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CURRENT EVIDENCE

Causes and consequences of recent degradation of the Magdalena River basin, Colombia

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Scientific Significance Statement

Large tropical rivers provide essential societal benefits, including food production, irrigation, hydropower, transportation, and trade routes. However, these human activities pose unprecedented challenges to the integrity of the river systems, a problem that, in most cases, occurs without fully understanding the natural dynamics of these valuable ecosystems. Here, we synthesize the status of recent and long-term (decades-centuries) anthropogenic impacts occurring in one of the world's hotspots of tropical fish diversity, the Magdalena River, Colombia. Unfortunately, the Magdalena River has attracted little research attention compared to similar tropical rivers. We seek to promote research on the compounding impacts of climate change, river impoundment, alien invasive species, catchment deforestation, and water pollution on the Magdalena and the ecosystem services it provides.

Abstract

The Magdalena River in Colombia is one of the world's largest (discharge = 7100 $m^3 s^{-1}$) tropical rivers, hosting > 170 aquatic vertebrate species. However, concise synthesis of the current ecological and environmental status is lacking. By documenting the anthropogenic stressors impacting the river on time scales ranging from centuries to decades, we found that the river system is subject to the compounding impacts of climate change, river impoundment, invasive alien species (IAS), catchment deforestation, and water pollution. We show that the Magdalena is a woefully understudied ecosystem relative to its critical importance to Colombia's economy, culture, and biodiversity compared with other similarly sized tropical rivers. We emphasize the need for research on (1) IAS population and ecological dynamics, (2) river damming and its links with IAS and climate change, and (3) land-use changes as well as identifying sources of water pollution and strategies for mitigation.

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[a]**Author Contribution Statement**: JS conceived the idea. JSA and FJ conceptualized the river dam section. JS and JBS conceptualized the invasive species section. MIV, LLC, CG, AL, and IA conceptualized the hydro-climatic section. FJ conceptualized the river Delta section. GL and JS conceptualized the water pollution section. JBS wrote the first draft. All authors contributed to the writing and editing of the manuscript.

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Large tropical rivers (> 1500-km long) provide essential benefits to society in terms of food production, irrigation, hydropower generation, transportation, and trade routes, among others (Bianchi 2016). However, several anthropogenic activities resulting in large-scale damming, water pollution, invasive alien species (IAS) introduction, deforestation and erosion, and climate change pose unprecedented ecological and environmental challenges to large rivers (Best 2019). Here, we document the status of recent and long-term (decades-centuries) anthropogenic activities that impact the Magdalena River basin in Colombia (northern South America) (Fig. 1), the prospectus for its continued importance as an economic and cultural center, and a hotbed of aquatic biodiversity.

The Magdalena River is one of the world's largest rivers, with a length of 1612 km and a discharge volume of 7100 m^3 s^{-1} (Restrepo and Kjerfve 2000) (Table 1). The river dissects Colombia from South to North running between the Central and Eastern Andes Mountain range accumulating one of the highest global sediment yields (184 Mt yr^{-1}) and the largest in South America (Restrepo 2008). Since pre-Hispanic times, the Magdalena River has served as the central freshwater and food resource for a large human population and remains the major fluvial trade route in the country (Rodríguez 2015; Archila 2021). The river has forged Colombia's cultural and economic growth for millennia (Davis 2020; Archila 2021). Today, the Magdalena River basin hosts more than 30 million inhabitants, around 70% of the country's population, and accounts for 80% of the Gross Domestic Product (Dane 2022). A rich ethnic and cultural diversity is also reflected by the more than 15 indigenous groups that have occupied and shaped the territories during pre-historic, colonial, and modern times (Archila 2021) and by the > 250 designated indigenous reservations corresponding to 34% of the nation's protected areas (IGAC 2012).

The Magdalena River is a hotspot of ecological significance, hosting more than 160 recorded fish species, of which 67 are endemic (Galvis and Mojica 2007; Rodríguez-Olarte et al. 2011;

