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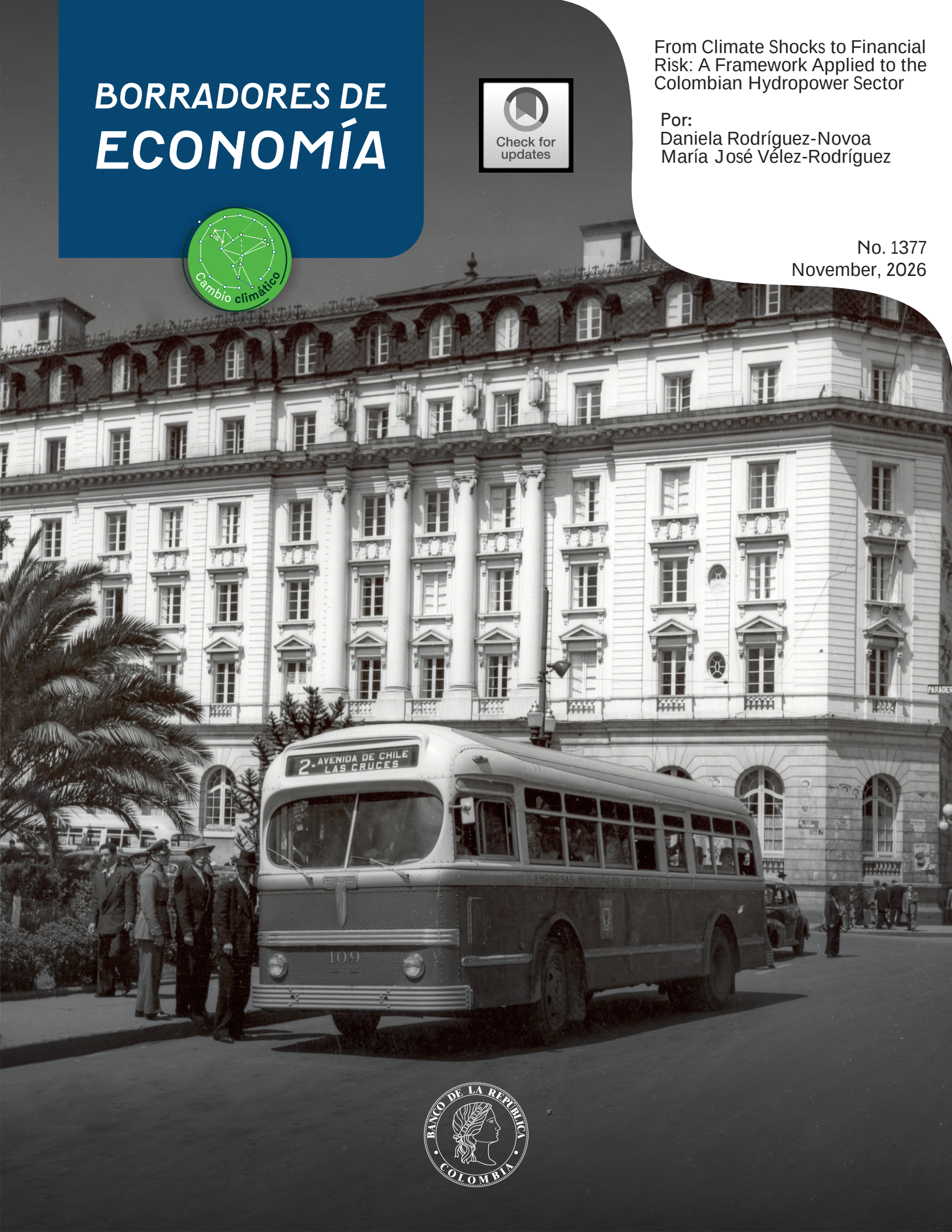
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From Climate Shocks to Financial Risk: A Framework Applied to the Colombian Hydropower Sector*

Daniela Rodríguez-Novoa† María José Vélez-Rodríguez‡

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Abstract

This paper develops a forward-looking climate stress-testing framework that integrates climate projections, plant-level hydropower production models, firm-level financial statements, and supervisory credit registry data to assess the potential implications of drought scenarios on the Colombian financial system. We first estimate the effects of extreme precipitation and drought on hydropower generation using a dynamic panel model and subsequently project electricity generation under alternative Shared Socioeconomic Pathway (SSP) climate scenarios. The simulated production shocks are translated into firms' revenues, operating costs, profitability, and debt-servicing capacity, and are ultimately mapped to banks' loan portfolios using supervisory credit registry information. The results indicate that hydropower generation is considerably more sensitive to extreme droughts than to periods of excessive rainfall. Under the proposed framework, projected reductions in hydropower generation propagate through firms' operating performance, weakening their financial resilience and ultimately deteriorating the credit quality of banks' loan portfolios exposed to the electricity generation sector.

JEL Codes: Q54, Q41, G21.

Keywords: Climate, energy, banks.

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De los choques climáticos al riesgo financiero: un marco aplicado al sector hidroeléctrico colombiano*

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Resumen

Este documento desarrolla un marco prospectivo de pruebas de estrés climático que integra proyecciones climáticas, modelos de producción hidroeléctrica a nivel de planta, estados financieros a nivel de firma e información de las operaciones activas de crédito del sistema financiero colombiano; con el fin de evaluar las posibles implicaciones de los escenarios de sequía sobre el sistema financiero. En primer lugar, se estiman los efectos de la precipitación y sequía extrema sobre la generación hidroeléctrica mediante un modelo de datos panel dinámico y, posteriormente, se proyecta la generación de electricidad bajo escenarios climáticos de las Trayectorias Socioeconómicas Compartidas (SSP, por su sigla en inglés). Los choques de producción simulados resultan afectando los ingresos, costos operativos, rentabilidad y capacidad de pago de las empresas hidroeléctricas para cumplir con sus obligaciones financieras, impactando de esta manera al sector financiero colombiano. Los resultados indican que la generación hidroeléctrica es considerablemente más sensible a las sequías extremas que a los periodos de lluvias excesivas. Bajo el marco propuesto, las reducciones proyectadas en la generación hidroeléctrica se transmiten hasta el desempeño operativo de las firmas, debilitando así su resiliencia financiera y deteriorando, en última instancia, la calidad crediticia de los portafolios de crédito de los bancos expuestos al sector de generación eléctrica.

Clasificación JEL: Q54, Q41, G21.

Palabras Clave: Clima, energía, bancos.

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1 Introduction

In recent years, preserving biodiversity and restoring degraded ecosystems have become central priorities for policymakers and researchers, reflecting growing concerns about the unprecedented rate at which nature is deteriorating and the implications for human well-being and the planet's habitability (NGFS, 2024; CBD, 2022). There is broad consensus that both nature degradation and the policies required to mitigate it will have important consequences for economic activity and the financial system. Consequently, international organizations, central banks, and financial supervisors have devoted increasing attention to understanding the macroeconomic and financial implications of transition policies, such as carbon pricing and emissions reduction measures, as well as the materialization of physical climate risks. These risks may affect economic activity, firms' profitability, asset prices, and financial stability through multiple transmission channels (FSB, 2020; ECB, 2020; NGFS, 2024; IMF, 2024).

Several studies have proposed frameworks and practical guidance to help central banks and financial authorities assess climate- and nature-related risks (ECB, 2020; NGFS, 2024). In particular, the NGFS proposes a three-phase framework to help central banks and supervisors identify, assess, and monitor material nature-related financial risks while supporting the design of policies consistent with their mandates and institutional context (NGFS, 2024). The first phase identifies the economic sectors and ecosystem services most exposed to physical and transition risks. The second phase assesses how these risks propagate through firms, households, and the broader economy via microeconomic and macroeconomic transmission channels. Finally, the third phase evaluates how these economic impacts are transmitted to financial institutions and the financial system through traditional risk categories, such as credit, market, liquidity, and operational risk.

Although the NGFS framework is intended as a flexible rather than a binding tool, its conceptual structure has inspired a growing body of work adapting its principles to different

jurisdictions, sectors, and policy objectives. Existing applications have focused on developing methodologies to assess the macroeconomic and financial implications of physical and transition climate risks through sector-specific analyses and climate stress-testing exercises. For example, Abuzied (2025) proposes a framework for evaluating the macroeconomic consequences of extreme climate events and the role of policy responses. Gourdel et al. (2024) develop an integrated framework to assess the double materiality of physical and transition climate risks in the euro area, explicitly linking climate hazards to macroeconomic and financial outcomes. Similarly, Ranger et al. (2022) present a scenario-generation framework to evaluate financial risks arising from physical climate shocks, while NGFS (2023) review practical methodologies adopted by central banks and supervisory authorities to incorporate environmental risks into financial risk analysis. Together, these studies illustrate how the NGFS conceptual approach can be tailored to different institutional settings and analytical purposes.

