THE DUAL ROLE OF WATER: DRIVER AND REFLECTOR OF SOCIO-ENVIRONMENTAL CHANGES

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Dedication

A mi esposo y mi Annita.

También a mis papás, mi hermana, mi abuelita, mi familia cercana, y todos mis amigos que son la familia que he construido en los últimos años y que me han apoyado todo este tiempo.

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Introduction

Water is a fundamental resource, essential not only for ecosystems and biodiversity but also for human development. In the last years, the importance of water has gained broader recognition in the research arena of environmental economics. This dissertation aims to underscore the value of water by examining both its role as a driver of change for socio-economic activities (Chapter 1) and the ways in which various human activities are reflected on water quality (Chapters 2 and 3).

In Chapter 1 “Race and income moderate the effect of parks on housing prices in a segregated city”, I evaluate how the value of park attributes varies across neighborhoods with different socio-economic and racial demographics, particularly in highly segregated cities. Using spatial data on park attributes, home values, and neighborhood demographics in the Twin-Cities area in the United States, I investigated how willingness to pay for park characteristics -including water amenities- vary by neighborhood income and race characteristics. Some park attributes such as tree canopy and the presence of a dog park had positive and significant impacts on property values across neighborhoods of varying race and income characteristics, whereas park size, bike trail access, and presence of water bodies in parks had positive or negative effects on property values depending on race and income of the surrounding neighborhoods.

In Chapter 2 “A spatio-temporal analysis of water investment allocation in Colombia and its impacts on drinking water quality”, I assess the extent to which different types of investments in the water sector affect water quality from three perspectives (resource management, operation management, and water quality management) by implementing fixed effects, nonparametric fixed effects, and structural equation models. I introduce an innovative spatial index to account for investments in water treatment and sewage made by upstream municipalities. I use a panel dataset from 2009 to 2014 with nearly 400 observations at the provider-municipality level in Colombia with information on drinking water quality, and key variables that may influence it such as investment in water and sewage, poverty, and rurality. I show that improving resource allocation could enhance the effect of investment on water quality. Provider size also plays a role: investments made by providers with 100–450 employees show significant improvements, while other provider sizes do not. Finally, we show the need for investment in chemical, physical, and microbiological components that improve water quality.

Finally, in Chapter 3 “On government, guerrilla and water resources in a post-conflict scenario”, I evaluate whether the ceasefire with the FARC led to improvements in access to drinking water, through changes marked by the end of armed attacks and the dissolution of FARC’s territorial control. I conduct two main analyses: the first focuses on the end of attacks, using differences-in-differences (DiD) and DiD combined with propensity score matching; the second examines the effects of the end of territorial control through a mediation analysis, considering deforestation and economic activity (GDP) as mediating factors. The results from both approaches show that drinking water quality improved following the ceasefire, driven by increased economic activity that expanded water infrastructure and by land formalization processes.

1. Race and income moderate the effect of parks on housing prices in a segregated city

1.1. Introduction

Parks provide essential ecosystem services for urban areas, including supporting physical and mental health (van den Bosch & Ode Sang, 2017) and social cohesion (Wan et al., 2021). Parks can also increase property values and attract investment in urban areas (Bolitzer & Netusil, 2000). However, the benefits of parks and green infrastructure are not evenly distributed (Rigolon et al., 2018) (Winkler et al., 2024). Historically, park investments have disproportionately benefited white and wealthy neighborhoods contributing to racial and economic disparities among urban communities (Rigolon et al., 2018; Winkler et al., 2024). Yet as urban planners seek to address disparities in park access and quality, this has raised new fears among low-income communities about the potential for gentrification and displacement following investments in new or improved park infrastructure, a new manifestation of environmental injustice known as "green gentrification" (Anguelovski, Connolly, et al., 2022). Park authorities and urban planners must navigate a complicated set of tradeoffs as they consider new investments in parks and green infrastructure. Parks are an important tool for cities in achieving environmental and sustainability goals (Melnychenko et al., 2022; Sadeghian et al., 2021). At the same time, park investments may exacerbate existing inequalities if investments lead to gentrification and displacement. Our work aims to enrich conversations about the relationship between park amenities, property values, and the economic and demographic characteristics of urban neighborhoods.

Our analysis focuses on the relationship between park attributes and property values in park-adjacent neighborhoods in two urban counties in the U.S. state of Minnesota. Like many metro areas in the U.S., the Twin Cities of Minneapolis and St. Paul are characterized by high levels of segregation and persistent racial disparities in homeownership (Ingraham, 2020). The Twin Cities area also boasts an extensive network of highly-rated parks and open spaces (Timar-Wilcox, Estelle, 2024; Trust for Public Land, 2024). We assemble a dataset of spatially-explicit housing transactions, park attributes, and economic and demographic information to investigate how the relationship between park amenities and property values is moderated by socioeconomic and demographic characteristics of neighborhoods. By advancing a more nuanced understanding of how park amenities are coupled with property values across different racial and economic characteristics at the neighborhood, this research aims to inform the work of planners and managers aiming to balance sustainability and greenspace goals with concerns over gentrification and displacement.

We find that the effect of park characteristics on property values is moderated by the racial and economic characteristics of park-adjacent neighborhoods. For example, the economic classification of neighborhoods reveals differing preferences: in higher-income neighborhoods, parks with extensive tree canopy cover and access to water bodies or beaches were associated with higher property sale values. In contrast, in low-income neighborhoods, only one park amenity—tree canopy area—had a significant impact on property values.

Similarly, analysis based on the racial demographics of neighborhoods reveals distinct patterns in willingness to pay for park amenities. In neighborhoods with a higher proportion of residents identifying as (Hispanic, non-Hispanic Black, non-Hispanic Asian, other non-White and non-Hispanic—hereafter referred to as People of Color (POC), property values showed a strong positive association with features such as tree canopy, dog parks, and shelters. In contrast, in predominantly White neighborhoods, park amenities exhibited a weaker influence on sales prices overall, with higher prices more closely linked to water-related features, such as water bodies and beach access.

Finally, combining economic and racial data reveals shifts in willingness to pay for various park amenities. For example, high-income neighborhoods show that willingness to pay for water-related features and tree canopy is predominantly driven by neighborhoods with high percentage of White residents, rather than those in POC neighborhoods. In contrast, within the medium-income group, racial differences become evident: while White neighborhoods exhibit relatively weak willingness to pay for park amenities, POC neighborhoods demonstrate a positive willingness to pay for tree canopy, dog parks, and shelters, but a negative one for water bodies. These patterns stand in contrast to the low-income group, where both White and POC neighborhoods generally show weak preferences for park amenities.

1.2. Literature review

Decades of hedonic research in cities across the globe has found positive relationships between park presence and property values. In Portland, Oregon (U.S.), park-adjacent properties are on average $2,500 more expensive than houses further away from parks (Bolitzer & Netusil, 2000). In the Dallas-Fort Worth Metropolitan area in Texas (U.S.), park-adjacent properties sold for 22% higher than houses further from parks (Miller, 2001). Hedonic analysis of the relationship between parks and housing prices in a range of global contexts echo these results—studies from Stockholm, Sweden, Gold Coast, Australia, and Jinan City, China all observed an increase in property values associated with park proximity (Iqbal & Wilhelmsson, 2018; Kong et al., 2007; Yen et al., 2023).

Property transaction data has also been used to investigate the impact of park characteristics and amenities on housing prices. Park amenities such as water bodies, sports fields, bike paths, beaches, dog parks, and shelters have been found to have significant positive effects on housing prices (Yen et al., 2023). Parks with amenities related to social activity—such as dining options, musical activities, and outdoor markets—were found to increase housing prices in studies conducted in Sweden (Czembrowski et al., 2019), Poland (Czembrowski & Kronenberg, 2016) and China (Kong et al., 2007).

Urban scholarship in the U.S. and globally has also documented disparities in the distribution of parks and associated park benefits (Wen et al., 2013). In a review of the literature on park access and quality in the U.S., Canada, and Europe, (Rigolon, 2016) found that POC and lower-income communities have access to less park acreage and fewer park amenities. A nationwide analysis of urban park access in the United States found that a 10% increase in residents living below the poverty line was correlated with a 1.27% decrease in park acreage; similarly, a 10% increase in the percentage of residents who are Black was associated with a 0.3% decline in the amount of greenspace (Wen et al., 2013). These racial and income disparities in park size and quality suggest deep and persistent environmental injustice in the distribution of parks and park amenities (Rigolon, 2016). In a U.S. context, these disparities are driven both by persistent residential segregation that continues to characterize U.S. metropolitan areas and a long history of park planning processes shaped by racial segregation (Walker et al., 2023).

Cities are increasingly investing in urban sustainability and greening efforts (Pearsall & Pierce, 2010), often framed in the language of environmental justice and promising to alleviate disparities in park access (Checker, 2011). Research has demonstrated that home prices in neighborhoods perceived as “Black” appreciate at rates lower than homes in “White” neighborhoods (Markley et al., 2020), suggesting that adding new green amenities in these neighborhoods may not yield the same property value benefits to homeowners in majority-POC neighborhoods. At the same time, new parks or upgrades to existing parks can increase the perceived desirability of an area, triggering or accelerating increases in property values that put vulnerable residents at risk of being priced out and displaced (Anguelovski et al., 2018; Pearsall & Pierce, 2010). This phenomenon, referred to as "green gentrification," exacerbates environmental inequalities: the disadvantaged populations, those who often bore the brunt of environmental pollution and lack of greenspace, are no longer able to afford to stay in their neighborhoods following investments in new park amenities (Gould & Lewis, 2016). Anguelovski , et al., (2022) found a correlation between greening and subsequent gentrification in 17 out of the 28 US and European cities in their sample. Kim & Wu, (2022) found that the characteristics of parks influence their effects, with "passive, natural, and medium-sized" parks exerting a stronger green gentrification effect. Meanwhile, Rigolon & Németh, (2020) found that location and use were more important than size, with parks with an active transportation component and parks closer to downtown more likely to contribute to gentrification.

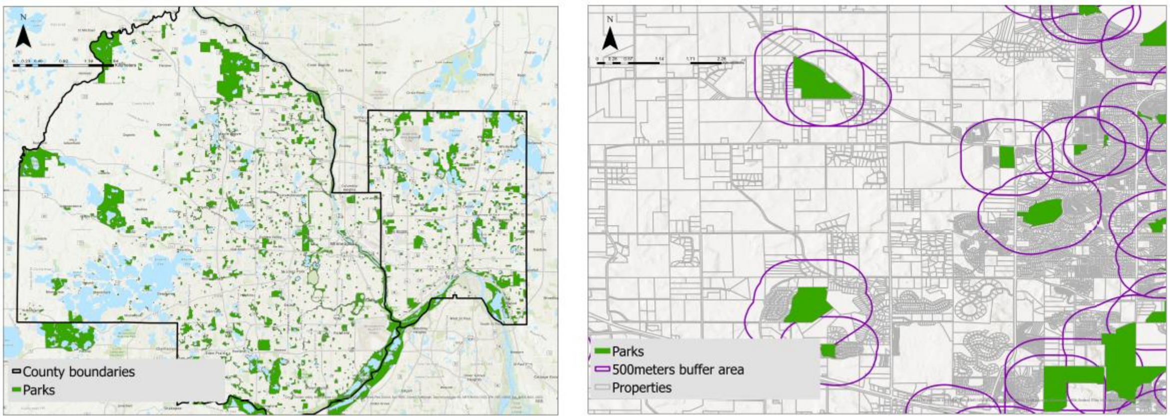
In summary, existing literature has shown that housing prices increase with the presence of nearby parks and park characteristics, including water bodies, sport amenities, tree canopy cover, and others (Czembrowski et al., 2019; Czembrowski & Kronenberg, 2016; Kong et al., 2007; Yen et al., 2023). A related line of research draws attention to how urban amenities such as parks might alleviate or exacerbate disparities in the distribution of wealth in cities (Migozzi et al., 2018). Lower income and minority neighborhoods have lower access to parks and may risk displacement or gentrification when investments are made in nearby park quality, size, or amenities. However, we still do not know how racial and economic characteristics of neighborhoods interact with parks and property markets to explain variation in the effects of parks and park amenities on home prices. As cities seek to remediate past injustices in park development, understanding how investments in park amenities affect property values differently based on the socioeconomic status of neighborhoods can help guide planners and policy makers as they navigate tensions between needed investments and fears of gentrification and displacement.

1.3. Methods

We investigate the relationship between park attributes and property values using information on 164,735 house sales from 1996 to 2019 in Hennepin and Ramsey counties, the two major metropolitan counties that contain the cities of Minneapolis and St. Paul in the U.S. state of Minnesota. Our dataset includes information about 81 different park characteristics compiled from a range of publicly available sources published by city and regional park authorities (Donahue et al., 2018). The park dataset provides information about park size, percentage of canopy cover, bike trail length, and presence of park amenities such as water bodies, dog parks, beaches, shelters, and sports facilities.

Data on house sales and house characteristics are provided by Zillow (Zillow Transaction and Assessment Dataset ZTRAX, 2021). The ZTRAX dataset provides information on sale transactions such as sale date, sale price, type of transaction (deed, mortgage, interfamily transfer, etc.) as well as property characteristics including number of bedrooms, number of bathrooms, property size and type of construction. Figure 1-1 illustrates the location of parks in our park dataset and the geographical boundary of Hennepin and Ramsey Counties, Minnesota.

Figure 1-1 Park locations and study design



Left panel: Locations of parks in Hennepin and Ramsey Counties, Minnesota, USA; Right panel: Locations of parks, 500-meter buffers around each park (purple contour), and the house locations as represented in the Zillow dataset.

We use GIS to geographically link properties in the Zillow dataset with parks and park attributes in our parks dataset (see Figure 1-1). We constrained our analysis to park-adjacent properties in order to investigate how park attributes and the sociodemographic characteristics of neighborhoods moderated the relationship between parks and property values. We reviewed the literature to assess distances used in previous studies to determine the effect of park proximity on property values. Studies varied, with the most common buffer distances being 400 to 600 meters (Crompton & Nicholls, 2021; Kolbe & Wüstemann, 2014; Kong et al., 2007; Panduro & Veie, 2013). Urban planners estimate a walkable distance as 500 meters, equivalent to a 5-10 minute walk (Kienast et al., 2012). Therefore, we use a distance of 500 meters as the cut-off to define park-adjacent properties.

We kept transactions classified as "Deed Transfer" and excluded transactions with a recorded value of less than $10,000 (Mamun et al., 2023; Swedberg et al., 2024). We also exclude properties that were classified as agricultural, commercial, or industrial. To analyze only owner-occupied properties, we excluded duplex, triplex, quadruplex, apartment buildings, and boarding houses. Following Fraenkel (2024), we exclude sales where the same property recorded multiple transactions within 90 days. To be able to compare sale prices over time, we deflated prices to the year 2019 (U.S. Bureau of Labor Statistics, 1984). The park characteristics data reflects park attributes in 2017, therefore we keep only the most recent transaction per house, recognizing that our dataset does not facilitate investigation of temporal changes in park attributes and associated impacts on property values.

The main explanatory variables used in our models are shown in Table 1-1. For park characteristics, we include park size, measured as the logarithm of the park area in square kilometers, percentage of total park area covered by tree canopy, and the length of bike trail within a 400 meter buffer from the park border. For park amenities, we include presence of a water body, presence of beach, presence of a dog park, and presence of a park shelter. For house characteristics, we include house age, number of bedrooms, building area, number of bathrooms, distance from each house to the nearest park, distance between each house and downtown, a dummy variable indicating if the house is located within 400 meters of rail or bus stop, and a categorical variable for the quarter of the year in which the transaction occurred.

For neighborhood characteristics, we include the total population at the census tract level, average vacancy rate, and school district.

Table 1-1 Explanatory variables

Explanatory variable	Measurement	Description
Park characteristics		
Park - Size	Continuous number	Logarithm of park area measured in km^2
Park - % area covered by tree canopy	Percentage	% of the park covered by tree canopy
Park - Bike trail	Meters	Bike trails within 400 meters from park
Park amenities		
Park - Dummy Water	Ordinal number	1 if the nearest park has water body, 0 otherwise
Park - Dummy Beach	Ordinal number	1 if the nearest park has beach, 0 otherwise
Park - Dummy Dog park	Ordinal number	1 if the nearest park has dog park, 0 otherwise
Park - Dummy Shelter	Ordinal number	1 if the nearest park has shelter, 0 otherwise
House characteristics		
Age	Years	Age of construction - year of sale
Total bedrooms	Ordinal number	Number of bedrooms
Building Area	Square meters	Building area in square meters
Number of bathrooms	Ordinal number	Number of bathrooms located in the property
Distance from house to park	Meters	Distance from each house to its nearest park
Distance from house to downtown	Meters	Distance from each house to nearest downtown
Dummy - Transit access	Ordinal number	1 if the house is located within 400 meters of rail or bus stop
Categorical – sale quarter of year	Categoric	Indicates the quarter of the year in which the house was sold
Neighborhood characteristics		
Total population	Ordinal number	Total population at census tract level
Vacancy rate	Percentage	Total properties classified as vacant at the census tract level
School district	Categoric	School district where the house is located

Our baseline dataset has 164,735 transaction records from 1996 to 2019. Table 1-2 presents descriptive statistics of the property and park datasets. Readers will note large variation in house characteristics in the baseline dataset reflecting a very heterogeneous sample (Appendix, Figure A-1).

Table 1-2 Summary statistics for baseline dataset

Variable	Min	Max	Mean	STD

Sale price	40,402.6	3,572,174.5	561,938.4	412,697.3
Park - Size (km2)	0.3	197,615.4	2,590.1	15,948.9
Park - % tree canopy area	0.0	1.0	0.3	0.2
Park - Bike trails (hundreds of meters)	0.0	384.7	5.8	32.5
Park - Dummy Water body	0.0	1.0	0.4	0.5
Park - Dummy Beach	0.0	1.0	0.1	0.2
Park - Dummy Dog park	0.0	1.0	0.0	0.1
Park - Dummy Shelter	0.0	1.0	0.0	0.2
Age	0.0	195.0	68.4	31.1
Total bedrooms	0.0	19.0	3.6	2.4
Building area (squared meters)	32.5	33,022.2	177.1	422.8
Number of bathrooms	0.0	8.0	1.6	0.8
Distance from house to park (meters)	0.0	499.9	208.0	130.8
Distance from house to downtown (meters)	5.1	18,174.3	3,398.0	1,783.4
Dummy - transit access	0.0	1.0	0.9	0.2
Total population	1,430.0	7,846.0	3,792.3	1,165.6
% Vacancy rate	0.0	18.0	5.1	3.5

Notes: N= 164,735

1.4.Empirical strategy

We estimate a hedonic regression model where our main explanatory variables are park characteristics (i.e., park size; tree canopy area; and bike trail access; presence of water, beaches, dog parks, and shelters), house and property transaction characteristics (i.e., sale price, date of sale, location, house age, number of bedrooms, building area, number of bathrooms, distances to park, downtown, and transit access), and neighborhood characteristics (i.e., total population and vacancy rate at the census tract level, school district information).

Data on house prices and park characteristics are likely to be spatially autocorrelated (Figure B-1 in Appendix) which can lead to bias estimators when using a classic Ordinary Least Squares (OLS) approach (Arbia, 2014; Paraguas & Kamil, 2005). We use spatial econometrics by estimating the Spatial AutoRegressive lag model (SAR) by maximum likelihood provided by the *spatial reg* R package (Bivand & Piras, 2015). The SAR is appropriate when there is a spatial dependence in the dependent variable with respect to their neighbors (Anselin, 2003).

When using the spatial term (WSalePrice in Equation 1), we aim to capture possible spatial dependencies in house price across our dataset. The model is specified as follows:

$$SalePrice_i = plagWSalePrice + ParkCharacteristics_{i,j}B + H_iB + N_iB + SD_iB + e_i \quad (1)$$

$SalePrice_i$ refers to the sale price for house i; *plag* is the spatial autoregressive coefficient that shows the spatial dependence in the observations (Bivand & Piras, 2015; LeSage, 2008); *WSalePrice* is the spatial lag term and contains information of the average values of sale price for all neighbors for house i; *$ParkCharacteristics_{i,j}$* represents a group of park attribute variables; H_i represents house characteristics for unit i; N_i represents neighborhood characteristics; SD_i represents the school district where the house i is located; and e_i represents the error term. To consider non-linear relationships between the house prices and the explanatory variables we adopt the log-linear form of Equation 1.

Our main model (Equation 1) includes the following assumptions. First, we assume that the error term e_i is normally distributed (LeSage, 2008). Second, we assume that house characteristics are time-invariant (except for age which is also constant at the time of transaction). Third, we assume the exogeneity of the different groups of variables: house, neighborhood, and park characteristics. Finally, we address the effects of time on house prices by deflating all house prices to a base year (2019) and only include the most recent transaction.

1.5. Selection process for park characteristics

Our study leveraged an existing dataset consisting of 81 different park characteristics and amenities collected and reported in Donahue et al., (2018). Here we describe the variable selection process that we used to determine which park characteristics to include in our final models. We first limited the park characteristics dataset to variables that had information for all the parks in our sample. With this subset of variables, we created multiple rounds of correlation matrices to evaluate the correlation between each park variable and our main dependent variable “sale price”. Park variables that were highly and significantly (at the 95% confidence level) correlated with other park variables were dropped keeping only the park variable that was most highly correlated with the sale price. At the end of these multiple rounds, we arrived a set of park characteristic variables that included park size, percent tree canopy cover, bike trail length, and four park amenity variables - presence of a water body, presence of a beach, presence of a dog park, and presence of a shelter (Appendix Figure C-1).

These park variables are consistent with previous studies showing that park size (Hoshino & Kuriyama, 2010), percent tree canopy cover (Macdonald & Franco, 2016), and bike trail length (Liu & Shi, 2017) were significantly related to property values. Similarly, the choice of park amenity variables is based on previous research showing that water or beach presence (J. Kim et al., 2020; Leggett & Bockstael, 2000; Mamun et al., 2023; Migozzi et al., 2018; H. W. Wendel & Mihelcic, 2009), dog park and park shelter (Dell'Anna et al., 2022; Pueffel et al., 2018) are significant predictors of house values.

1.6. Heterogeneous analysis based on income and race groups

We were interested in how economic and demographic characteristics of park-adjacent neighborhoods affect the relationship between park amenities and property values. We used socio-economic information at the census tract level taken from the American Community Survey 2019 (U.S. Census Bureau, 2019) to create eleven subcategories of race and income. For the income classification, we estimate the percentage of households below the federal poverty level as defined by the Census Bureau based on reporting at the census tract level. For race classification, we split neighborhoods into two groups based on percent White and percent non-White (including African-American, American Indian, Asian, Hawaiian, Alaska Native or Hispanic). We implement a step-by-step income clustering classification to create clusters based on combinations of race and income (described in detail in Appendix, Section D).

1.7. Results

1.7.1. Results for all park-adjacent properties

We first report on the relationship between park characteristics and property values for all transactions without adjusting for racial or economic clusters. Consistent with previous studies, we found that multiple park characteristics and amenities variables were important in explaining observed variation in property values (Table 1-3, column 2). The percentage of park area covered by tree canopy, presence of a water body, and presence of a beach were all significantly and positively related to property values.

We also found that property values were influenced by housing characteristics, neighborhood characteristics, and school districts. Consistent with previous findings, the number of bedrooms, house size, and number of bathrooms were positively related to house prices (Czembrowski & Kronenberg, 2016). We observed that greater distances to park and transit access in a neighborhood are negatively valued, while a greater distance to downtown has a positive influence on housing prices. The quarter at which property sales took place was also significant, with significantly higher transactions in the second quarter of the year compared to the first.

In terms of neighborhood characteristics, total population at the census tract level was positively and significantly related to house prices and vacancy rate in the census tract level had a negative effect on house prices. The school district variable was also significant, with some districts conferring positive or negative impacts on prices. For instance, we found that the wealthier school district of Edina had a significant and positive relationship with house prices. On the other hand, the Delano, Elk River, Orono, and Westonka School Districts had a significant negative relationship.

1.7.2. Results for heterogeneous analysis: considering racial and economic information

As noted above, we were interested in how racial and economic characteristics of neighborhoods moderated the relationship between park amenities and property values. Model results considering the effects of race and income clusters are included in Table 1-3 (columns 3 to 7) and Table 1-4 with notable insights described in the following text.

With respect to the relationship between park size and property values, we found a negative relationship in predominantly White (~\$10,500) and High-Income & White (~\$8,200) neighborhoods and a positive relationship between park size and property values in Medium-Income (~\$3,200), POC (~\$16,100), and Medium-Income & POC (~\$13,600) neighborhoods. This suggests that smaller parks may be valued differently than large parks based on the racial and economic make-up of park-adjacent communities.

Tree canopy coverage had a significant and positive effect on property values in POC neighborhoods (~\$162,500) with results driven by Medium-income & POC (~\$170,000) neighborhoods. Similarly, we see that the willingness to pay for the area covered by tree canopy for White (~\$77,000) neighborhoods is mainly driven by Medium-income (~\$49,300) and High-income (~\$110,500) White dominated neighborhoods.

The model variable representing length of the bike trail near parks was positively valued for most racial and economic subgroups; with White (Medium and High-income) predominant neighborhoods driving the results. Results indicate that house prices in POC neighborhoods have a significant negative relationship with bike trail length—more bike trails are correlated with lower home sale prices.

We found similar patterns for other park amenity variables, where park attributes had differing explanatory power based on racial and economic subgroups. The presence of water bodies was significantly and positively related to house prices for almost all of our group analysis, except for neighborhoods classified as low-income & POC (~\$22,500) and medium-income & POC (~\$59,100). Presence of a water body in the nearest park was associated with an increase in medium-income house sales of ~\$4,600 and an increase in high-income house sales of ~\$126,900.

The presence of beach(es) is valued positively by almost all subgroups, except for the low-income & POC predominant neighborhoods (~\$3,600), where this relationship is not statistically significant. The presence of a dog park was significantly correlated with house prices in the overall dataset, driven in particular by home sales in medium- and high-income POC neighborhoods. The results for presence of a park shelter show that the premium value this amenity adds to house prices is mainly driven by medium-income & POC (~$85,700) and high-income & White (~$61,300) predominant neighborhoods.

We found evidence of racial and economic characteristics moderating the relationship between distance to park and property values, however the effect of this variable on the house price was relatively low. For the distance to downtown variable, we observe that in the POC predominant census tract, greater distance to downtown was negatively valued, the in White predominant census tract, greater distance to downtown was valued positively; however, in both cases, the effect on house prices was minimal. A similar situation is observed for the transit access: where we observe that most of the negative association to this variable is driven by high-income & White predominant neighborhoods.

With respect to neighborhood characteristics, we observe that total population and vacancy rates in the neighborhood are variables that mostly do not depend either on race or income information. The effect of the school district variable can be explained generally on income status: when the house is located in a census tract classified as low-income, school districts do not explain house prices. However, school districts change house prices by around 2% in medium-income neighborhoods and by 17% in high-income neighborhoods. In addition, school district effects can be also explained by race information, in this case these effects are relevant only for neighborhoods classified as White.

For additional control variables such as **house and neighborhood characteristics and school district information**, we see that some variables do not depend on the racial and economic information, while others do. For instance, ***building area*** and ***number of bathrooms*** are valued *positively* and significantly independently from the income and race information. While the total ***number of bedrooms*** (low- and high-income POC: ~$4,100 and ~$84,700, respectively) and ***age*** (~$2,000) are valued negatively only by two subgroups.

Our results suggest that many park characteristics and amenities, including tree canopy, dog parks, and beaches are positively related to property values in park adjacent neighborhoods regardless of race or income characteristics. However, some park characteristics, including park size, bike trails, and presence of a water body, had statistically positive or negative impacts on property values depending on race and income of the surrounding neighborhood (Figure 1-2).

