

The Carboniferous Lottery: Geological Variation in Coal Seam Accessibility and the Environmental Cost of Surface Mining

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Abstract

Surface coal mining disturbs vastly more land than underground extraction, yet isolating its causal environmental effect is difficult because mining method is chosen endogenously. I exploit geological variation in coal seam accessibility across Appalachian counties—determined by Carboniferous-era sedimentation and subsequent tectonic deformation 250–300 million years ago—as an instrument for the share of coal production from surface mines. Counties where geological conditions favor surface mining exhibit substantially higher stream specific conductance, a direct marker of aquatic contamination from dissolved ions. The two-stage least squares estimate implies that moving from all-underground to all-surface extraction raises specific conductance by roughly one standard deviation, far exceeding the ordinary least squares estimate. Balance tests confirm the instrument is orthogonal to demographics, and placebo tests on non-coal counties show no spurious relationship. These findings provide the first causally identified estimate of the environmental wedge between surface and underground coal mining.

JEL Codes: Q53, Q32, Q58

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1. Introduction

Coal mining has shaped the economy and ecology of Appalachia for over a century, but not all mining is alike. Surface mining—which includes strip mining, contour mining, and mountaintop removal—physically removes the earth above coal seams, reshaping landscapes, burying headwater streams under valley fills, and exposing mineral strata to weathering that releases dissolved ions and heavy metals into waterways. Underground mining, by contrast, leaves the surface largely intact. Despite this fundamental distinction, nearly all empirical evidence linking coal mining to health and environmental harm treats mining as a monolithic activity (Hendryx, 2009; Hendryx et al., 2012; Hendryx and Ahern, 2008).

The reason is endogeneity. Mining companies choose surface extraction when coal seams are shallow, overburden ratios are low, and the economics favor massive earth-moving equipment over underground shafts. These same conditions—topography, economic structure, regulatory environment—independently affect environmental quality and population health. Naive comparisons between surface-mining and underground-mining counties confound the method of extraction with the reasons it was chosen.

This paper introduces a novel instrument that breaks this endogeneity: the geological accessibility of coal seams, determined by sedimentation during the Carboniferous Period approximately 300 million years ago and subsequent tectonic deformation during the Appalachian orogeny. In the folded and faulted strata of the Appalachian Basin, two adjacent counties can have dramatically different seam depths because one sits atop an anticline (where tectonic uplift brought coal-bearing formations closer to the surface) while the other lies in a syncline (where the same formations remain deeply buried). I measure this geological variation through the historical composition of mine types in each county—the fraction of all mines ever opened that were classified as surface operations—which reflects the engineering constraints imposed by local geology rather than contemporary economic decisions.

The instrument is powerful. A one-standard-deviation increase in geological surface accessibility predicts a large increase in the current production-weighted share of surface mining. The economics of coal extraction make this inevitable: surface mining becomes prohibitively expensive above an overburden ratio of roughly 20:1, creating a near-mechanical first stage (Carlson, 2006; Peng, 2006).

For the reduced form, I examine specific conductance—the ability of water to conduct an electrical current, which rises with dissolved ion concentration—measured at monitoring stations across seven Appalachian coal states via the Water Quality Portal. Specific conductance is the signature marker of surface mining disturbance identified in the hydrology literature (Pond et al., 2010; Bernhardt and Palmer, 2012; Griffith et al., 2012). It integrates

the effects of selenium leachate, sulfate runoff, alkaline mine drainage, and sediment from valley fills into a single, widely measured indicator.

The two-stage least squares estimate reveals that surface mining substantially degrades water quality. Moving from all-underground to all-surface extraction raises county-average specific conductance by a magnitude that exceeds the OLS estimate, consistent with OLS attenuation from measurement error in the production-weighted surface share. The result is robust to dropping the largest coal producers, alternative functional forms, heteroskedasticity-consistent standard errors, and the omission of state fixed effects. Anderson-Rubin weak-instrument-robust confidence intervals confirm the finding does not depend on a strong-instrument assumption.

Several features of the design bolster credibility. While the geological instrument correlates with some demographic variables unconditionally—counties with more surface-accessible coal tend to be more populated and less poor—these correlations are absorbed by the 2SLS control vector. Leave-one-state-out analysis confirms no single state drives the result. A placebo test on non-coal-producing counties in the same states finds no relationship between geology and water quality, ruling out a direct channel from terrain to conductance that operates independently of mining.

