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HOMAGE TO BRIJ GOPAL

Review Paper

Riparian wetlands of low-order streams in Brazil: extent, hydrology, vegetation cover, interactions with streams and uplands, and threats

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Abstract Low-order streams and riparian wetlands are important contributors to the drainage network in the landscape. However, there has been little research into the nature of these ecosystems in Brazil. Our estimates show that riparian wetlands of low-order streams and other small associated wetlands cover at least 25% of the forested part of the Amazon basin and about 10% of the Cerrado region. Information on the semi-arid Caatinga is lacking, but ~ 3% of the area may be occupied by riparian wetlands and other small wetland types, many of which are periodically dry. Riparian vegetation includes a very large richness in tree species. The amount and species richness of herbaceous plants depend on light availability. Instreams of the semi-arid region of Brazil, hydrophytes are restricted by unpredictable flash floods and periodic drought. Aquatic food webs are largely based on the organic matter produced by the riparian vegetation. Large-scale agriculture and cattle ranching pose a serious threat to riparian wetlands, their biodiversity, and their function as a buffer in the hydrological cycle of the landscape. A nation-wide screening program would provide a more detailed picture and allow the elaboration of a national conservation and restoration program for the Brazilian riparia.

Keywords Stream density · Size of riparian wetlands · Water chemistry · Riparian vegetation · Fish fauna · Food webs

In memory of Dr. Brij Gopal This article is dedicated to Dr. Brij Gopal, who passed away on January 4, 2021. Prof. Gopal was an internationally renowned wetland scientist and over many decades a friend of the authors of this article. He collaborated with us at the Max-Planck-Institute for Limnology in Plön, Germany and at the Federal University of Mato Grosso in Cuiabá, Brazil. He was a much-valued colleague, not only because of his vast scientific knowledge but also because of his friendly, down-to-earth manner and his kindness. The wetland community has lost an exceptional member, and we mourn this loss.

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Introduction

Riparian wetlands have been defined as "Lowland terrestrial ecotones, which derive their high-water tables and alluvial soils from drainage and erosion of adjacent uplands on the one side and or from periodic flooding from the other" (McCormick, 1979). They link terrestrial habitats with permanent aquatic ones, although the aquatic habitats in low-order rivers may periodically dry out completely. The multiple interactions of riparian wetlands with the uplands and with streams have to be considered when discussing their importance in the landscape. Riparian wetlands also link surface water with groundwater. Streams together with riparian wetlands form networks across all continents, with their density dependent on climate (mainly precipitation), geology, geomorphology, and vegetation cover. In Brazil, the wide range of these parameters results in many different types of riparian wetlands. The density of the network decreases from regions of high precipitation (> 2000 mm year^{-1}), such as the Amazon rain forest, to semi-arid regions, such as those in the Caatinga, where precipitation averages between 200 and 1,000 mm year.$^{-1}$

Streams cut their beds in the landscape, forming valleys with depths ranging from a few decimeters to many tens of meters. The larger of those valleys give rise to small, geomorphologically active, lateral floodplains where sediments are periodically deposited and then, during heavy rains, remobilized and transported further downstream. Riparian wetlands in a forested environment, such as the Amazon rain forest, are covered by flood-tolerant trees, which reduce herbaceous wetland vegetation through shading. In dryer regions, the contribution of trees to the riparian vegetation is smaller, allowing a higher density and richness of herbaceous plants. The importance of the vegetation cover of the catchment area for stream hydrology has been well evidenced by the adverse impact of the removal of the natural vegetation for large-scale agricultural projects (Chaves et al., 2008; Dias et al., 2015).

Low-order streams are important sources of water, and their riparian wetlands provide habitats for many plants and animals. However, the streams are often polluted by domestic, agricultural, and industrial waste while in many areas the riparian vegetation has been destroyed by expanding road networks, selective logging, mining, small hydropower dams, the overgrazing of domestic animals, and conversion to agricultural land. The destruction of riparian wetlands can lead to deep erosion and a lowering of the groundwater level, with dramatic consequences for terrestrial vegetation as well as aquatic plant and animal communities (Wantzen et al., 2006; Wantzen & Mol, 2013). In semi-arid areas, the construction of small reservoirs for domestic and agricultural use has interrupted longitudinal water flow (Ely et al., 2020).

Despite the wide distribution and multiple levels of streams and riparian wetlands in the Brazilian landscape and their importance for the human population, in-depth knowledge about these ecosystems is lacking. A comprehensive study has yet to be conducted (Melo et al., 2020). In this paper, we review the available information on the hydrology, extension, and vegetation of the riparian wetlands of low-order streams in Brazil. Human impact, gaps in knowledge, as well as measures aimed at improving the health of these ecosystems are also addressed.

This paper is part of an effort of the Brazilian Ministry of the Environment to establish a national wetland inventory, in cooperation with the National Institute of Science and Technology in Wetlands (INCT-INAU) at the Federal University of Mato Grosso, Cuiabá. Technical information was provided also by the Research Group on Ecology, Monitoring and Sustainable Use of Wetlands (MAUA), of the National Amazon Research Institute (INPA) at Manaus.

Stream density and the extent of riparian and other small wetlands

Streams can be classified by their size according to the stream-order system of Strahler (1952). In landscapes with low levels of vegetation, such as the Cerrado (Brazilian savanna) and Caatinga (xeric

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shrubland) (Fig. 1), stream density can be inventoried by optically based remote-sensing techniques. However, the use of this approach in Central Amazonia is limited as only 3rd-order streams and higher can be detected, because of the dense canopy of the rain forest (Melack & Hess, 2010). Brazil has no geographic database on its river catchment areas, but according to the global databank of Hydro RIVERS there are 79,250 rivers of 4th- to 5th-order in the country (Lehner & Grill, 2013). A higher-resolution vector product was offered for the Amazon basin by Venticinque et al. (2016), but it also lacks information on low-order streams.

