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GENERAL WETLAND SCIENCE

A Classification System for Colombian Wetlands: an Essential Step Forward in Open Environmental Policy-Making

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Abstract
Knowledge about the distribution and diversity of wetlands has become an essential tool for environmental management and policy-making. Yet, while recent estimates indicate that 27% of the area of Colombia is covered by wetlands and despite a number of regional studies, information about the diversity of wetlands nationally is scarce. In response, we present a national wetland classification system that is based on an ecological approach, from the perspective of wetland scientists, and which builds upon the assumptions underlying the flood pulse concept and hydrogeomorphic approach. Thus, the approach and structure of the Brazilian wetland classification system are used, with geomorphological adjustments made according to Colombia's topography. The classification is hierarchical, multi-scale, functional, and organized according to four levels (system, macroregion, subsystem, and class), with the wetland diversity of Colombia represented nationally by 89 macrohabitats across marine-coastal, inland, and anthropogenic systems. The primary purpose of this classification is to provide integrated and organized information on the distribution and diversity of Colombian wetlands that will serve as a baseline for transparent environmental policy-making.

Keywords Flood-pulse concept · Hydrogeomorphic approach · Macrohabitat · Policy-making · South America · Vegetation · Wetland classification · Wetland type

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Introduction

The multifunctional character of wetlands (Mitsch et al. 2009), including the resources and cultural services they provide (MEA 2005; de Groot et al. 2006), is well-established but their regulatory functions may be of greater importance, particularly the ability of wetlands to attenuate the consequences of natural events, such as extreme floods and droughts (Bullock and Acreman 2003; Erwin 2009; Acreman and Holden 2013; Ricaurte et al. 2017). However, climate variability and changes in land cover strongly impact the regulatory mechanisms that enable wetlands to attenuate hydrological processes (De Groot et al. 2002; Taylor et al. 2011; Zhang et al. 2016).

In recent years, Colombia has sought to respond to the consequences of climate change. The average annual temperature nationally is expected to increase by 0.9 °C by the year 2040, while annual precipitation is expected to decrease between 10 and 40% in ~32% of the country (IDEAM, PNUD, MADS, DNP CANCILLERÍA 2017). The incidence of climate events with strongly negative impacts, especially floods and droughts, increased up to two-fold between 1991 and 2011 (Sánchez and Calderón 2012). In 2010/2011, floods caused over USD ~6 billion worth of damage and affected 3.2 million people and 31% of the country (CEPAL 2012). In 2014 and 2016, the cumulative rainfall deficit reached 65% while droughts lowered the water levels of rivers and reservoirs to their lowest levels in the last 15 years. In the case of wetlands, in addition to climate-related effects, there has been a severe decline in their coverage, due to changes in land use, which have impacted 73,326.56 km^2 (24%) of the total wetland area (Patiño and Estupiñán 2016). Thus, of the 306,939.22 km^2 (27%) of the country defined as wetlands (Flórez et al. 2014), only 233,612.66 km^2 (20%) remain.

The Colombian Government has reacted to this situation by recognizing that existing knowledge about wetlands is not sufficient for the development of policies addressing extreme climatic events, such as El Niño and La Niña, and, over the long-term, climate change. In response, the Instituto de Investigación de Recursos Biológicos Alexander von Humboldt and the Fondo Adaptación coordinated a country-wide multidisciplinary research project on wetlands aimed at obtaining the technical and scientific background needed for the identification and mapping of wetlands in Colombia at a scale of 1:100,000. The national agencies responsible for the production of official maps, i.e., the Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM) and the Instituto Geográfico Agustín Codazzi (IGAC), were included in this project.

In this paper, we provide the first system for wetland classification at the national level in Colombia. It was developed by adjusting both the definition of wetlands and the classification system used in Brazil, by adding a new attribute that takes into account the geomorphological features that differentiate wetlands of the high Andes from those of the lowlands and coastal areas. The hydrological and vegetation parameters are the same as established for the Brazilian system. The hierarchical structure of the classification, the attributes, and the classes used to differentiate wetland types are presented below, followed by a discussion of the implications of this work for wetland policy in Colombia and in South America as a whole.

Data and Methods

Definition and Functional Delimitation of Colombian Wetlands

Although there are many definitions of wetlands (Finlayson et al. 1999; Mitsch and Gosselink 2015), most of them are based on the environmental conditions of temperate-zone wetlands, where the water levels are relatively stable and the wetland borders, formed by wetland vegetation and hydric soils, are well-defined. By contrast, most wetlands in the tropics and subtropics have fluctuating water levels as well as explicit dry phases characterized by drought and, frequently, fire. As a result, the biota ranges from aquatic/wetland to terrestrial plants and animals, with associated biogeochemical changes in the soils.

The definition of wetlands proposed by Junk et al. (2014) was an important step in the study of wetlands in the Neotropics. It stated that wetlands are “ecosystems at the interface between aquatic and terrestrial environments; they may be continental or coastal, surface or subterranean, natural or artificial, permanently or periodically inundated by shallow water or consist of waterlogged soils. Their waters, which may be fresh or highly or mildly saline, are home to plant and animal communities adapted to their water dynamics”.

However, a prerequisite in the mapping of wetlands at the national level is a conceptual basis that then allows a visualization of the interrelationship and connectivity of this interface and of the aquatic ecosystems that drive the flood pulses, which ultimately constitute the main driver of the formation and functioning of wetlands along rivers, streams, lakes, and seas. Accordingly, we proposed a definition that facilitated the mapping of Colombian wetlands (Vilardy et al. 2014), namely: “wetland is a type of ecosystem that, due to geomorphological and hydrological conditions, allows the accumulation of water (temporarily and permanently) and gives rise to characteristic types of soil and organisms adapted to these conditions.”

Unlike wetlands with stable water levels, in flood-pulsing systems the wetland boundary shifts between the dry and wet seasons, as described by the moving littoral of river floodplain systems in the flood pulse concept (FPC) (Junk et al. 1989).

For instance, in the Pantanal of Mato Grosso and in the Amazonian *várzeas* and *igapós*, 70–80% of the wetlands are dry during the dry season. In the floodplain of the Araguaia River, the percentage reaches 90%. Similar conditions are expected for most flood-pulsing wetlands in Colombia but they have yet to be identified and described. A consequence of a shifting wetland boundary is that temporarily dry areas are not identified as wetlands, such that human intervention and the conversion of wetlands into, e.g., agricultural lands have been allowed. Therefore, a wetland definition should be accompanied by conceptual elements that clearly establish its boundaries in a functional manner. This was recognized by Junk et al. (sensu Junk et al. 2014), "the extent of a wetland is determined by the border of the permanently flooded or waterlogged area, or in the case of fluctuating water levels, by the limit of the area influenced during the mean maximum flood, including, if present, internal permanently dry areas, as these habitats are of fundamental importance for the maintenance of the functional integrity and biodiversity of the respective wetland. The outer borders are indicated by the absence of hydromorphic soils and/or hydrophytes and/or specific woody species adapted to grow in periodically or permanently flooded or waterlogged soils." However, the elements used in wetland delimitation are not always evident (Osorio-Peláez and Lasso 2015), as in the case of subterranean wetlands that include all underground areas containing water occurring in caves and karst areas. Therefore, wetland delimitation requires the use of biological groups other than plants, as some life history characteristics directly indicate functional limits (Lasso et al. 2014b). Additionally, the uncertainty associated with a number of factors in wetland mapping should be taken into account. For example, epistemic uncertainty suggests a lack of knowledge, which can be addressed through research, monitoring, ground truthing, and participatory surveys by experts. Research uncertainty includes the uncertainty of measurement and data collection methods as well as the uncertainty of models that predict or represent a process (van Gelder et al. 2008).

Wetland Classification

Wetland classification is an essential tool to obtain an ecological baseline for policy-making aimed at the sustainable management of wetlands. Worldwide, there are many wetland classification systems; these differ from each other in their differences in wetland definition and classification parameters and in their purpose (Cowardin et al. 1979; Scott 1989; Brinson 1993; Finlayson and van der Valk 1995; Gopal and Sah 1995; Semeniuk and Semeniuk 1995; Warner and Rubec 1997; Finlayson et al. 1999; Finlayson et al. 2002; Mitsch et al. 2009; Ollis et al. 2015; Gerbeaux et al. 2018).

Wetland Classification in the Neotropics

The first elucidation of the diversity of Amazonian wetlands was provided by Prance (1979), who analyzed the water chemistry of forests subject to flood pulses (Sioli 1956). A few years later, Encarnación (1985) identified the main vegetation types associated with Amazonian floodplains in Peru, while Scott and Carbonell (1986) prepared the first Directory of Neotropical Wetlands, which grouped wetlands on the basis of their habitat and biogeographic location (Udvardy 1975). In a study of the upper Paraguay river, Wantzen et al. (2005) classified aquatic habitats based on the fluvial hydrosystem approach (Petts and Amoros 1996).