Likewise, a growing strand of the literature has extended these frameworks to quantify the effects of climate-related risks on firms' creditworthiness and banks' credit portfolios. For instance, CGFR (2023b) develop a framework to estimate the impact of physical climate hazards on bank loan default probabilities by linking climate scenarios with firm-level financial performance. Similarly, Trujillo-Galindo et al. (2025) propose a comprehensive climate stress-testing framework for the Peruvian financial system that combines climate scenarios with econometric models explicitly accounting for the geographic heterogeneity of climate exposure to project sector-specific default probabilities and the resulting implications for banking-sector credit risk. Focusing on transition risk, CGFR (2023a) assess the impact of climate-related transition policies on the default probabilities of thermal power companies, highlighting the importance of sector-specific analyses to capture the heterogeneous effects of climate shocks across the energy sector.

Building on this literature, we develop a sector-specific framework to assess the transmission of physical climate risk from extreme drought events to firms' financial vulnerability and

banking-sector credit risk. Following the first phase of the NGFS framework, we focus on the Colombian hydropower sector because it combines high exposure to precipitation shocks with systemic economic relevance. Hydropower accounts for approximately 60%-90% of Colombia's electricity generation, making electricity supply highly dependent on climate conditions. At the same time, the sector represents nearly 6% of the Colombian banking system's corporate credit portfolio, implying that climate-induced disruptions in electricity generation may have tangible implications for financial stability. Using plant-level production data, firm-level financial statements, supervisory credit registry information, and forward-looking climate scenarios, we develop an integrated framework that traces the transmission of precipitation shocks to hydropower generation, firms' operating performance, financial vulnerability, and ultimately banks' credit risk.

A related strand of the literature has examined the implications of climate variability for the hydropower sector, particularly in hydro-dominated electricity systems. For Colombia, Rios et al. (2024) analyze the effects of adverse weather events on retail electricity prices, showing that El Niño episodes increase electricity prices through higher wholesale spot prices. Similarly, Macías and Andrade (2013) evaluate the potential effects of climate change on future electricity generation under alternative climate scenarios, highlighting the vulnerability of Colombia's hydropower system to changes in precipitation. While these studies provide valuable evidence on the implications of climate variability for electricity generation and market outcomes, they do not assess how climate-related shocks affect firms' financial performance or how they propagate to the banking sector through credit risk. This paper contributes to the literature in several ways. First, we develop a forward-looking framework that integrates climate projections, plant-level hydropower production models, financial information of firms owning hydropower plants, and supervisory credit registry data to trace the transmission of precipitation shocks to banking-sector credit risk. Second, to the best of our knowledge, this is one of the first applications combining climate scenarios with econometric models of hydropower production to quantify how physical climate risk affects the financial resilience of electricity generation firms

under alternative climate pathways. Third, the proposed framework offers a practical methodology that enables central banks and financial supervisors to identify vulnerable sectors, firms, and credit exposures, thereby facilitating the incorporation of sector-specific physical climate risks into climate stress-testing exercises. Applying the framework to Colombia, we find that projected drought scenarios substantially reduce hydropower generation, potentially weakening firms' debt-servicing capacity and deteriorating the credit quality of banks' loan portfolios exposed to the electricity generation sector.

The remainder of the paper is organized as follows. Section 2 describes the Colombian Electricity Market and the institutional features that shape how droughts affect generation firms. Section 3 describes the data sources and explains how each of them feeds the modules of the framework. Section 4 introduces the proposed framework and its underlying assumptions. Section 5 presents the empirical results obtained by applying the framework to the Colombian hydropower sector. Finally, Section 6 concludes.

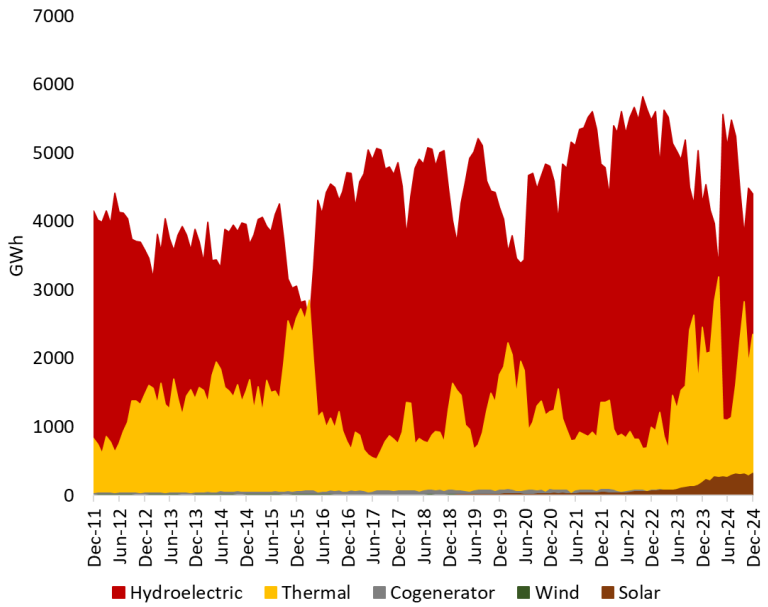
2 The Colombian Electricity Market

The Colombian electricity system comprises hydropower plants, thermal power plants fueled by natural gas, coal, and fuel oil, as well as non-conventional renewable energy sources, such as solar and wind power, whose participation has expanded in recent years. Nevertheless, electricity generation remains predominantly hydro-based. Under normal hydrological conditions, hydropower accounts for approximately 60–90% of total electricity generation, while the remaining share is supplied mainly by thermal power plants, with a modest contribution from solar generation since 2023. This generation mix provides Colombia with relatively low electricity generation costs and low carbon emissions but also makes the system highly vulnerable to prolonged droughts.

During periods of water scarcity, thermal generation plays a strategic role by compensating

for the reduction in hydropower output. As illustrated in Figure 1, the share of thermal generation increased substantially during the 2015–2016 El Niño episode, reaching nearly 50% of total electricity generation, and rose again, although to a lesser extent, during the 2023–2024 El Niño event. These episodes demonstrate that Colombia's heavy reliance on hydropower makes the electricity system particularly sensitive to climate variability and extreme drought events.

Figure 1: Electricity generation by energy source



Note: The figure depicts monthly electricity generation by source in the Colombian National Interconnected System (SIN), measured in GWh. Thermal generation includes natural gas, coal, and liquid-fuel power plants. Source: XM (Sinergox).

Author's calculation.

The Colombian electricity market consists of two levels: a wholesale market and a retail market. The Wholesale Electricity Market (MEM in Spanish) was established under Laws 142 and 143 of 1994 to promote competition in electricity generation and commercialization. Market participants include generators, transmission companies, distribution companies, retailers, and large non-regulated consumers. The objective of the MEM is to facilitate the exchange of electricity within the National Interconnected System (SIN in Spanish) at prices that reflect the marginal cost of generation.

In the MEM, electricity can be traded through two market segments: bilateral contracts

and the spot market. Physical dispatch is determined independently through the spot market, where all registered generators participate under centralized dispatch rules administered by the system operator. Meanwhile, bilateral contracts are privately negotiated long-term financial agreements between generators and retailers that specify the quantity, duration, and price of future electricity transactions. These contracts constitute financial obligations between the contracting parties but do not require the contracted generator to physically produce the committed electricity.

Given Colombia's exposure to severe droughts, the Reliability Charge was introduced through CREG Resolution 071 of 2006 to reduce the risk of electricity shortages and ensure the reliability of electricity supply. Under this mechanism, generators receive a fixed remuneration for making generation capacity available to fulfill previously assigned Firm Energy Obligations (OEF in Spanish). These obligations guarantee that sufficient electricity will be available during scarcity conditions, defined as periods when the wholesale spot price exceeds the scarcity price. A detailed description of the commercial design and operation of the Reliability Charge is provided by Bedoya et al. (2016), who explain its role and functioning within the MEM.

The product traded in the reliability market is the OEF contract. From an economic perspective, an OEF is equivalent to a call option through which the regulator acquires the right to purchase firm energy from generators at a predetermined exercise price, namely the scarcity price, for the duration of the obligation (Rios et al., 2024). To participate in the OEF auction, each generating plant must determine its Firm Energy for the Reliability Charge (ENFICC in Spanish), which corresponds to the maximum amount of energy that the plant can reliably deliver over one year under low-hydrology conditions. Consequently, the ENFICC establishes the maximum quantity of firm energy that the generator may commit through an OEF. The outcome of the allocation process is the assignment of an OEF, which has commitment period of at least one year.

Once an OEF has been assigned, generators receive a fixed remuneration in exchange for

committing to deliver the contracted amount of firm energy whenever scarcity conditions are triggered. If the wholesale spot price exceeds the scarcity price, the option is exercised and generators are required to supply the amount of energy specified in their OEF, according to the dispatch determined by the system operator. Consequently, the scarcity price represents the maximum price at which electricity delivered under activated OEF contracts is remunerated.

By combining an upfront capacity payment with an obligation to supply electricity during scarcity periods, the Reliability Charge encourages investment in generation capacity while ensuring that electricity demand can be met during severe drought episodes without exposing consumers to excessively high spot prices. However, according to Aguilar-Díaz and Sánchez-Sierra (2016), the Reliability Charge has not fully achieved its objective of ensuring energy reliability, as market interventions were required during both the 1997–1998 and 2015–2016 El Niño events. Moreover, during the latter episode, the unavailability of Termocandelaria further constrained electricity supply by preventing the fulfillment of its OEF.

