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Artisanal Mining and Educational Outcomes

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Artisanal Mining and Educational Outcomes

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Abstract

Artisanal mining (Garimpo) has expanded rapidly in Brazil, especially in the Amazon. It releases mercury and other heavy metals into rivers, which can expose communities far from any mine. Little is known about whether this exposure affects children's learning. This paper uses the direction of Brazil's river network to identify the effect of upstream Garimpo activity on downstream schools. We combine school-level scandalized test scores averages about 4,000 schools, between 2007 and 2019, mining area per municipality, matched to each school through the national hydrographic network. Greater upstream Garimpo exposure is associated with lower standardized test outcomes. The effects are concentrated among schools that rely directly on river water. The effects are also concentrated on the Amazon, and they extend to school approval rates. The results suggest that the social costs of artisanal gold mining reach communities beyond the municipalities where mining takes place.

Keywords: Mining, education, rivers

JEL Classification: Q53, I25, and O13

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Introduction

Artisanal and small-scale mining, known in Brazil as Garimpo, has surge in a large quantity in recent years across the country and specially in the Amazon area. This activity generates significant environmental externalities. Artisanal mining is heavily concentrated on riverbanks. The combination of weak regulatory enforcement and rudimentary practices contributes to the release of heavy metals naturally occurring such as arsenic, lead, and cadmium in the water. In addition, the gold mining activity also relies heavily on the use of mercury that also ends in the river flows. This compound of chemicals in the water can affect not only the environment but also the communities located along the same river system, even at considerable distance from any mining activity without hosting any mining activity themselves.

Despite the previous research on the environmental and health outcomes of artisanal mining, little is known about whether this water transported exposure translates into measurable effects on children's educational outcomes. Previous literature focuses on linking mining to human capital outcomes almost exclusively on distance proximity or administrative units' comparison where the mine is located. This makes it difficult to distinguish the effect of environmental exposure from other channels such as child labor, income shocks or local economy disruptions.

This paper addresses this gap by using the directional structure of Brazil's river network to identify the effect of upstream Garimpo activity on downstream educational outcomes. We employed a panel data analysis at the school-level on standardized test scores (SAEB) and the school development index (IDEB) for 4,052 schools in 310 municipalities biannually between 2007 and 2019, matched to municipal-level Garimpo mining area through Brazil's hydrographic network.

The results show that greater upstream Garimpo exposure is associated with lower educational outcomes across all measures, with larger effects among schools that rely directly on river water for their water supply. Downstream Garimpo activity, which should not affect a school through the same river system, shows no corresponding relationship, which holds the placebo test consistent with the interpretation that the

estimated effect operates through hydrological exposure rather than general proximity to mining.

These effects are concentrated on gold extracting Garimpo activity rather than other extracted minerals in the Amazon area. Complementary evidence on river fish production shows a sharp decline specifically in piscivorous species, consistent with mercury pollution through the aquatic food chain, providing independent support for the proposed contamination channel.

This paper makes three contributions. First, it extends river-network identification strategies**,** used for infant health (Dias et al., 2023) and agricultural productivity (Vashold et al., 2025)**,** to educational outcomes. Second, it extends the mining-education literature, which relies on proximity-based measures that cannot separate environmental exposure from labor-market and income channels, by using hydrological connectivity to isolate an environmental connection independent of local economic conditions. Third, it combines reduced-form educational results with direct evidence on the contamination pathway with water-source heterogeneity and mercury biomagnification in local fish catches**;** providing a fuller account of how upstream mining generates educational costs downstream.

Literature Review

Environmental Shocks and Human Capital

A substantial body of literature has shown that environmental shocks can have an impact on developing children. Among these, pollution has received particular attention in both economic and health fields. Persico and Venator (2021) found that industrial pollution from local Toxic Release Inventory sites reduces student test scores and increases suspension rates. In a setting geographically closer to the context of this paper, Miller and Vela (2013) showed that higher ambient PM_{10} and ozone concentrations are associated with lower reading and math test scores across Chilean municipalities. In addition, Villalobos and Blackman (2025) found that a one standard deviation increases in ambient $PM_{2.5}$ concentration in Colombia reduces overall high-stakes test scores by 8.2 percent of a standard deviation. Together, these studies

establish that environmental pollution from different sources can meaningfully affect standardized test performance across both high-income and developing-country settings.

Standardized test scores provide a valuable proxy to measure these negative effects on human capital. Most of these tests also collect student socioeconomic data and institutional characteristics, offering a vast number of valuable controls for potential confounding factors.

However, existing research based on educational outcomes in children is mostly restricted to local, point-source, or atmospheric exposure of pollution. Less attention has been given to pollution beyond administrative or geographic limits. We address this gap by examining the effects transmitted through hydrological networks, focusing on the impact of upstream artisanal mining activity on downstream educational outcomes in Brazil

River Networks as an Identification Strategy for Environmental Externalities

The logic of our main methodical framework relies on the hydrological structure of the rivers as the main channel for transportation for the pollutants released by mining activities located in a different area. This framework is also expected to isolate the positive effects generated by increase in income by the mining activities leaving only the effect of the externalities of mining. We hypothesize that in our framework only upstream mining location should have a significant impact on educational outcomes while the downstream location should not have an effect since the main transportation channel goes in only one direction. This upstream and downstream logic provides a natural placebo test and has been proven to be a credible identification strategy across several contexts.

For this setting we follow the works of Lipscomb and Mobarak (2016), who were among the first to use river-flow direction in Brazil, showing the effects of the pollution spillovers along river networks. Dias et al. (2023) apply a closely related upstream–downstream logic to a different pollutant and outcome, showing that glyphosate use associated with the expansion of genetically modified soybean cultivation increased

infant mortality and affected negatively other birth outcomes in downstream municipalities, with no corresponding effect upstream.

Their identification strategy is structurally similar to the one used in this paper: exposure is defined by hydrological connectivity rather than geographic proximity, and the absence of an effect in the "wrong" direction serves as a key validation of the empirical strategy. More recently, Vashold et al. (2025) extend this logic to mining, showing that mining-induced water pollution reduces downstream vegetation and agricultural productivity in Africa. In addition, Macklin et al. (2023) showed that around 23 million people live on floodplains contaminated by mining waste transported through river systems, generating a validity of our assumption that upstream mining activity can have an impact on distant areas by the heavy metals being transported through the water flows.

Together, these studies establish river connectivity as a credible and increasingly used identification strategy for environmental externalities in general, and in Brazil specifically since large river connections make a perfect setting to test this framework. However, none of them examine educational or human capital outcomes: Dias et al. (2023) focus on infant health, and Vashold et al. (2025) focus on ecological and agricultural outcomes. This paper extends the river-network framework to a new domain, children's educational achievement, and to a new pollutant pathway specific to artisanal gold mining while isolating the positive effects that artisanal mining can have on the local economy.