The hydrogeomorphic approach (HGM) has been used for the classification of wetlands in South America (Neiff 2001), Argentina (Brinson and Malvárez 2002; Ginzburg et al. 2005; Benzaquén et al. 2017), Mexico (Berlanga-Robles and Ruiz-Luna 2008), and the Paraná-Paraguay basin (Benzaquén et al. 2013). In Venezuela, Marrero (2017) defined wetland classes based on geomorphological environments, and in Argentina Quiros and Drago (1999) grouped the country's lakes into major divisions by combining water chemistry with geology, climate, and proximity to the sea. Clausen et al. (2006) applied an ecological approach based on the vegetation classes in Chile's Patagonian National Park, while the U.S. Fish and Wildlife Service's system (Cowardin et al. 1979) was applied in Costa Rica (Bravo Chacón and Windevoxhel Lora 1997), and the Ramsar wetland classification system (Scott 1989) in Ecuador (Briones et al. 1997; Briones et al. 1999; Briones et al. 2000; Briones et al. 2001a; Briones et al. 2001b) and Panamá (Flores et al. 2009).

The system proposed by Junk et al. (2014) to classify wetlands in Brazil serves as the backbone of wetland classification in South America. This hierarchical system based on ecological and hydrological attributes recognizes the importance of flood pulses for most Brazilian rivers and the impact on vegetation, as proposed by Gopal and Sah (1995) in India. In Brazil, this system has been used to classify the wetlands in the Amazonian lowlands (Junk et al. 2011), the savannas of the Pantanal of Mato Grosso (Nunes da Cunha and Junk 2011), the white-water river floodplains, or *várzeas* (Junk et al. 2012), and the black-water river floodplains, or *igapós* (Junk et al. 2015).

Wetland Classification in Colombia

In Colombia, the first wetland classification, proposed in 1992 (Duque et al. 2007), consisted of 39 wetland types defined by biological and physical attributes combined with an altitudinal zonation. In addition, Duque and Donato (1992) classified aquatic ecosystems into four provinces based on altitude. Similarly, the method of Naranjo (1997) included 27 natural wetland complexes classified according to their topographic and hydrological attributes.

In Amazonia, major studies were undertaken by Duque et al. (1997), who proposed 14 aquatic landscapes based on limnological, geological, and fish attributes, and by Núñez-Avellaneda and Duque (2001), in which a broader differentiation of Amazonian water types was applied. Both studies provided guidelines for subsequent studies in Colombia, Brazil and Peru (Ricaurte et al. 1998; Fabré et al. 1999; Ricaurte and Portugués 1999), in Amazonia (Ricaurte et al. 2004; Cárdenas 2010; Ricaurte et al. 2012; Núñez-Avellaneda et al. 2017), and in the Orinoco region (Caro et al. 2010). The latter was updated by Lasso et al. (2014a, b), who also extended it to the entire Colombian-Venezuelan Orinoco basin.

Classification studies, including coastal wetlands, have been carried out in the Pacific and Caribbean littoral. Several studies on mangroves were conducted using classifications based on hydrography, landforms, soils, and composition and distribution of vegetation according to species (West 1956; Sánchez-Páez et al. 1998; López Rodríguez et al. 2009; Urrego et al. 2009, 2014). Other approaches have been developed for transitional forests (del Valle 1996) and coastal-marine systems (INVEMAR 2017).

Colombia signed the Ramsar Convention in October 1998, with the Ministry of Environment and Sustainable Development as the official national representative institution. The Ramsar wetland classification system (Scott 1989), was included in the national wetland policy "Política Nacional de Humedales Interiores de Colombia" (MMA 2001) and is therefore used by many of the country's local environmental institutions. However, several reviews (Semeniuk and Semeniuk 1997; Gerbeaux et al. 2018) and our own experience have determined that it lacks specific settings allowing for a better differentiation of wetlands in the Neotropics and that the Brazilian approach (Junk et al. 2014) is better suited to Colombian wetlands.

Study Area

Colombia (1,142,000 km^2) is located in the equatorial zone (10°N and 2°S, 66° and 79°W). The projected population for 2018 is 49.6 million (DANE 2013), with most people (74.8%) living in cities (DANE 2015). Its national territory is divided into five major hydrological watersheds: Caribbean (102,786.68 km^2), Magdalena-Cauca (271,118.09 km^2), Orinoco (347,208.26 km^2), Amazonia (341,991.29 km^2), and Pacific (77,301.82 km^2) (IDEAM 2013). The large differences in altitude (0 to 5775 m.a.s.l.) and climate together with the presence of the intertropical convergence zone provide the environmental conditions for the biological diversity that places Colombia among the world's megadiverse countries (Hernández 1992; Mittermeier et al. 2011; Bernal et al. 2016; Ulloa Ulloa et al. 2017).

Geomorphological Settings for the Regional Differentiation of Wetlands

We define the geomorphological environments as large portions of territory with similar geomorphological processes that influence the structure and dynamics of the wetlands. Colombian geology and geomorphology are highly diverse and dynamic (Gómez-Alba et al. 2015) and are best described as a mosaic of geographical environments (Hermelin 2016) that drive wetland diversity. We identify four main geomorphological environments (Fig. 1), which are consequently split into sub-environments. However, for the purpose of this discussion only the higher level of geomorphological differentiation used to classify the wetlands is presented herein: (1) The geomorphic environment of the Andean mountain range includes the Andean range, which is divided in the south into the Western, Central, and Eastern Cordilleras, and in the north into the Sierra Nevada de Santa Marta, the Serranía del Perijá, and the Serranía Baudó-Darién ranges. This unit includes several sub-environments: glaciers, intramountain valleys, dissected mountains, high plains, aplanation surfaces, and depressions that provide conditions for the formation of several lakes and swamps. (2) The Interandean lowlands comprise the valleys of large rivers that flow to the Caribbean Sea and the Pacific Ocean, as well as the Momposina Depression, located in the north of the country, that was formed by the differential uplifting of the Andean range (IDEAM 2010a). Currently, the Momposina Depression is a large inland area with subsidence processes that encompass large wetland complexes related to the Magdalena and Cauca rivers. (3) In the east, the geomorphic environment of the piedmonts and alluvial plains in Amazonia and Orinoco includes the outer piedmonts (foothills) of the Eastern Cordillera (the Amazonia-Llanos Piedmont) and the alluvial plains of the Amazonia and Orinoco rivers. Other important geomorphological units in this environment are interfluves, isolated mountains and the Residual Guayana shield that extends towards the east. (4) The geomorphic environment encompassing the Atlantic and Pacific oceans includes coastal areas, islands and shallow marine areas associated with these bodies of water. It contains low hills as well as the alluvial plains that are linked to the main rivers before their outlet to the sea but before they are subject to tidal influences.

Climate and Hydrological Settings that Define Wetland Occurrence in Colombia

According to their hydrological conditions, Colombian wetlands can be divided into wetlands with a fluctuating water level and wetlands with a rather stable water level. The hydrological conditions depend on the annual hydroclimatic cycle of the region, which is dominated by the migration and dynamics of the intertropical convergence zone (ITCZ). Thus, the central part of the country has a bimodal regime with two