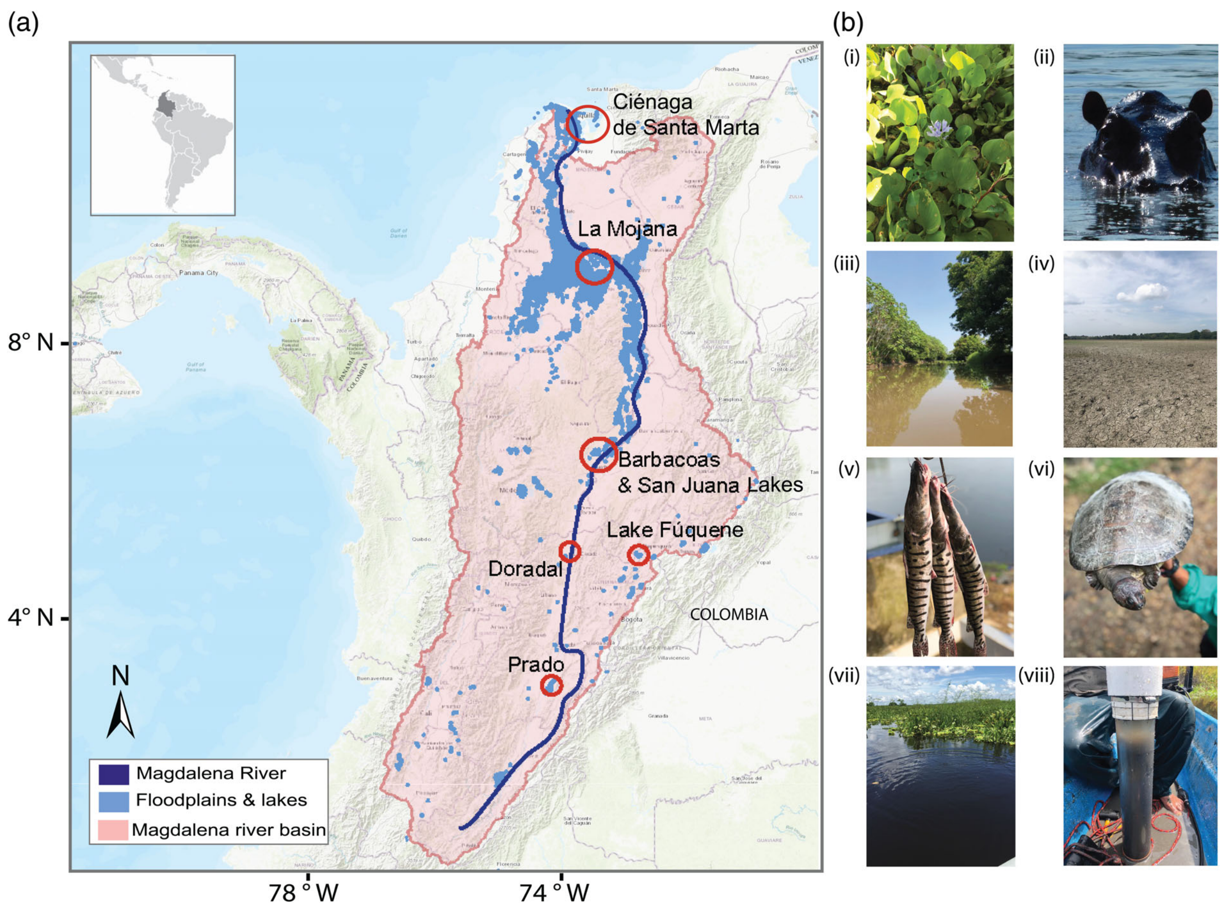

Fig. 1. (**a**) Map of the Magdalena River basin showing the main river (blue line) and exemplary sites addressed in the text; and (**b**) examples of stressors, native species, and paleolimnological methods: (i) water hyacinth (*E. crassipes*); (ii) African common hippopo (*H. amphibius*); (iii) River tributary with high sediment load; (iv) dried areas of a floodplain lake during El Niño (ENSO); (v) the Magdalena catfish (*P. magdaleniatum*); (vi) the Magdalena turtle (*P. lewyana*); (vii) wetland fringe in Barbacoas; and (viii) Lake sedimentary core for paleolimnological studies.

Table 1. Hydrological and biotic characteristics of the Magdalena River and other similar tropical large (> 1500 km) rivers.

River	Location	Length (km)	Drainage area (km^2)	Discharge ($m^3 s^{-1}$)	Fish spp. richness	Reference
Magdalena	South America	1612	257,438	7100	167	Restrepo and Kjerfve (2000)
Amazon	South America	6387	6,915,000	219,000	3000	Froese and Pauly (2022)
Orinoco	South America	2101	41,000	30,000	600	Froese and Pauly (2022)
Paraná	South America	3998	3,100,000	25,700	444	Froese and Pauly (2022)
Mekong	SE Asia	4023	810,000	16,000	877	Ziv et al. (2012)
Congo	Africa	4371	4,014,500	41,800	1044	Froese and Pauly (2022)
Nile	Africa	6690	2,870,000	5100	159	Froese and Pauly (2022)

Jiménez-Segura and Lasso 2020) (Table 1). Two of these endemic species, the Magdalena prochilodontid (*Prochilodus magdalenae*) and the Magdalena catfish (*Pseudoplatystoma magdaleniatum*), undergo reproductive migrations (Zapata and Usma 2013) and have high socio-economic value for local and national fisheries (Jiménez-Segura and Lasso 2020) (Fig. 1). Furthermore, the river is within the Tumbes–Chocó–Magdalena biodiversity hotspot (Myers et al. 2000), holding other iconic aquatic and semi-aquatic vertebrates such as the American manatee (*Trichechus manatus*), the river otter (*Lontra longicauda*), and the Magdalena turtle (*Podocnemis lewyana*) (Angel-Escobar et al. 2014).

However, changes in land use, pollution, and expected impacts from climate change raise concerns for the future of the river's unique biodiversity. Since the 1970s, human population growth, the rising demand for food and land, water and hydropower, and mining have generated increasing stresses on the main river and its tributaries (Etter et al. 2008; Restrepo et al. 2015; Angarita et al. 2018). The middle and lower basins of the river have been subjected to pervasive deforestation and water contamination from oil and mineral extraction, household and industrial effluents, extensive cattle ranching, and, more recently, an expanding palm oil agribusiness (Restrepo and Escobar 2018). More than 20 large dam projects (> 200 MW of hydroelectric capacity) have also been built along the main channel and its tributaries, and new dam projects (> 80) are being implemented as the national and international demand for power continues to grow (Angarita et al. 2018). Expanding populations of aquatic IAS such as the Amazonian water hyacinth (*Eichhornia crassipes*), the Asian Basa catfish (*Pangasianodon hypophthalmus*), and the first worldwide case of feral African common hippo (*Hippopotamus amphibius*) outside Africa, further contribute to the current ecological fragility of the Magdalena River. The human population living on, and directly or indirectly influencing the Magdalena River, will also likely continue increasing within the coming decades (Tessler et al. 2015). Thus, identifying the many environmental and ecological stressors impacting the Magdalena River and their interactions, and developing effective strategies for their mitigation, are of urgent concern in Colombia and globally.

We discuss the main anthropogenic stressors impacting the aquatic system on time scales ranging from centuries to decades using contemporary and paleolimnological (the study of lake sediments to reconstruct past environmental conditions) approaches. We propose a multidisciplinary research initiative focusing on (1) the understanding of the ecology and impacts of aquatic IAS; (2) promotion of forest restoration and mitigation of deforestation; (3) reversal and prevention of eutrophication and other forms of water pollution; (4) maintenance of river flow regimes; and (5) instituting consistent long-term monitoring to assess ecosystem health and detect and understand the causes of critical thresholds of change in condition.

Anthropogenic threats

River damming and regulation

Large dam projects pose one of the main threats to aquatic biodiversity in tropical rivers (Winemiller et al. 2016). Despite the value of water storage and electricity generation for promoting economic development, tropical river damming has far-reaching effects on the ecological integrity and biodiversity of rivers through water quality degradation and the restriction of movement of river flow, nutrients, major river-fed geochemical elements (e.g., Mg, Fe), and organisms (Poff et al. 2007) (Fig. 2). The impoundment of tropical rivers also affects the local climate (Degu and Hossain 2012), stimulating the growth of surrounding trees (Sun et al. 2021) and dampening natural hydrological variability (Jaramillo and Destouni 2015; Chaudhari and Pokhrel 2022). River damming further releases greenhouse gasses from sediments (Maavara et al. 2017) and increases evaporation levels from the water body's surface (Levi et al. 2015). Reservoir lentic conditions, when coupled with increases in nutrients (eutrophication), could additionally promote diatom species homogenization (Wengrat et al. 2018; Zorzal-Almeida et al. 2021), harmful algae blooms (HABs) (Labaut et al. 2020), and the invasion of multiple alien species (Johnson et al. 2008).