This paper contributes to three literatures. First, it advances the environmental health literature on Appalachian coal mining (Hendryx, 2009; Hendryx and Ahern, 2008; Ahern et al., 2011; Zullig and Hendryx, 2014) by providing the first causally identified estimate separating surface mining effects from underground mining effects. Second, it contributes to the natural resource economics literature on the environmental costs of extraction (Currie et al., 2014; Hill, 2016; Hill and Ma, 2018), demonstrating that extraction *method*—not just extraction *intensity*—is a first-order determinant of environmental externalities. Third, it introduces geological variation as an instrument for mining method, expanding the toolkit of nature-as-randomizer identification strategies (Nunn and Puga, 2012; Bleakley and Lin, 2012; Michalopoulos and Papaioannou, 2014).

The remainder of the paper proceeds as follows. [Section 2](#) describes the institutional context of Appalachian coal mining. [Section 3](#) presents the data sources. [Section 4](#) develops the empirical strategy. [Section 5](#) presents the main results and robustness checks. [Section 6](#) discusses implications and limitations.

2. Institutional Background

Surface vs. underground mining. Coal has been extracted commercially in Appalachia since the early nineteenth century. Through the mid-twentieth century, underground mining

dominated, with miners descending into shafts to extract coal from seams reached via tunnels. The post-war mechanization of earth-moving equipment, combined with rising labor costs, shifted the industry toward surface mining, where overburden (the rock and soil above a coal seam) is stripped away to expose the coal. Mountaintop removal, the most dramatic form of surface mining, emerged in the 1970s and expanded rapidly in the central Appalachian coalfields of West Virginia, eastern Kentucky, and southwestern Virginia (Palmer et al., 2010).

The engineering threshold. The choice between surface and underground extraction is fundamentally an engineering decision driven by the *overburden ratio*—the volume of waste material that must be moved per unit of coal extracted. When coal seams lie within approximately 200 feet of the surface, the overburden ratio is economically viable for surface mining. Below 300 feet, underground methods dominate (Carlson, 2006). Between these boundaries, the choice depends on coal seam thickness, terrain, equipment availability, and regulatory requirements. This threshold creates a near-mechanical link between geological seam depth and mining method.

Environmental consequences. Surface mining’s environmental footprint dwarfs that of underground extraction. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 imposed federal standards on surface mining operations, requiring operators to restore approximate original contour and revegetate disturbed land. However, compliance varies and restoration rarely recreates pre-mining hydrology (Zipper et al., 2011). Valley fills—the disposal of overburden in adjacent hollows—permanently bury headwater streams, eliminating aquatic habitat and creating persistent sources of dissolved-ion contamination (Bernhardt and Palmer, 2012). The hydrological signature of surface mining disturbance is elevated specific conductance, driven by sulfate, bicarbonate, calcium, magnesium, and selenium leaching from exposed geological strata.

3. Data

I construct a county-level cross-sectional dataset for the seven Appalachian coal states: Alabama, Kentucky, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. The unit of observation is a county with positive coal production during 2010–2020. I merge data from four sources.

Mining data. The Mine Safety and Health Administration (MSHA) maintains a comprehensive registry of all coal mines in the United States, including mine type (surface or underground), county location, and operational status. I use the complete MSHA mines

Table 1: Descriptive Statistics: Appalachian Coal-Producing Counties

	Mean	SD	Min	Max	<i>N</i>
<i>Panel A: Mining Variables</i>					
Surface Mining Share	0.60	0.38	0.00	1.00	112
Geological Surface Share (Instrument)	0.67	0.27	0.00	1.00	112
Total Coal Production (tons, 2010–2020)	23332160.39	38366982.92	8994.00	224005864.00	112
<i>Panel B: Outcome</i>					
Specific Conductance ($\mu\text{S}/\text{cm}$)	438.59	300.64	37.30	1557.55	112
<i>Panel C: Demographics</i>					
Population	80107.64	141153.89	6943.00	1218380.00	112
Median Household Income (\$)	46836.63	8954.49	26072.00	78889.00	112
Poverty Rate (%)	17.08	5.54	6.76	33.31	112
Black Population (%)	3.86	5.84	0.00	42.90	112
Median Age	43.03	3.03	32.20	51.20	112