Few data describing the low-order stream density in entire catchment areas are available. In some areas, stream density has been inventoried by local river basin committees, but these examples are rare (Table 1). Detailed studies have been conducted only

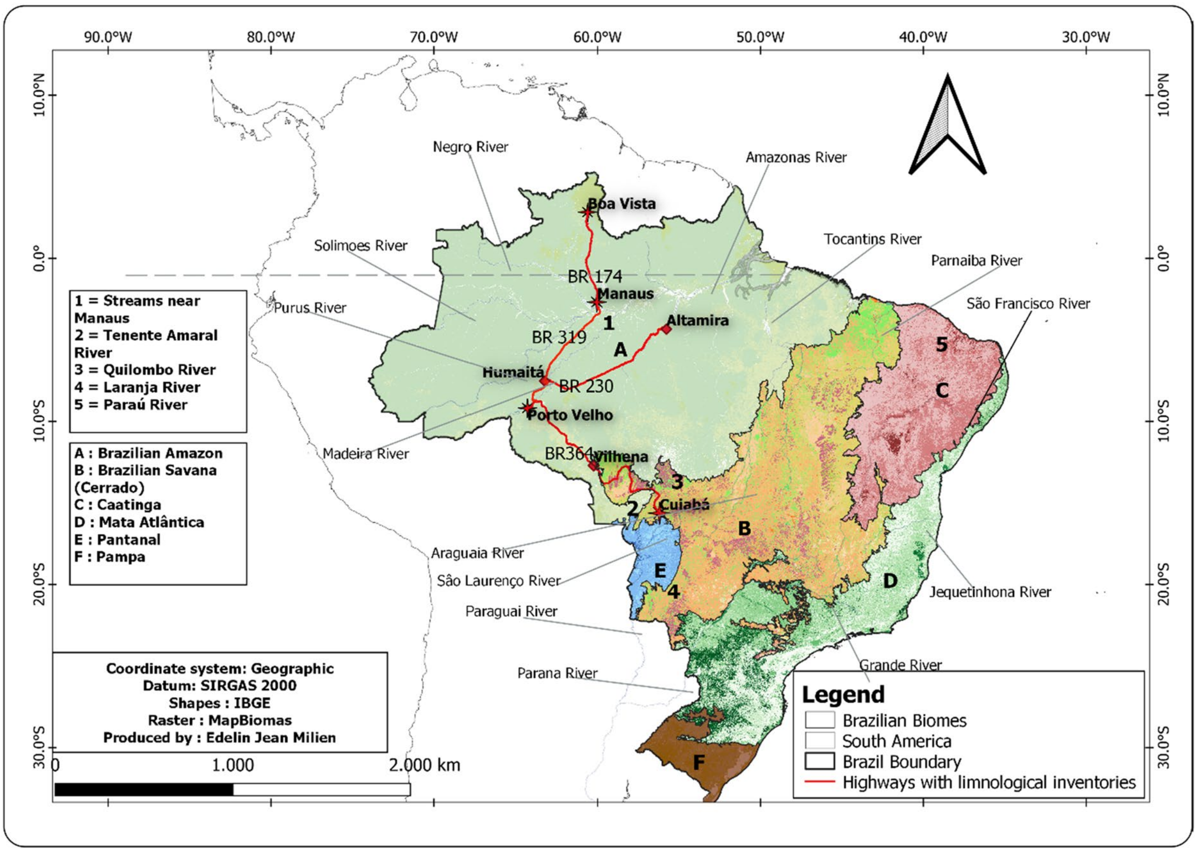


Fig. 1 Major phytogeographic units of Brazil and the locations of the major studied areas

Table 1 Drainage systems in different hydrographic basins*, precipitation, and density of 1st- and 2nd-order streams. The number in front of the river name indicates the geographic position of the basin as shown in Fig. 1

Catchment area name	Size (km^2)	Precipitation ($mm\ year^{-1}$)	Number of streams order					Density (km^{-2})	
			1	2	3	4	5	1st	2nd
1 Streams near Manaus*	927	2,100	800	180	42	12	2	0.864	0.194
2 Tenente Amaral River*	875	1,400	481	80	18	6	1	0.550	0.091
3 Quilombo River*	1,669	1,384	180	39	13	4	1	0.108	0.023
4 Laranja River**	1,056	1,276	84	14	4	1	0	0.080	0.013
5 Paraú River***	686	974	33	8	2	1	0	0.048	0.012

*This article, ** CPTI (2021), ***ANA (2018) in Central Amazonia (north of Manaus) and in the Cerrado (Tenente Amaral River and Quilombo River) (Fig. 1). Stream density as recorded in this limited dataset is highest in Central Amazonia and lowest in the semi-arid regions of Brazil.

Inventories of small wetlands of entire catchment areas are of fundamental importance to quantify the contribution of these water bodies to the hydrological cycle, to assess human impact, and to develop measures for wetland management and protection. In the early 1990s, the government of the State of Amazonas inventoried the soils in a 1.052 km^2 area of the District for Agriculture and Cattle Ranching of the Free Trade Zone of Manaus (SUFRAMA), along the Manaus–Boa Vista Highway, with the aim of developing the area for agriculture (Fig. 2, Rodrigues et al., 1971). This inventory covered the headwaters of various tributaries that drain into the Cuiairas, Urubú, and Preto da Eva Rivers, denominated here as "streams near Manaus." According to that report, the mean annual precipitation in the area is about 2,100 mm, but from June to October there is a water deficit.