Figure 1-2 Summary of results for park characteristics and amenities

Notes: This graph shows the summary of the impacts of park size, percentage of tree canopy, bike trails, presence of water body, beach, dog park, and shelter on house prices. The magnitude of the impact is color coded such that the darkest blue color represents the highest positive impact of the variable on house prices, while the darkest red color represents the lowest negative impact of the variable on house prices. Yellow stars represent the statistical significance: ***p<0.01, **p<0.05, *p<0.1.

Table 1-3 Estimation results for 500 meters buffer area

Variable	Whole	Income			Race	
		Low	**Medium**	**High**	**POC**	**White**
Intercept	6,376,988***	8,405,301***	4,614,558***	10,988,499***	4,838,990***	6,896,606***
	[15,312]	[100,021]	[11,006]	[65,123]	[158,057]	[15,378]
Park - Size (log of km2)	-2,918***	1,300	3,196***	-5,613	16,108***	-10,455***
	[1,028]	[1,014]	[738]	[4,150]	[1,421]	[977]
Park - % tree canopy area	123,491***	27,665***	78,235***	166,318***	162,533***	76,867***
	[9,787]	[9,842]	[7,019]	[38,724]	[14,800]	[9,697]
Park - Bike trails (hundreds of meters)	276***	-46	198***	77	-1,209***	322***
	[45]	[182]	[33]	[189]	[195]	[42]
Park - Dummy Water body	57,354***	3,475	4,613*	126,864***	-33,291***	86,421***
	[3,980]	[4,829]	[2,753]	[16,549]	[5,464]	[4,016]

Park - Dummy Beach	72,625***	12,973	10,277	55,261	64,900***	70,616***
	[9,249]	[16,214]	[6,985]	[35,660]	[21,492]	[8,060]
Park - Dummy Dog park	42,038***	8,146	15,606	79,971	144,108***	4,067
	[13,575]	[11,494]	[10,324]	[49,804]	[18,622]	[13,180]
Park - Dummy Shelter	44,834***	-10,401	-25,682***	45,553	155,143***	67,995***
	[9,229]	[15,833]	[7,565]	[35,240]	[17,644]	[8,724]
Age	4,946***	650***	3,273***	1,498***	2,603***	5,349***
	[52]	[62]	[41]	[110]	[76]	[63]
Total bedrooms	42,871***	6,843***	23,399***	1,244	19,713***	50,366***
	[794]	[1,078]	[674]	[1,574]	[1,368]	[933]
Building area (squared meters)	2***	8***	13***	1***	0	24***
	[0]	[1]	[0]	[0]	[0]	[0]
Number of bathrooms	13,658***	3,862***	7,174***	12,297***	12,369***	14,454***
	[122]	[144]	[113]	[247]	[237]	[143]
Distance from house to park (meters)	-75***	-15	-18**	-195***	2	-107***
	[12]	[12]	[9]	[46]	[16]	[12]
Distance from house to downtown (meters)	6***	1	4***	33***	-12***	6***
	[1]	[2]	[1]	[6]	[2]	[1]
Dummy - transit access	-35,644***	-2,683	-3,137	-38,711**	-12,657	-31,485***
	[5,036]	[6,733]	[3,857]	[15,951]	[10,054]	[5,065]
Categoric - Sale in 2nd quarter of the year	11,986***	8,715***	6,600***	7,842**	6,559***	14,394***
	[1,422]	[1,832]	[1,143]	[3,394]	[2,290]	[1,737]
Categoric - Sale in 3rd quarter of the year	-10,149***	8,806***	-5,657***	-6,738*	-1,206	-11,856***
	[1,520]	[2,039]	[1,217]	[3,615]	[2,482]	[1,853]
Total population	29***	12***	18***	31***	43***	30***
	[1]	[1]	[1]	[7]	[2]	[1]
% Vacancy rate	-7,878***	-1,619***	-2,531***	-20,441***	-6,192***	-6,551***
	[557]	[551]	[399]	[2,546]	[692]	[576]
n	164,735.0	12,310.0	100,753.0	51,672.0	41,440.0	123,295.0
p	42.0	33.0	42.0	41.0	35.0	42.0
npar	3.0	3.0	3.0	3.0	3.0	3.0
value	68548.5	-24075.5	14151.4	2478.8	10607.0	52960.1
AIC	68554.5	-24069.5	14157.4	2484.8	10613.0	52966.1
AICc	68554.5	-24069.5	14157.4	2484.8	10613.0	52966.1
Log Likelihood	-34274.3	12037.8	-7075.7	-1239.4	-5303.5	-26480.0
Deviance	164693.0	12277.0	100711.0	51631.0	41405.0	123253.0
pseudo.r.squared	0.2	0.1	0.2	0.1	0.2	0.2

(1) No fixed effects are included.; ***p<0.01, **p<0.05, *p<0.1.

Table 1-4 Estimation results for 500 meters buffer area – Intersection race and economic information

Variable	Low-income POC	Low-income White	Medium-income POC	Medium-income White	High-income POC	High-income White
Intercept	8,349,152***	8,469,659***	4,457,172***	4,699,362***	12,098,857***	12,229,242***
	[95,860]	[35,386]	[108,742]	[11,397]	[687,555]	[52,362]
Park - Size (log of km2)	-33	-1,471	13,573***	-522	6,603	-8,178**
	[1,763]	[1,458]	[1,222]	[741]	[26,019]	[3,433]
Park - % tree canopy area	-1,243	2,904	169,980***	49,270***	-274,755	109,441***
	[17,396]	[15,290]	[12,851]	[7,214]	[296,406]	[32,173]
Park - Bike trails (hundreds of meters)	503**	-1,166	-46	156***	-10,320***	304**
	[246]	[1,323]	[183]	[33]	[2,806]	[146]
Park - Dummy Water body	-22,538***	10,870	-59,158***	24,956***	496,524***	63,690***
	[7,465]	[7,317]	[4,461]	[2,888]	[116,182]	[13,746]
Park - Dummy Beach	-3,579	50,311***	18,265	7,505	364,737	94,865***
	[37,248]	[19,322]	[18,977]	[6,423]	[226,380]	[28,837]
Park - Dummy Dog park	24,042	-10,909	84,115***	-8,053	482,640*	40,358
	[14,958]	[12,488]	[17,242]	[10,545]	[249,644]	[42,745]
Park - Dummy Shelter	25,370	-22,177	85,732***	-6,397	127,820	61,288**
	[49,155]	[17,934]	[14,827]	[7,738]	[237,753]	[28,082]
Age	237***	54	2,045***	3,387***	-2,002**	1,618***
	[63]	[58]	[61]	[50]	[822]	[120]
Total bedrooms	-4,107***	5,046***	14,983***	22,836***	-84,664***	9,965***
	[1,101]	[1,168]	[1,148]	[778]	[13,491]	[1,660]
Building area (squared meters)	4***	6***	36***	8***	12***	23***
	[0]	[1]	[1]	[0]	[1]	[1]
Number of bathrooms	1,156***	2,203***	6,747***	7,139***	11,225***	13,731***
	[182]	[165]	[159]	[136]	[2,395]	[252]
Distance from house to park (meters)	33**	-26**	36**	-41***	-157	-119***
	[15]	[13]	[14]	[9]	[259]	[39]
Distance from house to downtown (meters)	-1	0	-7***	10***	29	3
	[3]	[3]	[2]	[1]	[73]	[5]
Dummy - transit access	-9,191	8,260	-18,571*	4,056	-110,853	-37,707***
	[9,146]	[11,370]	[9,501]	[3,856]	[95,702]	[13,599]
Categoric - Sale in 2nd quarter of the year	4,768	6,561**	1,712	7,373***	21,316	22,906***
	[3,075]	[2,791]	[1,249]	[1,399]	[20,823]	[3,832]
Categoric - Sale in 3rd quarter of the year	8	191	19,312***	-7,454***	42,984*	-17,044***
	[3,454]	[3,135]	[1,425]	[1,481]	[22,834]	[4,138]
Total population	15***	11***	21***	19***	-3	32***
	[3]	[4]	[2]	[1]	[56]	[5]
% Vacancy rate	-1,134	-2,161*	-1,449**	-3,408***	-20,021	-5,684***

	[931]	[1,152]	[611]	[426]	[15,229]	[2,113]
n	5,630.0	6,680.0	26,385.0	74,368.0	9,425.0	42,247.0
p	30.0	27.0	35.0	42.0	34.0	41.0
npar	3.0	3.0	3.0	3.0	3.0	3.0
value	-5698.8	-6984.1	-27480.2	20828.0	21185.0	-8281.7
AIC	-5692.8	-6978.1	-27474.2	20834.0	21191.0	-8275.7
AICc	-5692.8	-6978.1	-27474.2	20834.0	21191.0	-8275.7
Log Likelihood	2849.4	3492.0	13740.1	-10414.0	-10592.5	4140.9
Deviance	5600.0	6653.0	26350.0	74326.0	9391.0	42206.0
pseudo.r.squared	0.1	0.1	0.3	0.1	0.3	0.1

(1) No fixed effects are included.; ***p<0.01, **p<0.05, *p<0.1.

As additional robustness checks and to evaluate whether preferences change based on proximity to parks, we ran the same analysis for houses within 50 meters and 300 meters from parks (Appendix, Section E).

1.8. Discussion

Park amenities vary by race and economic characteristics of park-adjacent neighborhoods

Our dataset facilitates the comparison of park attributes and amenities among neighborhoods of varying economic and demographic characteristics. In Hennepin and Ramsey counties, parks located in neighborhoods characterized as high-income were more likely to have bodies of water, beaches, and park shelters than parks in lower income neighborhoods. Parks in higher income areas also had greater bike trail length and greater tree canopy than parks in tracts characterized as low-income. Similar patterns were observed when comparing the racial characteristics of neighborhoods, with predominantly White neighborhoods more likely to have parks with water bodies and greater bike trail length. These results are consistent with studies conducted in Latin America (Curitiba-Brazil, Santa Cruz-Bolivia, and Bucaramanga-Colombia), Africa (Potchefstroom, South Africa), Canada, and Spain (Anguelovski et al., 2018; Macedo & Haddad, 2016; Ramirez et al., 2017; H. E. W. Wendel et al., 2012). A global analysis found similar patterns, with parks located in high-income neighborhoods having more amenities and a greater diversity of amenities than parks located in low and middle-income neighborhoods (Allegretto et al., 2022).

Park amenities explain variation in adjacent property values

Our findings suggest that park tree canopy, presence of water bodies and beaches significantly influence the impact of a park on adjacent home values. Looking across our entire dataset, these variables have a large influence on house prices, explaining about 22%, 10%, and 13% of the total sale price, respectively. These findings are consistent with past literature on the impact of park type and characteristics on property values. Studies looking at cities in the US (New York City), China (Jinan City), and Singapore have found that more naturalistic or "landscape" parks (e.g., parks managed for ecological function and habitat) tend to have a greater positive effect on property values (Kong et al., 2007) compared to parks managed for sports and recreation (Hofe et al., 2018). Similarly, Y. Wang et al., (2017) in China (Guangzhou) found a positive effect between increasing tree canopy and home prices, though this analysis considered all urban tree canopy rather than looking exclusively at tree canopy in parks.

Our findings also point to the importance of water-related amenities such as water bodies and presence of beaches in parks as a driver of increased house prices. Previous literature in the U.S. has shown that the homebuyers are willing to pay a premium for proximity to a park with a water body and that this premium increases the closer the home is to the park (Darling, 1973). However, in contexts where the water quality is poor, for example in Santa Cruz (Bolivia), Mombai (India) (Migozzi et al., 2018; H. W. Wendel & Mihelcic, 2009), analyses find lower property values for properties nearer to the park's water bodies.

Race and income characteristics affect the relationship between parks and property values

We observe that the relationship between property values and park features is mediated by race and income characteristics at the neighborhood level. For income, we find that among medium and high-income neighborhoods, the presence of water bodies and water-related amenities has a significant positive effect on home prices. In neighborhoods with comparatively less wealth, house and neighborhood characteristics were more important drivers of home price than park characteristics. Schläpfer et al., (2015) in Switzerland and Fernandez & Bucaram, (2019) in New Zealand similarly observed a differential effect of beaches on property values across housing market segments, with the presence of beaches having a positive effect on home prices at the high end of the home price distribution but a negative effect on home prices at the low end of the housing market. In South Africa, Lategan et al., (2022) showed that proximity to high-quality amenities in parks has a positive effect on property values in high-income neighborhoods. Our research suggests wealthier buyers are willing to pay higher prices for homes with greater proximity to recreational amenities such as water bodies, lending support to the concerns about green gentrification in which lower-income residents fear that investments in new park amenities may spur rising home prices.

Neighborhood racial demographics appear to moderate the relationship between park characteristics and home prices. The positive effect on home prices of park tree canopy was higher in neighborhoods with a greater percentage of POC than in predominantly White neighborhoods (~$162,500 versus ~$76,900). A previous study of racial disparities in tree canopy in the cities of Minneapolis and St. Paul found that canopy cover is significantly and positively correlated with the share of White residents (Walker et al., 2023). With less access to residential canopy in private spaces, tree canopy in public spaces might exert a stronger positive effect on home prices. We observe the same pattern for the presence of dog parks and shelters—these amenities were positively correlated with home prices in both race sub-markets, but the effects were larger and only significant in predominantly POC neighborhoods. Few other studies have considered differences in the relationship between park amenities and home prices mediated by surrounding racial characteristics. One comparable study from Cape Town (South Africa), observed that the legacy of apartheid housing segregation swamped any effects of park proximity or park amenities on property (Migozzi et al., 2018).

Similar patterns emerge when we consider the intersection of both race and income on the relationship between park characteristics and home prices. For neighborhoods that are low-income and have a high percentage of POC, only bike trails exert significant positive influences on home prices, while the presence of water bodies has a negative effect. Due to the long history of racially segregating policies that concentrated parks in White, racially exclusive neighborhoods in Minneapolis (Walker et al., 2023), access to these amenities in low-income, majority POC neighborhoods is comparatively limited. In Minneapolis, non-white and Black residents have significantly less access to bike lanes and trails (J. Wang & Lindsey, 2019), perhaps increasing the premium placed by buyers on access to these types of infrastructure. On the other hand, neighborhoods with a larger population of high-income and White residents—the most advantaged sub-group— tree canopy, water bodies, presence of beaches, and shelters exerted a significant positive influence. These park characteristics are challenging to privatize, making public access to these amenities valuable even among the most advantaged sub-market.

In White and high-income neighborhoods, we observe a negative preference for park size, which contrasts with a positive preference observed among other racial-income groups. While this finding diverges from the majority of studies that report a positive relationship between park size and property values, it aligns with patterns observed in privileged neighborhoods, where the increased traffic and noise associated with large parks may be viewed as undesirable. This dynamic was similarly noted by Anderson & West, (2006) in their study of the Twin Cities area.

Notable differences emerge for other housing characteristics among racial and income neighborhood subgroups. Neighborhoods with a high percentage of People of Color (POC) exhibited a negative willingness to pay for homes with more bedrooms. In both the lowest- and highest-income neighborhoods with a high POC population, a larger number of bedrooms is associated with lower property values. In high-income neighborhoods, this may reflect a preference for more open layouts and modern homes with fewer bedrooms. Conversely, in low-income neighborhoods, the negative association could indicate that homes with fewer bedrooms are more affordable and better align with the financial constraints of residents.

As demonstrated in our study, both race and income were important factors mediating the relationship between parks and property values. In other global urban contexts, ethnic characteristics and immigration status may be more important factors. For example, in South Africa, the legacy of the apartheid has been associated with inequalities in the housing market and access to urban greenspaces (Migozzi et al., 2018; Venter et al., 2020).

Study limitations

Our results are limited by the information on race and income that is available only at the census tract level. In an ideal scenario, it would be useful to have race or ethnicity and income information at the transaction level rather than census tract, to analyze park preferences based on individual information. In addition, our results are also limited by the lack of information on how park characteristics and amenities change over time, which constrains our ability to evaluate how house prices respond to changes in park characteristics and amenities.

Moreover, ZTRAX data is based on tax assessor data compiled by multiple local jurisdictions, with varying degrees of missing and/or extreme values (Zabel et al., 2023). We have endeavored to fully describe data cleaning and preparation decisions in the Methods section to avoid potential problems with reproducibility (Nolte et al., 2024).

1.9. Conclusions

Our results lend support to the assumed positive relationship between parks and property values, with a focus on how specific park amenities explain variation in housing prices in park adjacent neighborhoods. The most amenity rich and desirable parks tend to be located in neighborhoods with a higher percentage of White and high-income residents. This potentially drives a feedback loop in which parks in wealthy neighborhoods may be better resourced in terms of maintenance, programming, safety, and amenities, making them more valuable for the people who can afford to live near them (Sullivan et al., 2016). Our study highlights the effects of structural racism and inequality in a U.S. context, the impacts of racial and ethnic discrimination, segregation, and colonialism shape both access to housing and to environmental amenities in cities in both the Global North and the Global South (Anguelovski, Brand, et al., 2022; Shackleton & Gwedla, 2021; Venter et al., 2020; Waldman, 2022).

In addition, we find evidence that confirms that the relationship between park characteristics and home prices is mediated by the racial and economic characteristics of the neighborhood. These results are consistent with those of other studies on park characteristics and gentrification that similarly found that parks "natural" landscaping exert stronger gentrification effects (Kim & Wu, 2022). In addition, numerous case studies have noted the importance of water-based parks as drivers of green gentrification (Curran & Hamilton, 2012; Sánchez et al., 2024).

Green gentrification is an issue of global importance, impacting communities in cities in both the Global North (Anguelovski, Connolly, et al., 2022) and the Global South (Anguelovski et al., 2018; Torres et al., 2022; Yazar et al., 2020). Adding new parks with these characteristics might pose a greater risk of increasing property values potentially triggering gentrification and displacement. These results point to the need for both community-centered park design that aims to serve the needs of existing local residents, as well as robust protections for housing affordability so that residents in these neighborhoods are able to benefit from new park amenities, rather than risking displacement. Similarly, the premium residents in predominantly POC neighborhoods were willing to pay for access to bike trails suggests demand for greater active transport options among this subgroup.

Research on how park features and socio-economic characteristics influences house prices at the neighborhood level can inform our understanding of how greenspaces shape wealth, with implications for our understanding of green gentrification and policies to promote more equitable investments in parks and greenspaces. We find that the relationship between property values and park characteristics is mediated by race and class characteristics at the neighborhood level. These results are relevant for park planning in the context of cities with social and environmental inequalities, features that characterize cities in both the Global North and Global South (Rigolon et al., 2018). Investments to reduce disparities in access to urban parks have the potential to ameliorate historic inequalities and ensure that all residents have access to the recreational and environmental benefits parks provide (van den Bosch & Ode Sang, 2017; Wan et al., 2021). Park planners and developers can gain insights from studies that attempt to disaggregate the presumed relationships between park amenities and property values. Park investments may not have the same impact on property values in all neighborhoods or contexts, offering potential solutions to combat the threat of green gentrification.

2. A spatio-temporal analysis of water investment allocation in Colombia and its impacts on drinking water quality

Providing water and sanitation services through centralized water providers (i.e., systems, or utilities, or companies) is the primary approach that most countries are taking to achieve Sustainable Development Goal 6 (SDG6) (i.e., providing "clean water and sanitation for all"). Notably, there has been a considerable policy push over the past several decades to invest in infrastructure to expand coverage and to promote water system consolidation (physical or otherwise). Beyond concerns with coverage, there are also concerns about the quality of drinking water provided by centralized water providers. These concerns are particularly accentuated in the present moment as many centralized water providers in low and medium-income countries (e.g., Colombia) are increasingly struggling to make adequate financial investments due to extensive funding gaps, which has led to years of deferred maintenance, dilapidated infrastructure, and consequently, poor drinking water quality. Though investments in coverage and water quality are both understood to be important for economic and social development, the extent to which different types of investments can be leveraged to improve drinking water quality outcomes is unclear. Shedding light on this question can allow for the development of a framework that can help decision-makers reallocate resources to maximize impacts on drinking water quality.

Previous research studies have sought to explain the impacts of investment decisions in the water sector had been addressed from diverse perspectives. In the public policy decision-making arena, research shows that policies that boost investment in the water sector not only increase drinking water quality but may also reduce government costs in other areas. For instance, efficient investment in water policies decreased the amount of hospitalizations in Brazil (Ferreira et al., 2021) and showed high returns for every dollar invested in Palau (Hasan & Gerber, 2008). In rural China, India, and Brazil, investment on piped tap water and increased access to water treatment plants also improved drinking water quality (Jalan & Ravallion, 2003; Merrick, 1985; Yue et al., 2017). Though these studies contribute to our understanding of the magnitude of the impacts of investment on improving drinking water quality, they do not address some of the challenges that water providers face in the intermediate steps of the provision of the service. Mainly, low baseline water quality levels due to contamination from municipalities upstream from their shared water source, provider characteristics, and investment decisions.

Investments directed toward impacting the mechanistic processes that determine water quality are thus likely to effectively improve water.[1] Yet only one study has explored how the investment in key physical and microbiological components improved drinking water (Roca et al., 2015). However, this study only addresses the geographical area of Chicago and not a nation-wide challenge with diverse baseline water quality and a complex orography and hydrology. Another challenge that previous studies have not addressed is the impact of investment by provider size. These considerations are not only important in the context of understanding the impacts of investment but also in the broader context of regionalization and opportunities for economies of scale that may arise as provider size increases. As governments face limited resources to finance the water sector, an analytical framework that integrates knowledge of water flows across municipalities and landscape, the mechanistic processes that determine water quality, and provider characteristics and decisions will help policymakers to make better decisions.

In this paper, we explore how investments in the water and sanitation sector improve water quality in the context of Colombia. As part of our work, we aim to shed light on how local decision-makers can better optimize limited available funding to improve water quality outcomes. To conduct our work, we compile a panel dataset from 2009 to 2014 with nearly 400 observations at the provider-municipality level in Colombia that includes information on drinking water quality, and key variables that may influence it such as investment in water and sewage, poverty, and rurality. We use this information to study how different types of investment improve water quality from three perspectives: resource management (e.g.,

[1] The mechanistic processes that determine baseline water quality are either physical (presence of particles that change color), chemical (composition and concentration of harmful/beneficial elements and compounds), or microbiological (presence of harmful organisms). Chemical products already present in water or used by providers in water treatment, along with natural and human activity residues, determine the water's chemical (e.g., pH, chlorides), physical (color, odor, turbidity), and microbiological (e.g., E. coli, coliforms) characteristics. Chlorides and slightly basic pH levels pose low toxicity risks and can improve water quality by inhibiting bacterial growth (Hashmi et al., 2009). Mercury, coliforms, and nitrites, have high toxicity levels and can cause gastrointestinal diseases (Michigan Department of Health and Human Services & Michigan Department of Environment, Great Lakes, and Energy, n.d.). Chlorides, Magnesium, and pH are classified as low toxicity risk for human health.

coverage, maintenance, design, and administrative), operative management (e.g., provider size), and water quality components (physical, chemical, and microbiological). We use distinct approaches to study each perspective: we study resource management using a fixed effects model, operative management using a nonparametric fixed effects model, and water components using a structural equation modeling framework. For each approach, we include additional explanatory variables to control for different factors such as surface water quality, per capita investment in sewage in the nearest upstream municipality, rurality percentage, and poverty level for each municipality.

Our work contributes to the literature on water management by focusing on regional-scale level. One of the main contributions of this study is that our analysis focuses on the whole country of Colombia. In doing so, it shifts the focus from traditional emphasis on the provider or city scale to the regional scale. Additionally, our work is also relevant for regions with declining populations where water utilities must consider at which point they should consolidate and merge with other regional utilities for the sake of efficiency. Finally, we contribute water investment management research by adding for the first time to the literature an index that identifies the relationships of all upstream municipalities to a specific municipality in a water quality and investment study. The contribution of including this index in this context is substantial because water quality not only depends on provider or local authorities, but also on the water quality and the wastewater decisions from upstream municipalities.

Our results suggest that infrastructure investment has a positive but nonsignificant effect on water quality, highlighting investment's limited impact. We find distinct impacts based on investment type: investments in repairs and maintenance significantly improve water quality, while expenditures on expanding coverage and "other spendings" do not. These results emphasize the importance of strategic resource allocation. Additionally, we observe that smaller providers (100-450 employees) improve water quality with smaller investments, while very small or large providers do not. With respect to water components, our findings indicate that changes in water quality are largely driven by changes in Free Residual Chlorine (36.9%), Coliforms (-2%), Color (-5%), and Turbidity (-6.5%). However, we find no significant relationship between investment and improvements in these components, suggesting a need for more targeted investment.

2.1. Background on water service provision in Colombia

Investment in the water sector has historically been heavily focused on expanding service coverage, prioritizing access over quality. As of 2024, it is estimated that 88% of the population already has access to water services(Ministerio de Vivienda, Ciudad y Territorio, 2024). Yet 74% of the Colombian population still lacks access to water that meets basic water quality regulations(World Bank, 2024). This disparity reflects the challenge of balancing expansion efforts with much needed quality improvements.

Centralized water providers vary substantially in terms of size and capacity. On the large end of the spectrum, Empresas Públicas de Medellín (EPM) serves 123 municipalities, whereas small providers like Empresa Triple A, serves just 17 municipalities(Empresas Públicas de Medellín, 2023; López Suárez, 2022). Small providers, particularly those serving fewer than 5,000 users, often struggle to meet basic water quality regulations (Comisión de Regulación de Agua Potable y Saneamiento Básico, 2018; Vidarte, 2022), exacerbating inconsistencies in service delivery.

From an operational point, providers are responsible for the entire water supply chain—collection, treatment, storage, and distribution—while ensuring compliance with safety standards. This includes sampling and analyzing water quality at multiple points, from the treatment plant to the end user (Concepto 36481 de 2023 CRA, 2023, p. 36). However, many providers fail to meet these critical requirements due to lack of technical knowledge, funding, or government control, resulting in unsafe water being delivered to consumers.

2.2. Data

2.2.1. Data sources

We conduct our analyses using municipality-year as our unit of analysis. We therefore create a database of institutional, socio-economic, and water information at the municipal level for each year of study. We use the following sources of data:

i) institutional characteristics from the Superintendencia de Servicios Públicos Domiciliarios SSPD (Superintendencia de Servicios Públicos Domiciliarios, 2024). This data includes information on investment and number of employees of the provider that provides the service in each municipality. Investment information is broken down into three categories: coverage, quality, and other expenditures. Coverage includes network expansion, studies, and designs, increase of volume of produced water, water transportation and distribution. Quality expenditure includes network maintenance, studies to repair networks, and cleaning of waste on water. Other expenditures are investments without specific use information. For further information on all variables, see Appendix, A.

ii) socio-economic from CEDE (Universidad de Los Andes, 2024). These data include municipal level information on poverty, rural vs urban proportion, and population.

