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THE IMPORTANCE OF EFFICIENT WATER PLANNING AND MANAGEMENT FOR AGRICULTURAL USE IN URABÁ DARIEN, COLOMBIA

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ABSTRACT

Integrated water management is one of the most significant challenges for industrial and subsistence agriculture in the context of global change. This situation necessitates a reconsideration of resource planning through democratic and participatory approaches. This study examines how technical, economic, social, political, historical, and ecological factors shape the need to develop strategies for water-use planning and management in agriculture in Urabá, Antioquia. The methodological process included the following: (i) formulation of the research question and objectives; (ii) general literature search; (iii) selection of references through an interdisciplinary lens contributed by various researchers; (iv) analysis of findings, identifying key themes and establishing connections among different perspectives; and (v) discussion of the results and formulation of conclusions to provide a clear and detailed perspective. Social violence and land grabbing have transformed the landscape, facilitated agricultural expansion, and produced direct effects on ecosystems, water demand, local food security, and population structure. Effective water management in Urabá is essential for sustainable development and must be integrated with technical, social, and environmental dimensions. It also emphasizes that the participation of local stakeholders is crucial for ensuring the equitable, efficient, and democratic use of water resources.

KEYWORDS: Agroecosystem, ecological factors, territorial development, socioecological systems, water governance, armed conflict, deforestation.

1. INTRODUCTION

The primary emphasis of agroecology is the study and development of resilient agrifood systems, a science of sustainability that integrates ecological, social, and economic concepts to support just and sustainable farming practices. This field studies the financial, cultural, and political factors that influence agroecosystems' biologic undefined and physicochemical interactions (Gómez et al., 2020). Other authors describe it as a transdisciplinary approach that integrates scientific principles with traditional and local knowledge to create production models that promote the efficient use of natural resources, such as water, while reducing environmental impacts and improving rural communities' livelihoods. This concept also provides a scientific framework for examining the planning and use of water for agricultural purposes in Urabá Antioqueño.

Water is especially important for agriculture, food security, agro-industry, and the livelihoods of millions of people worldwide (Kılıç, 2020). In Latin America and the Caribbean (LAC), managing water for agriculture is challenging because the sector is highly water-demanding and faces growing uncertainty from climate change (De Fraiture et al., 2010; Salazar et al., 2022). Agriculture is the main water user in the region, consuming between 35% and 86% of freshwater withdrawals, depending on the country and its specific conditions. The amount of water required for agriculture varies according to crop type, regional and climatic conditions, farming practices (such as rainfed versus irrigated systems, and conventional versus organic methods), crop varieties, growth cycles, and expected yields.

Although Latin America and the Caribbean have about 29 000 km^3 of water available each year, this figure can be misleading because water distribution across the region is highly uneven. For example, Brazil and Argentina have 5800 km^3 and 3050 km^3 per year, respectively, whereas Chile has only about 90 km^3. These differences illustrate how water availability directly influences usage patterns. In Argentina, for instance, agriculture can use about 86 % of national water use, whereas in Colombia, which also has significant water resources, the agricultural share is roughly 35 % (Salazar et al., 2022).

Moreover, climate change poses a challenge to water management due to altered precipitation patterns and increasing temperatures. These changes introduce greater uncertainty in water availability and modify hydrological regimes, thereby affecting hydraulic infrastructure planning and design and storage and distribution system operation. Consequently, the capacity to manage water resources is weakened, requiring urgent adaptation in water-use strategies (Hanjra & Qureshi, 2010).

In agricultural countries such as Colombia, the value added from agriculture, livestock, hunting, forestry, and fishing grew by 1.8 % in 2024, a rate 1.2 % above the national GDP growth (Caamal-Cauich, 2023). Sustaining this level requires intensifying water use (Carranza & Salinas, 2024). In addition, water demand and the blue water footprint have shown an increasing trend in recent years (IDEAM, 2023), and inadequate planning and management of water resources have compounded challenges, including soil salinization and contamination of water sources. Regardless of these challenges, strategies to optimize water use and reduce waste, such as improving irrigation practices and promoting resilient agricultural systems, must be implemented. Efficient and sustainable approaches are needed to ensure water security, strengthen the resilience of agricultural systems, and safeguard the sustainability of ecosystems and communities (Salazar et al., 2022).

Efficient water management for agriculture is crucial in Urabá, Antioquia, a strategic region in Colombia known for its significant economic contribution derived from agricultural production, particularly crops such as bananas (Toro-Trujillo et al., 2016), plantains, cocoa, and oil palms (Lombana Reyes, 2012). Water availability and quality Are key determinants of agricultural productivity and economic development in this region. Currently, this strategy focuses on improving water quality and availability, considering national policy and specific territorial and institutional contexts (Ministerio de Ambiente, Vivienda y Desarrollo Territorial, 2010). Through the formulation and implementation of management instruments, planning tools, and wastewater treatment measures aimed at reducing water contamination, efforts seek to ensure the functionality of natural and productive systems in the municipalities of the region, preserve the resource, and promote efficiency in its use and the protection of the ecosystems that depend on it. These efforts contribute to Urabá's sustainable development as an important banana-producing area in Colombia (Betancur et al., 2019).

However, this agro-industrial production has been shaped by historical processes that have transformed the region's ecological landscape and its cultural and social dynamics, interfering with the development of agroecological production systems that meet local food needs. In this context, the development of agricultural activities and effective water management requires the participation of local communities, particularly in rural and vulnerable territories. Ferreira Mariosa et al. (2024a) argued that the Social and Solidarity Economy promotes community collaboration in water governance through a decision-making process necessary to achieve equitable access to water (Ferreira Mariosa et al., 2024b).

