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Hydrology, water chemistry, and sediment dynamics of fluvial ecosystems of Venezuela: A systematic review

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ABSTRACT

Hydrology, water chemistry and sediment dynamics of fluvial ecosystems of Venezuela: A systematic review.

Venezuela has a vast and diverse network of rivers and streams that provide essential water resources and ecosystem services, supporting a high biodiversity. This review aims to consolidate knowledge on the abiotic characteristics, hydrology, water chemistry, and sediments of these fluvial ecosystems from 1993 to date, while highlighting key research areas. Over the past three decades, advancements have been made in understanding the physical and chemical properties of these environments. A systematic literature review identified 209 relevant publications, averaging 34 studies every five years. Most studies have focused on the Orinoco River Basin, covering 655 000 km² of Venezuela's land area. Consequently, the distribution of research sites was uneven, with 59% of studies concentrated in the Orinoco basin, followed by 14% in the Caribbean versant, and 11% in the Lake Maracaibo basin. Other basins, such as Paria-San Juan and Casiquiare-Negro, were notably underrepresented. The results revealed that 46% of the studies examined aspects of river hydrochemistry, 30% focused on hydrology, and 24% addressed sediments. The studies emphasized the importance of understanding hydrological dynamics, particularly in forecasting discharge and water levels in watersheds with large hydroelectric dams. While the database of fluvial ecosystems has increased, it is essential to continue these data collections in order to anticipate responses from human activities and climate change. Although the Orinoco, Caribbean, Lake Valencia, and Lake Maracaibo basins have received considerable attention, much of the knowledge is outdated. Additionally, the watersheds of Paria-San Juan, Casiquiare-Negro, and Cuyuní-Essequibo require urgent research due to recent environmental degradation.

KEY WORDS: water chemistry; fluvial physical characterization; tropical rivers; Orinoco; flood pulse; bibliometric analysis

RESUMEN

Hidrología, química de agua y dinámica de sedimentos en los sistemas fluviales de Venezuela: una revisión sistemática.

Venezuela cuenta con una vasta y diversa red de ríos y arroyos que brindan recursos hídricos esenciales y servicios ecosistémicos, que combinados sustentan una alta biodiversidad. Esta revisión tiene como objetivo consolidar el conocimiento sobre las características abióticas (hidrología, química del agua y sedimentos) de estos ecosistemas fluviales desde 1993 hasta el presente, al tiempo que destaca las áreas de investigación clave. La mayoría de los estudios se han centrado en la cuenca del río Orinoco, que abarca 655 000 km² de la superficie terrestre de Venezuela. Durante las últimas tres décadas, se han logrado avances en la comprensión de las propiedades físicas y químicas de estos ambientes. Una revisión sistemática de la literatura identificó 209 publicaciones relevantes, con un promedio de 34 estudios cada cinco años. Sin embargo, la distribución de los sitios de investigación fue desigual: el 59% de los estudios se concentraron en la cuenca del Orinoco, seguido del 14% en la vertiente del Caribe y el 11% en la cuenca del lago de Maracaibo. Otras cuencas, como Paria-San Juan y Casiquiare-Negro, estuvieron notablemente subrepresentadas. La investigación reveló que el 46% de los estudios examinaron aspectos de la hidroquímica de ríos, el 30% se concentró en la hidrología y el 24% abordó el tema de sedimentos. Los estudios enfatizaron la importancia de comprender la dinámica hidrológica, particularmente en la previsión de descargas y niveles de agua en cuencas hidrográficas con grandes represas hidroeléctricas. Si bien la base de datos de ecosistemas fluviales ha aumentado, es esencial continuar con la recopilación de estos datos para anticipar las respuestas a las actividades humanas y al cambio climático. Aunque las cuencas del Orinoco, el Caribe, el lago de Valencia y el lago de Maracaibo han recibido atención, gran parte del conocimiento está desactualizado. Además, las cuencas hidrográficas de Paria-San Juan, Casiquiare-Negro y Cuyuní-Esequibo requieren investigación urgente debido a la reciente degradación ambiental.

PALABRAS CLAVE: *caracterización física fluvial; ríos tropicales; Orinoco; pulso de inundación; análisis bibliométrico.*

INTRODUCTION

Hydrological aspects, water chemistry, and sediments are crucial components of aquatic habitats, significantly influencing biotic communities and overall ecosystem functioning (Allan et al., 2021; Hildrew & Giller, 2023). Hydrology determines the flow patterns, water levels, and seasonal variations that shape the physical environment of aquatic ecosystems, affecting the distribution and abundance of many species. Water chemistry, including parameters such as pH, nutrient levels, and dissolved oxygen, plays a vital role in supporting aquatic life, influencing processes like photosynthesis, respiration, and nutrient cycling. Sediments serve as both a habitat for benthic organisms and a reservoir for nutrients and contaminants, impacting food webs and ecosystem health. In addition, abiotic components of fluvial ecosystems are fundamental in providing important, valuable services to human communities, including water and energy provision, transportation and recreation, among others (Ferreira et al., 2023, Petsch et al., 2023).

The physiography of Venezuela with its heterogeneous orography (Andes, Guiana Shield and coastal ranges) and climate (Paredes-Trejo et al., 2020) has defined the country`s watersheds with more than 1100 streams and rivers, transporting more than 37 600 m^3/s of water across a diversity of ecosystems (Figs.1a-h) (Rengél-Avilés, 2018, Rodríguez-Olarte et al., 2019). In addition, this physiographic and climatic diversity also drive distinctive abiotic and biotic characteristics in streams and rivers associated to ten ecoregions (Abell et al., 2008) (Fig. 2a), that encompass seven watersheds: Orinoco, Casiquiare-Negro, Cuyuní-Essequibo, Paria-San Juan, Lake Valencia, Lake Maracaibo, and Caribbean drainages (Fig. 2b).

The Orinoco is the largest watershed collecting 85% of the runoff and dividing the country in two regions. In the region located north of the Orinoco (Fig. 2c), rivers and streams experience substantial anthropogenic impacts because this territory contains most of the country's population (75 %) (Siso-Quintero, 2012). It is also the region in which most of the research on fluvial ecosystems has been conducted (Cressa et al., 1993). The region South of the Orinoco River contains the watersheds of its main tributaries, one of which hosts the largest hydroelectric dam of the country (the Guri Dam) (Rodríguez-Olarte et al., 2025). In this region, the recent development of the "Orinoco River mining arc" has promoted high rates of deforestation (Fig. 2d) (Hansen et al., 2013, Torremorell et al., 2021).

Studies on hydrology, water chemistry, and sediment dynamics of rivers and streams in Venezuela began in the mid-19th century initially driven by engineering projects related to urban development, hydroelectricity, flow regulation, and flood control, and later as part of ecological research and environmental impact assessments (Cressa et al., 1993, Silva León, 2000). Over time, research has moved from being primarily descriptive to progressively incorporating functional aspects of ecosystems (Segnini et al., 2024, Rodríguez-Olarte et al., 2025). In the last 50 years, more interest and resources were allocated to the training of scientific personnel and studies on hydrology, water geochemistry, and fluvial geosciences flourished with the highest number of researchers in the mid-1970s and 1980s (De La Vega & Vargas, 2014). This resulted in many universities having departments devoted to aquatic sciences with the consequent development of graduate studies in hydrology, geosciences, and aquatic ecology. These highly specialised personnel, supported with modern facilities, promoted strong and diverse international collaborations that resulted in research projects and the pursuit of postgraduate studies, for Venezuelan faculty and students, in the US, Canada, and Europe (University of Waterloo, Texas A&M University, University of Colorado, Colorado State University, University of Georgia, Oakland University, University of the Basque Country-Spain, University of Michigan, Universidad of Coimbra-Portugal, among others).

