WORKING PAPER Nº IDB-WP-01636

Direct Water Requirement Patterns in Brazil, Colombia and Costa Rica: A Structural Decomposition Analysis

Giovanna Ferrazzo Naspolini
Jesse Libra
Santiago Cunial
María Pérez-Urdiales

Inter-American Development Bank
Water and Sanitation Division

September 2024

Direct Water Requirement Patterns in Brazil, Colombia and Costa Rica: A Structural Decomposition Analysis

Giovanna Ferrazzo Naspolini
Jesse Libra
Santiago Cunial
María Pérez-Urdiales

Inter-American Development Bank
Water and Sanitation Division

September 2024

Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library
Direct water requirement patterns in Brazil, Colombia and Costa Rica: a structural decomposition analysis / Giovanna Ferrazzo Naspolini, Jesse Libra, Santiago Cunial, María Pérez-Urdiales.
p. cm. — (IDB Working Paper Series ; 1636)
1. Climatic changes-Social aspects-Brazil. 2. Climatic changes-Social aspects-Colombia. 3. Climatic changes-Social aspects-Costa Rica. 4. Water-supply-Brazil. 5. Water-supply-Colombia. 6. Water-supply-Costa Rica. 7. Sustainable development-Brazil. 8. Sustainable development-Colombia. 9. Sustainable development-Costa Rica. I. Naspolini, Giovanna. II. Libra, Jesse. III. Cunial, Santiago. IV. Pérez Urdiales, María. V. Inter-American Development Bank. Water and Sanitation Division. VI. Series.
IDB-WP-1636

Keywords: input-output tables; sustainable development; water footprint
JEL codes: Q25; Q56; R15

http://www.iadb.org

Direct Water Requirement Patterns in Brazil, Colombia and Costa Rica: A Structural Decomposition Analysis

Giovanna Ferrazzo Naspolini[1,*], Jesse Libra[1], Santiago Cunial[1], and María Pérez-Urdiales[1]

[1] *Inter-American Development Bank, Water and Sanitation Division.*

[*] *Corresponding author.*

April 9, 2024

Abstract

Water is not only vital for human life but also is a critical economic input. Climate change will likely exacerbate conflicts over the multiple uses of water in Latin America. Adopting a south-south perspective approach, this study compares direct water requirement patterns over time among Brazil, Colombia, and Costa Rica, applying an environmental-extended Structural Decomposition Analysis between 2013 and 2017. While all countries experienced increased water consumption during the period, Brazil's and Colombia's results suggest gains in water productivity at the national level and for Agriculture. Results also indicate that Exports are the main water consumption driver of Agriculture in Brazil and Costa Rica. The Water and sanitation sector in Colombia experienced a decrease in direct water requirements, which is illustrated by a strong negative intensity effect. In contrast, an expressive positive intensity effect in Costa Rica resulted from a sectoral GDP fall. The findings of this study offer support to sectoral climate adaptation plans in all countries as well as water conservation and sustainable development policies.

1 Introduction

Latin America and the Caribbean (LAC) is home to approximately one-third of the world's freshwater supply. However, water resources in the region are not geographically aligned with demand, making much of it vulnerable to water scarcity [Libra, Collaer, Datshkovsky, and Pérez-Urdiales, 2022]. This vulnerability is expected to worsen as the average global temperature rises, with the IPCC predicting increases in the frequency and duration of droughts, changes in rainfall patterns, and more intense storms [Castellanos, Lemos, Astigarraga, Chacón, Huggel, Cuvi, Miranda, Vale, and Ometto, 2022].

Climate change is both an environmental emergency and a looming economic crisis. Economic systems depend on predictable weather patterns, and disruption to those patterns promises to affect economic growth, hamper poverty eradication, increase economic inequality, and threaten fiscal stability within Latin America and the Caribbean [Cavallo, Hoffmann, and Noy, 2023]. Repercussions like higher risk of food insecurity, amplified costs of natural disasters (both economic and human), and increased public health risks will directly affect the agricultural and water and sanitation sectors [Castellanos et al., 2022]. In this context, it is fundamental to understand better the interplay between climate change, economic dynamics and water resources to guide policy-makers aiming at designing sustainable resource management strategies.

Environmental-extended Structural Decomposition Analysis (SDA) is an essential tool for understanding the use of water resources over time throughout a national economy and their impact on supply and demand [Cazcarro, Duarte, and Sánchez-Chóliz, 2013, Wang, Huang, and Yajuan Yu, 2016, Fan, Jian-DaWang, Zhang, Kong, and Song, 2019, Naspolini, Ciasca, Rovere, and Jr, 2020]. In this study, we apply the SDA to decompose the water consumption change in Brazil, Colombia, and Costa Rica between 2013 and 2017 into sectoral water intensity, economic interdependence, and economic activity drivers. By comparing results across countries, we aim to provide insights from either a supply or demand perspective. We illustrate water productivity and resource allocation from the supply side, as economic activities have varying water demands that directly impact their productivity. From the demand side, we identify the value-added of the water abstracted by each economic sector by analyzing the sectoral Gross Domestic Product (GDP), shedding light on patterns and priorities of water usage by final users, and allowing the identification of embodied water on products represented in the final demand. Exploring the drivers of sectoral water consumption paves the way for more efficient and prudent water management practices that support economic development and national strategies for adaptation to climate change.

Despite SDA's methodological utility and policy relevance, research employing this method to understand shifts in water consumption patterns remains limited, particularly in Latin America. The literature presents a growing number of studies that rely on multi-region input-output tables at different geographical focuses, such as city [Feng, Chen, Hayat, Alsaedi, and Ahmad, 2017], province [Li, Deng, Wu, Ding, and

Chen, 2023], regions within a country [Xiong, Tian, Liu, and Tang, 2020, Zhao, Liu, Yang, Sun, and Varis, 2021, Long, Xie, Gao, Sun, and Su, 2022], and multi-nations at global level [Cazcarro, Schyns, Iñaki, and Sanz, 2022]. Input-output tables are also utilized in scenario analyses to assess water resources. Typically, these studies investigate the interdependence of global markets and the impacts of climate change on water resources by combining global Computable General Equilibrium (CGE) models with sectoral water models. This framework facilitates the exploration of potential future scenarios and their anticipated outcomes. For example, Calzadilla, Rehdanz, Betts, Falloon, Wiltshire, and Tol [2013a] examined the systemic effects of climate change on global agriculture, distinguishing between rain-fed and irrigated agriculture. Their findings indicate projected welfare losses and decreased food production by 2050. Similarly, Nechifor and Winning [2017] estimated the irrigation water requirements across various global socio-economic development scenarios by 2050. Their results suggest an 8.5–11% increase in global freshwater withdrawals, with Southeast and South Asia experiencing higher virtual water exports due to increased demand, particularly in India. Additionally, Calzadilla, Zhu, Rehdanz, Tol, and Ringler [2013b] explored alternative adaptation strategies for agriculture. Their analysis revealed that increasing irrigated areas and agricultural productivity in Sub-Saharan Africa as part of simulated adaptation plans could potentially reduce world food prices by 2050. More recently, Basheer, Nechifor, Calzadilla, Gebrechorkos, Pritchard, Forsythe, Gonzalez, Sheffield, Fowler, and Harou [2023] proposed a cooperative adaptive management policy for the Grand Ethiopian Renaissance Dam that balances the transboundary hydrological and socio-economic interests of Ethiopia, Sudan, and Egypt, compared to current transboundary policies and country-centric scenarios. National CGE models were developed for these countries as part of a four-stage planning framework approach for the Nilo River Basin. The framework associates climate change projections and their hydrological implications with the economy-wide impacts of adaptative plans for managing river system infrastructure.

At the national level, SDA literature related to water resources is more limited and usually focuses on developed countries such as Spain [Cazcarro et al., 2013] and China [Wang et al., 2016, Fan et al., 2019]. In LAC, only Naspolini et al. [2020] employed SDA to assess the change in Brazil's water consumption change from 2013 to 2015. This study is particularly relevant as it addresses water consumption changes during an economic deceleration and uncovering a 15% overall increase in water consumption by the Brazilian economy, specifically during the drought from 2013 to 2015. The role played by agricultural exports, not affected by the economic slowdown, emphasizes the pressure of water resources during a scarcity context and that neglecting environmental resources in macroeconomic assessments can lead to inaccurate and overly optimistic outcomes.

Even with the growing number of studies applying SDA to water consumption investigation at the national, there is currently a lack of research that facilitates a cross-country comparison to understand the performance of economic systems and their interlinked water demands. Adopting a South-South perspective, this study addresses this gap by examining water consumption patterns in Brazil, Colombia, and Costa Rica between 2013 and 2017. The aim is not only to contribute insights for adaptation and sustainable development policies in these countries but also to offer valuable comparisons among nations with similar socioeconomic conditions. Recognizing shared challenges emphasizes the potential for mutual learning and experience exchange across Latin America. Therefore, the country selection is of particular interest for three main reasons. First, these countries share a common reliance on water for their economies. Second, they struggle to provide universal water and sanitation services, and even though they are located in different Latin American regions, they all count on the geographic misalignment of water resources with water demand. Third, despite the commonalities, the countries present distinct demography, economic growth, and water consumption patterns, but they all grapple with sustainable development and increasing adaptation challenges, mainly due to vulnerability to climate change and more intense El Niño's impact on water resources [Wang, Luo, Yang, Sun, Cane, Cai, Yeh, and Liu, 2019, Castellanos et al., 2022].

Moreover, by focusing on these three countries, this study aims to fill the gap in cross-country comparisons of water consumption patterns and provide valuable insights for achieving Sustainable Development Goal 6 (SDG 6) on clean water and sanitation. Specifically, the findings will contribute to understanding progress toward target 6.4 (increasing water-use efficiency and ensuring sustainable withdrawals and freshwater supply). By identifying similarities and differences in water consumption behaviors, resource management strategies, and challenges faced by Brazil, Colombia, and Costa Rica, this research can inform targeted policies and interventions to enhance water security and promote sustainable development in alignment with the SDGs. Furthermore, the South-South perspective adopted in this study underscores the importance of regional cooperation and knowledge exchange in addressing common challenges and advancing shared goals for water management and resilience building across Latin America.

The SDA findings offer significant support to the sectoral climate adaptation plans of Brazil, Colombia, and Costa Rica. By integrating these insights into policymaking, decision-makers can formulate public policies and strategic investments that address inefficiencies while enhancing the resilience of vulnerable sectors. These climate adaptation plans typically articulate policy actions required at the sectoral level. A comprehensive understanding of water usage in water-intensive sectors, such as agriculture and water and sanitation, becomes crucial in developing these plans. This understanding illuminates the drivers of water requirements within these sectors, thereby guiding effective policy solutions.

To the best of our knowledge, this is the first attempt to compare direct water requirement patterns over time among countries, additionally giving special attention to the contribution of the most water-intensive and vulnerable economic activities: agriculture and water and sanitation. The rest of the paper is structured as follows: Section 2 presents a brief context of each country, focusing on economic and water scarcity aspects; Section 3 is dedicated to methodological aspects of the SDA applied and the database; Section 4 describes the results; Section 5 presents our discussion, and Section 6 reviews the main conclusions of the study and introduces recommendations for future research.