Hence, Ostrom (2000) assumed that resources such as water are defined by the inherent tension between their regenerative capacity (stock) and the extraction of their use units (flow), making regulation necessary to prevent overexploitation. Ostrom underscores that water, a common-pool resource, requires flexible actions that balance appropriation rights with maintenance responsibilities, thereby avoiding the "tragedy of the commons" through adaptive rules and collective oversight. This governance approach seeks to Move beyond exclusionary privatization and ineffective centralized regulation (Ostrom, 2000), an institutional challenge that still requires strengthening in the Urabá region of Antioquia.

This article provides a comprehensive analysis of the technical, economic, social, political, historical, and environmental factors that underscore the need to develop water-use planning and management strategies for Urabá's agriculture. Advancing this process requires a higher-order governance framework that supports agro-industrial development and small- and medium-scale agricultural producers without compromising domestic water supply or ecosystem integrity.

2. MATERIAL AND METHODS

This study is based on a systematic and interdisciplinary literature review, designed to synthesise existing knowledge on water planning and management for agricultural use in the Urabá-Darién region of Colombia. The methodological process comprised five sequential stages (as shown in Table I):

Table I. Methodological aspects of the narrative literature review.

Processes associated with the narrative review of literature related to the topic of interest	**Key methodological aspects**
i) Formulation of the research question	Technical, economic, social, political, historical, and Ecological factors influence the need to develop strategies for planning and managing water use in agriculture in Urabá, Antioquia?
ii) Extensive bibliographic Search	Search engines, bibliographic databases, and institutions repositories were consulted, such as 1) Google Scholar, which allows most of these documents to be located and redirects them to their original sources, and 2) Google Earth Engine, which is used for the construction of location maps, coverage loss, and land use. 2) Official institutional websites in Colombia CORPOURABÁ, IDEAM, DANE, Banco de la República, and the Ministry of Environment; and global websites, such as FAO, WHO, and UN. 3) Open-access Colombian journals, such as Nova, Razón Crítica, Inclusión y Desarrollo, and Revista Politécnica, sometimes indexed in Latindex, Redalyc, or Dialnet, in addition to their own websites. 4) Open access publishers. 5) Bibliographic databases such as ScienceDirect (Elsevier), Springer Link Science (AAAS), SciELO, PLOS ONE, MDPI (Forests), Taylor & Francis Online, and Wiley Online Library.
iii) Reflexive interdisciplinary selection of bibliographic references	Once each bibliographic source was collected and Analysed, the relevant information was selected and processed to answer the research question from each of the researchers' disciplinary perspectives.
iv) Analysis and interpretation of the findings	Key themes were identified through critical reading and ongoing comparison of ideas and viewpoints. The perspectives of different authors were contrasted, which allowed the findings to be validated, and their interpretation enriched through analytical triangulation.
v) Discussion of the results and drawing of conclusions	The main themes were analysed using the study findings and information. The conclusions provide useful evidence for practice, policy, or future research while remaining true to academic standards and the careful methods used in qualitative descriptive studies.

3. RESULTS AND DISCUSSION

3.1. Geospatial and Socioeconomic Aspects of the Antioquia Urabá Region

Located northwest of Colombia (as shown in

Figure 1). It is one of the nine subregions of the Department of Antioquia, covering an area of 11664 km², which constitutes 18.66% of the department's total territory, making it the largest subregion. Its strategic geographic location borders the Caribbean Sea to the north, the Chocó department to the south, Córdoba and other Antioquia subregions to the east, and again with Chocó to the west (Gobernación de Antioquia, 2023). This area lies within the Chocó-Darién Global Ecoregion, which comprises three sectors of humid forests: 1. Magdalena-Urabá, and 2. Chocó-Darién, areas directly influencing Antioquia's Urabá region, and the southern region between Colombia and Ecuador, known as Western Ecuador (Fagua & Ramsey, 2019).

In addition, the Urabá region includes 11 municipalities distributed across three distinct zones. In the northern region, comprising the municipalities of San Juan de Urabá, San Pedro de Urabá, Necoclí, and Arboletes, this area is the Caribbean zone. The central zone includes Turbo, Apartadó, Carepa, Chigorodó, and Mutatá. Finally, in the Atrato Medio zone Are the municipalities of Murindó and the Vigía Del Fuerte (Henao Rodríguez et al., 2020) (as shown in Figure 1). The region's topography ranges from 0 to 1250 m above sea level in its easternmost areas, particularly in the Serranía de Abibe and other smaller mountain systems. The Intertropical Convergence Zone (ITCZ) influences the climate, which regulates annual precipitation levels from 1500 to 4000 mm. The region is classified as warm semi-humid, with an average temperature of 21.1°C–28°C and a relative humidity of 85.9 % (Corporación para el Desarrollo Sostenible del Urabá, 2019; Pedraza et al., 2024). Rainfall is concentrated between April and December, followed by a dry period from January to March.