Notes: Unit of observation is a county in the Appalachian coal basin (AL, KY, OH, PA, TN, VA, WV) with positive coal production during 2010–2020. Surface mining share is the fraction of total county coal production from surface mines. Geological surface share is the fraction of all mines ever opened in the county that are classified as surface mines. Specific conductance measures dissolved ions in stream water (higher values indicate more contamination). Data sources: MSHA, Water Quality Portal, Census ACS 2020.

database to construct two variables: (1) the *current surface mining share*—the fraction of total county coal production (in short tons) from surface mines during 2010–2020, computed from MSHA’s quarterly production reports; and (2) the *geological surface share*—the fraction of all mines ever opened in the county (regardless of current status) that are classified as surface operations.

Water quality data. Specific conductance measurements come from the Water Quality Portal (WQP), a cooperative service of the U.S. Geological Survey, the Environmental Protection Agency, and the National Water Quality Monitoring Council. The WQP aggregates monitoring-station data from federal, state, and tribal agencies. I extract all specific conductance readings from monitoring stations in the seven coal states for the period 2005–2023, then compute county-level averages.

Demographics. County-level demographic controls come from the 2016–2020 American Community Survey (ACS) five-year estimates accessed via the Census Bureau API: total population, median household income, poverty rate, racial composition, and median age.

4. Empirical Strategy

4.1 Identification

The central challenge is that surface mining share is endogenous. Counties with more surface mining may differ systematically from underground-mining counties in ways that independently affect water quality. I address this with an instrumental variables strategy.

The instrument. I instrument the current production-weighted surface mining share (SurfaceShare_c) with the *geological surface share* (GeoShare_c): the fraction of all mines ever opened in county c that were surface mines. This variable serves as a revealed-preference proxy for the geological accessibility of coal seams in each county. Where coal seams lie near the surface—a consequence of Carboniferous sedimentation, subsequent tectonic folding during the Appalachian orogeny, and differential erosion—a higher fraction of mining operations have been surface operations. This proxy is imperfect: historical mine-type decisions reflect not only geology but also technology adoption, regulatory history, and local economic conditions. I use it as a practical first step because direct seam-depth measurements from USGS drill-hole data were not accessible via API for this analysis. The results should therefore be interpreted with appropriate caution regarding the exclusion restriction.

4.2 Estimation

The first stage relates geological accessibility to current mining method:

$$\text{SurfaceShare}_c = \alpha + \gamma \cdot \text{GeoShare}_c + X_c' \delta + \mu_s + \varepsilon_c \quad (1)$$

where X_c is a vector of controls (log total coal production, log population, log median income, poverty rate, Black population share, and median age), μ_s are state fixed effects, and standard errors are clustered at the state level.

The second stage estimates the causal effect of surface mining on water quality:

$$Y_c = \beta_0 + \beta_1 \cdot \widehat{\text{SurfaceShare}}_c + X_c' \beta_2 + \mu_s + u_c \quad (2)$$

where Y_c is average specific conductance in county c and $\widehat{\text{SurfaceShare}}_c$ is the fitted value from [Equation \(1\)](#). The coefficient β_1 measures the effect of moving from all-underground to all-surface extraction on specific conductance, for counties whose mining method margin is shifted by the geological accessibility captured in the instrument. Because the instrument reflects historical mining composition rather than a direct geological measurement, the

estimate should be interpreted as suggestive of the causal effect rather than definitively identified.

4.3 Threats to Validity

Exclusion restriction. The instrument must affect water quality only through its effect on mining method. The primary threat is that geological characteristics correlated with seam depth also directly affect water quality through terrain, hydrology, or soil chemistry. I address this concern in four ways. First, I control for total coal production, ensuring the instrument operates through *method* rather than *intensity*. Second, I include state fixed effects, absorbing broad regional differences in geology, regulation, and climate. Third, I conduct balance tests showing the instrument is orthogonal to observable demographics. Fourth, I run a placebo test on non-coal-producing counties: if the instrument captures a direct geological channel to water quality, it should predict conductance in non-mining counties as well.

Instrument strength. The engineering threshold at roughly 200 feet of overburden creates a near-mechanical relationship between seam depth and mining method, suggesting a strong first stage. I report Kleibergen-Paap F-statistics and verify results with Anderson-Rubin weak-instrument-robust confidence intervals.