Hydropower infrastructure accounts for almost half of Colombia's electric demand in the Magdalena River basin,

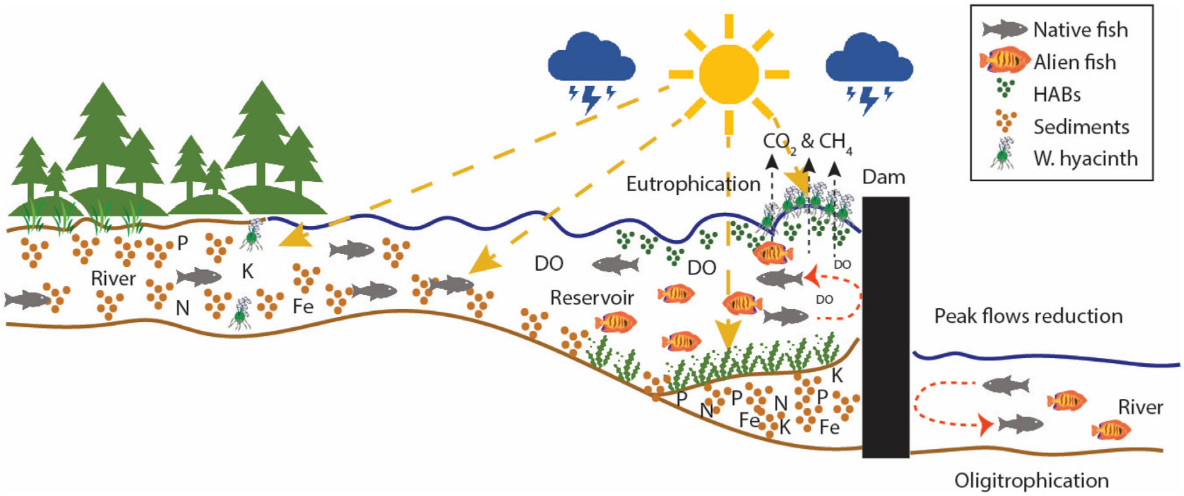

Fig. 2. Schematic diagram summarizing some of the major impacts of tropical river damming, including enhancement of primary productivity and harmful algae blooms (HABs), biogeochemical cycles alteration, species invasion, the restriction of movement of water, nutrients, and organisms, changes in local climate, deforestation, the dampening of a natural river, salinization, forest flooding, and the release of greenhouse gasses. Cl = chloride; DO = dissolved oxygen; Fe = iron; K = potassium; N = nitrogen; Na = sodium; P = phosphorus.

with an expected three-fold increase in the coming decades (Angarita et al. 2018). Appraisals of the impacts of these dams on the aquatic communities show that cumulative hydrologic alterations, coupled with the loss of longitudinal connectivity, will destabilize ecosystems by altering species composition and distribution, affecting the natural bimodal migration patterns, and reducing the extent of spawning habitats (Jimenez-Segura et al. 2022). Most fish endemism occurs across the tributary river headwaters; the longitudinal connectivity loss will pose a greater extinction risk for endemic species (Carvajal-Quintero et al. 2017). Basin-scale analyses on the lower river floodplains (Mojana; Fig. 1) further show that new hydropower infrastructure could drastically enhance (> 90%) habitat fragmentation between lowland floodplains and upstream fish spawning habitats (Angarita et al. 2018; Jimenez-Segura et al. 2022). It could also intercept > 80% sediment load through the new dams (Angarita et al. 2018). Dam release floods also increase egg mortality of Magdalena's turtle (*P. lewyana*; Gallego-Garcia and Castaño-Mora 2014), while the introduction of alien fish species in the reservoirs as food sources, further stresses native fish communities (Jiménez-Segura and Lasso 2020; Zapata-Londoño et al. 2020). Therefore, current and planned damming projects will likely increase the number of > 100 threatened vertebrate species in the region (Jimenéz-Segura and Lasso 2020; IUCN 2022).

Data from Prado Reservoir (Upper Magdalena basin; Fig. 1) show that river impoundment leads to eutrophication (Salazar et al. 2002; Guevara et al. 2009) and the suppression of minimum and maximum peaks of runoff through the regulation of the natural flows of tributaries (Zamora et al. 2020). Although beneficial for energy production, agriculture, and water management, the suppression of natural hydrologic variability further deprives many aquatic species of the conditions necessary for their reproduction, habitat, and migration (Carvajal-Quintero et al. 2017). In addition, eutrophication promotes HABs (Salazar et al. 2002; Roldán 2003), zooplankton community shifts from *Daphnia* sp. to *Bosmania longirostris* (Guevara et al. 2009), and the homogenization of physical and chemical conditions (Guevara et al. 2009). Data from Sogamoso Reservoir (middle basin; Fig. 1) further indicate substantial greenhouse gas emissions via organic matter decomposition at both in-filling (178,254.53-ton CO_2eq year^{-1}) and post-filling (466,946.57-ton CO_2eq year^{-1}) stages (Rodríguez and Peñuela 2022). The degradation of flooded forest organic material stored in large tropical reservoirs could take up to four to five decades (Campo and Sancholuz 1998; Salgado et al. 2020).

At the confluence with the Caribbean Sea, flow obstructions by dikes and sluices gates for flood control and agriculture have diminished runoff, and the river flows into the Magdalena River Delta (Jaramillo et al. 2018*a*). The deltas encompass alluvial plains and wetlands, mangrove forests, and one of the largest (4280 km^2) freshwater-brackish lagoons of South America, known as the *Cienega Grande de Santa Marta* (CGSM). Hydrological estimations from the period 2007–2011 indicate that freshwater from the main Magdalena River now reaches the CGSM only 30% of the days (Jaramillo et al. 2018*a*); a result that is surprisingly low, given that the CGSM is a significant part of the delta of the Magdalena River. Although smaller tributaries from La Sierra Nevada de Santa Marta (Fig. 1) help maintain freshwater inputs into the CGSM, the temporal disconnection from the Magdalena River results in hypersaline conditions in many areas of the wetland (Jaramillo et al. 2018*a*).

Aquatic alien species

There are currently many (> 50) alien species introduced in the Magdalena River, including fish (e.g., the common carp *Cyprinus carpio*, the black bass *Micropterus salmoides*, the Yellow Tilapia *Coptodon rendalli*; and the Basa catfish *P. hypophthalmus*; Jimenéz-Segura and Lasso 2020), macrophytes (e.g., water hyacinth *E. crassipes*; and Brazilian Elodea *Egeria densa*; Carrillo et al. 2006; Salgado et al. 2019), mollusks (e.g., the bivalve *Corbicula fluminea*; De la Hoz-Aristizabal 2008), and mammals (water buffalo *Bubalus bubalis*; and African hippo *H. amphibius*; Shurin et al. 2020; Restrepo-Calle and Cadena 2021). Many of these have the potential to become or are already considered IAS (Gutierrez et al 2012; Jiménez-Segura and Lasso 2020). Among these aquatic IAS, the water hyacinth (*E. crassipes*), the Asian Basa catfish (*P. hypophthalmus*), the water buffalo (*B. bubalis*), and the African hippo (*H. amphibius*) are the most significant examples (Fig. 3). Hippos, for instance, were introduced into the middle basin of the Magdalena River in 1981 by the drug lord Pablo Escobar (Fig. 1). Two captive animals became feral following Escobar's death in 1993, and the population has grown steadily, around 10% per year (Subalusky et al. 2021). This invasion is the first-ever recorded case of feral hippos outside Africa, and informal estimates peg the population at around 100 animals which have recently been observed > 300 km north of where the population originated. Habitat modeling projected an eventual steady-state population of about 1500 animals by 2050 distributed throughout the middle and lower basins of the Magdalena (Castelblanco-Martínez et al. 2021).