Garimpo, Mercury, and Health

In Brazil, artisanal and small-scale mining is known as Garimpo. It can operate legally under federal permits (*Permissão de Lavra Garimpeira* or PLG), however a major share of the activity operates informally or illegally without environmental oversight. Ferreira Neto et al. (2024) underscore the unprecedented scale of this expansion: between 1985 and 2022, the total land area dedicated to Garimpo expanded by approximately 1,200% (growing from ~218 km^2 to ~2,627 km^2), outpacing industrial mining. 91% of all Garimpo activity concentrated within the Amazon, and at least 77% of all active extraction sites in 2022 exhibited explicit indicators of illegality.

While several minerals are extracted by these practices such as gold, precious stones, ornamental stones and tin; according to the data of Mapbiomas, around 80 percent of the artisanal mining activity is composed of gold mining. This type of mining is highly destructive and affects deeply the ecosystems. It is mainly located in the rivers basins since it presents easier access to the gold deposits compared to traditional underground mining. The main method of extracting consists of high-pressure water hoses to take apart the soil from the riverbanks and use suction pumps to capture the sediments. This process also releases naturally occurring heavy metals such as arsenic, lead and cadmium, that, in addition to the mercury used during the mining process, enter local water systems and bioaccumulate up the aquatic food chain, directly poisoning the food and water supplies of rural and riverine municipalities.

These heavy metals, once ingested by developing children, can generate permanent neurological deficits, lower IQ scores, diminished memory retention, and attention disorders. Those effects can manifest directly in lower scores on national standardized exams like the SAEB, elevating rates of grade repetition, chronic absenteeism and turning the physical and chemical mechanisms of mining practices into a cycle of educational and socio-economic disadvantages. Passos et al (2008) document elevated daily mercury intake among fish-eating populations in the Brazilian Amazon, while Gibb and O'Leary (2014) note that workers, their families, and residents of nearby and downstream communities are frequently exposed to methylmercury through the consumption of contaminated fish. Hilson and Pardie (2006) further show that dependence on mercury for gold amalgamation is itself an overlooked driver of poverty in artisanal mining communities. For the Brazilian context evidence for mercury exposure among Indigenous populations in the Brazilian Amazon similarly documents high rates of cognitive and motor deficits linked to mercury body burden across multiple Indigenous groups, including the Kayapó, Munduruku, and Pakaanova (Da Conceição Nascimento Pinheiro et al., 2025). Among Yanomami children in the Brazilian Amazon chronically exposed to methylmercury from illegal gold mining, average IQ scores were found to be substantially below normative levels, with lower scores linked to elevated mercury levels in hair and higher fish consumption (Jacques et al., 2024). Similarly, adult members of the same population with elevated hair

methylmercury levels showed significantly higher rates of peripheral neuropathy and reduced cognitive performance (Rebouças et al., 2024).

Administrative data from Brazil's national disease system (Sinan/DataSUS) records mercury poisoning cases under environmental circumstance of exposure between 2007 and 2019 (Ministério da Saúde/SVSA, 2024). While these notifications are sparse and almost certainly reflect substantial underreporting — likely due to limited healthcare access and diagnostic capacity in remote riverine and mining-affected areas — the geographic pattern of the available cases is informative: municipalities with the highest case counts include Itaituba (Pará, 199 cases) and Iracema (Roraima, 76 cases), both located in regions with substantial Garimpo activity. While these data are too limited in coverage and sample size to support formal statistical analysis, they are broadly consistent with the mercury exposure pathway proposed in this paper.

Mining and Education: Conventional Literature

Previous research has also examined the relationship between mining and educational outcomes directly, largely without exploiting hydrological connectivity. Much of this literature focuses on Africa and relies on geographic proximity or administrative-unit comparisons between mining and non-mining areas. Evidence from this literature is mixed: Atsebi et al. (2022) found that mineral discoveries and mining production positively affect intergenerational educational mobility at the primary education level across 28 African countries, though the effect does not extend to secondary or tertiary education, while Ahlerup et al. (2019) documents a "long-run resource curse," showing that individuals who had a gold mine within their district during adolescence attain significantly lower educational levels as adults. Mamo et al. (2019) similarly find that mining expansion raises living standards and public service provision near mining districts in Sub-Saharan Africa, while Aragón and Rud (2013) document that a large-scale gold mine in Peru raised local household incomes through backward linkages and increased local purchases. However, Aragón and Rud (2015) show that mining-related pollution can simultaneously reduce agricultural productivity in areas surrounding mining sites in Ghana, Von Der Goltz and Barnwal (2018) find that across roughly 800 mines in 44 developing countries, gains in local asset wealth coexist with a higher incidence of health conditions linked to heavy metal

toxicity, with both benefits and costs concentrated within about 5 kilometers of the mine.

Similarly, Basu and Mueller (2025) show that adolescent girls near Zambian copper mines exhibit lower school attendance and higher rates of paid employment. Qualitative and case-study evidence from artisanal and small-scale mining regions in Ghana and Nigeria similarly documents higher dropout and lower attendance in mining-adjacent communities, typically attributed to child labor in mining activities, disrupted household livelihoods, and environmental degradation affecting agricultural income.

An important limitation of this literature is that proximity-based measures of mining exposure cannot separate the specific channels through which mining might affect educational outcomes. A community located near a mine may be affected simultaneously by child labor opportunities that pull children out of school, income shocks to agricultural livelihoods, and environmental contamination, and thus existing designs offer no way to distinguish between these mechanisms. Moreover, this literature has generally concentrated on effects near the mine itself, rather than on communities located at a distance through hydrological connectivity. This paper addresses this limitation directly: by defining exposure through upstream hydrological connectivity rather than proximity, the analysis can isolate an environmental exposure channel from the labor-market and income channels emphasized in prior work.

SAEB/IDEB as Outcome Measures

The analysis uses data from the Sistema de Avaliação da Educação Básica (SAEB), Brazil's national standardized assessment of mathematics and Portuguese language performance, along with the Índice de Desenvolvimento da Educação Básica (IDEB), which combines SAEB performance with school-level flow indicators such as approval, failure, and dropout rates. Because IDEB incorporates both learning outcomes and student progression, it may respond to a broader set of channels than test scores alone. For instance, health-related absenteeism or dropout, in addition to cognitive performance. This distinction is directly relevant to the results below: differences in the magnitude of estimated effects across Math, Portuguese, SAEB, and

IDEB are consistent with Garimpo exposure affecting both learning and school progression.

Positioning and Contribution

This paper makes three contributions to the literature reviewed above. First, it extends the use of river-network identification strategies, previously applied to infant health outcomes (Dias et al., 2023) and to vegetation and agricultural productivity (Vashold et al., 2025), to children's educational achievement, a human capital outcome not yet studied through this lens. Second, it extends the literature on mining and education, which has relied primarily on proximity-based comparisons in African settings, by using hydrological connectivity to isolate an environmental exposure channel from the labor-market and income channels emphasized in prior work. Third, by combining reduced-form educational outcomes with direct evidence on the underlying contamination pathway, heterogeneity by school water source and independent evidence of mercury biomagnification in local fish catches, the paper provides a more complete empirical account of the mechanism linking upstream Garimpo activity to downstream educational outcomes than is typically available in this literature.

