maximum flow (r = -0.336) and a significant positive trend in the 25th percentile (r = 0.224). Gauley River (Watershed 3) had a significant positive trend in minimum flow (r = 0.191). For the unmined watersheds there were no statistically significant trends.

As noted by ** in Table 3, Tygart Valley River at Belington (Unmined, Watershed 4) experienced higher flows than Big Coal River (Mined, Watershed 1), Tygart Valley River at Philippi (Unmined, Watershed 5) had higher flow than Guyandotte River (Mined, Watershed 2) but Gauley River (Mined, Watershed 3) had higher flows than Greenbrier River (Unmined, Watershed 6).

Pearson r correlation test between hydrologic flow metrics and mining for each watershed found significant correlation for hydrologic flow metrics and mining history in two of the mined watersheds (Table 5). Big Coal River had a strong positive correlation between mining and minimum flow with an r value of 0.479** (p value = 0.000) and a strong positive correlation between mining and the 25th percentile with an r value of 0.300* and a p value of 0.025. In the Pearson r correlation test Big Coal River also showed a correlation between maximum flow and mining with an *r* value of -0.263 and a *p* value of 0.05 which was considered significant. Guyandotte River (Table 5) showed a significant negative correlation for mining and its maximum flow with an *r* value of -0.544* (*p* value = 0.000). Gauley River had no significant correlation between hydrologic metrics and mining, however maximum flow, the 75th Percentile, and Interquartile did have negative *r* values.

*Table 3 Mann-Whitney U test values. Comparing hydrologic metrics between each pair. Statistical significance is indicated with * with null hypothesis of similarity between metrics of the watershed pair retained with p < 0.05. ** denotes watershed with higher flow in each pair. 1, 2 and 3 are mined; 4, 5 and 6 are unmined. 1) Big Coal River, 2) Guyandotte River, 3) Gauley River, 4) Tygart Valley River at Belington, 5) Tygart Valley River at Philippi, and 6) Greenbrier River.*

Mann Whitney U test (2-tailed)			
	p value		
Hydrologic metrics	**1 & 4****	**2 & 5****	**3** & 6**
average annual flow	0.00	0.00	0.00
minimum flow	0.00	0.00	0.00
maximum flow	0.01	0.00	0.00
25th Percentile	0.02	0.11*	0.00
75th Percentile	0.00	0.00	0.00
Interquartile	0.00	0.00	0.00
Mining	0.00	0.00	0.00

*Table 4 Kendall's tau-b nonparametric test for hydrologic metric trends in each watershed. Values marked by * are significant at $p < 0.05$. 1) Big Coal River, 2) Guyandotte River, 3) Gauley River, 4) Tygart Valley River at Belington, 5) Tygart Valley River at Philippi, and 6) Greenbrier River.*

Kendall's tau-b nonparametric test for hydrology metrics vs. year						
r values		*mined*			*unmined*	
Hydrologic metrics	**1**	**2**	**3**	**4**	**5**	**6**
average annual flow	0.129	0.095	0.104	0.057	0.104	0.077
minimum flow	0.368**	0.144	0.191*	-0.070	0.010	-0.022
maximum flow	-0.19*	-0.336**	-0.040	-0.087	0.040	-0.107
25th Percentile	0.257**	0.224*	0.111	0.068	0.101	0.023
75th Percentile	0.183*	0.154	0.100	0.054	0.105	0.137
Interquartile	0.123	0.102	0.035	0.047	0.098	0.160

*Table 5 Pearson correlation test for mining history and each hydrologic metric. 2-tailed test using 0.05 significance. Statistically significant values are marked with * at a significance of $p \leq 0.05$. 1) Big Coal River, 2) Guyandotte River, 3) Gauley River, 4) Tygart Valley River at Belington, 5) Tygart Valley River at Philippi, and 6) Greenbrier River.*