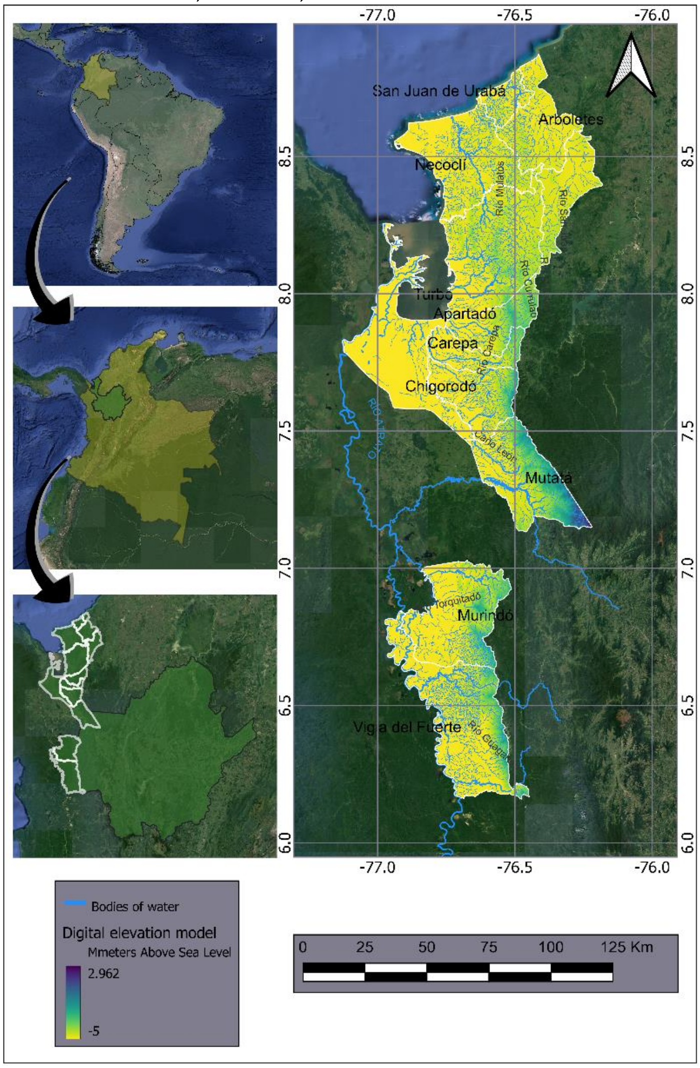

Figure 1. Location of the Study Area.

At the national level, the banana crop accounts for more than 75% of total fruit production. In this region, the economy is centered on banana production, a key activity that generates significant regional and national income (DANE, 2019). According to Kalmanovich and López (2006), banana crops in the Urabá region of Antioquia began with the Gros Michel variety introduced by the Albingia consortium in the early 1960s, driven by the interest of the U.S. multinational United Fruit Company. The company initiated Uraba's banana exports in 1964, marking the beginning of the region's development As a Major banana-producing area. By 1966, Urabá accounted For 74.3 percentage of national exports by 1966, and during the 1970s, 90 percentage of the national banana production originated in the Urabá region of Antioquia. This share decreased to ~70 percentage in the 1980s due to local armed conflict.

This crop became the regional economy's axis, around which a new territorial, political, and social reality emerged. However, none of these transformations were driven by consensus-building processes or efforts to promote the population's social well-being. Violence, dispossession, and overexploitation became the forces that shaped the region's history from that point onward (Lombana Reyes, 2012). This reveals the origins of banana plantations in Urabá during the 20th century, a phenomenon associated with the influx of agricultural labor from the northern coastal zone and the interior of Colombia, particularly Afro-descendant populations from the departments of Bolívar and Chocó.

Likewise, from the savannas of Córdoba and Sucre, a population descended from Black and Zenú Indigenous groups arrived in the region in the early twentieth century as workers during the expansion of the agricultural frontier. This group has been locally referred to as "Chilapos", a term that has become widespread in northwestern Colombia to describe people from the Caribbean lowlands. The term originates from the vocabulary of sawyers and refers to the remnants of a log left after extracting the central, homogeneous, and fine blocks; that is, leftover pieces that are not used despite having contributed to the growth of the tree (Molano & Ramírez, 1996, in Gálvez et al., 2009). The Chilapo group played a central role in expanding the agricultural frontier in the Córdoba, Sucre, and Urabá regions through timber extraction. They became the primary agents in transforming forests into pastureland, working as sawyers hired by intermediaries who commercialized timber in Antioquia and later consolidated cattle ranches. This process began with forest clearing, followed by burning vegetation and the establishment of temporary dryland maize and/or rice crops, thereby taking advantage of the soil fertility for 1 year. Once the harvests were completed, the growth of pastures transplanted from other farms was promoted along with periodic weeding of new trees and invasive plants. Months later, this enabled the establishment of cattle production. This process, which has severely threatened biodiversity sanctuaries, such as those in the Chocó–Darién, has also been documented in the Amazonas (FAO, 2012; Martino, 2007) and Córdoba (Ocampo, 2007) departments.

This agricultural transformation attracted not only Afro-descendant and chilapo laborers but also peasants from the interior of the country who became incorporated into the plantations. As the industry expanded, the Sindicato de Trabajadores Agropecuarios de Antioquia (SINTRAINAGRO) and the Sindicato de Trabajadores Bananeros (SINTRABANANO) emerged. These unions later formed associations with the guerrilla groups Esperanza, Paz y Libertad (EPL), and the Fuerzas Armadas Revolucionarias de Colombia (FARC) (Ramírez, 2001; Álvarez Salas & Gálvez, 2014). Furthermore, these guerrilla groups played a role in one of the most emblematic massacres of the armed conflict, which was carried out by the FARC in the SINTRAINAGRO workers' neighborhood known as La Chinita.