These experiences illustrate that, although the ENFICC is designed to represent the amount of energy that a generating plant can reliably supply under adverse hydrological conditions, actual generation may still fall below this level during exceptionally severe droughts, prolonged periods of below-average precipitation, reservoir operating constraints, or unexpected failures. In such circumstances, generators holding OEF contracts remain responsible for fulfilling their contractual commitments and may therefore need to purchase electricity in the wholesale market to cover the resulting energy shortfall. Because spot prices are typically elevated during these periods, the cost of covering the shortfall can rise substantially even though the energy delivered under an activated OEF is remunerated at the scarcity price. Consequently, severe drought episodes may translate into higher operating costs for hydroelectric generators despite the existence of the Reliability Charge mechanism (Aguilar-Díaz and Sánchez-Sierra, 2016).

This dual role of the Reliability Charge, which strengthens the security of electricity supply while simultaneously exposing generators to the cost of covering energy shortfalls, is the central

institutional feature exploited by the framework developed below. Building on this institutional setting, the remainder of the paper develops a forward-looking framework to evaluate how extreme drought events may affect the financial resilience of hydropower firms. Specifically, we quantify the impact of projected precipitation shocks on hydropower generation, firms' operating performance, and financial vulnerability, and subsequently assess the implications for credit risk in the Colombian banking system.

3 Data

Our empirical analysis draws on five sources of information, spanning climate, energy sector, corporate, and credit market data from 2000 to 2024. Each source feeds a specific module of the framework presented in Section 4. Observed and projected precipitation characterize the physical climate risk that constitutes the starting point of the analysis. Plant-level generation data, together with wholesale market prices, are used to estimate the relationship between precipitation and hydropower production and to value the energy shortfall that firms must cover during drought episodes. Firm-level financial statements provide the baseline operating income and financial expenses from which stressed profitability and debt-servicing capacity are computed. Finally, supervisory credit registry data link financially vulnerable firms to their lender banks and to the supervisory credit quality classification through which the shock reaches the banking sector. The following subsections describe each source and the variables drawn from it, and the last subsection explains how information reported at different frequencies is aligned into a single analytical dataset.

3.1 Precipitation Data

Observed precipitation: historical monthly precipitation is taken from CHIRPS v3.0 (Funk et al., 2015), a high-resolution gridded rainfall dataset that combines satellite estimates with

ground station observations and is widely used in hydrological and drought studies. Because the framework operates at the plant level, the gridded data are averaged within the boundaries of each municipality where a hydropower plant operates, yielding a monthly precipitation series for each municipality over 2000–2024. These series are used to estimate the generation model in Section 4 and serve as the observational baseline to which all projected precipitation is calibrated.

Projected precipitation: precipitation projections through 2100 are obtained from the global climate models of the Coupled Model Intercomparison Project Phase 6 (CMIP6), distributed by the Copernicus Climate Change Service (C3S). We consider two scenarios at opposite ends of the emissions range: SSP1-2.6, a sustainability-oriented pathway broadly consistent with the Paris Agreement's below-2°C target, and SSP5-8.5, a fossil-fuel-intensive, high-emissions pathway (O'Neill et al., 2017; Riahi et al., 2017). Together, these scenarios bound the range of projected precipitation outcomes.

3.2 Hydropower Sector Data

Data on the hydropower sector are obtained from Sinergox, the platform that centralizes public information on Colombia's Wholesale Energy Market and the operation of the National Interconnected System. The dataset includes daily electricity generation at the plant level, spot prices, scarcity prices, and the geographic location of each hydropower plant. To ensure consistency with the monthly precipitation dataset, daily generation data are aggregated to the monthly frequency prior to the empirical analysis. Two variables drawn from this source play a specific role in the framework. Plant-level generation is the dependent variable of the production model of Section 4 and, once aggregated by agent, the basis for the revenue shock. The scarcity price is the settlement price of activated OEF contracts and is therefore used to value the energy shortfall that firms must cover in the wholesale market; it is fixed at COP

782.7 per kWh, the average level observed during the 2023–2024 El Niño episode.

3.3 Firm level financial data

Annual financial information for the companies that own hydropower plants is collected from the Superintendence of Companies and complemented, where necessary, with the financial statements published on the companies' own websites. Three variables enter the framework directly: earnings before interest and taxes (EBIT), which defines baseline operating income; financial expenses, which form the denominator of the interest coverage ratio; and total assets, used to characterize the size of the firms in the sample. In addition, we construct for each firm the share of hydropower in its total electricity generation, which determines how much of its revenue is exposed to precipitation shocks and is therefore the parameter that generates heterogeneity in the size of the shock across firms.

3.4 Credit Exposure Data

Firm-bank level credit exposure data are sourced from Form 34 of the Financial Superintendence of Colombia. This regulatory dataset, reported quarterly by credit entities, provides information on outstanding credit amounts, days past due, credit scores, interest rates, and the economic sector classification of borrowing firms. The credit score corresponds to the supervisory classification applied to commercial loans in Colombia, which ranges from Category A, normal credit quality, to Category E, unrecoverable loans, and is assigned on the basis of payment delinquency and banks' internal risk assessments. This classification is the variable through which firm-level vulnerability is translated into a banking-sector indicator in the final module of the framework. The sector classification is used to isolate the electricity generation sector within the broader energy sector.

3.5 Descriptive statistics

Before turning to the econometric analysis, we present descriptive evidence on the key variables used throughout the paper. The objective is first, characterize the structure and evolution of the hydropower sector and its exposure to climatic conditions. Second, analyze the relevance of the sector for the Colombian financial system through its credit linkages with financial institutions. Third, illustrate how periods of low precipitation associated with El Niño events affect electricity generation and trigger changes in spot market prices and scarcity-price conditions, potentially increasing financial pressures on hydropower firms. Overall, these evidences provide preliminary insights into the channels through which climate shocks can propagate from hydropower production to firms' financial performance and, ultimately, to credit risk within the financial system.

Table 1 presents the summary statistics on hydropower generation by year for the period 2000–2024. Daily hydropower generation data are aggregated to the monthly level to ensure consistency with the observed precipitation data. This procedure yields a monthly panel dataset spanning January 2000 to December 2024.

The sample consists of seven firms operating in 30 hydropower plants located across 26 municipalities in Colombia. This coverage allows us to capture both the temporal evolution of hydropower generation and the geographic heterogeneity in precipitation patterns.

The table shows the evolution of hydropower generation over the 24-year sample period. In addition to the number of firms and operating plants, it reports annual statistics on average, minimum and maximum generation levels.

A particularly noteworthy result is observed in 2015, when hydropower generation experienced its most pronounced decline in the entire sample. This contraction coincided with the El Niño fenomena in 2015-2016, one of the most severe drought episodes recorded in Colombia.

This pattern provides preliminary evidence of the sector's dependence on hydrological conditions: periods of reduced precipitation and declining reservoir levels are associated with substantial reductions in generation.

The vulnerability observed during El Niño episode in 2015-2016 motivates the econometric analysis presented in the following sections. Specifically, we quantify the extent to which precipitation shocks affect hydropower generation and, subsequently, the financial capacity of firms to meet their obligations.

Table 1: Summary statistics of Hydropower Generation by Year (2000–2024)

Year	Firms	Hydropower Plants	Mean Generation (kWh)	Min Generation (kWh)	Max Generation (kWh)
2000	6	16	163,614,727	9,883,000	480,757,584
2001	6	18	163,416,831	638,462	427,490,192
2002	6	19	143,346,782	12,499,875	415,063,959
2003	6	19	168,125,638	1,626,695	500,733,268
2004	6	19	177,941,380	12,520,358	622,592,100
2005	6	19	173,437,784	312,547	505,835,456
2006	6	19	181,932,914	550,073	644,148,628
2007	6	19	190,563,569	21,352,119	597,418,920
2008	6	19	207,043,853	20,158,827	657,368,481
2009	6	19	116,124,060	7,967,571	388,418,165
2010	6	19	194,707,631	19,713,022	749,204,768
2011	6	20	195,705,107	15,106,393	581,088,243
2012	6	20	168,593,669	1,087,699	551,247,968
2013	6	20	177,885,834	2,669,680	512,826,558
2014	6	24	150,900,088	4,388,504	473,228,324
2015	7	28	103,867,897	1,671,151	389,217,886
2016	7	28	156,895,765	902,322	529,854,298
2017	7	28	160,492,202	15,947,232	641,328,499
2018	7	28	146,592,341	1,236,343	519,014,730
2019	7	29	132,392,908	708,717	460,392,903
2020	7	29	150,523,431	662,868	664,290,063
2021	7	29	153,390,566	1,401,500	621,265,396
2022	7	30	169,442,767	10,994,401	626,133,461
2023	7	30	131,835,495	1,016,602	679,998,532
2024	7	30	135,702,341	117,784	716,199,045

The table reports summary statistics of hydropower generation. Source: Authors' calculations.