Pearson r correlation test on flow metrics vs. mining (1963-2018)						
r values		*mined*			*unmined*	
Hydrologic metrics	**1**	**2**	**3**	**4**	**5**	**6**
average annual flow	0.110	0.021	0.024	-0.065	0.106	0.015
minimum flow	0.479**	0.139	0.069	-0.029	0.027	-0.085
maximum flow	-0.263*	-0.544*	-0.114	-0.010	0.055	-0.046
25th Percentile	0.300*	0.211	0.141	-0.150	-0.003	-0.081
75th Percentile	0.196	0.170	-0.009	-0.085	0.079	0.035
Interquartile	0.099	0.121	-0.070	-0.047	0.108	0.081

5 DISCUSSION

The two mined watersheds Big Coal River and Guyandotte River showed significant negative trends in maximum flow over time as well as significant correlation between maximum flow and mining permit history (Table 4, 5). Big Coal and Guyandotte also showed significant increases in 25th percentile, while Big Coal and Gauley River showed significant increasing minimum flow. For the mined watersheds, the lack of change in annual flow and increasing response for minimum flow and 25th percentile appears to be in line with the findings of Negley *et al.* (2006) as well as Nippgen *et al.* (2017). The former reasoned that reduced infiltration led to increased runoff, and the latter suggested the presence of valley fill leads to increased storage capacity as well as prolonged storage times, leading to higher baseflows. Unmined watersheds might show correlation of flow metrics and mining permit history if their mining history varied more significantly, along with having a similar extent of mining permit history as the mined watersheds, however they did not (Table 4, Figure 12). No significant correlation between percent mining cover and Q/P was found for any watershed (Figure 19). This lack of effect on Q/P is notable considering the correlations found for several flow metrics in Big Coal and Guyandotte, and their mining permit history.

Big Coal River underwent an increase in minimum flow in the 1970’s that began before recorded mining (Figure 14), however a significant statistical correlation (Table 5) between mining permit history and minimum flow suggests the need for a closer examination to separate land-use/land-change from mining disturbance. Like the Big Coal River watershed, Gauley River experienced an upward shift in minimum flow before recorded mining. There are multiple possible reasons for the streamflow behavior of Gauley River found in this study that must be investigated in future work. Firstly, the preparatory deforestation in advance of mining, second, an increase in impermeable surfaces from urbanizing activities, and third, an increase in agriculture or pasture for livestock. The construction of Summersville Dam from 1960 to 1966 is an important consideration for Gauley River experiencing a decrease in maximum flow, significant increase in minimum flow, clear regime changes in both metrics, along with no significant correlation between mining history and these trends (Marcinkowski *et al.*, 2017).

Mined watersheds did not express similar relationships with mining permits for all metrics, which may be attributed to one or many reasons: 1) Big Coal River at Ashford had 3.48% maximum percentage of possible unaccounted for mining permit area and Guyandotte River had 1.89% while Gauley River only had 0.65%, 2) The dynamic mining permit history over time for each mined watershed (Figure 12), 3) Differences in infiltrability and general soil compositions, 4) Differences in land use/land change over time, 5) Location of SFM/VF. As this study did not include underground mining, future work should take the underground mining permits into account. Differences in location of mining permits, such as one watershed having more mining permits located at the headwaters than other watersheds, may also have some influence on differences in flow response.