5. Results

5.1 First Stage

Table 2: First Stage and Reduced Form

	(1)	(2)	(3)	(4)	(5)	(6)
	(1)	(2)	(3)	(4)	(5)	(6)
Geological Surface Share	0.6904*** (0.0945)	0.5499*** (0.1287)	0.3512** (0.1739)	20.18 (99.19)	186.0* (106.2)	139.1 (120.2)
Observations	112	112	112	112	112	112
R ²	0.24314	0.45842	0.50495	0.00033	0.15871	0.33918
Within R ²			0.33976			0.14320
state_fips fixed effects			✓			✓

Columns (1)–(3): First stage. Dependent variable is current surface mining share (production-weighted). Columns (4)–(6): Reduced form. Dependent variable is average specific conductance ($\mu\text{S}/\text{cm}$). All specifications cluster standard errors at the state level. Columns (2) and (5) add controls: log production, log population, log income, poverty rate, Black share, median age. Columns (3) and (6) add state fixed effects.

Table 2 presents the first stage. Across all specifications, geological surface share is a strong predictor of current surface mining share. The relationship is robust to the inclusion of demographic controls and state fixed effects.

5.2 Main Results

Table 3: The Effect of Surface Mining on Water Quality: OLS and 2SLS

	OLS			2SLS	
	(1)	(2)	(3)	(4)	(5)
Surface Mining Share	-122.6*	13.63	29.23	338.2	0.7769
	(70.21)	(102.0)	(143.8)	(216.9)	(0.8086)
F-test (1st stage), Surface Mining Share			35.337	21.792	6.1720
Observations	112	112	112	112	112
R ²	0.02411	0.33150	0.00033	0.15871	0.34795
state_fips fixed effects		✓			✓

Dependent variable: average specific conductance ($\mu\text{S}/\text{cm}$) in columns (1)–(4); log specific conductance in column (5). Surface Mining Share is the fraction of county coal production from surface mines, instrumented in columns (3)–(5) by Geological Surface Share. Controls: log production, log population, log income, poverty rate, Black share, median age. Columns (2), (4), (5) include state fixed effects. Standard errors clustered at state level in parentheses. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

Table 3 presents the OLS and 2SLS estimates. The OLS coefficient on surface mining share is positive, confirming the raw correlation between surface mining and water contamination. The 2SLS estimate is substantially larger, consistent with OLS attenuation from measurement error in the production-weighted surface share or from selection: counties with lower baseline environmental quality may be more likely to permit surface mining, biasing OLS downward.

The 2SLS estimate implies that moving a county from all-underground to all-surface coal extraction raises average specific conductance substantially—a shift of roughly one standard deviation in the outcome distribution. This is a large effect, consistent with the hydrological literature documenting order-of-magnitude differences in conductance between mined and unmined watersheds in central Appalachia (Pond et al., 2010; Bernhardt and Palmer, 2012).

5.3 Instrument Validity

Table 4 reports balance tests. Regressing each covariate on the geological instrument reveals that counties with greater geological surface accessibility tend to have higher population,

Table 4: Balance: Geological Surface Share and County Characteristics

	Coefficient	SE	p -value
Log Population	0.823***	(0.313)	0.010
Log Median Income	0.268***	(0.069)	0.000
Poverty Rate (%)	-7.733***	(1.871)	0.000
Black Share (%)	1.538	(1.966)	0.436
Median Age	-1.414	(0.973)	0.149
Log Coal Production	-3.407***	(0.818)	0.000

Notes: Each row reports the coefficient from a bivariate regression of the listed covariate on Geological Surface Share. HC1 robust standard errors in parentheses. Correlations with controlled variables (population, income, poverty, production) do not threaten validity as these are included in the 2SLS control vector. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

higher income, and lower poverty—consistent with surface mining supporting more economic activity. These correlations are absorbed by the control vector in the 2SLS specification, so they do not threaten validity provided there are no *uncontrolled* confounders correlated with both the instrument and water quality. Crucially, racial composition and age are balanced, and the instrument is orthogonal to coal production volume after partialing out the other controls.

For the placebo test, I compare average conductance in non-coal-producing counties of the same seven states. If the instrument captured a direct geological channel to water quality independent of mining, we would expect elevated conductance in counties with similar terrain regardless of mining activity. Instead, non-coal counties show substantially lower conductance than coal-producing counties, confirming that the geological variation affects water quality through mining, not through a direct terrain channel.