For this publication, several Venezuelan researchers belonging to universities, research centres and institutes set out to compile limnological information referring to fluvial physical and chemical attributes published in the last three decades, with the purpose to provide an update of the review published more than three decades ago (Cressa et al., 1993) and to complement a recent publication focused on the biotic components of streams and rivers of Venezuela (Segnini et al., 2024). In this study, we intend to review, summarize and analyse the scientific work that has been done since 1993 to identify research gaps for future projects and programs. Our overall objective is to develop a systematic review to establish the state of the art in these abiotic aspects of fluvial environments in Venezuela covering the period 1993-2024. Specifically, we aim to: a) Analyse the compiled information, b) Identify information gaps and limitations for the development of the research area, and c) Suggest new routes and future projects and programs that address underdeveloped research topics and strengthen and update existing areas.

Figure 1. Rivers and streams of Venezuela. a) Headwaters of Sai Sai stream, a tributary of Chama River at 3500 m asl (Maracaibo ecoregion), b) Capaz River (Maracaibo ecoregion), c) Camurí River at basal flows (Caribbean drainages ecoregion), d) Caño Negro on Marahuaka Massif (Orinoco Guiana Shield ecoregion), e) Negro River (Rio Negro ecoregion), f) Morichal Largo River (Orinoco Delta and coastal drainages ecoregion), (g) Cinaruco River (Orinoco Llanos ecoregion), h) Orinoco River (Orinoco Llanos ecoregion). Pictures taken by S. Segnini (1a), J.E. Rincón (1b), C. Cressa (1c), M.M. Castillo (1d), J. Paolini (1e), L. Sánchez (1f, h), and J.V. Montoya (1g). Ríos y arroyos de Venezuela. *a) Cabeceras del arroyo Sai Sai, afluente del río Chama a 3500 m s. n. m. (ecorregión de Maracaibo), b) Río Capaz (ecorregión de Maracaibo), c) Río Camurí en caudal basal (ecorregión de los drenajes del Caribe), d) Caño Negro en el Macizo de Marahuaka (ecorregión del escudo Guayanés del Orinoco), e) Río Negro (ecorregión del Río Negro), f) Río Morichal Largo (ecorregión del Delta del Orinoco y drenajes costeros), g) Río Cinaruco (ecorregión de los llanos del Orinoco), h) Río Orinoco (ecorregión de los llanos del Orinoco). Fotografías tomadas por S. Segnini (1a), J.E. Rincón (1b), C. Cressa (1c), M.M. Castillo (1d), J. Paolini (1e), L. Sanchez (1f, h), y J.V. Montoya (1g).*

METHODS

We conducted a systematic bibliographic search from 1993 to 2024 in the Web of Science database (WoS). Also, as a complement, we extensively reviewed publications in national and international journals compiled previously by the authors (personal databases, "registers") about subjects related to hydrology, water chemistry composition and sediment dynamics of fluvial systems in Venezuela. Particular attention was paid to ensuring that no duplicate documents from this set overlapped with those retrieved via the WoS search. To do this we followed the PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Liberati et al., 2009) as shown in Fig. 3.

Literature searches were conducted in the WoS on 03 Jul 2024. We used the following terms and operators in this string: (hydrolog* OR physicochem* OR hydrochem* OR "water chemistry" OR "water quality" OR water OR sediment*) AND (river OR stream OR creek OR fluvial) AND (Venezuela) NOT (marine OR seawater OR coastal). The main searching terms were searched in the document title, abstract, topic, and keywords fields.

From the total list of records generated in the database searches, duplicates were identified through the title and authors fields and removed manually. First, any duplicates within the WoS search were discarded. Then, we ensured no overlap existed between publications sourced from the coauthors' personal databases and the document list retrieved via the WoS search. In the screening step we identified records eligible to be

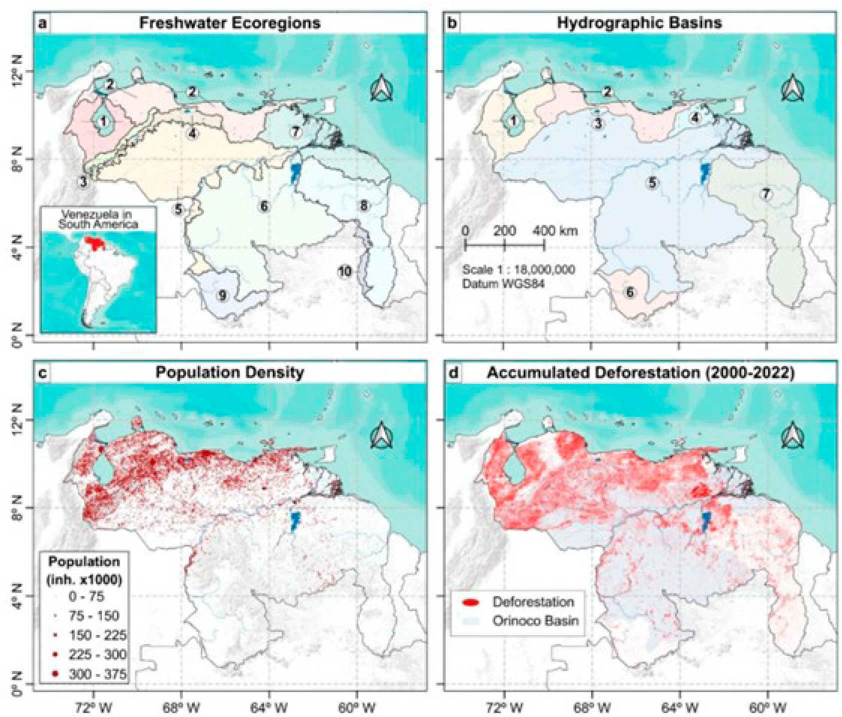

Figure 2. Freshwater ecoregions (Abell et al., 2008): 1) Maracaibo, 2) South America Caribbean Drainages-Trinidad, 3) Orinoco High Andes, 4) Orinoco Piedmont, 5) Orinoco Llanos, 6) Orinoco Guiana Shield, 7) Orinoco Delta and Coastal Drainages, 8) Essequibo, 9) Rio Negro, 10) Amazonas Guiana Shield. b) Hydrographic basins (modified from IGVSB, 2025): 1) Lake Maracaibo, 2) Caribbean versant, 3) Lake Valencia, 4) Paria-San Juan, 5) Orinoco, 6) Casiquiare-Negro, 7) Cuyuní-Essequibo. c) Population density in Venezuela (IGVSB, 2025). d) Accumulated Global Deforestation (2000-2022) (Hansen et al., 2013). *a) Ecorregiones de agua dulce (Abell et al., 2008): 1) Maracaibo, 2) Drenajes del Caribe Sudamericano-Trinidad, 3) Altos Andes del Orinoco, 4) Piedemonte del Orinoco, 5) Llanos del Orinoco, 6) Escudo Guayanés del Orinoco, 7) Delta del Orinoco y drenajes costeros, 8) Esequibo, 9) Río Negro, 10) Escudo guayanés amazónico. (b) Cuencas hidrográficas (modificado de IGVSB, 2025): 1) Lago de Maracaibo, 2) Vertiente del Caribe, 3) Lago de Valencia, 4) Paria-San Juan, 5) Orinoco, 6) Casiquiare-Negro, 7) Cuyuní-Esequibo. c) Densidad de población en Venezuela (IGVSB, 2025). d) Deforestación acumulada (2000-2022) en Venezuela (Hansen et al., 2013).*