To study watersheds at the large scale while also using a paired catchment method meant the possibility of using watersheds outside the south west region of West Virginia (Figure 8). Due to the size of the watersheds chosen for pairing, one unmined watershed (Greenbrier) is located partly within a separate physiographic province as compared to their mined counterpart. The Greenbrier watershed is almost completely divided lengthwise between Appalachian Plateau and Ridge & Valley provinces. Ridge & Valley typically expresses a trellis drainage pattern with streams that flow parallel to mountains while Appalachian plateau regions have more dendritic patterns of drainage (Wiley *et al.*, 2013). The dendritic drainage pattern for the mined watersheds could suggest more of a reliance on mountain slope storages for baseflow. Gauley River watershed expressed consistently higher flow than its unmined counterpart (Greenbrier watershed), and it is worth further investigation to determine whether this may be due in part to a higher volume of mountainous storage area (Figure 4) as compared to Greenbrier River (Figure 7) or what other factors may be at play. Gauley River watershed experienced higher levels of precipitation than Greenbrier, however Big Coal River also experienced higher levels of precipitation than Belington and so this does not seem to explain the consistently higher levels of flow, or else this similar trend in higher flow would be seen in Big Coal River's relationship with Belington.

Big Coal River and Guyandotte River presented with a strong decline in their maximum flow as SFM/VF approached 2% but Gauley River did not experience a year of mining permitted area greater or equal to 2%. These possible threshold findings require future investigation. Valley fill and deep mine drainage have been attributed to decreasing maximum flow, which is significant for this study as Big Coal River and Guyandotte River experienced less than 1% area permitted for VF during any given year (Zégre *et al.*, 2014; Ross *et al.*, 2016). Future work should account for the (underground) mining not analyzed in this study to determine the role it may play in the significant declining maximum annual flow both Big Coal River and Guyandotte River experienced. Future work should also look to additive modeling such as nested streamgages to examine the possible threshold behavior found in this study. Additive models have been used to look for thresholds in watershed response to mining, evaluating a watershed or a section of watershed and then adding further sections until a change has been found such as changes in the health of biotic communities (Petty *et al.*, 2010; Bernhardt *et al.*, 2012). Finally, as mining for coal in West Virginia began more than a century ago, future work should investigate whether historic mining data exists that would allow for the application of the methods developed in this study (Burns, 2005).

6 CONCLUSIONS

This study assessed long-term hydrology in six large-scale watersheds divided into three pairs of watersheds (mined and unmined) to look for trends in annual hydrologic metrics and any significant correlation between mining permit history and annual hydrologic metrics. Significant trends in minimum and maximum flow were found in two mined watersheds as well as significant correlation between several metrics in mined watersheds and their respective mining permit history. This study found no significant correlation between mining permit history and Q/P. This lack effect on Q/P is notable considering the significant correlations between flow metrics and mining permit history for two of the heavily permitted watersheds and requires investigation to determine what factors are at play. Visual analysis suggested possible thresholds of mining disturbance for streamflow regime change in several watersheds that require more in-depth future examination. The mining permit data used for this study allowed for a high resolution (annual) view of mining history in each watershed. Permit data format limits our understanding of the true relationship of mining disturbance to reclamation and land-use/land change in each watershed. When evaluating mining impact on streamflow in large-scale watersheds future work should examine annual and long-term land-use/land-change to separate mining disturbance from other landscape changes.

Suggestions for further research include increasing the resolution of data for the hydrologic time series to monthly rather than annual metrics and developing time series of mining data for more than one mining condition, such as including underground mining in the time series. While this study compared Q/P to mining permit history, future work should include the use of double-mass curves when evaluating flow metrics and seek to rule out precipitation as a contributor to any positive or negative trends in streamflow. Further suggestions would include a more robust analysis of sources of impermeability within each watershed as well as developing more streamgage pairs at more refined values of disturbance, such as pairing watersheds with 1 - 3% cumulative mining permit history rather than restricting the study to using watersheds with a cumulative permit history greater or equal to 3%. Pairing watersheds at 1 - 3% cumulative mining permit history may offer a more detailed understanding of the differences in streamflow response between paired watersheds. Finally, future work should investigate whether the methods developed in this study are applicable to any existing historic mining data.