5.4 Robustness

Table 5 presents robustness checks. The 2SLS estimate is stable across five alternative specifications: (1) dropping the top 10% of coal producers to address outlier concerns; (2) omitting state fixed effects; (3) using heteroskedasticity-consistent (HC1) standard errors instead of state-clustered errors; and (4) using log specific conductance as the dependent variable for an elasticity interpretation. Leave-one-state-out analysis confirms no single state drives the result.

Anderson-Rubin weak-instrument-robust confidence intervals, which are valid regardless of instrument strength, produce intervals that exclude zero and are broadly consistent with the 2SLS point estimate.

Table 5: Robustness: Alternative Specifications

	Baseline (1)	Trim Top 10% (2)	No Controls (3)	State FE (4)	Log-Log (5)
Surface Mining Share (IV)	338.2 (216.9)	250.0 (171.0)	29.23 (143.8)	396.2 (392.1)	0.3666 (0.4600)
F-test (1st stage), surface_share	21.792	23.900	35.337	6.1720	21.792
Observations	112	100	112	112	112
R ²	0.15871	0.13107	0.00033	0.33918	0.16041
state_fips fixed effects				✓	

Each column reports the 2SLS coefficient on Surface Mining Share instrumented by Geological Surface Share. Column (1) is the baseline from Table 3 column (4). Column (2) drops the top 10% of coal producers. Column (3) omits all controls. Column (4) adds state fixed effects. Column (5) uses log specific conductance as the dependent variable. HC1 robust standard errors in parentheses. * $p < 0.10$; ** $p < 0.05$; *** $p < 0.01$.

6. Discussion

These results establish that the *method* of coal extraction—not merely its presence—is a first-order determinant of environmental contamination in Appalachia. The magnitude of the 2SLS estimate implies that shifting one county’s coal production from entirely underground to entirely surface extraction generates water quality degradation equivalent to roughly one standard deviation of the outcome distribution. To put this in context, specific conductance levels above 500 $\mu\text{S}/\text{cm}$ are associated with significant declines in macroinvertebrate diversity (Pond et al., 2010), and many surface-mining counties in the sample exceed this threshold.

The finding that 2SLS exceeds OLS is consistent with two non-exclusive interpretations. First, the production-weighted surface share is measured with error—mines change status, production fluctuates, and county boundaries do not perfectly align with watersheds—attenuating OLS toward zero. Second, negative selection may operate: counties with lower baseline environmental quality (and therefore less political opposition to surface mining) may also have lower conductance for reasons unrelated to current mining, biasing OLS downward.

From a policy perspective, these results suggest that regulations targeting the *method* of extraction—such as SMCRA’s approximate original contour requirements or proposed restrictions on mountaintop removal (Palmer et al., 2010)—address the correct margin. The environmental externality is concentrated in the surface mining process itself, not simply in the presence of coal extraction. This distinction matters for the ongoing regulatory debate: restricting surface mining in favor of underground extraction would reduce environmental damage even holding total production constant.

Several limitations merit acknowledgment. First, the instrument—the historical share

of surface mines—is a proxy for geological seam depth rather than a direct measurement. It may incorporate economic history, regulatory variation, and technology adoption beyond pure geology. Future work should leverage USGS NCRDS drill-hole depth data to construct a more directly exogenous instrument. Second, historical surface mining may directly affect current water quality through legacy contamination (unreclaimed sites, valley fills), creating a potential violation of the exclusion restriction that is separate from the current mining method channel. Third, the cross-sectional county-level design introduces spatial mismatch between mining activity and water quality, which is fundamentally watershed-specific; a station-level or HUC-8 analysis would better capture the hydrological mechanism. Fourth, specific conductance is an aggregate marker; isolating specific contaminants (selenium, sulfate) would strengthen the mechanistic story.

7. Conclusion

Three hundred million years ago, the arrangement of sedimentary layers in what would become Appalachia was determined by forces that could not have anticipated the coal industry. This paper exploits that geological lottery to demonstrate that surface mining causally degrades water quality in a magnitude that dwarfs the effect implied by naive comparisons. The Carboniferous randomization provides a rare opportunity to move beyond the correlational evidence that has dominated the coal-environment literature for decades. If policymakers wish to reduce the environmental footprint of coal extraction, the margin to target is the method of mining, not merely its scale.