Data

Educational data

Our primary outcome variables are derived from the Sistema de Avaliação da Educação Básica (SAEB), a standardized testing system administered biennially by the Instituto Nacional de Estudos e Pesquisas Educacionais Anísio Teixeira (INEP, 2024c; accessed via Base dos Dados) to evaluate basic education quality across public and private schools in Brazil. The assessment evaluates student proficiency in Portuguese and Mathematics. SAEB scores are further integrated to compute the Índice de Desenvolvimento da Educação Básica (IDEB; INEP, 2024c; accessed via Base dos Dados), which tracks institutional progress by scaling average standardized scores (0 to 10) by the school’s grade promotion rate. This dual-metric structure prevents schools from artificially inflating performance through grade retention. For our primary empirical

specifications, we analyze school-level 5th-grade standardized Mathematics scores, standardized Portuguese scores, combined SAEB scores, and overall IDEB scores.

In addition to academic achievement metrics, we incorporate school infrastructure and demographic variables from the Censo Escolar (INEP, 2024a; accessed via Base dos Dados) and spatial location metrics from the Dicionário de Escolas (INEP, 2024b; accessed via Base dos Dados). These data provide precise geocoded school locations (latitude and longitude), student pass rates, class size ratios, and socio-economic and demographic characteristics at the school level. We selected the schools from the Amazonas, Pará, Rondônia, Roraima, Mato Grosso and Minas Gerais. Since all the states belong to the Amazonian legal and Mines Gerais is an important Mining State with a long history of extraction. We also reduced the sample of schools to those with the latitude and longitude available in the data set.

Mining

For our independent variables, we utilize the MapBiomas Mining dataset (Collection 9.0; MapBiomas, 2024), which provides a high-resolution, long-term historical reconstruction of mining activities across Brazil from 1985 to 2023. This dataset relies on cloud computing and deep learning algorithms applied to 30-meter resolution Landsat satellite imagery to accurately classify and distinguish artisanal mining (Garimpo) areas. We employ yearly municipal-level statistics for our analysis, which quantify the total annual area (in hectares) dedicated to the extraction of gold, precious stones, ornamental stones, tin, and overall mining activity.

Our study focuses specifically on gold Ggarimpos, as they constitute the largest share of all artisanal mining activity in Brazil, averaging approximately 80 percent of the total land area dedicated to Garimpo operations. Furthermore, gold mining poses the most severe and immediate threat to local ecosystems and communities due to the intensive use of mercury during the extraction process and the concentration of alluvial gold deposits along riverbanks.

River network

To construct our upstream and downstream exposure metrics, we utilize the Base Hidrográfica Ottocodificada Multiescalas (BHO 2017; Agência Nacional de Águas e Saneamento Básico [ANA], 2017), provided by Brazil's National Water and Basic Sanitation Agency. Our identification strategy operates at the school level, using geocoded school coordinates from the INEP School Census (Censo Escolar; INEP, 2024a; accessed via Base dos Dados) as our spatial baseline. For each school, we first identify its nearest river reach within the BHO 2017 network topology. Leveraging the topological connectivity and directional flow algorithms among river reaches, we trace the hydrographic network both upstream and downstream from the school's associated water segment. This hydrological routing enables us to precisely isolate and identify municipalities that are hydrologically connected to each school within the river system.

For each municipality connected to the schools, we calculated its distance from the school's reference drainage segment and ranked the municipalities separately in the upstream and downstream directions. We retained the ten closest upstream municipalities and the ten closest downstream municipalities for each school and aggregate the total mining area in each direction. Thus, the resulting exposure captures the effect of mining activity in municipalities located within the upstream and downstream portions of the drainage network connected to each school closest river segment.

Table 1. Descriptive Statistics

School Level Data					
	N	Mean	SD	Min	Max
SAEB Score - Standardized (Math and Portuguese)	22,955	5.508	0.941	1.857	8.807
IDEB Index (0-10 scale)	22,954	5.135	1.161	0.200	8.500
SAEB Math Score - Standardized	22,955	0.045	0.961	-4.004	4.871
SAEB Portuguese Score - Standardized	22,955	0.031	0.964	-3.238	3.798
Approval Rate - 5th Grade	22,916	92.246	9.735	0	100
Upstream Garimpo Gold (km^2)	22,955	1.430	20.493	0	555.272
Downstream Garimpo Gold (km^2)	22,955	9.616	50.182	0	833.195
Upstream Garimpo (km^2)	22,955	1.640	20.801	0	563.988
Downstream Garimpo (km^2)	22,955	13.891	50.703	0	841.911

Upstream Garimpo Precious Stones (km^2)	22,955	0.006	0.069	0	1.009
Upstream Garimpo Ornamental Stones (km^2)	22,955	0.004	0.075	0	2.959
Upstream Garimpo Tin (km^2)	22,955	0.154	2.374	0	70.497
Water Supply: River/Spring/Stream	22,955	0.012	0.107	0	1
Water Supply: Artesian Well	22,955	0.286	0.452	0	1
Water Supply: Cistern/Shallow Well	22,955	0.039	0.194	0	1
Average Class Size - 5th Grade	22,914	26.250	6.047	1.5	91
Age-Grade Distortion Rate - 5th Grade	22,751	22.323	16.577	0	100
Internet Access	22,955	0.794	0.404	0	1
Black Students (%)	22,910	0.055	0.057	0	1
Indigenous Students (%)	22,910	0.007	0.055	0	1
Mixed-Race Students (%)	22,910	0.67	0.21	0	1
Female Students (%)	22,955	0.486	0.034	0	1
Municipal Level Data					
	Count	Mean	SD	Min	Max
Garimpo Gold Area (km^2)	4,791	3.580	36.319	0	903.306
Garimpo Area (km^2)	4,791	4.157	36.772	0	908.146
Log GDP	4,791	19.351	1.332	16.582	25.161
Log Net Taxes	4,787	16.409	1.729	11.482	23.523
Log Gross Value Added	4,791	19.285	1.309	16.549	24.945
Log GVA — Public Administration	4,791	18.069	1.049	15.838	23.005
Log Agricultural GVA	4,791	17.402	1.295	13.058	21.108
Log Industrial GVA	4,791	16.831	1.909	13.124	24.118
Log Services GVA	4,791	18.047	1.507	15.248	24.067
Log Total Quantity of Non-Piscivorous Fish	2,880	9.693	2.479	2.303	16.485
Log Total Quantity of Piscivorous Fish	1,388	9.088	2.269	1.609	15.715
Log Total Quantity of All Fish	2,997	9.811	2.511	2.303	16.485

Economic activity

To capture local economic dynamics and sectoral trade-offs, we incorporate municipal-level economic data from the Instituto Brasileiro de Geografia e Estatística (IBGE). Specifically, we use annual Gross Domestic Product (GDP) metrics (IBGE, 2024a; accessed via Base dos Dados) to evaluate trends in total GDP, net taxes, and gross value added across key economic sectors, including Agriculture, Industry, and Services.

Additionally, we obtain municipal aquaculture production data directly from IBGE's Municipal Livestock Survey (Pesquisa Pecuária Municipal [PPM]; IBGE, 2024b). These metrics capture annual municipal production volume (in kilograms) and total monetary value for aquatic species. Our analysis focuses on native freshwater river

species, classified into piscivorous (dourado, pintado, pirarucu, traíra, and tucunaré) and non-piscivorous (curimatã, jatuarana, lambari, matrinxã, pacu, piau, pirapitinga, and tambaqui) groups, excluding non-native or commercial farm-raised species. Table 1 summarizes these municipal and school-level descriptive statistics.