Roughly 800 1st-order and 180 2nd-order streams were identified in the area, but due to their small size the uncertainty in these estimates is 10% and 5%, respectively (Fig. 2). Riparian wetlands, swamps,

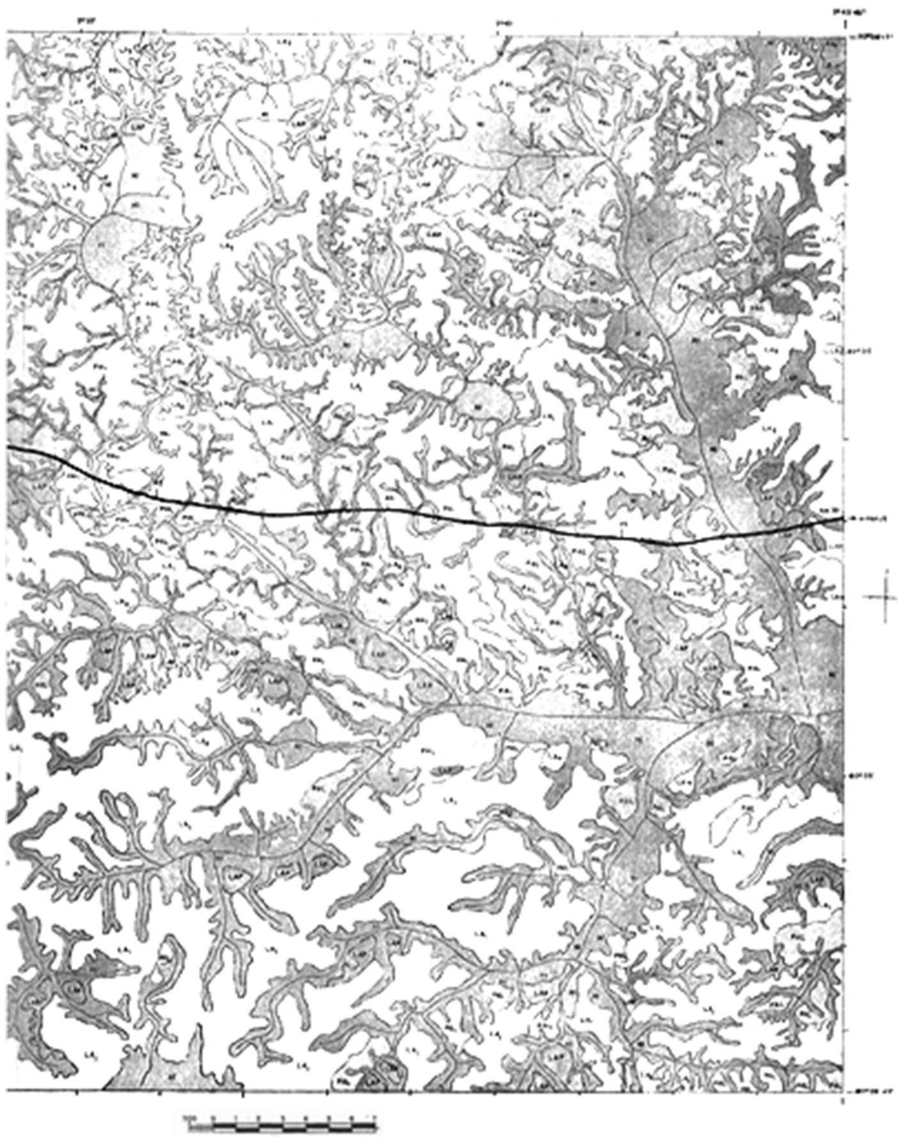


Fig. 2 Map of part of the area of the District for Agriculture and Cattle Ranching of the Free Trade Zone of Manaus (SUFRAMA) along highway BR 174 Manaus–Caracaraí. The drainage system and soil types are shown (Rodrigues et al., 1971). The area was inventoried by the Team of the Instituto de Pesquisas e Experimentação Agropecuárias do Norte, Setor de Solos (IPAAOc)

and hydromorphic soils (indicated as HI in Fig. 2), cover 447.2 km^2, corresponding to 48% of an analyzed area of 927.2 km^2. The highly acidic soils are frequently inundated by streams or are permanently waterlogged, such that they are of little value for agricultural purposes. Riparian wetlands "sensu stricto," i.e., backswamps, and hydromorphic soils, cannot be readily distinguished because they are interconnected, mainly during the rainy season. Given their large numbers, 1st- and 2nd-order streams account for a large proportion of the total riparian wetland area. Wantzen et al. (2008) differentiate along tropical streams eight riparian habitats: hygrometric zones, rock pools, para- and orthofluvial ponds, anabranches and floodplain channels, moist zones on the riparian floodplain, unforested streamside swamps, forested streamside swamps, and peat-swamp forests. These habitats can also be found in Brazilian riparian wetlands of low-order streams.

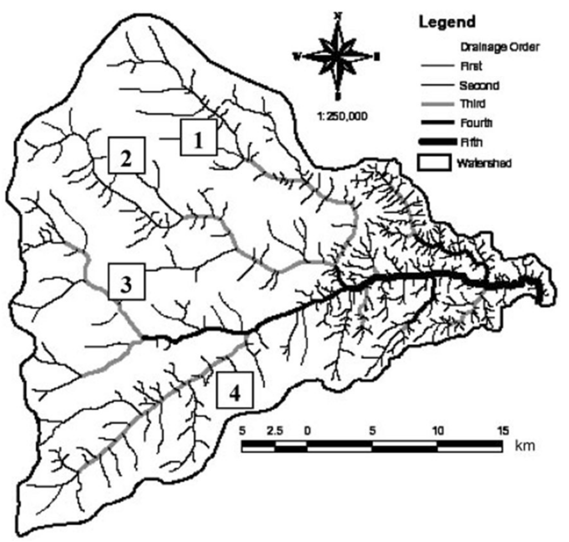


Fig. 3 Map of 1st- to 5th-order streams of the subbasins (1) Brilhante, (2) Tenente Amaral, (3) Verde, and (4) Saia Branca (Wantzen et al., 2006)

In the dryer Cerrado biome, the stream density is usually lower. The basin of the 5th-order Tenente Amaral River (Fig. 3), located near the City of Cuiabá, contains 481 1st-order and 80 2nd-order streams. The catchment size is 875 km^2 and annual precipitation is 1,400 mm (Wantzen et al., 2006). As in the other river basins, total wetland area was calculated because the transition between riparian wetlands "sensu stricto" and other wetland types, such as marshy campos (veredas) and swamp forests, is often unclear (Fig. 4, Wantzen et al., 2006). Wetlands occupy 23.5% of the basin, with roughly half of the area made up of riparian wetlands. Their extent varies from a few meters to hundreds of meters in areas where the streams pass through marshy campos and swamp forests.