Later, self-defense groups emerged as a response of landowners and local business elites seeking protection from guerrilla forces. However, their evolution into armed organizations with autonomous agendas became consolidated with the creation of the Autodefensas Unidas de Colombia (AUC) in the 1990s, from which the Autodefensas Campesinas de Córdoba y Urabá (ACCU) were established. The paramilitary incursion into Urabá by the ACCU was carried out by the Bloque Bananero and the Bloque Elmer Cárdenas, bringing a wave of violence and repression. Their strategies to control drug trafficking routes include massacres and forced displacement, pushing the use of fertile lands for agro-industrial expansion, defeating guerrilla groups, imposing territorial control, eliminating resistance, and disciplining the labor force (Ortiz-Lancheros, 2022; Morales Correa, 2020). Their presence also affected the local government, leading to corruption within institutions and agricultural enterprises, as well as the manipulation of electoral processes (Correa, 2020). Despite the disarmament efforts of the AUC in the 2000s, the region continues to deal with the consequences of the conflict, including reparations and reconciliation.

In 2017, the Fiscalía General de la Nación charged several banana companies with aggravated criminal conspiracy for financing the ACCU's Bloque Bananero. In 2024, the U.S. District Court for the Southern District of Florida, based in Miami, ruled in favour of a group of Colombian victims in a case against Chiquita Brands International, ordering the company to pay compensation to nine families affected by forced disappearances. The ruling was based on evidence that Chiquita had made payments to the AUC between 1997 and 2004 totalling approximately USD 1.7 million, funds that facilitated the expansion and operational capacity of these groups in regions such as Urabá, where they perpetrated massacres and disappearances. The Miami ruling not only recognized the suffering endured by victims and their families but also underscored corporate responsibility in armed conflicts and set an important precedent for future cases concerning business accountability for human rights violations (Correa, 2020).

Thus, once dominated by natural forests and small dispersed peasant plots, the landscape underwent a violent process of land concentration, resulting in the proletarianization of the peasant population or their forced displacement to regional peripheries, thereby expanding the agricultural frontier. The initial 10 000 Ha allocated for banana cultivation in 1960 increased to 19 300 Ha by 1982. Another crop with a similar growing area pattern was the African palm rose, growing from 351 hectares in 1977 to 2260 hectares in 1982 (Lombana, 2012).

3.2. The Crucial Role of Forests and Water in Urabá

Tropical deforestation contributes to global climate change and represents the second-largest net source of greenhouse gas (GHG) emissions into the atmosphere after fossil fuel (van der Werf et al. 2009). From 1996 to 2021, forest cover in the Magdalena–Urabá ecoregion declined from 43350 ha during 1996–2000 to 37763 ha during 2015–2021, while non-forest areas increased from 4004 ha to 49223 ha over the same period, affecting rural zones in the region (Pedraza et al., 2024). A close relationship exists between the loss of primary forest cover and the proximity to pasture installation for cattle ranching, zones of agricultural specialization, and river corridors in the central and northern zones of the study area. These correspond to interactions between proximate and underlying causes related to infrastructure expansion, commercial agriculture growth, soil fertility, and demographic dynamics. This pattern contrasts with global temporal trends in deforestation, in which agricultural export markets and urban expansion replaced the primary drivers of tropical forest conversion, historically linked to directed colonization and rural population growth (Rudel et al., 2009; DeFries et al., 2010).

In the Urabá region, a long history of illegal logging and unregulated forest exploitation has contributed substantially to Forest cover loss. Timber extraction for commercial and domestic use, often conducted without permits and within protected areas, has degraded forest areas, fragmented habitats, and affected local biodiversity. According to CORPOURABA, illegal logging remains a persistent threat to the remaining forests in the region, intensified by inadequate and ineffective monitoring in remote areas. Thus, in the Urabá region, multiple coexisting and correlated factors are driving deforestation (Ramírez Sosa and Orrego Suaza, 2011), contributing to disturbances in the hydrological cycle that affect water availability for agriculture and human consumption. These effects Areare worsened by factors such as precipitation and temperature, as well as by topography and soil characteristics associated with the orobiomes and pedobiomes of the region (Pedraza et al., 2024).

Between 2000 and 2023, forests in the area declined significantly, affecting water bodies, rivers, streams, and aquifers, as well as the standard of living of communities that depended on these resources (as shown in Figure 2). Using data from Google Earth Engine (2024), we found that the Urabá region has lost approximately 70000 ha of forest: 13821 ha of forest were lost between 2000 and 2004 (19.7 %); forest loss then increased to 16770 Ha between 2005 and 2009 (23.9 %), reaching a peak of 17,857 ha between 2010 and 2014 (25.5 %). Between 2015 and 2019, deforestation decreased to 13435 Ha (19.2 %) and declined further to 8227 Ha (11.7 %) between 2020 and 2023. This pattern reveals strong anthropogenic pressure on forest ecosystems, with apparent recent shifts possibly linked to conservation efforts or reduced exploitation of forest lands, including the effects of the COVID-19 pandemic and the post-pandemic period, although the cumulative impacts of the earlier period have left a substantial footprint.