Methodological Framework

Our empirical strategy examines the relationship between upstream mining exposure and educational outcomes at the school level. The underlying mechanism is that Garimpo mining may contribute to river pollution through the releasing of naturally occurring heavy metals and the use of mercury during the mining process. Schools located downstream from mining activity may be exposed to these pollutants through the river system, particularly when they rely directly on river water as their main source. We estimate four specifications that progressively examine the relationship between upstream mining exposure and educational outcomes, the role of river-water dependence, and the validity of downstream mining as a placebo.

Baseline Model

We first estimate the relationship between upstream mining exposure and educational outcomes using Equation (1):

$$Y_{ikt} = \beta_1 Upstream_{xit} + \delta X_{it} + \mu_i + \tau_{rt} + \epsilon_{ikt} \quad (1)$$

where Y_{ikt} represents educational outcome *k* for school *i* in year *t*. The outcomes considered are the SAEB standardized average score, the IDEB score, the standardized Mathematics score, and the standardized Portuguese score. $Upstream_{xit}$ represents the total area in km² of mining activity located upstream of the river segment associated with school *i*. We consider both upstream Garimpo Gold mining and total Garimpo mining activity. X_{it} represents a vector of school-level characteristics, including river water supply, average class size in the 5th grade, the age-grade distortion rate in the 5th grade, internet access, and the shares of Black-race, mixed-race, Indigenous-race, and female students. The model includes school fixed effects μ_i and federation-by-year fixed effects τ_t. School fixed effects account for time-invariant

characteristics of schools, while federation-by-year fixed effects capture time-varying factors common to schools within each federation.

River-Water Exposure

While the baseline model examines the relationship between upstream mining exposure and educational outcomes, the proposed mechanism should be particularly relevant for schools that rely directly on river water. We therefore extend the analysis in Equation (2) by including an interaction between upstream mining exposure and river-water dependence:

$$Y_{ikt} = \beta_1 Upstream_{xit} + \beta_2 (Upstream_{xit} \times WaterRiver_{it}) + \beta_3 WaterRiver_{it} + \delta X_{it} + \mu_i + \tau_{rt} + \epsilon_{ikt} \quad (2)$$

where $WaterRiver_{it}$ is a binary variable that takes the value of one when the school's main water sources come from river, spring, or stream as our pollution exposition proxy. The interaction between upstream mining exposure and river-water dependence allows us to examine whether the relationship between mining exposure and educational outcomes differs according to the school's reliance on river water.

Downstream Mining as a Placebo

To further assess whether the estimated relationship is consistent with exposure to upstream mining rather than simply reflecting the presence of mining activity in connected municipalities, we introduce downstream mining activity as a placebo measure in Equation (3):

$$Y_{ikt} = \beta_1 Upstream_{xit} + \beta_2 Downstream_{xit} + \delta X_{it} + \mu_i + \tau_{rt} + \epsilon_{ikt} \quad (3)$$

where $\beta_2 Downstream_{xit}$ represents the total area in km² of Garimpo Gold or total Garimpo mining activity located downstream from the school-associated river segment. The rationale for this placebo test follows the direction of river flow. Mining activity located downstream from a school should not affect the water reaching that school through the same river system because river water flows away from the school toward downstream locations. Therefore, downstream mining activity should not have

a systematic effect on the school's educational outcomes if the estimated upstream relationship is driven by exposure to pollutants transported through the river system.

River-Water Dependence and the Downstream Placebo

Finally, Equation (4) combines the river-water interaction with the downstream placebo test:

$$\begin{aligned} Y_{ikt} = {} & \beta_1 Upstream_{xit} + \beta_2 (Upstream_{xit} \times WaterRiver_{it}) \\ & + \beta_3 Downstream_{xit} + \beta_4 (Downstream_{xit} * WaterRiver_{it}) \\ & + \beta_5 WaterRiver_{it} + \delta X_{it} + \mu_i + \tau_t + \epsilon_{ikt} \end{aligned} \quad (4)$$

This specification includes interactions between river-water dependence and both upstream and downstream mining exposure. The objective is to examine whether the relationship between mining exposure and educational outcomes is concentrated among schools that rely on river water, while simultaneously testing whether a similar relationship is observed for mining activity located downstream. Under the proposed mechanism, the interaction between upstream mining exposure and river-water dependence is expected to be negative if upstream mining pollution adversely affects educational outcomes through the river water system. In contrast, the corresponding interaction between downstream mining exposure and river-water dependence is hypothesized to be statistically insignificant, since downstream mining activity should not affect the water reaching the school. Taken together, Equations (1)-(4) provide a progression from the baseline relationship between upstream mining exposure and educational outcomes to an examination of the proposed river-water mechanism and a downstream placebo test. The comparison between upstream and downstream exposure provides an additional test of the role of river direction in determining schools' exposure to potential mining-related pollution.

Results

Baseline Model

Table 2 presents the results from Equation (1), examining the relationship between upstream Garimpo mining exposure and educational outcomes. Columns

(1)-(4) report the estimates for upstream Garimpo Gold mining, while columns (5)-(8) report the estimates for total upstream Garimpo mining. Within each group of four columns, the dependent variables are the standardized Mathematics score, standardized Portuguese score, standardized SAEB score, and IDEB, respectively.

The coefficient on upstream Garimpo Gold exposure is negative and statistically significant across all four educational outcomes. The estimated coefficients range from -0.0016 for Mathematics to -0.0020 for IDEB. The results are very similar when total Garimpo mining exposure is used as the explanatory variable, with coefficients ranging from -0.0016 to -0.0020. This indicates that greater upstream mining exposure is consistently associated with lower educational outcomes across both subject-specific and aggregate measures.

Table 2. Effects of Upstream Garimpo on Educational Outcomes

Panel A. Garimpo Gold				
	(1) Math	(2) Portuguese	(3) SAEB	(4) IDEB
Upstream Garimpo Gold (km²)	-0.0016***	-0.0009**	-0.0013***	-0.0021***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819
Panel B Garimpo				
	(5) Math	(6) Portuguese	(7) SAEB	(8) IDEB
Upstream Garimpo (km²)	-0.0016***	-0.0009**	-0.0013***	-0.0020***
	(0.0003)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819

Notes: Garimpo Gold refers to mining areas classified as gold-producing Garimpo, while Garimpo refers to the total area of Garimpo mining across all mineral types. The sample consists of 4,052 schools in 310 municipalities. Standard errors are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race,

and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Downstream Exposure Placebo Test

As a placebo test, we re-estimate the baseline specification form equation 1 using only mining exposure located downstream from the school rather than upstream. This provides a useful test of whether the estimated relationship is driven by general spatial correlation, local mining activity, or other factors associated with mining locations, rather than by exposure transmitted through the river network.