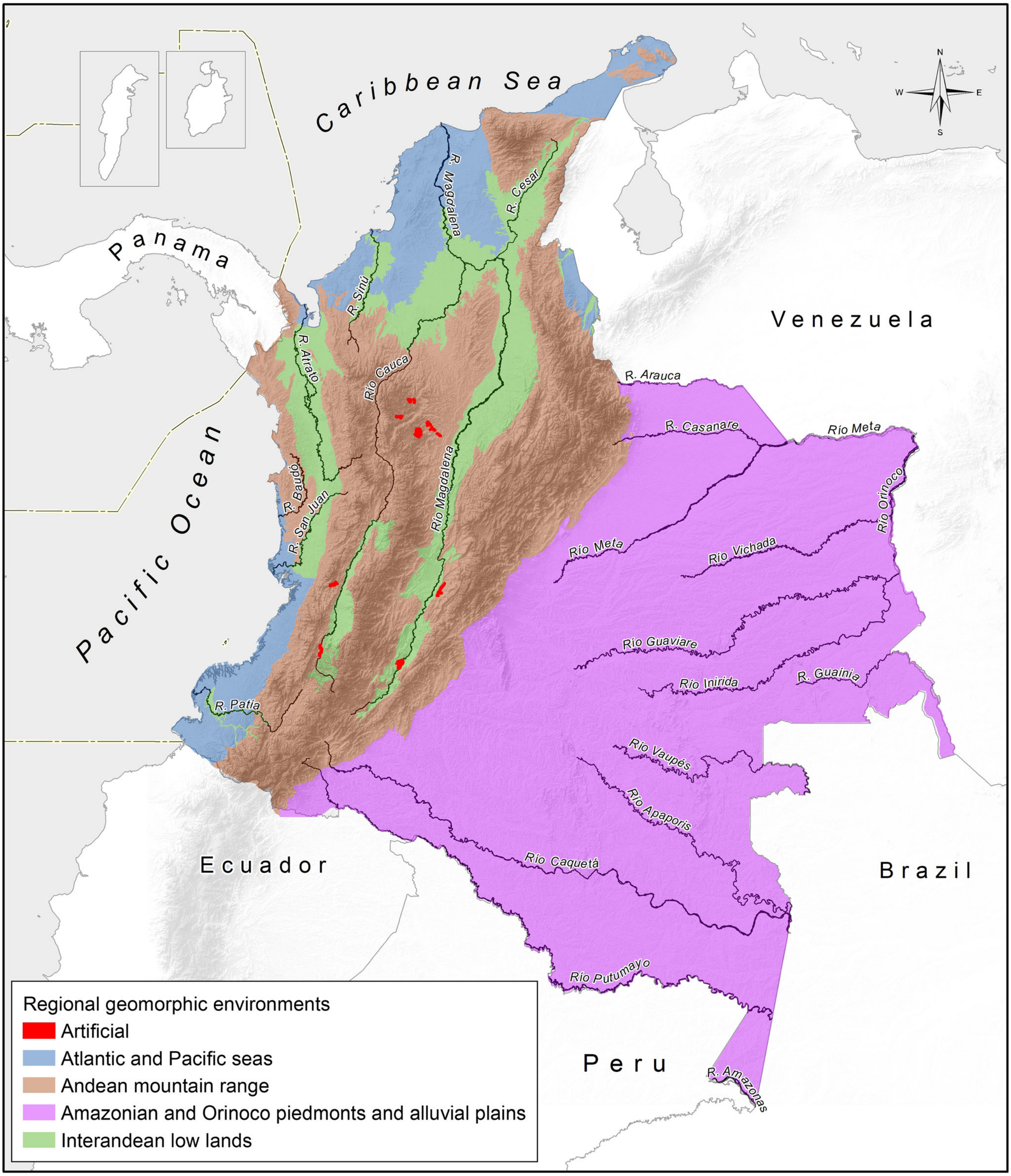

Fig. 1 Geomorphological environments for the Wetland Classification System of Colombia (IDEAM 2010a). Islands are not visible in this map due to the spatial scale

rainy seasons (April–May, and October–November) and two dry seasons (December – February, and June–August), while further south and north regions the regime is unimodal (IDEAM 2015).

Precipitation in Colombia is spatially varied (Fig. 2). The lowest amount of rainfall falls in the semi-arid northeast (< 500 mm), in the Guajira region, and the highest in the humid southwest (> 11,000 mm), in the Choco region. Between these

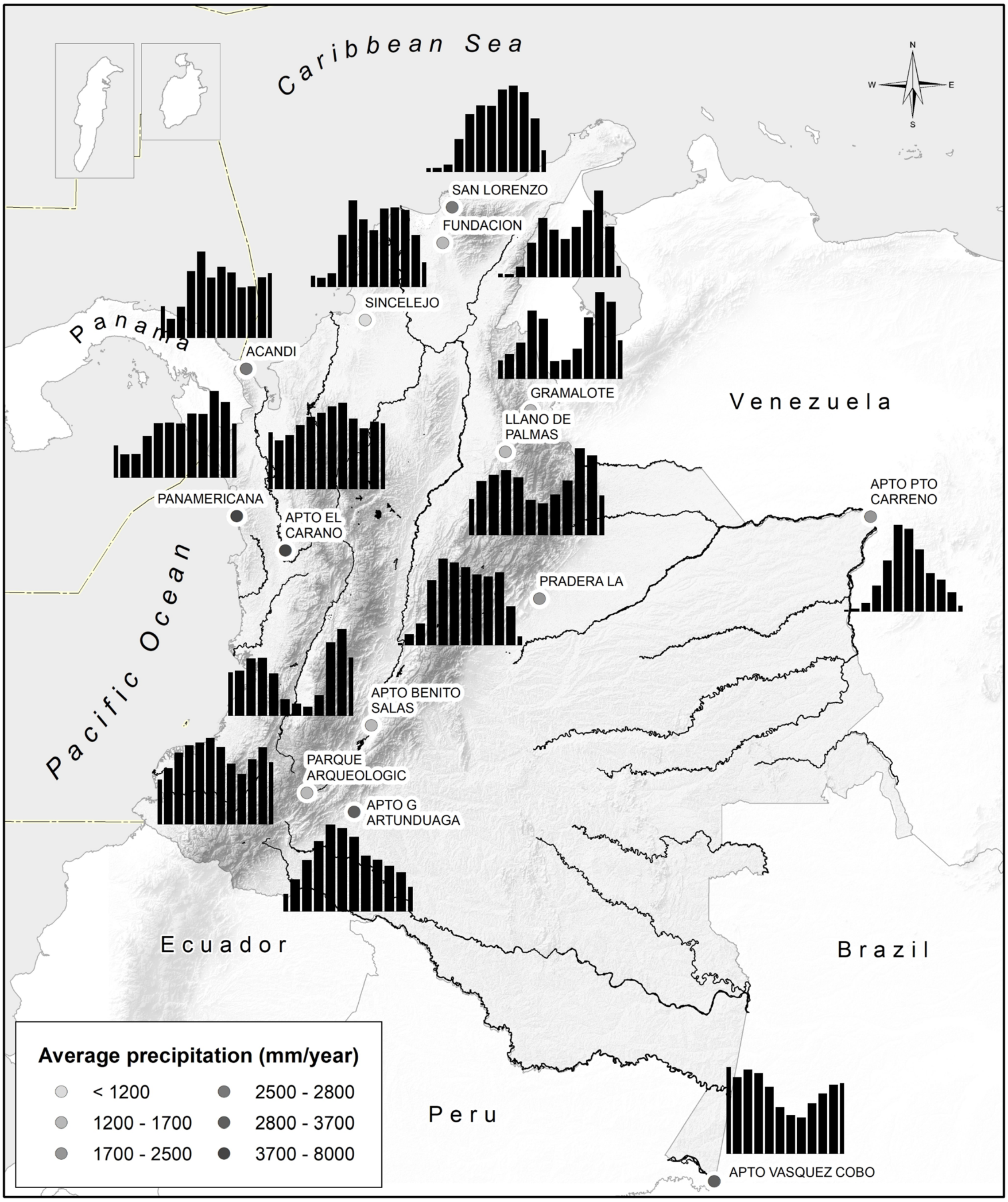

Fig. 2 Distribution of rainfall throughout Colombia. Data source: IDEAM (2014)

two extremes are the equatorial climate in Amazonia and the lowlands (3000–4000 mm) and the tropical savanna (*llanos*) climate, especially in Orinoco and other lowland areas (2000–3000 mm). In the high Andes and in some areas along the Caribbean coast, rainfall fluctuates between 500 and 1500 mm but in some places may exceed 4000 mm (IDEAM 2015).

In South America, all large rivers are subjected to flood pulses that result in important differences in their water levels (Junk et al. 1989; Neiff 1999; Junk and Wantzen 2004). The flood pulse refers to all the physical characteristics (attributes) that define the dynamic behavior of wetlands. These attributes have both dimensional and temporal features. For example, the change in wetland water level represents a dimensional change in the superficial flood area, and it has direct effects on wetland vegetation and soils. The temporal dimension of these changes affects the adaptive ability of the biota. Primary and secondary production in large river floodplains is the sum of their activities in their aquatic and terrestrial phases, i.e. when the wetlands are completely dry or wet. Floodplain fertility depends on the quantity of nutrients in the water, the transport of sediments from the river, and therefore on the water quality of tributary rivers and watershed runoff. The length, amplitude, frequency, timing, and predictability of the flood pulse determine the occurrences, life cycles, and abundances of primary and secondary producers and decomposers, which in turn affect the level of exploitation and regeneration of the nutrient pool as well as its supply (Sioli 1984).

The Colombian hydrographic network includes surface (rivers, streams, lakes, reservoirs) and subterranean waters. Some rivers are intermittent while others have a constant flow throughout the hydrologic year. The annual surface runoff greatly varies from catchment to catchment: 8400–10,300 m^3/s at the Magdalena River, 2427 m^3/s at the Cauca River, and as high as 26,891 m^3/s and 15,210 m^3/s at the Amazon and Orinoco rivers, respectively (Fig. 3, stations 15 and 5). Large rivers of the Amazonia catchment include the Caquetá River, with an annual average of 9540 m^3/s, and the Putumayo River, where a maximum monthly runoff of 10,700 m^3/s has been recorded (IDEAM 2014).