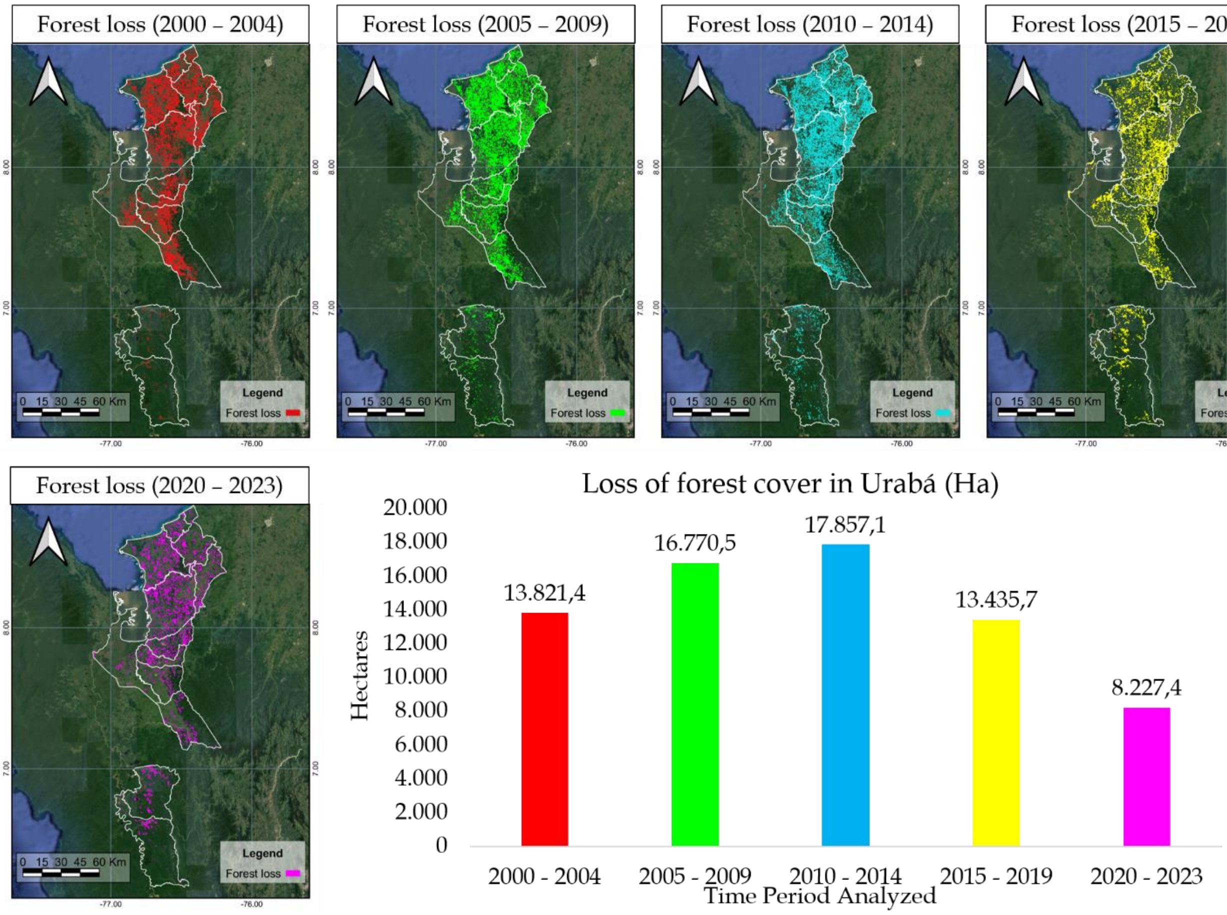

Figure 2. Forest cover loss in Urabá (2000-2023).

Data obtained from Google Earth Engine, 2024

Deforestation in Urabá can significantly affect the natural regulation of the water cycle by reducing tree cover and altering soil infiltration capacity, water balance, and aquifer recharge, which leads to lower river base flows during the dry season (Ellison et al., 2017). Similarly, Bonan (2008) explained that deforestation could leave vulnerable communities in the region due to accelerated surface runoff and reduced water retention capacity. Forests act as natural sponges, mitigating both flooding during the rainy season and water scarcity during dry periods.

Bruijnzeel (2004) noted that deforestation has significant repercussions on the region's water quality. Soil erosion increases in areas where Forest cover has been severely reduced, leading to the transport of sediments and nutrients from affected areas into water bodies, thereby changing water turbidity and physicochemical quality. In the Case of Urabá, this has led to an increased sediment load in key rivers, such as the Atrato and the León. Foley et al. (2005) also report that erosion and subsequent sediment accumulation affect aquatic ecosystems, altering the habitats of critical species and thereby affecting local biodiversity.

According to Rodríguez et al. (2011), the relationship between deforestation and limited water availability for drinking and irrigation directly impacts food security among rural populations, especially those reliant on subsistence agriculture. The reduction in water quality and its contamination by sediments or agrochemicals increase the risk of waterborne diseases, including diarrhea, one of the leading causes of morbidity in vulnerable communities with limited access to treated drinking water (Prüss-Ustün et al., 2008). In Urabá, where sanitation infrastructure is limited, the deterioration of water quality intensified by deforestation places an additional public health burden on rural populations.