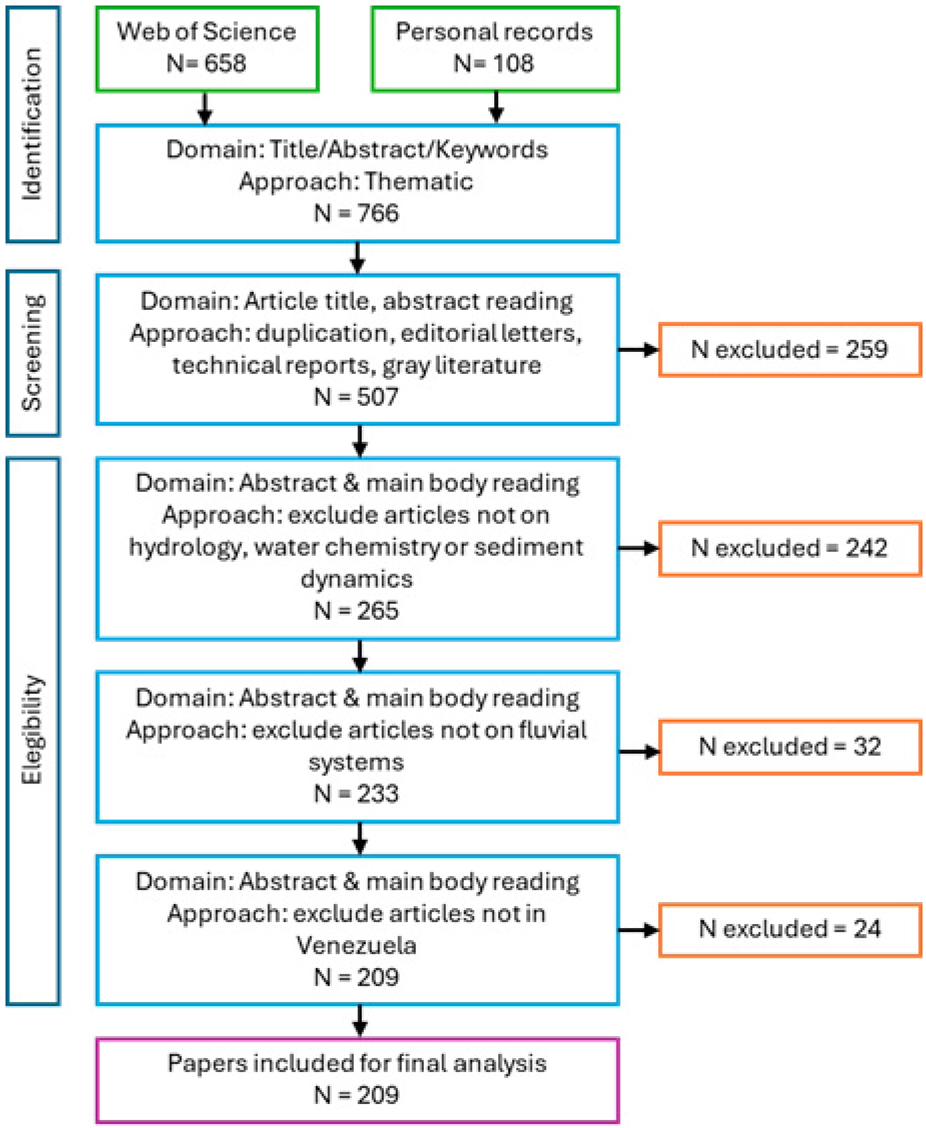

Figure 3. Flow of information through the different phases of the systematic review (PRISMA diagram) on hydrology, water chemistry and sediment dynamics of fluvial systems in Venezuela using the Web of Science database and authors' personal databases. *Flujo de información a través de las diferentes fases de la revisión sistemática (diagrama PRISMA) sobre hidrología, hidroquímica y dinámica de sedimentos de los sistemas fluviales en Venezuela utilizando la base de datos Web of Science y bases de datos personales de los autores.*

included based on the title and abstract of documents, leaving out technical reports and grey literature. Eligibility criteria consisted of a stepwise process starting by identifying that hydrology, water chemistry and/or sediments were addressed as the main subjects of the study. A second inclusion criterion was that the study was conducted in lotic freshwater systems, excluding marine and coastal environments. Finally, the third criterion was that the study was conducted in Venezuela. After each step, papers not meeting a criterion were removed.

We included all peer-reviewed papers meeting the eligibility criteria, whether original research or reviews, and regardless of language (English or Spanish). The total number of identified records through database searching and via the author's databases, as well as the resulting numbers after the entire eligibility process are presented in Fig. 3. From the list of records retained after the selection process, a thorough screening of the main text of each study was conducted to classify all records in three different categories: hydrology, water chemistry, and sediments. When a record could be assigned to several of those categories, the most relevant category was selected. Also, each record was assigned to one (or several) of the seven main hydrographic basins of Venezuela shown in Fig. 2b.

Although some papers were not strictly hydrological, they were considered eligible because hydrological factors such as water level changes and water discharge were measured and were considered the main variable in explaining some ecological or limnological processes. The same applies for those studies selected in the category of water chemistry and sediment dynamics. Studies dealing exclusively with engineering processes related with water quality such as those involving water treatment plants were not included. All publications obtained from Web of Science search and from the personal records were compiled and included as a supplementary file (available at https://www.limnetica.com/en/limnetica). All records retrieved in this systematic review were used to quantitatively summarize the information, yet not all of them were cited in the main narrative of this work due to space limitations, and to avoid redundancy. Only a representative selection of them was used to elaborate on the most relevant aspects of the main subjects of this study.

RESULTS AND DISCUSSION

Bibliometric analysis

Our literature search from 1993 to 2024 yielded 209 relevant publications, with numbers ranging between 26 and 54 publications (34.5 ± 10.7, mean ± 1SD) per five-year period (Fig. 4a). Production presented few fluctuations between 1993 and 2022, except for a marked increase in 1998-2002, when 54 publications in 5 years were achieved (Fig. 4a, b). The results indicated that 153 publications (73.2%) had the first author or corresponding author affiliated with a Venezuelan institution, while only 56 publications (26.8%) were affiliated with foreign institutions, particularly from the USA and France (Fig. 4c). Universities accounted for a major portion (68.6%) of the publications produced by Venezuelan institutions between 1993 and 2024 (Fig. 4d). Among them, the Universidad Central de Venezuela (UCV) led with 30 publications, followed by the Universidad de Los Andes (ULA) with 13, and the Universidad del Zulia (LUZ) with 11. The rest of the university institutions produced a third of the total number of publications (51). Moreover, the Instituto Venezolano de Investigaciones Científicas (IVIC) and Fundación La Salle de Ciencias Naturales (FLASA) contributed 19 (12.4%) and 12 (7.8%) publications, respectively, during the same period. Finally, government agencies and private consulting firms produced 15 and 2 publications, respectively.

The distribution of study sites across the different river basins in Venezuela was uneven, with the Orinoco basin (n=124, 59.3%) the most represented, followed by Caribbean basin (n=30, 14.4%) and Lake Maracaibo basin (n=22, 10.5%) (Fig. 4e). The remaining basins were underrepresented, particularly the Paria-San Juan (n=3; 1.5%) and Casiquiare-Negro (n=2; 1.0%) (Fig. 4e). The publications in the Orinoco basin showed a high percentage of first or correspondence authors affiliated to Venezuelan institutions (79) but also foreign institutions contributed with a high number (45) of publications in this basin. In contrast, no publications with the first or corresponding author affiliated to foreign institutions were recorded for the Lake Maracaibo, Lake Valencia, and Paria-San Juan basins. On the other hand, the 2 publications conducted exclusively in the Casiquiare-Negro basin were led by authors from foreign institutions. Most of the published studies (n=96, 45.9%) focused on water chemistry, while fewer studies addressed hydrology (n=62, 29.7%) or sediments (n=51, 24.4%) (Fig. 4f).