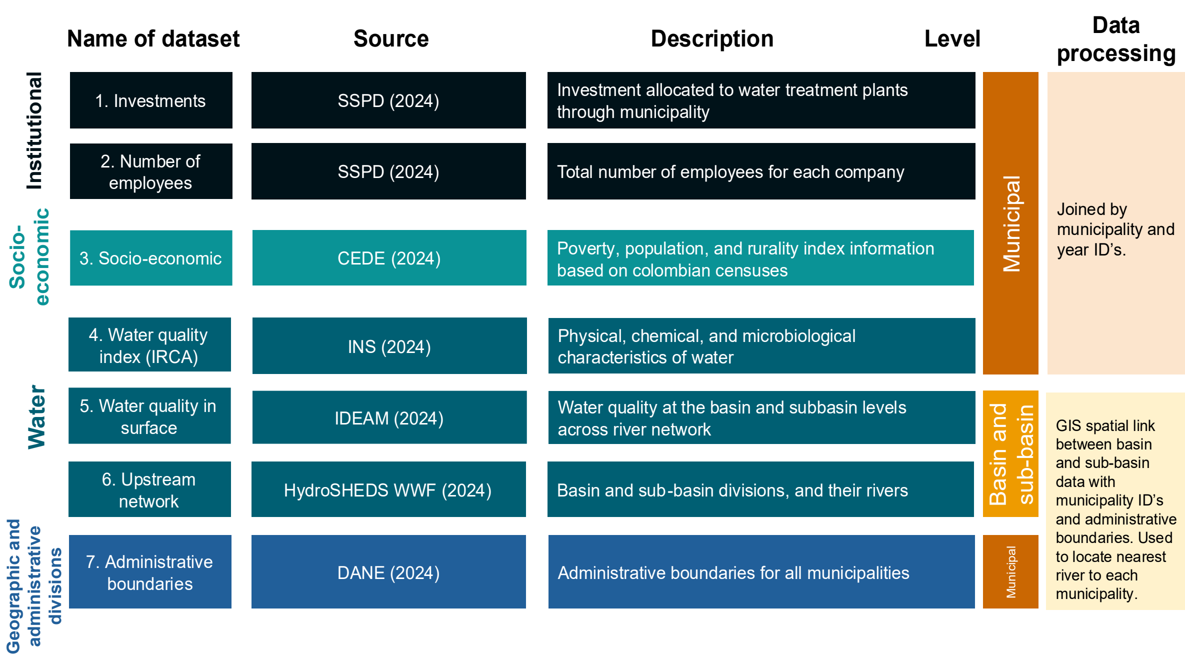
iii) water quality information for surface water and upstream network), from INS (Instituto Nacional de Salud, 2024), IDEAM (Instituto de Hidrología, Metereología y Estudios Ambientales, 2024), and HydroSHEDS WWF (World Wild Life, 2024);

iv) shapefiles for geographic and administrative divisions from Departamento Administrativo Nacional de Estadística DANE (Departamento Administrativo Nacional de Estadística, 2024).

To create our final dataset, we first combined the institutional and socioeconomic datasets with the water quality dataset using the municipality and year ID variables. We then used GIS techniques to identify each municipality's corresponding basin, sub-basin, and closest river (see Figure 2-1).

We apply some exclusion criteria to the final dataset. First, we exclude years after 2014 because of a significant policy change that would introduce endogeneity. As discussed in Appendix B, the Colombian government started to condition financing upon the quality of the water supplied after 2014 for one of the most important sources of financing. Excluding data after 2014 avoids possible endogeneity issues and reduces chances of artificially high values due to corruption schemes that might inflate values to obtain funding. Second, we remove providers located in the four biggest cities in the country to get a more homogenous sample. The final dataset is a panel dataset with 352 observations for six years (from 2009 until 2014).

Figure 2-1 Data process



Source: Authors.

2.2.2. Water upstream relationships index

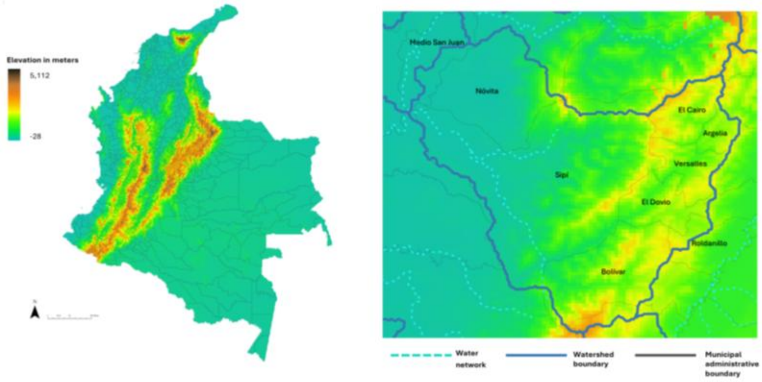
Water quality and waste production are naturally linked through basins. Therefore, the water quality of a given municipality depends on that of municipalities located upstream within the same river network. Similarly, sewage investments in upstream municipalities will impact water quality in downstream municipalities. The impact of upstream municipalities on water quality can be inferred by simply measuring it before water enters downstream municipalities. However, this assessment would not provide information about the impact that upstream investments had on the receiving water. To account for this, we use upstream and downstream watershed data from WWF (World Wild Life, 2024) to develop an upstream investment index. This index measures the influence that sewage investment from upstream municipalities has on a target municipality.

To create our upstream investment index, we start by identifying all micro-watersheds upstream of a municipality. Then, we performed a spatial join to determine which municipalities belong to each micro-watershed. This allowed us to track all upstream municipalities and account for their investments in wastewater discharge. For computational efficiency, we limit the index to the nearest upstream municipality. The index accounts for the varying influence of upstream municipalities, giving greater weight to those that share water resources with a target municipality through multiple micro-watersheds. To do this, we multiply the sewage investment of an upstream municipality by the number of micro-watersheds shared with the target municipality. For example, an upstream municipality sharing water resources with a target municipality through five micro-watersheds is weighed five times more than an upstream municipality affecting it through only one micro-watershed. This index is then included in the models that assess which type of investment most impacts water quality (see below). Therefore, we account for inter-municipal dependencies within a shared river network (see Appendix C for further geographic visualization). By including this index in our models, we can discern whether efficiencies or inefficiencies occur in the target municipality, in the upstream municipalities, or both.

Figure 2-2 shows elevation, river network, administrative division, and watersheds information. The left panel shows Colombia's elevation map, while the right panel shows an example of the Water Index. The "Nóvita" municipality, at the lowest elevation, is below higher-elevation municipalities (Sipí, El Cairo, Argelia, Versalles, El Dovio, Roldanillo, and

Bolívar). Since the river network passes only through Sipí, Bolívar, and Nóvita, the index identifies Sipí and Bolívar as upstream municipalities for Nóvita, incorporating their water investment information.

Figure 2-2 Upstream Index: an identification of upstream water quality relationships for all municipalities



Source: Authors using information from (Departamento Administrativo Nacional de Estadística, 2024; World Wild Life, 2024), and (Earth Science Data Systems, 2024).

2.2.3. *Summary statistics*

An overview reveals that the country generally maintains relatively safe levels of water quality over time, at 79.1 points. The country has relatively good quality water in surface sources: 73.7 points. This indicates that, on average, the treated water quality surpasses that of surface water sources. While the average water quality score stands at 79.1, there are large disparities in water quality across the country. As shown in Table 2-1, some municipalities exhibit a water quality risk of 0 while others are at 100. Furthermore, more funding has been historically invested in the wastewater sector relative to the water sector (~4 thousand million and ~1 thousand million Colombian pesos, respectively). With respect to socio-demographics, the distribution of population between rural and urban areas appears relatively balanced. The poverty rate is relatively low over time at around 26%. However, there are significant differences in the poverty rate across municipalities, with some having 81.3%, while others report 5.5%.

Table 2-1 Summary Statistics

Variable	Min	Max	Mean	STD
Water Quality Index	0.0	100.0	79.1	22.4
Total investment in water sector (i,t-1)	7,605,701	23,911,538,688	1,265,923,742	2,713,751,180
Water quality in source (i,t)	38.3	95.6	73.7	12.6
Total investment in wastewater in closest upstream municipality (i,t)	0.0	119,585,292,288	4,080,377,583	18,467,815,605
Rurality index (i,t)	1.6	92.1	47.4	22.3
Poverty index (i,t)	5.5	81.3	25.7	13.8

Notes: N= 352. All values are in Colombian pesos.

We aggregate spending items for better comparison: "coverage" (production, design, and coverage), "quality" (network distribution and maintenance), and "other spendings". Quality investment has the highest mean overtime, followed by coverage and other spendings. Investment in maintenance is the lowest. Additionally, there are municipalities with zero investment in any category (Appendix, Table D-1).

Our sample includes 273 water treatment providers serving 730 municipalities, with an average of 4,895 consumers per provider (Table D-2). Most providers serve one municipality, while others serve up to 21. On average, there are 43 employees per provider.

Water component statistics show high-risk components with non-zero minimum values (Table D-3). For example, Coliforms average 299.8 microorganisms per 100cm3, and turbidity averages 4.9, indicating some components do not meet safe consumption criteria.

2.3. Methodology

We evaluate whether investment impacts water quality from three perspectives: resource management, operational management, and water components. In all our models, we use a measure of water quality as our dependent variable and log-transformed measures of investment as our main explanatory variable. We estimate our models by breaking down investments into the amount spent on increasing coverage, quality, and other types of investments, or the total spent on all three categories. We log-transform the investment variable to normalize the sample distribution and reduce outlier influence. We also include several control variables in our models to account for other factors that may affect water quality. First, we expect an important influence of upstream wastewater control in our municipality of analysis; thus, we include the investment in wastewater residuals management made in the upstream municipality. Second, the water quality of a municipality depends on the quality of the water at the source, thus we also include the quality of the surface water at its origin. Last, we acknowledge that pressure on water resources and the provision of the water service varies by socio-economical context; thus, we also include the proportion of people living in the rural area for each municipality and the poverty levels of each municipality.

2.3.1. Resource management: Type of investment

To determine which type of investment most impacts water quality, we use a model with investment types as explanatory variables and water quality as the dependent variable, represented by Equation 1-a:

$$WaterQuality_{i,t} = b_1 InvestmentCoveragePerCapita_{i,t-1} + b_2 InvestmentQualityPerCapita_{i,t-1} + b_3 InvestmentOtherSpendingsPerCapita_{i,t-1} + b_4 SewageInvestmentUpstream_{i,t-1} + b_5 WaterQualitySource_{i,t} + b_6 Rurality_{i,t} + b_7 Poverty_{i,t} + YearFE_t + IndFE_i + e_{i,t}$$

(Equation 1-a)

We hypothesize that increasing investment in coverage (b1) or quality (b2) will improve water quality, and we expect both b1 and b2 to be positive. Conversely, we expect a negative relationship between other spendings and water quality due to a substitution effect against quality-related investments. All investments are in logarithmic form.

To capture the delayed impact of investments, we include a one-year lag (t-1) of the investment variables, allowing us to account for effects stemming from previous investments. Because lag terms can cause error correlation and heterogeneity, leading to biased estimators(Arellano & Bond, 1991; Driscoll & Kraay, 1998), we use Driscoll and Kraay's (1998) methodology, which corrects standard errors by adjusting orthogonality conditions, providing a consistent covariance matrix.

We do not include a lag for repair and maintenance investments, as their impact on water quality is expected to be immediate. Similarly, "other spendings" are not lagged because they are not directly related to water quality (e.g., provider transformation, climate change adaptation).

2.3.2. Operational management: provider size

We assess the marginal effects of investment on water quality based on provider size, defined by the number of employees. The model, shown in Equation 1-b, focuses on the interaction between the logarithm of investment ($\mathrm{InvestmentPerCapita}_{\mathrm{i,t-1}}$) and provider size ($providerSize_{i,t}$). This interaction allows us to estimate the changes in water quality as response to changes in investment at each level of provider size. To account for the possible nonlinear relationship between provider size and marginal changes in water quality, we use the square of the provider size. Our model is as follows:

$$WaterQuality_{i,t} = b_1 InvestmentPerCapita_{i,t-1} + b_2 ProviderSize_{i,t} + b_3 ProviderSize^2{}_{i,t} + b_4 InvestmentPerCapita_{i,t-1} ProviderSize_{i,t} ProviderSize^2{}_{i,t} + b_5 SewageInvestmentUpstream_{i,t} + b_6 WaterQualitySource_{i,t} + b_7 Rurality_{i,t} + b_8 Poverty_{i,t} + YearFE_t + IndFE_i + e_{i,t}$$

(Equation 1-b)

2.3.3. *Water components: Physical, chemical, and microbiological*

To understand how investment affects specific water quality components: Free Residual Chlorine, pH, Coliforms, Color, and Turbidity, we use a Structural Equation Modeling (SEM) framework to account for both the indirect and direct effects of investment and determine how each water component mediates the impact of investment on water quality. As shown in Figure 2-3, we account for the indirect effects by modeling how each water component (mediation variables) responds to changes in the logarithm of investment (independent variables).: This involves two sets of equations (Figure 2-3). The first set (Equation 1-c-1) assesses how each water component (mediation variables) responds to changes in the logarithm of investment (independent variables). This results in five equations for the components: Free Residual Chlorine, pH, Coliforms, Color, and Turbidity.

$$MediationVariable_{i,t} = b_1 Investment(PerCapita)_{i,t-1}$$

(Equation 1-c-1)

Where $MediationVariable_{i,t}$ represents the value of the logarithm of the water component we are analyzing, except for pH. We then account for the direct effects of investment on water quality by modeling water quality as the dependent variable, with each water component and investment as explanatory variables. These relationships are shown in Equation 1-c-2:

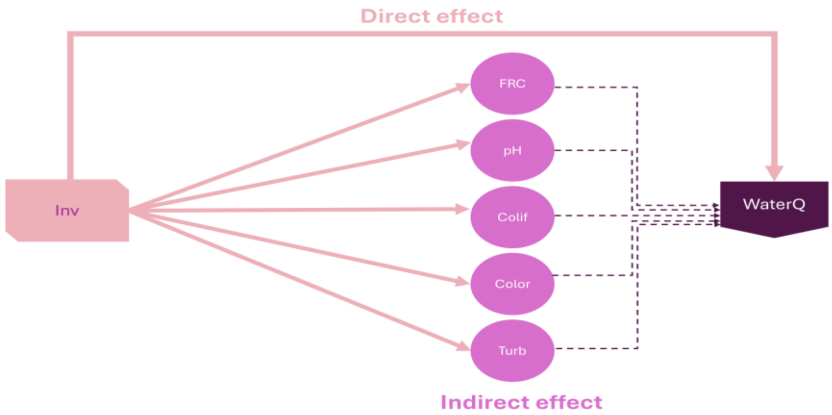
$$WaterQuality_{i,t} = b_1 MediationVariable1_{i,t} + b_2 MediationVariable2_{i,t} + b_3 MediationVariable3_{i,t} + b_4 MediationVariable4_{i,t} + b_5 MediationVariable5_{i,t} + b_6 Investment(PerCapita)_{i,t-1} + e_{i,t}$$

(Equation 1-c-2)

Equation 1-c-2 complements these equations by including water quality as the dependent variable, with each water component and investment as explanatory variables. The sign of the investment coefficient varies based on whether the water component is beneficial or harmful.

Free Residual Chlorine and pH effects depend on concentration, making their investment impact unpredictable (signs of b_1 and b_2). However, we expect Coliforms, Color, and Turbidity to decrease with increased investment (negative b_3, b_4, and b_5).

Figure 2-3 Structural Equation Model (SEM)



Note: 1) This graph represents SEM Model (Equations 1-c-1 and 1-c-2). 2) Water quality (WaterQ); investment (Inv). 3) Mediation variables are FRC (Free Residual Chlorine), pH, Colif (Coliforms), Color, and Turb (Turbidity).

2.4. Results

2.4.1. Resource management: Type of investment

Our analysis provides evidence that supports our main hypothesis: investments aimed at improving water quality show a positive and statistically significant relationship (Table 2-2). Specifically, for each percentage unit increase in investment in quality, we find that water quality improves by 0.012 points on the water quality index. Conversely, investments categorized under other types and coverage do not exhibit statistically significant impacts on water quality. Additionally, variables such as the rurality index and poverty levels also show non-significant relationships with water quality (for further information on the results for the total investment, see Appendix E).

Table 2-2 Resource management: Type of investment

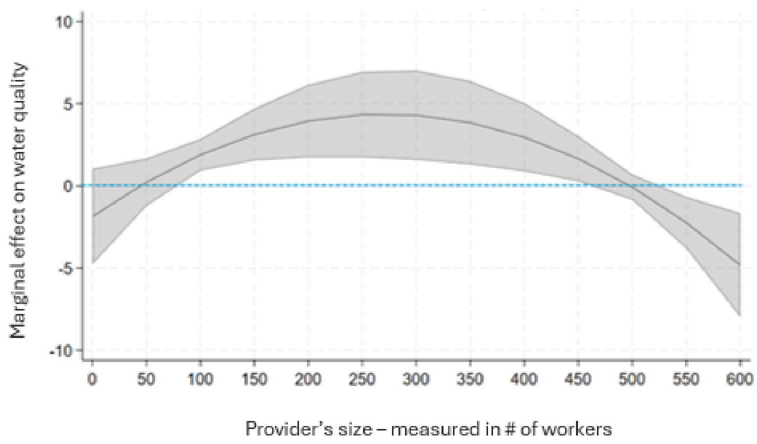
	Water Quality (i,t)
Investment in coverage (i,t-1)	0.930
	(0.433)
Investment in quality (i,t-1)	1.287*
	(0.461)
Investment in other spendings (i,t-1)	-0.282
	(0.216)
Investment in wastewater in closest upstream municipality (i,t-1)	0.557
	(0.168)
Water quality in source (i,t)	0.059
	(0.129)
Rurality index (i,t)	-5.858
	(3.570)
Poverty index (i,t)	1.330
	(0.480)
Observations	222
Adj R^2	0.467

Notes: Fixed effects included at year and municipality level. * $p<0.05$, ** $p<0.01$, *** $p<0.001$

2.4.2. Operational management: provider size

Our analysis of the relationship between marginal changes in water quality and investment across provider size suggests potential inefficiencies in investment allocation (Figure 2-4). The marginal effects of investment appear to vary significantly across provider sizes: small (up to 100 employees), medium (100 to 450 employees), and large (over 450 employees) providers. For small providers, we observe increasing but statistically non-significant marginal effects of investment on water quality. Medium-sized providers exhibit a significant positive effect of investment on water quality. Conversely, large providers show negative marginal effects, indicating that beyond a certain size (around 300 employees), increased investment correlates with decreased water quality.

Figure 2-4 Marginal effects of investment on water quality, considering provider size



2.4.3. Water components: Physical, chemical, and microbiological

The results of our SEM model are shown in Table 2-3 below. The results highlight that the relationship of investment with water quality cannot be fully explained through water components alone. The indirect effect of investment on water quality is not statistically significant.

The direct effects highlight the importance of specific water components in determining water quality. For instance, a 1% increase in Free Residual Chlorine correlates with a 36.9% improvement in water quality, while a 1% increase in Coliforms reduces water quality by 2%. Color and Turbidity have similar negative impacts (5% and 6.4%, respectively). However, the direct effect is positive but not significant (0.057), indicating that investment alone does not significantly improve water quality. Furthermore, investment shows no significant direct relationship with any individual water component.

The total effect combines the direct effect (0.057) and the indirect effect (-0.316), resulting in an overall effect of -0.259. This total effect is not statistically significant, aligning with our additional findings that direct investment does not significantly impact water quality. A significant portion of the total effect derives from indirect pathways influenced by water components (Figure 2-5).

In summary, the overall impact of investment is primarily driven by indirect effects. The insignificance of the total effect supports the lack of significant direct effects observed in previous sections of this study.

Table 2-3 Water components and investment

INDIRECT EFFECTS	**Coef.**	**Std. Err.**	**P>|z|**
Water quality (i,t)			
Investment (i,t-1)	-0.316	0.528	0.5485

DIRECT EFFECTS	**Coef.**	**Std. Err.**	**P>|z|**
Water quality (i,t)			
Free Residual Chlorine	**36.944**	**6.738**	**0**
pH	0.041	0.796	0.9601
Coliforms	**-2.008**	**0.226**	**0**
Color	**-5.01**	**1.067**	**0**
Turbidity	**-6.488**	**1.449**	**0**
Investment (i,t-1)	0.057	0.355	0.8729
FreeResidualChlorine			
Investment (i,t-1)	-0.001	0.007	0.8887

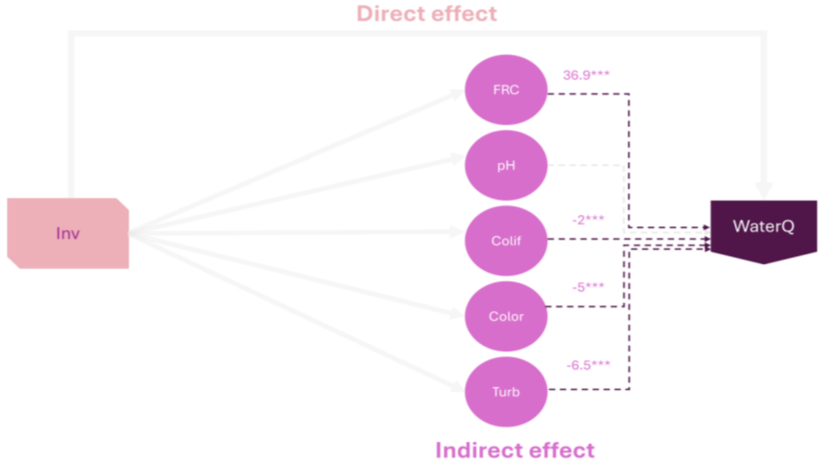
pH			
Investment (i,t-1)	-0.027	0.019	0.1556
Coliforms			
Investment (i,t-1)	-0.055	0.081	0.4965
Color			
Investment (i,t-1)	0.042	0.025	0.093
Turbidity			
Investment (i,t-1)	0.028	0.018	0.1188

TOTAL EFFECTS	**Coef.**	**Std. Err.**	**P>|z|**
Water quality (i,t)			
Free Residual Chlorine	**36.944**	**6.738**	**0**
pH	0.041	0.796	0.9601
Coliforms	**-2.008**	**0.226**	**0**
Color	**-5.01**	**1.067**	**0**
Turbidity	**-6.488**	**1.449**	**0**
Investment (i,t-1)	-0.259	0.651	0.6892
FreeResidualChlorine			
Investment (i,t-1)	-0.001	0.007	0.8887
pH			
Investment (i,t-1)	-0.027	0.019	0.1556
Coliforms			
Investment (i,t-1)	-0.055	0.081	0.4965
Color			
Investment (i,t-1)	0.042	0.025	0.093

Turbidity			
Investment (i,t-1)	0.028	0.018	0.1188

Notes: This table represents the results from SEM Model presented in the Methods section C.

Figure 2-5 Structural Equation Model Results



Note: 1) This graph represents the Structural Equation Model from Equations 1-c-1 and 1-c-2. 2) Line fades (path of relationship between variables) are proportional to the level of statistical significance of the estimation. 3) The numbers represent the coefficient estimates for each regression.

2.4.4. Robustness checks

To evaluate whether our results are robust to different specifications, we evaluate the relationship between investment and drinking water quality when considering two and three years of lag of investment implementation (Appendix, F).

2.5. Discussion

Though previous studies have found a positive relationship between investment and water quality (Ferreira et al., 2021; Hasan & Gerber, 2008), our analysis finds this relationship statistically insignificant. This discrepancy can in part be explained by our inclusion of investment in management, operations, and water components analyses. The difference can also potentially be explained by the inclusion of the influence of upstream municipalities in downstream water quality through our spatial index.

Resource management perspective suggests that investments that are specific to water quality improve water quality, while other categories of investment (i.e., coverage and other spendings) do not. Moreover, if we exclude these investments from our analysis and keep only the investment in quality, our results become statistically significant. These findings suggest that allocating resources to coverage and other spendings, though perhaps beneficial for other areas of operation, do little to improve water quality. Spending on coverage dedicates resources towards increasing the distribution networks or the water volume produced; spending on others involves things not directly related to the water production, such as green investments and institutional strengthening. Both spending categories are aimed towards increasing the number of consumers instead of addressing water quality. This has been well documented in the US by Copeland (2010).

Furthermore, in many developing countries with limited resources and aging or damaged water networks, expanding service coverage can sometimes result in declining water quality. This is because the additional pressure on inadequate infrastructure can lead to leaks, further contaminating water that may already be of poor quality, and insufficient treatment, with these negative effects often worsening over time as the state of the infrastructure system decays.

Operational management perspective shows that water quality improvements vary by provider size. Large providers already provide high drinking water quality (90.7). Thus, the room for improvement is small and this is possibly why their investments are less focused on quality. Small providers, often in rural areas, have significant room for improvement but their investments are not effective. Medium-sized providers show positive effects from investment. These results are consistent with those observed in Navia Díaz et al., (2022) and likely explained by how providers invest based on their drinking water quality baseline indicator and their institutional capacities. Large providers spend a significant portion on network distribution (~30%) and "other spendings" (~70%) with minimal investment in maintenance and repairs (~0%) (Appendix, section G). For example, “Acueducto Y Alcantarillado Metropolitano de Santa Marta S.A. ESP” highlights the improvements regarding prevention in water loss, increments in water coverage, and administrative improvements while less references are made for maintenance in water treatment plants (Superintendencia de Servicios Públicos Domiciliarios, 2013b). Yet, it faces challenges with water quality: water abduction (damages in networks of water acquisition distribution) and treatment (changes in water treatment due to the decrease of surface water) of the service provided (Superintendencia de Servicios Públicos Domiciliarios, 2015a). A similar situation is observed for “Aguas Kpital Cúcuta S.A. E.S.P.”: the evaluation claimed for immediate actions to improve turbidity in water (Superintendencia de Servicios Públicos Domiciliarios, 2013a).

Small providers generally invest more than two thirds of their resources (~69%) in “network distribution” and “other spendings”, while the percentage of investment focused on maintenance and repairs is only 0.67%. Additionally, many of these small providers do not have proper infrastructure to provide their water services (Fernández, Diego, 2004). For example, the “Empresa de Acueducto y Alcantarillado de Puerto Asis E.S.P.", reports in 2016 many technical infrastructure deficiencies: “*The operation ... is limited to the application of coagulant without testing the containers, (use of) disinfectant without analysis ...the system has been out of service for several years and the maintenance performed on the filter is limited to manual removal of the upper layer of the sandy bed, which is filled with the solid material resulting from coagulation-flocculation and sedimentation ... there is no laboratory equipped with the necessary equipment for their analysis, since there is hardly a pH meter, Turbidimeter and color meter*” (Superintendencia de Servicios Públicos Domiciliarios, 2016). In addition to these infrastructure challenges, small providers face institutional challenges as their limited capacity to collect technical, administrative, and financial information (Parra et al., 2018) together with their lack of secure resources for investments (Vivanco Castillo, Christopher et al., 2022) make it difficult to improve drinking water quality.

On the other hand, medium-sized providers seem to distribute their investments more effectively than larger or smaller providers: 50% of their resources are allocated toward maintaining the network distribution. We find supporting evidence of this finding in case studies on medium-sized providers like “Empresa de Acueducto y Alcantarillado de Pereira”, “Acueducto y Alcantarillado de Popayán”, and “Proactiva Aguas de Tunja”. These cases find that none of them have negative claims from their consumers about the quality of the water provided despite facing other issues such as lack of capacity to measure water delivered to consumers (Superintendencia de Servicios Públicos Domiciliarios, 2014, 2015b, 2015c).

Water Quality Management Perspective revealed significant relationships between various water components and overall water quality. However, we did not observe a significant impact of investment on improving these components, likely because current investments are not specifically targeted toward altering them. For instance, physical components such as color and turbidity, which pose minimal health risks, receive limited resources for treatment. We would anticipate stronger correlations between investments and high-risk components, such as coliform concentrations, which are closely associated with gastrointestinal diseases (Craun et al., 1997; Gruber et al., 2014). Such correlations would suggest quality improvements, similar to those observed in Chicago (Pluth et al., 2021; Roca et al., 2015). However, our data did not reveal this relationship, suggesting that current investments may not specifically target these contaminants.

Our results align with previous studies that have found a positive relationship between investment and water quality in various regions around the world (Ferreira et al., 2021; Jalan & Ravallion, 2003; Pluth et al., 2021; Roca et al., 2015). Our study further advances this body of knowledge by being the first to demonstrate how investment decisions can be optimized from different perspectives. By analyzing the type of investment, operational information, and water components while considering spatial relationships between municipalities, we offer a more comprehensive view of the relationship between investment and water quality. Furthermore, our study not only highlights the importance of evaluating investments through multiple complementary lenses but also provides a pathway to address potential challenges from these diverse perspectives. This makes our research a valuable resource for guiding the development of a dynamic investment allocation framework tailored to sector needs, regional hydrography, and network connectivity, particularly in resource-constrained settings such as countries in the developing world. Additionally, our findings can serve as a practical guide to improving water quality by informing decisions on where to prioritize investment, whether in maintenance, repairs, or expanding coverage. Finally, with our results we contribute to the policy discussion for the need to consider potential benefits of economies of scale by coordinating investments across municipalities within a watershed.