In addition, the Figure 2 illustrates the evolution of hydropower generation, including the spot electricity price and the scarcity price between 2011 and 2024. The shaded areas indicate recent El Niño episodes.

A clear pattern emerges during these events, particularly in 2015–2016 and 2023–2024. Hydropower generation declines substantially as lower precipitation reduces water availability in reservoirs. At the same time, spot electricity prices increase sharply, reflecting the relative

scarcity of energy supply within the system. As explained in Section 2, this combination is precisely what exposes generators holding OEF contracts to higher operating costs, since the energy they cannot produce must be covered in a market where prices are elevated.

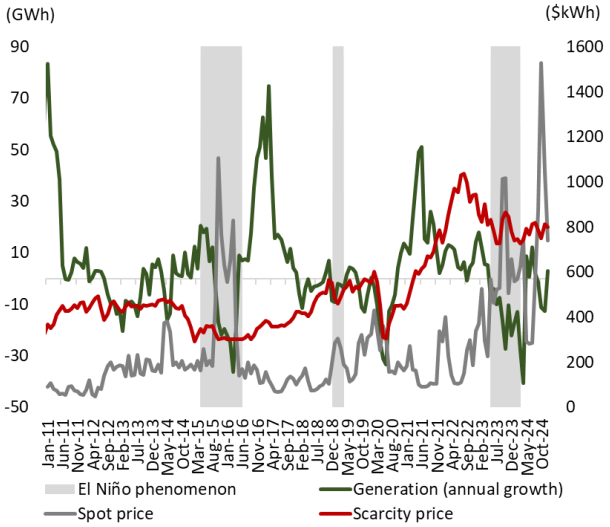
Given Colombia's strong reliance on hydropower generation, the country implemented a reliability mechanism known as Firm Energy Obligations (OEF) to prevent electricity rationing and ensure system reliability during periods of severe drought. Under this scheme, generators receive payments in exchange for committing to make a specified amount of firm energy available whenever the system requires it. In return, they assume an obligation to deliver that energy during scarcity conditions.

The mechanism is activated whenever the spot electricity price exceeds the scarcity price. The scarcity price is a regulated threshold that serves as the trigger for the scheme. Once this threshold is surpassed, generators holding OEF contracts must fulfill their delivery commitments and are remunerated at the scarcity price, even when the spot market price is higher.

This arrangement creates a particularly important source of vulnerability for hydropower producers during drought episodes. When low precipitation reduces generation capacity, firms may be required to purchase electricity in the spot market to meet their contractual obligations. Because spot prices are typically elevated during these periods, compliance costs can rise substantially, leading to a deterioration in profitability and financial performance.

Therefore, while the OEF mechanism strengthens the reliability and security of Colombia's electricity supply, it also represents one of the primary channels through which droughts can translate into financial stress for hydropower firms. Understanding this mechanism is crucial for explaining how a climate-related shock can ultimately propagate into credit risk within the financial system.

Figure 2: Hydropower Generation and Wholesale Electricity Prices



Note: Shaded areas correspond to El Niño episodes. Source: Sinergox XM.

Authors' calculations.

Extending the analysis to a more disaggregated sectoral level and examining the linkages between the energy sector and the financial system, Figure 3 presents the evolution of outstanding credit balances between 2015 and 2024, disaggregated into three categories: economic sectors excluding the energy sector, the energy sector as a whole, and electricity generation companies.

A first observation is that, although the energy sector accounts for a relatively small share of total credit in the financial system, approximately 8.9%, its credit exposure has increased substantially over the sample period.

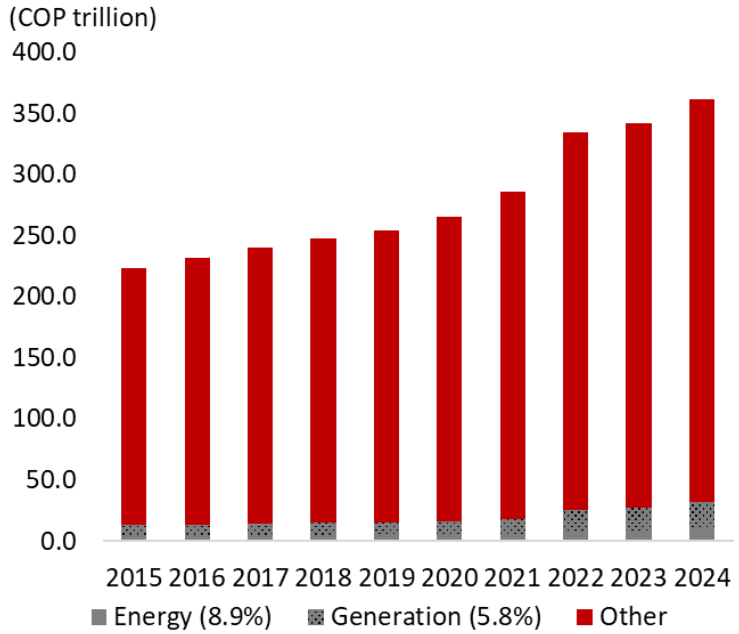
More importantly for the purposes of this study, 65.4% of the credit extended to the energy sector is concentrated in electricity generation companies. This implies that a significant portion of banks' exposure is directed toward firms whose performance depends directly on the availability of water resources.

Consequently, when a negative precipitation shock occurs, such as during an El Niño event, the resulting decline in hydropower generation may weaken the financial position of these firms

and, through this channel, increase credit risk for the financial institutions that lend to them.

Therefore, although the energy sector does not represent one of the largest recipients of credit in aggregate terms, its strong dependence on climatic conditions makes it a particularly relevant sector for assessing climate-related financial risks within the Colombian financial system.

Figure 3: Banking system exposure to the energy sector



Note: The figure depicts outstanding credit balances of the banking system between 2015 and 2024, in COP trillion, distinguishing the energy sector and, within it, electricity generation companies. Shares in the legend correspond to the average over the period. Source: Financial Superintendence of Colombia.

Authors' calculations.

4 Framework of the model

The NGFS (NGFS, 2024) proposes a three-phase framework to help central banks and supervisors identify and assess nature-related financial risks that may become material to the economy and the financial system. In the first phase, authorities identify the economic sectors and ecosystem services that are most exposed to nature-related risks in order to prioritize the assessment of material vulnerabilities. This involves identifying the main sources of physical and transition risks by evaluating economic activities according to their dependence on and impact on nature, as well as their relevance to the economy and the financial sector. Subsequently, a forward-looking risk assessment evaluates how physical and transition risks may materialize under alternative climate scenarios. Together, these two steps help identify the sectors in which climate-related financial risks are most likely to arise and therefore warrant a more detailed assessment.

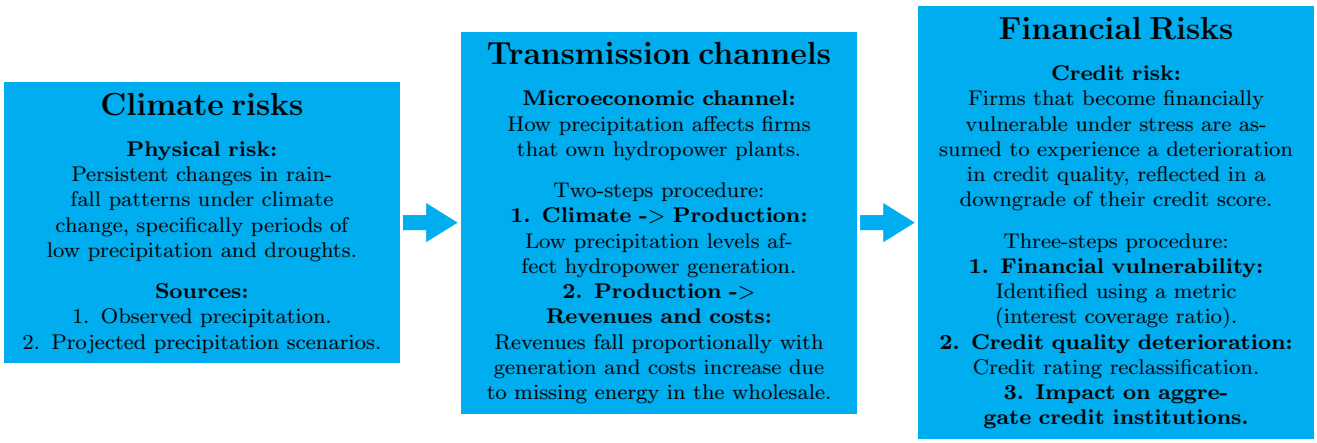
The second phase of the NGFS framework consists of assessing the economic consequences of climate-related shocks by identifying the transmission channels through which physical and transition risks affect firms, households, and the broader economy. These effects can propagate through both direct and indirect channels and may materialize at the microeconomic and macroeconomic levels. At the microeconomic level, climate risks may reduce firms' production capacity, revenues, and profitability, particularly for activities that rely heavily on ecosystem services. At the macroeconomic level, these shocks may affect productivity, investment, prices, fiscal balances, trade, capital flows, and financial conditions. The magnitude of these effects depends not only on the exposure of economic agents to climate hazards but also on their sensitivity and adaptive capacity.