2 Countries context

Brazil, Colombia, and Costa Rica exhibit variances in geographical locations and economic scale. Brazil stands as the largest nation and the economy in LAC, with a Gross Domestic Product (GDP) of approximately USD 1.9 trillion[1]. Colombia, situated in South America within the Andineam region, account for a GDP of USD 300 million, ranking it as the 4^{th} largest economy in LAC. Althought Costa Rica's economy and geographic dimension are not among the largest in the region (USD 69 million), the Central American nation holds the highest GDP per capita among the countries analyzed [WorldBank, 2023]. Economic performance was also not homogeneous among the countries between 2013 and 2017. While Colombia and Costa Rica presented an economic expansion of their economies, Brazil faced an expressive economic recession during the period [IMF, 2023, OECD, 2021]. This is an interesting case for analyzing how distinct macroeconomic scenarios impact economic systems' water demand.

Despite differences in geography, population, and economy in Brazil, Colombia, and Costa Rica, their economic systems share similarities. Services are the main economic activity, accounting for an average of 55% of GDP in these countries. This sector also grew in importance in all three nations between 2013 and 2017. Manufacturing is the second most significant sector, with Brazil and Costa Rica having a higher share of GDP (37% on average) compared to Colombia (31%). Agriculture also plays a similar role in each country, contributing around 5% to GDP.

Colombia relies more on mining for its GDP (6% on average) than Brazil (2%), while mining is insignificant in Costa Rica's GDP. Although these countries are relatively closed economies, with exports not a major component of GDP, mining and agriculture still play a crucial role in their trade. For instance, between 2013 and 2017, mining and agriculture accounted for 30% of Brazil's exports. Colombia has diversified its economy during this period, reducing the share of mining in exports from 52% in 2013 to 37% in 2017, with manufacturing and services expanding. Costa Rica has the most open economy, with exports contributing 25% to GDP, primarily driven by services (73%), followed by manufacturing (44%) and agriculture (12%).

Mining and agriculture are primary water-intensive economic activities, making these economies vulnerable to climate change and El Niño's impact on water resources. More recently, Brazil, Colombia, and Costa Rica have legislated and implemented governance instruments for climate change adaptation, indicating a proactive response to evolving environmental and economic landscapes. The adaptation framework is usually transversal to water management policies. Table 1 illustrates the countries' state-of-the-art governance instruments for climate change adaptation and water management policies.

[1] All values expressed in constant 2015 USD.

Table 1: Water management & climate change adaptation framework for Brazil, Colombia, & Costa Rica

	Water Governance	Adaptation Governance
Brazil	Plano Nacional de Recursos Hídricos Ciclo I (2012-2015) Ciclo II (2016-2021) Ciclo III (2022-2040)	Plano Nacional Adaptação à Mudança do Clima (2016-2020)
Colombia	Plan Hídrico Nacional Fase I (2012-2014) Fase II (2015-2018)	Plan Nacional de Adaptación al Cambio Climático: Lineas de Acción Prioritarias (2018)
Costa Rica	Plan Nacional de Gestion Integrada de los Recursos Hidricos (2008)	Plan Nacional de Adaptación al Cambio Climático 2022–2026 (2022)

Source: Authors' elaboration.

All three countries have comprehensive national plans encompassing water management in the context of adaptation to climate change. The approach for the integration of climate change adaptation is multifaceted in all of them, varying from enhancements to sectoral efficiency, such as improving irrigation efficiency, reducing non-revenue water, and implementing sector-specific initiatives, land use planning and educational policies to increase the awareness to climate changes impacts and adaptation and mitigation measures. Additionally, each country had established sustainable water management governance, contributing to a complex governance framework for water resources. Considering the economic systems overview and the countries' commitment tto water governance and climate change adaptation, the following sections summarize the main features related to water scarcity context in Brazil, Colombia, and Costa Rica.

2.1 Brazil

Brazil has about one-fifth of the world's freshwater resources, accounting approximately 26,000 m^3 of renewable internal freshwater resources per person. However, the nation faces profound challenges in water resource management, given that 70% of water resources lie in the Amazon region in the northwest, while dense population clusters are concentrated in major cities in the southeast and northeast of the country [WorldBank, 2021a]. Differences in geographic distribution between water resources and population pose relevant water management challenges in providing safe water and sanitation access for human populations and satisfying water demand for economic activities.

Since 2012, Brazil has faced escalating water crises. These crises have affected the historical water scarcity in the northeast and central parts of the country and extended into the previously water-secure southeast and midwest. These crises stem from human causes (changing precipitation patterns, increasing demand, changing land use) and natural factors (El Niño).

Deforestation plays a relevant role in land use changes across the country; Amazon and Cerrado forests have been cleared to open space for agricultural activities, especially livestock watering and construction of irrigation infrastructure. This deforestation has altered rainfall patterns and negatively affected water availability [Salmona, Matricardi, Skole, Silva, Coelho Filho, Pedlowski, Sampaio, Castrillón, Brandão, Silva, et al., 2023].

Changing precipitation patterns and prolonged dry periods have profoundly impacted rivers and the replenishment of aquifers. El Niño events have also led to more severe droughts in the northeast and floods in southern Brazil. Future projections indicate a growing water deficit, particularly in Brazil's central and northern regions. On a national scale, Brazil is expected to face increasingly arid conditions and more severe droughts as we approach mid-century and beyond, placing more strain on the country's water resources [WorldBank, 2021a].

2.2 Colombia

Colombia is among the most water-rich nations globally, with approximately 50,000 m^3 of renewable water resources per person annually [WorldBank, 2021b]. Despite its abundant water reserves, the country faces profound challenges in water resource management, many of which mirror those of Brazil. Differences in geographic distribution between water resources and population affect the provision of safe water and sanitation services for human populations and pose challenges to satisfying sectoral water demand. Dense population clusters on the Caribbean coast and the highlands are especially vulnerable. Anthropogenic impacts such as deforestation, poor environmental water quality, and the region's erratic rainfall patterns compound water resource management challenges.

The El Niño Southern Oscillation strongly influences erratic rainfall patterns, which substantially reduces river flows, especially in key river basins. During El Niño events, the Magdalena-Cauca river basin experiences a 26% flow reduction. In contrast, the middle Cauca river basin steep 38%, and regions like Sumapaz and Antioquia Department see reductions in river flow between 30-40%. Conversely, La Niña events can amplify the Cauca River's flows, exceeding up to 60% of their typical levels. The implications of such flow variations are manifold, particularly considering that over 60% of Colombia's energy infrastructure relies predominantly on hydro-power [WorldBank, 2021b].

2.3 Costa Rica

Costa Rica is also water-rich, with over 22,000 m^3 per person per year in available freshwater resources. Despite this abundance, Costa Rica also suffers from a spatial distribution of water availability that does not align with high-use basins [Stan, Sanchez-Azofeifa, and Ludwig, 2022]. This leads to water scarcity in certain areas, particularly the Northern Pacific region of the country. This scarcity is further aggravated by overuse, inefficiency in water usage, and the effects of El Niño.

Water is a crucial input to many of the largest sectors in Costa Rica. 79% of Costa Rica's energy portfolio comes from hydrogeneration, while the agricultural sector accounts for 12% of the nation's jobs [WorldBank, 2021c]. The agro-food sector receives more than 90% of water concessions by volume, with 85% allocated to agriculture and 6% to agroindustry. Both the energy and agricultural sectors have significant forward linkages throughout the economy, making it essential to understand the vulnerability of these sectors to water scarcity.

Changes in precipitation patterns are bound to influence the availability of water resources throughout Costa Rica. Research assessing the susceptibility to climate variations in the three crucial river basins of Costa Rica—Reventazón, Térraba, and Grande de Tárcoles—indicates significant declines in runoff rates and modifications to the hydrological cycle. Such changes in the water cycle have the potential to alter water runoff, erosion, and sedimentation, leading to severe flood-related complications. These effects are anticipated using water resources like hydroelectric power generation, irrigation networks, aqueducts, and sewage systems. Costa Rica is also projected to undergo enhanced drying trends in the latter half of the century [WorldBank, 2021c].

3 Methodology

3.1 Environmental-extended input-output model

The input-output model (IOM) describes the economic system throughout the interdependence of sectoral production to meet final demand. The model has an infinity range for empirical economic system analysis, including those from environmental concerns [Leontief, 1970].

The IOM relies on a linear equation system to describe the economy's interdependence. The elementary model equation is given by Equation (1):

$$X = (I - A)^{-1} * F = L * F \tag{1}$$

where X is the total output, $(I - A)^{-1}$ is a Leontief Inverse matrix, with I identity matrix and A the technical coefficient matrix, and F is a matrix of final demand components. a_{ij} is the elements in matrix A and represents the amount of direct inputs i used for the output in sector j.

Miller and Blair [2009] illustrate the environmental extension of the traditional IOM by considering a vector that relates the external environmental variable to sectoral output. Let w be a vector that represents the direct water requirements (DWR) of each economic sector in hm^3, and $\check{A}$ a technical water coefficient matrix, whose elements relate the direct water requirements w_j and the total output x_j in sector j. Multiplying both sides of equation 1 by $\check{A}$ builds the environmental-extended IOM.

$$w = \breve{A} * L * F \tag{2}$$

Equation (2) estimates the economic system's direct and indirect embodied water (or virtual water) flows to meet the final demand. Each element $\breve{a}_j * L_{ij} * F_j$ captures direct and indirect embodied water of inputs i required by sector j to produce its final demand. After estimating the total water incorporated in the economic system in two different periods (2013 and 2017), a Structural Decomposition Analysis is employed to decompose the DWR alterations (i.e., the modifications on vector w), allowing for the identification of drivers of change in sectoral water consumption.

3.2 Structural Decomposition Analysis

The Structural Decomposition Analysis (SDA) is a widely used tool for evaluating the underlying drivers or determinants that contribute to changes in the economic system over time. By breaking down a time trend of a variable into distinct driving forces acting as accelerators or retardants, SDA effectively decomposes historical changes into economic, environmental, employment, or other socioeconomic indicators [Dietzenbacher and Los, 1998, Wachsmann, Wood, Lenzen, and Schaeffer, 2009, Naspolini et al., 2020, Hoekstra and van den Bergh, 2003].

Considering 0 as the initial period (2013) and 1 as the final period (2017), it is possible to assume that the changes in direct water requirements of an economy (w) are defined as $\Delta w = w^1 - w^0$. Thus, the changes in direct water requirements are expressed as:

$$\Delta w = \breve{A}^1 * L^1 * F^1 - \breve{A}^0 * L^0 * F^0 \tag{3}$$

To perform an SDA to identify the contribution of each driver to the total DWR change, Equation (3) must be rearranged in a way that isolates the change of its terms, i.e., $\Delta\breve{A}$ (change in technical water coefficients), ΔL (change in sectoral interdependence), and ΔF (change in final demand). Such rearrangement enables measuring each variable's contribution to the changes in w_j over time. These three variables' variations are translated into drivers that illustrate how each change impacted the overall change in the total direct water requirements.