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APPENDICES

Appendix A

Appendix A.1 Lifetime hydrologic metrics

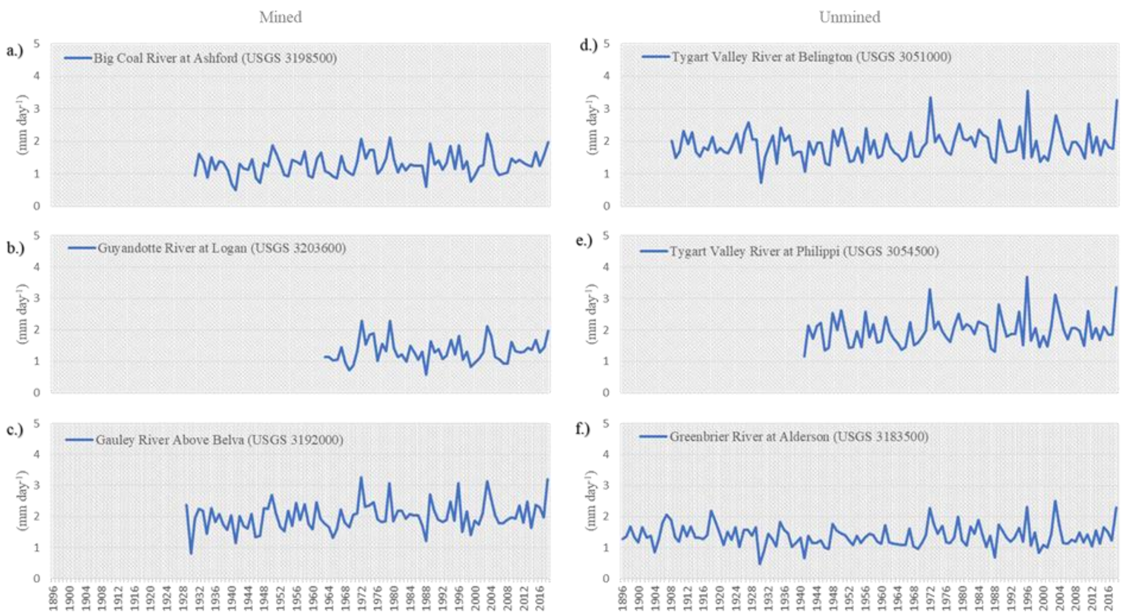

Figure 20 Lifetime average annual flow.