In their natural range, hippos function as ecosystem engineers, vectoring nutrients acquired while grazing on land that is recycled as wastes in aquatic ecosystems (Stears et al. 2018). Hippo-driven excessive fertilization can lead to eutrophication, associated mass mortality of fishes, HABs, and disease vectors (Dutton et al. 2018). Comparing the trophic status of small artificial lakes with and without resident Colombian hippo populations confirmed that hippos may recapitulate their role as water fertilizers in their non-native range (Shurin et al. 2020). However, the results found statistically detectable but relatively minor differences in trophic status between hippo and non-hippo lakes. These differences were within the range of natural spatial variability among lakes. The lack of dramatic differences may partly be explained by more significant annual precipitation (compared to East African Savannas) and a comparable pervasive fertilizing impact of cattle ranching that simultaneously contaminates the studied lakes (Shurin et al. 2020). A lack of historical environmental and ecological information about the lakes in pre-hippos' time may also complicate the interpretation of the results. More research on the ecology of hippos in the wild is hence required. Important research foci to consider the genetic variation among the establishing population, the effects of hippos within the broader human-impact context of the river's catchment area (including water pollution and climate), and the links with other, more numerous introduced species with fewer media and scientific appeals such as cattle (*Bos taurus*) and water buffalo (*B. bubalis*).

Three different breeds of water buffalo have been introduced since the 1960s across the middle and lower basins of the Magdalena for the palm oil industry, meat, and dairy products (ICA 2017). Like hippos and cattle, buffalos are amphibious ecosystem engineers (Mihailou and Massaro 2021). By digging and wallowing on wetland margins, they can destabilize soil, expose large areas to evaporation, and reduce water retention during the dry periods (Skeat et al. 1996). Buffalos also suppress woody riparian vegetation by grazing on seedlings and saplings and promoting nutrient load and bioturbation (Petty et al. 2007). Herds of water buffalos are now commonly seen roaming the middle and lower basins of the Magdalena River and its floodplain lakes (e.g., Barbacoas Lake; Fig. 1). However, more research on their population dynamics and ecosystem effects in their non-native range is necessary.

Water hyacinth is considered among the 100 most invasive aquatic species worldwide, with annual management economic costs in South and Central America estimated at around USD 179.9 million (Heringer et al. 2021). Widespread records of this species have been reported across the Magdalena main reservoirs (e.g., Hidroituango, Porce II and III, Betania, and Prado), natural upland lakes (e.g., Fúquene Lake), lowland floodplain lakes (e.g., Barbacoas, Mojana), and in the river's main channel (Fig. 1). Water hyacinth's spread and dominance have been widely associated with lentic conditions and nutrient increases (Villamagna and Murphy 2010). Dense floating mats contribute to water anoxia by shading and preventing photosynthesis, impacting submerged biota, and producing decomposed organic matter (Salgado et al. 2019). Paleolimnological assessments (using plant macrofossils, pollen, and trace elements) from two ^{210}Pb dated cores in Lake Fúquene (Fig. 1) similarly showed that steadier hydrological conditions and increased nutrient loading stimulated *Eichhornia* proliferation over the last two centuries to its current levels of covering > 60% of the lake's surface area (Salgado et al. 2019). In reservoirs, the high catchment nutrient loading during the infilling process and the novel artificial lentic conditions create optimal conditions for *Eichhornia* to bloom (Thomaz et al. 2015). Historical and paleolimnological accounts in Brokopondo Reservoir, Surinam (Van Donselaar 1968), and the Panama Canal (Salgado et al. 2020) indicate that *Eichhornia* may, dominate reservoirs faster (1–5 years) than natural lakes. Costly remediation programs are required to control this nuisance species (Hearne 1966). Unfortunately, despite the ongoing expansion of hydropower and agricultural development in the Magdalena River, little attention has been paid to the invasion, ecology, and spread dynamics.