The other inventory in the Cerrado covered the catchment area of the 5th-order Quilombo River, with a size of 1,669 km^2 (Fig. 5, Gonçalves, 2022). Mean annual precipitation is 1,384 mm. In this area, 180 1st-order and 39 2nd-order streams were recorded. Despite the similar amounts of precipitation in catchments of the Tenente Amaral and Quilombo rivers, their stream densities differ considerably (0.550 vs. 0.108 1st-order and 0.091 vs. 0.023 2nd-order streams per km^2) due to geomorphological differences, as the Quilombo River area is hillier and streams are restricted to the narrow valleys. Wetlands cover 196.71 km^2, corresponding

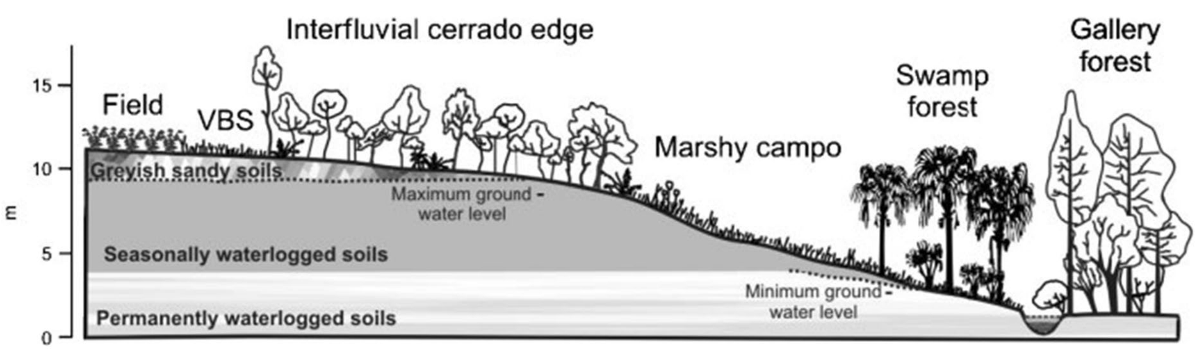
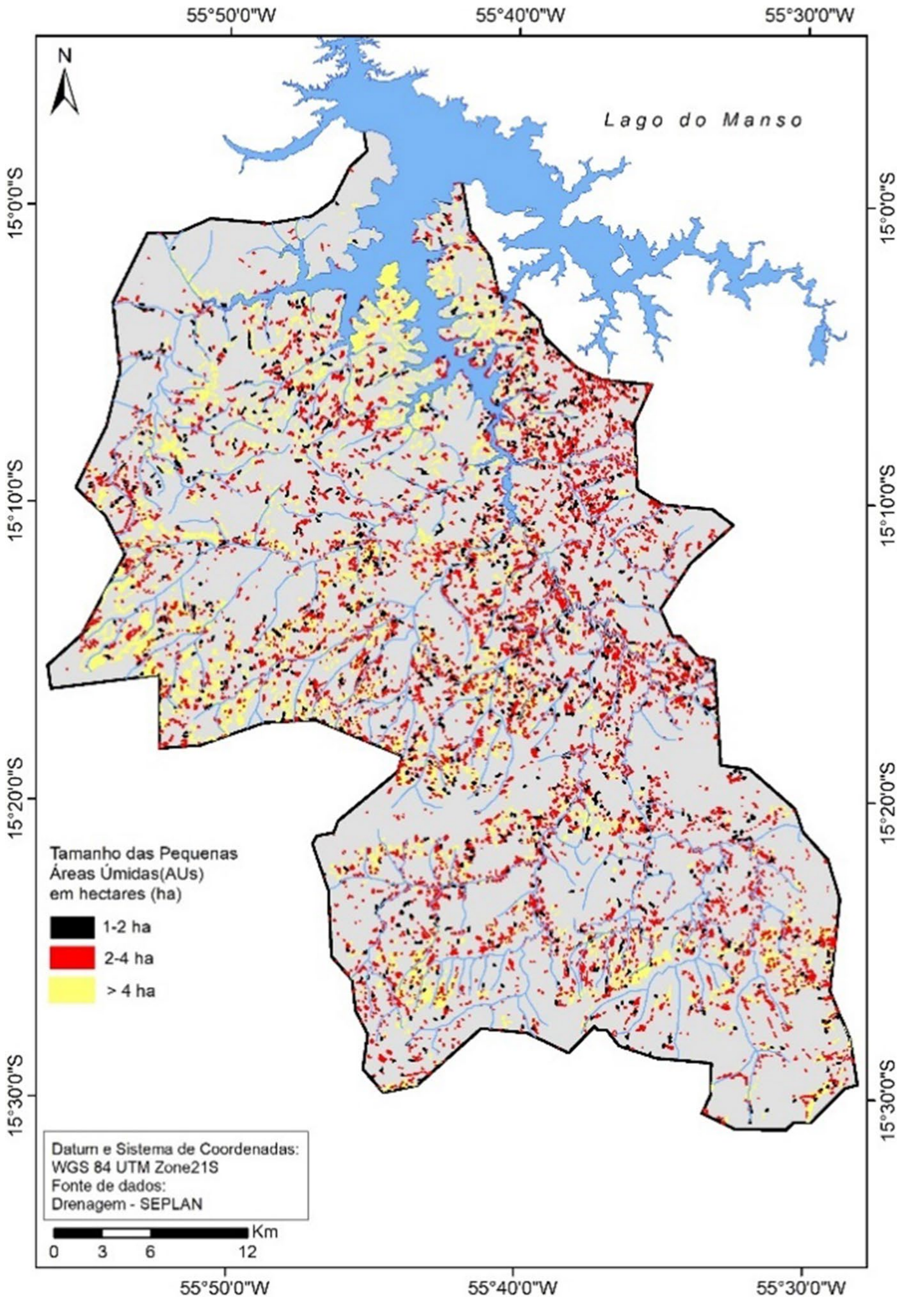