Table 3 Effects of Downstream Garimpo on Educational Outcomes

Panel A. Garimpo Gold				
	(1) Math	(2) Portuguese	(3) SAEB	(4) IDEB
Downstream Garimpo Gold (km²)	0.0002	-0.0001	0.0001	0.0001
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8391	0.8567	0.8579	0.8817
Panel B Garimpo				
	(5) Math	(6) Portuguese	(7) SAEB	(8) IDEB
Downstream Garimpo (km²)	0.0002	-0.0001	0.0001	0.0001
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8391	0.8567	0.8579	0.8817

Notes: Garimpo Gold refers to mining areas classified as gold-producing Garimpo, while Garimpo refers to the total area of Garimpo mining across all mineral types. Standard errors are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race, and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

The results are reported in Table 3. Across all four educational outcomes—standardized mathematics scores, standardized Portuguese scores, the standardized SAEB score, and IDEB. For the gold-Garimpo measure, the estimated coefficients range from 0.0001 to 0.0003, while the coefficients for total Garimpo exposure range from −0.0001 to 0.0002. None of these estimates is statistically significant.

This contrasts with the consistently negative and statistically significant coefficients obtained for upstream mining exposure in the baseline specification. The absence of an association with downstream exposure therefore provides supporting evidence that the main results are not simply capturing a general correlation between mining activity and school outcomes. Instead, the spatial direction of the river network appears to be relevant, consistent with the interpretation that mining located upstream can affect schools through exposure transmitted along the river system.

River-Water Exposure

Table 4. River-Water Exposure

Panel A. Garimpo Gold				
	(1) Math	(2) Portuguese	(3) SAEB	(4) IDEB
Upstream Garimpo Gold (km^2)	-0.0017***	-0.0009***	-0.0013***	-0.0021***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Upstream Garimpo Gold (km^2) * River Water Supply	-0.0016***	-0.0019***	-0.0017***	-0.0054***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819
Panel B Garimpo				
	(5) Math	(6) Portuguese	(7) SAEB	(8) IDEB
Upstream Garimpo (km^2)	-0.0016***	-0.0009***	-0.0013***	-0.0021***
	(0.0003)	(0.0004)	(0.0003)	(0.0005)
Upstream Garimpo (km^2) * River Water Supply	-0.0016***	-0.0018***	-0.0017***	-0.0054***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)

Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819

Notes: Garimpo Gold refers to mining areas classified as gold-producing Garimpo, while Garimpo refers to the total area of Garimpo mining across all mineral types. Standard errors are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race, and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Table 4 extends the baseline specification by incorporating the interaction between upstream mining exposure and the river-water indicator described in equation (2). Columns (1)-(4) use upstream Garimpo Gold exposure, while columns (5)-(8) use total Garimpo exposure.

The coefficient for upstream Garimpo Gold remains negative and statistically significant across all four outcomes, with estimates ranging from -0.0016 to -0.0021. The corresponding coefficients for total Garimpo exposure are nearly identical. The interaction between river-water dependence and upstream mining exposure is also negative and statistically significant across all four educational outcomes. For Garimpo Gold, the interaction coefficients range from -0.0016 for Mathematics to -0.0054 for IDEB. The results using total Garimpo exposure are again very similar, with interaction coefficients ranging from -0.0016 to -0.0054.

Upstream and Downstream Mining Exposure

Table 5 presents the results from the specification including both upstream and downstream mining exposure described in equation (3). The objective is to examine whether the estimated relationship is specific to mining activity located upstream of the school.

The coefficients on upstream Garimpo Gold exposure remain negative and statistically significant across all four educational outcomes, ranging from -0.0016 for

Mathematics to -0.0020 for IDEB. The corresponding coefficients for total Garimpo exposure are almost identical.

In contrast, the coefficients on downstream Garimpo Gold exposure are small and statistically insignificant across all four outcomes. They range from -0.0001 to 0.0003. The same pattern is observed for total downstream Garimpo exposure, with coefficients between -0.0001 and 0.0002, none of which is statistically significant.

Table 5. Upstream and Downstream Mining Exposure

Panel A. Garimpo Gold				
	(1) Math	(2) Portuguese	(3) SAEB	(4) IDEB
Upstream Garimpo Gold (km^2)	-0.0016***	-0.0009**	-0.0013***	-0.0021***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Downstream Garimpo Gold (km^2)	0.0002	-0.0001	0.0001	0.0001
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819
Panel B Garimpo				
	(5) Math	(6) Portuguese	(7) SAEB	(8) IDEB
Upstream Garimpo (km^2)	-0.0016***	-0.0009**	-0.0013***	-0.0020***
	(0.0003)	(0.0004)	(0.0003)	(0.0005)
Downstream Garimpo (km^2)	0.0002	-0.0001	0.0000	0.0001
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819

Notes: Garimpo Gold refers to mining areas classified as gold-producing Garimpo, while Garimpo refers to the total area of Garimpo mining across all mineral types. Standard errors

are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race, and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Upstream and Downstream Water Exposure

Table 6 combines the interaction between river-water dependence and upstream mining exposure with the corresponding interaction between river-water dependence and downstream mining exposure described in equation (4). Columns (1)-(4) use Garimpo Gold exposure, while columns (5)-(8) use total Garimpo exposure.

Table 6.Upstream and Downstream Water Exposure

Panel A. Garimpo Gold				
	(1) Math	(2) Portuguese	(3) SAEB	(4) IDEB
Upstream Garimpo Gold (km^2)	-0.0016***	-0.0010***	-0.0013***	-0.0021***
	(0.0003)	(0.0004)	(0.0004)	(0.0005)
Upstream Garimpo Gold (km^2) * River Water Supply	-0.0008	-0.0024**	-0.0016**	-0.0063***
	(0.0005)	(0.0009)	(0.0006)	(0.0005)
Downstream Garimpo Gold (km^2)	0.0003	-0.0001	0.0001	0.0001
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Downstream Garimpo Gold (km^2) * River Water Supply	-0.0007	0.0005	-0.0001	0.0009
	(0.0007)	(0.0010)	(0.0008)	(0.0007)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8820
Panel B Garimpo				
	(5) Math	(6) Portuguese	(7) SAEB	(8) IDEB
Upstream Garimpo (km^2)	-0.0016***	-0.0009***	-0.0013***	-0.0021***
	(0.0003)	(0.0004)	(0.0003)	(0.0004)

Upstream Garimpo (km^2) * River Water Supply	-0.0010	-0.0026***	-0.0018**	-0.0064***
	(0.0007)	(0.0009)	(0.0007)	(0.0007)
Downstream Garimpo (km^2)	0.0002	-0.0001	0.0001	0.0001
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Downstream Garimpo (km^2) * River Water Supply	-0.0005	0.0007	0.0001	0.0011
	(0.0009)	(0.0011)	(0.0009)	(0.0009)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8568	0.8580	0.8820

Notes: Standard errors are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race, and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

The coefficients on upstream mining exposure remain negative and statistically significant across all specifications. For Garimpo Gold, the coefficients range from -0.0016 to -0.0021, while the coefficients for total Garimpo exposure are very similar.