Data Limitations Despite our study is able to provide insight into the relationship between investment and water quality, our study is limited by the lack of a formal database with comprehensive spending information for each provider. Our study relies on the assumption that the data on centralized information is accurate, that the process for how providers spend and allocate resources is not affected by municipalities themselves, and that providers spend and allocate all their resources as planned by local and national authorities. If better data were available, future research could consider an examination of actual spending at the provider level. Moreover, future research would greatly benefit from specifying whether providers are classified as private or public entities.

2.6. Conclusion

Our results highlight the importance of studying investment in the water sector using a framework that considers investments beyond infrastructure network, i.e., investments in maintenance. We find that the impacts of investment may differ by provider characteristics such as their size, the type of investment, and the baseline water quality levels they face.

At a regional level, funds could be allocated to providers with specific goals based on the upstream dependencies. That is, if a downstream municipality has water issues, the government could allocate resources to providers managing water quality in upstream municipalities in addition to those managing the target municipality. Moreover, at a regional scale, our results also highlight the need to consider economies of scale in the provision of water service due to the lack of capacity of small providers. Providers in municipalities with already high levels of coverage may want to prioritize investments in water quality over coverage and other expenditures until quality levels are beyond the threshold for safety. Regularly assessing the impact and efficiency of investments in upstream municipalities may also serve as a tool to determine the extent to which investments should be reallocated within or among municipalities, especially for providers serving several municipalities. The specific causes of inefficiencies likely vary widely among providers and thus, strategies to address these inefficiencies should be tailored to each provider. However, an annual assessment of investment efficiency could serve as a tool to build an effective plan of action. The efficiency assessment would entail analyses of resource management (coverage vs quality vs other investments) and water quality management (i.e., physical, chemical, and microbiological components), similar to those performed in this study, to help understand and shed light on tradeoffs. Then, local knowledge at the provider level could be used to configure the best plan of action that is logistically feasible given provider prospects, constraints, and limitations.

Adopting a fluid framework would require implementing a few strategies into the sector. First, our results indicate that providers would benefit from ***improved institutional capacity and knowledge.*** Second, we observe a need to ***regionalize the service*** in contexts of low productivity and high-maintenance costs. Third, there is a need for better ***inter-institutional coordination*** between entities that address water contamination issues in Colombia to enable collaboration across municipalities and establish a national database of provider spending information. Fourth, our findings suggest the necessity to shift ***historical needs,*** such as coverage, to current needs, such as quality. Finally, we highlight the importance of targeting physical, chemical, and biological processes to increase water quality by explicitly including ***water components into the policy agenda***. While implementing these strategies will not be exempt from challenges, we believe that the benefits would have cascading effects across the health and economic sectors of developing countries.

3. On government, guerrilla and water resources in a post-conflict scenario

3.1. Introduction

Drinking water in developing countries is often polluted by economic activities such as industry and agriculture. Yet, those under armed conflict like Colombia face the additional challenge of providing safe drinking water across the country while navigating the conflicting interests of citizens, militarized groups, and the official government (Bernal et al., 2024; Organización para la Cooperación y Desarrollo Económico, 2014). The impacts of such armed conflicts on drinking water quality are, however, severely understudied.

Conflict has immediate and long-term effects on water quality. Immediate effects result from deliberate attacks on rivers, water treatment plants, and infrastructure[2]. According to *Programa de las Naciones Unidas para el Desarrollo* (2018), attacks on oil pipelines have significantly increased river pollution in Colombia. Illicit cultivation of drug crops, particularly marijuana and coca plantations, and illegal mining have also increased runoff of toxic chemicals that contaminate rivers such as toxic chemicals in and runoff from[3].

The long-term effects include exacerbated institutional fragility at multiple levels of government, resulting in inadequate investment in both infrastructure and management of water quality (Quevedo Niño & Walteros Moreno, 2019; Valencia & Ecuyer, 2023). This institutional weakening has reduced the state's capacity to regulate, monitor, and invest in

[2] Several incidents illustrate the vulnerability of public services during the armed conflict in Colombia. In 2014, an attack in Meta severely damaged the region's drinking water infrastructure, leaving nearly 60,000 people without access to water (El Espectador, 2014). Similarly, in 2009, the Colombian government reported to the International Committee of the Red Cross (ICRC) an assault on Villavicencio's water supply system, which disrupted service for 300,000 residents. At the time, this was considered the most impactful attack of its kind in the country's history (El Tiempo, 2009). The *Ejército de Liberación Nacional ELN* also targeted water infrastructure, notably in 2002 when it destroyed the Pailitas-Cesar drinking water system, affecting a town of approximately 20,000 inhabitants (El Tiempo, 2009).

[3] According to the Departamento Nacional de Planeación, (2016), each year of peace in Colombia could result in savings of 7.1 billion pesos (approximately \$233 million USD, based on the July 2022 exchange rate) in environmental degradation costs. These savings would stem from reduced expenses related to the recovery of deforested areas, avoided CO_2 emissions, lower cleanup costs, and the preservation of oil resources and ecosystem services affected by environmental incidents such as oil spills.

essential water systems, thereby making communities more vulnerable to water-related risks. Furthermore, conflict has indirectly affected water resources through its impacts on other environmental assets, such as forests and soils, which act as natural filters of pollutants and take part of the regions' water cycle that maintains water availability and quality (Vera Solano, 2018).

Among the various conflicts that exist in developing countries, the cease fire treaty that took place within Colombia with the Revolutionary Armed Forces of Colombia (FARC) provides a valuable opportunity to understand how conflict -through attacks and weakness of local government- can impact water resources in developing countries. Beyond immediate environmental harm through attacks on oil pipelines, rivers, and water infrastructure, the FARC has systematically undermined local governance by exercising territorial control over municipalities, creating long-term effects over the water resources. For instance, they often prohibited the installation of new government infrastructure for water and sanitation service provision, interfered in local electoral outcomes, kidnapped civilians and political figures (Post, 2009; Stanford University, 2022), and manipulated water access and its provision (Betancur-Alarcón & Krause, 2020). Studying both attacks and territorial control in a pre- and post-conflict scenario offers an opportunity to understand their impact on water resources not only through immediate effects, but also through long-term effects that accelerated deforestation and environmental degradation, further threatening watershed ecosystems and water security.

A substantial body of literature examining conflict in developing countries has primarily focused on the effects of armed violence on social and economic outcomes. Key areas of inquiry include changes in land use patterns (Eklund et al., 2017), impacts on economic growth (Miguel et al., 2004), and price fluctuations (Dube & Vargas, 2013; Janus & Riera-Crichton, 2015). Despite this growing literature, relatively little attention has been given to the consequences of conflict on natural resources — and particularly on water resources.

Among the studies that have explored the relationship between conflict and natural resources, the majority have concentrated on how the mismanagement or competition over natural resources can trigger or prolong civil conflicts (Assal, 2006; Betancur-Alarcón & Krause, 2020; Ross, 2004; Schollaert & Van de gaer, 2009; Thies, 2009). Far fewer have examined the inverse relationship: how armed conflicts themselves directly affect the availability, quality, and governance of natural resources such as water. This represents a significant gap in the existing literature, especially given the central role that water plays in sustaining livelihoods, public health, and post-conflict reconstruction in affected regions.

Within the literature examining the relationship between conflict and natural resources, most studies have focused on resources indirectly related to water availability, such as forests, while overlooking water itself. For example, civil wars have been associated with increased deforestation in Sierra Leone (Burgess et al., 2015) and Nicaragua (Stevens et al., 2011). In the Democratic Republic of Congo, deforestation intensified as communities became increasingly reliant on wood for fuel and bushmeat during periods of armed conflict (Draulans & Krunkelsven, 2002). In Colombia, illegal activities carried out by paramilitary groups — including illicit crop cultivation, illegal mining, and large-scale agriculture — have significantly driven deforestation (Fergusson et al., 2014). More recently, deforestation has surged in some regions as a result of economic reactivation following the 2016 peace agreement with the FARC (Prem et al., 2020). However, while these studies highlight the environmental consequences of conflict, few have examined its direct impact on water quality.

Although a growing body of research has examined the relationship between armed conflict and water resources, most studies have done so at global or regional levels, often without systematically quantifying these effects at national scales. Armed violence has been linked to water scarcity in countries such as Iraq (Acheson, 1992; Zolnikov, 2013), Yemen (Abu-Lohom et al., 2018), Syria (Faour & Fayad, 2014), and across parts of East Africa, including Sudan, Uganda, Kenya, Somalia, Ethiopia, Eritrea, and Djibouti (Solomon et al., 2018). A smaller number of studies have also explored the consequences of conflict on water quality, documenting increases in water pollution in conflict-affected settings such as Syria (Faour & Fayad, 2014) and Chechnya (Batal al-Shishani, 2006), which have in turn contributed to rises in waterborne diseases like diarrhea, typhoid fever, and hepatitis (Oldfield et al., 1991). In Colombia, Vera Solano (2018) and Fergusson et al., (2014) found that activities carried out by armed groups such as the FARC and the *Autodefensas Unidas de Colombia AUC* have negatively affected water quality in specific regions. However, no empirical research has yet assessed the nationwide effects of Colombia's prolonged internal armed conflict and its end on either water availability or water quality. This represents a significant gap in the literature and limits our understanding of how long-running armed conflicts influence water resources at the national level — a gap this study seeks to address.

In this paper I aim to study the effects of the ceasefire with FARC *guerrillas* on drinking water quality in Colombia. This research is the first quantitative study to assess how a ceasefire agreement has influenced water resources, with a specific focus on drinking water quality at the national level. By examining the relationship between the ceasefire and changes in water quality, this research also contributes to both the environmental and social dimensions of conflict studies, while also offering new insights into the mechanisms through which armed conflict can affect the physical, chemical, and biological characteristics of drinking water.

Moreover, understanding how drinking water quality is impacted by the ceasefire carries important implications for public policy in Colombia. It provides critical evidence for designing more effective and equitable investments in the water and sanitation sector, particularly in areas where water quality has deteriorated or improved most following the ceasefire. Given the direct connection between drinking water quality and public health — especially in conflict-affected areas with high poverty rates — this research also contributes to a better understanding of health dynamics in Colombia. Finally, by shedding light on the ceasefire's impact on water resources, the study offers a valuable framework for assessing how other armed groups may continue to affect drinking water quality in the country.

The results from this study show that the end of territorial control by the FARC rather than a decline in number of attacks explain positive changes in water quality across the nation. Moreover, the results confirm the importance of mechanisms such as deforestation and economic activity in explaining changes in water quality in an armed conflict context such as that of Colombia.

The rest of this paper is organized as follows. Section 2 presents the context of the drinking water quality and the conflict with FARC in Colombia. Section 3 discusses data. Section 4 explains the methodology. Section 5 presents results. Section 6 and 7 show discussion and conclusions, respectively.

3.2. Context

3.2.1. *Water provision in Colombia*

In Colombia, drinking water services are provided by private, public, and mixed-ownership companies, as established by Law 142 of 1994. While these companies predominantly serve urban areas, institutional limitations and gaps in service provision in remote, rural regions have led to the recognition of community-managed water systems. Under the same law, community organizations are permitted to manage their own water services in these areas (see Appendix Table A.1). As such, community-managed systems have emerged as collective, autonomous responses to local water supply needs and can be understood as decentralized, self-organized models of water management (Montoya Domínguez, 2016).

Water providers in Colombia also differ not only in their organizational structure but in their operational scale. Large-scale providers are defined as those serving more than 5,000 subscribers and typically operate with modern infrastructure, including pipelines, treatment facilities, laboratories, and quality control systems[4]. In contrast, small-scale providers serve 5,000 or fewer subscribers and often lack adequate infrastructure, have limited or inconsistent water quality monitoring, and frequently maintain incomplete records of their water sources and treatment processes (Superintendencia de Servicios Públicos Domiciliarios, 2020).

Significant disparities also exist in both water service coverage and quality across Colombia, particularly between urban and rural areas. According to the *Instituto Nacional de Salud INS* (2020), these gaps remain substantial. For example, Ibáñez (2016) reported that in 2016, drinking water and sanitation coverage in rural areas reached 73% and 68%, respectively, compared to 97% and 93% in urban areas.

To monitor water safety, the Colombian government compiles information on drinking water quality through several indicators, the most prominent being the Water Quality Risk Index

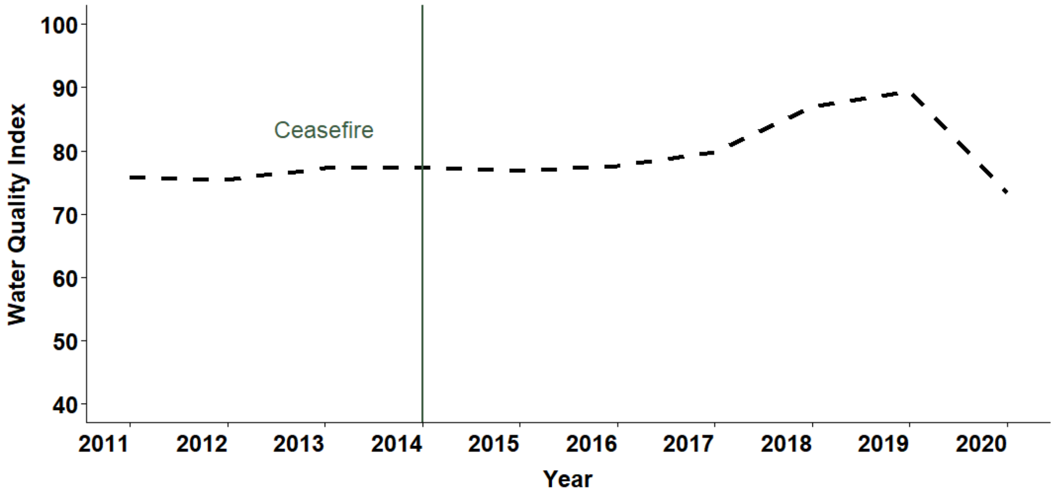
[4] These large providers supply more than 80% of the urban population of the country (Superintendencia de Servicios Públicos Domiciliarios, 2020).

(IRCA)[5]. The IRCA assesses the physical, chemical, and microbiological characteristics of drinking water and classifies its risk to human health on a scale from 0 to 100, with 0 representing the highest quality, safest water, and 100 the most unsafe. For ease of interpretation, this study uses the inverse of the IRCA, so that higher values reflect safer drinking water and lower values indicate greater risk. Since water providers are required to collect and report this information under Resolution 2115 of 2007 (Resolución 2115 - 2007, n.d.), IRCA data is consistently available at the municipal level from 2007 onwards. Additionally, these data are geographically disaggregated into urban, rural, and total municipal coverage, enabling a more nuanced assessment of drinking water quality conditions across different territorial contexts (Castillo-Castillo et al., 2025).

As seen in Figure 3-1, the quality of drinking water in Colombia has improved over time across all geographic areas. However, this progress has not been uniform when comparing urban and rural areas. The differences in water provision characteristics, coverage, and infrastructure between urban and rural areas play a key role in this difference. In rural regions, water services are primarily managed by local community organizations, while in urban centers, service provision is typically handled by public or private medium- and large-scale companies with greater institutional and technical capacity. This creates a significant institutional and economic gap in the ability to respond to FARC-related disruptions in both geographic areas, both during the conflict and in the post-ceasefire period. Moreover, considering a context in which the FARC presence was historically concentrated in rural areas, the implementation of the ceasefire and subsequent demobilization may have opened opportunities for improved government-led service provision in these territories.

Figure 3-1 Water quality in Colombia, 2011-2020

[5] Following Resolution 2115 of 2007 (Resolución 2115 - 2007, n.d.), IRCA considers physical characteristics (such as color, smell, taste and turbidity) and chemical characteristics (such as the presence of chemical elements harmful to health such as mercury, nickel, lead, copper, and others).
This resolution also established that it is mandatory for municipalities to collect information from water samples and send the results of the laboratory to the national entity in charge of defining the risk index for each municipality. As expected, some municipalities do not have the necessary equipment to collect the samples and, furthermore, due to institutional characteristics related to poverty, corruption (or others) some of the municipalities do not send any information to the central entity. Thus, there is a large amount of underreporting of the water risk index in the rural area.



Note: This graph shows drinking water quality evolution through time for Colombia. X-axis represents years, and Y-axis represents drinking water quality index measured by the inverse of the IRCA index. Green vertical line indicates the start of the ceasefire.

3.2.2. FARC, their activities and its implications on water resources in Colombia

The FARC emerged in the late 1940s and 1950s as a peasant self-defense guerrilla movement, fighting for land equality and greater government presence in rural Colombia (Saab & and Taylor, 2009). Over time, the persistent absence of state institutions in these areas allowed the FARC to fill the governance void, exerting significant political, economic, and social influence over the territories they controlled (Betancur-Alarcón & Krause, 2020; Lehoczki & Ayala Castiblanco, 2024).

The FARC's activities across Colombia can be divided into two main categories[6]**.** The first involved **immediate-impact actions**, such as bombings and assaults on civilians, particularly in urban areas. These attacks were isolated incidents, such as bombings in public spaces and kidnappings, without sustained interference in local governance structures. In rural areas, the FARC carried out systematic attacks, including sabotage of oil pipelines and various types of infrastructure, causing significant environmental damage and harming local watersheds

[6] For a more detailed version on a few examples of attacks by the FARC, please see Appendix A2.

(McClanahan et al., 2019; Ríos et al., 2023)[7]. Consequently, the FARC's urban presence was limited and less visible compared to their dominance in rural areas.

In contrast, the FARC's second type of activity —**long-term strategies aimed at consolidating territorial control**— was much more prominent in rural regions[8]. In regions often characterized by weak or absent state institutions, the FARC capitalized on governance vacuums (Castillo-Niño et al., 2022), consolidating power and embedding themselves within local structures. This statelessness created ideal conditions for the guerrillas to entrench their authority and operate with relative impunity.

In the territories under their control, the FARC governed through a combination of coercion and negotiation, establishing informal institutions that regulated governance, economic activity, and environmental management (Betancur-Alarcón & Krause, 2020). Functioning as a de facto state in areas with minimal government presence, the FARC influenced local elections, controlled access to public services, and dictated the allocation of infrastructure contracts (Centro Nacional de Memoria Histórica, 2020; Duarte & Betancourt, 2017). The FARC also restricted outsider access, limited state force operations, and positioned themselves as protectors of local peasants (Centro Nacional de Memoria Histórica, 2020). Their authority included taxing legal and illicit activities, resolving disputes, and redistributing land, often in conflict with official property rights (Betancur-Alarcón & Krause, 2020; Castillo-Niño et al., 2022). They further shaped social life by regulating leisure, religion, and political participation (Castillo-Niño et al., 2022).

In managing natural resources, the FARC imposed strict rules on water use and access. They controlled who could access water resources and when, regulating activities like fishing and prohibiting landowners from restricting peasants' access to water sources (Betancur-Alarcón & Krause, 2020). They also created informal conservation zones, designating certain

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[7] Moreover, their economic activities in rural areas as the dependance on illicit crop cultivation, especially marijuana and coca, contributed to deforestation, soil degradation, and water contamination (McClanahan et al., 2019). Additionally, their involvement in illegal gold mining further damaged the environment, releasing mercury into Colombia's watersheds and contaminating rivers (McClanahan et al., 2019). However, I do not count with sufficient data to include this information in this study.

[8] The decentralization reforms of Colombia's 1991 Constitution inadvertently strengthened the FARC's influence in areas where the state's presence was weak (Castillo-Niño et al., 2022). These reforms, meant to empower municipalities, created opportunities for the FARC to dominate local decision-making, exploiting the limited capacity of formal government institutions. Appendix A3 shows FARC's territorial control by 2012.

forest areas as reserves where resource exploitation was prohibited (Centro Nacional de Memoria Histórica, 2020).

By 2008, growing public opposition to the FARC's violence and illegal activities, along with the group's weakening, set the stage for peace negotiations under President Juan Manuel Santos. Initiated in 2012 with international support, the talks addressed agrarian reform, political participation, conflict resolution, illicit drugs, victims' rights, and agreement implementation (Centro Nacional de Memoria Histórica, 2020). A ceasefire in 2014 reduced violence and allowed state institutions to re-enter former FARC territories (González González & Moreno Botero, 2023; Leguízamo, 2021). The 2016 Peace Agreement formalized this transition, enabling ex-combatants to enter political life and boosting civil society engagement, especially in expanding public services like water, health, and sanitation in long-neglected rural areas (Duarte & Betancourt, 2017). This shift led to a greater focus on improving living conditions, especially in rural regions that had been neglected by the state.

The ceasefire transformed the social and political landscape of former FARC territories. As the group withdrew, many ex-combatants entered political and civil society roles, increasing participation in community projects and public service delivery, particularly in water, health, education, and sanitation (Duarte & Betancourt, 2017). Their departure also left a power vacuum over land and natural resources, prompting new governance dynamics. As Betancur-Alarcón and Krause (2022) describe, territories experienced a shift from a "social order under FARC control to a State-regulated phase." However, this transition was marked by significant uncertainty, as the rules governing access to and control over land and natural resources were often unclear to local populations.

In the post-ceasefire context, economic and governmental actors—including landowners, ecotourism entrepreneurs, and foreign companies—moved to exploit newly accessible resources, increasing pressure on land and natural assets (Krause et al., 2022; McClanahan et al., 2019). In response, the government expanded public services and infrastructure, while institutions like the Corporaciones Autónomas Regionales (CARs) gained a more prominent role (Betancur-Alarcón & Krause, 2020).

These developments improved water service coverage and quality but also imposed new access restrictions. Informal systems historically used by peasants, such as homemade pipelines, were dismantled or blocked by landowners, limiting water access for human consumption and agriculture (Betancur-Alarcón & Krause, 2020). With CARs now resolving disputes once managed by the FARC, many communities were forced to rely on surface water. As irrigation became more difficult and ecotourism expanded, traditional agricultural practices declined, prompting significant shifts in land use (Méndez-Garzón et al., 2024).

The new regulatory framework, led by institutions like the CARs, formalized and privatized water services, replacing communal systems with access based on legal ownership and taxation (Betancur-Alarcón & Krause, 2020; Plataforma Colombiana de Derechos Humanos Democracia y Desarrollo, 2022). Requirements such as formal land titles excluded many rural communities from legal water access. Local organizations attempting self-management faced the same strict regulations as established utilities, including compliance with national bodies like the Superintendencia de Servicios Públicos Domiciliarios SSPD and CRA, placing significant legal and administrative burdens on resource-poor communities (Valencia & Ecuyer, 2023).

The post-conflict period introduced technical tools like the IRCA to regulate water use and quality, reflecting a shift to "technical functionalist models" focused on modernization and market efficiency (Betancur-Alarcón & Krause, 2020). However, these models, rooted in technocratic and market-driven approaches, often conflicted with the social and environmental realities of rural areas, creating new inequalities (Valencia & Ecuyer, 2023).

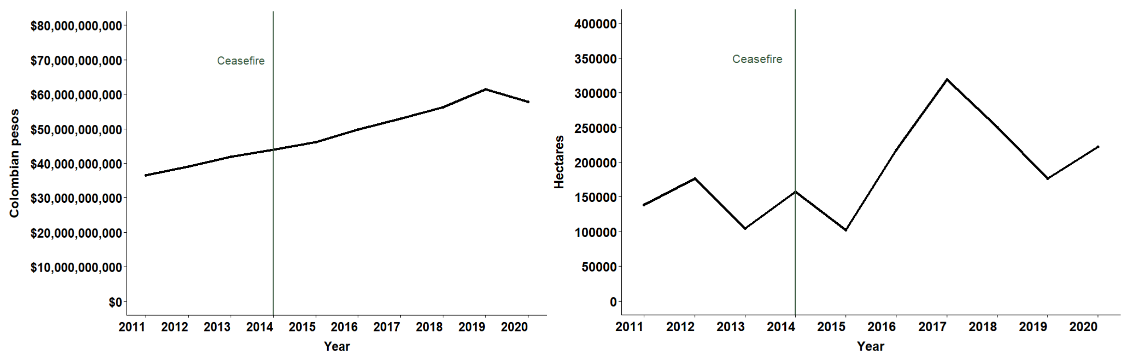
The arrival of new economic actors, particularly in agro-industry, palm oil, ecotourism, and petroleum, reshaped land use and ownership, with large tracts being acquired by foreign companies (Vásquez, 2023). The government promoted infrastructure development as a way to foster regional growth in the post-conflict phase[9]. However, these economic activities led to increased deforestation and environmental degradation (Ideam, 2024; McClanahan et al., 2019).

Meanwhile, the role of the CARs expanded to focus on protecting natural resources like water and forests. The government also introduced the Planes de Desarrollo con Enfoque Territorial

[9] These companies were encouraged to invest in Colombia through the creation of an economic framework offering tax incentives, improved infrastructure, stronger protections for property rights, and duty-free zones (Vásquez, 2023).

(PDET), which focused on territorial development with a strong emphasis on improving access to safe drinking water and sanitation services (Valencia & Ecuyer, 2023).

Figure 3-2 Gross Domestic Product GDP (left) and Deforestation (right), 2011-2020



Note: Left graph shows the mean gross domestic product (GDP) from 2011 until 2020; Right graph shows the total deforested areas from 2011 until 2020. For both graphs, the X-axis represents years. The vertical line highlights when the ceasefire was implemented (2014).

3.3. Aims and hypotheses

Considering the importance of both immediate and long-term effects of FARC activities and presence over water resources, and specifically on water quality, I study both of these effects. I assess the immediate impacts by analyzing the number of attacks before the ceasefire, expecting that the cessation of violence led to improvements in water services and quality.

To analyze the long-term effects of territorial control, I use a mediation analysis framework that allows me to evaluate both the direct and indirect impacts of the ceasefire on water quality. Specifically, I focus on two key pathways through which the end of territorial control may have influenced water outcomes.

First, the ceasefire made conflict-affected areas safer, encouraging government investment, improving resource allocation for infrastructure and institutional capacity — including water management — and boosting economic activity. Higher levels of economic activity, measured by GDP, are expected to reflect improvements in water quality. Thus, GDP serves as the first mediator in the analysis.

Second, increased economic activity also led to higher rates of deforestation, which negatively impacts water resources by degrading the chemical, biological, and physical characteristics of water (Murillo-Sandoval et al., 2020). Therefore, deforestation is the second key mediator considered in the analysis.

3.4. Data

3.4.1. Sources

I construct a panel dataset of 894 municipalities covering the years 2011 to 2020, drawing from seven different sources. The first source is the *Instituto Nacional de Salud INS* (2024) , which provides data on the Water Quality Index (IRCA), as well as the physical, chemical, and biological characteristics of water. The second source is the World Resources Institute (Harris et al., 2021), where I get the deforestation information at the municipality level. The third source is the *Centro de Estudios de Desarrollo Económico CEDE* (2024) , which offers information on poverty levels and the size of the rural population at the municipal level. The fourth source (Departamento Nacional de Planeación, 2023) provides data on public spending related to wastewater and water treatment. The fifth source is the *Departamento Administrativo Nacional de Estadística DANE* (2024), which supplies administrative boundary data for each municipality. The sixth source of information consists of two datasets: the first reports the number of FARC-related attacks, and the second provides information on whether a municipality was under territorial control by the FARC —both at the municipal level. Finally, the seventh source is the upstream municipality index developed by Castillo-Castillo (2025).