By contrast, the hydrographic network in arid zones of the northern Guajira region is characterized by very low runoff, with annual rates as low as 1.8–2.22 m^3/s at the Rancheria River and as high as 244 m^3/s at the Catatumbo River, located further south and draining into the Gulf of Maracaibo. In the Pacific region, runoff varies between 854 m^3/s at the Mira River and 2186 m^3/s at the San Juan River (Fig. 3) (IDEAM 2014; Estupiñán-Suárez et al. 2015). Because of the varying precipitation pattern, the large majority of Colombian wetlands belong to the category of flood-pulsing wetlands. But there are also wetlands with a rather stable water level, such as different types of swamps and marshes in the lowlands and on high Andean planes as indicated in Table 1 and described under results.

Definition of Wetland Types and Mapping

In the elaboration of a wetland classification, we began by convening a panel of 28 experts, chosen on the basis of their cutting-edge knowledge and expertise on Colombian and tropical wetlands and on wetland classification. The composition of the group ensured the accuracy of the information. For data-gathering, individual and group interviews were conducted, which were verified in the field and with secondary information. The classification system was validated by the panel of experts in a 5-day workshop held in Cartagena, Colombia, in September 2015. Next, the proposed classification system was presented spatially using GIS techniques. For data processing, a Geodatabase was created to integrate into a single file three inputs layers: the geomorphological environments of Colombia (IDEAM 2010a), the map of the potential wetlands area (Flórez et al. 2014), and the Corine Land Cover data for Colombia (IDEAM 2010b). The geographical combinations of these three inputs were established and then contrasted with the proposed wetland classification system. To ensure the thematic accuracy of the new wetland map, 12 technical meetings were held to confirm the wetland types. All data were projected using the coordinate reference system MAGNA-SIRGAS Colombia Bogota zone (EPSG 3116), with general mapping undertaken using ModelBuilder, ArcGIS 10.3, Advanced (ArcInfo). The data were analyzed using IBM SPSS Statistics 22.

Results: The New Wetland Classification System of Colombia

Conceptual Approach

The system used to classify Colombian wetlands is based on an ecological approach from the perspective of wetland scientists and corresponding to the underlying assumptions used to develop the FPC (Junk et al. 1989) and HGM (Brinson 1993; Semeniuk and Semeniuk 1995). It employs the structure used in the Brazilian classification (Junk et al. 2014) but with the above-described conceptual and geomorphological adjustments. The classification system is thus a hierarchical, multiscale, and functional system organized in four levels: System, Macroregion, Subsystem, and Class. Its purpose is to respond to the current need for information to develop wetland policy and promote conservation in Colombia.

Parameters Used to Classify Wetland Types (Macrohabitats)

Climate and Geomorphology

Climate has the greatest influence on wetlands because it influences all of their other parameters. Colombia is a tropical country, but due to its geological setting has different climatic zones. These correspond to the geomorphological environments described in Section 2.4. Here we define these environments as macroregions: (i) Andean mountain range, with low temperatures, (ii) Interandean lowlands, with monomodal or bimodal rainfall patterns, (iii) Amazonia and Orinoco piedmonts and alluvial plains, with monomodal rainfall patterns, and (iv) Atlantic and Pacific seas, coasts, and islands, with micro- or macro-tides.

Hydrology

Hydrology is the second most important factor in wetland classification because the availability and sources of water determine the wetland type. Wetlands may be

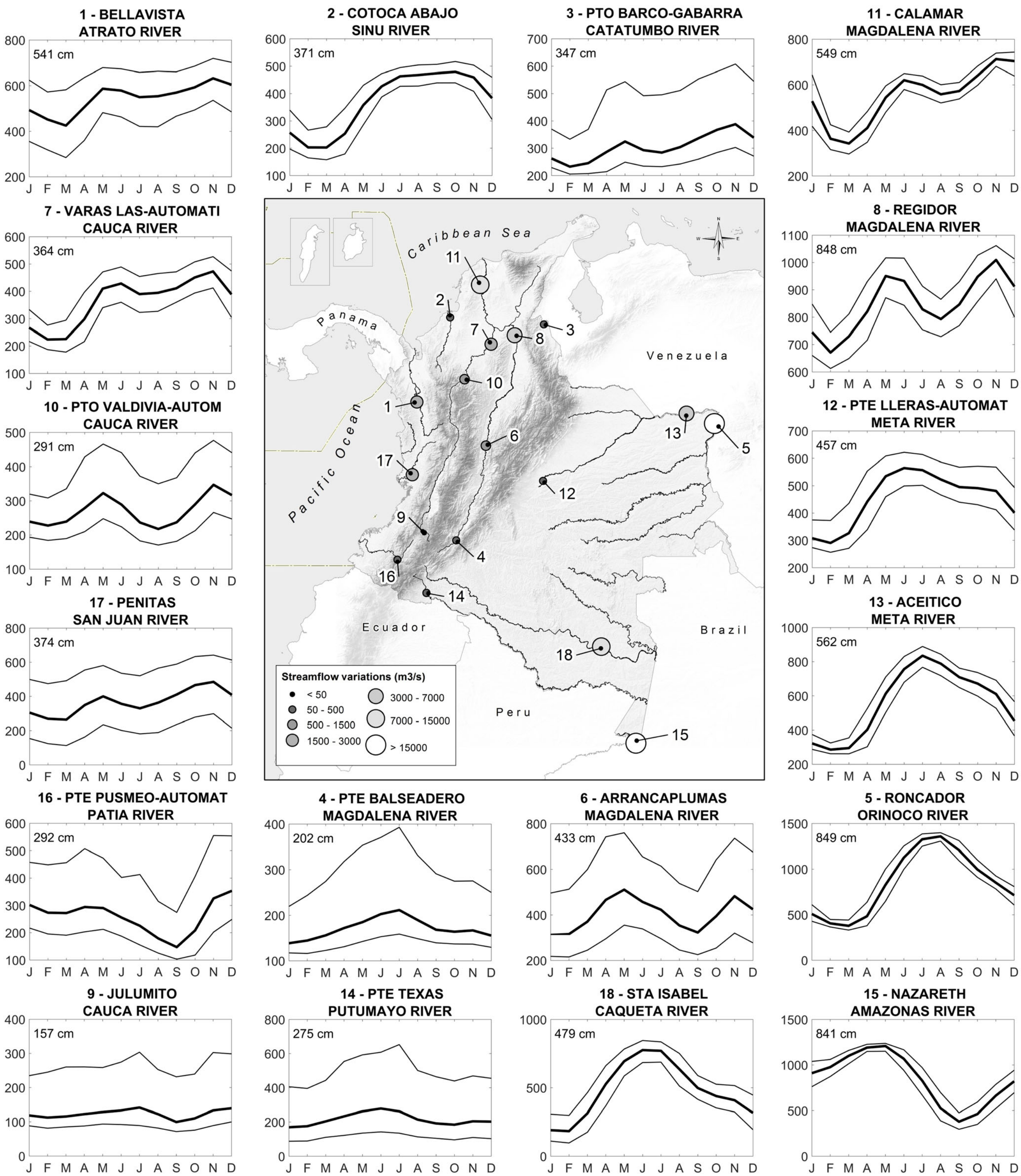

Fig. 3 Hydrographs for some Colombian rivers. Dots and numbers on the maps depict the location of the water data stations. The curves represent the water level fluctuation (cm) during the annual cycle between 1974 and 2012 (IDEAM 2014). From top to bottom, the curves indicate the yearly maximum, average, and minimum water level. The numbers in the upper left corner indicate the annual mean values of the flood pulse amplitude (cm)

permanently covered with water or permanently waterlogged (permanent wetlands) or they maybe periodically dry (periodically inundated or periodically waterlogged wetlands, also called flood-pulsing wetlands) (Table 1). The hydrological terms used in the classification are defined as follows:

Table 1 Classification of Colombian wetlands according to their hydrological parameters

Wetlands with a reasonably stable water level:			
			Type of wetlands
			- Different types of marshes and swamps in lowlands - Andean wetlands with glacial influence - Wetlands in Andean high plains, dissected mountains and intramountain valleys - Wetlands on isolated tepuis in the Amazonia and Orinoco regions - Geothermals - Springs
Wetlands with flood pulses:			
Predictability	Frequency	Amplitude	Type of affected wetland
predictable	monomodal	high	- Floodplains along most large rivers in the Amazonia and Orinoco regions
		medium	- Wetland complex of the Momposina Depression
		low	- Large interfluvial wetlands in the Amazonia and Orinoco regions - Wetlands in the Atlantic coast
	bimodal	high	- Wetlands along the Pacific coast - Wetlands along the Magdalena-Cauca (upper and middle river basin), Atrato, Catatumbo, San Juan, Cesar, and Patía-Sanquianga rivers
		low	- Coastal wetlands on marine islands
	polymodal	high	- Coastal wetlands on marine islands - Pacific tidal coastal wetlands (meso−/macro-tidal >4 m)
		low	- Atlantic (Caribbean) tidal coastal wetlands (micro-tidal <1 m)
unpredictable	polymodal	variable	- Wetlands in the Orinoco high plains and interfluves, and the Amazonian-llanos piedmont - Wetlands on isolated tepuis in the Amazonia and Orinoco regions - Small wetlands along streams and creeks
	multi-annual	low	- Wetlands in arid zones
variable	variable	variable	- Wetlands influenced by human-induced pulses

Flood pulse is the water-level fluctuation in wetlands, which leads to the formation of an aquatic-terrestrial transition zone (ATTZ), with periods of inundation and droughts. The ATTZ may cover >90% of a river-floodplain system, with river channels, permanent lakes and permanent swamps covering the remaining 10%. In small, rainwater-fed wetlands that dry out completely, the ATTZ corresponds to 100% of the wetland area.