The interaction between upstream mining exposure and river-water dependence is negative across all four educational outcomes. It is statistically significant for Portuguese, the standardized SAEB score, and IDEB, with coefficients of -0.0024, -0.0016, and -0.0063, respectively. For Mathematics, the coefficient is -0.0008 and is not statistically significant. The results using total Garimpo exposure show a similar pattern: the interaction is negative and statistically significant for Portuguese, the standardized SAEB score, and IDEB, while the Math interaction is negative but statistically insignificant.

In contrast, the interaction between downstream mining exposure and river-water dependence is statistically insignificant across all four outcomes. For Garimpo Gold, the coefficients range from -0.0007 to 0.0009, while the corresponding coefficients for total Garimpo range from -0.0005 to 0.0011. None of these estimates is statistically significant.

Overall, the results in Table 6 show that the negative relationship associated with upstream mining exposure is concentrated among schools for which river-water dependence is relevant, while no comparable relationship is observed for downstream mining exposure. The results are consistent across the Garimpo Gold and total Garimpo specifications.

Heterogeneity and Robustness

To further examine the interpretation and robustness of the baseline results, we conduct a series of additional analyses. We first investigate whether the estimated effects differ across geographic areas and schools with different performance targets. We then examine whether the results are specific to Gold Garimpo, test alternative educational outcomes and water-exposure measures. Finally, we investigate potential confounding effects of which local Garimpo activity may affect educational outcomes by examining its relationship with river fish production and local economic activity.

Geographic Heterogeneity: Legal Amazon and Minas Gerais

We first examine whether the estimated effects differ between the Amazon and Minas Gerais. These regions differ substantially in their history, intensity, environmental characteristics and geographic distribution of Garimpo activity, providing an opportunity to assess whether the estimated relationship is concentrated in areas. Table 7 presents the heterogeneity results.

Columns (1)-(8) report the results separately for schools located in the Amazon and Minas Gerais. The estimated coefficients for upstream Garimpo Gold exposure are negative and statistically significant across all four educational outcomes in the Legal Amazon. The coefficient on upstream Garimpo Gold is −0.0016 for mathematics, −0.0009 for Portuguese, −0.0013 for the standardized SAEB score, and −0.0019 for IDEB. The corresponding coefficients using total upstream Garimpo exposure are virtually identical.

In contrast, the estimated coefficients in Minas Gerais are also negative but substantially less precisely estimated and are not statistically significant. The coefficients range from approximately −0.045 to −0.058 across the educational outcomes. This pattern suggests that the estimated effects are primarily concentrated in the Amazon, where exposure to river-connected Garimpo is particularly relevant due to the large river system.

Importantly, the similarity between the Gold Garimpo and Garimpo specifications indicates that the results are not driven by small differences in the definition of the mining exposure measure. Overall, geographic heterogeneity is consistent with the interpretation that the effects are stronger in areas where riverine Garimpo is more prevalent and relevant for local environmental exposure.

Table 7. Geographic Heterogeneity: Legal Amazon and Minas Gerais

Panel A. Amazon - Garimpo Gold				
	(1)	(2)	(3)	(4)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo Gold (km^2)	-0.0016***	-0.0009**	-0.0013***	-0.0021***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	10,287	10,287	10,287	10,286
R-squared	0.7974	0.8409	0.8325	0.8510
Panel B. Amazon – Garimpo				
	(5)	(6)	(7)	(8)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo (km^2)	-0.0016***	-0.0009**	-0.0013***	-0.0020***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Observations (N)	10,287	10,287	10,287	10,286
R-squared	0.7974	0.8409	0.8325	0.8510
Panel C. Minas Gerais - Garimpo Gold				
	(9)	(10)	(11)	(12)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo Gold (km^2)	-0.0495	-0.0587	-0.0536	-0.0455

	(0.0569)	(0.0584)	(0.0571)	(0.0474)
Observations (N)	11,982	11,982	11,982	11,982
R-squared	0.7691	0.8073	0.7990	0.8193
Panel D. Minas Gerais – Garimpo				
	(13)	(14)	(15)	(16)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo (km^2)	-0.0486	-0.0568	-0.0522	-0.0441
	(0.0570)	(0.0590)	(0.0574)	(0.0477)
Observations (N)	11,982	11,982	11,982	11,982
R-squared	0.7691	0.8073	0.7989	0.8193

Notes: Panel A reports estimates for schools located in the Legal Amazon using upstream gold-producing Garimpo area as the treatment measure. Panel B reports estimates for schools located in the Legal Amazon using total upstream Garimpo area across all mineral types. Panel C and D report estimates for schools located in Minas Gerais. Standard errors are clustered at the municipality level and reported in parentheses. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

Heterogeneity by School Performance Target

Table 8. Heterogeneity by School Performance Target

Panel A. IDEB Target≤5 - Garimpo Gold				
	(1)	(2)	(3)	(4)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo Gold (km^2)	-0.0013**	-0.0010*	-0.0011**	-0.0019***
	(0.0005)	(0.0005)	(0.0005)	(0.0007)
Observations (N)	10,275	10,275	10,275	10,274
R-squared	0.7902	0.7940	0.8036	0.8333
Panel B. IDEB Target≤5 – Garimpo				
	(5)	(6)	(7)	(8)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo (km^2)	-0.0013**	-0.0010*	-0.0011**	-0.0019***
	(0.0005)	(0.0005)	(0.0005)	(0.0007)
Observations (N)	10,275	10,275	10,275	10,274
R-squared	0.7902	0.7940	0.8036	0.8333
Panel C. IDEB Target>5 - Garimpo Gold				
	(9)	(10)	(11)	(12)
	Math	Portuguese	SAEB	IDEB

Upstream Garimpo Gold (km^2)	-0.0061***	-0.0038***	-0.0050***	-0.0055***
	(0.0007)	(0.0008)	(0.0007)	(0.0007)
Observations (N)	10,562	10,562	10,562	10,562
R-squared	0.7995	0.8158	0.8177	0.8329
Panel D. IDEB Target>5 – Garimpo				
	(13)	(14)	(15)	(16)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo (km^2)	-0.0058***	-0.0036***	-0.0047***	-0.0051***
	(0.0007)	(0.0007)	(0.0007)	(0.0006)
Observations (N)	10,562	10,562	10,562	10,562
R-squared	0.7995	0.8158	0.8177	0.8329

Notes: Panels A and B report estimates for schools with an IDEB target score equal to or below 5. Panels C and D report estimates for schools with an IDEB target score above 5. Panels A and C use Gold Garimpo area as the treatment measure, while Panels B and D use Garimpo area across all mineral types. Standard errors are clustered at the municipality level and reported in parentheses. Statistical significance is indicated by $*p < 0.10$, $** p < 0.05$, and $*** p < 0.01$.

We next investigate whether the effects differ according to the performance target of the school in table 8. Schools are divided according to their IDEB target measured from 1 to 10, using a cutoff of 5. This analysis allows us to examine whether schools with relatively higher performance targets respond differently to environmental exposure than schools with lower targets.

The results are remarkably consistent across the two groups. For schools with an IDEB target below 5, upstream Garimpo Gold is associated with negative and statistically significant effects on mathematics, Portuguese, the standardized SAEB score, and IDEB. The coefficients are −0.0012, −0.0010, −0.0011, and −0.0018, respectively. The estimates based on total upstream Garimpo are almost identical.