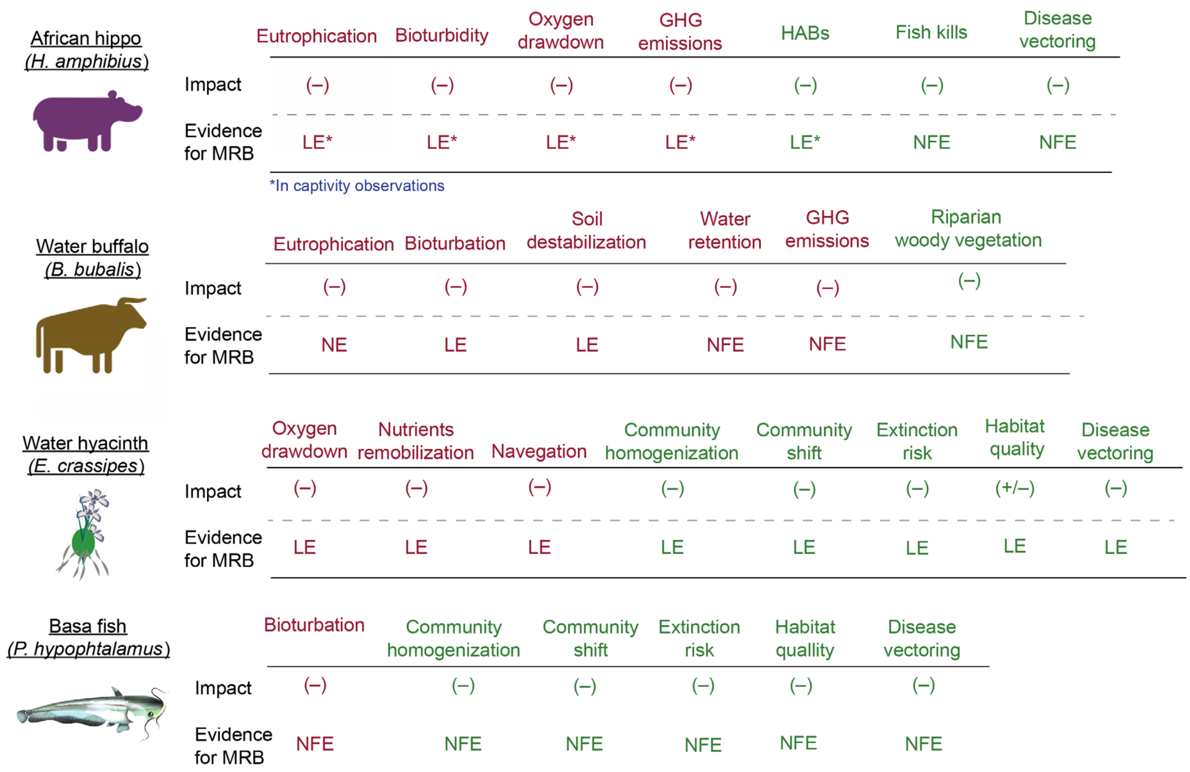

Fig. 3. Schematic diagram of exemplary physicochemical (red) and ecological (green) impacts of the African hippo (*H. amphibius*), the water buffalo (*B. bubalis*), the water hyacinth (*E. crassipes*), and the Basa fish (*P. hypophthalmus*) on tropical rivers. The degree of evidence found in the literature for the Magdalena River basin (MRB) is categorized into strong evidence (HE; > 10 supporting references), medium evidence (ME; 6–10 supporting references); insufficient evidence (LE; < 5 supporting references) and not found evidence (NFE). Negative impacts are denoted by (–) and positive impacts by (+). GHG = greenhouse gasses; HABs = Harmful algal blooms.

Another spreading alien species is the Basa catfish (*P. hypophthalmus*), native to the Mekong River Delta in Vietnam (Southeast Asia). This migratory fish has a broad diet, a tolerance to extreme environmental conditions, and high reproductive and growth rates (Lakra and Singh 2010). The Basa fish is now one of the fastest-growing aquaculture crops in the tropics, being sold across > 100 countries (Singh and Lakra 2012). As reported for other tropical river systems (Garcia et al. 2018), it is believed that the Basa catfish were illegally introduced into the Magdalena River through local aquaculture programs and ornamental aquariums (Valderrama et al. 2016). The first captures in the wild date from 2015 across the main channel, tributaries, and floodplain lakes, and now it is rapidly expanding throughout the lowlands of the Magdalena basin (Valderrama et al. 2016). Studies from other tropical rivers have reported that Basa fish can impact native fish communities, affect habitat quality through bioturbation, and facilitate the transmission of fish pathogens (Thuy et al. 2010). A contributing factor to the potential spread of Basa toward likely invasive levels in the Magdalena River is the Colombian Decree 1780 issued by the Colombian Government (MADR and AUNAP 2015). This decree allows species used for fish farming purposes, whether introduced legally or illegally to the country, to be declared "naturalized." Thus, they can become protected from conservational management strategies (Valderrama et al. 2016). We, therefore, urge studies on the Basa catfish ecology and impacts in the Magdalena River, as are also efforts to prevent its further spread and remove its "naturalized" status.

Ecohydrology of the Magdalena River basin

El Niño–Southern Oscillation (ENSO) influences the hydroclimatological conditions of the Magdalena River basin, with extended periods of low precipitation (droughts) during El Niño events and prolonged rains (floods) during La Niña events (Restrepo and Kjerfve 2000). These climatological conditions are essential in connecting the main river and adjacent wetland and lake systems (Blanco et al. 2006; Jimenez-Segura et al. 2022) (Fig. 4). A paleolimnological reconstruction (diatoms and trace elements) from ^{210}Pb dated cores covering the last centuries of Barbacoas and San Juana Lakes (Fig. 1) showed lake surface area to vary according to ENSO and degree of connectivity to the Magdalena (Lopera-Congote et al. 2021). For instance, during a sequence of intense El Niño events between 1987 and 1992, Barbacoas Lake, directly