More than one alternative rearrangement can be derived from Equation (3) to express it in terms of $\Delta\breve{A}$, ΔL, and ΔF. For example, the first period can be used to weight the changes in the variables by substituting $\breve{A}^0 = \breve{A}^1 - \Delta\breve{A}$, $L^0 = L^1 - \Delta L$, and $F^0 = F^1 - \Delta F$ in Equation (3). Some algebraic rearrangements lead to Equation (4):

$$\Delta w = \Delta\breve{A} * L^1 * F^1 + \breve{A}^0 * \Delta L * \breve{A}^1 + \breve{A}^0 * L^0 * \Delta F \tag{4}$$

Analogously, the second period also can be used to weigh the changes in the variables in Equation (3).

Thus, rearranging the terms according to $\check{A}^1 = \check{A}^0 + \Delta\check{A}$, and successively for the other variables, leads to Equation (5):

$$\Delta w = \Delta\check{A} * L^0 * F^0 + \check{A}^1 * \Delta L * \check{A}^0 + \check{A}^1 * L^1 * \Delta F \tag{5}$$

Miller and Blair [2009] explain that a multiplicative decomposition of 3 n variables can be performed in $n!$ different ways. However, Dietzenbacher and Los [1998] demonstrated the average of the two above-mentioned polar decompositions provides a good approximation of the average of the $n!$ exact decomposition forms. Assuming this approach, Equation (6) defines the SDA by illustrating the drivers of change in w associated with each effect. The drivers play a role in quantifying how a specific variable influenced the observed change in w. A positive sign indicates that the variable contributed to the increase, while a negative sign indicates it hindered the change.

$$\begin{aligned} \Delta w =& \\ &+ 1/2 * [\Delta\check{A} * (L^0 * F^0 + L^1 * F^1)] \\ &+ 1/2 * (\check{A}^1 * \Delta L * F^0 + \check{A}^0 * \Delta L * F^1) \\ &+ 1/2 * (\check{A}^0 * L^0 + \check{A}^1 * L^1) * \Delta F \end{aligned} \tag{6}$$

The first driver is the Water Intensity Effect. It isolates the change in water technical coefficients ($\check{a}_j$) and how they contribute to the overall change in direct water requirements. This analysis plays a key role in the economy's dependence on water consumption by economic activities. For example, a negative effect indicates that the sector increased its water productivity, which induced less direct water requirements by an output unit. Conversely, a positive effect could mean a decrease in water productivity, which would point in two directions: either the sector lost water efficiency, or there was a productive change within the sector's production structure, increasing direct water requirements for a unit of output (for example, the water and sanitation sector expands its sewage treatment facilities, demanding more self-supplied DWR in its production structure).

The second driver is the Structural Effect, which measures the economic system's dependence on water resources. More specifically, it quantifies changes in the economic system's structure over time (i.e., in l_{ij}) by assessing how alterations in the productive structure on the supply side influence direct water requirements during the period. At the national level, a positive structural effect indicates that the economic system became more dependent on water resources, whereas a negative effect suggests the opposite. The structural effect of the agriculture and water and sanitation sectors illustrates whether the sectors' supply chains become more dependent on water resources.

The structural effect measures the change in the economic system's dependency on water resources.

As the study spans a relatively short time series (2013-2017), the structural effect most likely captures situational rather than structural changes in the economy. Structural changes in economic systems usually rely on long-term strategies, except in the face of a disruptive event, such as supply or demand shocks, when the occasion forces the economic structure to quickly adapt to the occurrence[2]. Changes in the economic system captured by the structural effects are mainly related to how shifts in the economy's sectoral composition contribute to changes in direct water requirements from the supply-side perspective. Being the most water-intensive sector, agriculture plays a key role in the economy's dependence on water. For example, a negative structural effect indicates the economy shifted towards less water-intensive economic sectors, ultimately meaning that agriculture lost participation in GDP composition during the period. The same reasoning applies when analyzing changes in the economic system through the lens of improvement in productive techniques. Requiring fewer water-intensive (agricultural) inputs for the same output thereby enhances the water efficiency of the production structure. However, changes in production techniques, including intermediate consumption, may result in reduced demand for domestic inputs due to an increase in imported inputs, marking a shift in the pattern of intermediate consumption trade. It's crucial to note that this shift doesn't necessarily signify increased water efficiency; instead, it involves substituting domestic inputs with imported ones. However, OECD data shows that the exchange rates in these countries depreciated during the period, suggesting that this effect might be positive rather than negative (substitution of imported goods by domestic ones). Given the study's focus on structural economic changes and its dependency on water resources (in addition to data limitation), analyzing the role of imported goods on the impact on water resources is beyond the scope of this study. Still, it opens an avenue for future studies in this area.

The third driver is the Final Demand Effect. It centers on isolating the impact of economic activity expansion or recession) on direct water requirements trends. The analysis quantifies how changes in economic activity level influence sectoral direct water requirements from the demand-side perspective. Additionally, this component allows us to evaluate separately how each final demand component, such as households or exports, has changed the total direct water requirements.

By decomposing DWR into Water Input Effect, Structural Effect, and Final Demand Effect, a comprehensive understanding of the underlying economic drivers that have shaped the evolution of water consumption in Brazil, Colombia, and Costa Rica can be achieved. Such insights are crucial for formulating effective water management strategies and planning sustainable resource allocation.

[2] Wars, pandemics, or environmental disasters illustrate examples of disruptive events. In the next sections, the results of this study show the structural effect has minor participation in the overall direct water requirements change, except for Costa Rica, which suffered an intense water crisis during the period.

3.3 Data

The environmental-extended IOM requires combining Input-output tables (IOT) and sectoral physical water data. The need to harmonize these data inputs to enable cross-country comparison restricts the temporal and sectoral breadth of analysis to 2013-2017 and three sectors: Agriculture, Water and sanitation, and other activities, represented as the Rest of the economy. This section briefly describes the input datasets, their processing, and how their characteristics shape the final analysis.

Economic information required for building the environmental-extended IOM is sourced from the Organization for Economic Co-operation and Development's (OECD) extensive IOT datasets, including data from 66 countries up to 2018 [OECD, 2021]. The national data is broken down into 45 economic sectors, comprehending imports and domestic production. Domestic IOT are used in this study since only national production consumes water resources. The final demand components from the OECD data are merged into three categories: Households, Other internal expenditures (Non-profit institutions, Government, Gross Fixed Capital Formation, and Stock variation), and Exports. Finally, to avoid the influence of prices and exchange rate changes, IOTs were deflated using the GDP deflator index [IMF, 2023] and applied exchange rates [OECD, 2021] using the base year 2015.

Physical water data, specifically the DWR vector, is sourced from the System of Environmental-Economic Accounting for Water (SEEA-Water), a standard guideline the United Nations promotes for countries that aim to include water accountability in their System of National Accounting. Datasets are comprised of several components, including Physical Supply and Use Tables (PSUTs), which describe the water flows between the economic system and the environment in physical units; Hybrid and Economic Tables, which combine physical water flows to monetary data; and Asset Tables, which aim to measure water resources within a country [UN, 2012]. Brazil [IBGE, 2020], Colombia [DANE, 2020], and Costa Rica [BCCR, 2021] have publicly published national SEEA-Water datasets; however, the countries' datasets have distinct data features.

Given the differences between the countries' SEEA-Water datasets, the primary water variable used in this study is the estimation of DWR, which is defined as the sum of consumptive water use and water losses. The elements of DWR are determined differently across countries. Sectoral water consumption data is the principal variable extracted from the PSUTs, whose estimation methodology varies across countries. Brazil estimates sectoral consumptive use explicitly by the difference between water abstraction and return flows. Colombia adopts a bottom-up approach to estimate sectoral water usage, while in Costa Rica, consumptive use is estimated using fixed coefficients applied to sectoral water abstraction.

The periods of data coverage and the sectoral aggregations for each country also vary. Brazil's SEEA-Water dataset covers 2013 to 2017, Colombia's dataset covers 2010 to 2020, and Costa Rica's covers 2012 to 2017. This variation constrains the analysis to 2013-2017 to enable cross-country comparability. Sectoral aggregations also vary across countries and, in the case of Costa Rica, even within the same country between years. These differences and the levels of sectoral aggregation in the OECD dataset necessitate harmonizing sectoral categories, limiting sectoral aggregation to the least granular level among the three SEEA-Water datasets and the OECD IOTs. For example, OECD datasets represent water and sanitation as a single economic sector, forcing the harmonization of the SEEA-Water data from the individual water and sanitation sectors into one sectoral category [Naspolini, Libra, and Pérez-Urdiales, 2023]. Due to these sectoral constraints and the relative importance of agricultural and water and sanitation sectors in terms of water consumption, three final sectoral aggregates were determined: Agriculture, Water and sanitation, and Rest of the economy. The Rest of the economy encompasses all other economic sectors, including the mining, manufacturing, energy, and services industries. While these activities generally account for a large share of GDP, they account for a trivial fraction of nation-wide DWR. As these activities are highly heterogeneous and have low relative DWR, analyzing water consumption patterns related to this sectoral aggregate is not the main focus of the analysis.

Another data limitation refers to Costa Rica's water data not being strictly comparable between 2013 and 2017 due to changes in methodological estimation [BCCR, 2019a]. The issue is mainly related to water abstraction for self-supply in Agriculture and the Rest of the economy, which generally does not represent much of the overall DWR. Indeed, self-supplied water can be central when accounting for water losses in the Water and sanitation sector. Fortunately, the Water and Sanitation sector does not present problems of data comparability [BCCR, 2019a]. That said, results at the national level and for the agricultural sector in Costa Rica should be interpreted with caution, especially regarding intensity effect results (which measure the impact of water technical coefficients in overall change in DWR). Additional features and limitations of each country's SEEA-Water dataset and the OECD IOTs, as well as details on the harmonization process, are available in Naspolini et al. [2023].

4 Results

We adopt a two-tiered approach to present the SDA results of Brazil, Colombia, and Costa Rica. First, we provide economy-wide results, offering a comprehensive overview of water consumption across economies. This overarching perspective allows us to identify broad trends and disparities in water intensity at the national level. Additionally, we detail the final demand effect by illustrating the amount of DWR triggered by Households, Exports, and Other Internal final demand components (Gross Fixed Capital Formation, Government, and Inventories), aiming to provide insights into whether the economies are embodied water exporters.

Second, we focus on results for water-intensive sectors: Agriculture and Water and sanitation. This sectoral breakdown enables us to conduct a detailed comparison of sectoral SDA results among the three countries, shedding light on variations and highlighting areas where improvements or policy interventions may be needed. For the agricultural sector, we also detail the role Exports play in the final demand effect, given the relevance of the export of agricultural products for Brazil, Colombia, and Costa Rica. Through this dual approach, we aim to provide a nuanced and informative assessment of water consumption at the national and sectoral levels.

4.1 Economy and direct water requirement trends between 2013 and 2017

Table 2 presents the results for economy-wide and sectoral DWR and GDP for Brazil, Colombia, and Costa Rica. The results highlight the relevance of the Agriculture and Water and sanitation sectors for economy-wide DWR estimation, even though the Rest of the Economy accounts for the largest share of economy-wide economic output.