Table 3-1 Variable description

Variable	**Measurement**	**Description**
Water quality	Continuous number	Water quality index from 0 to 100
Deforestation	Hectares	Hectares lost by deforestation

GDP	Colombian pesos	Gross Domestic Product by millions of Colombian pesos
Rurality %	Percentage	Measures the proportion of rural population over total population for each municipality
Total population	Continuous number	Total people
Investment in wastewater for upstream municipality	Colombian pesos	Investment in wastewater treatment and cleaning for upstream municipality by millions of Colombian pesos
Investment in water treatment	Colombian pesos	Investment in water treatment cleaning by millions of Colombian pesos
Number of FARC attacks (Continuous)	Continuous number	Number of FARC attacks made by the FARC before 2014
Territorial control (Dummy)	Discrete	1 if the municipality was under FARC territorial control before 2014, 0 otherwise

3.4.2. Data description

On average, drinking water quality in Colombia is considered safe, with a mean score of 78.9. However, there are significant disparities across municipalities. Some municipalities report a score of 100, indicating water that is completely safe for human consumption, while others face extremely high-risk conditions, with water quality scores as low as 0.

A similar pattern is observed in the explanatory variables. For example, while the average annual deforestation per municipality is 207 hectares, some municipalities report no deforestation, whereas others have experienced up to 31,826 hectares of forest loss. The municipalities included in this analysis have an average population of approximately 35,000 inhabitants.

As expected, public investment in water treatment is greater than investment in wastewater management, with municipalities allocating an average of 94.3 million Colombian pesos to water treatment compared to 77.6 million pesos for wastewater infrastructure.

Lastly, among the treatment group — defined by the number of attacks — municipalities experienced an average of 1.4 attacks per year. Additionally, on average, 3% of the municipalities in the sample were under territorial control by the FARC prior to the ceasefire.

Table 3-2 Summary statistics

Statistic	**Mean**	**St. Dev.**	**Min**	**Max**
Water quality index	78.9	22.1	0	100
Deforestation	207	1,064	0	31,826
GDP	50,998.4	207,868.7	741.3	5,943,497.0
Rurality %	56.6	23.4	0.6	98.3
Total population	34,755.1	108,266.3	1,066	2,533,424
Investment in wastewater for upstream municipality	77.6	326.1	0	16,060.8
Investment in water treatment	94.3	444.4	0	21,093.1
Number of FARC attacks (Continuous)	1.4	6.9	0	179
Territorial control (Dummy)	0.03	0.2	0	1

Notes: Number of observations: 8,462

3.5. Methodology

Using data on drinking water quality, I use two approaches to evaluate both the immediate and long-term effects.

3.5.1. Immediate effects (number of attacks)

- Differences in Differences (DiD)

My initial approach focuses on analyzing the immediate effects of FARC attacks on water quality. To estimate the impact of the FARC ceasefire on water quality outcomes, I modify the treatment variable proposed by Guerra-Cujar et al., (2020) by defining it as a continuous variable representing the total number of attacks a municipality experienced by the FARC prior to the 2014 ceasefire.

Given the social, economic, and political context of the civil conflict in Colombia, this study does not rely on random sampling but instead utilizes a quasi-experimental design. To address potential biases inherent in this quasi-experimental approach, I apply the DiD methodology (Glewwe & Todd, 2022), as specified in Equation 1:

$$WaterQuality_{m,t+1} = \delta_m + \rho_t + \beta_1 Cease_t * FARC\_Treatment_m + \beta_2 Rurality\%_{m,t} + \beta_3 TotalPopulation_{m,t} + \beta_4 InvWastewaterTreatment_{m-j,t} + \beta_5 InvWaterTreatment_{m,t} + \varepsilon_{mt} \qquad (1)$$

The sub-indexes indicate municipality m in year *t*. $WaterQuality$ is the quality of drinking water for each municipality in year $t+1$; Since it is expected that there is a lag between the end of the conflict and when the water quality changes, water quality is evaluated in t+1. δ_m is the municipality fixed effect; ρ_t represents year fixed effect; $Cease$ is a dummy indicating 0 if the time is previous to the FARC ceasefire that occurred in 2014, and 1 if the year is from 2014 and forward. In model 1, $FARC\_Treatment_m$ represents the total number of attacks by the FARC before 2014. $Rurality\%$ and $TotalPopulation$ are explanatory variables that account for the percentage of the population living in rural areas, and the total population for each municipality, respectively. $InvWaterTreatment_{m,t}$ represents the investment that each municipality *m* does for their water treatment drinking water quality safeness.

Acknowledging that upstream water quality can directly affect downstream conditions (Castillo-Castillo et al., 2025), I include the $InvWastewaterTreatment_{m-j,t}$ variable that represents investment in the closest upstream j municipality in time *t*. This adjustment helps address potential spillover effects between municipalities, thereby supporting the Stable Unit Treatment Value Assumption (SUTVA) required for causal inference (Sinclair et al., 2012).

- Propensity Score Matching (PSM)

Considering that the municipalities targeted by FARC attacks may differ substantially from those that were not attacked — and that these very differences might explain why they experienced attacks in the first place — a conventional DiD approach may not be sufficient to identify an appropriate control group for the treated municipalities (those that experienced

FARC attacks)[10]. To address this bias, I also implement a PSM methodology (Glewwe & Todd, 2022) where I find the best control group based on some municipality characteristics.

To construct the Propensity Score Matching (PSM), I selected a set of observable characteristics based on two criteria. First, the variables chosen are relatively stable over time. Second, they are likely to influence both water quality and the number of FARC attacks across municipalities. Selecting variables that meet these conditions helps ensure a better balance between the treatment and control groups. This approach is consistent with the assumption outlined by Glewwe and Todd (2022): conditional on the observed characteristics (Z), the number of attacks in each municipality is independent of the potential outcomes (Y)—in this case, water quality. The list of the covariates used for the matching are:

Table 3-3 Variable description for matching process

Variable	**Measurement**	**Description**
Poverty	Percentage	Percentage of people in multidimensional poverty for each municipality
Elevation above sea	Meters	Measure that indicates the elevation above the see in meters
Distance to market	Kilometers	Indicates the distance in kilometers of each municipality to the closest main market center
Distance to the capital	Kilometers	Indicates the distance in kilometers of each municipality to the closest capital of the department

The rationale for selecting these specific variables is based on their demonstrated relevance to both water quality and FARC activity. For instance, poverty is strongly correlated with water quality (Castillo-Castillo et al., 2025) and is also a good explanatory variable for FARC activity (Vélez, 2001). Similarly, geographic variables such as elevation above sea, distance to the main market, and distance to the capital of the department are also determinants of FARC activity (Vélez, 2001). At the same time, these factors also influence water quality and management in Colombian municipalities (Pérez-Urdiales & Castillo-Castillo, n.d.).

[10] See Appendix B1 for the results of parallel trends assumption from the DiD methodology.

Because the intensity of the conflict—measured by the number of FARC attacks—varies significantly across municipalities, incorporating this information can improve the accuracy of propensity score estimation in the matching process. Therefore, I use the number of FARC attacks as the basis for constructing the propensity scores.

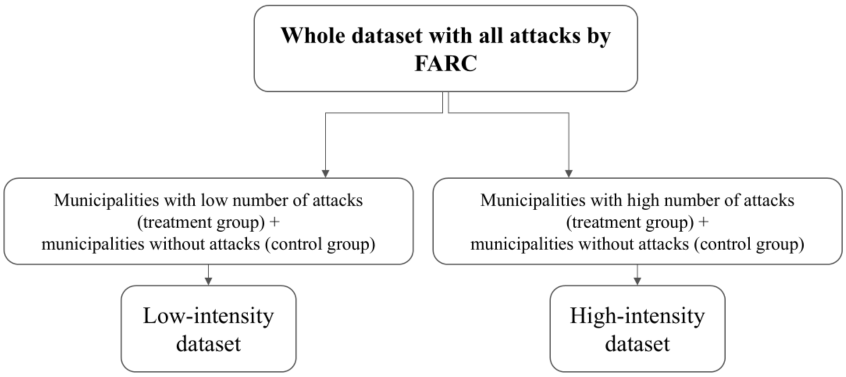
However, since propensity score estimation requires a binary treatment variable, I adopt a multi-step approach. First, among municipalities that experienced at least one FARC attack, I calculate the percentiles of attack counts and divide them into two groups: those in the lower 50th percentile and those in the upper 50th percentile. Next, I append the municipalities with zero recorded attacks to both groups. This results in two separate datasets: the low-intensity dataset, which includes municipalities with low levels of violence along with those with no attacks, and the high-intensity dataset, which includes municipalities with high levels of violence and also those with no attacks.

For each dataset, I define a binary treatment variable that equals 1 if a municipality experienced any FARC attack and 0 if it did not. I then implement a full matching procedure using the MatchIt package in R (Ho et al., 2025). This approach includes all observations from the treatment and control groups and estimates a propensity score for each unit using a probit regression model. The resulting propensity scores are used to identify the best possible matches between treated and control municipalities. Full matching also generates weights for each observation, reflecting its relative contribution to achieving covariate balance within matched sets. I apply this same procedure separately to both the low-intensity and high-intensity datasets.

Finally, after estimating the propensity scores and weights for both conflict intensity subsets, I merge them to create a single, final matched dataset. The results of the matching procedure are presented in Appendix B2.

Once the PSM is implemented, I run the same DiD equation (1) on this new set of better matched observations and their weights.

Figure 3-3 PSM procedure based on the intensity of the number of attacks



Note: This graph illustrates the Propensity Score Matching (PSM) procedure and the creation of two subsets used to define propensity scores, based on conflict intensity as measured by the number of FARC attacks in each municipality prior to the ceasefire in 2014.

3.5.2. Long-term effects (territorial control)

- Mediation analysis

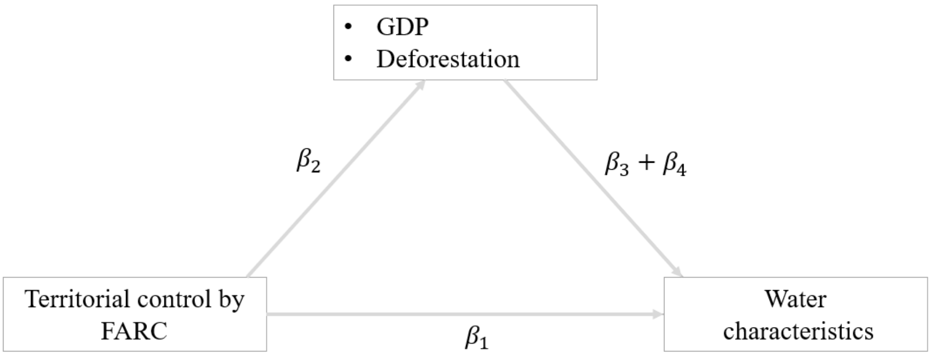
To better understand the effect caused by territorial control in the long-term, I define the treatment municipalities as those that were under territorial control by FARC before 2014. Conversely, control municipalities are defined as the municipalities under no territorial control before 2014.

To better understand the pathways through which the ceasefire affected drinking water quality for municipalities under territorial control in the long-term, I examine two mechanisms related to the territorial control and to the water resources. The first mechanism is the economic activity -measured through the GDP- and the second mechanism is deforestation. These mechanisms are analyzed using a mediation analysis framework, which allows me to estimate both the direct and indirect effects of the ceasefire from territorial control on water quality characteristics.

Specifically, I conduct separate mediation analyses for each of the water quality indicators used to construct the overall water quality index: free residual chlorine, coliforms, *E. coli*[11], color, pH, and turbidity. In each analysis, the dependent variable (DV) is one of these water quality characteristics. The primary independent variable (X) is territorial control by the FARC prior to the ceasefire, while the mediating variables are GDP (M1) and deforestation (M2).

The conceptual structure of these relationships — between territorial control, the mediators, and the water quality outcomes — is summarized in the following graph:

Figure 3-4 Ceasefire and mechanisms for water quality changes



Note: This graph presents a mediation analysis examining the impact of FARC territorial control on water quality. The independent variable, "Territorial control by FARC," may affect the dependent variable, "Water characteristics," through two main pathways. The end of territorial control can lead to shifts in economic activity (as measured by GDP) or increases in deforestation. These intermediate changes, in turn, can influence water quality outcomes.

As shown in Figure 3-4, I hypothesized relationships between territorial control by the FARC (X), the mediating variables — GDP (M1) and deforestation (M2) — and the water characteristics outcomes (DV). The mediation analysis estimates both the direct effect of territorial control on water characteristics and the indirect effects operating through changes in economic activity (GDP) and deforestation.

[11] These contaminants are closely associated with water pollution and the incidence of waterborne diseases, including diarrhea, as documented in previous studies (add cites).

The first relationship, territorial control by FARC on water characteristics, is represented in equation 2:

$$WaterCharacteristic_{m,t+1} = \delta_m + \rho_t + \beta_1 Cease_t * FARC\_TerritorialControl_m + \beta_2 Rurality\%_{m,t} + \beta_3 TotalPopulation_{m,t} + \beta_4 InvWastewaterTreatment_{m-j,t} + \beta_5 InvWaterTreatment_{m,t} + \varepsilon_{mt} \qquad (2)$$

Where $\beta_1$represents the estimation of the effect of the ceasefire in municipalities over territorial control by FARC on each one of the water characteristics. The second relationship of interest, effect of ceasefire on GDP or deforestation can be modeled in the following equation 3:

$$MediationVariable_{m,t} = \delta_m + \rho_t + \beta_{11} Cease_t * FARC\_TerritorialControl_m + \beta_2 Rurality\%_{m,t} + \beta_3 TotalPopulation_{m,t} + \beta_4 InvWastewaterTreatment_{m-j,t} + \beta_5 InvWaterTreatment_{m,t} + \varepsilon_{mt} \qquad (3)$$

Where β_{11}represents the estimation of the effect of the ceasefire in municipalities over territorial control by FARC on each one of the mediation variables. Each one of the mediation variables are represented by $MediationVariable_{m,t}$; this is, either GDP or deforestation for municipality m at year t. Finally, the total effect is represented by equation 4:

$$WaterCharacteristic_{m,t+1} = \delta_m + \rho_t + \beta_{111} Cease_t * FARC\_TerritorialControl_m + MediationVariable_{m,t} + \beta_2 Rurality\%_{m,t} + \beta_3 TotalPopulation_{m,t} + \beta_4 InvWastewaterTreatment_{m-j,t} + \beta_5 InvWaterTreatment_{m,t} + \varepsilon_{mt} \qquad (4)$$

3.5.3. Robustness checks

To check the validity of the results found by the DiD and the PSM-DiD, I run an additional analysis using synthetic differences-in-differences. This methodology introduced by (Arkhangelsky et al., 2021) combines the methodologies of classic DiD and Synthetic control. The results of this analysis are in the Appendix C.

3.6. Results

3.6.1. Immediate effects (number of attacks)

Table 3-4 presents the results for the direct effects estimated through the DiD approach (Column 1) and the PSM-DiD methodology (Column 2). As expected, the proportion of rural population in a municipality is negatively associated with drinking water quality. Specifically, a one-percentage-point increase in the rural population share reduces the water quality index by 19.8 points in the DiD model and by 14.6 points in the PSM-DiD model.

A similar pattern is observed for the total population variable. In this case, an increase of one person in the municipal population is associated with a decrease of 0.0001 points in the water quality index in both models.

Regarding the impact of FARC attacks, the results suggest that the ceasefire is positively associated with water quality in municipalities previously exposed to FARC-related violence. However, this relationship is not statistically significant in both DiD or the PSM-DiD models. This lack of significance motivates a deeper investigation into the underlying mechanisms driving changes in water quality following the ceasefire.

Table 3-4 Results for immediate effects

	Water quality	
	DiD (1)	**PSM-DiD (2)**
Number of attacks * Cease	0.004	0.002
	(0.010)	(0.010)
Rurality %	-19.924^{***}	-14.673^{***}
	(4.677)	(5.001)
Total population	-0.0001^{***}	-0.0001^{***}
	(0.00003)	(0.00003)
Investment in wastewater for upstream municipality	0.017	0.021
	(0.056)	(0.055)
Investment in water treatment	-0.048	-0.024
	(0.086)	(0.088)
Observations	8,899	8,462
R^2	0.006	0.006
Adjusted R^2	-0.114	-0.114
F Statistic	9.794^{***} (df = 5; 7939)	8.353^{***} (df = 5; 7552)

*Note: (1) ; (2) . Clustered robust standard errors are at municipality level. Municipality and year fixed effects are used. Standard error in parenthesis. *p<0.1; **p<0.05; ***p<0.01*

3.6.2. Indirect Long-term effects (territorial control)

The mediation analysis results are presented in Table 3-5. The findings indicate that deforestation significantly explains changes in coliforms and *E. coli* levels. Specifically, the Average Causal Mediated Effect (ACME) — the portion of the effect transmitted through deforestation — shows that deforestation leads to a statistically significant reduction of 7.4% - 0.077 units of Colony Forming Units (CFU)/100 cm3) in coliforms. Regarding the Average Direct Effect (ADE) — the effect of the ceasefire not mediated by deforestation — the results reveal significant reductions of 49% (-0.678) units in coliforms and 50% (-0.695) units in *E. coli* (also measured in Colony Forming Units (CFU)/100 cm3). Lastly, the Total Effect (the sum of ACME and ADE) indicates an overall reduction of 53% (-0.756) units in coliforms and 52% (-0.749) units in *E. coli* associated with the ceasefire, accounting for both the mediated and direct effects.

GDP, displays a pattern similar to that observed for deforestation. The ADE remains identical to the estimates found for deforestation: a reduction of 49% (-0.678) units in Coliforms and 50% (-0.695) units in E. coli. However, unlike deforestation, the ACME through GDP is not statistically significant for either water quality indicator. This suggests that changes in municipal GDP following the ceasefire did not meaningfully mediate the relationship between reduced conflict and improvements in water quality. As a result, the Total Effect mediated by GDP is smaller than that mediated through deforestation, since the indirect pathway via GDP does not contribute significantly to the overall outcome.

The results in Table 3-5 also highlight the varying relationships between other water quality characteristics—chemical, physical, and biological—and the mediation variables, deforestation and GDP. Although many of these estimates are not statistically significant, the direction of the effects remains consistent across both mediators. For example, the indirect effects of the end of territorial control on free residual chlorine—mediated through both deforestation and GDP—are negative. A similar pattern is observed for color and turbidity, which also show negative mediated effects. In contrast, pH exhibits an opposite trend, with positive effects through both mediation pathways.

Table 3-5 Results for long-term effects

Dependent variable	Estimation	Deforestation			GDP		
		ACME	**ADE**	**Total effect**	**ACME**	**ADE**	**Total effect**
Free residual chloride	Coefficient	-0.001	-0.007	-0.008	0	-0.007	-0.007
	p-value	0.788	0.808	0.788	0.924	0.804	0.816
Coliforms	Coefficient	-0.077*	-0.678***	-0.756**	0	-0.678***	-0.678***
	p-value	0.084	0.008	0.004	0.892	0	0
E. coli	Coefficient	-0.055	-0.695***	-0.749***	-0.002	-0.695***	-0.696***
	p-value	0.1	0	0	0.964	0	0
Color	Coefficient	-0.015	-0.032	-0.047	-0.002	-0.032	-0.034
	p-value	0.176	0.732	0.6	0.72	0.672	0.652
pH	Coefficient	0.001	0	0.001	0	0	0.001
	p-value	0.408	0.972	0.964	0.908	0.88	0.876
Turbidity	Coefficient	-0.003	-0.05	-0.053	-0.002	-0.05	-0.052
	p-value	0.664	0.668	0.632	0.776	0.656	0.636

*Note: *p<0.1; **p<0.05; ***p<0.01. This table shows the estimates of the mediation analysis for each one of the mediation variables: Deforestation and GDP. ACME indicates Average Causal Mediated Effect; ADE indicates Average Direct Effect; Total effect refers to the sum of both ACME and ADE. Cluster standard errors are at municipality level. Municipality and year fixed effects are used. All dependent variables (free residual chloride, coliforms, E. coli, color, pH, and turbidity are measured in logarithm).*

3.7. Discussion

This study finds that water quality improved in the post-conflict period following the ceasefire with the FARC. This conclusion is supported by both analytical approaches employed: one based on the number of FARC attacks and the other based on the extent of FARC territorial control. Incorporating GDP and deforestation as mediating variables to assess how the end of FARC territorial control affected the physical, chemical, and biological characteristics of water increased the depth of the analysis and confirm the robustness of the results. In both models, deforestation and GDP were associated with improvements in water quality, particularly through reductions in harmful, health-related components such as coliforms and *E. coli*. These results highlight the need for a multifaceted approach to water assessment and management in post-conflict settings—one that integrates both environmental sustainability and public health considerations.

The **immediate effects** of the ceasefire — measured by the reduction in attacks — are positively associated with improvements in water quality. This relationship may be explained by the nature of the activities evaluated: bombings of oil pipelines that caused hydrocarbon spills into rivers and streams. The end of these harmful activities likely contributed to an immediate positive impact on water resources. Although this positive association is consistent with findings from previous studies (Castellanos Santos, 2013; Vera Solano, 2021), it is not statistically significant in my analysis. These results, derived from the number of attacks, underscore the importance of examining additional mechanisms through which the end of conflict affects water quality—beyond the direct impact of violence. One such mechanism is the loss of territorial control following a ceasefire, which may offer an alternative explanation for changes in water quality.

The end of **territorial control** had two major consequences: it boosted economic activity (GDP) while also exerting pressure on natural resources, notably through increased deforestation. Both dynamics have implications for water quality. Both GDP growth and deforestation were positively associated with improvements in water quality indicators — particularly biological contaminants such as coliforms and *E. coli*. However, this result contrasts with findings from previous research on post-conflict impacts on water resources in Colombia and other countries (Batal al-Shishani, 2006; Faour & Fayad, 2014; Murillo-Sandoval et al., 2020; Oldfield et al., 1991; Salazar, 2019; Vera Solano, 2018, 2021), which generally report deteriorations in environmental conditions following conflict. Several factors may explain these differences. First, unlike earlier studies that rely on qualitative methods such as interviews to local inhabitants (Betancur-Alarcón & Krause, 2020), analysis of journalistic information (Castillo-Niño et al., 2022) or the combination of both (Valencia & Ecuyer, 2023), my analysis uses quantitative methods like statistical analysis of relationships between different variables, considering spatial relationships and time variations. Second, my study is conducted at the national level, whereas much of the previous research focuses on specific regions (Betancur-Alarcón & Krause, 2020; Castillo-Niño et al., 2022; Méndez-Garzón et al., 2024). Third and most importantly, I prioritize indicators directly linked to human health — such as the IRCA and its components — while earlier studies have often examined environmental or technical changes in water quality such as changes in drainage systems, sedimentation process and biodiversity (Plataforma Colombiana de Derechos Humanos Democracia y Desarrollo, 2022) or changes in water management (Valencia & Ecuyer, 2023).

In particular, the mediation analysis using the **economic activity variable -measured through municipal GDP-**, emerged as a relevant mechanism. Although increased economic activity is often associated with greater environmental risks and potential water pollution, particularly in contexts with weak institutions (Vásquez, 2023), my findings suggest a different pattern. In this study, the end of territorial control contributed to reductions of 49% in coliforms and 50% in *E. coli* concentrations through increases in GDP. This result likely reflects how the end of territorial control can stimulate economic growth and public investment, which, in well-governed areas, translates into better water management and improved infrastructure and services (Castillo-Castillo et al., 2025). Moreover, ecotourism has emerged as one of the most prominent economic activities in the post-ceasefire period (Díaz Rocca & Zielinski, 2022; Murillo-Sandoval et al., 2023). By definition, ecotourism depends on the preservation of ecosystems and natural resources, and it cannot thrive in the long term if environmental degradation occurs. It is possible that the success and profitability of ecotourism have incentivized municipalities to reinvest in improving water quality, both to ensure the safety of visitors and to support the continued growth of the industry.

The indirect effect of conflict, operating through increased **deforestation**, was also associated with decreases in harmful biological components in water, specifically coliforms (by 53%) and *E. coli* (by 52%). While deforestation following the ceasefire is generally expected to harm water resources (Foley et al., 2001; Malmqvist & Rundle, 2002), these results suggest that the net benefits of reduced territorial control and therefore, improved governance outweighed the environmental costs, leading to better drinking water quality. One possible explanation for this is that new economic and government activities in territories formerly controlled by the FARC have led to changes in land use (Betancur-Alarcón & Krause, 2020; Méndez-Garzón et al., 2024). These new land uses are for example new lands dedicated to ecotourism,-construction of new water infrastructure, and diverse entrepreneurs companies dedicated to manufacture or construction (Bernal et al., 2024; Betancur-Alarcón & Krause, 2020; Foley et al., 2001).

However, the end of territorial control may also result in these new activities being subject to regulations and protocols aimed at maintaining appropriate water quality. For instance, while pre-ceasefire activities such as illegal mining and illicit crop cultivation typically disregarded water quality standards, the new legal activities are more likely to comply with water regulations due to the formalization of land (Batinich, 2024; Betancur-Alarcón & Krause, 2020). Additionally, the conversion of areas previously associated with harmful water practices into conservation zones established by the CARs may also contribute to water quality improvements (Arias Miranda, 2022; Corporación Autónoma Regional de Cundinamarca, 2023; Peña Guzmán, 2010). In summary, both the new economic developments and the creation of protected environmental areas must now follow standard water quality protocols. These changes have likely contributed to the observed reductions in biological contaminants such as coliforms and *E. coli*.

When comparing the long-term impacts of GDP and deforestation, the findings suggest that both of these mechanisms are associated with improvements in water quality (seen in decreases in coliforms and *E. coli*). However, these results also show that improvements in water quality resulting from increases in deforestation -due to land use changes- are larger than those resulting from increases in economic activity alone. This finding highlights the importance of the formalization of land ownership and use, which requires observance of water-related legal requirements. This is coherent with what has been found in previous studies with respect to improvements in natural resources due to changes in land formalization like in Benin (Wren-Lewis et al., 2020) and specifically, in water resources in Senegal (Hughes et al., 2019), and from a literature review (Katusiime & Schütt, 2020). This insight highlights the institutional dimension of post-conflict recovery and the importance of managing land use transitions carefully.

Overall, the results indicate that water quality in Colombia improved in the aftermath of the FARC ceasefire, with these improvements driven primarily by changes in territorial control rather than by a simple reduction in the intensity of attacks. This suggests that the influence of conflict on water quality is determined less by conflict intensity and more by the nature of territorial governance. The erosion of FARC's territorial dominance facilitated the expansion of institutional frameworks, enabling broader access to water services in previously marginalized areas (Betancur-Alarcón & Krause, 2020; Valencia & Ecuyer, 2023) and the establishment of enhanced water treatment protocols for human consumption. In many rural regions where local community organizations oversee water provision, the ceasefire strengthened both institutional and financial capacities, leading to significant service improvements. However, in areas where institutional weaknesses persisted, water quality continued to decline even after the cessation of hostilities, underscoring the uneven distribution of post-conflict benefits.

From a policy perspective, these findings underscore the critical importance of strengthening institutional support in formerly conflict-affected territories during post-conflict transitions. While peace processes can create opportunities to stimulate economic activity and improve water resource management—particularly through the expansion of public service delivery—they may also impose new institutional demands on territories that are unprepared to navigate unfamiliar legal and regulatory frameworks governing water use and access, as found by Valencia & Ecuyer (2023). In this context, post-conflict transitions present additional challenges, such as the need to monitor water management using standardized indicators, like the IRCA index, which are often unfamiliar to local communities and primarily designed to meet governmental public health objectives.

The use of an index such as the IRCA—which specifically targets improvements in drinking water safety for human consumption—and the adoption of a new regulatory framework prioritizing investments in water management from a public health perspective, may help explain the differences between my findings and those of previous studies regarding the effects of the end of territorial control on water quality. Unlike prior research, which often emphasizes broader environmental indicators, in this study I focus on metrics directly linked to human health outcomes, offering a different lens through which the impacts of post-conflict transitions on water resources are assessed.