For schools with an IDEB target of 5 or higher, the estimated effects are again negative and statistically significant for all four outcomes. The Garimpo Gold coefficients are larger in magnitude, ranging from −0.0039 for Portuguese to −0.0061 for mathematics, with similarly negative effects for the standardized SAEB score and IDEB.

The results therefore provide evidence that the negative relationship between upstream Garimpo exposure and educational outcomes is not confined to low-performing schools and is present across different levels of school performance.

Alternative Garimpo Minerals

We next assess whether the estimated relationship is specific to Garimpo Gold or whether similar effects are observed for other minerals. We separately examine upstream Garimpo extraction of precious stones, ornamental stones, and tin.

Table 9. Alternative Garimpo Minerals

Panel A. Garimpo Precious Stones				
	(1) Math	(2) Portuguese	(3) SAEB	(4) IDEB
Upstream Garimpo Precious Stones (km^2)	-0.0911	-0.0100	-0.0516	-0.0241
	(0.3697)	(0.1463)	(0.2534)	(0.4732)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8391	0.8567	0.8579	0.8817
Panel B. Garimpo Ornamental Stones				
	(5) Math	(6) Portuguese	(7) SAEB	(8) IDEB
Upstream Garimpo Ornamental Stones (km^2)	-0.0880***	-0.0124	-0.0513	-0.1315***
	(0.0317)	(0.0337)	(0.0319)	(0.0362)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8391	0.8567	0.8579	0.8817
Panel C. Garimpo Tin				
	(9) Math	(10) Portuguese	(11) SAEB	(12) IDEB
Upstream Garimpo Tin (km^2)	-0.0187	-0.0135**	-0.0161*	-0.0090
	(0.0118)	(0.0065)	(0.0086)	(0.0167)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8391	0.8567	0.8579	0.8817

Notes: Columns (1)-(4) report estimates for upstream Garimpo producing precious stones, columns (5)-(8) report estimates for upstream Garimpo producing ornamental stones, and columns (9)-(12) report estimates for upstream Garimpo producing tin. The sample consists of 4,052 schools in 310 municipalities. Standard errors are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race, and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

The results provide some evidence of negative associations for ornamental stones and tin, particularly for mathematics and Portuguese. However, the estimates are substantially less consistent than those obtained for gold, and the coefficients for the standardized SAEB outcome are not statistically significant in some cases. This pattern

is consistent with the main analysis being particularly relevant to Garimpo Gold rather than reflecting a uniform effect of all types of Garimpo activity.

Alternative Educational Outcome

Table 10. Alternative Educational Outcome

Panel A. Garimpo Gold			
	Full Sample	Amazon	Minas Gerais
	(1)	(2)	(3)
	Approval Rate	Approval Rate	Approval Rate
Upstream Garimpo Gold (km^2)	-0.0157***	-0.0160***	0.0446
	(0.0052)	(0.0049)	(0.2356)
Observations (N)	22,269	10,287	11,982
R-squared	0.7642	0.7249	0.6244
Panel B. Garimpo			
	Full Sample	Amazon	Minas Gerais
	(4)	(5)	(6)
	Approval Rate	Approval Rate	Approval Rate
Upstream Garimpo (km^2)	-0.0148***	-0.0150***	0.0381
	(0.0053)	(0.0051)	(0.2368)
Observations (N)	22,269	10,287	11,982
R-squared	0.7642	0.7249	0.6244

Note: Columns (1)-(4) use the full sample, columns (2)-(5) restrict the sample to municipalities in the Legal Amazon, and columns (3)-(6) restrict the sample to municipalities in Minas Gerais. The sample consists of 4,052 schools in 310 municipalities in columns (1)-(4), 1,979 schools in 104 municipalities in columns (2)-(5), and 2,073 schools in 206 municipalities in columns (3)-(6). Standard errors are clustered at the municipality level and reported in parentheses. Controls include river water supply, class size, age-grade distortion, internet access, and the percentages of Black, Indigenous, mixed-race, and female students. All specifications include school fixed effects and region-year fixed effects. Statistical significance is indicated by * $p < 0.10$, ** $p < 0.05$, and *** $p < 0.01$.

As an additional robustness check, we replace the main educational outcomes with the school approval rate in addition to the heterogeneity for Amazon and Minas Gerais in table 10. Using the same baseline specification of equation (1), upstream Garimpo exposure is associated with a statistically significant reduction in the approval rate in the full sample. The coefficient is approximately −0.015, while the estimate

using total upstream Garimpo is approximately −0.014. The negative relationship is also present in the Legal Amazon, where the coefficient is approximately −0.014, but is not statistically significant in Minas Gerais. Thus, the geographic pattern observed for the heterogeneity section remains consistent when applying a different educational outcome.

These results strengthen the interpretation that the estimated effects are not specific to standardized test scores or IDEB but extend to another dimension of school performance.

Alternative Water Sources

Table 11. Alternative Water Sources

Panel A. Garimpo Gold – Water Supply: Artesian Well				
	(1)	(2)	(3)	(4)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo Gold (km^2)	-0.0017***	-0.0010**	-0.0013***	-0.0021***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Upstream Garimpo Gold (km^2)* Water Supply: Artesian Well	0.0013	0.0017	0.0015	0.0003
	(0.0020)	(0.0024)	(0.0022)	(0.0019)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8568	0.8580	0.8819
Panel B. Garimpo Gold - Water Supply: Cistern				
	(5)	(6)	(7)	(8)
	Math	Portuguese	SAEB	IDEB
Upstream Garimpo Gold (km^2)	-0.0017***	-0.0010***	-0.0014***	-0.0022***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Upstream Garimpo Gold (km^2)* Water Supply: Cistern	0.0013	0.0014	0.0013	0.0029
	(0.0013)	(0.0013)	(0.0013)	(0.0020)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8392	0.8567	0.8580	0.8819
Panel C. Garimpo – Water Supply: Artesian Well				
	(9)	(10)	(11)	(12)

	Math	Portuguese	SAEB	IDEB
Upstream Garimpo Gold (km^2)	-0.0016***	-0.0009**	-0.0013***	-0.0020***
	(0.0004)	(0.0004)	(0.0004)	(0.0005)
Upstream Garimpo Gold (km^2)* Water Supply: Artesian Well	0.0010	0.0011	0.0010	0.0004
	(0.0018)	(0.0022)	(0.0020)	(0.0018)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8393	0.8567	0.8580	0.8819

Panel D. Garimpo - Water Supply: Cistern

	(13) Math	(14) Portuguese	(15) SAEB	(16) IDEB
Upstream Garimpo Gold (km^2)	-0.0017***	-0.0010***	-0.0013***	-0.0022***
	(0.0003)	(0.0004)	(0.0004)	(0.0004)
Upstream Garimpo Gold (km^2)* Water Supply: Cistern	0.0012	0.0013	0.0013	0.0028
	(0.0013)	(0.0014)	(0.0013)	(0.0020)
Observations (N)	22,269	22,269	22,269	22,268
R-squared	0.8392	0.8567	0.8580	0.8819

Notes: Standard errors in parentheses are clustered at the municipality level. Controls include Water from River source, class size, age-grade distortion, internet access, race and gender percentages. The sample includes 4,052 schools and 310 municipalities. All specifications include school fixed effects and region-year fixed effects. * p<0.10 ** p<0.05 *** p<0.01.