Table 2: Sectoral economic growth and direct water requirements trends

	Economy-wide	Agriculture	Water and Sanitation	Rest of the economy
Brazil				
2013 DWR (hm^3)	330,199 (100%)	318,993 (96.6%)	6,711 (2.0%)	4,495 (1.4%)
2017 DWR (hm^3)	332,775 (100%)	322,001 (96.8%)	6,864 (2.1%)	3,910 (1.2%)
Δ DWR	0.78%	0.94%	2.3%	-13%
2013 GDP (million USD)	1,880,736 (100%)	65,245 (3.5%)	6,781 (0.4%)	1,808,710 (96.2%)
2017 GDP (million USD)	1,772,467 (100%)	72,424 (4.1%)	7,929 (0.4%)	1,692,115 (95.5%)
Δ GDP	-6.4%	11%	17%	-6%
Colombia				
2013 DWR (hm^3)	97,032 (100%)	90,622 (93.4%)	3,643 (3.8%)	2,767 (2.9%)
2017 DWR (hm^3)	115,194 (100%)	109,026 (94.6%)	3,547 (3.1%)	2,622 (2.3%)
Δ DWR	19%	20%	-2.6%	-5.3%
2013 GDP (million USD)	284,306 (100%)	11,440 (4.0%)	3,000 (1.1%)	269,865 (94.9%)
2017 GDP (million USD)	318,977 (100%)	14,605 (4.6%)	3,195 (1.0%)	301,176 (94.4%)
Δ GDP	12%	28%	6.5%	12%
Costa Rica				
2013 DWR (hm^3)	2,029 (100%)	1,396 (68.8%)	595 (29.3%)	38 (1.9%)
2017 DWR (hm^3)	2,220 (100%)	1,544 (69.6%)	597 (26.9%)	78 (3.5%)
Δ DWR	9.4%	11%	0.28%	107%
2013 GDP (million USD)	57,697 (100%)	2,758 (4.8%)	402 (0.7%)	54,537 (94.5%)
2017 GDP (million USD)	65,293 (100%)	2,998 (4.6%)	311 (0.5%)	61,983 (94.9%)
Δ GDP	13%	9%	-23%	14%

Source: Authors' elaboration.

We observe distinct variations in indicators and growth patterns among the countries analyzed. As discussed in Section 2, Brazil faced an economic recession between 2013 and 2017, whereas Colombia and Costa Rica experienced economic expansion during the same period. However, when we focus on the specific sectors, we find that their trends may not necessarily mimic economy-wide behavior. For example, while the Brazilian recession accounted for a -6.4% fall in the economy-wide GDP, Agriculture and Water and sanitation's GDP grew by 11% and 17% in the same period, respectively, having the Rest of the economy been affected by the economic slowdown. Conversely, Costa Rica's GDP at the national level grew by 13%, as Agriculture (9%) and the Rest of the economy (14%). However, Water and sanitation experienced a reduction of -23% in its sectoral GDP. For the Colombian case, all sectors accompanied the economic expansion at the national level, especially Agriculture, which GDP grown up more than two times compared to the national indicator.

We also observe disparities in the direction of DWR and GDP growth. On the one hand, the Brazilian economic recession (-6.4%) occurred simultaneously with a slight rise in the economy-wide DWR (0.78%). On the other hand, Colombia and Costa Rica experienced similar economic growth rates (12 and 13% respectively), but in Colombia, the DWR grew at a faster pace than the GDP (19%); in Costa Rica, the DWR growth was slower (9.4%).

Agricultural trends show a much closer relationship between GDP and DWR. Colombia's agricultural GDP grew by 28% between 2013 and 2017, inducing an increase of 20% in DWR for the same period. In Costa Rica, agriculture's GDP grew by 9% and the associated DWR by 11%. This trend is less distinct in Brazil, where the agricultural sector seems the most water efficient, boosting GDP by 11% while only increasing DWR by 0.94%.

Finally, Water and sanitation also presents distinct behavior regarding GDP and DWR growth rates in the study period. Costa Rica's sector faced a strong GDP reduction of 23%, with little change in the DWR over the study period. Brazil and Colombia's sectors presented impressive economic growth. However, both sectors triggered opposite behavior on DWR growth rates. For example, while in Brazil, the economic activity induced an increase in the DWR (2.3%), in Colombia, the outcome was the opposite (-2.6%).

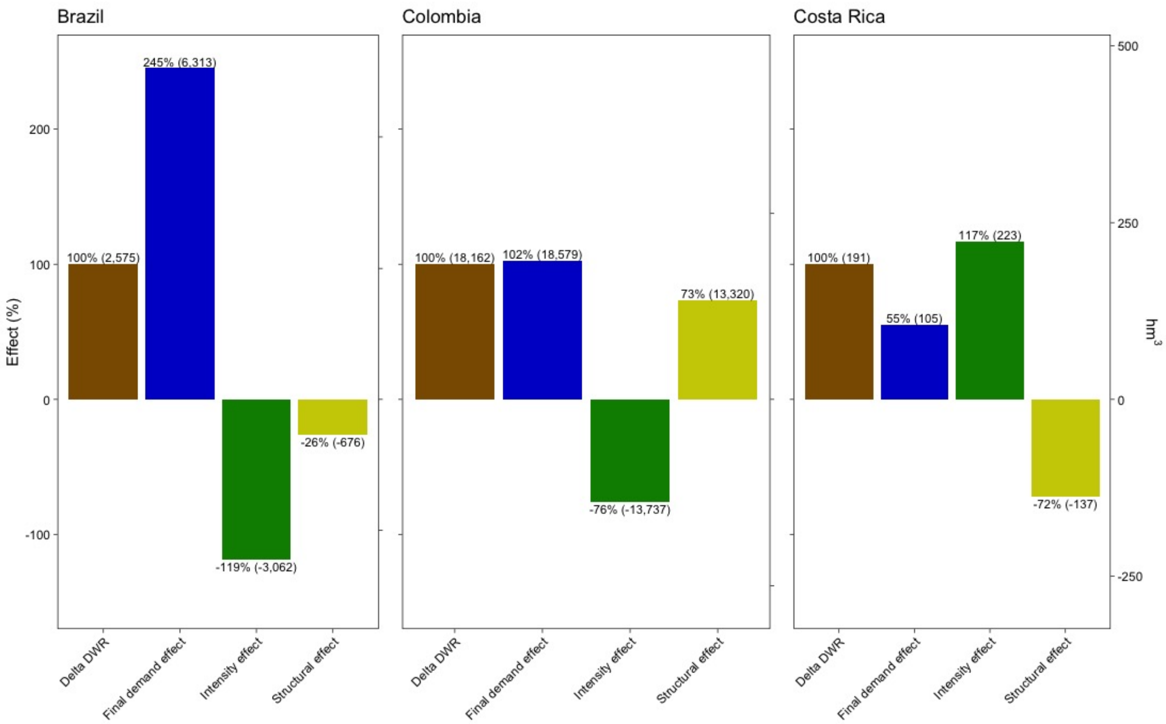
The following section will elucidate these findings in the context of SDA effects. Analyzing the individual components of the overall DWR change over the 2013-2017 period allows us to assess the impact of economic activity and water productivity. This examination also helps determine whether the economic system has increasingly relied on water resources.

4.2 Drivers of change in direct water requirement between 2013 and 2017

4.2.1 Economy-wide

Figure 1 illustrates the SDA results at the national level for Brazil, Colombia, and Costa Rica, divided into intensity, structural, and final demand effects. All the countries experienced an increase in DWR between 2013 and 2017; however, the driver dynamics of this increase differ among them. Brazil and Colombia show a negative intensity effect – meaning that the economic system required less water per unit of gross output – an indication of increasing water productivity at the national level. As discussed in subsection 3.3, results for Costa Rica at the national level and for agriculture should be interpreted with caution due to disparities in physical water data time series.

Figure 1: SDA for Brazil, Colombia, and Costa Rica



Source: Authors' elaboration.

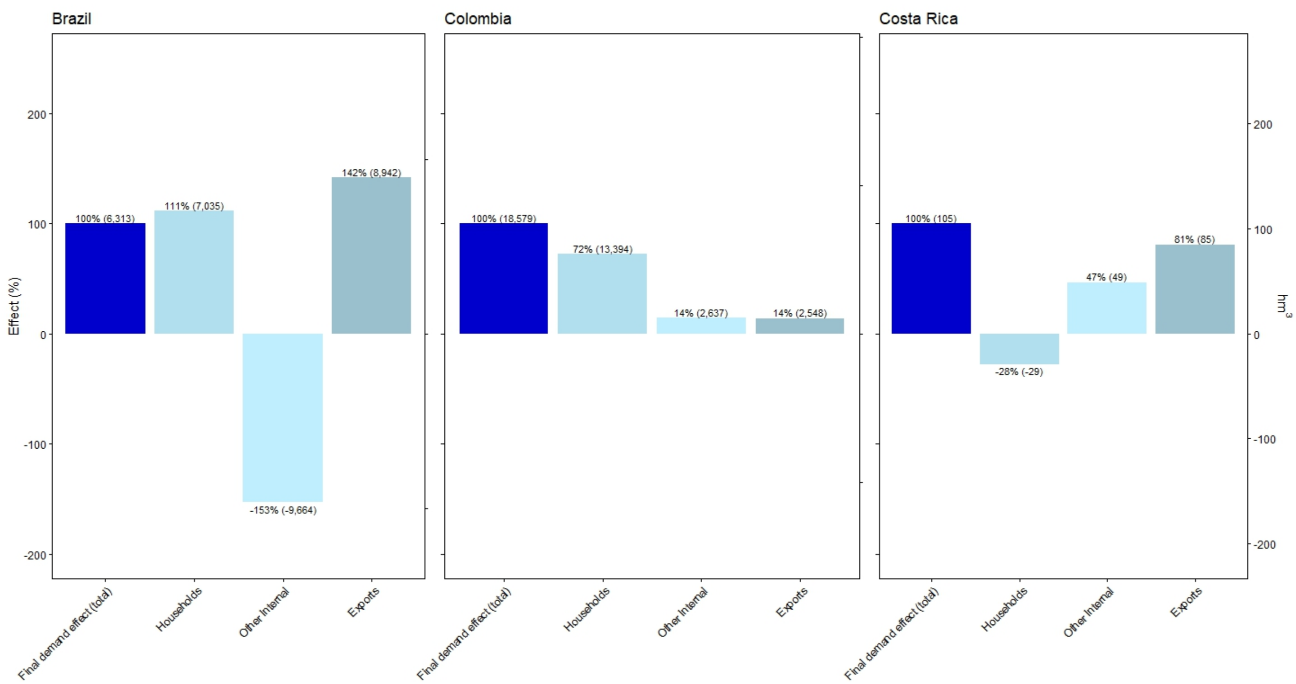
The structural effect indicates how the economic system moved towards water-intensive sectors (such as agriculture). A positive (negative) effect indicates the economic system became more (less) dependent on water resources. For example, when the intermediate consumption (i.e., changes in the Leontief inverse matrix) of water-intensive goods increases (decreases), a positive (negative) structural effect signalizes the dimension and direction of the change. Having this in mind, Brazil and Costa Rica's economies became less water-dependent during the period of analysis, as they show negative structural effects, whereas we observe the opposite in Colombia, that is, its economic system became more water-intensive.