In the third phase, authorities assess how the economic impacts derived from climate-related risks or nature degradation and related policies are transmitted to financial institutions and the financial system. Climate-related shocks may impair firms' repayment capacity, reduce

collateral values, and ultimately affect financial risks, such as credit, market, liquidity, and operational risks.

Building on these three phases, Figure 4 presents the analytical framework developed in this paper. We focus on the Colombian hydropower sector because, as discussed in Section 3, it is highly dependent on precipitation and represents an important component of both electricity generation and the banking sector's corporate credit portfolio. The framework consists of three interconnected modules that trace the transmission of physical climate risk from precipitation shocks to firm-level financial vulnerability and, ultimately, to the banking sector.

Figure 4: Framework for mapping of climate-related risks and transmission channels to the Colombian hydropower sector



Author's elaboration.

The first module characterizes physical climate risk using both observed precipitation and projected precipitation under alternative climate scenarios. These data is used to capture rainfall patterns and determine the occurrence of extreme rainfall and drought events affecting hydropower production.

The second module represents the microeconomic transmission channel. First, projected precipitation scenarios are translated into changes in hydropower generation using a dynamic panel model estimated with historical plant-level data. The projected generation paths are then aggregated at the firm level and used to simulate firms' revenues and operating costs

under assumptions consistent with the Colombian wholesale electricity market. In particular, the framework considers two main transmission mechanisms. On the revenue side, lower hydropower generation reduces electricity sales in proportion to each firm's dependence on hydropower generation. On the cost side, firms holding OEF may need to purchase electricity in the wholesale market to meet their contractual commitments whenever reduced hydropower generation prevents them from supplying the committed energy, thereby increasing operating costs.

The third module captures the financial transmission channel by evaluating how deteriorating operating performance affects firms' financial resilience. Projected operating income is used to compute stressed interest coverage ratios (ICR), allowing the identification of firms that become financially vulnerable under climate stress.[1] These firms are subsequently matched with supervisory credit registry data to identify their lender banks. Afterwards, their credit quality is then assumed to deteriorate through a one-notch downgrade in their supervisory credit rating, enabling us to quantify the resulting deterioration in the aggregate credit risk indicator for the electricity generation sector.

Overall, the proposed framework provides a forward-looking methodology for tracing the transmission of physical climate risk from precipitation shocks to firm-level financial vulnerability and, ultimately, to credit risk in the banking sector.

To illustrate the application of the framework, we focus on the Colombian hydropower sector, given its strong dependence on precipitation. We first estimate the relationship between monthly precipitation and hydropower generation using observed historical data. Following Trujillo-Galindo et al. (2025), we estimate the following dynamic panel model at the hydropower

[1]The interest coverage ratio is defined as earnings divided by interest expenses and is broadly used as a core financial vulnerability indicator

plant level:

$$log(Generation)_{j,i,t} = \beta_{rains} \sum_{h=1}^{12} D_{i,t-h}^{n,rains} + \boldsymbol{\beta_{droughts}} \sum_{h=1}^{12} D_{i,t-h}^{n,droughts} + \alpha_j + f(t) + \epsilon_{j,i,t}. \quad (1)$$

The analysis is conducted at the hydropower plant level i because a single firm may own multiple plants located in different municipalities j. Consequently, exposure to precipitation shocks differs across plants according to local rainfall patterns. Plant-level estimation therefore allows us to capture the geographic heterogeneity of climate exposure before aggregating the results to the firm level.

The coefficient of primary interest is $\boldsymbol{\beta_{droughts}}$, which measures the sensitivity of hydropower generation to extreme drought conditions. To identify extreme precipitation events, we follow the approach commonly adopted in the empirical literature (Arteaga et al., 2025; Jayachandran, 2006; Otero-Cortés and Bohorquez-Penuela, 2020; Kaur, 2019), which classifies monthly precipitation relative to its historical municipal distribution. Rainfall observations above the 80th, 85th, 90th, 95th, and 99th percentiles are classified as heavy rainfall events, while observations below the 20th, 15th, 10th, 5th, and 1st percentiles are classified as drought events.

$$D_{i,t-h}^{n,droughts} = \begin{cases} 1 & X_{i,t-h} < Percentile_n(X_i) \\ 0 & X_{i,t-h} \geq Percentile_n(X_i) \end{cases}$$

where $n \in \{1, 5, 10, 15, 20\}$.

$$D_{i,t-h}^{n,rains} = \begin{cases} 1 & X_{i,t-h} > Percentile_n(X_i) \\ 0 & X_{i,t-h} \leq Percentile_n(X_i) \end{cases}$$

where $n \in \{80, 85, 90, 95, 99\}$.

Since five different activation thresholds for heavy rains and five different activation thresholds for droughts were evaluated, a total of 3,125 panel data regressions were estimated. These specifications allow us to identify the marginal effects of extreme precipitation events occurring over the previous 12 months, and to determine the threshold that best captures the relationship between precipitation extremes and hydropower generation.

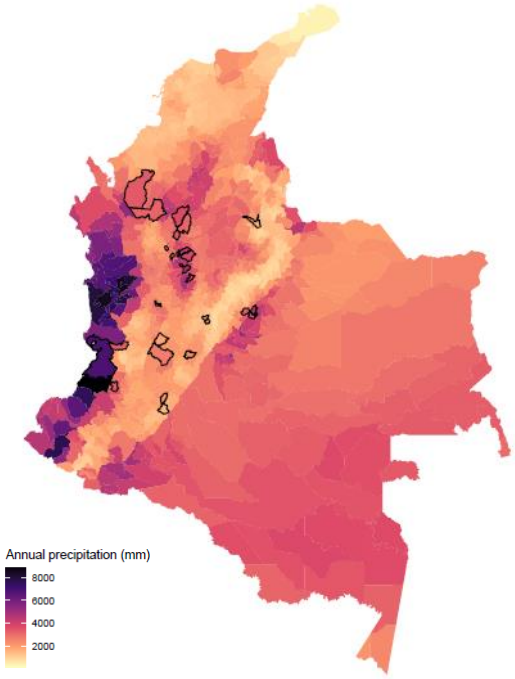
Once the effects of extreme precipitation have been characterized, we estimate a second dynamic panel model that relates monthly hydropower generation at the plant level i to observed precipitation in municipality j, while accounting for persistence in generation and delayed climate effects:

$$log(Generation)_{i,j,t} = \gamma log(Generation)_{i,j,t-1} + \beta_h \sum_{h=0}^{2} log(Precipitation)_{j,t-h} + \alpha_i + f(t) + \epsilon_{i,j,t}. \quad (2)$$

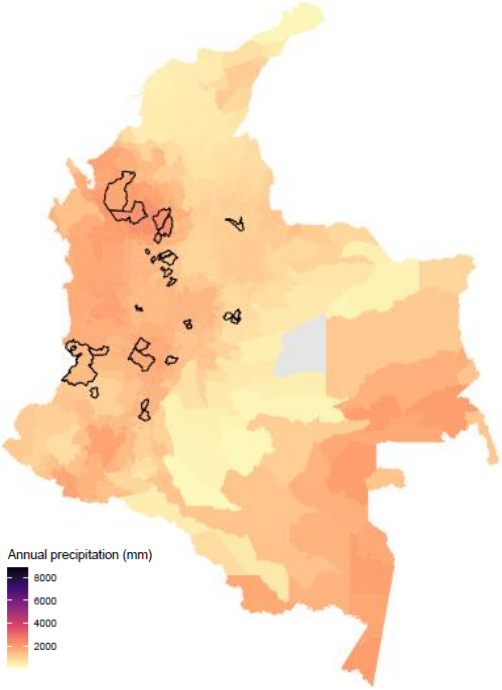
The purpose of estimating this second model is to project future hydropower generation under alternative precipitation scenarios derived from climate projections. Figure 5a presents the average monthly precipitation observed at the municipal level during the 2000–2024 period, which constitutes the historical dataset used to estimate Equation 2. Figures 5b and 5c present two illustrative climate scenarios used to project future hydropower generation. As discussed in Section 3, both scenarios are characterized by drier conditions relative to the historical baseline, although they differ in the magnitude of the projected precipitation decline. For each hydropower plant, climate model, and scenario, projected precipitation replaces observed precipitation, and future hydropower generation is recursively simulated using the estimated dynamic model.