Hydrology

Hydrological studies of rivers in Venezuela have focused mainly on the large rivers of the Orinoco watershed, likely due to its basin extension

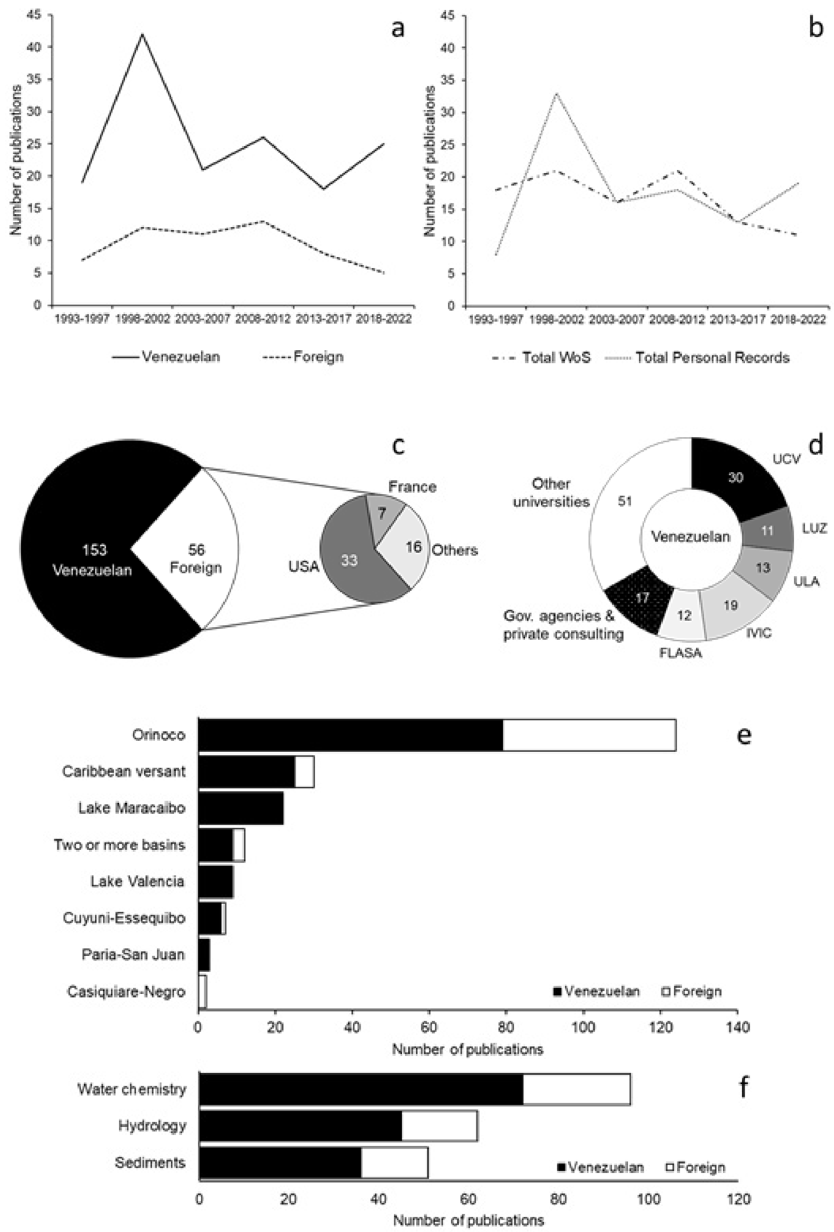

Figure 4. Number of studies published on hydrology, water chemistry, and sediments in Venezuela by first or corresponding authors affiliated with Venezuelan or foreign institutions separated by 5-year periods from 1993 to 2022 (a), and those from the results in Web of Science search (WoS) and those from coauthors´ registers (personal records) (b). Total publications for the period 1993-2024 by first or corresponding authors affiliated with Venezuelan and foreign institutions, and main countries where authors were affiliated (c). Main institutions where Venezuelan affiliated authors appeared as first or corresponding authors (d). Publications grouped by hydrographic basin (e) and main research subject (f). Abbreviations are described in the main text. *Número de estudios publicados sobre hidrología, química del agua y sedimentos en Venezuela por autores principales o autores correspondientes afiliados a instituciones venezolanas o extranjeras separados por períodos de 5 años de 1993 a 2022 (a), y aquellos de los resultados de la búsqueda en Web of Science (WoS) y aquellos de los registros de coautores (registros personales) (b). Total de publicaciones para el período 1993-2024 por autores principales o autores de correspondencia afiliados a instituciones venezolanas y extranjeras, y principales países donde los autores estaban afiliados (c). Principales instituciones donde los autores venezolanos afiliados aparecen como autores principales o autores de correspondencia (d). Publicaciones agrupadas por cuenca hidrográfica (e) y tema principal de investigación (f). Las abreviaturas se describen en el texto principal.*

occupying 71.5% of Venezuelan territory (Silva León, 2005), and that the Orinoco River itself ranks third largest in the world in terms of mean annual water discharge (~ 38 000 m^3/s) (Lewis et al., 1995) and about tenth largest in sediment discharge (~ 150 x 10^6 tons per year) (Meade, 1994).

The hydrological regime of large rivers in Venezuela is largely influenced by the climatic dynamics imposed by the annual latitudinal migration of the Intertropical Convergence Zone (ITCZ), which dictates the strong seasonality of dry and wet seasons in the region (Latrubesse et al., 2005, Syvitski et al., 2014). The Orinoco River and its large tributaries exhibit a single annual flood pulse, with low interannual variability (Fig. 5a). This pattern is directly tied to the ITCZ's northward passage, reaching its northernmost position (~10°N) around July. This brings heavy, sustained rainfall to the Orinoco Basin, resulting in a distinct wet season from April to October, with peak flow around June-August. Then, between November and March, the ITCZ shifts southward (~5°S), leaving the Orinoco Basin under the influence of drier easterly trade winds. (Latrubesse et al., 2005). This annual monomodal flood pulse hydrology not only shapes ecological processes, which sustain the Orinoco's riparian wetlands, supporting biodiversity (e.g., migratory fish spawning) and ecological processes (Montoya et al., 2006, 2011, Winemiller et al., 2014, Machado-Allison, 2021), but also human livelihoods by synchronising agriculture, fisheries, and transportation (Rodríguez et al., 2007, Montoya et al., 2011, 2017).

Climate change-induced shifts in ITCZ dynamics (e.g., intensified rainfall or altered migration timing) could disrupt the annual hydrological regime, with cascading impacts on the region's water resources (Hamilton, 2010; Paredes-Trejo et al., 2023). Anomalous ITCZ positions (e.g., stalled northward shifts during La Niña years) can prolong wet seasons, causing severe flooding (Espinoza et al., 2011). Conversely, the ITCZ's southward shifts during El Niño years can extend the dry season, causing severe energy and water shortages in a country whose energy matrix (electricity) depends more than 65% on hydroelectricity (Paredes-Trejo et al., 2023). These hydrological anomalies are clearly depicted in the Caura River hydrograph (Fig. 5a) as represented by years with large departures from the mean discharge during the wet and dry seasons, respectively.

While ITCZ acts as the metronome of the Orinoco's large rivers hydrology, dictating its distinct wet-dry seasonality, not all large rivers in Venezuela show this very distinctive monomodal hydrological regime. Some present bimodal regimes, such as the Catatumbo River in the Lake Maracaibo basin, which follows a bimodal precipitation regime with two maxima, the highest between September and November, and a secondary peak between April and May (Segnini-Flores et al., 2025).

On the other hand, low to medium order streams and creeks experience a greater variability in their hydrological patterns, reflecting a much larger influence of local winds and storms, orography and land use changes in their smaller watersheds (Gordon et al., 2004, Syvitski et al., 2014). The Guasare River watershed, draining to the Lake Maracaibo basin, exemplifies the typical hydrology of Venezuelan small streams in the semiarid and arid regions (Fig. 5b). Furthermore, its location in the semiarid of northwestern Venezuela, in a highly anthropogenically altered region due to deforestation, the heavy extraction of water, and coal mining (Rincón, 1994, Rincón & Cressa, 2000), heightens the flashy nature of its flow variability. Its flashiness also reflects the impact of individual rainstorms, producing flash floods, which are a signature of this kind of stream (Cressa & Senior, 1987, Gordon et al., 2004, Syvitski et al., 2014).