Monomodal flood pulse is a predictable pulse of long duration and high or low amplitude that inundates the ATTZ once in the hydrological year. It is the result of the change between the annual rainy and dry seasons and occurs in floodplains along large rivers (high-amplitude) and in large interfluvial wetlands (low-amplitude) with a hydrological buffering capacity sufficient to integrate the annual rainfall pattern.

Bimodal flood pulse is a predictable pulse of long duration and of high or low amplitude that inundates the ATTZ twice in each hydrological year. It occurs only in floodplains along the lower courses of some large Colombian rivers, such as the Magdalena and Cauca rivers.

Predictable polymodal flood pulse is a pulse of low to high amplitude that is created by tides.

Unpredictable polymodal flood pulse is the set of many individual, unpredictable, short flood pulses of varying height that are created by heavy local or regional rainfall events. It affects small wetlands with a low hydrological buffering capacity, e.g., those along low-order streams or in small to medium-sized depressions.

Pluriannual flood pulse is an unpredictable flood pulse that inundates the wetlands in arid or semi-arid regions only in years of high precipitation. Examples are the dry Guajira region and the dry Interandean lowlands. These wetlands may remain dry during several consecutive years.

Marshes and swamps are wetlands with a stable water level or with permanently waterlogged soils. The ATTZ is absent or small. In these areas, organic matter accumulates because permanent anoxia in the soils retards the decomposition of organic material. The depth of the organic layer depends on the geomorphology and water retention capacity of the underlying substrate. Marshes refer to wetlands covered by herbaceous plants, and swamps to wetlands that have shrub and tree (including palms) cover.

Chemical Quality of Water and Sediments

In wetland classification, the chemical composition of the water and sediments ranks third in importance because of its impact on the occurrence and productivity of wetland plants.

However, given the scale of analysis and data availability, the Colombian classification system differentiates roughly between wetlands associated with 1) sediment-rich white-water rivers and 2) sediment-poor clear-water and black-water rivers. White-water rivers are differentiated into fertile rivers (≥50 μScm^{-1}) and infertile rivers (<50 μScm^{-1}). All clear-water and black-water rivers are infertile (<50 μScm^{-1}). Electrical conductivity is used as a criterion, because many studies on primary production in Amazonian wetlands have shown that it is a good indicator of wetland fertility and can be easily measured (Duque et al. 1997; Núñez-Avellaneda and Duque 2000; Núñez-Avellaneda and Duque 2001; Ríos-Villamizar et al. 2013).

Biological Criteria

Biological criteria form the fourth level of classification. Plants are especially appropriate because they are long-lived and thus reflect the impacts of environmental conditions over years, decades, or centuries. The type of vegetation cover that occurs at each wetland type is defined by the predominant vegetation physiognomy, which refers to the dominant growth forms, height (Rietz 1930; Raunkiaer 1934; Braun-Blanquet 1964; Edwards 1983; Rangel-Ch and Velásquez 1997), and appearance of the vegetation. For instance, woody physiognomy includes formations dominated by palms (>5 m), even though they lack secondary growth tissue. A shrubby coverage is made of herbaceous plants with a height exceeding 1.5 m, such as *Montricardia arborescenses,* which is incapable of secondary growth or the formation of multiple stems but which reaches heights of up to 5 m. There are other types of cover, especially in shallow marine wetlands, where corals and seaweeds prevail. There are also wetlands with sandy and rocky substrates and thus without any kind of coverage but nevertheless providing habitat for living organisms. However, most wetlands in the Amazonian alluvial plains and in the Interandean lowlands are forested, while those in the Orinoco River lowlands are in part covered by savanna vegetation. Bryophytes, herbaceous vegetation, and shrubs cover High-Andean wetlands. Animals are not included in this classification system because they are mobile and often migrate between different ecosystems. Furthermore, the inclusion of animals would make the classification system too complex for management purposes. Nonetheless, an exception has been made for the shallow soft bottoms of marine waters, whose benthic communities include mollusks, polychaete worms, echinoderms, and crustaceans (Table 2).

Classification Hierarchy

In the first and second hierarchical levels, the wetlands are differentiated into three *systems* with different *macroregions* representing the geographic heterogeneity of Colombia:

(1) Marine-coastal system (macroregions: Atlantic and Pacific seas, coasts and islands). These wetlands are defined as all wetlands, permanent or temporary, with fresh, brackish, or saline waters under either the direct influence of the tides or saline intrusions or the influence of atmospheric deposition of dissolved or particulate substances and/or propagules from the ocean.

(2) Inland system (macroregions: Andean mountain range, Interandean lowlands, and Amazonia and Orinoco piedmonts and alluvial plains). These wetlands are defined as all wetlands, permanent or temporary, with fresh, brackish or salt water and located in the Colombian inland. They are without direct or indirect marine influence.

(3) Human-made system. These wetlands are defined as all wetlands, coastal or inland, deriving from either organized or unorganized human activities. The former includes fish farms and paddy rice plantations, and the latter the wetlands around reservoirs and wetlands developing in the backwaters behind weirs, in streams, or in depressions from the excavation of soil for roads, construction, etc. They are classified only as macrohabitats.

The third hierarchical level is defined by the hydrological characteristics of the flood pulse predominating in macroregions. It consists of *subsystems*, *orders* and *suborders*. *Subsystem* aggregates the water regime and its predictability, *order* defines the frequency, and *suborder* the amplitude.

The fourth hierarchical level is divided into *class* and *subclass*, to differentiate wetlands according to their hydrochemical and vegetation parameters, which are introduced as appropriate. At the *class* level, the water is classified into saline and freshwater, with freshwater further classified into fertile and non-fertile water. *Class* covers large and complex marine-coastal and inland wetland landscapes, which often require specific subdivision into many macrohabitats. *Subclass* includes vegetation. The smallest unit is *macrohabitat*, defined according to Junk et al. (2015) but adapted to the present proposal. Thus, *macrohabitat* is a "landscape unit in the respective wetland, subject to similar geomorphological and hydrological conditions and covered by a specific and characteristic vegetation, animal community or another biological element, or, in its absence, subject to a similar terrestrial or aquatic environment" (Table 3; Figs. 4, 5, and 6).

Mapping at a scale of 1:100,000 resulted in 89 types of macrohabitats (Fig. 7), with only marine wetlands left unmapped due to a lack of mapping inputs for the seabed. Of the 89 macrohabitat types, 60.7% correspond to the inland system, 28.19% to the coastal system, and 11.2% to the human-made system. In total, the mapped wetland types occupy 26,960,115 ha, most of which are located in the inland system (72%), followed by the human-made (23%), and coastal (4%) systems.

Table 2 Cover types used in the classification of wetlands in Colombia

Type	Description	Examples of wetland type
1. With vegetation		
a. Woody	Vegetation units dominated by plants with a height > 5 m and characterized by a stem or central axis; includes trees and palms	Riparian forests, "matas de monte," palm swamps, flooded forests (várzeas and igapós), coastal forests and mangroves
b. Shrubby	Vegetation units dominated by plants with heights of 1.5–5 m; includes shrubs and grasses	Monodominant marshes of *Montrichardia arborescens, Typha angustifolia, Juncus* spp.; dwarf mangroves; scrub with *Rubus floribundus, Pentacalia* spp., *Ludwigia peruviana*, *Hypericum* spp.
c. Herbaceous	Vegetation units dominated by plants with a height between 0.3 and 1.5 m.	Grasslands and non-graminoid vegetation (grasslands, juncales, tifales, helechales), *Pentacalia* spp., Typha spp.
d. Ground-level	Vegetation units dominated by herbaceous plants with a height < 30 cm	Flooded savannas, creepers, plants on beaches, peat bogs and meadows. These plants form mats that cover the substrate or ground, such as grasses, bryophytes, and clubmosses; cushions (*Plantago rigida, Distichia muscoides, Oreobolus*)
e. Aquatic	All types of macrophytes associated with freshwater wetlands	Lakes, swamps, marshes, oxbow lakes, rivers and streams, and artificial wetlands
	Submerged vegetation associated with shallow marine wetlands, saline and semi-saline waters	Underwater meadows, seagrass beds, seaweeds: seagrasses, macroalgae, algae
f. Dispersed	There is no continuous vegetation cover; plants are isolated and widely dispersed. The plants include trees, palms, shrubs, herbs and grazing species that do not form a continuous layer.	Scattered plants without continuous strata; absence of a continuous layer; for example, beaches with dispersed palms, rocky outcrops, and steep shores
2. Without vegetation		
Other organisms	Areas free of vegetation cover	Dominated by macroalgae, corals, octocorals, coral debris, crustaceans, mollusks
Without a plant cover	Wetlands without live plant or other cover	The emerging component of the ecosystem is the substrate: consolidated substrate (rock), unconsolidated substrate (sediments, muds), and soil

An analysis of the distribution of the wetlands by macroregion showed that the largest area is located in the Amazonia and Orinoco regions, where 28 macrohabitats cover a total of 16,588,007 ha. Next is the human-made system, with 10 macrohabitats and a total area of 6,214,622 ha, followed by the Interandean lowlands, with 10 macrohabitats and 2,599,009 ha, the coastal system, with 25 macrohabitats covering 1,209,283 ha, and the Andean range, with 16 macrohabitats covering 349,192 ha.