Figure 5: Observed and projected precipitations at the national level (mm per month)

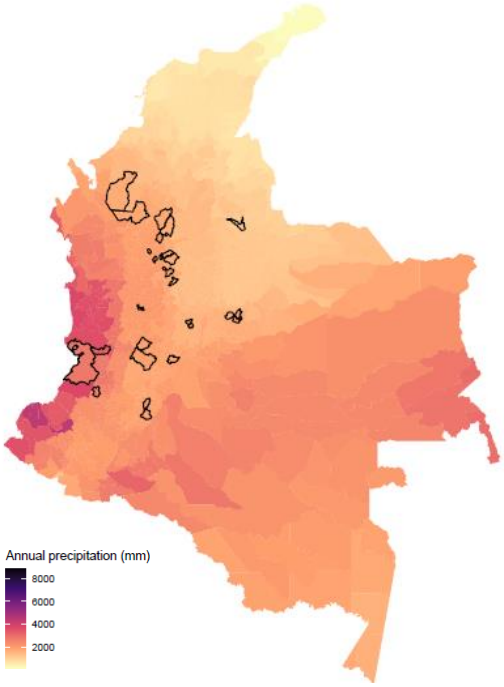
(a) Observed: Average 2000-2024



(b) SSP1-2.6: 2074



(c) SSP5-8.5: 2090



Note: Panel (a) presents the average observed monthly precipitation during 2000–2024. Panels (b) and (c) show projected precipitation under alternative CMIP6 climate scenarios. Compared with the historical distribution, the projected scenarios are characterized by lower precipitation levels, implying more persistent drought conditions.Municipalities outlined in black correspond to locations where one or more hydropower plants operate. Source: CHIRPSv3.0 for observed precipitation; CMIP6 for projected precipitation: model cams_csm1_0 under SSP1-2.6 scenario and model gfdl_esm4 under SSP5-8.5 scenario.

Authors' calculations.

The final stage of the framework translates projected changes in hydropower generation into firm-level financial outcomes and, ultimately, into credit risk. Since detailed information on firms' revenues and operating costs is not publicly available, we simulate the impact of climate shocks on firms' income statements using a set of assumptions that reflect the institutional features of the Colombian wholesale electricity market. The simulation relies on the following assumptions.

Assumption 1. Revenue from hydropower generation is affected by precipitation shocks. We assume that changes in hydropower generation translate proportionally into changes in revenues derived from hydropower activities. The dynamic panel model produces projections of hydropower generation at the plant level under each climate model and scenario. Because firms may own multiple hydropower plants located in different municipalities, projected generation is first aggregated across all plants belonging to the same firm to obtain firm-level hydropower generation. The projected percentage change in firm-level generation is then calculated relative to the baseline and assumed to translate proportionally into revenues from hydropower activities. Since some firms also generate electricity using other technologies, the revenue shock is weighted by the share of hydropower generation in each firm's total electricity generation. Consequently, firms with a greater reliance on hydropower experience larger revenue losses under adverse precipitation scenarios.

Let g_f denote the projected percentage change in hydropower generation for firm f, and let θ_f denote the share of hydropower generation in the firm's total electricity generation. The change in revenue is computed as:

$$\Delta Revenue_{f,t+1} = Revenue_{f,t} \times \theta_f \times g_f. \tag{3}$$

Assumption 2. Operating costs increase when firms are unable to fulfill their contracted energy commitments. During drought episodes, reduced hydropower generation may prevent firms from supplying the amount of energy they have contracted. In the absence of firm-level information on contractual positions and OEF, we assume that each firm's baseline hydropower generation represents its committed energy under normal operating conditions. Consequently, any reduction in projected generation relative to the baseline is interpreted as an energy shortfall that must be covered through purchases in the wholesale electricity market.

We approximate the resulting increase in operating costs by valuing the energy shortfall at the scarcity price. Although electricity purchases in the wholesale market are settled at the spot price, the scarcity price represents the settlement price for OEF when they are activated and provides a conservative approximation of additional operating costs, as the spot price typically exceeds the scarcity price during severe drought episodes. The scarcity price is fixed at the average value observed during the most recent El Niño episode in Colombia (2023–2024), equal to COP 782.7/kWh.

Let $G_{f,t}^{\text{base}}$ denote the baseline hydropower generation of firm f, $G_{f,t+1}^{\text{proj}}$ the projected generation under the climate stress scenario, and P^{scarcity} the scarcity price. The increase in operating costs is computed as

$$\Delta Costs_{f,t+1} = \left(G_{f,t}^{\text{base}} - G_{f,t+1}^{\text{proj}}\right) \times P^{scarcity}. \tag{4}$$

The term $\left(G_{f,t}^{\text{base}} - G_{f,t+1}^{\text{proj}}\right)$ represents the estimated energy shortfall resulting from the precipitation shock and therefore the amount of electricity that firms are assumed to purchase in the wholesale market.

Assumption 3. Climate shocks affect firms' operating profitability through changes in revenues and operating costs. Stressed operating income is obtained by adjusting each firm's observed earnings before interest and taxes (EBIT) to account for the simulated reduction in revenues and the increase in operating costs resulting from lower hydropower generation. Specifically, stressed EBIT is computed as

$$EBIT_{f,t+1}^{\text{stress}} = EBIT_{f,t} + \Delta Revenue_{f,t+1} - \Delta Costs_{f,t+1}, \tag{5}$$

where $EBIT_{f,t}$ denotes the firm's observed operating income in the baseline period.

Assumption 4. Firms with weak debt-servicing capacity become financially vulnerable. The stressed EBIT is used to calculate the stressed ICR as

$$ICR_{f,t+1}^{\text{stress}} = \frac{EBIT_{f,t+1}^{\text{stress}}}{FinancialExpenses_{f,t}}, \tag{6}$$

which measures a firm's ability to meet its interest payments using operating earnings. Financial expenses are assumed to remain constant throughout the stress horizon due to the lack of information on firms' future financing conditions. Although this is a simplifying assumption, it allows the analysis to isolate the impact of climate-induced changes in operating performance on firms' debt-servicing capacity.

Following the IMF (2024), firms with an ICR below 1.5 are classified as financially vulnerable, as this threshold identifies firms with limited capacity to service debt under adverse conditions. An ICR below 1 indicates that operating earnings are insufficient to cover interest payments and is generally interpreted as a signal of severe financial distress.

The stressed ICR therefore serves as the criterion for identifying firms whose credit quality is assumed to deteriorate under the climate stress scenario. These firms constitute the basis for the subsequent credit risk assessment, which evaluates how firm-level financial vulnerability is transmitted to the banking sector through changes in credit quality.

Assumption 5. Financial vulnerability leads to a deterioration in credit quality. Financially vulnerable firms identified through the stressed ICR are matched with the supervisory credit registry to identify their lender banks, outstanding credit exposures, and supervisory credit ratings.

In Colombia, commercial loans are classified into five supervisory credit quality categories, ranging from A (normal credit quality) to E (unrecoverable loans). The classification is based on payment delinquency and banks' internal credit risk assessments. Since all firms in our sample are initially classified as Category A, they are not included in the Quality Indicator Risk (QIR), which measures the share of commercial credit exposures classified in categories B through E.

We assume that firms identified as financially vulnerable under the climate stress scenario experience a one-notch deterioration in their supervisory credit rating, moving from Category A to Category B. This assumption reflects the deterioration in firms' repayment capacity resulting from lower operating profitability under adverse climate conditions. As a consequence, these firms become part of the numerator of the QIR, allowing us to quantify the increase in the aggregate credit risk indicator for the electricity generation sector attributable to climate stress.

Together, these assumptions provide a practical approach for translating climate-induced changes in hydropower generation into firm-level financial vulnerability and banking-sector credit risk.

5 Results

This section presents the results of applying the climate stress-testing framework to the Colombian hydropower sector. As mentioned, we first estimate the relationship between precipitation and hydropower generation to use the specification to project future generation under

alternative climate scenarios. Next, projected generation is translated into firm-level financial outcomes through the microeconomic transmission module. Finally, we evaluate the implications for firms' financial vulnerability and the quality of banks' credit portfolios.

5.1 The impact of precipitation on hydropower generation

We begin by estimating the dynamic relationship between precipitation and hydropower generation at the plant level. The first set of regressions evaluates whether extreme precipitation events have persistent effects on electricity generation using alternative drought and heavy rainfall thresholds. Subsequently, we estimate the dynamic panel model relating observed precipitation to hydropower generation, which serves as the basis for projecting future generation under alternative climate scenarios.