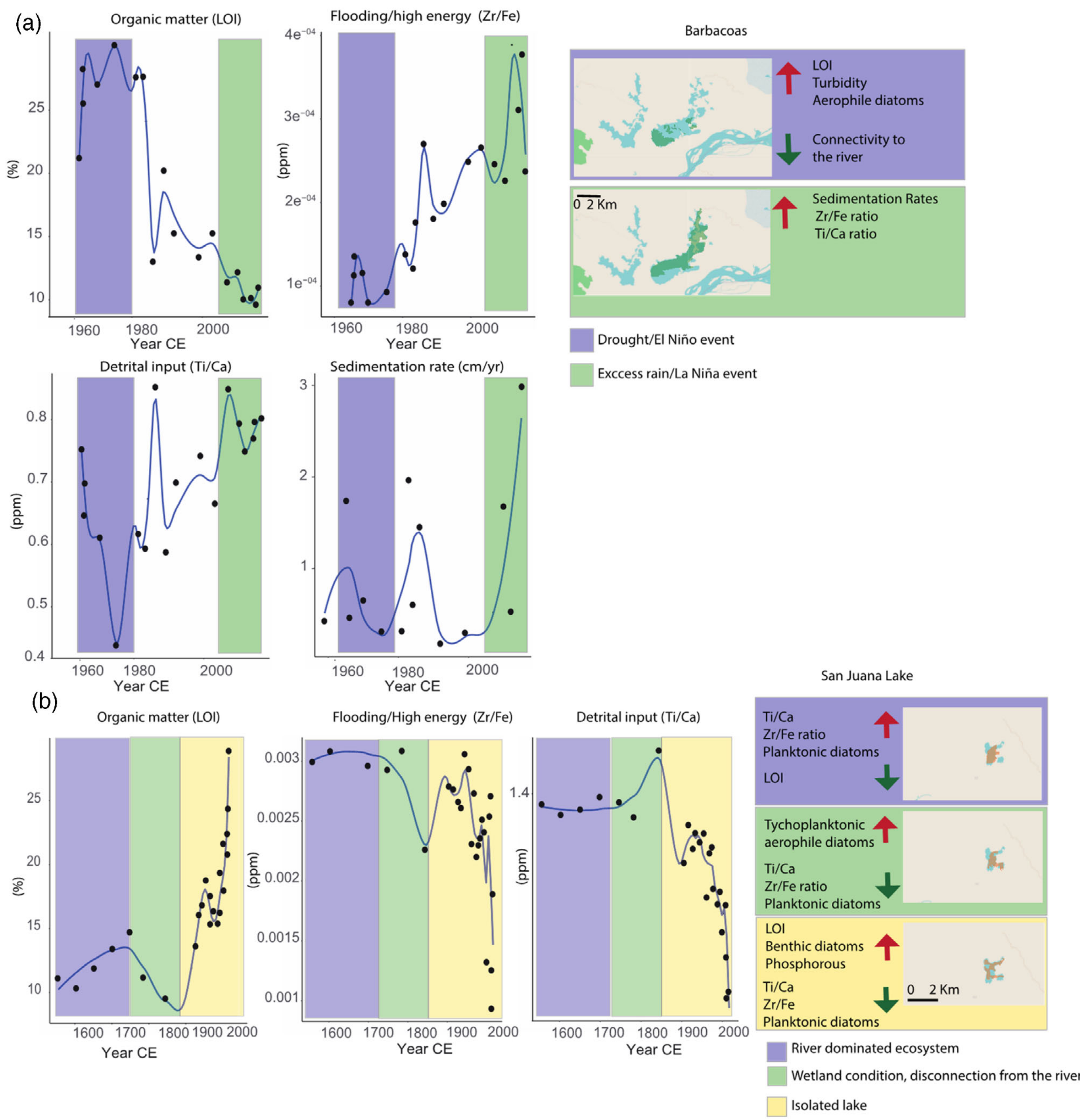

Fig. 4. Schematic diagram of the long-term (decades-centuries) paleolimnological evidence found for hydrological, ecological, and geochemical changes in the floodplain lakes (**a**) Barbacoas and (**b**) Sanjuana in response to ENSO events.

connected to the Magdalena, responded acutely during these dry years and was severely desiccated (Fig. 4). In turn, the surface area of the San Juana Lake, which is connected to the main river course through a series of tributaries (Fig. 4), lost only 10% of its historical value (Lopera-Congote et al. 2021). Similarly, in the delta region of the CGSM, the ENSO-driven periods of flood and drought influence the freshwater input from the Magdalena River into the CGSM wetland complex resulting in hypersaline conditions during dry events (Jaramillo et al. 2018*b*). Together these results suggest that during El Niño years, floodplain lakes with a higher degree of connectivity to the Magdalena River could face major droughts and substantial reductions in river flow, leaving them hydrologically isolated (Jimenez-Segura et al. 2022).

The Magdalena River and its tributaries have also experienced increasing sediment loads (Restrepo 2008). Fueled by industrialization and socioeconomic policies adopted in the 1970s, the Andean regions of the Magdalena River basin have witnessed unparalleled deforestation (Etter et al. 2008). Lowland savannas and floodplains have suffered equally strong transformations due to irrigation, replacing native forests and grasses by introducing pastures and crops (Etter et al. 2008). The recent globalization of agriculture has also resulted in large extensions of industrial agriculture (e.g., palm oil) across the central and lower basins of the river. Anthropogenic land use has transformed > 40 Mha of the river basin, accounting for 70% of national deforestation (Restrepo and Escobar 2018). Almost 69% of Andean forests and 30% of lowland forests were cut down by 2000, whereas between 2005 and 2010, deforestation in the river basin accounted for 24% of the combined deforestation in Colombia (Restrepo et al. 2015). All these developments contribute to sediment loading to the Magdalena.

Standing forests regulate land's hydrological and biogeochemical processes, ultimately determining the amount of organic matter, nutrients, and sediments reaching the river channel (Ellison et al. 2011; Ward et al. 2017). Uncontrolled land-use experiments comparing natural forest cover against standard agricultural and productive land covers show that deforestation in the Magdalena River basin could significantly reduce infiltration, enhance runoff from soil compaction by livestock trampling, and promote excess nutrient load from crops (Suescún et al. 2017). Estimates of sediment released by deforestation in the Magdalena basin indicate that between 1972 and 2010, erosion increased by more than 30% (Restrepo and Escobar 2018), from which 9% is loaded into the Magdalena through its tributaries. Between 2000 and 2010, the annual sediment load increased by 33% concerning pre-2000 conditions (Restrepo et al. 2015).

Land-use change in the Magdalena basin may exceed the rate of climate-driven erosion by several orders of magnitude (Restrepo and Escobar 2018). However, climate change and higher precipitation rates with more frequent extreme events (i.e., drought and flooding) may further magnify anthropogenic land-use impacts as an additional regional source of soil erosion. For instance, limestone and sand quarrying combined with erosive rain events have led to unprecedented loads of sediment into main tropical American rivers and estuaries (Jaramillo et al. 2016). Furthermore, rainfall will intensify under all climate change scenarios (IPCC 2021) on the Magdalena Andean slopes, with levels expected to increase by 5–20% by the end of the century. Seasonality is also projected to be more pronounced as the difference between the rainy and the dry seasons become larger, directly affecting the productivity of agricultural lands and natural ecosystems. More frequent consecutive rainfall events (IPCC 2021) would also lead to an increased risk of landslides, flooding, and soil erosion, increasing sediment load. All these climate changes are, thus, expected to amplify the effects of human-driven land-use changes on the Magdalena. Nonetheless, to the best of our knowledge, there has not been a study on the hydro-climatic conditions of the river basin due to a lack of consistent baseline long-term discharge data (Åhlén et al. 2021). As such, attributing changes in runoff from the basin due to climate and land-use intensification is challenging.

Paleolimnological records offer one view of past sedimentological conditions and regimes of climatic variability in the absence of monitoring data. The reconstructions based on ^{210}Pb dated cores from Barbacoas and San Juana Lakes indicate a two-fold increase in sediment accumulation since 2000 (Lopera-Congote et al. 2021) (Fig. 4). Sediment accumulation in Barbacoas Lake (2–3 $cm\,yr^{-1}$) was almost 10-fold higher than those of San Juana Lake (0.2–0.4 $cm\,yr^{-1}$) and the greatest reported among 10 other studied lakes across Central and North America (Yang et al. unpubl.). The parallel increases in accumulation rates post-2000 in Barbacoas and San Juana Lakes concurred during a wetter decade period that coincided with an increase in catchment deforestation (Restrepo et al. 2015; Restrepo and Escobar 2018). Most floodplain lakes in the middle and lower parts of the Magdalena River are shallow (< 4-m depth). Increases in erosional sediment load coupled with more frequent droughts and floods would likely double the natural rate of the lake infilling process and disconnection from the main channel (Restrepo and Kjerfve 2000). Disconnection from the main channel and reduced lake water levels may also enhance primary productivity and spread the already-occurring water hyacinth and other wetland flora (Fig. 2; Salgado et al. 2019). In addition, increases in sediment load and water hyacinth densities could promote suspended solids and water turbidity, oxygen drawdown, and alter food web structure (Mercer et al. 2014; Salgado et al. 2019).