Last, the final demand effects present surprising results. In Brazil, the strong positive final demand effect does not mirror the country's economic recession in the period. This is a contradictory result given that the final demand effect identifies the impact of economic activity on direct water requirements, an economic recession could potentially lead to a reduction in the magnitude of DWR.

The final demand effect for Colombia and Costa Rica illustrates how economic growth pushed up water consumption between 2013 and 2017. Both countries presented positive final demand effects, which differed in magnitude. Results indicate that Colombia supported its economic growth at the same pace as improving water productivity, i.e., gains in efficiency hinder DWR induced by gross economic scale (positive final demand effect and negative intensity effect). In the case of Costa Rica, results show that at the national level, the economy grew by getting more water-intensive.

Figure 2 gives a more detailed picture of the composition of the final demand effect. It illustrates the contribution of Exports, Households, and Other internal final demand components to the increase in DWR induced by the economic activity. Exports push up DWR in all countries, signaling the relevance of this final demand component in triggering DWR through economic systems. Even in times of economic recession, as in the case of Brazil, Exports and Households sustained an increase in the DWR induced by the economic activity, primarily due to the economic expansion of Agriculture. Other internal components of final demand illustrate the economic slowdown observed in the period, notably the fall in Gross Fixed Capital Formation [OECD, 2021, IBGE, 2019].

Figure 2: The role of Exports on economy-wide final demand effect



Source: Authors' elaboration.

Colombia has all final demand components pushing up the increase in DWR. Households' consumption was the main driver of DWR induced by economic activity, representing about 70% of the final demand effect. Exports are the primary driver of Costa Rica's final demand effect. Household consumption decreased in the same analysis period—results for Costa Rica point to a change in the consumption basket of Costa Rican families. For example, households might have demanded fewer agricultural goods or water and sanitation services.

4.2.2 Agriculture

The agricultural sector considered in this study is an aggregate of all primary agrarian activities (agriculture, livestock, hunting, forestry, fishing, and aquaculture). This sector composition varies among countries by either the share of the economic activities in the aggregated composition or the national agriculture portfolio. For example, in Brazil, soybean, livestock and sugarcane are the main agrarian products, representing 24%, 13% and 10% of the overall Agriculture output, respectively [IBGE, 2019]. In Colombia, the livestock accounts for 33% of Agriculture, followed by the coffee production (10%) [DANE, 2019]. In Costa Rica, livestock (19%) is the main product of Agriculture, followed by bananas (18%) and pineapples (18%) [BCCR, 2019b].

Despite the substantial differences in terms of agricultural sector composition, this sector has a relevant contribution to the national GDP, including Exports, for the three countries considered in the analysis. Given the natural reliance on water resources for agricultural activity, it is a key sector when analyzing the changes in DWR. SDA results for the Agriculture sector provide insights into the sustainable management of water resources.

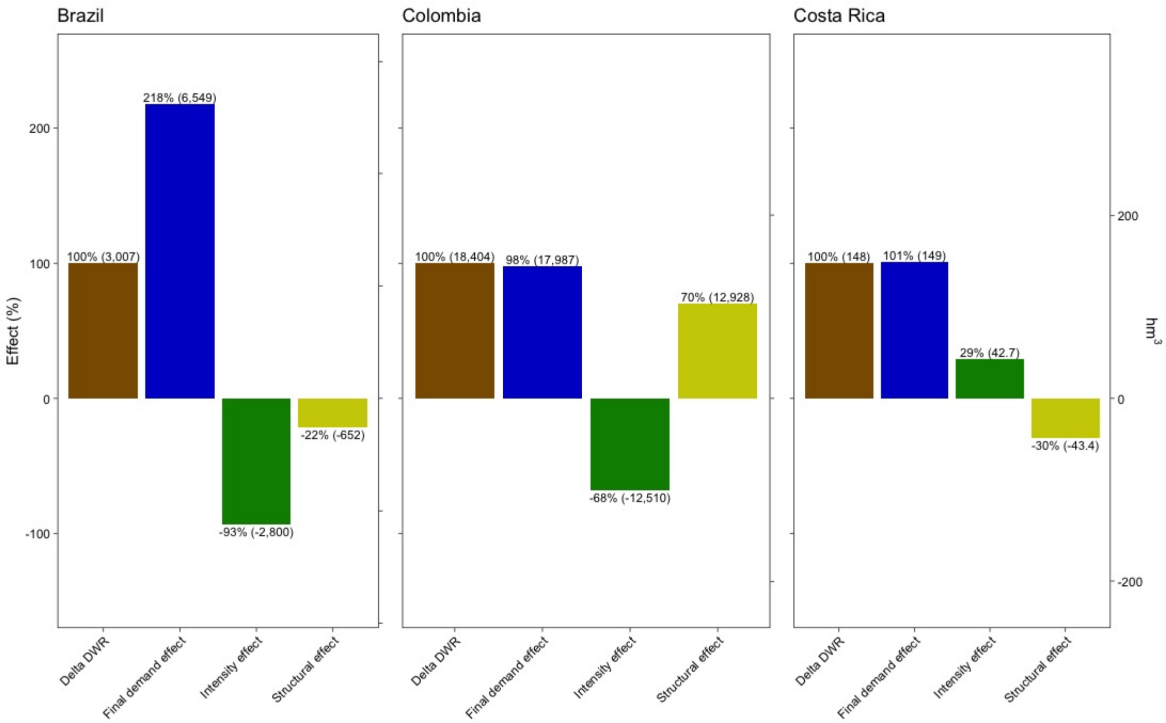
Agriculture in all countries experienced economic growth during the period, illustrated by positive, strong effects in SDA results (Figure 3). However, the sectoral economic growth was accompanied by a decrease of DWR induced by economic output (negative intensity effect) in the case of Brazil and Colombia, whereas Costa Rica became more water-intensive during the period of analysis, as is shown by the positive intensity effect.

In Brazil, both intensity and structural effects inhibited the increase of DWR induced by gross economic scale. It means that the sector improved its water productivity between 2013 and 2017, contributing to more economy-wide water efficiency in Brazil (i.e., the entire economic system became less dependent on water resources). In simpler terms, had the agricultural sector not become more efficient, the escalation in total water consumption would have been far more substantial.

Results for Colombia's agriculture show the same increase in water productivity as Brazil's. However, its economic system's structural effect signalized a shift in its dependence on water resources. Either agricultural sector participation in GDP increased, or the depreciation of exchange rates [OECD, 2021] are most likely the explanations for the effect (i.e., as imported imports had gotten more expensive, farmers substituted them by national inputs, triggering more input production within the national economic system). Nevertheless, the results indicate the gains in sectoral water productivity were offset by the water requirements induced by economic structure. Results for Costa Rica presented an opposite behavior than those for Colombia. The negative structural effect indicates that the economic system became more water-dependent and that water productivity in the agricultural sector diminished.

Agriculture is critical to food security and Exports in Brazil, Colombia, and Costa Rica. Figure 4 dis-

Figure 3: SDA results for the Agricultural Sector



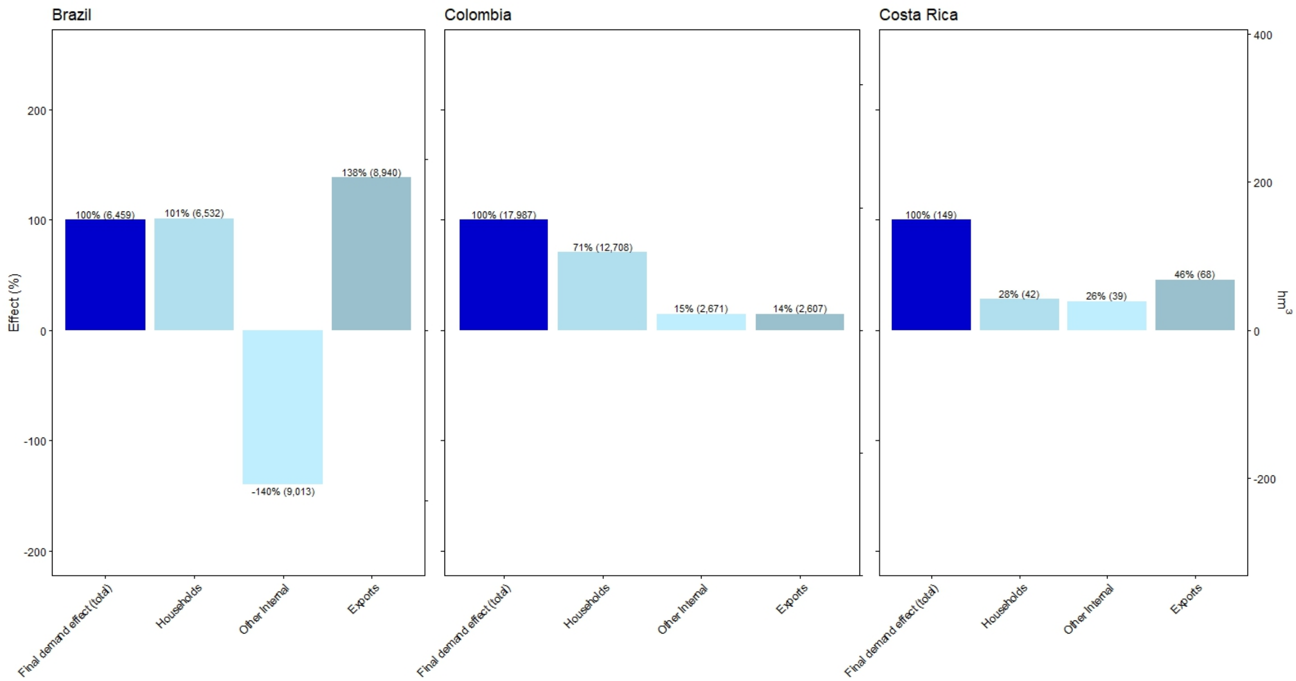
Source: Authors' elaboration.

closes the gross economic scale driver into three final demand components: Households, Exports, and Other Internal. The results give insights into the importance of Exports in inducing shifts in agricultural DWR and compare it to the importance of Households and Other internal consumption in explaining the observed changes. As expected, the Water and Sanitation sector is irrelevant to Exports. Thus, we only present the final demand effect detailing for Agriculture. Nonetheless, the Water and Sanitation sector is vital to Households, and insights on its DWR changes are discussed in the next section.

The economic crises in Brazil impacted the Other internal GDP components by crashing their demand for agricultural products, as illustrated by the negative component of agriculture's total final demand effect. Although relevant, the decrease in other internal demand did not impact the overall economic growth of the sector. Exports are the main component contributing to the gross economic scale (final demand effect), followed by Households. These results shed light on the importance of agricultural commodities for the Brazilian economy and how resilient investments are crucial when designing sustainable development policies for the sector. Colombia and Costa Rica did not face economic crises during the study, so the final demand effect presented positive values for all components. Colombia primarily relied on Household demand for its agricultural production. Exports played a crucial role in inducing shifts in agricultural DWR during the period, especially for Costa Rica and Brazil.