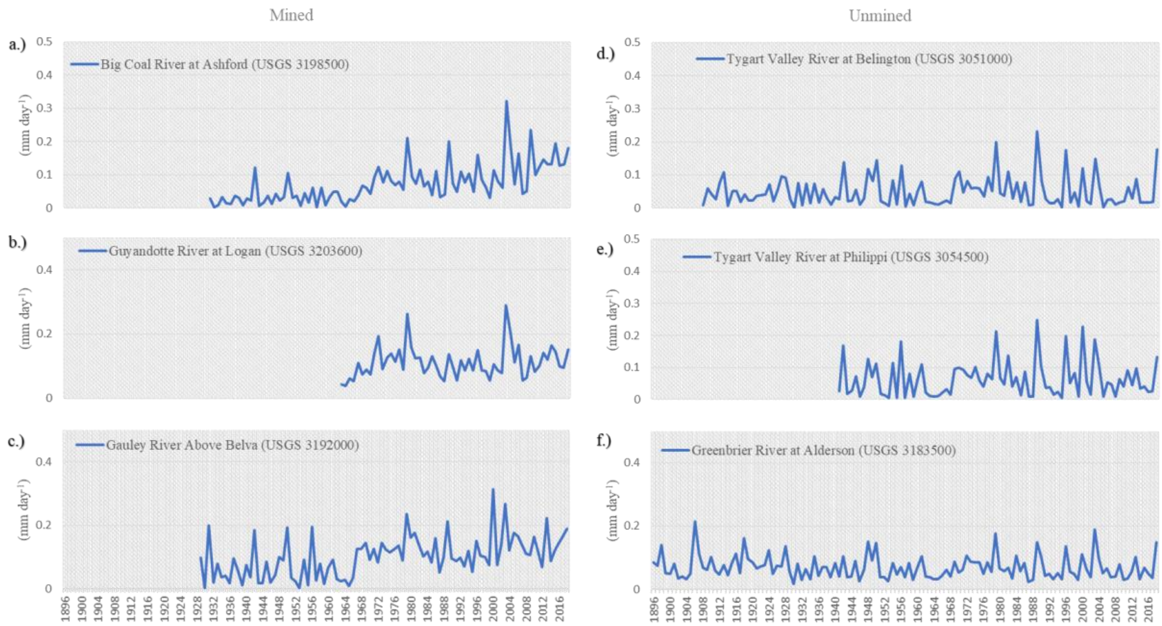

Figure 21 Lifetime minimum flow.

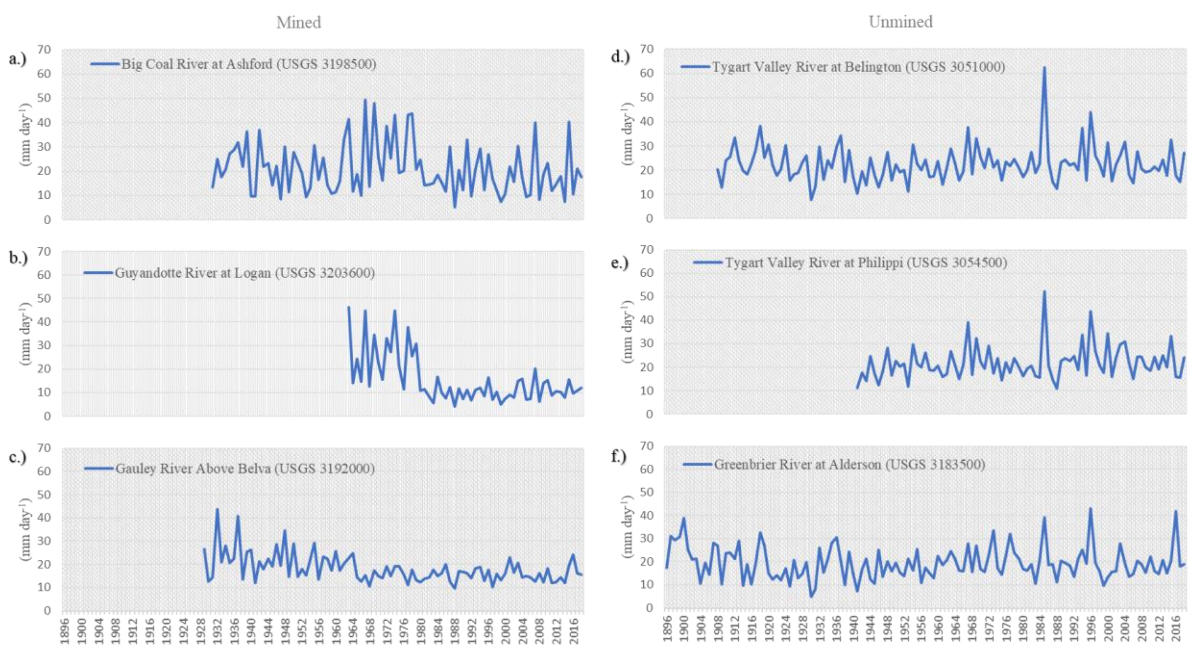

Figure 22 Lifetime maximum flow.