Studies on hydrological dynamics in fluvial systems of Venezuela include the description and modelling of the hydrology of rivers and streams, as well as that from the floodplain of large rivers. Hydrological studies in which discharge and/or water level of rivers are forecasted in watersheds where large hydroelectric dams are located were key to the monitoring of rivers and reservoirs. The Caroní River watershed in Venezuelan Guiana Shield is one of the most monitored systems in the country since it is the source of more than 70% of the electricity produced in Venezuela (Hastenrath et al., 1999). Prediction models of the minimum discharges during the dry season (critical periods) were developed by Hastenrath et al. (1999), based on relatively extended time series and were instrumental for the functioning and management of the electricity company foreseeing the production, supply and distribution of electricity in Venezuela.

To the best of our knowledge, there are not any further published studies updating those models within the last 20 years at least, even considering that the dry spells during 2009-2010 in the country (El Niño years) were harsh (but see Paredes-Trejo et al., 2020). Nevertheless, Méndez et al. (2017) forecasted the future scenarios in different rivers of the country including the most optimistic (RCP 2.6) and most pessimistic (RCP 8.5) greenhouse gas concentration pathways for the years 2050 and 2070. Their study showed climate-change-driven discharge decreases for the Apure and Caura (Orinoco) and Matícora and Neverí (Caribbean versant), with the exception of the Negro River (Amazon) which increased.

Building upon the findings of Méndez et al. (2017), Paredes-Trejo et al. (2018) investigated the response of Venezuelan river systems to meteorological droughts, with a particular focus on their hydrological resilience, defined as the rate at which rivers recover following drought events. Their analysis revealed that basins exhibiting greater resilience were typically associated with extensive drainage networks, dense-canopy vegetation, humid climatic conditions, and limited exposure to meteorological droughts, as exemplified by the Casiquiare-Negro and Orinoco basins. In contrast, basins located in the Caribbean versant and the Lake Maracaibo region demonstrated markedly lower levels of hydrological resilience. These basins have less dense canopy vegetation, smaller watersheds, and are located in drier climatic regimes.

As part of the large watersheds of the Orinoco River in Venezuela, the plains in the central and western region of the country contain a large floodplain system (Hamilton et al., 2002, Mon-

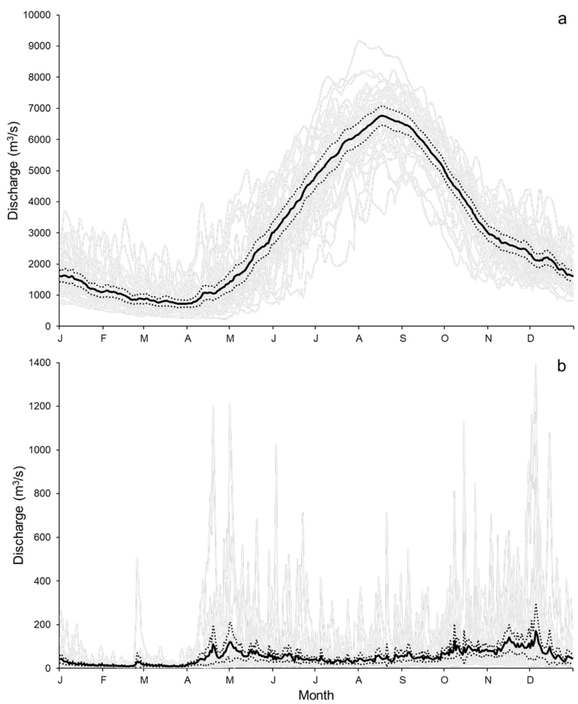

Figure 5. Hydrographs of a) Caura River at Maripa (Orinoco River Basin) and b) Guasare River at El Carbón (Lake Maracaibo Basin) showing their annual hydrological regime. Daily discharges (Q, m^3/s) per year are plotted as grey lines. Discharge mean and 95% CI are shown in black bold continuous and dotted lines, respectively. Data from 1968 to 2005 in a, and from 1964 to 1998 in b. Data from INAMEH, Venezuela. *Hidrogramas de a) Río Caura en Maripa (Cuenca del Río Orinoco) y b) Río Guasare en El Carbón (Cuenca del Lago de Maracaibo) que muestran su régimen hidrológico anual. Los caudales diarios (Q, m^3/s) por año se representan como líneas grises. El caudal medio y el IC del 95% se muestran en líneas negras continuas y punteadas, respectivamente. Datos de 1968 a 2005 en a, y de 1964 a 1998 en b. Datos de INAMEH, Venezuela.*

toya et al., 2011). A comparative approach was used by Hamilton et al. (2002, 2004) to study the Orinoco Llanos floodplains with the Llanos of Moxos in Bolivia (Mamoré River, Amazon Basin), and with the Central Amazon floodplains in Brazil. In those studies, using satellite imagery and data from historic time series, they described the hydrological spatial and temporal extents of the flooding through the plains. Their results showed more consistent annual monomodal flooding and drainage but with higher variability in the maximum extent of inundation for the Orinoco Llanos, which can reach 107 530 km^2, becoming within the highest fluvial flood extensions in South America. The mean annual inundation area was 34 700 km^2. Also, using remote sensing Smith et al. (2006) provided digital elevation models (DEM) for a modified flooding plains in the western llanos of Venezuela. That area, called "módulos de Mantecal" is an area that is flood controlled and retains water during the dry season.

Hydrological research conducted in other river basins apart from the Orinoco have paying special attention to the intersection between hydrology, hydrogeomorphology, natural risks assessment and mitigation, and engineering for the monitoring and protection of fluvial systems prone to extreme floods, landslides, and debris flows events (e.g., Coelho & Cartaya, 2022, López et al., 2001, 2010, Navas, 2011). Most of those studies were conducted in relatively small watersheds of the Caribbean versant, in which mountain streams draining the central Cordillera de la Costa range usually have a very steep slope, narrow coastal plains, and alluvial fans that experienced extreme floods and debris flows events (Larsen et al., 2001, Larsen & Wieczorek, 2006, López, 2011).

Of special interest in this area of research was the tremendous precipitation records during December 14-16, 1999 in the montane streams draining to the Caribbean versant in the La Guaira State (formerly Vargas State) that ended in catastrophic floods and debris flows, categorising the La Guaira floods as one of the worst natural disasters in the Americas with an uncertain death toll that varied between 15 000 to 35 000 people (López et al., 2001, Humphries et al., 2024). Studies dealing with causes and consequences of those events, as well as a summary of the mitigation measures implemented after the flooding events were presented by López (2011).

We identified that studies on the hydrological dynamics of streams and rivers, including an ecological perspective, have been done in all regions of the country. Data on hydrology are essential for ecological studies in fluvial systems, as many investigations in rivers and streams incorporate at least flow measurements and basic modelling of river flows and hydrological regimes. This abiotic data depicts an essential physical context, helping to explain the dynamics of aquatic populations, communities, and ecosystems (e.g., Castillo et al., 2004, Allan et al., 2006, Mendoza et al., 2018).

Comprehensive integration of hydrological sciences with ecology are well represented in, for instance, Rosales et al. (2002, 2008) and Warne et al. (2002), whose results on ecosystem dynamics and integrity, from large river lowland floodplains and the Orinoco Delta, are rooted in the field of ecohydrology. Those studies examined patterns and processes at the aquatic ecosystem and community levels through the physical template associated with the conservative annual monomodal hydrological regime of the Orinoco River basin. Ecohydrological approaches incorporating landscape features of watersheds have also been explored, focusing on land use and/or climate change effects on water chemistry (e.g., Castillo, 2010), and environmental flows (e.g., Sánchez et al., 2021).