Fig. 4 Sequence of wetland types in the Cerrado (Wantzen et al., 2006)

Fig. 5 Drainage system and wetlands of the Quilombo River basin (adapted from Gonçalves, 2022)



to 11.79% of the catchment area (Fig. 5). Riparian wetlands form small strips or patches along most streams, contributing 90.8 km^2 (5.44%) to the total area. Among the estimated 8,810 wetlands, > 6,000 of them are < 1 ha; 984 are 1–2 ha, 757 are 3–4 ha, and 807 are > 4 ha in size.

Hydrological studies

Studies of the hydrology of low-order streams indicate a close correlation between local rainfall events and stream discharge, as shown for the Tenente Amaral River (Fig. 6; Wantzen, 2003; Couto et al., 2015). In addition to differences in individual

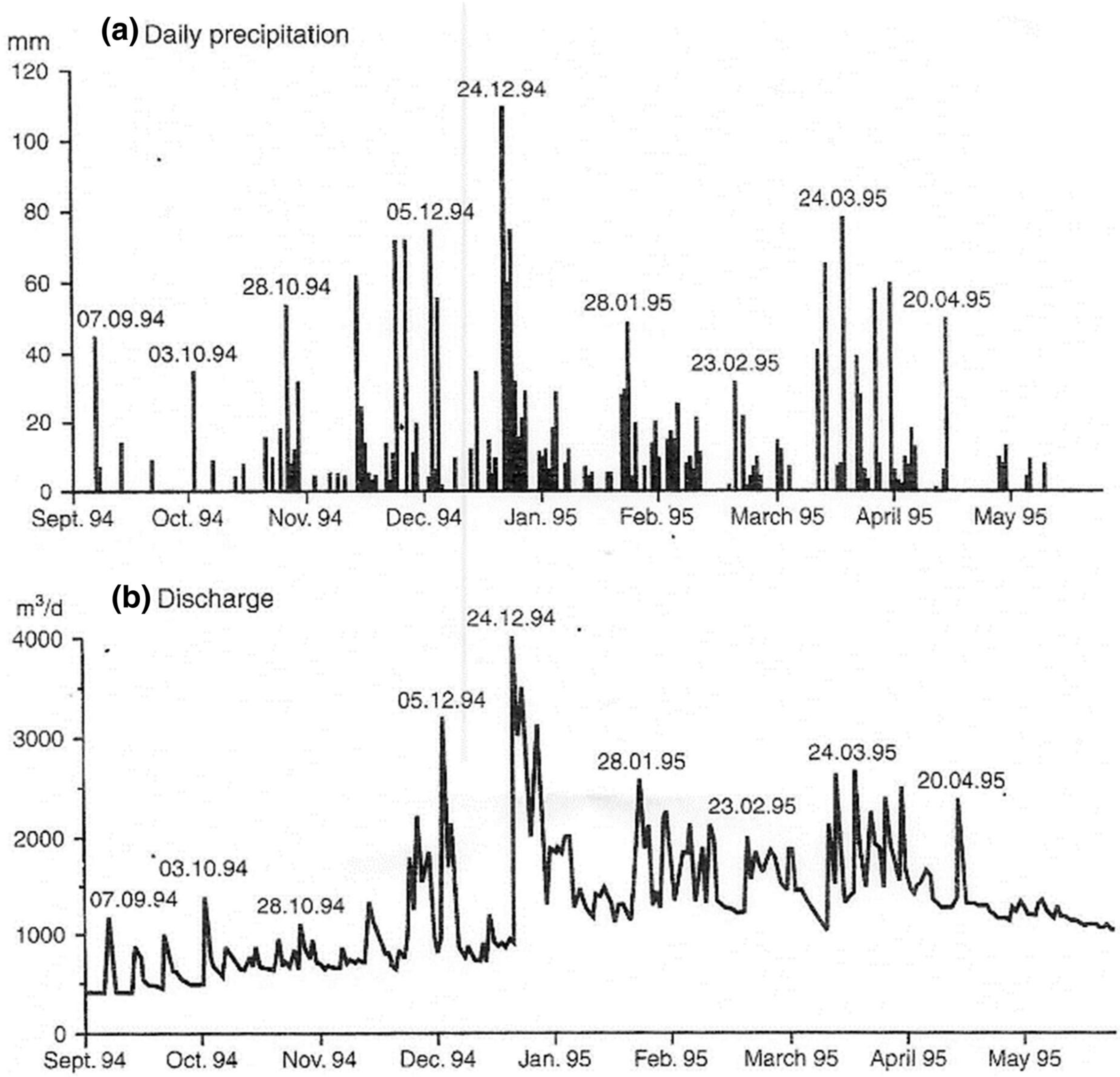


Fig. 6 Precipitation and discharge for the Tenente Amaral River (data from Wantzen, 2003)

rainfall events, there are considerable differences in the amount of precipitation during the dry vs. the rainy season. Lewis et al. (1995) studied neotropical rivers in savannas and found a mean annual variation in discharge of 20-fold in dry forests and 10-fold in humid forests. The variability diminished with the size of the rivers. In the Cerrado, Wantzen (2003) estimated a 10- to 30-fold variation in 1st- to 2nd-order streams in the Chapada dos Guimarães and a 3- to 10-fold variation in the 2nd- to 3rd-order sections of the Tenente Amaral River.