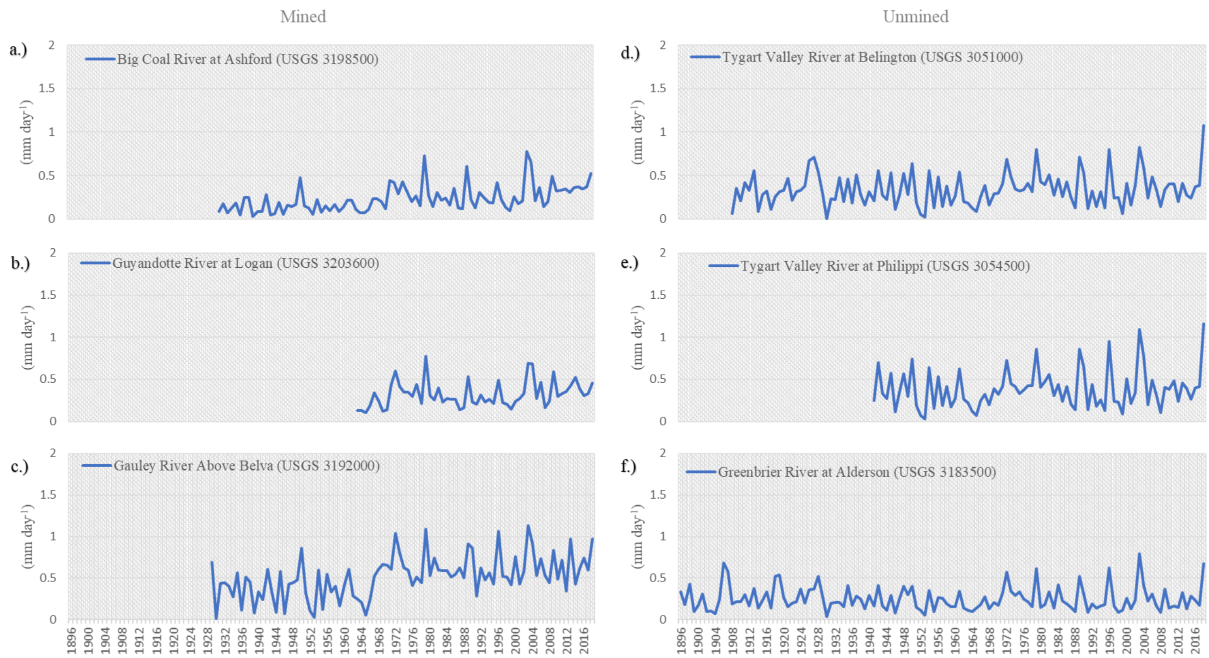

Figure 23 Lifetime 25th Percentile flow.