The final demand profile also provides insights into the differences in water footprint estimations by

Figure 4: The role of Exports on agricultural final demand effect



Source: Authors' elaboration.

Naspolini et al. [2023]. Agriculture in Colombia accounts for an average water footprint of 0.21 m^3 per USD, followed by Brazil (0.10 m^3 per USD) and Costa Rica (0.03 m^3 per USD). This is a case of an increase in water productivity by increasing goods value-added rather than reducing water requirements (for example, curbing losses on irrigation systems). Such an effect suggests why agriculture in Costa Rica has lower water footprints than in Brazil and Colombia.

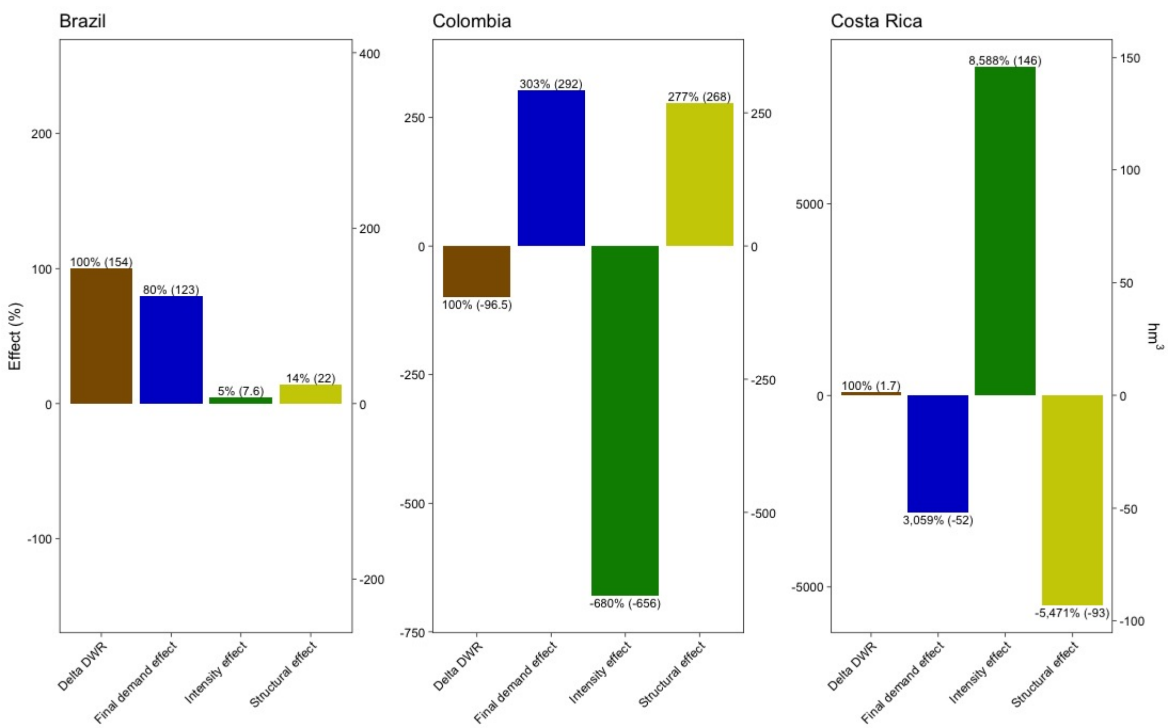
4.2.3 Water and Sanitation

Water and sanitation sector exhibits a high degree of homogeneity in their production techniques across Brazil, Colombia, and Costa Rica. For example, the water provision systems mainly abstract water from surface resources or reservoirs and wastewater treatment plants are primarily primary effluent treatment facilities. Even though sanitation output may vary across countries (implying in a more diversified sectoral output portfolio), a more direct comparison of shifts in water productivity, economic system reliance on water resources, and gross economic scale can emerge from the water and sanitation sector SDA results.

Water and sanitation are sectors that exhibit a high degree of homogeneity in their production techniques. However, the sector's nature can vary depending on whether it involves both water supply and treatment or just one of these components. For instance, in countries like Brazil, Colombia, and Costa Rica, water provision systems mainly draw water from surface resources or reservoirs, while wastewater treatment primarily involves primary effluent treatment facilities. This variation can impact the sector's weight in different countries. The SDA results from the water and sanitation sector can provide a more direct comparison of shifts in water productivity, the economic system's reliance on water resources, and the gross economic scale.

Figure 5 presents distinct drivers of change in the Water and sanitation sector' DWR. The negative final demand effect represents the substantial fall in sectoral GDP in Costa Rica (-23%) (Table 2). In contrast, the structural effects also expressively curbed the increase in DWR induced by a decrease in water productivity (strong positive intensity effect). Economic results shed light on a 21% fall in sectoral gross output in the Water and sanitation sector of Costa Rica. It represents a substantial supply shock in the Water and sanitation sector. For Brazil and Colombia, the final demand effect aligns with the sectoral GDP growth in these countries (17% and 6.5%, respectively).

Figure 5: SDA results for the Water and Sanitation sector



Source: Authors' elaboration.

Among the countries analyzed, Colombia is the only country where the sectoral DWR decreased in absolute levels (-2.6% or -96 hm^3) between 2013 and 2017 (Table 1). Results show that the water input effect mainly contributed to the decrease in the sector's DWR, meaning the sector improved its water productivity during the period of gross output growth. In contrast, the structural effect has barely the same magnitude as the final demand effect, pointing to an increase in the water and sanitation sector's water dependence at the economic system level. It means that in 2017, the interdependence triggered by water and sanitation sector input was more intense in water. Brazil also presented the same results for the structural effect, and, as in Colombia, the phenomenon is most likely due to the increase in the share of agricultural products in the countries' GDP.

5 Discussion

5.1 Economy-wide

Although not within the direct scope of this analysis, non-consumptive water usage for electricity generation plays a crucial role in the LAC energy sector [3]. The need for effective water management policies, particularly in regions such as Brazil and the Andean countries, calls for a paradigm shift in assessing the economic viability of large-scale dam construction projects. Latrubesse, Arima, Dunne, Park, Baker, d'Horta, Wight, Wittmann, Zuanon, Baker, Ribas, Norgaard, Filizola, Ansar, Flyvbjerg, and Stevaux [2017] emphasize the importance of governmental agencies recognizing the extensive impacts of dam-building activities on ecosystem services within downstream water systems. This recognition underscores the importance of transboundary communication and cooperation, advocating for revitalizing and enhancing policy instruments such as the Amazon Cooperation Treaty Organization. Furthermore, there is an urgent need to integrate energy, transportation, and environmental considerations into basin-scale frameworks to promote sustainable development. Basheer et al. [2023] suggest that utilizing artificial intelligence-based approaches can aid in designing adaptive management plans that balance the economic interests of riparian countries with the preservation of river systems, as seen in the management policy for the Grand Ethiopian Renaissance Dam. In this context, participatory governance becomes essential to ensure inclusivity and effectiveness in water management policies. Latrubesse et al. [2017] advocate for the engagement of stakeholders at various levels to promote basin-integrated management, exemplified by initiatives for integrated management of the Acre River in Bolivia, Brazil, and Peru organized by civil society. Effective participatory governance fosters transparency and accountability and the incorporation of diverse perspectives into policy formulation and implementation. Furthermore, integrating climate adaptation considerations into water management strategies is paramount, especially in regions vulnerable to extreme weather events induced by climate change. Basheer et al. [2023] highlight the importance of collaborative adaptive solutions in mitigating the adverse impacts of climate change on river systems and riparian countries' economies. Failure to implement such solutions leads to significant economic costs and exacerbates tensions among riparian nations, as evidenced by negotiations over the GERD and broader Nile management. Thus, fostering participatory governance and integrating climate adaptation into water management policies are essential to ensure water resources' sustainability and resilience in the face of evolving environmental challenges.

The findings of this study explore the intricate dynamics between economic growth and water con-

[3] Naspolini et al. [2023] briefly discuss the role of hydropower on energy mix in Brazil, Colombia, and Costa Rica.

sumption in Brazil, Colombia, and Costa Rica. At the national level, Brazil experienced an increase in DWR even during an economic recession, attributable to a surge in the demand for agricultural products. However, this uptick was counterbalanced by a negative intensity effect, leading to a decrease in the overall water dependence of the economic system—marked by a negative structural effect. Colombia also exhibited a noteworthy negative intensity effect, effectively offsetting the rise in demand. Unlike Brazil, Colombia's economic landscape witnessed increased water dependence during the analysis period. Meanwhile, Costa Rica stood out with a robust positive intensity effect, indicating a heightened water intensity at the national level (hm^3 per million USD). Paradoxically, despite this intensified water use, the country's economic system displayed a reduction in overall dependency on water resources. These findings highlight the nuanced relationships between economic activities, water consumption, and dependency, offering valuable insights for sustainable resource management strategies in diverse national contexts.

The structural effect measures the change in the economic system's dependency on water resources. As the study spans a relatively short time series (2013-2017), and the structural effect most likely captures situational rather than structural changes in the economy. For example, Cazcarro et al. [2013] isolated the structural changes in the Spanish agricultural sector between 1980 and 2007 and observed that the increase in water productivity during those decades can be attributed to a shift in agricultural production towards higher-value-added products, improved efficiency in the use of agricultural inputs, and the economy has witnessed a substitution of traditional agricultural inputs with chemical and industrial products. Furthermore, increased water efficiency in agriculture implied decreased embodied water in its forward sectors (mainly the food industry, hotels, and restaurants). In the case of our results, the change in water dependence lies in changes in the participation of agriculture over the national GDP. When agrarian participation rises, the economic system becomes more dependent on water resources (and the same for the opposite).

Households and Exports are usually important drivers for water consumption increase over time [Naspolini et al., 2023, Cazcarro et al., 2013, Wang et al., 2016, Fan et al., 2019]. Economic growth is inextricably linked with sectoral embodied water from a demand-side perspective, meaning the final demand effect on DWR is generally positive outside of recession scenarios. This is especially true for exports and internal production. In the case of Brazil, the results of this analysis agree with Naspolini et al. [2020] where even during the economic recession, the Brazilian economy kept demanding water-intensive products either by interindustry transactions or final demand. A positive final demand effect on water consumption increase means that some sectors of the economy are growing and increasingly demanding water, notably the agricultural sector.

The investigation into the contribution of final demand components for the increase in direct water requirements at the country level unveils distinctive patterns in Colombia, Costa Rica, and Brazil. In Colombia, results emphasize the role of residential consumption in increasing water consumption at the national level. In Costa Rica, the findings highlight the influence of international trade dynamics on domestic water consumption and a negative contribution of household consumption, i.e., households demanded less water-intensive products (from agriculture and water and sanitation sectors) during the period of analysis. Brazil's scenario involves a decline in Exports and internal demand components, with Households being the primary driver of water demand at the national level. A sector-level analysis provides insights into the role of exports in agricultural demand and the performance of the water and sanitation sector in meeting population needs. This examination contributes to a more comprehensive understanding of the relationships between consumption patterns, economic activities, and water demand at national and sectoral levels.