Discussion

A New System for the Classification of Colombian Wetlands

Here we present the first classification system for Colombian wetlands at a scale of 1:100,000. It is based on the Brazilian wetland classification system, whose conceptual strengths, in particular its use of the FPC, its hierarchical structure, and its orientation towards wetland management (Junk et al. 2014), served as a model. However, given the high variance in the topography of Colombia, the Brazilian system approach was adjusted by the addition of the HGM, which enabled the extension of the classification system to the Andean mountain range and the Atlantic and Pacific marine coastal systems. By combining these two approaches, wetland classification becomes a functional tool, since hydrology and geomorphology also define wetland health, by assessing their capacity to provide ecosystem services. These represent the main link between nature and society and are therefore a key tool for wetland management (de Groot et al. 2006; Taylor et al. 2011; Ricaurte et al. 2017).

The proposed hierarchical structure also allows the clustering and disaggregation of wetland types into major and minor categories, facilitating comparisons at several levels (region, basin, biome), as shown in Brazil following different analyses of wetland macrohabitats (Junk et al. 2011; Nunes da Cunha and Junk 2011; Junk et al. 2012; Junk et al. 2015). For instance, our classification system includes a differentiation of the Andean wetlands, with their rather stable water level (Subsystem 2.1.1), wide variety of macrohabitats, and dominant plant species that determine the type of wetland, based on a phytosociological method (Table 3). By contrast, wetlands in the Interandean low lands and Amazonia and Orinoco regions, with a predictable flood pulse of long duration (Order 2.2.1.2 and Order 2.3.2.1), cover huge areas and contain

Table 3 Detailed description of the macrohabitats in the Andean range. The table provides an example of how the hierarchical structure of the proposed classification system allows the clustering and disaggregation of wetland types into major and minor categories

Subsystem	Order	Suborder	Class	Subclass	Macrohabitat
2.1.1. Wetlands with a reasonably stable water level					
			Lakes		- Shallow glacial lakes (subject to drying out for 1–2 months of the year) with amphibious plant species such as *Crassula*, *Elatine*, *Eleocharis* (small), *Gratiola*, *Limosella*, *Montia*, *Plagiobothrys* - Deep Andean lakes with *Nitella* (deepest), *Isoetes*, *Potamogeton* and *Myriophyllum quitense*. Also, submerged bryophyte species
			Streams		- Rheophytic vegetation in streams with bryophytes and *Isoetes* spp.
			Peatlands, mires and swamps		
				- Vascular cushion bogs dominated by	
					- *Distichia muscoides* (mesotrophic) - *Plantago rigida* (mesotrophic) - *Oreobolus cleefii* (oligotrophic) - *Xyris subulata* flat cushions (oligotrophic)
				- Sphagnum bogs	
					- *Sphagnum* - *Xyris* peat bogs with *Espeletia* spp. - *Sphagnum* peat bogs with bamboo (mainly *Chusquea tessellata*) and large *Puya* spp. - *Sphagnum* peat bogs with *Diplostephium revolutum* - *Cyperus* spp. sphagnum peat bogs
				- Mossy superparamo peat bogs - Large *Carex* dominating meadows (*C. pichinchensis*, occasionally with *C. jamesonii* pioneering on recent wet sediments) - Quagmires (Tremedales) of *Calamagrostis ligulata* with *pleurocarpous mosses* and/or *Sphagnum* spp.	
			Geothermal wetlands		- Thermals - Mineral springs

several macrohabitats that have not yet been classified. A review of all the information available on Colombian wetland classification revealed important gaps in data availability, as some regions have been better studied than others. For example, Lasso et al. (2014a, 2014b) provided a large body of data on the Orinoco wetlands, but the data must be reorganized to be integrated into our classification system. The same limitation applies to Amazonia (Duivenvoorden and Lips 1993; Urrego 1997), the Andean (Cleef 1981; Bosman et al. 1993; Hernández and Rangel 2009), Caribbean, and Pacific regions, and to the Momposina Depression. Thus, there is a clear need to standardize and define the many different terms being used to describe wetlands (Finlayson and van der Valk 1995; Gerbeaux et al. 2018).

The classification of wetlands as a tool for wetland management must be supported by theoretical and technical bases for wetland delimitation. This has been achieved using the attributes that make up our system of Colombia wetland classification. Nonetheless, the attributes used for wetland classification may eventually need revision, due to natural or anthropic drivers. For example, in the lowland wetlands along Colombia's Magdalena, Cauca, Atrato, Sinú, and other rivers, increasing sedimentation rates are transforming the spatial distribution of the wetlands by removing and/or increasing wetland area. Likewise, hydrochemistry is currently strongly impacted by the increased discharges of heavy metals from gold mining and the agricultural industry (Marrugo-Negrete et al. 2015). These drivers are changing the geomorphology, water chemistry (fertility), and land cover, attributes used in our classification system and directly related to wetland monitoring. Thus, our wetland classification represents a valuable decision-making tool that can contribute information for wetland management.

Another relevant aspect of wetland classification is the definition of wetlands. Previous studies have highlighted the need for a unique definition of wetlands (Scott and Jones 1995,

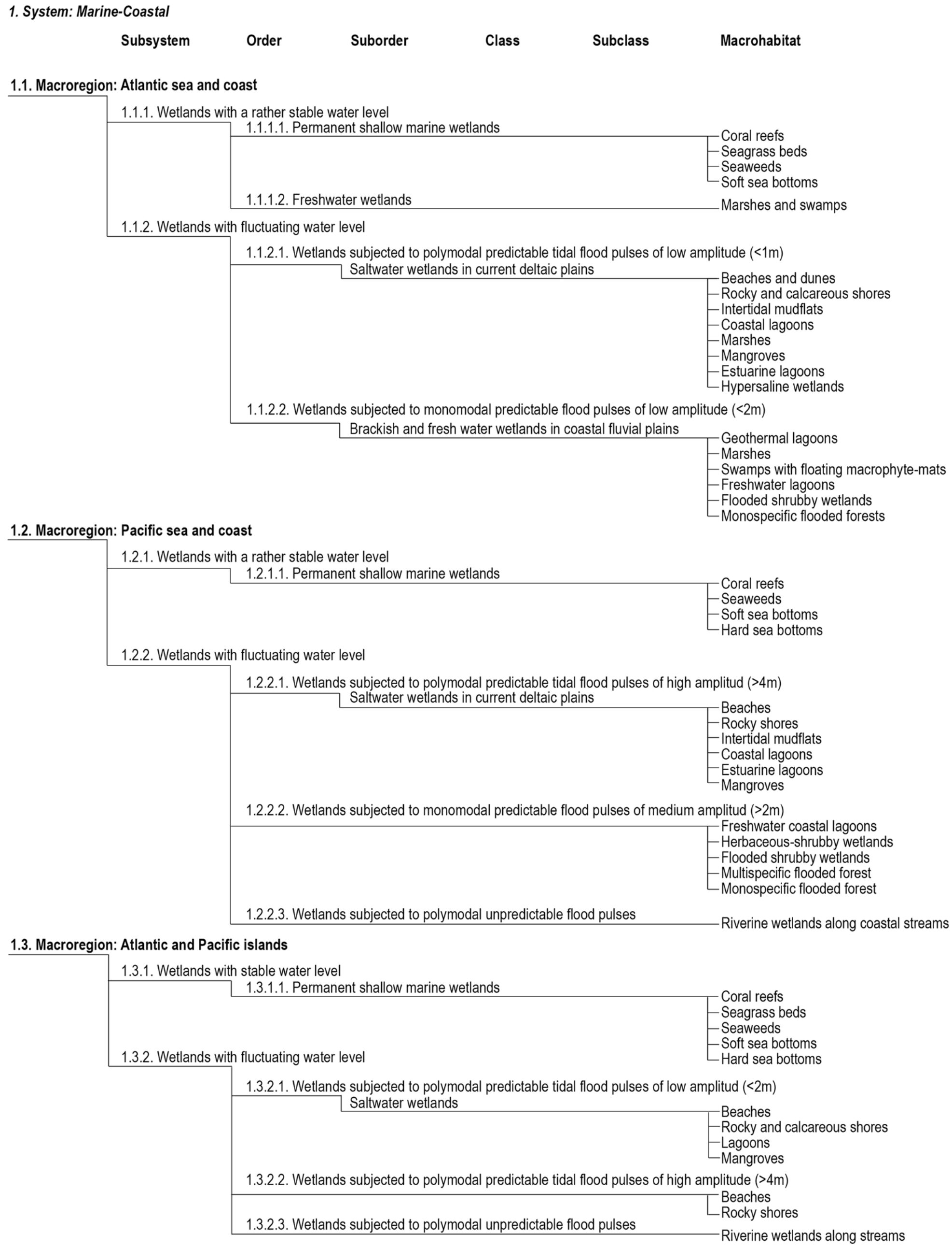

Fig. 4 The classification system of marine-coastal wetlands in Colombia based on geomorphological, hydrological, water chemistry and vegetation attributes