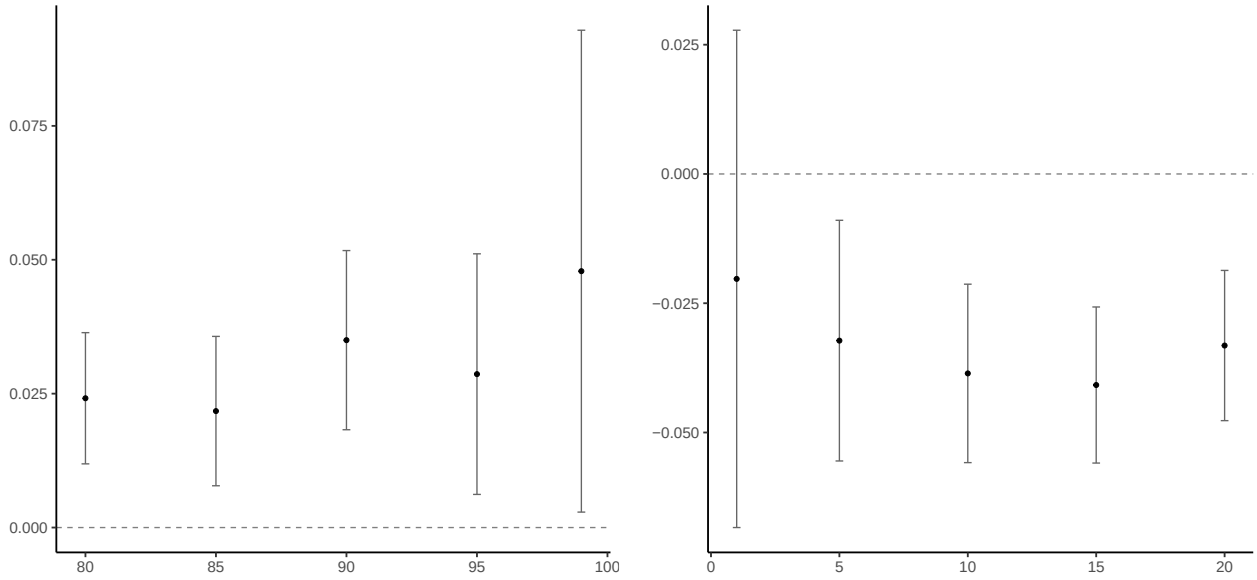
Figure 6 summarizes the estimated coefficients $\boldsymbol{\beta}_{\text{droughts}}$ and $\boldsymbol{\beta}_{\text{rains}}$ across the alternative thresholds used to identify extreme drought and heavy rainfall events. The estimated coefficients are broadly stable across thresholds. Heavy rainfall events, defined as monthly precipitation above the 80th to 99th percentiles of the historical municipal distribution, increase hydropower generation by approximately 2.7% (Figure 6a). In contrast, drought events, defined as precipitation below the 20th to 5th percentiles, reduce hydropower generation by around 4% (Figure 6b).

These results reveal an asymmetric response of hydropower generation to extreme precipitation. While abundant rainfall only modestly increases electricity generation, drought conditions produce larger declines. This asymmetry reflects the characteristics of the Colombian electricity system, where hydropower already accounts for the majority of electricity generation under normal hydrological conditions. Consequently, additional rainfall provides limited scope for further increases in generation, whereas water shortages directly constrain reservoir inflows and generation capacity.

As highlighted in Section 2, under normal conditions, hydropower plants supply between 60% to 90% of total electricity generation, while thermal generation accounts for the remaining 10% to 40%. However, during the 2015–2016 El Niño event, the share of hydropower generation fell below 50%, accompanied by a sharp increase in thermal generation. This substitution reflects the reduced availability of water resources during prolonged drought conditions. Therefore, these findings corroborate that negative precipitation shocks have considerably larger effects on electricity generation than positive shocks.

Figure 6: Estimated effect of precipitation on hydropower generation

(a) High precipitation (b) Low precipitation



Note: The figure reports the estimated effects of drought and heavy rainfall events on hydropower generation across alternative precipitation thresholds. Drought conditions produce substantially larger reductions in hydropower generation than the increases associated with heavy rainfall, reflecting the asymmetric response of the Colombian hydropower system to precipitation shocks.

Authors' calculations.

Regarding the dynamic panel model relating observed precipitation to hydropower generation, Table 2 reports the estimated coefficients. The results indicate that hydropower generation responds significantly to precipitation, with the largest effects occurring contemporaneously and during the months immediately following precipitation shocks. The lagged dependent variable is positive and statistically significant, indicating persistence in electricity generation over time.

Overall, these results confirm that precipitation is a key determinant of hydropower generation in Colombia and provide the empirical basis for translating climate scenarios into future electricity production.

Table 2: Dynamic Panel Estimates of the Effect of Precipitation on Hydropower Generation

	log(Hydropower Generation)
$\log(\text{Hydropower Generation})_{t-1}$	0.339^{***}
	(0.011)
$\log(\text{Precipitation})_t$	0.079^{***}
	(0.014)
$\log(\text{Precipitation})_{t-1}$	0.062^{***}
	(0.016)
$\log(\text{Precipitation})_{t-2}$	0.045^{***}
	(0.014)
Observations	6,791
R^2	0.145
Adjusted R^2	0.141
F-Statistic	191.569^{***}
Time effects	YES
Individual effects	YES

The table reports the estimated coefficients of the dynamic panel model relating hydropower generation to observed precipitation. This specification is subsequently used to project hydropower generation under alternative climate scenarios. Robust standard errors reported in parentheses. *, **, and ***, indicate significance at the 10%, 5%, and 1% respectively.

Authors' calculations.

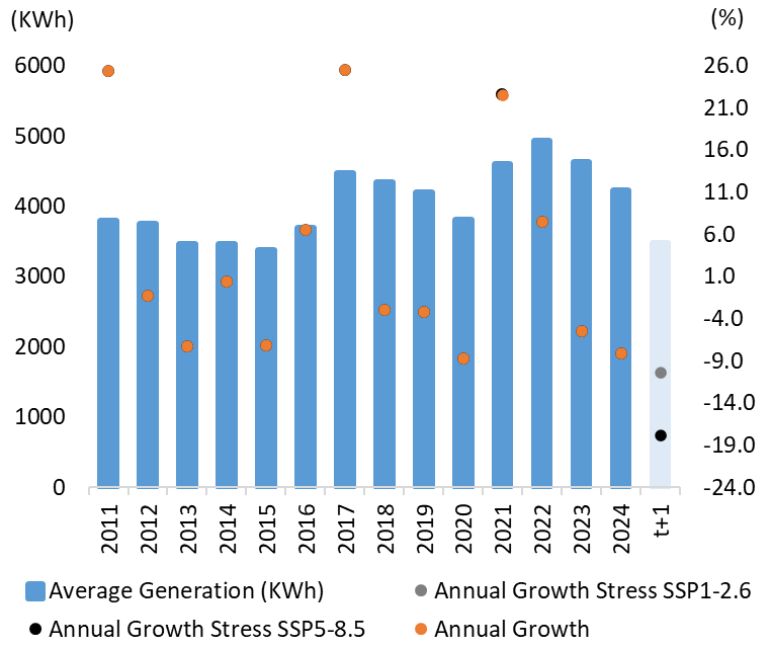
5.2 Projected hydropower generation under climate scenarios

Using the estimated dynamic panel model, we simulate hydropower generation under the alternative precipitation scenarios described in Section 4. Hydropower generation is first projected at the plant level and subsequently aggregated across plants owned by the same firm. Firm-level annual growth rates are then computed and aggregated to obtain the projected

growth of hydropower generation for the sector.

Figure 7 presents the projected annual growth of aggregate hydropower generation under the two different climate scenarios. Both scenarios imply lower electricity generation relative to the historical baseline, although the magnitude of the decline varies across climate models and emissions pathways. Under the SSP1-2.6 scenario, aggregate hydropower generation declines by approximately 10%, whereas under the SSP5-8.5 scenario the reduction reaches 18%. In general, scenarios associated with higher greenhouse gas emissions produce larger contractions in hydropower generation, reflecting the greater intensity of projected drought conditions. These projected reductions in hydropower generation constitute the primary physical climate shock in our framework and provide the basis for the subsequent simulation of firms' financial performance and credit risk.

Figure 7: Projected hydropower generation under climate stressed scenarios



Note: The figure presents the projected annual growth of aggregate hydropower generation under alternative CMIP6 climate scenarios. More adverse climate scenarios are associated with larger declines in hydropower generation, which constitute the primary physical climate shock analyzed in the stress-testing framework. Source: Sinergox XM.

Author's calculation.

5.3 Financial implications for hydropower firms

Projected reductions in hydropower generation are translated into firms' income statements according to the assumptions described in Section 4. Lower hydropower generation reduces revenues in proportion to each firm's reliance on hydropower generation. To approximate the additional operating costs associated with reduced generation, we assume that each firm's observed hydropower generation in the baseline period represents its contracted energy commitments. Under this assumption, any projected shortfall in generation is covered through purchases in the wholesale electricity market at the scarcity price.

Although the magnitude of the shock varies across firms, those with a greater dependence on hydropower generation experience the largest deterioration in operating profitability. The combined effect of lower revenues and higher operating costs results in a decline in EBIT, reducing firms' ability to meet their financial obligations.

5.4 Financial vulnerability

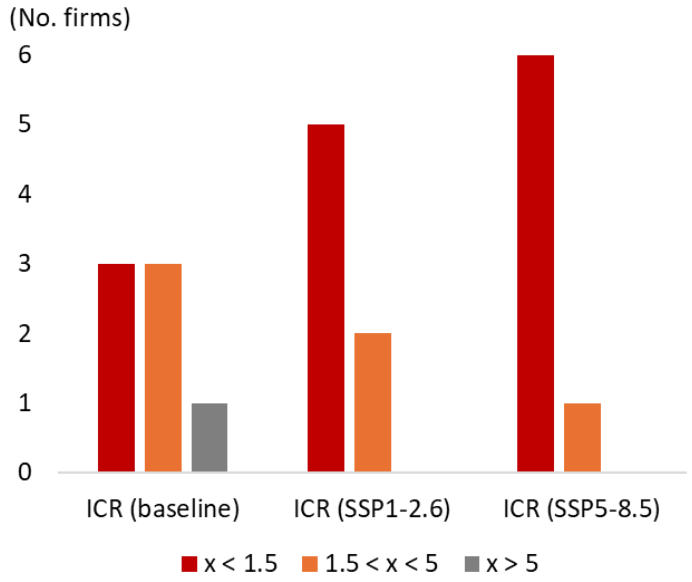
The deterioration in operating profitability is assessed through the stressed ICR. Figure 8 compares firms' baseline and stressed ICRs under the alternative climate scenarios. The results show that climate-induced reductions in hydropower generation substantially weaken firms' debt-servicing capacity, shifting the distribution of ICR toward lower values.