Studies in a small stream near Manaus showed that a mean 22% of the rainfall was intercepted by the canopy, 45.7% was returned to the atmosphere by evapotranspiration, and 32.3 entered the streams, but only 2.8% left the catchment by superficial flow (Franken & Leopoldo, 1986). The authors concluded that a reduction of the forest cover would significantly alter these proportions, with serious consequences for water discharge, erosion, and sediment transport and a reduction in the water residence time in the catchment. In their study of the model basin Tarumã-Açu, near Manaus, Salati & Vose (1984) reported 25.6% interception, 48.5% evapotranspiration, and 25.9% streamflow.

In two catchments of small streams in the Serra do Mar, near the City of São Paulo, 15% of the total precipitation was shown to be returned to the atmosphere by evapotranspiration, an additional 15% was intercepted by the forest canopy, 59% entered the soil and groundwater, and 11% entered the streams by surface run-off, in part after passing through lateral wetlands (Fujieda et al., 1997). Melo et al. (2020) summarized hydrological studies in Brazil. Human impacts on the hydrology of streams and riparian wetlands are discussed below in Sect. 6.

Ecological studies

The flora and fauna of streams are closely linked to riparian wetlands. In the following section we provide a short general characterization of the hydrochemistry of Amazonian and Cerrado streams and point out the interactions of those water bodies with invertebrates and fishes. Information about other regions is scarce. The impact of the destruction of riparian wetlands on the aquatic flora and fauna is discussed in Sect. 6.

Hydrochemistry

Until the 1970s, the Amazon rain forest and large parts of the Cerrado were accessible only by expeditions, such that access to streams was mostly limited to areas around cities. However, the extensive highway construction that began in the 1970s provided access to many low-order rivers in the Amazon rain forest and the Cerrado, including a highway from Manaus to Porto Velho, between the Madeira and Purús Rivers, and from there to Cuiabá in Mato Grosso. The Trans-Amazonian highway covers an east–west transect between João Pessoa and Humaitá. Basic hydrochemical surveys of 126 low-order streams along these highways are provided in Furch & Junk (1980) and in Furch (1985). Those studies considered hydrochemical parameters with respect to geological formations and vegetation units.

With the exception of the streams in a few areas with carboniferous soils, such as at the border of the Pantanal, the water in Amazon rain forest and Cerrado streams is acidic (pH 5.0–6.5) and the total content of dissolved minerals, expressed by the specific conductivity in µS cm^{-1} at 20°C, is low to very low (5–50 µS cm^{-1}). Compared to the worldwide mean value, as reported by Livingstone (1963) and Bowen (1966) (in Furch, 1984), the concentrations of major cations (Na, K, Mg, Ca), anions (HCO_3, Cl, SO_4), and trace elements (Ba, Sr, Al, Cu) are also low to very low. Only the concentrations of Si and Fe are in the range of the mean global value whereas Mn and H concentrations are higher.

The relatively large variability reflects the geology of the area. The alkali-earth metals Ca and Mg are the main cations while HCO_3 is the main anion in the waters of the streams draining from carboniferous soils into the Paraguay River, and in waters of Andean origin, so-called carbonated waters. In other waters, the alkali metals Na and K are the principal cations. These waters are non-carbonated and only slightly buffered. The occurrence of HCO_3 as the dominant anion even in waters of low mineral content is due to the chemical decomposition of silicates (Furch, 1985). Hydrochemical data from studies of other Amazonian and Cerrado streams (Horbe et al., 2005; Ferreira et al., 2012, and many others) are consistent with these findings.

Aquatic invertebrates

The first studies on aquatic invertebrates in Central Amazonian streams were those by Fittkau (1964, 1967). They described the low light penetration resulting from the dense forest canopy, which in turn led to low algal growth and the absence of aquatic macrophytes. Chironomidae comprised the most diverse group of aquatic invertebrates, with > 100 species. The absence of mollusks was explained by the lack of calcium in the water.

Most aquatic invertebrates in Brazilian streams are small and their impact on litter decomposition is low. There are no large shredders, unlike in-streams of temperate regions, which host highly efficient and numerous gammarids (Wantzen & Wagner, 2006). Some specialists (chironomid genus *Stenochironomus*) mine the mesophyll of freshly fallen leaf litter, but a large part of the food web depends on non-leaf organic matter (e.g., terrestrial insects, instream algal production). Classical shredders can be found in temporary ponds and moist leaf accumulations outside the stream channel, thus providing further evidence of the functional importance of the riparian wetlands of headwater streams (Wantzen & Wagner, 2006; Wantzen et al., 2008).

The decomposition of leaf litter is initiated by fungi, not by bacteria, which makes its uptake by filter-feeding invertebrates difficult (Walker, 1986, 1995). Leaf structure is weakened by fungi such that after its repeated remobilization by the current the litter slowly undergoes fragmentation. In the nutrient-poor, acidic water of the igapó of the Negro River, a decomposition time for leaf litter of 6.3 years was calculated (Irmler & Furch, 1980).

Detailed studies of invertebrates in the catchment area of the Tenente Amaral River have been published by Wantzen (1998, 2003) and Wantzen & Pinto-Silva (2006). A review of the taxa recorded in tributaries of the Pantanal can be found in Wantzen et al. (2011a), and a summary of the taxonomy, biology, and ecology of Amazonian aquatic insects in Hamada et al. (2014).

Ichthyological studies

Early studies on stream fish and their feeding habits in Central Amazonia include the study by Knöppel (1970), who reported 49 species using the entire spectrum of available food items throughout the year. Aquatic insects and their larvae, but also many allochthonous materials, such as detritus from the forest canopy and terrestrial insects (e.g., ants), were part of the diet of the large majority of the species. The author observed that the streams, despite their low content of mineral salts, provided sufficient food for an abundant fish fauna. In the following years many studies confirmed these findings and added additional information. Kemenes & Forsberg (2014) collected 66 species in 34 headwater streams of the Jaú River system, the right tributary of the Negro River, and described the relationship of species assemblages to stream size and to the distribution and diversity of bottom substrates.