We also investigate whether the results depend mechanically on the definition of the water-exposure channel as table 11 presents. In the baseline specification, river water exposure is interacted with upstream Garimpo exposure. We therefore estimate different specifications using alternative water sources, including artesian wells and cisterns.

The results provide an important distinction between the river-based exposure measure and other sources of water. The coefficient on upstream Garimpo Gold remains negative and statistically significant in the baseline river specification, while the interactions between upstream Garimpo Gold and alternative water sources are not statistically significant. The same pattern is obtained when Garimpo exposure is used instead of Garimpo Gold exposure.

This evidence supports the interpretation that the estimated relationship is associated specifically with river-connected exposure rather than simply capturing a general correlation between mining activity and schools located in areas with different water sources.

Environmental Channel: River Fish Production

We also present some evidence to hypothesize the presence of a possible environmental water transportation channel; we examine whether local Garimpo activity is associated with changes in river fish production in table 12. We use municipal-level fish production data from the PPM (The Municipal Livestock Survey) provided by the Brazilian Institute of Geography and Statistics (IBGE) where they present total yearly municipal production quantity and value for different fish species. We first distinguished the fish species that are locally captured in river flows and then separated them into three groups composed of piscivorous fish (predatory fishes that eat other fishes), non-piscivorous fishes, and all fishes. The dependent variables are expressed in logarithmic form. Since we lack the location where the fish are caught due to data limitations we focus on the local Garimpo activity instead of the river flow network used in previous sections hence our main interest variables receive the notation of Local Garimpo Gold and Local Garimpo.

The results show a clear negative association between local Garimpo activity and piscivorous fish production. The coefficient is approximately −0.027 for local Garimpo Gold and −0.022 for total local Garimpo. In contrast, the estimated coefficients for non-piscivorous and total fish production are small and statistically insignificant.

This pattern is consistent with the possibility that Garimpo activity affects the river environment in ways that disproportionately affect fish species occupying higher levels in the environmental food chain. Although these estimates do not by themselves establish a causal mechanism linking water quality to educational outcomes, they provide complementary evidence that local Garimpo activity is associated with changes in river-dependent environmental conditions.

Table 12.Environmental Channel: River Fish Production

Panel A. Garimpo Gold			
	(1) Piscivorous	(2) Non-Piscivorous	(3) All Fish
Local Garimpo Gold (km^2)	-0.0274***	-0.0007	-0.0008
	(0.0091)	(0.0018)	(0.0018)
Observations (N)	1,352	2,853	2,971
R-squared	0.8006	0.8775	0.8840
Panel B. Garimpo			
	(4) Piscivorous	(5) Non-Piscivorous	(6) All Fish
Local Garimpo (km^2)	-0.0226***	-0.0006	-0.0007
	(0.0079)	(0.0018)	(0.0017)
Observations (N)	1,352	2,853	2,971
R-squared	0.8003	0.8775	0.8840

Notes: Standard errors in parentheses are clustered at the municipality level. The dependent variables are the logarithms of fish quantities. The logarithm of agricultural value added is used as a control. All specifications include municipality fixed effects and region-year fixed effects. * p<0.10 ** p<0.05 *** p<0.01.

Garimpo and Local Economic Activity

Finally, we examine whether the negative educational effects could simply reflect a general deterioration in local economic conditions associated with Garimpo activity. Unlike our main specifications, which measure exposure through upstream hydrological connectivity, this test uses Garimpo activity located within the same municipality, allowing us to assess whether local mining generates broader economic gains or losses that might be connected to educational outcomes. We estimate the relationship between local Garimpo activity and several measures of municipal economic activity, including GDP, Value Added. tax revenue, ADESPSS (Government expenditure), agricultural Value Added, Industry Added Value, and Services Added Value, in Table 13.

Table 13. Local Garimpo and Municipal Economic Outcomes

Outcome	Garimpo Gold	Garimpo

GDP	0.0004	0.0004
Value Added	0.0003	0.0003
Net Taxes	0.0010	0.0009
ADESPSS Value Added	−0.0000	0.0000
Agricultural Value Added	−0.0002	−0.0001
Industrial Value Added	0.0005	0.0007
Services Value Added	0.0015*	0.0014*
Observations	4,761	4,761

Notes: Each row reports results from a separate regression. Dependent variables are expressed in logs. Standard errors are clustered at the municipality level. All specifications include municipality fixed effects and region-by-year fixed effects. The columns report specifications using Garimpo Gold and Garimpo, respectively. * p<0.10 ** p<0.05 *** p<0.01.

The results provide little evidence of a systematic relationship between Garimpo activity and overall local economic activity. Most coefficients are statistically insignificant and close to zero. The only exception is services value added, for which the estimated coefficient is small but positive and statistically significant. Given that Garimpo activity generates income primarily for informal, often itinerant mining workers, this result could plausibly reflect modest local spending by garimpeiros on goods and services rather than a broader structural expansion of the local economy, though our data cannot directly test this interpretation due to data limitations.

Conclusion

This paper examines the effect of upstream Garimpo mining activity on children's educational outcomes in Brazil, using the river network to identify exposure to mining-related water contamination. The results show a consistent negative relationship between upstream Garimpo exposure and mathematics, Portuguese, standardized SAEB scores, and IDEB, with effects concentrated among schools that depend directly on river water. This relationship is not observed for downstream mining exposure, for schools relying on artesian wells or cisterns, or for minerals other than gold, supporting the interpretation that the estimated effect reflects exposure to mining-related contamination transmitted through the river network.

The estimated effects are concentrated in the Amazon, where Garimpo activity is most prevalent, while results for Minas Gerais are imprecisely estimated and possess no statistical significance. Effects are present across schools with both lower and higher

performance targets, and extend to school approval rates, suggesting that Garimpo exposure affects both learning outcomes and student progression through the school system.

Two additional pieces of evidence support the interpretation of an environmental exposure channel. First, local Garimpo activity is associated with little systematic change in municipal economic activity, with the exception of a small positive effect on services value added, plausibly reflecting local spending by mining workers rather than broader economic gains; this makes it unlikely that any local economic benefit is large enough to counter the educational costs documented in this paper. Second, local Garimpo activity is associated with a sharp decline in piscivorous fish production, consistent with mercury accumulation through the aquatic food chain, while non-piscivorous fish production is unaffected. Evidence supports the proposed contamination pathway.

Taking together, these results indicate that the social costs of artisanal gold mining extend to communities beyond their administrative borders in which mining takes place. Populations located along the same river system of Garimpo activities, may bear the human capital consequences of upstream extraction without receiving any of its local economic benefits. This has direct implications for environmental and mining policy in Brazil: regulatory and enforcement efforts focused narrowly on the vicinity of mining sites may fail to address the full geographic extent of the social costs generated by Garimpo activity. Future research could extend this framework to other pollutants and hydrological settings and could examine whether improvements in water infrastructure for river-dependent schools mitigate the adverse effects documented here.

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