Water chemistry

Research on water chemistry of Venezuelan rivers has indicated that studies conducted in the Orinoco River, its floodplain, and main tributaries comprise a slightly higher percentage (51.6%) than those in lower order streams (48.4%). On the other hand, hydrological seasonality studies, based on the chemical properties of nutrients and organic carbon, conducted during the 1990s and early 2000, showed a higher bias since 72.1% were made in the Orinoco River and only 27.6% in the others watersheds, resulting in a great breach of information.

Seasonal changes in organic carbon and organic nitrogen particles in the Lower Orinoco were described by Paolini (1995). The author indicated that particulate organic carbon (POC) and particulate nitrogen (PN) fluctuate with water discharge, with higher values during the rising limb than during the falling limb (ranging between 0.84 and 9.06% for POC and 0.08 and 1.45% for PN).

The relationship between floodplains and the Orinoco floods was illustrated by Vegas-Vilarrúbia & Herrera (1993a, b). They describe how the Orinoco floods affect the hydrochemistry of the overflowing and stagnant waters of the Mapire River since the floods of the Orinoco, act like a dam for the Mapire River causing the system to become a standing lake, with thermal and chemical stratification, which reverses to a flowing system during the dry season. Lewis et al. (2000) indicate that the Orinoco floodplain (15-year studies) shows that the apparent complexity in this ecosystem, such as geomorphological and hydrological factors that affect biochemical and biotic processes, can be resolved through chains of cause and effect that are pervasive and predictable over the system as a whole (deterministic effects).

Battin (1998) reported high concentrations of dissolved organic carbon (DOC; 4.50 to 20.39 mg C/l) in the Surumoni, a tributary of the Upper Orinoco, and in the main channel of this river (4.48 to 16.89 mg C/l), documenting a strong effect of the connectivity with the floodplain on DOC composition. In clear and black water rivers of the middle Orinoco basin, nutrients and DOC exhibited distinct seasonal patterns, related to inputs from terrestrial sources and the influence of the floodplain (Castillo, 2000, Castillo et al., 2004). Water chemistry including anions, cations, DOC and the relationship between dissolved and suspended load was studied by Tosiani et al. (2004) in the Cuyuní River and several of its tributaries. Laraque et al. (2019) working at the Casiquiare River, a channel that connects the Orinoco with the Amazon, reported the flux of total suspended sediment at the interaction zone between the Orinoco, Guainia and Negro Rivers (79.69 kg/s, 0.51 kg/s and 44.90 kg/s, respectively) as well as at the Casiquiare mouth (48.94 kg/s).

More recently, studies on the main tributaries of the Orinoco River have focused on aquatic geochemistry and pollutants. In the Orinoco, Caura and Apure Rivers, the concentrations of Ca, Na and Mg decrease during the rainy season due to the dilution effect. Contrary to this, K increases in the Orinoco due to the contribution of tributaries that flow through feldspathic terrain of the Guiana Shield. In the Apure River, the increase in K is a consequence of clay leachates and decomposing plant material coming from the floodplains (Mora et al., 2009, 2010a, b). A different pattern is shown by streams that flow through a terrestrial-aquatic ecotone known as morichal in the eastern savannas. In these streams, nutrients, cations and trace elements increase during the rainy season, unlike what is observed in the Orinoco. This indicates that inputs of elements from soil and rock weathering along with rainfall enriched with marine salts can outweigh the dilution effect caused by increased flow during the rainy season (Mora et al., 2008). In these rivers, P and nitrate concentrations are low (total P, between 9.45 and 21.73 µg/l; nitrates, between 0.01 and 0.22 mg/l), although total N can reach higher values (0.43 to 0.58 mg/l) suggesting that most nitrogen is in organic form. In addition, benthic chlorophyll concentration showed high variation (from 2.25 to 10.58 mg/m^2) (Castillo et al., 2012). Due to these conditions, Castillo et al. (2012) found that Morichal streams are vulnerable to human pressures such as the conversion of savanna vegetation into agriculture and urban areas. These changes can increase conductivity and nutrient concentrations, resulting in higher chlorophyll levels.

In the Cataniapo River, a tributary of the middle Orinoco, Astiz (2012) documented high concentrations of Pb, Ni, and Hg in the water, likely related to fuel spills and mining activities. In rivers of the Apure basin draining the Andes, Allan et al. (2006) observed greater concentrations of nitrogen (NO_3, NH_4) and phosphorus in rivers that showed higher water yield and forest cover in the upper part of their catchments. The studied rivers showed low N:P ratios suggesting nitrogen limitation. In Río Las Marías, also located in this region, Solomon et al. (2009) reported that actual and potential denitrification rates ranged from 0 to 160 and from 0 to 740 µg $NO_{2-}N$ m^{-2} h^{-1}, respectively and indicated that substrate texture and anthropic sedimentation are the factors influencing denitrification rates.

In rivers draining the Guiana Shield, Yamashita et al. (2010) documented the influence of terrestrial and microbial sources on DOC concentrations and the influence of geology and vegetation cover on the spatial variation of DOC characteristics. López et al. (2012) determined that the transport of organic carbon from the Orinoco River to the eastern Caribbean, responds more to the seasonality of the flow than to changes in the concentration of organic carbon in the river. Likewise, Laraque et al. (2013b) found that seasonal variations in fluxes of dissolved solids and DOC are controlled by variations in discharge.

Studies on particulate and dissolved organic matter have also been conducted in rivers draining the Andes and piedmont (Allan et al., 2006, Segnini & Chacón, 2017, Rincón et al., 2018), the Llanos (Roelke et al., 2006), the central-Caribbean drainages (Mendoza et al., 2018), and in small intermittent streams in the northwestern region of the country (Rincón, 2009). In this region, average benthic organic matter (72.04 g/m^2; 129.1-27.2 g/m^2) in depositional habitats was estimated showing seasonal variation (Pirela & Rincón, 2012). Seasonal variations in the sources of dissolved organic matter (DOM) in the Cinaruco River (Orinoco Llanos) were investigated by Roelke et al. (2006). Using excitation–emission fluorescence spectroscopy and DOM absorption spectra, the authors found that during the low-water period, the DOM signatures in river water closely resembled those of leaf leachates and lagoon water. In contrast, during the falling-water season, DOM in the river exhibited distinct spectral characteristics, differing from both leaf and lagoon sources. This shift was interpreted as evidence of an additional DOM source during this period, likely originating from the drainage of inundated savannas within the river's floodplain.

Outside of the Orinoco Basin, in the central, north and western regions of Venezuela, several studies have been carried out on the hydrochemistry of lotic environments. Coal mining in the Guasare River basin affected water quality, increasing dissolved solids, sediments, some metals and sulphate concentrations in rivers and streams (Rincón, 1994). The Chama and Catatumbo Rivers transport a large amount of total P (4.26 and 18.87 t/d, respectively) and total N (9.65 and 53.45 t/d, respectively) to Lake Maracaibo, mostly from urban and agricultural sources, contributing to its eutrophication and pollution (Rivas et al., 2005, Chacón & Segnini, 2007, Segnini & Chacón, 2017, Rincón et al., 2018). Similarly, but in the Caribbean versant, the impact of the landscape on the nutrient concentration of the Guare River, a tributary of the Tuy River, in the central Caribbean region was documented by Castillo (2010). The author showed a variation of nitrate between 8 to 880 µg/l, with higher values associated with cropland having a large proportion of the catchment (14-45%). Also, in rivers draining the Caribbean versant, water quality was determined during the rainy season in the Tuy, Capaya, and Curiepe Rivers at sampling sites near the coast (Herrera & Bone, 2011). Comparatively, the Tuy River had the highest impact on the coastal zone in terms of discharge (246.39 m^3/s), nutrient fluxes (659.61 ± 503.27 g/s total nitrogen; 52 ± 53.09 g/s total phosphorus), and sediment transport (9320.84 ± 9728.15 g/s).