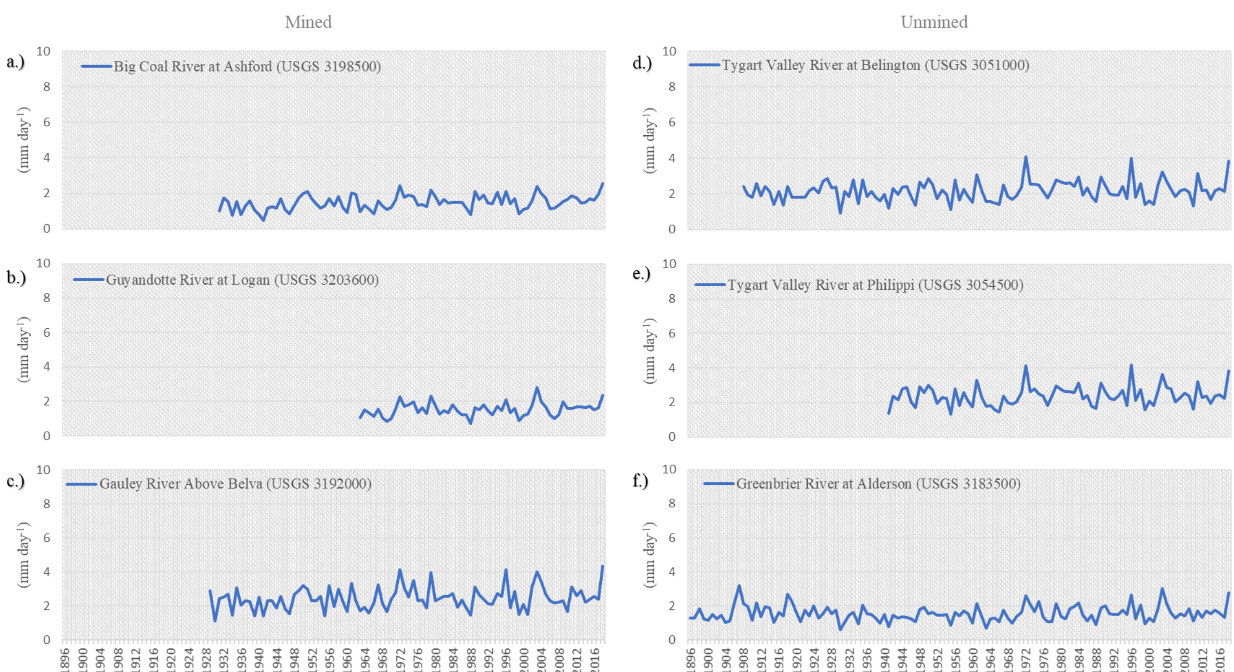

Figure 24 Lifetime 75th Percentile flow.

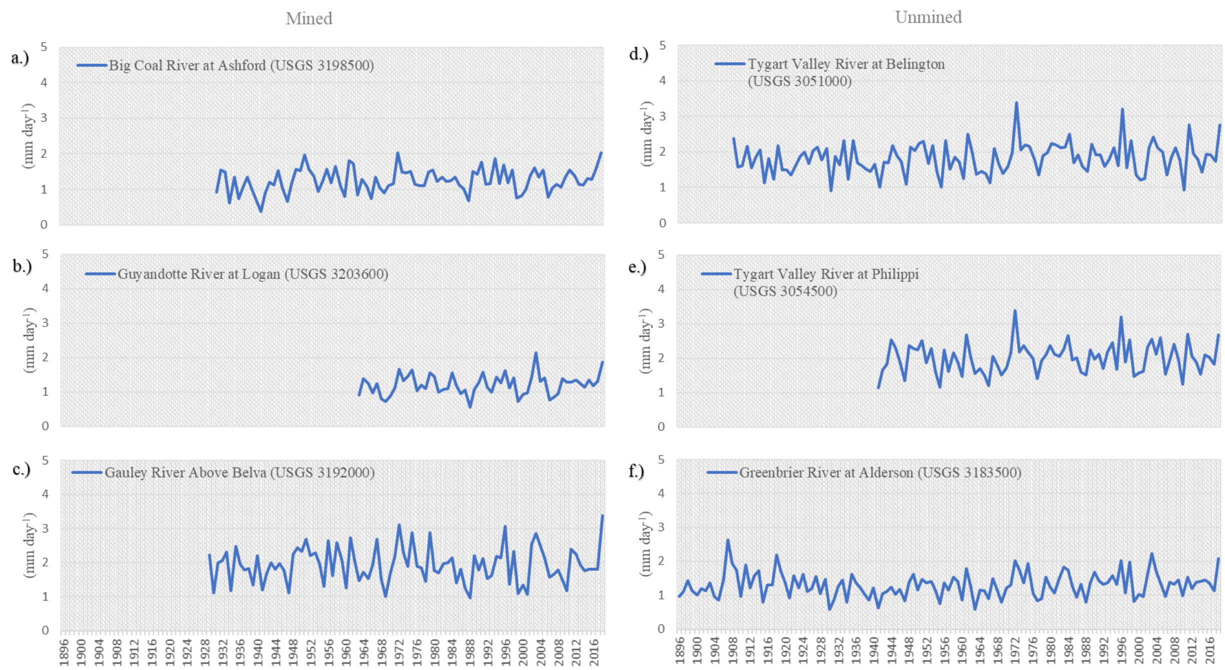

Figure 25 *Lifetime interquartile flow.*