Species diversity in individual stream sections can be low, but beta-diversity is generally high. In an inventory of 38 50-m sections in various streams of the Reserva Ducke, near the City of Manaus, a total of 49 species were detected, but with only a mean of nine species per section (Mendonça et al., 2005). The authors concluded that the establishment of a network of reserves is necessary to protect fish species diversity in Amazonian streams. This conclusion was supported by an earlier study demonstrating the importance of drainage basins in structuring fish communities in the streams of the Madeira–Purus interfluve (Araújo-Lima et al., 1999). Catchment boundaries are potential barriers to fish dispersion and in small streams they have a greater influence on fish community structure than either physical structures or the physico-chemical characteristics of the water.

Small backwaters in the riparian zone increase habitat diversity and food resources, as shown in a stream at Ducke Forest Reserve. During heavy rainfall events, fish abundance in the backwaters was higher than in the main channel. When the backwaters started to dry as the water level fell, the fish returned to the channel, thus maintaining the stability of the population (Espírito-Santo & Zuanon, 2016).

Riparian vegetation

The riparian vegetation of Brazilian streams belongs to the group classified as hydrophytes. An amplified definition of Weaver & Clements (1938), with the explicit citation of woody vegetation, describes hydrophytes as *herbaceous and woody plants that grow in water, in soil covered by water, or in soil that is periodically saturated.* Riparian vegetation grows on bedload composed of rock, sand, or clay, depending on the surrounding soils and on the water velocity in the stream bed and riparian zone, which together determine sediment deposition. These sediments may be periodically or permanently covered or saturated with water and are often hypoxic or anoxic. Species colonizing the sediments must therefore be adapted to their conditions. As already shown above, the riparian vegetation is of fundamental importance for streams and shows multiple interactions with in-stream flora and fauna.

Herbaceous hydrophytes

Studies on herbaceous plants in riparian wetlands along Brazilian streams are rare. The low-water depth of low-order streams, the occurrence of small backwaters in the riparian zone, and the fluctuating water levels allow the inclusion of aquatic macrophytes in the group comprising herbaceous hydrophytes of the riparian zone. A preliminary survey of aquatic macrophytes was conducted during the collection of water samples along a transect between Cuiabá, Porto Velho, and Manaus (Furch & Junk, 1980). Inventories were restricted to sections ~ 100 m upstream and downstream of the highway. Aquatic macrophytes were found in 25 of the 46 sampled streams. They were absent in the first section, which drains into the Paraguay River, abundant in the Cerrado area, and absent in Central Amazonia. In parts of Central Amazonia, the stream beds near the highway had been strongly modified, such that their environmental conditions were not representative. Along streams of near-natural conditions, light limitation by the dense forest canopy hindered macrophyte growth.

Characteristic white-water species occurred in-streams located in the section passing through nutrient-rich várzea sediments deposited along the Amazon River, such as the aquatic grasses *Paspalum repens* P.J. Bergius, *Paspalum fasciculatum* Willd. ex Flügge, *Echinochloa polystachya* (Kunth) Hitchc., *Leersia hexandra* Sw., and *Oryza perennis* Moench, as well as many floating species, such as *Eichhornia crassipes* (Mart.) Solms, *Pontederia rotundifolia* L. f., and *Salvinia* spp.

The streams in the Cerrado section were characterized by an exuberant growth of macrophytes in crystal clear water, including *Sagittaria rhombifolia* Cham., *Eichhornia pauciflora* Seub., *Elodea granatensis* Bonpl., *Cabomba piauhyensis* Gardner, *Nymphaea rudgeana* G. Mey., *Nymphoides humboldtiana* (Kunth) Kuntze, *Mayaca fluviatilis* Aubl., and *Mayaca kunthii* Seub. In the rapids, different species of Podostemaceae were found.

In the Tenente Amaral River system in the Cerrado, aquatic macrophytes were mostly limited to rapids (Podostemaceae), while the specific floral assemblages of graminoid plants from the vereda vegetation reached the riparian zone in open stream sections. Due to the nutrient-poor conditions, carnivorous plants (Utriculariaceae) were common. In-streams suffering from sand inputs due to man-made erosion, all colonizable surfaces were either scoured or covered by sand, making the growth of benthic algae or aquatic macrophytes impossible.

Lentic and lotic systems in the Brazilian semi-arid region are characterized by flash floods that occur during the rainy season and whose magnitude varies according to the rainfall (Maltchick & Medeiros, 2006). Matias et al. (2021) examined aquatic macrophytes in different water bodies and found evidence of the strong impact of hydric disturbances.

These results and unpublished observations of many other streams by the first author led to the following conclusions: the occurrence and abundance of herbaceous plants in the riparian wetlands of the low-order streams of Central Amazonia and in the Cerrado depend on the availability of light. Turbidity, high concentrations of colored humic substances in black-water, and the dense forest canopy hinder the growth of these plants. Species that occur in water with very low concentrations of mineral salts differ in their nutrient requirements from species colonizing nutrient-rich Amazonian white-water rivers and their floodplains, whose water and sediments are of Andean origin. In-streams of the Brazilian semi-arid region, irregular flash floods and periodic dry stages strongly select for species with high resistance and resilience in response to hydric disturbances. A classification of herbaceous and woody plants occurring in wetlands will be provided by Junk et al. in a book on aquatic plants in Brazil, edited by Pivari et al. (in press).

Riparian forests

Structure, floristic composition, and species richness in riparian forests of Central Amazonia

In Central Amazonia, trees growing in the riparian zones of low-order streams must cope with water-logging of the soils as well as light limitation, because valley substrates are shaded by the canopy of large trees. These stressors give rise to a characteristic species composition that reflects specific adaptations and functional traits. However, there are few studies of Central Amazonian riparian forests. The following results were collected in the Ducke Forest Reserve, near the City of Manaus. There, riparian trees are relatively small, reaching a mean height of 16–20 m and rarely growing higher than 25 m. In the adjacent upland, the mean tree height is 35–40 m, with emergent trees often growing higher. Tree density, including that of palms, is 550–700 individuals ha^{-1} ($\geq$10 cm dbh) and thus does not differ from that of other Amazonian forest types (Tello, 1994; Carneiro, 2004; Brito, 2009). However, aboveground biomass is only 154–166 Mg ha^{-1} (Brito, 2009), which corresponds to 50–60% of that of upland forests and the floodplain forests of várzeas and igapós (Schöngart et al., 2010).