Access to detailed data on the physical, chemical, and biological characteristics of water—specifically those affected by economic activities that intensified following the end of territorial control, such as illicit mining, agricultural contamination, oil spills, pesticide use, glyphosate application, and pollutants associated with industry—would enable a more comprehensive evaluation of the medium-term effects of conflict cessation on water quality from an environmental perspective, rather than solely from a human health perspective, as pursued in this study. A key limitation of the present analysis is the absence of sufficiently detailed environmental data. However, efforts are currently underway to obtain such information, which will be incorporated into future research to provide a more holistic understanding of the relationship between post-conflict transitions and water resource quality.

Moreover, an additional valuable direction for future research would be to integrate information on water quality from both human health and environmental perspectives. Specifically, a next step would involve analyzing the long-term effects of activities such as deforestation, illegal mining, and other environmentally disruptive practices—triggered by the end of territorial control—on specific human health outcomes. For example, future studies could examine changes in chronic illness rates associated with contaminants like mercury in water, while also accounting for regional variation, as the impacts of the loss of territorial control have differed significantly across the country.

3.8. Conclusions

This study contributes to the growing body of literature examining the consequences of armed conflict, with a particular focus on water resources in Colombia. The implementation of the ceasefire led to a substantial reduction in armed attacks and represented an important step toward building a stable and lasting peace. It also allowed the prioritization of improving living conditions in rural areas that had historically been neglected by the state. A central element of these efforts was the expansion of public services, particularly the construction and enhancement of local water treatment plants and wastewater management systems, aimed at ensuring reliable access to safe drinking water and sanitation for the communities most affected by the conflict.

Moreover, ecosystems and territories that had previously been inaccessible due to FARC prohibitions (McClanahan et al., 2019) were now opened, allowing the arrival of new economic activities and a range of new institutional and economic actors into these rural areas (Suarez et al., 2018). Additionally, similar to other countries and in post-conflict scenarios, the end of territorial control had a marked increase in deforestation and significant changes in land use after the conflict (Suarez et al., 2018) that have significant consequences on the water resources management and its quality.

All the changes in the water use and access led to the conclusion that water was not only a key tool for the FARC's territorial control but also a resource severely impacted by the conflict (Quevedo Niño & Walteros Moreno, 2019; McClanahan et al., 2019). Specifically, the new institutional and economic landscape introduced a more complex set of regulations governing water access and usage. These changes affected not only water consumption but also the provision and management of water services and the allocation of their benefits. As Betancur-Alarcón and Krause (2020) note, this shift included "the construction of infrastructure, the granting of water allocation permits, the establishment of legal frameworks for water-related conservation programs, and the implementation of social interventions and technical assistance."

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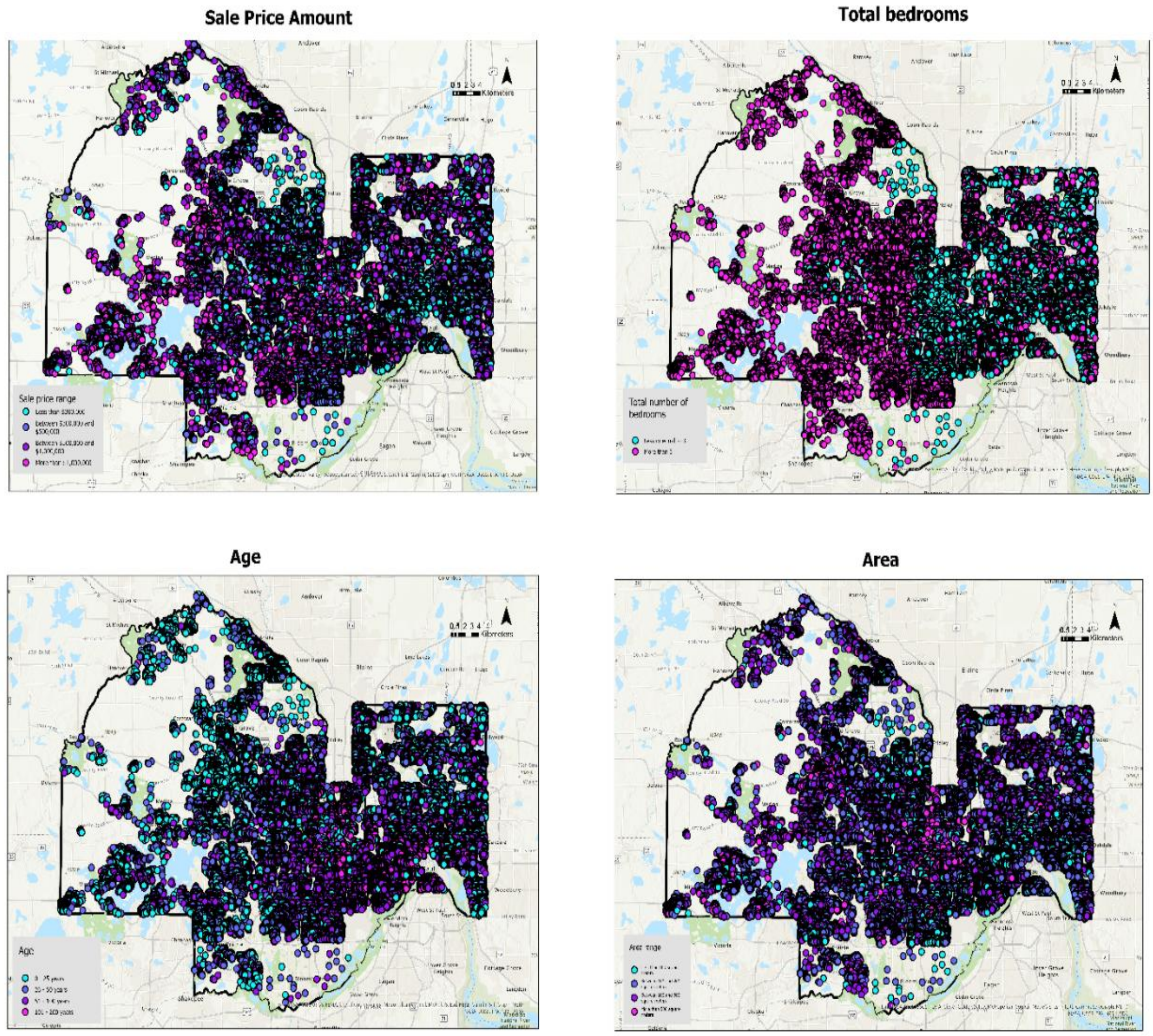
Appendix

Appendix to Chapter 1

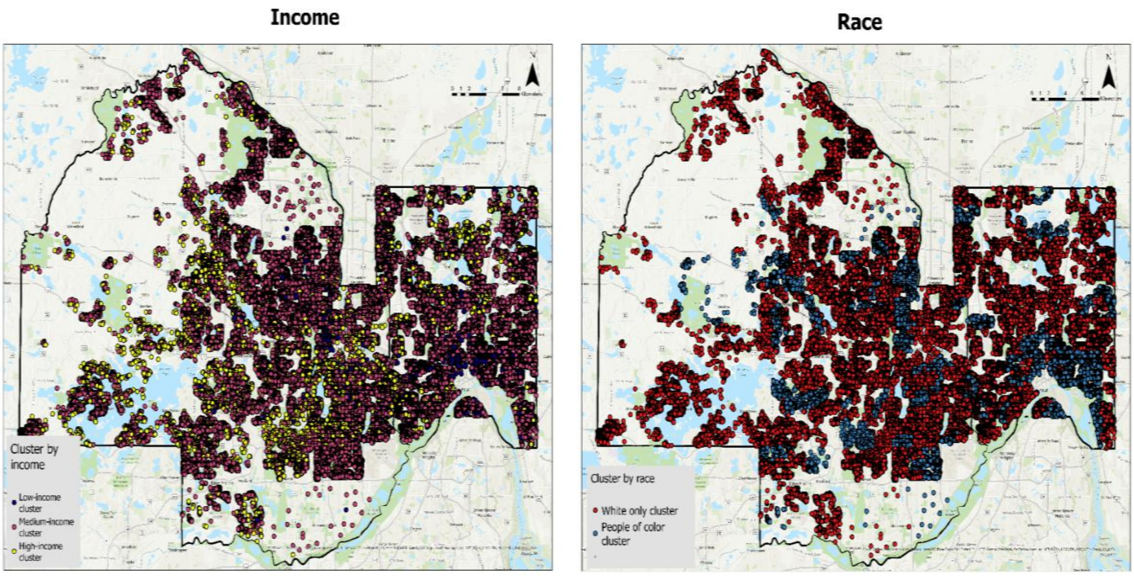
A. Spatial distribution of house prices and explanatory variables

Figure A-1.



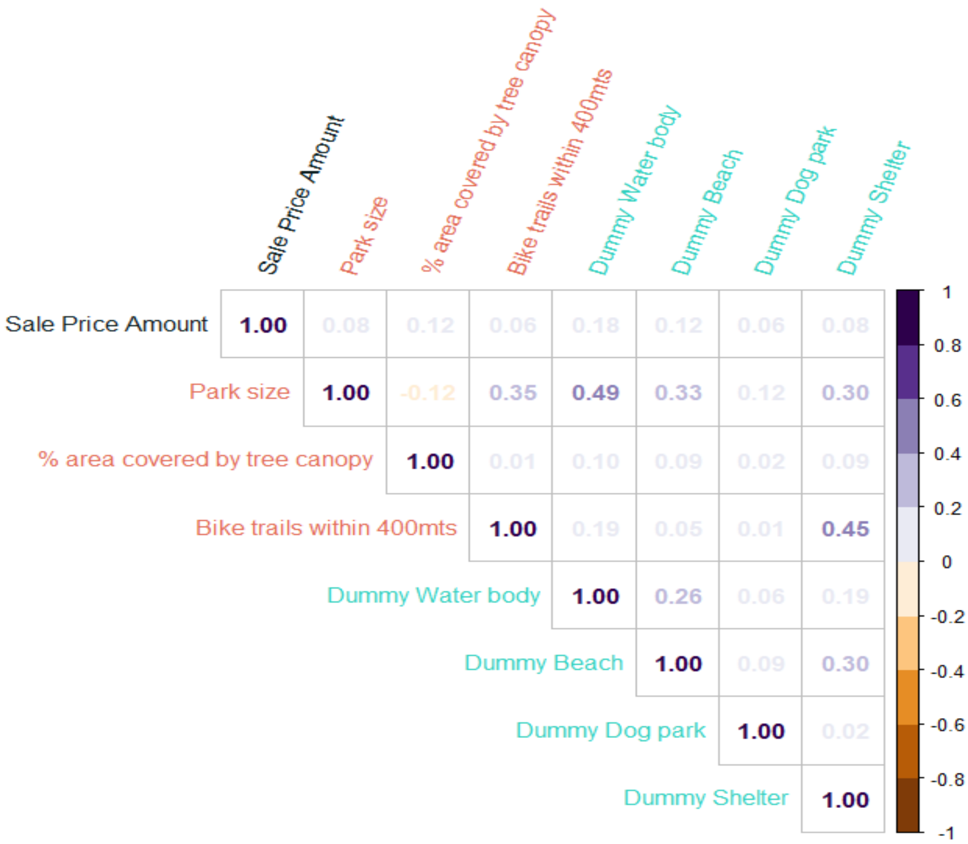
B. Cluster

Figure B-1. Cluster results



C. Correlation

Figure C-1 Correlation map



D. Heterogeneity analysis

- Income

Based on American Community Survey (ACS) data we split the census tracts into two clusters: (1) low-income and (2) medium & upper-incomes. Since there is the case where houses of high value are located in census tracts classified as low-income, we want to be sure that our low-income census tracts classification only includes houses within the lowest range of prices. For this, our next step is to use the sale price information from ZTRAX. With this information we split each of the two initial clusters (1 low-income and 2 medium & upper-incomes) into three additional subclusters. This means that for each of the initial clusters we have: 1 low-income, 2 medium-income, and 3 high-income subclusters. Finally, using the information from the two previous steps, we create our final three income classifications based on the income thresholds that result from the cluster steps. The first group, low-income, is formed by the census tracts whose average house sale price is ~ \$220,000. The second group, medium-income, is formed by census tracts with a range of house sale prices between ~\$300,000 and ~\$600,000. The third group, high-income, is formed by houses whose average price is ~\$1,000,000 (Figure D-1).

- Race

Also using information from the ACS, we split census tracts into two groups based on : (1) percentage of people who consider themselves as White alone for each census tract and, (2) percentage of people who consider themselves as non-White (this is, African-American, American Indian, Asian, Hawaiian, Alaska Native) or as Hispanic. With these two variables and the Stats package from R (R Core Team, 2023), we create race clusters at the census tract level. For the % of POC variable, we create two clusters of census tracts: 1) low % of POC and 2) high % of POC (same for the % of White alone variable). The lowest % of POC census tracts cluster have, on average, 20% of people who identify themselves as other races different than White, while for the highest % of POC census tracts cluster is 62%. On the other hand, the lowest % of White census tracts cluster have, on average, 37% of people who identify themselves as White, while for the highest % of White census tracts cluster is 80%. Since our interest is focusing on the most possible differentiation between races, our final race clusters are defined by choosing the clusters with the highest percentage of each group of race. This means that our group of POC is defined by the cluster that has the highest percentage of POC at the census tract level (Figure D-2).

In addition to these income and race classifications, we also investigate interaction of race and income categories. The interaction of groups of income and race yielded a total of 6 groups: POC & low-income, White & low-income; POC & medium-income, White & medium-income; and POC & upper-income, White & upper-income.

Since our main hypothesis is that house prices are influenced differently by park characteristics based on income and race characteristics, we implement equation 1 for each one of the 11 subgroups previous mentioned (low-income, medium-income, high-income, POC, White, POC & low-income, White & low-income; POC & medium-income, White & medium-income; and POC & upper-income, White & upper-income).

Figure D-1. Income

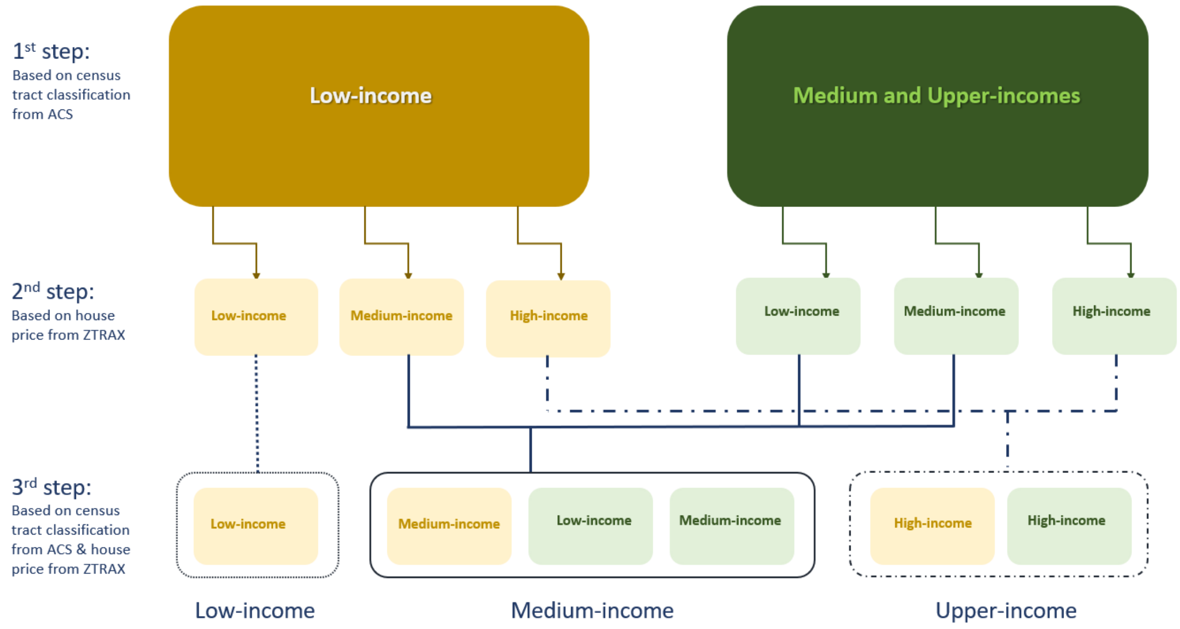
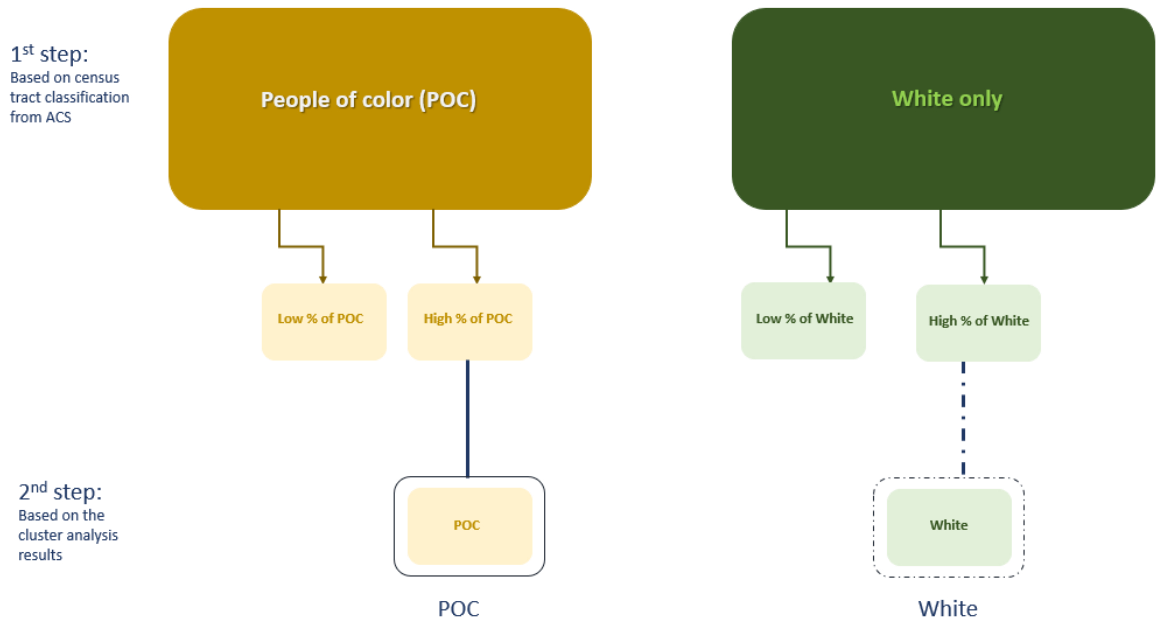


Figure D-2. Race



E. Robustness checks

Our robustness check results are consistent with what we found in our main results with a 500 meters buffer area. With respect to park characteristics, we also found that the ***park size*** valuation depends on the income and race cluster classification. We observed house prices of houses located in a 300 meters buffer area have more clusters where this relationship is significant than for houses located in a 50 meters buffer area. For instance, we found that only for high-income and White but low-income, the park size has a significant relationship with the house price for houses within a 50 meters buffer area. While we found that this relationship is significant for low and high-income, POC and White census tracts, and all combinations of income and White census tracts in houses located in a 300 meters buffer area. With the ***tree canopy percentage,*** we confirmed that this is one of the characteristics that is most valued the most for owners, both for properties located in the 300 and 50 meters buffer area. The ***bike trail*** shows that this characteristic is only important for houses within the 300 meters area, but not for the properties inside the 50 meters area.

Variables related to park amenities also confirm the importance of racial and income cluster classifications. For instance, the ***presence of a water body*** confirms that this variable is relevant for the house market real estate in our study area and is highly and positively preferred by white census tract clusters. There is not a clear pattern of the importance of the presence of ***beach(es)***: while it is highly preferred in low-income and White census tracts located in the 300 meters buffer area, when the properties area within the 50 meters, this characteristic is only valued by high-income census tracts, independent of race.

We confirmed that, same as for the 500 meters buffer area, for a 300 meters buffer area, the importance of the presence of ***dog park***(s) amenity is driven mainly by the group of people living in POC census tracts. However, when considering a 50 meters buffer area, we see that the results are driven only by high-income census tracts. Presence of a ***shelter(s)*** results show that this amenity is a preference for properties located within the 300 meters buffer area, independent from race; however for the 50 meters area it seems to be a preference for houses located in high-income White census tracts.

Figure E-1: Summary of results for park characteristics and amenities for 300 meters

Notes: This graph shows the summary of the impacts of park characteristics (size (logarithm of square kilometers), percentage of tree canopy area, and hundreds of meters of bike trails) and amenities (presence of water body, beach, dog park, and shelter) variables on house prices. The magnitude of the impact is presented in a blue, white, and red scale. Where the darkest blue color represents the highest positive impact of the variable on house prices, while the darkest red color represents the lowest negative impact of the variable on house prices. Yellow stars represent the statistical significance: ***p<0.01, **p<0.05, *p<0.1.

Figure E-2: Summary of results for park characteristics and amenities for 50 meters

Notes: This graph shows the summary of the impacts of park characteristics (size (logarithm of square kilometers), percentage of tree canopy area, and hundreds of meters of bike trails) and amenities (presence of water body, beach, dog park, and shelter) variables on house prices. The magnitude of the impact is presented in a blue, white, and red scale. Where the darkest blue color represents the highest positive impact of the variable on house prices, while the darkest red color represents the lowest negative impact of the variable on house prices. Yellow stars represent the statistical significance: ***p<0.01, **p<0.05, *p<0.1.

Table E-1: Results for LAG Spatial Model - 300 meters buffer area

	Whole	Income			Low-income		Race		Medium-		High-income	
Variable		Low	Medium	High	POC	White	POC	White	POC	White	POC	White
Park - Size (log of km2)	-2,944**	-73,016**	1,337	-5,287***	-88	-104,540*	10,955***	-9,598***	9,202	-14,003***	-4,150	-8,566*
	[1,246]	[34,390]	[1,423]	[1,520]	[1,505]	[57,622]	[1,603]	[1,185]	[6,768]	[4,570]	[4,226]	[5,137]
Park - % tree canopy area	92,219***	203,936	65,426***	85,869***	-1,540	587,734	16,933	87,347***	9,999	77,449**	29,031	147,836***
	[11,724]	[332,045]	[13,624]	[13,945]	[15,413]	[485,997]	[16,387]	[11,523]	[57,939]	[39,191]	[34,478]	[45,608]
Park - Bike trails (hundreds of meters)	282***	-4,820	329***	339***	506**	6,360	-1,684***	356***	-837	476***	-578	340*
	[54]	[5,619]	[64]	[65]	[224]	[7,037]	[206]	[50]	[1,126]	[142]	[704]	[205]
Park - Dummy Water body	78,752***	404,930***	50,177***	66,931***	-22,344***	426,777*	-16,548***	105,422***	-45,073*	97,243***	-24,495	106,404***
	[4,680]	[156,009]	[5,385]	[5,662]	[6,632]	[221,128]	[5,854]	[4,687]	[27,127]	[16,352]	[18,804]	[21,945]
Park - Dummy Beach	70,397***	526,379**	12,238	25,348**	-3,789	735,291**	55,271***	60,863***	38	-4,742	30,687	5,361
	[10,177]	[257,876]	[12,141]	[12,625]	[36,483]	[370,408]	[18,680]	[9,007]	[44,762]	[30,263]	[32,394]	[35,909]
Park - Dummy Dog park	52,036***	-266,706	-10,215	31,202*	23,654*	-478,243	110,047***	27,303**	65,327	-17,776	113,330***	-75,639
	[14,838]	[226,020]	[18,751]	[17,943]	[12,456]	[351,772]	[27,018]	[13,833]	[51,331]	[71,696]	[32,880]	[59,424]
Park - Dummy Shelter	33,372***	366,596	-20,264	10,135	25,185	68,105	138,933***	62,499***	26,307	-12,062	47,883	26,640
	[10,365]	[382,389]	[12,820]	[12,336]	[47,367]	[557,667]	[14,369]	[10,172]	[67,403]	[38,857]	[47,518]	[43,600]
Age	5,668***	-753	5,444***	3,227***	236***	-656	1,776***	5,925***	-359**	734**	-131	318
	[60]	[902]	[70]	[68]	[58]	[1,688]	[84]	[74]	[179]	[354]	[113]	[261]
Total bedrooms	46,344***	-59,274***	44,753***	30,568***	-4,140***	-16,746	8,164***	56,526***	-7,525***	10,113***	-18,627***	7,428***
	[914]	[14,694]	[1,103]	[981]	[1,055]	[21,519]	[1,548]	[1,078]	[2,600]	[2,849]	[1,892]	[2,494]
Building area (squared meters)	29***	44***	18***	22***	4***	72***	26***	22***	20***	6***	40***	11***
	[0]	[4]	[1]	[0]	[0]	[7]	[1]	[0]	[2]	[1]	[1]	[1]
Number of bathrooms	13,934***	18,513***	12,133***	12,390***	1,152***	16,716***	13,396***	15,031***	10,412***	11,766***	7,080***	13,604***
	[133]	[2,977]	[178]	[137]	[175]	[3,139]	[272]	[160]	[536]	[525]	[332]	[544]
Distance from house to park (meters)	-140***	-760*	-64**	-134***	34***	-522	-47*	-166***	-13	-8	-25	-137***
	[21]	[390]	[25]	[25]	[13]	[767]	[27]	[22]	[56]	[79]	[38]	[50]
Distance from house to downtown (meters)	13***	136	15***	5**	-1	249	-9***	6***	-8	2	-7	-19
	[2]	[138]	[2]	[2]	[3]	[198]	[2]	[2]	[18]	[7]	[11]	[13]
Dummy - transit access	-29,101***	-78,788	-11,417*	-51,138***	-9,099	-141,852	-13,577	-30,250***	10,758	-3,549	-90,183***	-46,592***
	[3,823]	[130,780]	[6,773]	[6,830]	[8,334]	[228,318]	[11,369]	[3,781]	[21,119]	[11,770]	[16,881]	[16,230]
Categoric - Sale in 2nd quarter of the year	13,143***	32,907	9,268***	4,432***	4,666	58,488	12,798***	12,647***	28,778***	26,817***	8,003*	15,142***
	[1,574]	[27,435]	[1,787]	[1,675]	[3,019]	[47,540]	[2,521]	[1,974]	[5,016]	[6,201]	[4,448]	[3,913]
Categoric - Sale in 3rd quarter of the year	-11,979***	-897	-7,880***	-23,679***	-79	-24,875	-4,977*	-15,542***	-17,252***	-6,533	-3,612	-17,629***
	[1,689]	[29,306]	[1,877]	[1,836]	[3,372]	[54,301]	[2,786]	[2,111]	[5,261]	[6,428]	[4,861]	[4,107]
Total population	31***	20	30***	13***	15***	101	38***	29***	21	19***	19*	13
	[2]	[87]	[2]	[2]	[3]	[143]	[2]	[2]	[16]	[6]	[10]	[11]
% Vacancy rate	-9,647***	-54,718**	-7,000***	-2,189***	-1,130	-99,782**	-6,707***	-4,595***	-807	-2,008	-706	-3,598
	[665]	[22,864]	[774]	[816]	[825]	[46,108]	[738]	[695]	[3,455]	[2,357]	[2,250]	[3,371]
n	121,111.0	7,219.0	60,187.0	53,705.0	5,630.0	4,271.0	30,106.0	91,005.0	14,927.0	45,260.0	12,231.0	41,474.0
p	42	38	42	42	30	37	35	42	35	42	34	42
npar	3	3	3	3	3	3	3	3	3	3	3	3
AIC	41910.13	16979.92	13672.74	-23603.6	-5691.44	9492.69	1194.36	37355.24	26747.39	86390.32	4666.74	46378.1
AICc	41910.13	16979.93	13672.74	-23603.6	-5691.43	9492.7	1194.36	37355.24	26747.39	86390.32	4666.74	46378.1
Log Likelihood	-20952.07	-8486.96	-6833.37	11804.8	2848.72	-4743.35	-594.18	-18674.62	-13370.7	-43192.16	-2330.37	-23186.05
Deviance	121069	7181	60145	53663	5600	4234	30071	90963	14892	45218	12197	41432
pseudo.r.squared	0.26	0.34	0.25	0.31	0.1	0.29	0.19	0.28	0.2	0.13	0.37	0.3