5.2 Agriculture

Brazil's agricultural sector had the most growth and improved water productivity in the period. Colombia also grew increasing the sectoral water productivity but to a lesser extent (-93% versus -68% as the contribution of the intensity effect to overall DWR change). On the contrary, results show that the agricultural sector in Costa Rica increased DWR per USD during the period (contribution of 29% in the overall change). Results at the sectoral level reveal an interesting finding regarding the contribution of final demand components to the overall change in DWR. While at the national level, households are the main contributor, for the agricultural sector, Exports are the main driver pushing up the increase in DWR observed in the period.

Examining the role of exports in agriculture in Costa Rica and Brazil highlights the potential impact of international markets on water resources. Failure to integrate development policies into water management and adaptation frameworks poses risks to water resources and may escalate conflicts over water use. In addition to the expanding trend of irrigated farming, changes in rainfall patterns may drive increased demand for supplementary irrigation, even in areas not affected by droughts in the past. This complex relationship between agricultural exports, international markets, and changing climatic conditions underscores the necessity for a comprehensive and integrated approach to water resource management in these countries.

In regions with greater water scarcity and, consequently, with higher limitations on abstractions, irrigation expansion can lead to different pathways. On the one hand, introducing newer technologies or crop portfolio substitution can reduce the demand for water and increase water productivity. On the other hand, in the absence of integrated water and adaptation governance, irrigation may lead to an increase in water-use conflicts, leading to difficulties in enforcement of the decisions at the local level and hindering water conservation efforts.

Irrigated farming usually exhibits high elasticity in water use [MMA, 2016]. With the availability of water-saving irrigation techniques and the potential to switch to less water-demanding crops, the irrigation activity may reduce abstracted volumes to align with current water availability. This flexibility underscores the importance of incorporating adaptive strategies into water management practices.

Findings point to the need for resilient investments when designing socio-economic development policies, especially those contemplating water resources conservation efforts. The prerequisite of environmental licenses for public and private irrigation projects and fiscal incentives for more efficient irrigation equipment acquisition, as considered in the Brazilian Irrigation Act [2013], aims to promote water productivity and sustainable management of water resources. In addition to this framework, water conservation and recovery must be contemplated when designing economic instruments.

Considering the vital role of agriculture in sustainable development and water conservation efforts, the results emphasize the importance of more integrated and transversal environmental regulation. Additionally, we emphasize the impact of international markets, particularly the role of exports in agriculture in Costa Rica and Brazil. It warns of potential risks to water resources and increased conflicts if development policies are not seamlessly integrated into the water management and adaptation framework. This highlights the importance of aligning economic and agricultural policies with water conservation goals to ensure a harmonious and sustainable approach to water resource management.

5.3 Water and Sanitation

Costa Rica faced a severe drought in 2014 and 2015, when precipitation was reduced by 30% and 63%, respectively, compared to 2013 levels [Castro, Sanchez-Azofeifa, and Sato, 2018]. Since the country does not have transboundary water flows filling in its territory, it only relies on rain-fed water to maintain its water resource stock levels [BCCR, 2021]. The results indicate an economic recession in the Water and Sanitation sector induced by a scarcity context. The agriculture seems not to have been impacted, though. Such results highlight the importance of integrated water management policies and resilient infrastructure for sustainability to address either economic activity that delivers fundamental services for the population or exported-oriented production. Demand for water and sanitation followed the supply chock and fell strongly during the drought, encouraged by the demand management carried out by utilities during the drought period.

The positive intensity effect in Costa Rica can be a reflection of the Los Tajos operation, the first wastewater treatment plant of Costa Rica, inaugurated in 2015.[4] As few big utilities provide water and sanitation services in the country, such expressive investment may have increased water technical coefficients at the national level. For example, before the inauguration of the sewage treatment plant, the sector mainly provided water services. So, the technological process of the sector's gross output relied on input related to abstracting, cleaning, and distributing water. However, when the new treatment plant started operating, new and more inputs started being demanded to move with the sewage treatment, ultimately

[4] Acciona inaugurates *"Los Tajos"* wastewater treatment plant in Costa Rica

implying changes in the sectoral technological production and, to a further extent, in more physical units of water per unit of sectoral output.[5]

Gains in water productivity have not accompanied the economic growth of Brazil's water and sanitation sector, as shown by the positive intensity effect. However, it does not account for expressive magnitude. It could have two interpretations: while one could conclude that the sector became more inefficient in water use (for example, by having the volume of non-revenue water increased during the period), changes in the production technology (such as investment in treatment plants) may have increased the sector's direct water requirements, resulting in increases in self-water consumption. The expressive sectoral GDP growth of 17% (Table 2) supports the approach of more investments in the water and sanitation sector.

Brazil recently enacted a new regulatory framework for water and sanitation services [Brazil, 2020]. More specifically, The Sanitation Act (2020) opens space for private companies to provide public sanitation services by ending new direct contracts between state-owned companies and municipalities, apart from requiring economic-financial capacity proof of current and future agreements to meet service targets for universalizing water (99%) and sanitation (90%) by 2033. Results show Brazil's water and sanitation sector faces a challenge in pursuing water-saving gains.

In 2014 and 2015, Brazil faced one of the most intensive droughts registered [MMA, 2014]. The event is especially grave since it happened in the country's most populated region, served by the *Sao Paulo Cantareira* water supply system. Ciasca, Klemz, Raepple, Kroeger, Acosta, Cho, Barreto, Bracale, and Cesário [2023] highlight the economic viability of the hypothetical Nature-based solutions scenario in mitigating extreme climatic events, mainly involving forest restoration implemented via a mixture of passive and active restoration techniques, expecting to generate water security benefits. More specifically, the authors showed that potential avoided costs of implementing nature-based solutions could increase by 28%, improving water availability for the industrial and water sectors under drought conditions, increasing carbon sequestration, and reducing the economic cost of drought.

As per the case of Colombia, the results show that the water input effect mainly contributed to the decrease in the sector's DWR. This trend may be explained by two different mechanisms. The first mechanism relates to changes in water and sanitation tariffs. If the price of water and sanitation services increased during the period, one may expect an increase in the output value would decrease the water per output ratio, thereby leading to a negative intensity effect. However, the evidence shows that water and sanitation tariffs remained relatively constant during the period, and it was only by 2017 that they started to increase [Brichetti, Serebrisky, and Solís, 2022]. This leads to the consideration of the second potential mechanism that may be explaining the negative sign in the water intensity effect: gains in efficiency within the sec-

[5]This rationale is supported by the sector-technology hypotheses admitted in the OECD input-output tables dataset. By doing so, the input estimation is based on the average technological production process of the sectors, no matter how many different output products it produces. On the contrary, the product-technology hypothesis admits that the technological process of the sector is given by the technological aspects of the main output product this sector produces.

tor. While beyond the immediate scope of our analysis, several developments may have increased water productivity in the sector, such as the reduction of losses, the expansion of the network, increasing the number of consumers paying bills, and/or gains of scale in production. All these, in turn, may have driven a decrease in the relationship between DWR and economic activity during the period. The government of Colombia has indeed promoted policies to reduce water losses, such as the CRA resolution 688 of 2014, and a national program to expand the water network to rural areas in the country in 2014. Finally, according to CEPAL [2024], the public investment in Water and sanitation, as a share of the GDP, had substantially increased in Colombia since 2008, which could also explain productivity sectoral gains.

Given countries aim to expand water access and improve sanitation conditions, water efficiency plays a fundamental role in the sector. To maintain and improve water access, curb losses is the primary action to improve water efficiency within the sector. Improving sanitation services increases sectoral water consumption due to the commissioning and operation of new wastewater treatment facilities. As water access is relatively high among the countries analyzed, expanding sanitation services requires sectoral policies oriented to improve efficiency and sustainable management of water resources.

6 Conclusion

This study underscores the intricate interplay between climate change, economic dynamics, and water resource management within Latin America. The findings reveal a dual challenge of environmental emergency and economic crisis, as disruptions to weather patterns pose significant threats to economic growth and poverty eradication. The results demonstrate varying impacts on water dependency and productivity in Brazil, Costa Rica, and Colombia, with distinct drivers in each country's economy.

Results reveal an augmented reliance on water resources in the economies of Brazil and Costa Rica, contrasting with a reduced dependency in Colombia. Concurrently, Brazil and Colombia have enhanced their water productivity, while Costa Rica has exhibited an elevation in direct water requirements per USD at the national level. In Colombia, households emerged as the primary contributor to the increase in direct water requirements during the period, whereas in Costa Rica, exports played a pivotal role. In Brazil, the findings, marked by a decline in Exports and other internal components of final demand at the national level, emphasize Households as the primary factor driving the increasing water demand; however, it is noteworthy that Exports contribute substantially to the increase in direct water requirements within the agriculture sector.

In the agricultural sector, the possibility of conflicts arising from multiple water use is heightened, potentially influenced by international market dynamics. This is particularly evident in the agricultural practices of Brazil and Costa Rica, where exports play a pivotal role, posing challenges to effective water resource management. Shifting focus to water and sanitation, a challenge arises in simultaneously ensuring universal access to water and sanitation services amid increasing scarcity, driven by climate change. Notably, observations in Brazil and Costa Rica highlight a decline in water productivity, emphasizing the necessity for tailored water conservation policies at the sectoral level.

The results underscore the necessity for targeted interventions to address the evolving economic and environmental dynamics, particularly in sectors crucial for sustainable development and water security. The policy implications emphasize the importance of cross-cutting water conservation policies and fostering effective, participatory governance across all levels of water management administration and policy decisions. Emphasizing economic and environmental planning within the context of climate change adaptation is paramount in ensuring a comprehensive and strategic approach to address these challenges.

Addressing the limitations of this study, it is crucial to acknowledge the constraints imposed by the availability of water data, which limited the scope of countries under examination and sectoral disaggregation. Additionally, the fact that within such a short period of analysis, the captured effects may be situational rather than structural. It points to the need to extend the analysis as longer time series become available. This limitation suggests an opportunity to leverage initiatives like SEEA-Water for regional data dissemination and standardization. Additionally for future research, fostering the development of multi-region input-output tables at national and regional levels could enhance the depth and breadth of economic-environmental analyses, enabling a more comprehensive understanding of the region's economic integration and facilitating informed policy decisions. Beyond input-output analysis, the findings of this study indicate the need for a more detailed analysis of the Water and sanitation sector in Colombia (to investigate the drivers behind the water productivity gains), and in Costa Rica, where results suggests a sector's supply shock induced by water scarcity.

In light of these findings and limitations, the study advocates for implementing water conservation policies and effective governance mechanisms as essential components of a comprehensive strategy to address the complex interconnections between climate change, economics, and water resources in Latin America. Furthermore, it underscores the importance of continued efforts to improve data availability and standardization for a more nuanced and extensive examination of the region's socioeconomic and environmental dynamics.