Finlayson 1995). However, at the global level there is a wide variety of definitions as well as a tendency to propose a new definition for each country, as noted in our review of wetland classification. Some countries use the definition provided by the Ramsar Convention, while others opt for their own definition, based on the specific characteristics of the wetlands either as shallow swamps and marshes or as transitional ecosystems between terrestrial and aquatic areas. We propose a broader concept that provides a better understanding of wetlands as complex and dynamic systems. Moreover, it considers not only the natural hydrological variability of wetland ecosystems, but also that extreme floods often create serious economic and social problems when wetland areas are not adequately recognized and managed. An important and novel aspect of our system is the inclusion of permanently terrestrial areas inside large wetland complexes as intrinsic parts of the wetland ecosystem. Species diversity in these wetlands is the sum of terrestrial and aquatic species (Gopal et al. 2000) and its maintenance requires the movement of terrestrial organisms between periodically and permanently dry areas.

Information Gaps as an Opportunity for Future Research

The development of our classification system revealed two areas for future research. Firstly, there is no classification of

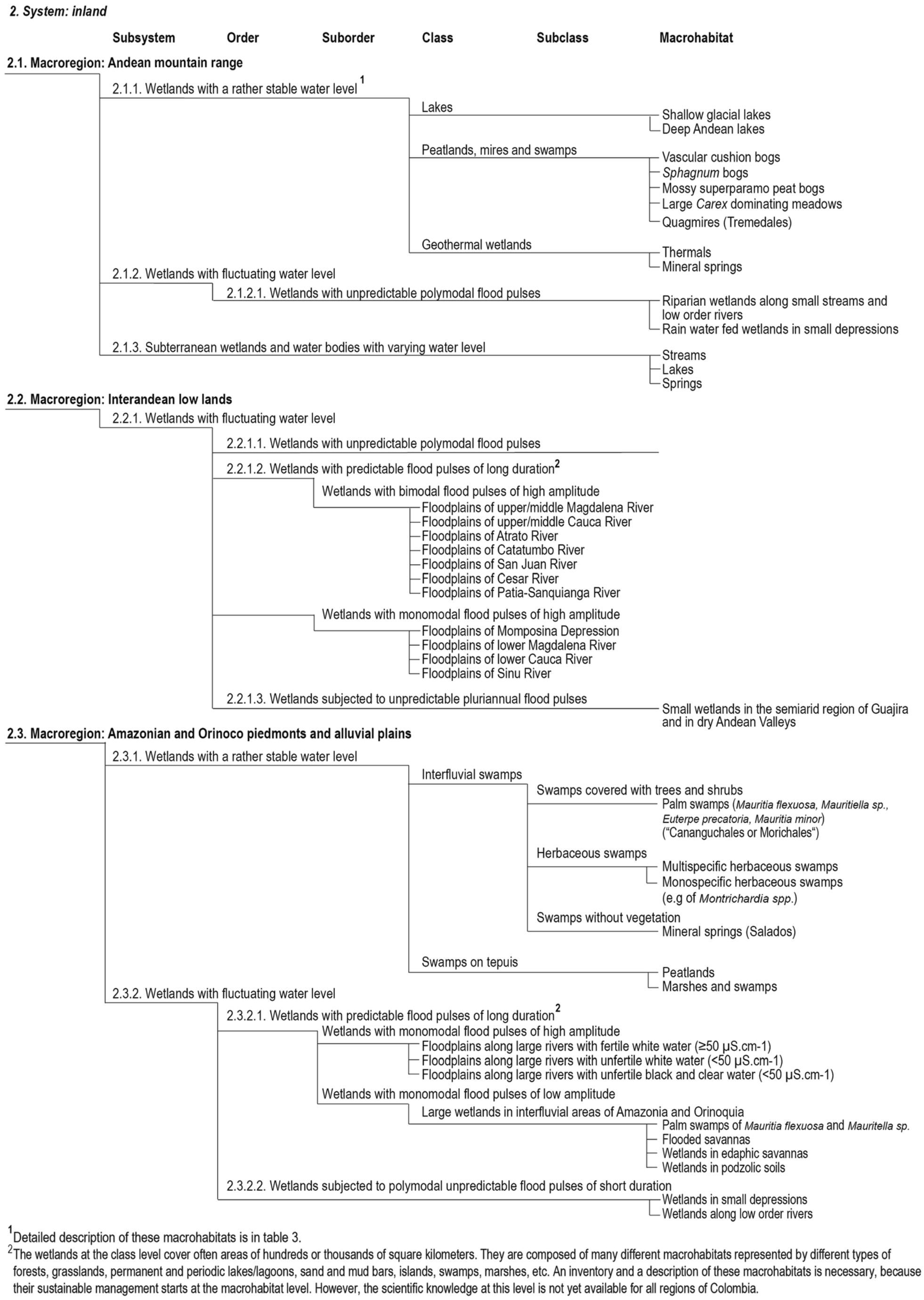

Fig. 5 The classification system of inland wetlands in Colombia based on geomorphological, hydrological and vegetation attributes

water type at the national level. The sensu stricto concept of water typology (white, black, and clear water) (Sioli 1956) has been broadly applied to the Amazonia and Orinoco regions, but in Colombia only for the Amazonia region is there a large set of chemical and biological data collected in the field and used to define new water types, for example, the transparent water of the Amazonian piedmont (Duque et al. 1997; Ricaurte et al. 2004; Ricaurte et al. 2012). We therefore propose the concept of "water fertility" (Duque et al. 1997; Núñez-Avellaneda and Duque 2000; Núñez-Avellaneda and Duque 2001; Ríos-Villamizar et al. 2013) to address the use of water chemistry as a wetland classification attribute. Justification for the use of this concept comes from the fact that it is defined based on conductivity, and data for most of the large wetland complexes in the country are available. However, our application of this term is so far limited to a first approximation based on expert knowledge. It is our hope that this issue will eventually be addressed at the national level.

Secondly, the depth defining shallow marine wetlands has yet to be determined, and the existing information is

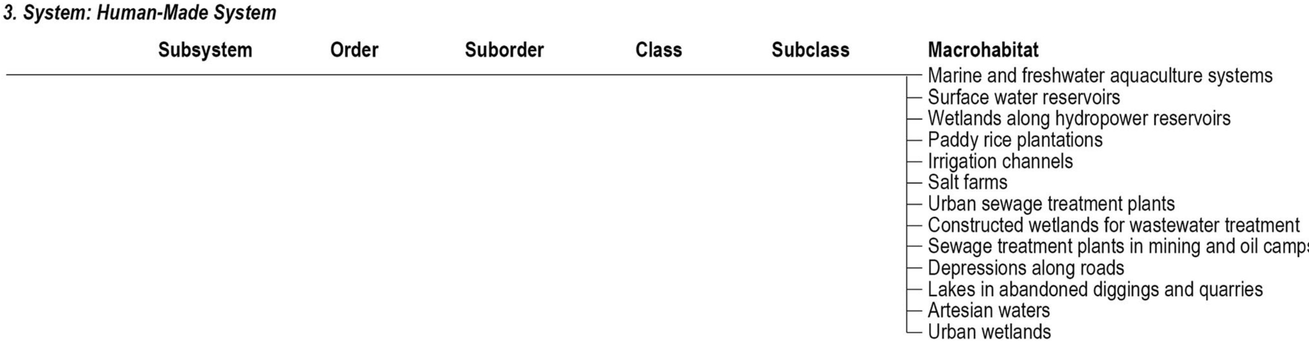

Fig. 6 The classification system of human-made wetlands in Colombia

technically insufficient for this purpose. According to Corine Land Cover for Colombia (IDEAM 2010b), marine wetlands include all shallow areas with a depth not exceeding 15 m. While this could be used as a guide for the delimitation of shallow marine wetlands for policy-making purposes, given the complexity of the seabed and its geoforms it would be presumptuous to apply this definition to the Caribbean and Pacific littorals without adequate cartography and bathymetry, in addition to validation through a national consensus. Considering the enormous threats to shallow marine wetlands arising from human influence and climate variability, this is an urgent issue.