In the baseline scenario, most firms exhibit an ICR above 1.5, indicating sufficient operating earnings to cover their interest payments. Under both the SSP1-2.6 and SSP5-8.5 scenarios, the distribution shifts markedly to the left: no firm records an ICR above 5, while the number of firms with an ICR below the vulnerability threshold of 1.5 increases considerably. According to IMF (2024), these firms are classified as financially vulnerable.

The deterioration is more pronounced under the SSP5-8.5 scenario, reflecting the larger de-

cline in projected hydropower generation under a more severe climate pathway. Consequently, a greater number of firms become financially vulnerable, illustrating how increasingly severe precipitation shocks amplify firms' debt-servicing constraints. Overall, these results highlight the heterogeneous effects of climate risk across firms according to their dependence on hydropower generation and their initial financial position.

Figure 8: Interest Coverage Ratio



Note: The figure compares firms' baseline and stressed Interest Coverage Ratios (ICR) under the SSP1-2.6 and SSP5-8.5 climate scenarios. Lower hydropower generation reduces firms' operating profitability, shifting the distribution of ICRs toward lower values and increasing the number of financially vulnerable firms. Source: Superintendence of Companies.

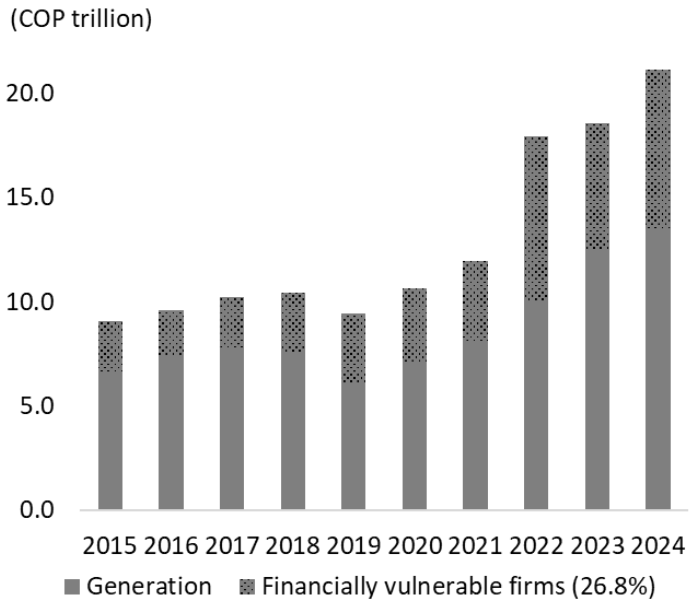
Author's calculation.

5.5 Implications for banking-sector credit quality

The final step evaluates how firm-level financial vulnerability is transmitted to the banking sector through changes in credit quality. Financially vulnerable firms are matched with supervisory credit registry data to identify their lender banks and outstanding credit exposures. Figure 9 presents banks' exposure to financially vulnerable firms. As discussed in Section 3, loans to the electricity generation sector account for approximately 6% of total commercial credit. Within this sector, firms identified as financially vulnerable represent nearly 27%. Con-

sequently, these firms account for around 2% of total commercial loans in the banking system.

Figure 9: Bank exposure to firms under financial stress

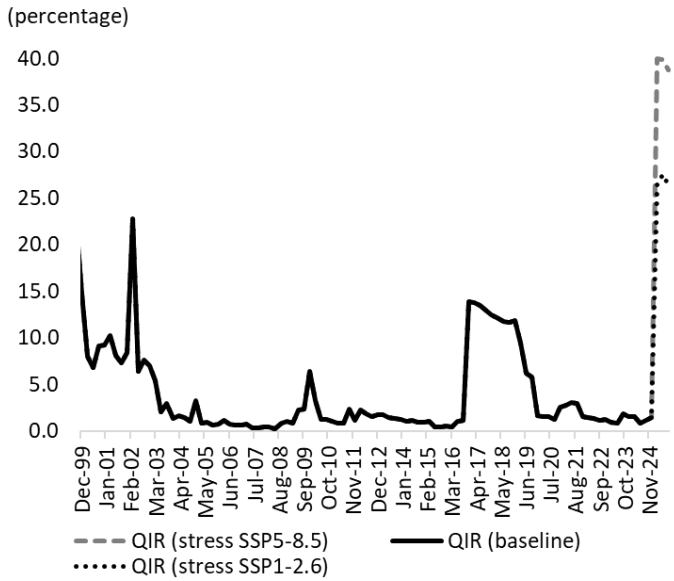


Note: The figure reports banks' credit exposures to firms identified as financially vulnerable under the climate stress scenarios. Although the aggregate exposure is moderate, the concentration of vulnerable borrowers varies across credit institutions. Source: Financial Superintendence of Colombia.

Author's calculation.

Under the stress scenarios, financially vulnerable firms are assumed to experience a one-notch deterioration in their supervisory credit rating, moving from Category A to Category B. Figure 10 reports the resulting QIR for the electricity generation sector. Since all firms are initially classified as Category A, the baseline QIR is close to zero. Following the simulated credit quality deterioration, loans to financially vulnerable firms are included in the numerator of the QIR, which increases the share of loans classified in supervisory categories B through E. As a result, the QIR rises by 25 and 38 percentage points under the SSP1-2.6 and SSP5-8.5 scenarios, respectively. These values are substantially higher than the deterioration observed during the 2015-2016 El Niño episode, when the QIR for the electricity generation sector rose by approximately 13 percentage points.

Figure 10: Aggregate credit risk indicator for the electricity generation sector



The figure presents the simulated Quality Indicator Risk (QIR) for the electricity generation sector following the assumed deterioration in firms' supervisory credit ratings. Climate stress substantially increases the share of loans classified in supervisory categories B through E, with simulated deteriorations exceeding those observed during the 2015–2016 El Niño episode. Source: Financial Superintendence of Colombia.

Author's calculation.

Although banks' aggregate exposure to financially vulnerable firms is relatively limited, the impact is heterogeneous across institutions, depending on the concentration of their loan portfolios in vulnerable firms within the electricity generation sector.

6 Concluding Remarks

This paper develops a forward-looking framework to assess how physical climate risk can propagate from precipitation shocks to firms' financial condition and, ultimately, to the banking sector. Focusing on the Colombian hydropower sector, we combine climate projections, a plant-level production model, firm-level financial statements, and supervisory credit registry data to trace the transmission of climate shocks through the financial system.

Our empirical results indicate that hydropower generation is considerably more sensitive to extreme drought conditions than to periods of excessive rainfall, highlighting the asymmetric effects of precipitation on electricity production. Under the climate scenarios considered, projected reductions in precipitation translate into substantial declines in hydropower generation, ranging from approximately 10% under the SSP1-2.6 scenario to nearly 18% under the SSP5-8.5 scenario. These production losses deteriorate firms' operating performance, reducing EBIT and weakening their debt-servicing capacity as measured by the ICR. Consequently, the number of financially vulnerable firms increases under both climate scenarios.

The deterioration in firms' financial condition is subsequently transmitted to the banking sector through a decline in supervisory credit quality. Under the proposed stress scenarios, the QIR for the electricity generation sector increases by 25 and 38 percentage points under the SSP1-2.6 and SSP5-8.5 scenarios, respectively. These simulated deteriorations exceed the approximately 13-percentage-point increase observed during the 2015–2016 El Niño episode, suggesting that more persistent or severe drought conditions associated with future climate change could generate substantially larger financial impacts than those experienced historically.

Beyond these empirical findings, the proposed framework provides a practical methodology for integrating climate projections, sector-specific production models, firm-level financial information, and supervisory credit registry data into a unified climate stress-testing exercise. The results should nevertheless be interpreted in light of several simplifying assumptions. The

analysis assumes that firms' baseline hydropower generation represents their contracted energy commitments, that revenues vary proportionally with hydropower generation, that financial expenses remain constant throughout the stress horizon, and that financially vulnerable firms experience a one-notch deterioration in their supervisory credit rating. Moreover, the framework does not account for firms' adaptation strategies, banks' behavioral responses, policy interventions, or macroeconomic feedback effects, and therefore should be interpreted as a partial-equilibrium assessment of the direct transmission of physical climate risk through the hydropower sector.

Future research could extend the framework by incorporating detailed information on firms' contractual obligations, endogenous adaptation measures, probabilistic credit migration models, and macro-financial feedback effects. Such extensions would contribute to a more comprehensive assessment of climate-related financial risks while preserving the operational nature of the proposed methodology.

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