3.3. Local Water Conditions

In this region, four major watersheds have been identified: the Turbo–Currulao, León, Río Sucio Alto, and Medio Atrato rivers. In addition, the region contains an important hydrogeological system of groundwater resources. The main characteristics of this hydrological system are as follows: The Turbo–

Currulao watershed is characterized by a humid climate and includes premontane humid forest (bh-PM) and tropical very humid forest (bmh-T). This region stands out for its high endemism and biodiversity, resulting from the interaction among climate, topography, geological processes, and precipitation. The piedmont, which corresponds to the final foothills of the Serranía de Abibe, has elevations below 200 m above sea level and consists of heavily altered areas with only limited remnants of natural forest. Large quantities of sediments accumulate in this zone during the rainy season, increasing streamflow levels. Although the soils have low agricultural capacity and a natural forest vocation, temporary crops such as maize, cacao, rice, cassava, fruit trees, and murrapo are cultivated (Minambiente et al., 2018).

The banana-producing zone lies in the alluvial fan, characterized by sediments of alluvial and hillside origin. Banana and plantain agriculture predominates here, alongside extensive low-productivity cattle ranching and a small proportion of smallholder farming. The coastal complex, which includes the Gulf of Urabá, estuaries, and mangroves, is shaped by waves, wind, tides, and marine currents, which favor a natural landscape and limit commercial land use. Lastly, the hill system, formed by the foothills of the mountain range, contains soils with a good amount of organic matter, although these areas are heavily altered and retain only limited remnants of natural forest (Minambiente et al., 2018). Within this watershed, CORPOURABÁ has established a monitoring network of 128 stations since 2002, measuring in situ parameters such as pH, temperature, electrical conductivity, and dissolved oxygen, as well as laboratory analyses of nitrates, total coliforms, COD, and BOD. In 2018, the ICA reported poor water quality for the resource, with some sections showing only fair conditions (Minambiente et al., 2018).

For its part, the Río León watershed is located in the municipalities of Mutatá, Chigorodó, Carepa, Apartadó, and Turbo. It covers an area of 220137.82 Ha and has the Grande, Apartadó, Carepa, Chigorodó, Guapa, Juradó, and Villarteaga rivers its main tributaries. Of this total, 99.49% of the watershed is in rural territory (219017.47 Ha) and 0.51% is in Urban territory (1120.35 Ha). The River originates in the southwestern foothills of the Serranía de Abibe, North of Mutatá, and flows into the Gulf of Urabá in Turbo. The Paramillo National Natural Park lies in its upper basin. It borders to the east with the Sinú River watershed and to the West with the Río Sucio watershed, a tributary of the Atrato River. The Río León watershed is located within the Urabá Basin, which is part of the Caribbean Basin, situated in the northwestern corner of South America on the Caribbean Plate, which is bounded by the North American, South American, Cocos, and Nazca Plates. The watershed is classified into five regions: fluvial, fluvial-denudational, marine, structural-denudational, and structural.

Within this territory are the Indigenous Reserves of Yaberaradó, Polines, Las Playas, Jaikerazavi, Dokerazavi, and La Palma, as well as the Afro-descendant Community Councils of Puerto Girón, Los Mangos, and Manatíes (Fondo Adaptación et al., 2019c). Since 2004, CORPOURABÁ has conducted water-quality monitoring in rivers of the watershed using the NSF Water Quality Index (ICA-NSF), which evaluates water quality As a General attribute of surface waters. In the Río León watershed, 52%, 32%, and 16% of the monitoring stations showed medium, good, and poor water quality, respectively (Fondo Adaptación et al., 2019a).

A third major watershed in the region is the Río Sucio Alto watershed, which is in the western subregion of Antioquia and covers an area of 217,475.11 hectares, encompasses the municipalities of Abriaquí (13.65%), Cañasgordas (16.76%), Dabeiba (40.88%), Frontino (16.49%), and Uramita (12.22%). It is one of the main Atrato River tributaries. The watershed includes 229 rural settlements (called veredas), 14 administrative districts (corregimientos), and the municipal seats of these municipalities. This watershed is part of the Caribbean Hydrographic Area, within the Caribbean Coastal Hydrographic Zone and the Atrato–Darién Subzone, and is affected by one of the most severe desertification processes in Colombia, which is critically affecting some areas. Additionally, eight certified Indigenous Reserves are in its vicinity, inhabited mainly by the Embera and Embera Katío peoples, including the Chuscal, Tuguridocito, Sever, and Santa María el Charcón reserves (Minambiente et al., 2019a, 2019b). Water quality measurements conducted by CORPOURABÁ show that although parameters such as pH, dissolved oxygen, and BOD comply with regulations, levels of total suspended solids (TSS) and Escherichia coli exceed permitted limits. High nitrogen and phosphorus concentrations have also been identified, which could lead to eutrophication, particularly during the dry season. Furthermore, the ICA indicates better water quality at higher-altitude stations, whereas lower-basin stations exhibit greater problems influenced by human activities, such as livestock production, which places pressure on hydrological systems and reduces their self-purification capacity during dry years (Minambiente et al., 2019c).

Lastly, according to the Ministry of Environment and Sustainable Development (2016), the middle basin of the Atrato River is in the Chocó department and forms part of the Chocó Biogeographic area, which is characterized by high biodiversity and 71% forest cover (2,696,402 ha), making it highly susceptible to environmental pressures. It is one of the world's rainiest regions, with a hydrological network extending 750km. The river, which originates in Carmen del Atrato and flows into the Gulf of Urabá, has a large discharge, reaching 5000 m^3/s. The basin, rich in biodiversity and minerals such as platinum and gold, has been exploited since the fifteenth century, generating socio-environmental conflicts, particularly in the middle basin, in municipalities such as Paimadó and San Isidro. Historically, artisanal and industrial mining have intensively exploited the river, resulting in severe ecological problems, including mercury contamination affecting local communities. In response, Ruling T-622 of 2016 sought to mitigate these impacts by promoting more sustainable river management while considering the traditional practices of ethnic communities, such as the Emberá Katío, who have historically managed the river sustainably (Jurado & Urrea, 2023).