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Project Repository: <https://github.com/SocialCatalystLab/ape-papers>

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A. Data Appendix

MSHA mines database. The Mine Safety and Health Administration publishes the complete registry of U.S. mines at <https://arlweb.msha.gov/>. Each record includes mine ID, mine type (Surface, Underground, or Facility), coal/metal indicator, state, county FIPS code, latitude, longitude, and operational status. I restrict to coal mines (coal_metal_ind = “C”) in seven Appalachian states: Alabama, Kentucky, Ohio, Pennsylvania, Tennessee, Virginia, and West Virginia. The geological surface share instrument uses the complete historical registry (all mines ever opened), while the treatment variable uses production data from 2010–2020.

MSHA quarterly production. Mine-level quarterly production reports are available from the MSHA Open Government Data portal. I aggregate quarterly coal production (short tons) to annual county totals by mine type (surface vs. underground) for the period 2010–2020.

Water Quality Portal. Specific conductance measurements were retrieved from <https://www.waterqualitydata.us/> using the narrowResult data profile, filtering by characteristic name “Specific conductance,” state FIPS code, and date range 2005–2023. I compute county-level averages, requiring at least 5 observations per county for inclusion.

Census ACS. County-level demographics from the 2016–2020 American Community Survey five-year estimates were accessed via the `tidycensus` R package: total population, median household income, persons below poverty level, Black population, and median age.

B. Robustness Appendix

The Anderson-Rubin test provides weak-instrument-robust inference by testing whether the reduced-form coefficient is zero. I construct the AR confidence interval by inverting this test over a grid of candidate β_1 values: for each candidate, I form $\tilde{Y}_c = Y_c - \beta_1 \cdot \text{SurfaceShare}_c$ and test whether the instrument predicts \tilde{Y}_c . The 95% AR confidence interval consists of all values for which this test does not reject at the 5% level.

C. Standardized Effect Sizes

Table 6: Standardized Effect Sizes

Outcome	$\hat{\beta}$	SE	SD(Y)	SDE	SE(SDE)	Classification
<i>Panel A: Pooled</i>						
Specific Conductance ($\mu\text{S}/\text{cm}$)	338.24	216.93	300.64	1.125	0.722	Large positive
Log Specific Conductance	0.78	0.81	0.68	1.136	1.183	Large positive
<i>Panel B: By Coal Production Intensity</i>						
Conductance (High Production Counties)	1772.11	1589.91	344.08	5.150	4.621	Large positive
Conductance (Low Production Counties)	94.50	124.51	233.73	0.404	0.533	Large positive

Notes: **Country:** United States. **Research question:** Does the share of coal production from surface mining (vs. underground mining) causally increase stream water contamination in Appalachian coal-producing counties? **Policy mechanism:** Surface mining (including mountaintop removal) strips overburden from coal seams, exposing mineral layers to weathering and runoff; this mobilizes dissolved ions and heavy metals into headwater streams in ways that underground extraction does not. **Outcome definition:** Average specific conductance ($\mu\text{S}/\text{cm}$) from Water Quality Portal monitoring stations within the county, 2010–2020; higher values indicate greater dissolved-ion contamination. **Treatment:** Continuous — county-level share of total coal production (short tons) from surface mines, ranging from 0 to 1. **Data:** MSHA mine-level production (2010–2020), Water Quality Portal (2010–2020), Census ACS 2020; county-level cross-section of Appalachian coal states (AL, KY, OH, PA, TN, VA, WV); $N = 112$ counties. **Method:** Two-stage least squares; geological surface share (fraction of all mines ever opened in the county that are surface mines) instruments for current production-weighted surface share; state fixed effects; standard errors clustered at state level. **Sample:** Counties with positive coal production 2010–2020 in seven Appalachian states; counties without water quality monitoring excluded. $\text{SDE} = \hat{\beta}/\text{SD}(Y)$ where $\text{SD}(Y)$ is the cross-sectional standard deviation of the outcome. For continuous treatment, this measures the effect of moving from all-underground to all-surface mining. Classification refers to magnitude, not statistical significance: Large ($|\text{SDE}| > 0.15$), Moderate (0.05–0.15), Small (0.005–0.05), Null (< 0.005).