Implications for Wetland Policy in Colombia and South America

In Colombia, during the last flood events (2010–2011 and 2017), while traditional stilt-house settlements were not severely affected, thousands of people lost their homes and belongings, and in some cases their lives, because their houses were built in high-risk areas, such as floodplains and riparian wetlands. This tragedy demonstrated the conflict of interests between different stakeholders resulting from the peculiar hydrological conditions in flood-pulsing wetlands. Many agronomists, planners, and politicians seek to use wetland areas for traditional agriculture, cattle ranching, infrastructure, and home construction, while ecologists propose the sustainable management and protection of these areas, including the maintenance of their hydrological buffering capacity. The same conflict is taking place in Brazil. The old Brazilian Forest Code referred to the mean maximum flood level as the limit of wetlands along streams and rivers, whereas the new code refers to the "regular channel," as the limit, defined as "the channel, where the water flows regularly during the year," i.e., at low water. This leaves most of the floodplains and riparian wetlands unprotected and completely ignores their value (De Sousa et al. 2011; Piedade et al. 2012).

In Colombia, there is a wide range of legislation regulating the use of wetlands but, regrettably, none of the laws define the limit of wetlands according to hydrological parameters. Only recently was this set forth by Decree 2245 (29 December 2017), in which the "riparian buffer zone" was established as both a norm of superior hierarchy and as a determining factor in environmental decision-making. It is defined as "the strip parallel to the line of maximum tides or to permanent channel of rivers and lakes, up to 30 meters wide. Likewise, the afferent protection or conservation area will also be part of the riparian buffer zone;" and it will be delimited "by the maximum elevation produced by high tides and spring tides." However, there are still many technical aspects to be reviewed in order to manage wetlands, especially the 30-m limit for riparian zones, which does not take into account the hydrological order of the rivers and their size, thus leaving out important areas of wetlands and dry areas, even though in high waters the two are closely linked.

The development of a classification system for Colombian wetlands received substantial funding from the Colombian Government, due to the concerns about wetlands that were raised after the floods in 2010–2011. The project provides a politically supported approach to the emerging problem caused by more frequent and intensive precipitation in light of the current state of the natural wetland cover, whose capacity to regulate and attenuate the impacts of floods has been severely diminished. Under the framework of the most ambitious wetland science-policy project carried out in Colombia, wetland mapping and classification represent the basis for new guidelines that will define the opportunities and constraints for wetland conservation in the country (Vilardy et al. 2014; Jaramillo et al. 2015; Cortés-Duque and Estupiñán-Suárez 2016; Jaramillo et al. 2016; Patiño and Estupiñán 2016; Ricaurte et al. 2017).

Furthermore, for South America, our study represents a successful step in a broader approach to wetland science, as this is the first time that two countries, Colombia and Brazil, agreed to develop a common wetland classification system. This was only possible because of the cutting-edge knowledge of the respective research groups in their discussions of the similarities in the hydrology, geomorphology, soils, water chemistry, vegetation, and ecology of the wetlands in the two countries. The researchers' efforts highlighted the benefits of joint action on environmental issues, especially since ecosystems have no borders and related socioeconomic and political problems are more common than different. Because

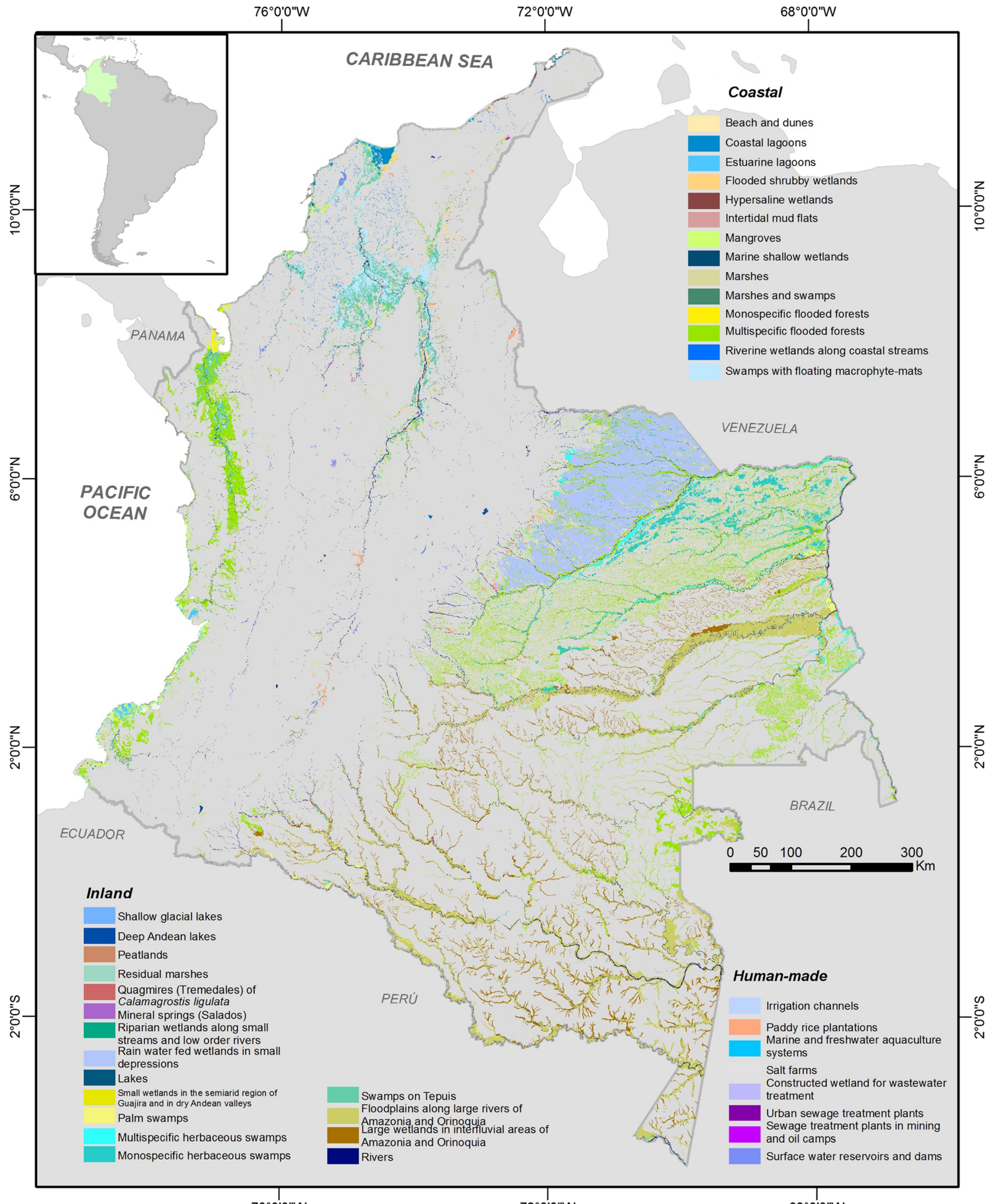

Fig. 7 Distribution of the wetland macrohabitats in Colombia at a scale 1:100,000. On this map, the wetland types are grouped into the higher classes in the classification. The marine wetlands were not mapped due to lack of mapping inputs for the seabed

Colombia and Brazil share both river basins and biomes, as well as cultures, the formulation of proposals for wetland management becomes more meaningful and powerful when a unified approach is adopted.

Finally, there is an urgent need to develop international wetland policies that promote the sustainable conservation of wetlands (Finlayson et al. 2017), which in the twenty-first century face increasingly more serious threats (Gardner et al. 2015). Developing and transitional countries depend primarily on the agricultural industry for food and fuel production, as well as on mining, the main source of energy today. However, the resulting loss of wetlands, in addition to affecting ecological processes of global importance, has serious impacts on local livelihoods and human wellbeing, by increasing poverty and unemployment and by reducing opportunities for fair and equitable development.

Conclusions

Floods between 2010 and 2011 set off alarms about the inability of Colombian wetlands to mitigate the impact of natural events. The country's capacity to adapt to climate variability was also called into question, such that priority was given to the undertaking of a major national wetland research project, to obtain the information needed for environmental decision-making. This is the first national wetland classification effort conducted in the country, and its results have drawn attention to the great diversity of wetlands, represented in 89 macrohabitats. The proposed hierarchical approach allows a better understanding of the functioning and spatial composition of the wetlands in different scales.

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