Agricultural and livestock activities occupy 16% of the area (611,198 ha), whereas water bodies cover 3.46%. Terrestrial (74%) and aquatic (25%) ecosystems predominate, including the basal floodplain forest, which covers 400,962 ha. Consequently, illegal mining and forest exploitation have caused deforestation and contamination with mercury and cyanide. In total, 690132 Ha have been deforested, representing 19% of the basin area. The Quito River (64%) and the Cacarica River (46%) are the most affected areas. Mining activities in these municipalities release between 0.88 and 2.5 tons of mercury annually (Ministry of Environment and Sustainable Development, 2016), and this contamination poses serious health risks to communities in Quibdó, Río Quito, and Cantón de San Pablo, where blood mercury levels exceed the World Health Organization (WHO) limits.

The groundwater is significant in the region, supplying both Urban and rural populations and serving the banana industry. Consequently, its demand exceeds 24 million cubic meters of groundwater per year. The groundwater hydrogeological system of Urabá comprises a shallow unconfined aquifer and a confined multilayer aquifer, formed by a complex sequence of permeable and semipermeable layers and lenses. Thus, the unconfined aquifer receives direct and diffuse recharge, while the multilayer system is fed from areas where it outcrops in the Serranía or through percolation from the unconfined aquifer across clay layers at its base (Betancur Vargas et al., 2020). This shows that water resources in the region Are abundant and highly important to ecological and socioeconomic systems; however, water sources undergo significant structural and quality changes, hindering their availability. Aristizabal-Tique et al. (2024) argued that although there is a diversity of research on the coastal ecosystem of the Gulf of Urabá, there is a lack of specific studies addressing water quality in the rivers, particularly those linked to agricultural production, and the monitoring of physicochemical and microbiological parameters in water bodies.

A previous study revealed that the waters of the Turbo, Guadualito, Currulao, Arcua, Grande, Apartadó, Zungo, Carepa, Chigorodó, and León rivers, which together constitute the Río León watershed, exhibit significant variations in the correlations of pH, BOD_5, and COD with respect to coastal distance. These correlations indicate a possible seawater intrusion, which is potentially associated with the overexploitation of aquifers and surface waters. Rivers near populated areas, such as those in Apartadó, showed poor water quality due to inadequate sanitation systems, posing ecological risks in the absence of wastewater treatment infrastructure. In contrast, the León River exhibited superior water quality, benefiting from more natural conditions. The authors emphasize the importance of continuous monitoring to ensure water resource quality. Furthermore, community participation and education are crucial factors for ensuring the sustainability of agro-industrial processes, where the adoption of sustainable practices and effective management is necessary to promote better water quality and maintain productivity, both essential for developing the strategic planning and management required through the coordinated action of various territorial entities, community organizations, and both public and private sectors.

3.4. Challenges in the management of agricultural water use in the Antioquia Urabá region

Despite the abundance of water in the Urabá region of Antioquia, it faces several challenges in managing this resource for agricultural use (Pérez-Valbuena, 2007), including competition for water resources among sectors, such as agriculture, livestock production, industry, and tourism, as well as contamination of water from the use of agrochemicals and deforestation (Camacho, A. & Pérez, S. (Comps.), 2014). On the other hand, climate change is intensifying climate variability, which may affect water availability and agricultural productivity in the future (Pérez-Valbuena, 2007; Camacho & Pérez, 2014). This phenomenon impacts strategic areas and ecosystems, including the mangroves of the Gulf of Urabá; the Serranía de Abibe, where the region's main rivers originate and where aquifer recharge occurs, and the wetlands associated with the León, Atrato, and Suriquí rivers (Minambiente et al., 2019; Fondo Adaptación et al., 2019b). All these conditions unfold in the context of armed conflict, which has driven control over resources, altered relationships between communities, and affected water and soil availability. This scenario demands consideration of the society-nature relationship, power structures, and the democratization of access to information to promote transparency in resource management.

According to Álvarez et al. (2014), the Urabá region of Antioquia can be analyzed through the notion of complex systems, based on the relationship between society and nature, resulting in the transformation of the natural landscape to an agricultural production system characterized by monoculture and low-productivity plantations (as shown in Figure 3). This system relies on modified seeds, intensive agrochemical application, and large-scale infrastructure for postharvest processing and agricultural product transportation.

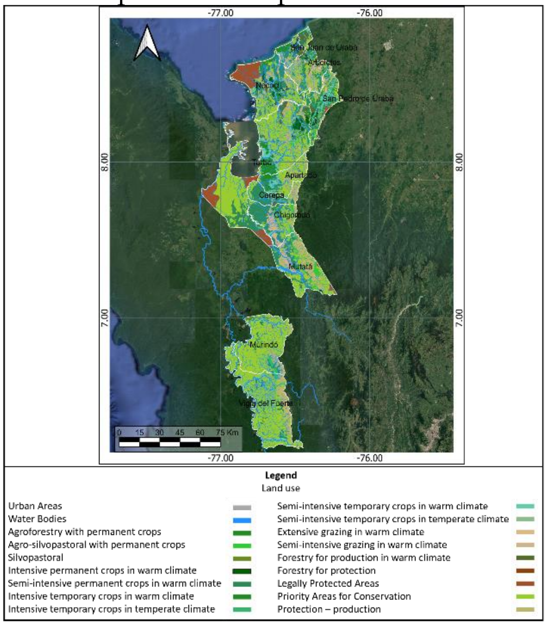

Figure 3. Land Use and Agricultural Practices in the Urabá Region of Antioquia.