One of Colombia's most significant infrastructure projects is to restore the navigability of the Magdalena River for large cargo ships by 2023. To this aim, the width and depth of the middle and lower basins of the river must be increased to allow navigability during the low water season. Such an engineering endeavor requires intensive dredging, and 1.4 million square meters of sediment have already been dredged (Cormagdalena 2021). In the Panama Canal, our paleolimnological assessments showed a four-fold increase in sedimentation rates with the significant expansion works to accommodate increasing global trade (Salgado et al. 2020). Thus, the sedimentation dynamics and hydrological connectivity between reservoirs, the Magdalena, and its floodplain lakes and delta will inevitably be even more altered, compromising the stability of these fragile ecosystems.

Impacts on the Magdalena River Delta

The delta region of CGSM is part of a more extensive estuary system characterized by a wide variety of mangrove and swamp areas designated as an internationally important wetland under the Ramsar Convention (Gardner and Davidson 2011) and protected under a National Park designation in the *Parque Isla de Salamanca*. A mixture of coastal roads construction, flow regulation for agribusiness, urbanization, and pollution have led to the salinization and eutrophication of the CGSM system, resulting in a loss of more than 300 km^2 of mangrove coverage during the last 30 years; one of the most significant ever-recorded mangrove ecosystem losses in tropical Americas (Botero and Salzwedel 1999; Blanco et al. 2006; Restrepo et al. 2007; Vilardy et al. 2012; Röderstein et al. 2014). The collapse of this coastal ecosystem also corresponded with anomalous drought conditions (Jaramillo et al. 2018*a*,*b*). Paleoenvironmental reconstructions and ecosystem services risk analysis based on paleo-data and socio-ecological history have indicated that variation in salinity has been associated with the most significant temporal changes in the CGSM's aquatic ecosystems, including mangroves (Vilardy et al. 2011; Velez et al. 2014; Gutierrez-Cala 2020). Risk analysis pointed to hydrological connectivity with tributaries and the Caribbean as a management priority to minimize the risk of losing the services offered by the CGSM that benefit more than 300,000 people (Vilardy et al. 2011; Velez et al. 2018).

A lack of systematic river flow monitoring data from the Magdalena River and associated tributaries at the time of the mass mangrove mortality in the CGSM has hindered so far, the assessment of the overall ecosystem resilience (Zipper et al. 2020), and the partitioning of the specific roles of climate and anthropogenic activities on ecosystem change (Jaramillo et al. 2018*a*). Nevertheless, remote sensing data suggest a lateral connectivity fragmentation between the Magdalena River and the CGSM system through flow regulation (Jaramillo et al. 2018*a*). This hydrological fragmentation may have been responsible to a large extent for the current increases in salinity and eutrophication attributed to the death of the mangroves (Jaramillo et al. 2018*a*). Furthermore, radar interferometry— to construct maps of water level change show that currently, the Magdalena River delta, including the CGSM, does not exhibit the typical flow conditions of similar unregulated floodplains in the country, such as the Atrato River in the western part of Colombia (Palomino-Ángel et al. 2019).

A restoration program for the CGSM is underway, aiming to reduce the salinity of current hypersaline areas of the lagoon by removing dead mangrove coverage and opening some channels. As of 2015, mangrove coverage had rebounded to approximately 400 km^2, but the percentage cover has remained stagnant since 2011. Despite these restoration efforts, the CGSM is still in a bad environmental and ecological state and hence, it is included within the Montreaux Record (Hamman et al. 2019). The Montreaux Record is a list of Ramsar wetlands with priority conservation needs due to ongoing changes in ecological character resulting from human interference activities (Hamman et al. 2019).

Water pollution and urbanization

Water pollution is an emerging threat of significant concern in the Magdalena River (Fig. 5), about which little evidence is available but whose effects likely contribute to further degrading the river ecosystem. The pollution is a straightforward consequence of a direct discharge of domestic and industrial sewage and runoff of nutrients and chemicals from agriculture, mining, and oil activities in the Magdalena River and its tributaries (Tejeda-Benitez et al. 2016). In the upper basin of the Magdalena, the city of Neiva is responsible for the first significant river pollution discharge due to a lack of a wastewater management system and oil and agricultural activities (Tejeda-Benitez et al. 2016). In the middle basin, the Magdalena River receives one of the significant pollutant contributors, the Bogotá River, which runs through the capital city of Bogotá before reaching the Magdalena. This tributary is

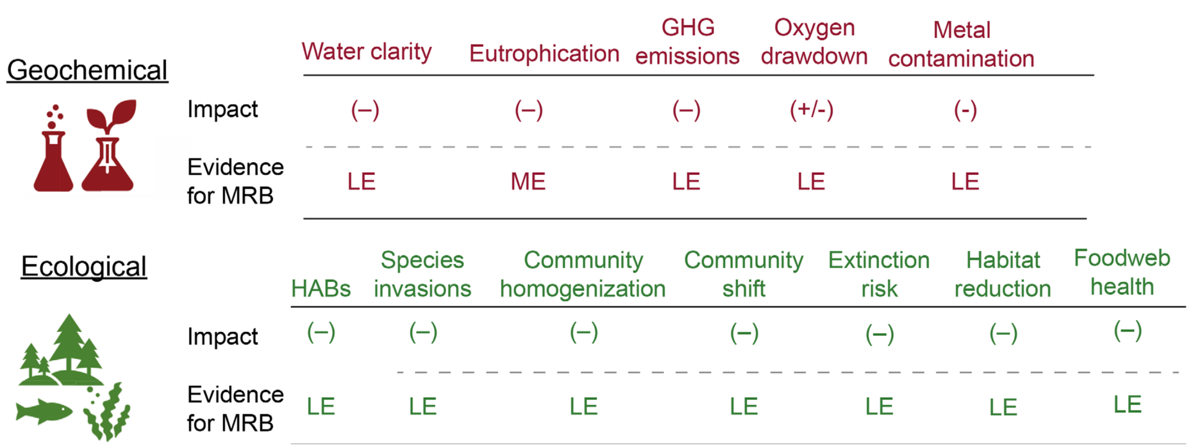

Fig. 5. Schematic diagrams summarizing exemplary geochemical (red) and ecological (green) effects of water pollution on tropical river systems. The degree of evidence found in the literature for the Magdalena River basin (MRB) is categorized into strong evidence (HE; > 10 supporting references), medium evidence (ME; 6–10 supporting references); insufficient evidence (LE; < 5 supporting references) and not found evidence (NFE). Negative impacts are denoted by (−) and positive impacts by (+). GHG = greenhouse gasses; HABs = Harmful algal blooms.

among the topmost polluted rivers worldwide (Venegas et al. 2015; Díaz-Casallas et al. 2019). Physiological analyses of the aquatic biota from the Bogotá River have shown high bioaccumulation levels above the health standards of lead (Pb), chromium (Cr), and cadmium (Cd) (Forero et al. 2009). Mining activities coupled with extensive cattle ranching and agrofarms further promote pollution down the mouth of the Bogotá River, posing a high ecological risk to the associated biota in the middle and lower basins of the Magdalena River (Tejeda-Benitez et al. 2016).