Sediment dynamics

As with water chemistry and hydrology, most studies on sediment dynamics have been conducted in the Orinoco River basin. This river has an annual sediment load of 150 x 10^6 tons, and the concentration of total suspended sediments (TSS) shows a bimodal response to the seasonal variation in discharge (Meade, 1994). The TSS shows a first peak after the onset of the rains, and a second, more moderate peak, during the descending stage of the annual flood (Paolini, 1995, Mora et al., 2009, Laraque et al., 2013b). The first peak results from the mobilisation of sediments from the river and transported by runoff. The second peak occurs when sediments deposited near the tributary mouth due to backwater during maximum flow return to the main channel (Meade, 1994, Paolini, 1995, Mora et al., 2009, Laraque et al., 2013b). Fluxes of total suspended solids estimated by Laraque et al. (2013a) were 20% lower than previously reported (Lewis & Saunders, 1989, Paolini et al., 1987), likely explained by differences in sampling and calculation methods and the construction of dams in Andean tributaries.

Lately, remote sensing images have been used to estimate suspended sediment concentrations and loads of the Orinoco, showing that in combination with field measurements, they can facilitate the monitoring of sediment dynamics in large rivers (Yépez et al., 2018b, Gallay et al., 2019). For the Casiquiare channel in the Upper Orinoco, Laraque et al. (2019) estimated sediment fluxes (31.66 kg/s) and constructed a budget at the bifurcation with the Orinoco and confluence with the Guainía.

Gualtieri et al. (2022) presented a detailed investigation into total suspended solids (TSS) and surface sediment loads in the lower Orinoco River at Ciudad Bolívar during the period 2012–2017. Their findings revealed TSS concentrations ranging from 12 to 277 mg/l and sedimentary fluxes between 68 and 113 million tons annually. The data indicated a bimodal sediment regime characterized by two distinct peaks surrounding the river's maximum discharge event. The study further examined the interactions among hydrodynamic conditions, sediment transport mechanisms, and morphodynamic processes. Analysis of bed shear stress distribution provided insights into predominant transport modalities and the upper grain-size limits of suspended sediments. Under moderate to high flow conditions, fine sand was the dominant fraction, while very fine sand prevailed during periods of low discharge.

Additionally, Rodriguez et al. (2019) in the lower Orinoco floodplain observed that sedimentation rates during flood events exhibited substantial spatial variation. These rates ranged from areas with no sediment deposition to sites with extremely high accumulation reaching 225.46 kg m^{-2} yr^{-1}. Notably, banks and levees tended to receive significantly more sediment, averaging 39.6 kg m^{-2} yr^{-1}. In contrast, regions farther from the main water channels, such as floodplains and backswamps, accumulated less sediment, with mean rates around 17.7 kg m^{-2} yr^{-1}. This pattern highlights how proximity to water flow greatly influences sediment distribution during flooding events. Significant differences in sedimentation rates were observed in two major vegetation types: dense herbaceous and shrubby vegetation (42.2 kg m^{-2} yr^{-1}) and flooded forest (12.7 kg m^{-2} yr^{-1}).

Furthermore, Rodríguez et al. (2019) pointed out that overbank sedimentation is influenced by a dynamic interplay between hydrosedimentary forces and vegetation dynamics, which together shape the formation of fluvial landforms. A key finding from the study highlights the role of the El Niño Southern Oscillation (ENSO) cycle, specifically the shift between El Niño and La Niña in controlling sediment supply and deposition across floodplains. Interestingly, in whitewater rivers, where suspended sediment is plentiful, the most critical factor affecting sedimentation was not the sediment concentration itself, but rather hydrological connectivity, the degree to which water moves between the river and the floodplain.

Other studies have focused on sedimentation patterns and characterization of sediments in the Orinoco River and its tributaries. Dezzeo et al. (2000) estimated sediment deposition rates during a flood event in the Mapire and Caura forested floodplains and analysed the mineral and nutrient compositions of the deposited sediments. They found a wide range of deposition rates, from 0.07 to 73.60 kg/m², influenced by factors like sediment mobilization, geomorphic environments, and upstream erosion. The mineralogical composition of the sediments reflected intense weathering processes in the river catchments. The chemical composition of the sediments also varied due to differences in mineral composition and particle size distribution. Guzmán et al. (2021) characterised the sediment deposits and transport and deposition mechanisms in the anastomosed channels of the middle Apure River. The authors found a predominance of fine to medium silt (71%) in relation to the clay (18%) and sand (11%). This variation is mainly associated with the existence of controls of lithological origin. This study reveals that sorting and transport of sediment in the anastomosis system of the study area is mainly influenced by the morphodinamics changes in the position of bars and islands. The concentrations of elements associated with sediments have also been investigated in the Orinoco floodplains and tributaries. In the Caura, major, minor and trace elements in sediments are lower than the Apure values, due to its low pH and the presence of kaolinite and gibbsite with poor cation exchange capacity (Mora et al., 2013). In contrast, the Apure and Orinoco Rivers show higher elemental concentrations, attributed to Fe-oxyhydroxides and clays from intermediate weathering that can adsorb these elements. Downstream in the Orinoco, increasing fine sediment deposition from the Apure River correlates with elevated element levels. Near the Matanzas industrial zone, unusually high Fe, Zn, Cr, and Pb levels suggest contamination from industrial wastewater and mining activities.

Furthermore, Narayan et al. (2020) reported greater concentrations of heavy metals in sediments through the year in floodplains lakes of the Orinoco under the influence of industrial and urban effluents. In this study sediments of the most impacted lagoon showed higher concentrations of Al, Pb, Cu, and Cr than sediments of the less-polluted and the unpolluted lagoons during all the hydrological stages. Other studies related to sediment transport and deposition have focused on the formation of sand waves and bars in the Lower Orinoco (Yepez et al., 2018a), long-term changes in the Apure River channel (Guzmán et al., 2013) and sediment dynamics in the Orinoco Delta, including the effects of flow regulation (Echezuría et al., 2002, Warne et al., 2002).

In the Tuy River and its tributaries, in north-central Venezuela, the influence of human activities on chemical characteristics of sediment humic and fulvic acids was studied by García et al. (1994). This study highlights that human activities significantly impact the elemental makeup and chemical structure of humic substances. Additionally, vegetation type and seasonal rainfall contribute to variations in the chemical structure of humic and fulvic acids, indicating that climatic conditions influence their chemical characteristics and, to a lesser degree, their elemental composition. Similarly, Mogollón et al. (1995) investigated the influence of lithology on metal concentrations in stream bed sediments. They concluded that human activities in the basin are contributing to Pb and Zn enrichments up to 4 times in the main channel sediments of the Tuy River system.

Romero-González et al. (2001) and Ledo et al. (2004) characterized the speciation of phosphorus and metals in sediments of the Catatumbo River, highlighting their environmental implications for Lake Maracaibo. Total phosphorus (Total P) concentrations ranged from 121 to 581 μg/g DW, with inorganic forms (~64%) predominating over organic forms (~36%). The dominant species was calcium-bound phosphorus, primarily as apatite. A significant portion of Total P originated from the Colombian sector of the watershed, attributed to intensive agricultural and mining activities. Given that the Catatumbo River supplies ~70% of the sediment load to Lake Maracaibo, a eutrophic system with an anoxic hypolimnion, conditions are favourable for phosphorus remobilization. This process may release inorganic P, increasing its bioavailability to aquatic organisms such as macrophytes, algae, and cyanobacteria, thereby exacerbating eutrophication. Ledo et al. (2004) also quantified mean metal concentrations at the river outlet, following the sequence: Fe (0.802) > Al (0.563) > Mg (0.070) > Ca (0.018) > Mn (6.9×10^{-4}) mmol/g dry sediment. These findings suggest that metals from both natural weathering and anthropogenic inputs are ultimately accumulated in the estuarine sediments of Lake Maracaibo.