References

Mohammed Basheer, Victor Nechifor, Alvaro Calzadilla, Solomon Gebrechorkos, David Pritchard, Nathan Forsythe, Jose M. Gonzalez, Justin Sheffield, Hayley J. Fowler, and Julien J. Harou. Cooperative adaptive management of the nile river with climate and socio-economic uncertainties. Nature Climate Change, 13:48–57, 2023. doi: 10.1038/s41558-022-01556-6.

BCCR. Cuenta del agua 2016. Technical report, Banco Central de Costa Rica, 2019a.

BCCR. Cuentas nacionales anuales - período de referencia 2017. Banco Central de Costa Rica, 2019b.

BCCR. Cuenta del agua 2017. Technical report, Banco Central de Costa Rica, 2021.

Brazil, 2013. URL https://www.planalto.gov.br/ccivil03/Ato2011-2014/2013/Lei/L12787.htm. LEI Nº 12.787 DE 11 DE JANEIRO DE 2013 - Política Nacional de Irrigação.

Brazil, 2020. URL https://legis.senado.leg.br/norma/32462863/publicacao/32491972. LEI Nº 14.026 DE 15 DE JULHO DE 2020 - Novo Marco Regulatório Saneamento.

Juan Pablo Brichetti, Tomás Serebrisky, and Ben Solís. La evolución de los precios de los servicios de infraestructura en américa latina y el caribe entre 2012 y 2022. Technical report, Inter-American Development Bank, 2022.

Alvaro Calzadilla, Katrin Rehdanz, Richard Betts, Pete Falloon, Andy Wiltshire, and Richard S. J. Tol. Climate change impacts on global agriculture. Climatic Change, 120:357–374, 2013a. doi: 10.1007/s10584-013-0822-4.

Alvaro Calzadilla, Tingju Zhu, Katrin Rehdanz, Richard S.J. Tol, and Claudia Ringler. Economywide impacts of climate change on agriculture in sub-saharan africa. Ecological Ecnomics, 93:150–165, 2013b. doi: 10.1016/j.ecolecon.2013.05.006.

E Castellanos, M F Lemos, L Astigarraga, N Chacón, C Huggel, N Cuvi, L Miranda, M Moncassim Vale, and J P Ometto. Central and south america. In Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022.

S M Castro, G A Sanchez-Azofeifa, and H Sato. Effect of drought on productivity in a costa rican tropical dry forest. Envrionmental Research Letters, 13:045001, 2018. doi: 10.1088/1748-9326/aaacbc.

Eduardo Cavallo, Bridget Hoffmann, and Ilan Noy. Disasters and climate change in latin america and the caribbean: An introduction to the special issue. Economics of Disasters and Climate Change, pages 1–11, 2023.

Ignacio Cazcarro, Rosa Duarte, and Julio Sánchez-Chóliz. Economic growth and the evolution of water consumption in spain: A structural decomposition analysis. Ecological Economics, 96:57–61, 2013. doi: /10.1016/j.ecolecon.2013.09.010.

Ignacio Cazcarro, Joep F Schyns, ARTO Iñaki, and M Jose Sanz. Nations' water footprints and virtual water trade of wood products. Advances in water resources, 164:104188, 2022.

CEPAL. Cepalstat. Technical report, Comisión Económica para América Latina y el Caribe – CEPAL, 2024.

Bruna Stein Ciasca, Claudio Klemz, Justus Raepple, Timm Kroeger, Eileen Andrea Acosta, Se Jong Cho, Samuel Barreto, Henrique Bracale, and Fernando Cesário. Economic cost of drought and potential benefits of investing in nature-based solutions: A case study in são paulo, brazil. Water, 15:466, 2023. doi: 10.3390/w15030466.

DANE. Cuentas nacionales anuales - Base 2015. Departamento Administrativo Nacional de Estadística, 2019.

DANE. Cuenta ambiental y económica de flujos del agua - metodologia general. Technical report, Departamento Administrativo Nacional de Estadística de Colombia, 2020.

Erik Dietzenbacher and Bart Los. Structural decomposition techniques: Sense and sensitivity. Economic Systems Research, 10(4):307–324, 1998. doi: 10.1080/09535319800000023.

Jing-Li Fan, Jian-DaWang, Xian Zhang, Ling-Si Kong, and Qin-Ying Song. Exploring the changes and driving forces of water footprints in china from 2002 to 2012: A perspective of final demand. Science of the Total Environment, 650:1101–1111, 2019. doi: 10.1016/j.scitotenv.2018.08.426.

Le Feng, Bin Chen, Tasawar Hayat, Ahmed Alsaedi, and Bashir Ahmad. The driving force of water footprint under the rapid urbanization process: a structural decomposition analysis for zhangye city in china. Journal of Cleaner Production, 163:S322–S328, 2017.

Rutger Hoekstra and Jeroen van den Bergh. Comparing structural decomposition analysis and index. Energy Economics, 25(1):39–64, 2003. doi: 10.1016/S0140-9883(02)00059-2.

IBGE. Sistema de contas nacionais : Brasil : 2017. Instituto Brasileiro de Geografia e Estatística, 2019.

IBGE. Contas econômicas e ambientais da Água 2013-2017. Technical report, Instituto Brasileiro de Geografia e Estatística, 2020.

IMF. International financial statistics - gross domestic product and components selected indicators. Technical report, International Monetary Fund, 2023.

Edgardo M. Latrubesse, Eugenio Y. Arima, Thomas Dunne, Edward Park, Victor R. Baker, Fernando M. d'Horta, Charles Wight, Florian Wittmann, Jansen Zuanon, Paul A. Baker, Camila C. Ribas, Richard B. Norgaard, Naziano Filizola, Atif Ansar, Bent Flyvbjerg, and Jose C. Stevaux. Damming the rivers of the amazon basin. Nature, 546:363–369, 2017. doi: 10.1038/nature22333.

W. Leontief. Environmental repercussions and the economic structure: An input-output approach. Review of Economics and Statistics, 52:262–277, 1970. doi: 10.2307/1926294.

Qianqian Li, Guangwei Deng, Huaqing Wu, Tao Ding, and Ya Chen. Exploring water use in mildly water-scarce regions: A structural decomposition analysis for anhui province in china. Water Economics & Policy, 9(2), 2023.

Jesse Madden Libra, Julien Sylvain Marinus Collaer, Darcia Datshkovsky, and Maria Pérez-Urdiales. Scarcity in the land of plenty. Technical report, Water and Sanitation Division Technical Note, 2022.

Haiyu Long, Rui Xie, Chao Gao, Meng Sun, and Bin Su. Analysis of china's regional differences in water consumption based on spatial structural decomposition analysis model. Science of The Total Environment, 848:157629, 2022.

Ronald Miller and Peter Blair. Input-Output Analysis Foundations and Extensions. Cambridge University Press, New York, 2 edition, 2009. ISBN 13 978-0-511-65103-8.

MMA. Conjuntura dos recursos hídricos no brasil - encarte especial sobre a crise hídrica. Technical report, Ministério do Meio Ambiente - Superintendência de Planejamento de Recursos Hídricos, 2014. URL https://www.snirh.gov.br/portal/centrais-de-conteudos/conjuntura-dos-recursos-hidricos/crisehidrica2014.pdf.

MMA. National adaptation plan to climate change - volume ii: Sectoral and thematic strategies. Technical report, Brazilian Ministry of Environment, 2016. URL https://www.gov.br/mma/pt-br/assuntos/climaozoniodesertificacao/clima/arquivos/bookpnavolume-ii-v4.pdf.

Giovanna Ferrazzo Naspolini, Bruna Stein Ciasca, Emilio Lèbre La Rovere, and Amaro Olimpio Pereira Jr. Brazilian environmental-economic accounting for water: A structural decomposition analysis. Journal of Environmental Management, 265:110508, 2020. doi: 10.1016/j.jenvman.2020.110508.

Giovanna Ferrazzo Naspolini, Jesse Madem Libra, and María Pérez-Urdiales. Water footprint estimation in latin america. Technical report, Inter-American Development Bank, 2023.

V. Nechifor and M. Winning. Projecting irrigation water requirements across multiple socio-economic development futures – a global cge assessment. Water Resources and Economics, 20:16–30, 2017. doi: 10.1016/j.wre.2017.09.003.

OECD. Input-output tables. Technical report, Organization for Economic Co-operation and Development, 2021.

Yuri Botelho Salmona, Eraldo Aparecido Trondoli Matricardi, David Lewis Skole, João Flávio Andrade Silva, Osmar de Araújo Coelho Filho, Marcos Antonio Pedlowski, James Matos Sampaio, Leidi Cahola Ramírez Castrillón, Reuber Albuquerque Brandão, Andréa Leme da Silva, et al. A worrying future for river flows in the brazilian cerrado provoked by land use and climate changes. Sustainability, 15(5): 4251, 2023.

Kayla D. Stan, Arturo Sanchez-Azofeifa, and Ralf Ludwig. Sustainability of costa rica's water supply under climate change scenarios. Environmental Science Policy, 136:67–77, 2022. doi: 10.1016/j.envsci.2022.05.021.

UN. System of environmental-economic accounting for water. Technical report, United Nations, 2012.

Ulrike Wachsmann, Richard Wood, Manfred Lenzen, and Roberto Schaeffer. Structural decomposition of energy use in brazil from 1970 to 1996. Applied Energy, 86(4):578–587, 2009. doi: 10.1016/j.apenergy.2008.08.003.

Bin Wang, Xiao Luo, Young-Min Yang, Weiyi Sun, Mark A. Cane, Wenju Cai, Sang-Wook Yeh, and Jian Liu. Historical change of el niño properties sheds light on future changes of extreme el niño. Proceedings of the National Academy of Sciences, 116:45, 2019. doi: 10.1073/pnas.1911130116.

Xiaomeng Wang, Kai Huang, and Yanjie Xu Yajuan Yu, Tingting Hu. An input-output structural decomposition analysis of changes in sectoral water footprint in china. Ecological Indicators, 69:26–34, 2016. doi: 10.1016/j.ecolind.2016.03.029.

WorldBank. Climate risk country profile - brazil. Technical report, The World Bank Group, 2021a. URL https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15915-WBBrazil%20Country%20Profile-WEB.pdf.

WorldBank. Climate risk country profile - colombia. Technical report, The World Bank Group, 2021b. URL https://climateknowledgeportal.worldbank.org/sites/default/files/2021-07/15520-WBColombia%20Country%20Profile-WEB%20%283%29.pdf.

WorldBank. Climate risk country profile - costa rica. Technical report, The World Bank Group, 2021c. URL https://climateknowledgeportal.worldbank.org/sites/default/

files/country-profiles/15989-WBCosta%20Rica%20Country%20Profile-WEB.pdf.

WorldBank. Databank: World development indicators. Technical report, The World Bank Group, 2023. URL https://data.worldbank.org/?locations=BR-CO-CR.

Yiling Xiong, Xin Tian, Shangwei Liu, and Zhipeng Tang. New patterns in china's water footprint: analysis of spatial and structural transitions from a regional perspective. Journal of Cleaner Production, 245: 118942, 2020.

Dandan Zhao, Junguo Liu, Hong Yang, Laixiang Sun, and Olli Varis. Socioeconomic drivers of provincial-level changes in the blue and green water footprints in china. Resources, Conservation and Recycling, 175:105834, 2021.