Table E-2: Results for LAG Spatial Model - 50 meters buffer area

	Whole				Race		Low-income		Medium-income			High-income
Variable		Low	Medium	High	POC	White	POC	White	POC	White	POC	White
Park - Size (log of km2)	-30,891	-1,616	-26,372	-147,857**	-3,841	-32,853	-7,048	-13,827*	17,117	-32,564		-17,980
	[20,428]	[6,590]	[16,965]	[70,614]	[11,312]	[23,321]	[25,003]	[8,096]	[12,259]	[20,606]		[214,770]
Park - % tree canopy area	490,740***	103,980*	404,078***	815,046	-262,552*	640,276***	-322,253	295,920***	-74,643	472,098**		4,702,448**
	[184,087]	[59,525]	[150,191]	[631,288]	[139,399]	[232,251]	[202,299]	[79,410]	[102,598]	[202,243]		[1,979,518]
Park - Bike trails (hundreds of meters)	630	74	368	-13,786	-1,663	836	-1,612	139	-1,941	417		-75,942
	[829]	[271]	[609]	[11,086]	[1,691]	[694]	[1,929]	[348]	[1,709]	[592]		[50,090]
Park - Dummy Water body	229,918***	64,104**	174,213***	806,908***	-68,235	294,013***	-175,522**	160,856***	-125,535***	276,350***		701,979
	[83,226]	[26,019]	[63,108]	[234,484]	[41,500]	[96,337]	[83,801]	[39,000]	[43,466]	[79,635]		[754,887]
Park - Dummy Beach	200,555	-37,266	62,335	1,940,771***	-17,098	173,169	413,277**	-57,725	-84,532	57,640		453,493
	[150,494]	[40,465]	[117,838]	[450,177]	[162,679]	[139,942]	[188,395]	[51,898]	[123,896]	[123,403]		[1,283,252]
Park - Dummy Dog park	237,540	112,413	131,326	1,111,594**	12,000	120,339	-195,031	12,671	49,005	46,394		020,332
	[232,162]	[70,970]	[204,653]	[531,971]	[136,137]	[299,592]	[227,440]	[87,613]	[75,404]	[294,555]		[1,173,125]
Park - Dummy Shelter	-4,632	16,078	-59,498	995,660*	329,997***	152,441	-31,123	-18,414	32,369	98,787		3,143,809*
	[170,045]	[52,911]	[139,740]	[554,286]	[103,698]	[155,284]	[186,206]	[77,595]	[127,188]	[130,291]		[1,787,961]
Age	2,098**	1,471***	2,821***	8,477***	-963*	3,407***	-2,508**	-2,299***	272	3,426***		-11,904**
	[1,047]	[406]	[788]	[2,223]	[548]	[1,287]	[1,263]	[598]	[391]	[1,069]		[5,906]
Total bedrooms	33,332***	30,494***	21,112**	118,530***	-20,986*	69,546***	-6,270	19,726***	-2,607	35,681***		22,106
	[12,246]	[5,136]	[10,644]	[33,070]	[11,357]	[13,440]	[13,621]	[6,334]	[7,623]	[11,160]		[100,777]
Building area (squared meters)	59***	59***	35***	108***	40***	59***	28***	56***	54***	34***		205***
	[3]	[3]	[3]	[11]	[3]	[4]	[5]	[3]	[5]	[4]		[25]
Number of bathrooms	38,641***	14,125***	32,401***	34,029***	19,841***	40,483***	-1,848	5,154***	15,776***	34,334***		40,560***
	[2,335]	[949]	[2,014]	[5,746]	[1,902]	[2,541]	[3,383]	[1,111]	[1,506]	[2,235]		[13,060]
Distance from house to park (meters)	-2,675**	-210	-2,863***	-7,018	-2,670**	-2,314	230	-2,619***	-1,992***	-2,499*		-4,706
	[1,132]	[599]	[942]	[5,840]	[1,045]	[1,601]	[2,058]	[735]	[596]	[1,397]		[9,005]
Distance from house to downtown (meters)	-16	-2	-21	-79	-42*	-59	-40	-26*	4	-51*		17
	[49]	[8]	[33]	[89]	[24]	[37]	[34]	[14]	[29]	[30]		[575]
Dummy - transit access	-29,202	-62,007**	-81,042	-179,084	-105,935	-4,368	-107,492	-43,379	-100,199	-56,730		91,002
	[68,002]	[23,424]	[31,911]	[393,688]	[63,229]	[73,339]	[84,028]	[32,327]	[74,070]	[34,228]		[1,083,746]
Categoric - Sale in 2nd quarter of the year	84,273***	30,216*	64,457***	243,419***	85,916***	72,353***	3,537	38,059*	92,619***	46,460**		148,207
	[17,881]	[16,410]	[16,821]	[48,830]	[30,787]	[23,448]	[67,140]	[19,758]	[19,568]	[21,280]		[222,519]
Categoric - Sale in 3rd quarter of the year	-10,496	-41,571**	-7,020	42,515	16,006	-38,348	7,282	-24,440	34,571	-34,597		-221,872
	[19,958]	[17,407]	[18,369]	[49,849]	[32,834]	[25,702]	[72,002]	[21,278]	[21,155]	[23,345]		[226,795]
Total population	29	0	13	188**	82***	19	-15	8	2	19		-587
	[42]	[9]	[31]	[87]	[14]	[38]	[34]	[15]	[25]	[32]		[423]
% Vacancy rate	-27,761**	4,167	-7,686	-100,398***	-17,143***	-1,341	21,058*	-11,664**	4,844	-2,753		29,821
	[12,485]	[3,430]	[10,396]	[28,485]	[6,037]	[15,955]	[11,563]	[5,420]	[5,525]	[13,528]		[134,780]
n	20,193.0	4,366.0	14,302.0	1,525.0	4,259.0	15,934.0	560.0	3,806.0	2,861.0	11,441.0		687.0
p	41	38	41	33	34	41	32	38	34	41		32
npar	3	3	3	3	3	3	3	3	3	3		3
AIC	37553.78	-3110.1	24751.51	848.74	7352.7	28358.65	-311.45	-463.62	4002.1	19767.7		1302.43
AICc	37553.78	-3110.1	24751.51	848.76	7352.71	28358.65	-311.41	-463.61	4002.11	19767.7		1302.47
Log Likelihood	-18773.89	1558.05	-12372.76	-421.37	-3673.35	-14176.33	158.72	234.81	-1998.05	-9880.85		-648.22
Deviance	20152	4328	14261	1492	4225	15893	528	3768	2827	11400		655
pseudo.r.squared	0.31	0.18	0.27	0.33	0.33	0.35	0.33	0.27	0.24	0.31		0.45

F. Spatial autocorrelation tests

Table D-1: Moran's test results for LAG model specification

	Moran's test results
Moran I statistic	0.267477395175
Expectation	-0.000006493844
Variance	0.000003816042
Standard deviate	136.93
P-value	0.00000000000000022

Notes: This table shows Moran's results for the baseline dataset. Since the p-value is less than 0.01, there is spatial autocorrelation that needs to be addressed by using a SAR model.

Appendix to Chapter 2

A. Variables

Table A-1: Definition of variables

Variable	**Definition**	**Use**
Water quality index	Is the inverse of the IRCA index. In this modified version, the highest value (100) corresponds to drinking water quality perfectly safe for human consumption, and 0 otherwise.	DV
Investment	Is the total amount of money that each municipality spends on activities related to the provision of the water service. In our paper, these activities are classified in "coverage"[a], "quality"[b], and "other types of investment"[c]. We divide this amount by the total population in each municipality i at year t.	IV
Wastewater investment in upstream municipality	Is the total amount of money that each municipality spends on activities related to the treatment of wastewater. Since the treatment of waste in each municipality influences water quality for all downstream municipalities, we identify how much the closest upstream municipality invest in treating waste. We divide this amount by the total population in each municipality i at year t.	EV
Water quality in source	Is an index that goes from 0 to 1 that measures the water quality in basins at different points (Figure C-1-3). This index weights physical, chemical, and microbiological components as follows: dissolved oxygen OD (0.21), pH (0.08), Biochemical Oxygen Demand DBO (0.15), coliform (0.16), turbidity (0.07), Total dissolved solids (0.07), phosphorus (0.08), Total dissolved solids (0.05), color (0.05), nitrogen (0.08) (Torres, P. et al., 2009).	EV
Rurality index	The proportion of population living in rural zones out of the total population for a municipality i for year t.	EV
Poverty index	% of population with basic unsatisfied needs (NBI). According to the DANE, the NBI is defined as "The simple indicators selected are: Inadequate housing, Housing with critical overcrowding, Housing with inadequate services, Housing with high economic dependency, Housing with school-age children who do not attend school." (Departamento Administrativo Nacional de Estadística, n.d.).	EV

Note: DV=dependent variable; IV=independent variable; EV=explanatory variable.

[a]: Total investment in "coverage" is the total of:

- Coverage: Is the amount of money spent on increasing the coverage of the drinking water service. This includes, for example, investment in infrastructure to increase distribution networks.
  Some specific examples are: “(i) The construction of infrastructure for supply and distribution systems, with their accessories (macro-meters, valves, anchors, containment structures or structures in general, equipment or devices to supply, distribute, control or measure raw water or treated, in the case of supply and matrix distribution; (ii) Activities of studies, acquisition or property reorganization (land, resettlements and easements); (iii) Studies, designs or consultancies developed for the construction of the systems. (iv) Construction and intervention; (v) The legal commitments derived from the construction of the main water treatment supply and distribution systems.” (Departamento Nacional de Planeación, 2020a).
- Design: Is the amount spent on studies to increase coverage and quality. Some of these spendings are wages for engineers, environmental impact assessments, permitting approvals, topographic and geological zone studies, hydrological studies, studies on how to collect water from the collection to the treatment point, demand for water, and others (Dirección de Política y Regulación - SINAS, 2021)
- Production: Is the investment spent on water production capacity such as the investment in plants capacity to have new lines of production (Empresas Públicas de Medellín, 2023).

[b]: Total investment in “quality” is the total of:

- Network distribution: Network distributions are the lines used to transport water from a treatment plant to the users (Gur, Eytan & Spuhler, Dorothee, 2020).
- Repairs and maintenance: Amount of money spent to maintain the optimal functioning of the service. This spending includes replacements and repairs of network material for water conduction, renovation of drinking Water Pumping Stations, wells, pipes, tanks, water collection points (for ground and surface water). It also includes spending on water treatment and disinfection (Departamento Nacional de Planeación, 2020b; Subgerencia Gestión de Sistemas Comunales, 2019).

[c]: Total investment in “other spendings” is the total of:

- “Non-counted water reduction programs; Institutional Strengthening; Business Transformation; Macro and Micro Measurement Programs; Green Investments; Climate Change Adaptation; Information Management; Risk Management; Energy Efficiency” (Dirección de Política y Regulación - SINAS, 2021).

Table A-2: Water components: toxicity levels.

Component	Unit	Allowed range	Associated diseases	Toxicity level
Chloride	mG/L	250	Diarrhea, nauseas (Bashir et al., 2012)	
Magnesium	mG/L	36	"Cardiovascular disease, growth retardation, reproductive failure (Sengupta, 2013)	
Nitrate	mG/L	1,0	infant methemoglobinemia, cancer (colorectal cancer, bladder, and breast cancer), birth defects, thyroid disease (Ward et al., 2018)	
Sulphate	mG/L	250	Gastroenteritis, Diarrhea, nauseas (Bashir et al., 2012)	
Zinc	mG/L	3	sideroblastic anemia (Rahman et al., 2019)	
Fluorides	mG/L	1,0	dental fluorosis, dental decay, dental caries, Endemic skeletal fluorosis, cancer, possible spontaneous abortion or congenital malformations (Fawell, John et al., 2006)	
Copper	mG/L	1,0	(Fewtrell et al., 2002)	
Iron	mG/L	0,3	High concentrations can cause diarrhea, vomiting, and possible cardiovascular and central nervous system diseases (Rahman et al., 2019)	
Alkalinity	mG/L	200	"More alkaline distilled water has more health benefits in contrast to acidic water"(Mills, 2019)	
Aluminum	mG/L	0,2	associated with dementia and Alzheimer's disease illness (Nieboer et al., 1995)	
Calcium	mG/L	60	(The British Columniba Ground Water Association, 2007)	
Free residual chlorine	mG/L	0.3 – 2.0	"bladder, rectal, colon, and gastrointestinal cancers"(Kalmaz & Kalmaz, 1981)	
Phosphate	mG/L	0,025	(Jereb et al., 2017)	
Manganese	mG/L	0,1	Neurotoxicity (Rahman et al., 2019)	
pH	pH units	6.5 – 8.5	(World Health Organization, n.d.)	
Color	Platinum Cobalt Units	Maximum 15	Gastrointestinal symptoms (Rupani et al., 2016)	
Hardness	mG/L	300	"Cardiovascular disease, growth retardation, reproductive failure"(Sengupta, 2013)	
Turbidity	Nephelometric turbidity units (NTU)	Maximum 2	gastrointestinal illness (Mann et al., 2007)	
Nitrite	mG/L	0,1	"The major biological effect of nitrite is its involvement in the oxidation of normal hemoglobin to methaemoglobin, which is unable to transport oxygen to the tissues"(Fadaei & Sadeghi, 2014)	
Coliform; E-coli	Number of microorganisms in 100 cm3	No	Vomiting, diarrhea, fever (Michigan Department of Health and Human Services & Michigan Department of Environment, Great Lakes, and Energy, n.d.)	
Mercury	mG/L	0,001	Haemolysis, "nonspecific cell injury or even cell death, cessation of microtubule formation, enzyme inhibition, oxidative stress, cessation of protein and DNA synthesis, and autoimmune responses"(Zulaikhah et al., 2020); neurological, nephrological, immunological, cardiac, motor, reproductive and even genetic (Zahir et al., 2005).	

B. Data exclusion criteria

- Exclusion of Years: water companies receive funding from various sources, with the Sistema General de Participaciones (SGP) being the most significant (Working paper, Perez-Urdinola & Castillo-Castillo, 2024). Since its inception in 2007, the SGP has provided resources to water companies through municipalities, which are responsible for managing and allocating these funds based on local needs.

  However, in 2015, the Decreto 1077 introduced new criteria for managing these funds in municipalities with populations over 30,001. Under this regulation, the administration of SGP funds became contingent on the water quality provided in urban areas. If municipalities failed to meet the minimum water quality standards, the responsibility for fund administration shifted to higher government levels (departments).

  This regulation had significant implications for funding in the water and sanitation sector. One concern is that it may have incentivized municipal governments to misreport water quality to retain control over fund allocation. Because our study focuses on water quality, we aim to minimize the influence of potential corruption on this variable. This is why we have excluded the years following the implementation of this regulation.

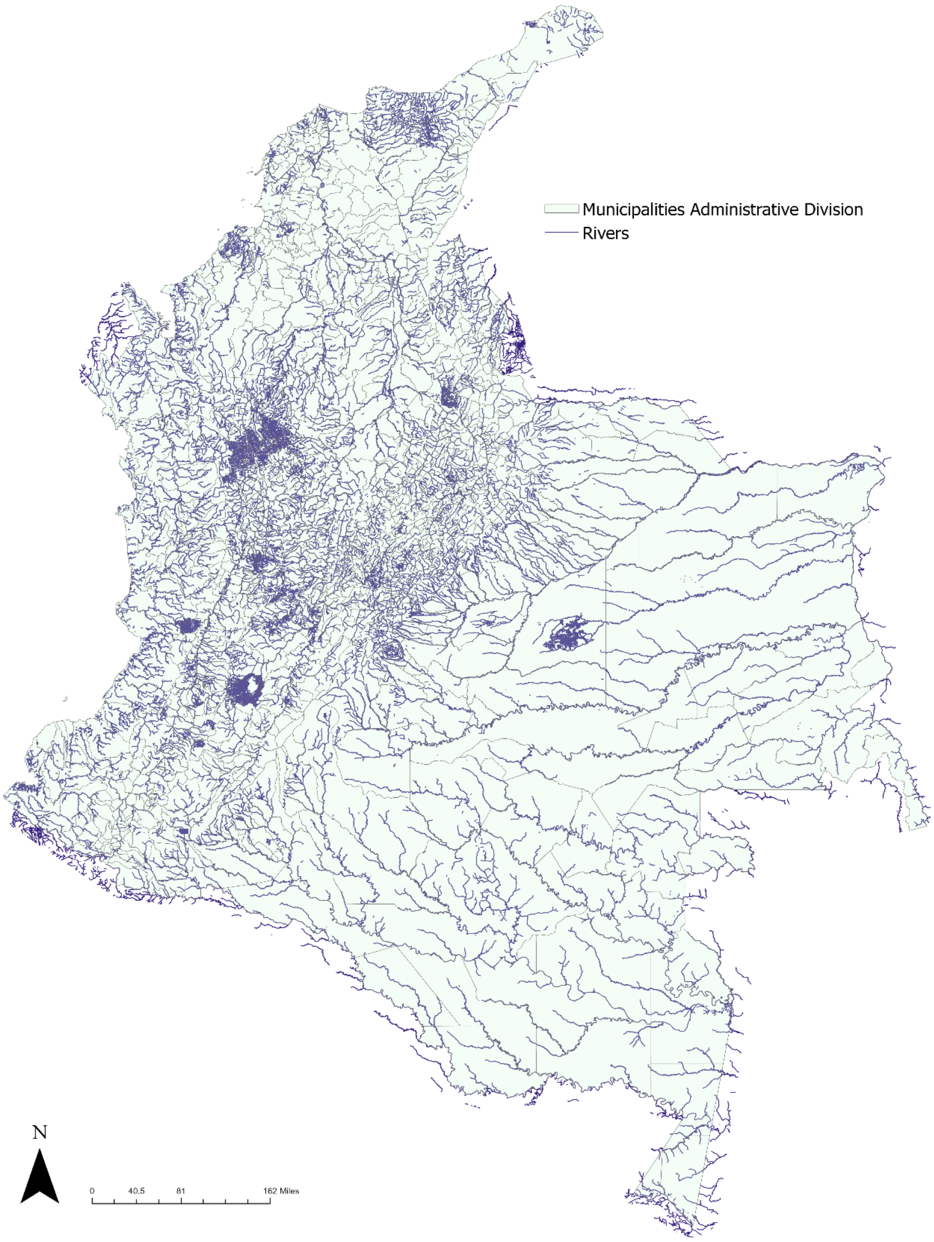
  While we recognize the value of examining a broader time frame to fully understand investment in the water and sanitation sector, we believe that including data from post-2014 requires a separate study that includes corruption data.

- Exclusion of Municipalities: The exclusion of the four largest municipalities is justified for several reasons. These municipalities have substantially higher investment levels and a larger workforce than smaller municipalities, which would introduce outliers in our sample. Including these outliers could skew the results, potentially distorting the regression model and leading to poor model fit.

  Moreover, these municipalities typically have the highest water quality in the country, leaving little room for analysis of how investment impacts water quality, compared to smaller cities where investment can have a more significant effect.

C. Water in Colombia

Figure C-1: River networks and administrative political division in Colombia.



Note: This map shows all rivers and administrative divisions for Colombia.

D. *Summary statistics*

Table D-1 – Resource Management: Summary Statistics

Variable	Min	Max	Mean	STD
Total investment in coverage (i,t-1)	0	295,975.8	18,980	41,560
Total investment in quality (i,t-1)	0	452,534.9	21,071	62,040
Total investment in other spendings (i,t-1)	0	999,252.6	29,518	108,408

Notes: N= 352. All values are in Colombian pesos.

Table D-2 – Operational Management: Summary Statistics

Variable	Min	Max	Mean	STD
Number of employees	1	521	43	89

Table D-3 – Water Components: Summary Statistics

Variable	Min	Max	Mean	STD
Free Residual Chlorine	0.0	8.4	0.8	0.6
pH	5.7	14.6	7.2	0.6
Coliforms	0.0	6,612.0	299.8	759.7
Colour	0.2	83.3	10.5	12.7
Turbidity	0.1	499.0	4.9	29.3

E. *General analysis*

To evaluate whether the investment improves water quality, we consider the model in Equation (1). In this model, our key explanatory variable is the logarithm of *InvestmentPerCapita_i,t-1*, that represents the total per capita investment in municipality *i* in the previous year *t-1*. *WaterQualitySource_i,t* accounts for the quality of the surface water sources for municipality *i* in year *t*. The logarithm of *SewageInvestmentUpstream_i,t-1* allows us to account for the high spatial correlation existing between upstream municipalities; then, this variable represents the investment of the closest upstream municipality j in year $t-1$. $RuralityIndex\_i,t$ and $PovertyIndex\_i,t$ are socio-economic variables that represent the percentage of people living in rural areas out of the total population and poverty in municipality i in year t, respectively. $YearFE\_t$ and $IndFE\_i$ represent municipality and time fixed effects, respectively. The error term is represented by e_i,t.

$$WaterQuality_{i,t} = b_1 Investment_{i,t-1} + b_2 SewageInvUpstream_{i,t-1} + b_3 WaterQualitySource_{i,t} + b_4 Rurality_{i,t} + b_5 Poverty_{i,t} + YearFE_t + IndFE_i + +\varepsilon_{i,t}$$

(Equation 1)

We include the lag (t-1) of the investment variables in Equation 1 -and also for all the rest of the equations- because it is expected that investment effects will be seen in the future and not in the present when the investment was made. Investment was log-transformed to normalise the distribution of our sample and consequently reduce the influence of possible outlier observations. The use of lags generates serious error correlation and heterogeneity problems, which can lead to biassed estimators (Arellano & Bond, 1991; Driscoll & Kraay, 1998). To correct these two methodological problems, we use the methodology proposed by Driscoll and Kraay (1998). In this methodology, the standard errors are corrected by changing the orthogonality conditions, hence providing a consistent covariance matrix.

Considering that investment is intended to increase water quality, we expect b1 to be positive. Similarly, considering that more investment on upstream water municipalities and that good water quality on surface water improves water quality in municipality *i*, we also expect b2 and b3 to be positive. Finally, we expect a negative relationship between both the rurality index (represented by b4) and the poverty level (represented by b5) with the water quality.

- Results from general analysis

As expected, we find that investment has a positive relationship with water quality (Table 2). We observe that one (percentage) in investment increases water quality by 0.00474 points, all other covariates constant. However, we see that this result is not statistically significant. The lack of significance of the investment coefficient suggests that, as hypothesised, investments are currently not yielding an immediate improvement in water quality in Colombia.

When analysing the other explanatory variables, we see that, as expected, the water quality at the source point (WaterQualitySource_i,t) is positively related to the water quality index. Similarly, we also observe that the investment made in the closest upstream municipality in the previous year (SewageInvestmentUpstream_i,t-1) has a positive relationship with water quality. However, none of these coefficients are statistically significant. Finally, we see a significant statistical relationship between rurality and poverty variables with the water quality. For the former, we see that the higher the percentage of population in rural areas in a municipality (RuralityIndex_i,t), the lower the water quality in a municipality. For the latter, we see that the higher the poverty rate in a municipality, the higher the water quality.

Table E-1 – General analysis

	WaterQuality (i,t)
Total investment in water sector (i,t-1)	0.474
	(0.540)
Total investment in wastewater in closest upstream municipality (i,t-1)	0.027
	(0.061)
Water quality in source (i,t)	0.141
	(0.108)
Rurality index (i,t)	-3.796
	(1.894)
Poverty index (i,t)	1.330
	(0.554)
Observations	222
Adj R^2	0.125

Notes: Fixed effects included at year and municipality level. * p<0.05, ** p<0.01, *** p<0.001

F. Robustness checks

Our analysis rests on the hypothesis that investments in infrastructure take time to materialize in measurable outcomes, particularly in countries like Colombia, where bureaucratic processes for securing funding are often lengthy. This delay is partly due to the complexities of large-scale infrastructure projects, which require careful planning and coordination with other city divisions, such as transportation and neighbourhood development offices. Moreover, water and sanitation infrastructure projects typically take around one year to complete.

With these factors in mind, our primary analysis includes a one-year lag as a baseline to account for the time it takes for investments to yield observable results. However, due to the diverse institutional structures (including local governments and city departments) and geographic variations, some infrastructure projects may require longer to show their impact. Therefore, we also conducted robustness checks by applying lags of two and three years to our analysis.

To assess the robustness of our models, we reran the model specified in Equation 1, extending the lag of investment effects to two and three years (see Table F-1).

Table F-1: Robustness checks equations

General (2 years of lag)	

	$$WaterQuality_{i,t} = b_1Investment_{i,t-2} + b_2SewageInvUpstream_{i,t-1} + b_3WaterQualitySource_{i,t} + b_4Rurality_{i,t} + b_5Poverty_{i,t} + YearFE_t + IndFE_i + +\varepsilon_{i,t}$$
General (3 years of lag)	$$WaterQuality_{i,t} = b_1Investment_{i,t-3} + b_2SewageInvUpstream_{i,t-1} + b_3WaterQualitySource_{i,t} + b_4Rurality_{i,t} + b_5Poverty_{i,t} + YearFE_t + IndFE_i + +\varepsilon_{i,t}$$

Our main findings, based on a one-year lag in investment, are supported by the robustness checks. When we extend the analysis to a two-year lag (Table 3, Column 1), the relationship between investment and drinking water quality remains statistically non-significant. This same pattern holds when we test for a three-year lag (Table 3, Column 2). In other words, regardless of the lag period considered, we do not observe a statistically significant association between investment in water and sanitation infrastructure and improvements in drinking water quality.

These results highlight the importance of understanding why investments in the water and sanitation sector may not yield the anticipated improvements in drinking water quality. The findings suggest a need for further investigation into how investments are managed and executed within the sector, as well as whether additional complementary measures might be required to translate financial inputs into tangible quality improvements in drinking water.

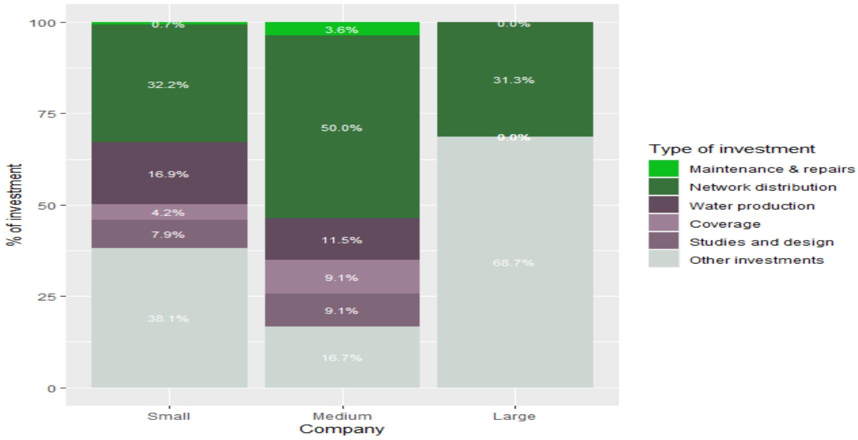
Table 3: Robustness checks

	(1) WaterQuality (i,t)	(2) WaterQuality (i,t)
Total investment in water sector (i,t-2)	2.173	
	(1.161)	
Total investment in water sector (i,t-3)		-0.670
		(1.029)
Total investment in wastewater in closest upstream municipality (i,t-1)	-0.310	-0.219
	(0.180)	(0.130)
Water quality in source (i,t)	0.143	-0.370*
	(0.234)	(0.079)
Rurality index (i,t)	-2.079	-5.037
	(3.252)	(2.586)
Poverty index (i,t)	0.454	3.213
	(0.952)	(0.855)
Observations	141	97
Adj R^2	0.233	0.433

Notes: Fixed effects included at year and municipality level. * p<0.05, ** p<0.01, *** p<0.001. Column 1: 2 years of lag of investment. Column 2: 3 years of lag of investment.