Specifically, banana cultivation requires adequate water to achieve ideal productivity and yield. Toro-Trujillo et al. (2016) calculated irrigation requirements and predicted yields for banana crops in the Urabá region of Antioquia using a simulation model, as shown in Table 2.

Table 2: Relationship between water requirement and banana crop productivity.

Scenario	Planting Date	Water Volume (m^3/ha)	Approximate yield (t/ha)	Interpretation
Wet (20%)	Dry Season	2000–3000	30-35	The yield is high with a moderate water supply. However, in dry seasons, the yield May be lower due to the need for irrigation during critical periods.
	Wet Season	1800–2800	28-33	Yields may be lower in wet seasons due to reduced irrigation, but adequate supply during dry periods improves yields.
Average (50%)	Dry Season	2200–3200	32-37	A regular water supply in dry seasons provides good yield. The yield is higher in the wet scenario than in the dry scenario due to increased irrigation during critical periods.
	Wet Season	1900–2900	30-35	In wet seasons, the yield remains consistent with that in the dry season due to sufficient water supply during the rainy season.
Dry (80%)	Dry Season	2500–3500	35-40	High water supply during dry seasons optimizes

Scenario	Planting Date	Water Volume (m³/ha)	Approximate yield (t/ha)	Interpretation
				yield, although it may lead to higher associated costs. The crop thrives with increased water availability throughout the growth period.
	Wet Season	2200–3200	32-37	A reliable water supply is crucial for achieving high yields, although less critical than dry conditions. Maintaining adequate irrigation during the rainy season enhances crop yields.

Source: Toro Trujillo et al. (2016).

These data suggest that an adequate water supply is crucial for maximizing banana crop yield. In dry scenarios, where water is more limited, yield can improve with higher irrigation volumes, whereas yield can also be good in wet scenarios. However, the exact water volume is less critical.

Thus, water planning and management necessitate multidimensional and historical readings. Without understanding this aspect, grasping the transformation of phenomena and the structuring and destructuring of systems is impossible. The Urabá region demonstrates that systems change continuously in structure and function from the actors involved in the processes and power relations that shape them. Ultimately, what drives or modifies the system is power relations, which determines the information flows and access to that information for decision-making.

In this context, coordination between water management and participatory governance depends on a robust institutional framework that fosters multilevel cooperation. Bauby (2011) emphasized that water governance must be grounded in collaboration rather than competition, requiring diverse stakeholders, ranging from local authorities to regulatory agencies. More recently, Pahl-Wostl (2015) argued that adaptive water governance — which emphasizes continuous learning, flexible decision-making, and stakeholder participation under uncertainty— is essential for managing water resources in Urabá, a region affected by climate variability and social conflict. Complementing this view, the OECD (2025) highlights those Latin American countries, including Colombia, face persistent challenges in aligning local water management with national policies and recommends the creation of multi-stakeholder platforms that integrate technical, social, and political dimensions. Brazil's National Water Resources Management System exemplifies this approach by incorporating collegiate bodies that design water policies through participatory processes (Ferreira Mariosa et al., 2024a). Participatory and ecosystem-based approaches are essential for ensuring long-term water security in vulnerable tropical regions, as noted by the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Water program (2023), particularly where agriculture and armed conflict have historically shaped water access and land use.

The purpose of sustainability science is to generate research and knowledge that supports decision-making, ensuring that actors have a voice and can make decisions regarding their own realities. Understanding that the flow of information among system actors is critical for recognizing reality and enabling informed decisions is essential. Consequently, more sustainable approaches to water resource planning and management can fill the gaps created by the lack of information and distortions in information flows.

When information flows horizontally, the ability to access, understand, and process it enables more rational decision-making. However, only when actors become aware of their political role and the power inherent in them can research conducted within the framework of sustainability fulfill its social and political function of contributing to the transformation of reality.

4. CONCLUSIONS

Water-resource planning for the agricultural sector in the Urabá region of Antioquia is indispensable for ensuring food security, promoting economic development, and preserving the environment. In this regard, a multifactorial approach is proposed that combines the analysis of environmental characteristics, such as climate, topography, and biomes, with social processes, such as urban and agro-industrial infrastructure, economy, culture, and historical and political dynamics. Such an approach would facilitate understanding of the nature–society interrelations that are essential for addressing current and future challenges in water management and for promoting sustainable development in the region, ensuring water availability in Urabá.

Therefore, planning and management processes must be conducted through an integrated approach that, in addition to considering technical, economic, social, cultural, and political aspects, involves the participation of diverse institutions and actors across multiple settings, grounded in the historical and environmental context that has shaped the reality of the Urabá region of Antioquia. This condition may serve as a reference framework to generate impact through careful, collaborative planning for the sustainable management of water in the region's strategic agricultural and ecological zones.

In the face of climate change and regional development challenges, sustainable water management in Urabá is important: integrating watershed conservation policies, appropriate soil management, and sustainable agricultural practices can mitigate negative impacts and ensure long-term availability. Involving local communities in decision-making and fostering environmental education are key steps toward a more equitable and efficient use of water resources.

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