Toxic metals, such as mercury (Hg), Pb, and arsenic (As), related to gold mining have been also found in the Magdalena catchment area, and to be incorporated into the aquatic food web (Mancera-Rodríguez and Álvarez-León 2006; Marrugo-Negrete et al. 2008*a*,*b*; Zapata et al. 2014). Mercury, for instance, is the third most toxic element for human health, according to the USA Agency for Toxic Substances and Disease Registry (Budnik and Casteleyn 2019). Its prevalence in water may also result in being re-emitted into the atmosphere or captured in the lake and river sediments (Kocman et al. 2017). Currently, methyl-mercury (Hg form in water) values in the lower basin of the Magdalena River are three to four times higher than pre-industrial times (1850) natural background values (Marrugo-Negrete et al. 2008*a*,*b*; Olivero-Verbel et al. 2015). The sources of this Hg pollution in the river are still debatable. Still, the evidence so far points toward a combination of a regional atmospheric deposition from cities and industry and from point sources of gold mining that have increased in the last two decades (Yang et al. unpubl.; Olivero-Verbel et al. 2015). In Barbacoas Lake, the paleo-sedimentary records indicate relatively high but constant Hg concentrations over the last six decades, with no clear indication of a recent significant increase in Hg related to mining activities (Yang et al. unpubl.). This is not surprising given that Barbacoas Lake is located south of the current gold mining hotspots (Northeast of Antioquia and South of Bolivar states; Fig. 1). Furthermore, the observed marked increase in sedimentation since the early 2000s and El Niño conditions may have also diluted the Hg concentrations in the lake sediments (Yang et al. unpubl.).

The widespread, uncontrolled application of nitrogen (N) and phosphorous (P) fertilizers and pesticides in agriculture and the aerial fumigation of herbicides as part of illegal drug eradication policies pose additional threats to the health of the Magdalena Basin ecosystem. Nitrogen and phosphorus biogeochemical cycles are completely disrupted, and current levels in the Magdalena exceed pre-1950 levels by one order of magnitude (Restrepo 2008). This nutrient excess affects many biological processes in riverine, terrestrial, and marine ecosystems (e.g., Ramírez-Valencia et al. 2021). Catchment urbanization across the Magdalena River basin is also expanding rapidly. Urbanization may change river discharge, reduce infiltration, and influence the delivery of organic matter enriched in nutrients, stimulating the growth of heterotrophic microorganisms (Kaushal et al. 2014; Wang et al. 2017). Transforming the river basin and hydrological characteristics may lead to eutrophication, hypoxia, HABs, and excess partial pressure of aquatic CO_2 (Wang et al. 2017; Zhang et al. 2021). Projected urban development in the Magdalena River basin will thus likely increase water demand intensifying stagnant waters, oxygen drawdown, and potentially associated HABs among urban tributaries, especially during dry periods (Johnson et al. 2022).

Concluding remarks and future research

Relative to its critical importance to Colombia's economy, culture, and biodiversity, the Magdalena River basin is a woefully understudied ecosystem compared to other similarly sized rivers worldwide. The limited evidence suggests that it is experiencing the compounding impacts of local and global environmental changes that may threaten ecological integrity and economic vitality (Tessler et al. 2015; Best 2019). The main emerging threats underpinning the social-ecological balance of the river system include large-scale damming, the spread of aquatic IAS, and the interconnected effects between catchment deforestation, erosion, and shifts in the hydro climatological characteristics of the basin. To understand these changes, our combined contemporary and paleolimnological research on the Magdalena River and associated floodplain lakes yield a more robust picture of variability over recent centuries and the main factors that destabilize and jeopardize the health of the community in the Magdalena River and tributaries. This information deficit hinders the development of strategic activities from reducing stresses and restoring ecosystem integrity, biodiversity, and ecosystem services (Tickner et al. 2020). To address these deficiencies, we recommend addressing the following knowledge gaps.

- Long-term studies of aquatic IAS are imperative to understand their distribution patterns, population dynamics (i.e., introduction, lag-phases, and exponential phase), and spread pathways (Strayer et al. 2006). Furthermore, research and management strategies must also be driven by scientific expertise (Restrepo-Calle and Cadena 2021) and by assessing many more species' economic, genetic, and ecological impact rather than focusing on species with a charismatic appeal (Beever et al. 2019). Consideration should be given to building scientific expertise in relevant areas, e.g., taxonomy of IAS, modeling pathways of spread, and ecological requirements of potential novel IAS (Sternberg et al. 2018).
- There is a need for more studies of river flow regimes for the natural functioning of the river channel, backwaters, and associated floodplain lakes (Chaudhari and Pokhrel 2022). Understanding ecological implications and societal effects (Moran et al. 2018), especially for indigenous communities of altered flow regimes, is also imperative (Anderson et al. 2019).

- A deeper understanding of how reforestation might serve as a mitigation strategy with collateral benefits for terrestrial, riparian, and aquatic biodiversity, climate regulation, flood control, human health, and local economies (Ellison et al. 2011). Modeling data and paleolimnological reconstructions show that deforestation degrades water quality and promotes hydrologic alteration and isolation of floodplain lakes from the river channel.
- Assess river ecosystem integrity based on continuous long-term monitoring data along the channel, its floodplains, and within the tributaries of subbasins. This will help detect and understand changes in the functioning of the river as a tightly connected hydrologic and ecological system and will provide reference baselines for delineation of management and conservation targets and objectives for restoration action plans (Poff et al. 2007).
- Understanding the consequences of extreme events, such as fluvial and coastal flooding or severe droughts, which act over short- and long-term time scales (Tessler et al. 2015). Assessing the intensity and distribution of hazardous events and how they interact with the other anthropogenic stressors is essential to determining future risk and the social and ecological integrity of the river delta (Santos and Dekker 2020).

Despite the ongoing anthropogenic issues stated here, we believe the Magdalena River is still a resilient system. However, to successfully rescue this unique and precious river system, it is imperative to address research knowledge gaps and strengthen inter-institutional coordination (e.g., RAMSAR-Government) for the management and decision making.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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