G. Investment allocations

Figure G-1: Type of investment by Provider size



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Appendix to Chapter 3

A. Context

A1 - Water in Colombia

Table - A. 1 Number of water service providers in Colombia – 2020

Providers	Small-scale	Large-scale
By 2020, 3,289 water service providers were registered at the national level	of which 2,318 were classified as small providers, in the urban area, there are 1,874 water supply providers and 958 wastewater service providers	476 as large providers and 504 were registered providers in use In rural areas there are 1,424 service providers. There are 1,403 water services and 106 wastewater services.

Note: This table has summary information about drinking water and wastewater provision service in Colombia. Source: Superintendencia de Servicios Públicos Domiciliarios (2020a)

A2 - FARC: environmental and institutional attacks in Colombia

Table - A. 2 Environmental related attacks by FARC

Year	Place	Occurrence	Direct or indirect affectation	Water affectation?
Between 1995-2015	Choco, Valle del Cauca, Cauca, and Narino areas	Illegal mining by FARC (and some other armed groups) caused environmental affectations (Defensoría del Pueblo, 2016, 142). With the presence of backhoes, the use of poisonous and explosive products along many of the rivers in these departments -often with the permission of local authorities- the environment has rapidly degenerated and water sources used for consumption have been contaminated. (CNMH, 2014, retos para la reintegración, 359).	Direct	Yes
2015	Narino department	"The FARC bombed the Transandino oil pipeline in Nariño, an attack that contaminated waterways. As a result, 150,000 people lost access to water. 10,000 barrels of oil spilled into the waterways, making the attack the worst environmental disaster in Colombia's history" (Mapping Militant Organizations. Stanford University, 2019).	Direct	Yes

2010-2012	Colombian rural areas with illicit crops	Regarding illicit crops belonging to guerrilla groups, the national government has focused on their eradication from aerial sprays, which contaminate the sources of water used for human consumption in addition to destroying potato, cassava, corn, and pancoger crops (CNMH, 2014, retos para la reintegración, 60).	Direct	Yes
2014	Ariari region - Meta	The FARC attacked the Ariari regional water drinking service that was inaugurated on June 29, 2013 and in which the National Government invested more than $9.5 billion pesos. This caused that at least 16,000 inhabitants of the rural sector of the municipalities of Granada and Fuente de oro were left without drinking water service. In addition to this, regarding Arauca, two factors stand out about guerrilla activities and oil activity. First, the oil distribution money. Each bomb that affected the oil infrastructure system caused both the loss of huge amounts of money, and also the affectation to natural resources lost at the time of the attack but also for the money that must be invested in the reconstruction of the pipeline infrastructure. In 2001 alone, the pipeline was blown up 98 times (Castellanos Santos, 2013, 36).	Direct	Yes
1998-2006	Areas affected by the attacks on the pipelines	Attacks on the pipeline caused thousands of oil losses that in turn generated innumerable environmental damage. These spills have great impacts on tropical ecosystems, "more than 70% of hydrocarbon spills in Colombia affect rivers and streams, and about 30% are associated with swamp systems", permanently affecting ecological processes (Castellanos Santos, 2013, 38). The damage caused to ecosystems also affected the population since it disrupts the social infrastructure of the department, due to large amounts of money that could have been invested in education and health need to go to its reconstruction. According to Ecopetrol, in mid-2001 "losses from the attacks could reach 330 million dollars so far this year" (Castellanos Santos, 2013, 41).	Direct	Yes
Since 1980s	La Gabarra	Coca cultivation had its beginnings in La Gabarra under the control of the Front 33 of the FARC. Since the 1980s, they were the first group to directly intervene in the coca production chain, they regulated, energized and sustained the coca business.	Indirect	Yes

1970s-1980s	Municipalities of Catatumbo	The FARC affected the environment and water sources in the municipalities of Catatumbo, with their attack on the oil infrastructure of Tibpu, which caused the contamination of water sources (which supply local or municipal drinking water services), fish mortality, damage to pastures and crops. About this, an inhabitant of the area explains how “every time the guerrillas attack on the oil pipeline and the crude comes to fall on the river Tibú, where the water is drawn for us. I have lasted at least 15 days without a drop of water, without being able to, you can even say without bathing” (CNMH, 2018).	Direct	Yes
1985-2005	Cordoba	The FARC arrived in the area in 1985, holding a military hegemony for nearly two decades, prior to the arrival of the paramilitaries. During its time of rule, the FARC carried out acts of sabotage against the hydrocarbon transport infrastructure, the road network, the electricity network, and private vehicles and farms. (Ideaspaz, 2011: 11).	Indirect	Yes
1990s	Santanderes and southern Cesar	The FARC arrived in the territory in 1980 with the 41st front. Its economy was consolidated with the coca economy, especially in the 1990s. In addition, in this area, the guerrillas carried out extortion, kidnapping, cattle rustling, assassinations, and illegal roadblocks. (Observatory of the Presidential Program for Human Rights and IHL. Dynamics of the armed confrontation at the confluence between the Santanderes and southern Cesar. 2006 Bogotá: Imprecal Ltda.) In these areas, the guerrillas impacted the water resources by intervening in the production and sale of coca, which, as we have mentioned previously, causes significant damage to water sources due to the use of chemicals that are later disposed of in nearby rivers	Direct	Yes

Note: This table has summary information about FARC activity affectations to the environment.

Table - A. 3 Institutional related attacks by FARC

Year	Place	Occurrence	Direct or indirect affectation	Water affectation?

In early 2000s	Caqueta, Arauca and Cauca regions	FARC carried out the assassination of mayors (CNMH, 2013, 18) to control the regions.	Indirect	No
1997	Remedios - Antioquia	Through social mobilization the arrival of the FARC in the late 1990s stopped all the wastewater treatment work initiatives from States. (CNMH, silenciar la democracia, 2014, 254). This type of communal initiative is no exception in the rural areas of the country, given the lack of state action, the peasants had to organize to meet the needs that were not being satisfied by the Government. This is the case with community water drinking service, understood as small and medium-sized organizations, created by groups of neighbors united to build and guarantee access and supply of water. According to the Superintendencia de Servicios Públicos Domiciliarios, it is estimated that there are about 12,000 community aqueducts in the country (Red Nacional de Acueductos Comunitarios de Colombia, 2017)	Indirect	No
1970s-1980s	Catatumbo is a border region with Venezuela, located north of Norte de Santander.	When three guerrilla groups arrived and settled in the region: the ELN, the EPL and the FARC. These guerrillas had their greatest impact from 1979 to 1999, when the paramilitary project in the region was consolidated. At first, the FARC was present in the town of La Gabarra, due to its implications with coca crops, and later they expanded to the municipalities of Sardinata and Tibú in the late nineties, it was during the first decade of the 21st century, when the FARC extended its influence to municipalities such as El Tarra, San Calixto, La Playa and Hacarí. In the Catatumbo, these three guerrillas coexisted (CNMH, 2018).	Indirect	Yes
2000s	Caribbean region, in the stilt houses of Magdalena	The precarious situation in which they lived deepened after the guerrilla attacks in the 2000s, and due to the weakness of the State to solve the problems, the situation has deepened. In this way, conditions of extreme poverty are identified, with the absence of basic services such as health and drinking water, education, among other deficiencies (CNMH, 2014b, Llegó en canoa, 21). Given the absence of the Colombian State in the area, the water sources are indiscriminately contaminated. Either with the diversion of rivers to be used in livestock and irrigation of industrial crops of oil palm and bananas or with the dumping of agro-industrial pollutants such as fertilizers, fungicides, and pesticides in the Ciénaga. The problem lies in	Indirect	Yes

		the fact that the waters of the Ciénaga, used for human consumption without any additional treatment, are chemically polluted (CNMH, 2014b, Llegó en canoa, 88). According to the investigations carried out by Invemar, the waters of the Complejo lagunar present "not optimal" conditions to be consumed due to the presence of heavy metals and feces. As it does not have a basic sanitation system, all types of material and liquid waste are discharged into the complex's waters due to the lack of a garbage management plan. (CNMH, 2014b, Llegó en canoa, 151).		

Note: This table has summary information about FARC activity affectations to institutions.

A3 - FARC: territorial control by 2012

Figure - A. 1 Territorial control by FARC in 2012

Source: Centro Nacional de Memoria Histórica, (2020)

B. Methodology

B1 – Immediate effects: Differences in differences

Table B1: Immediate effects: Parallel trends assumption results

	Dependent variable:
	Calidad Agua
Dummy treatment * Year2007	0.4
	(1.3)
Dummy treatment * Year2008	0.1
	(1.3)
Dummy treatment * Year2009	-1.8
	(1.3)
Dummy treatment * Year2010	-0.2
	(1.3)
Dummy treatment * Year2011	0.2
	(1.3)
Dummy treatment * Year2012	-1.4
	(1.3)
Dummy treatment * Year2013	-2.1
	(1.3)
Dummy treatment * Year2014	-2.1
	(1.3)
Dummy treatment * Year2015	-1.9
	(1.3)
Dummy treatment * Year2016	0.3
	(1.3)
Dummy treatment * Year2017	-1.5
	(1.3)
Dummy treatment * Year2018	-1.4
	(1.3)
Dummy treatment * Year2019	-2.6^{**}
	(1.3)
Observations	14595
R^2	0.001
Adjusted R^2	-0.1
F Statistic	1.3 (df = 13; 13466)

*Note: *p<0.1; **p<0.05; ***p<0.01. This table shows the estimates of the parallel trends' assumption check for FARC activity for total, urban, and rural water quality areas for each municipality. Cluster standard errors are at municipality level. Municipality and year fixed effects are used. Robust standard errors in parentheses. Significance levels: *** p<0.01, ** p<0.05, * p<0.1.*

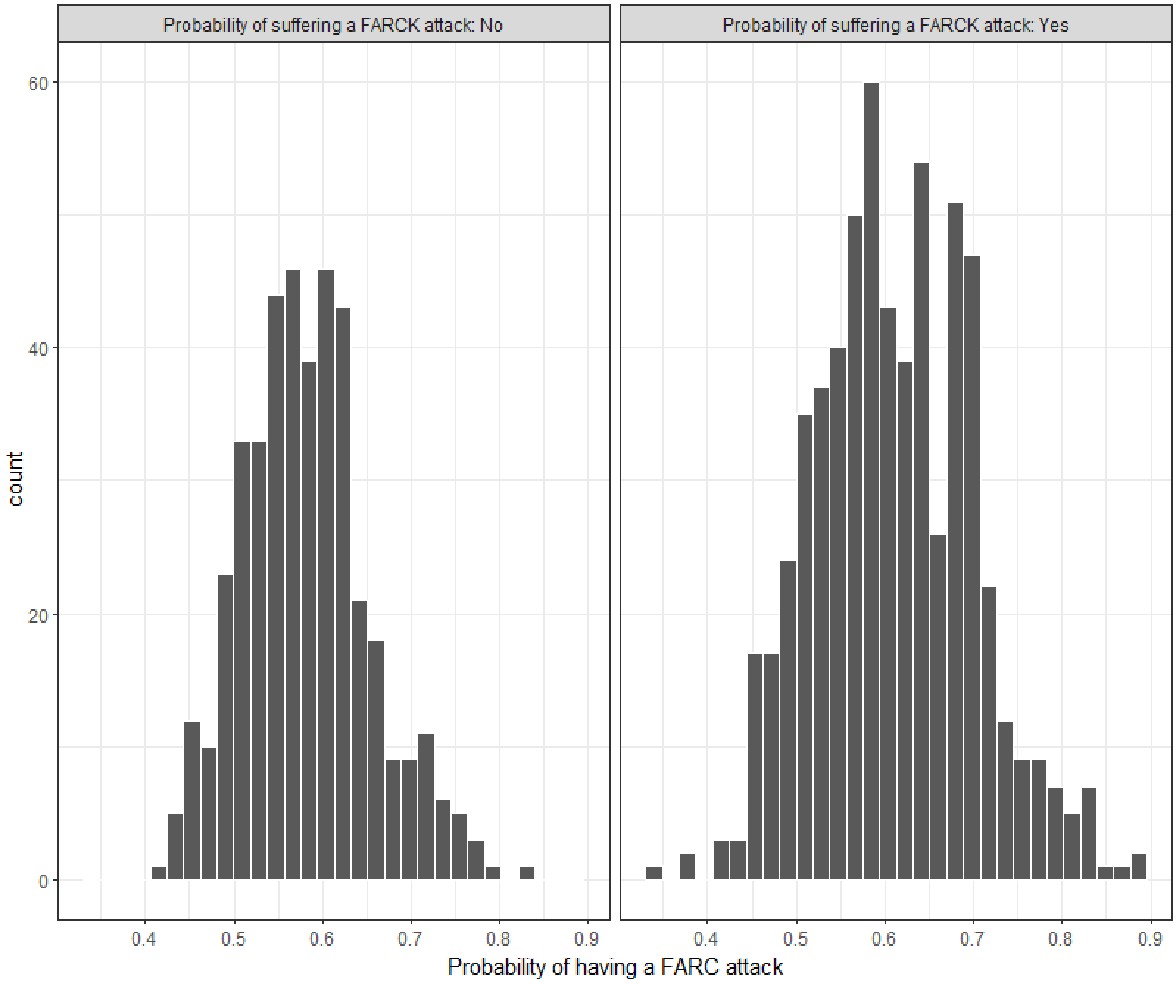
B2 – Immediate effects: Propensity Score Matching

Table B2: Covariate balance before matching for the whole sample

	Dependent variable:
	Discrete variable based on the number of FARC attacks
Poverty	-1.6^{***}
	(0.2)
Elevation above sea	-0.000^{***}
	(0.00)
Distance to main market	0.01^{***}
	(0.001)
Distance to state's capital	-0.003^{***}
	(0.001)
Constant	1.5^{***}
	(0.1)
Observations	7301
Log Likelihood	-4807.5
Akaike Inf. Crit.	9625

*Note:*p<0.1; **p<0.05; ***p<0.01*

Figure B1: Comparison of probability of suffering a FARC attack between treatment and control groups

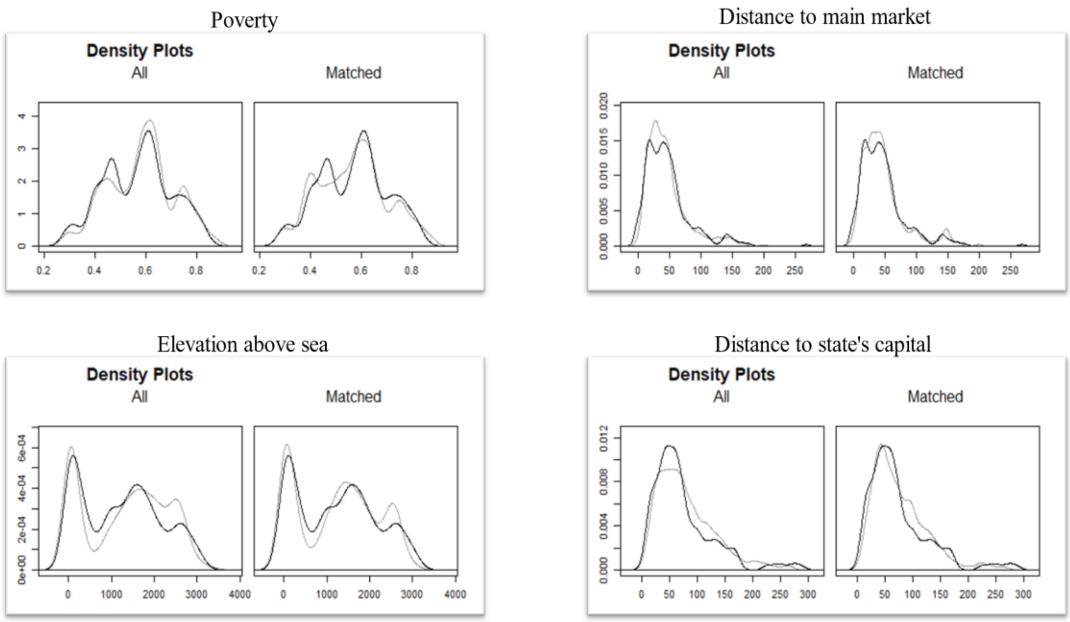


B2.1 – Matching for low-intensity conflict dataset

Table B2.1: Low-intensity matching

	Means Treated	Means Control	Std. Mean Diff.	Var. Ratio	eCDF Mean	eCDF Max	Std. Pair Dist.
Distance	0.4449	0.4448	0.0021	1.0105	0.0027	0.0153	0.0112
Poverty	0.5689	0.5656	0.0248	0.9616	0.0186	0.0595	0.9409
Elevation above sea	1233.3252	1234.3255	-0.0011	0.9971	0.0247	0.0746	1.0001
Distance to main market	46.3908	46.9947	-0.0169	1.0607	0.0172	0.0556	0.9707
Distance to state's capital	74.5914	76.817	-0.0406	1.2962	0.0371	0.0874	0.8738

Figure B2.1 – Density plots for low-intensity matching



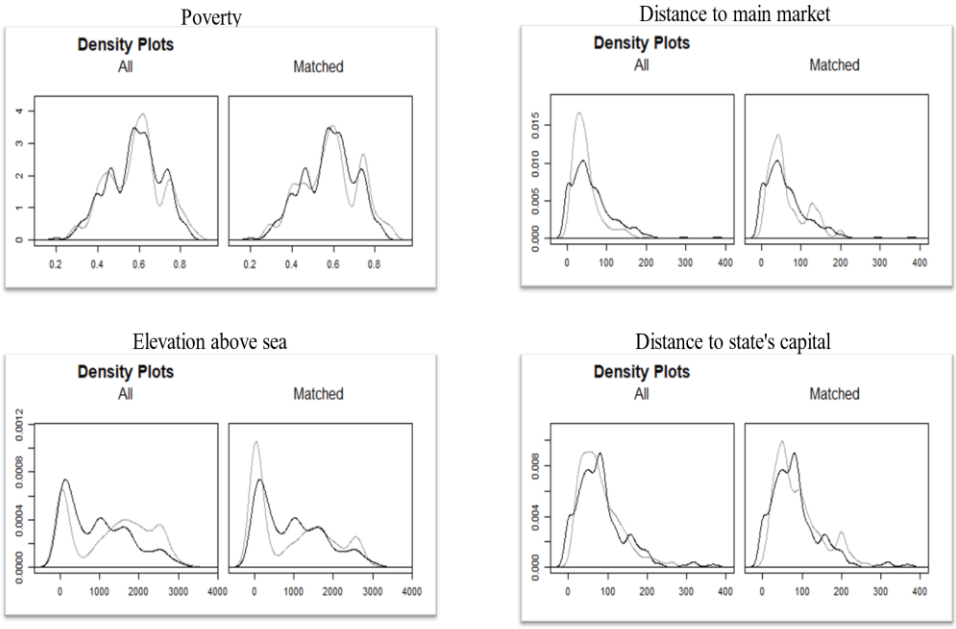
B2.2 – Matching for high-intensity conflict dataset

Figure B2.2 – Density plots for high-intensity matching

Table B2: High-intensity matching

	Means Treated	**Means Control**	**Std. Mean Diff.**	**Var. Ratio**	**eCDF Mean**	**eCDF Max**	**Std. Pair Dist.**
Distance	0.4568	0.4555	0.0084	1.0551	0.0028	0.0201	0.0171
Poverty	0.5786	0.5872	-0.0693	0.8266	0.0273	0.0975	1.1025
Elevation above sea	959.7953	944.363	0.0189	0.7528	0.0748	0.2171	0.6904
Distance to main market	61.0092	63.6868	-0.0506	1.2831	0.0417	0.1345	0.5971
Distance to state's capital	82.1714	89.0504	-0.1098	1.1617	0.039	0.0933	0.9575

Figure B2.2 – Density plots for high-intensity matching



C. Robustness analysis

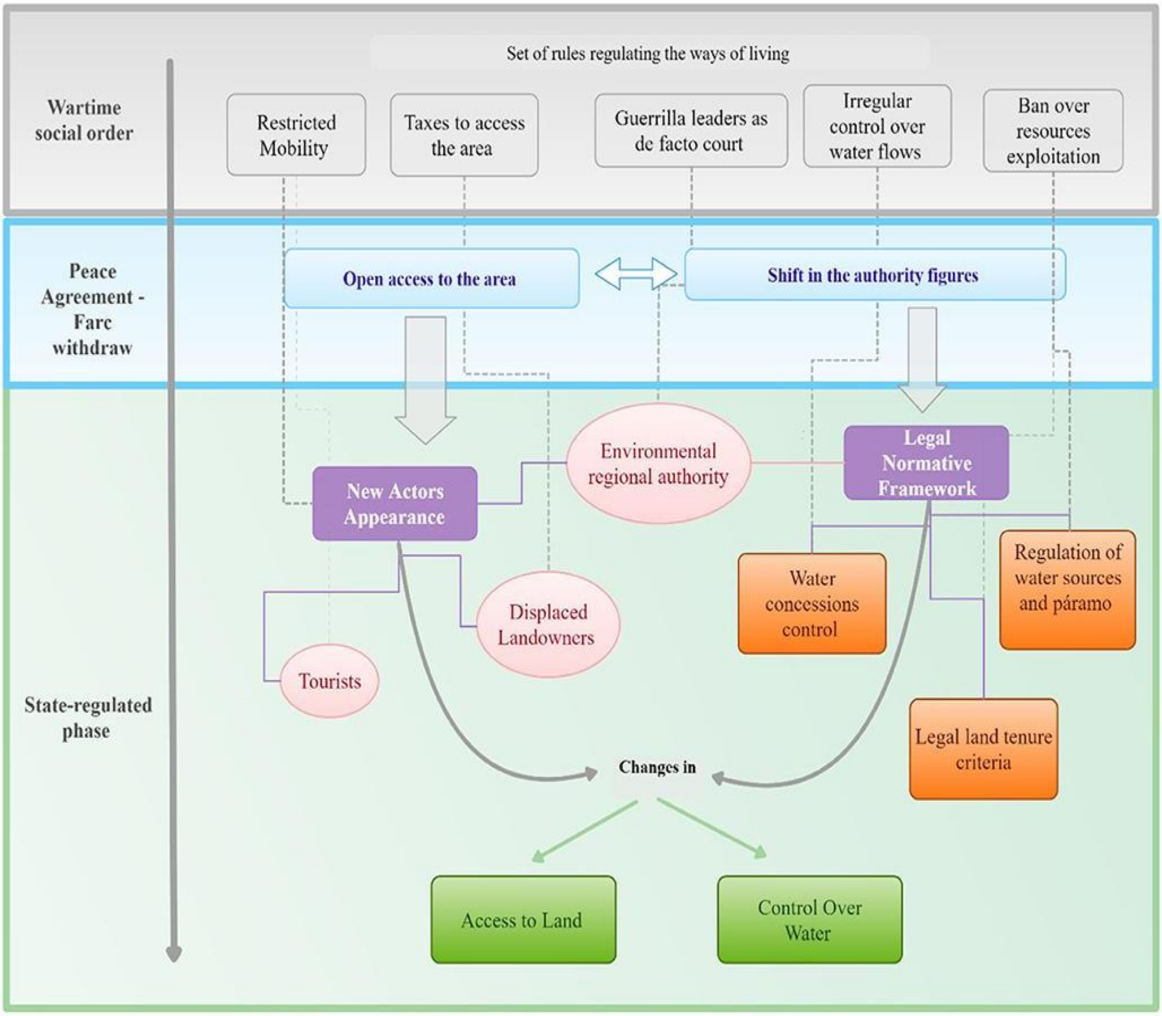
Table C1 – Results for synthetic differences-in-differences

	Dependent variable:
	Discrete variable based on the number of FARC attacks
DiD	1.322
	(0.1927)
Observations	4560
Note:	*p<0.1; **p<0.05; ***p<0.01

Note: This table shows the estimates of the results from the synthetic differences in differences. Cluster standard errors are at municipality level. Municipality and year fixed effects are used. Robust standard errors in parentheses. Significance levels: *** p<0.01, ** p<0.05, * p<0.1.

D. Complementary information

Figure D1 – Socio-environmental implications of the transition between the Farc-led control to a State regulated phase



Source: Betancur-Alarcón & Krause, (2020)

Table D1 – Relevant examples of positive and negative socio-political and ecological effects after the peace agreement of the Colombian government with FARC-EP

Positive effects of the peace agreement in the last 5 years	Negative effects of the peace agreement in the last 5 years
Socio-political	**Socio-political**
The Special Jurisdiction of Peace started to investigate and prosecute the human rights violations and crimes committed during the armed conflicts, counteracting previous impunity.	Power vacuum in remote regions increased permeability of illegal actors and land grabbing/transformation. The government could not counteract these dynamics effectively, being *de facto* absent in several regions.
Recent social mobilization (for instance during the Paro Nacional), and the results of this year's presidential elections, shows that societal awareness and organization to demand the state's action to implement the Peace Agreements is growing in the country. It has also become evident that more people in the country recognize the importance of securing land access and tenure of smallholders, peasant, indigenous and afro-Colombian groups for material and societal reproduction of their culture and well-being.	Historically, cattle ranching as a means for landowners, agribusiness, narco-traffickers and regional elites to secure land tenure and showcase wealth. Yet, the power vacuum created after FARC demobilization presented a window of opportunities for many powerful economic actors to expand and find new sources of capital by integrating forest lands to global market dynamics, speculate with *de facto* land tenure in remote frontier areas.
International support and financing to tackle deforestation and support the peace process continues (for instance Vision Amazonia financed by Governments of Norway, United Kingdom, Germany) and the recent announcement of Sweden to strengthen their support for Colombia.	Illegal and legal road expansion allows for an increase in extractive activities (cattle, mining, coca plantations), driving deforestation in protected areas and indigenous territories, causing forced displacement and environmental degradation.
Socio-economic	**Socio-economic**
Sense of increased safety in areas that were not accessible or considered safe for locals or visitors during the armed conflict. Examples of these areas include the Sumapaz páramo and its nearby surroundings1.	Increased foreign investments into extractive industries and mining operations, causing environmental conflicts and injustices.
Before the SARS-CoV-2 pandemic, ecotourism was growing offering a potential alternative source of income and development with benefits for biodiversity conservation.	International trade in deforestation risk commodities (illicit crops, minerals, leather, meat, etc.).
(Note, however, that a number of communities oppose ecotourism, such as those of the Sumapaz rural district of Bogotá – which is embedded within the Sumapaz páramo – because of its potential negative impacts on sensitive ecosystems and the local culture.)	Increasing threats and violence towards environmental defenders, social leaders, including farmers, indigenous communities, human rights activists, park rangers, researchers, teachers.
Increased foreign investments to support Colombian industry and service sector fostering job and income opportunities.	
Opportunities to re-design or even create transformative land-use policies that highlight and include the role of local traditional knowledge for a transformative and sustainable management of forests. As well as the legitimization of existing instruments that limit the accumulation of land, such as peasant reserve zones.	
Ecological	**Ecological**
Increase of societal awareness about the importance of Colombia's natural richness and biodiversity for human well-being.	Deforestation and forest degradation has increased dramatically, especially along Colombia's agricultural frontier in the Amazon affecting ecological connectivity
Rise in scientific research and species inventories in formerly inaccessible and understudied areas – mapping of the natural wealth of Colombia.	Increased conversion of natural ecosystem across the country, especially severe in protected areas and legally recognized indigenous territories (Clerici et al., 2020).
Emerging innovative bioeconomy projects across the country that are locally anchored to conserve and restore biodiversity and ecosystem functions.	Loss of biodiversity before it could even be scientifically described.

Source: Krause et al., (2022)