The analysis of the information presented on the interaction between water flow and transport of solid material shows that these processes, being associated with climatic seasonality, participate in the control of the structure and functioning of riverine ecosystems. This knowledge is essential for understanding the functioning of rivers and streams, and thus improving their use, management and conservation. Likewise, this knowledge leads to detection of information gaps that need to be addressed and resolved, to contribute to resolving the main threats to the hydrological and sedimentary processes of rivers in Venezuela.

FINAL REMARKS

Our review indicates that research conducted since 1993 has primarily concentrated on the Orinoco River, Lake Maracaibo, and the Caribbean basins (Fig. 4e); however, recent data on hydrology, water chemistry, and sediment transport for the main rivers are relatively scarce (Rodríguez-Olarte et al., 2025, Segnini-Flores et al., 2025). Although there are recent estimates of nutrient fluxes for the Orinoco (Mora et al., 2020, Gualtieri et al., 2022), updated knowledge on hydrology and water chemistry is necessary for rivers draining the Guiana Shield, which have been significantly affected by mining activity in the "Orinoco mining arc" over the last two decades (Lozada, 2019, Stachowicz et al., 2023). Additionally, we found that the Paria-San Juan and Casiquiare-Negro basins are poorly studied (Fig. 4e). The low number of publications on these river basins is likely due to their remote locations. Oil spills and illegal gold mining are degrading these river ecosystems, and the extent of the damage remains unknown (SOS Orinoco, 2019, ACFIMAN, 2022). Overall, Venezuela's watersheds have experienced significant changes in land use and pollutant loading that can affect water quality, not only in rivers but also in coastal and oceanic ecosystems (Rodríguez-Olarte et al., 2019). In addition, complementary research on ecological processes, such as carbon and nutrient cycling as well as community dynamics and interactions, in streams and rivers needs to be addressed.

Understanding of hydrological alterations and extreme events resulting from climate and land use changes are needed for larger rivers of the Orinoco basin and for smaller basins of the northern coastal region, where a significant portion of the Venezuelan population resides and major disasters have occurred in the last decades (López et al., 2001, López, 2011). An important limitation for the development of hydrological studies is the inadequate and limited availability of continuous data records from hydrological and meteorological stations. This situation requires an increase and modernization of infrastructure and equipment to enable long-term monitoring across the hydrographic network. We urge the identification of fragile fluvial ecosystems (e.g., morichales) that should be prioritised for research based on the threats they may face in the near future.

The greatest development in all areas of science and technology in Venezuela occurred between 1958 and 1998 (Requena, 2022). During this period, Venezuela transitioned from having a few scientific laboratories in the main cities to hundreds distributed across the country, equipped with well-trained scientists (Requena, 2021). Furthermore, Requena (2022) also documented a steady increase in publications from 1960 to 2008. Although this was the general trend for the scientific community, our analysis shows that the number of publications on hydrology, water chemistry and sediments (Fig. 4a, b) remained almost steady from 1993 to 2022, with an increase during the period 1998-2002 (doubling that of the previous period). However, the number of publications included in the WoS showed a tendency to decline continuously after 2008-2012 (Fig. 4b), likely due to reduced funding and migration of freshwater scientists.

Despite the challenging context reflected in indicators of scientific productivity and capacity building related to hydrology, water chemistry, and sediment dynamics of Venezuelan rivers, there have been notable positive developments that have sustained, and projected into the future, research activity in this field. Collaborations with international scientific networks such as IBEPECOR (Torremorell et al., 2021), CELLDEX (Tiegs et al., 2019), and DecoDiv (Boyero et al., 2015) have contributed to maintaining and even enhancing the scientific output and impact of Venezuelan researchers and institutions. Additionally, recent research agendas and funding calls focused on the environment and climate change, promoted by the Ministerio del Poder Popular para Ciencia y Tecnología (MINCyT), have stimulated new initiatives in research and education on these research fields. However, the strengthening of those strategies in the national science policy in combination with incentives for researchers returning to the country, training of new specialised personnel and the involvement of institutions and researchers within international networks are urgently needed for the recovery and eventual improvement of scientific capacities in stream and river sciences in Venezuela.

CONCLUSIONS

a) Our comprehensive review of literature from 1993 to 2024 reveals a consistent research output on Venezuelan rivers, with a total of 209 publications and a notable surge during 1998–2002. The majority of studies (73.2%) were led by authors affiliated with Venezuelan institutions, particularly universities, with the Universidad Central de Venezuela

(UCV), Universidad de Los Andes (ULA) and Universidad del Zulia (LUZ) being the most prolific contributors. Foreign institutions, primarily from the USA and France, accounted for 26.8% of the publications, with their involvement concentrated in the Orinoco basin. Geographically, research efforts were unevenly distributed, with the Orinoco basin dominating (59.3%) and other basins such as Lake Maracaibo, Lake Valencia, and Cuyuni-Essequibo receiving somewhat lower attention. The Casiquiare-Negro basin was exclusively studied by foreign institutions, highlighting a gap in national research coverage.

b) Thematically, studies focused predominantly on water chemistry (45.9%), with fewer addressing hydrology (29.7%) and sediment dynamics (24.4%). Our results suggest a strong national academic presence in freshwater research, yet also point to significant geographic and disciplinary imbalances. Addressing these gaps through targeted research (e.g., climate change, hydrologic risk assessment) and enhanced international collaboration could foster a more comprehensive understanding of Venezuela's diverse aquatic ecosystems.

c) Even though research was geographically not homogeneous around the country, some watersheds were intensely covered and some seasonal patterns in hydrology as well as in chemistry were well described. However, it is important to note that many of the ecosystems studied require new studies to describe their current conditions in order to quantify and assess the changes that ecosystems have been over all these years, particularly regarding an increase in anthropogenic intervention. In particular, there is a need to describe their hydrologic, chemical and sediment dynamics to assess the plausible impact of climate change. Obviously, this will require an update of the infrastructure and methods where international collaboration will be a plus. Furthermore, long-term research studies are needed, particularly in highly variable and unpredictable ecosystems to assess their dynamics.

Our systematic review indicates that while there is noteworthy basic documentation on Venezuelan rivers, there is an urgent need to update baseline information on abiotic characteristics of fluvial ecosystems, including low order streams and rivers. This will increase knowledge and better understanding of the functioning of tropical streams and rivers and contribute to their conservation and to face the climate changes on these ecosystems.

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DISCLOSURE STATEMENT

The authors declare not to have any potential conflict of interest.

AUTHOR CONTRIBUTIONS

J.E.R.: Conceptualization, methodology, investigation, resources, data curation, writing-original draft, writing-review & editing, visualization, supervision, project administration; C.C.: Conceptualization, methodology, investigation, resources, data curation, writing-original draft, writing-review & editing, visualization, supervision, project administration; J.V.M.: Conceptualization, methodology, investigation, resources, data curation, writing-original draft, writing-review & editing, visualization, supervision, project administration; M.M.C.: Conceptualization, methodology, investigation, resources, data curation, writing-original draft, writing-review & editing, visualization, supervision, project administration; E.G.: Investigation, writing-original draft, writing-review & editing; S.S.: Investigation, writing-original draft; J.P.: Investigation, writing-original draft. MB: Investigation, writing-original draft; D.R.O.: Investigation, writing-original draft; L.S.: Investigation, writing-original draft. EG: Investigation, writing-original draft; L.M.S.: Investigation, writing-original draft; J.S.F: Investigation, resources, writing-original draft, writing-review & editing, data visualization; C.L.: Investigation, writing-original draft.

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