In the species list of Ribeiro et al. (1999), which describes the flora of the Ducke Reserve, 1,362 woody species were recorded, with 600 (44%) occurring in the riparian zone and associated wet depressions, of which 210 species (15.4%) were preferentially established in this habitat. In further inventories performed along Central Amazonian riparian forests by Porto et al. (1976), Tello (1994), Carneiro (2004), and Brito (2009), the mean species richness ranged from 117 to 190 species ha^{-1} ($\geq$10 cm dbh).

The most important families were Arecaceae (20% of all collected individuals), Myristicaceae (11.5%), Fabaceae (10%), Lecythidaceae, Burseraceae, and Sapotaceae (5% each). *Oenocarpus bataua* (Araceae) was the most frequent species (15.7% of all individuals) whereas 107 species (44.8% of the total number) were represented by a single individual.

However, those inventories did not provide information on stream-order, hydrology, or soil texture, such that conclusions regarding general compositional patterns were not possible. Nonetheless, they showed that riparian forests and connected backswamps are highly diverse habitats, reflecting the fact that they attract tree species from both strictly terrestrial and floodplain habitats.

Genera adapted to high-level, prolonged flooding in várzeas and igapós, such as *Carapa* (Meliaceae), *Myrcia* and *Eugenia* (Myrtaceae), *Duroia* (Rubiaceae), *Terminalia* (Combretaceae), *Sloanea* (Elaeocarpaceae), *Mabea* and *Hevea* (Euphorbiaceae), and *Swartzia* and *Vatairea* (Fabaceae), share species with riparian habitats. The sandy substrate in the riparian zone may also favor the occurrence of species from the partly hydromorphic Amazonian white-sand forests (campinarana), such as those belonging to the genera *Aldina* and *Swartzia* (Fabaceae), *Caraipa* (Calophyllaceae), *Manilkara* (Sapotaceae), *Vitex* (Lamiaceae), and *Simaba* and *Simarouba* (Simaroubaceae). The poorly drained, finely textured soils in the backswamps are colonized by species adapted to permanently anoxic soils. They often develop adventitious roots and even pneumatophores. The palm *O. bataua* Mart. is an indicator species, often forming monospecific stands or associated with other palm species such as *Mauritia flexuosa* L. f., *Mauritiella armata* (Mart.) Burret, *Iriartella setigera* (Mart.) H. Wendl., *Hyospathe elegans* Mart., *Socratea exorrhiza* (Mart.) H. Wendl., and several species of the genus *Bactris*. Associated dicot species are *Virola pavonis* (A. DC.) A.C. Sm. (Myristicaceae), *Swartzia cuspidate* Spruce ex Benth. (Fabaceae), *Goupia glabra* Aubl. (Celastraceae), *Symphonia globulifera* L. f. (Clusiaceae), and *Ecclinusa guianensis* Eyma (Sapotaceae).

Structure, floristic composition, and species richness in riparian forests of the Cerrado and Caatinga

In the more arid biomes of the Cerrado and Caatinga, riparian zones provide water for tree growth. This allows for the development of a plant community that differs considerably from the surrounding vegetation. The Cerrado is characterized by a highly heterogeneous vegetation cover and biodiversity, because of differences in climatic, geographic, and edaphic factors (Ratter & Dargie, 1992). Both temperature and water deficit increase from southeast to northeast. Two important climatic barriers that cross the biome are the occurrence of frost south of 20° S and severe drought north of 15° S and east of 45° E (Castro & Martins, 1999). Altitude and topography also strongly influence the vegetation cover, which can vary from grasslands to forests with a closed canopy (Oliveira-Filho et al., 1994; Ratter et al., 2003).

Several floristic studies have been conducted in the riparian forests of the Cerrado. Since the trees are smaller than those in Central Amazonia, trees at 5 cm dbh were included in the inventories, which makes comparisons between the respective studies difficult. Forest structure and floristic composition depend mainly on the topography and the degree of water saturation of the soil (Oliveira-Filho et al., 1994; Rodrigues & Nave, 2000). Inundation of the aerial parts of plants is normally of short duration and occurs sporadically after heavy rainfall events. The majority of the tree species establish their root systems near or even below groundwater level.

Riparian forests represent a sub-community of the Cerrado forest, without endemic species. The riparian forests of the Tenente Amaral River headwaters are species-rich, with up to 65 woody plant species ha^{-1} (Wantzen et al., 2011b). In their analysis of 43 inventories, Rodrigues & Nave (2000) found low floristic similarity (< 30%) between different streams. Similar results were reported by Souza et al. (2004) based on nine inventories of riparian forests in the upper Paraná River basin, where > 50% of the species occurred exclusively in one locality. Metzger et al. (1997) reported that 42% of all species recorded in inventories of four riparian forests of São Paulo State were rare and occurred in only one locality. These results reflect the large beta-diversity of the Cerrado vegetation and, in turn differences in geomorphology, water availability, sediment load, and soil fertility in catchment areas. Moreover, the flora of the riparian forests of the Cerrado along the transition zone may be strongly influenced by species from neighboring biomes, such as the Mata Atlântica in the east, the Caatinga in the northeast, Amazonia in the north, and the Pampas in the south (Rizzini, 1997; Ratter et al., 2003; Marimon et al., 2006).

In an analysis of 19 floristic inventories, Wittmann (2012) identified the following families as the most species-rich: Fabaceae (11.5%), Myrtaceae (6.5%), Lauraceae (5%), Euphorbiaceae (4.5%), and Meliaceae (4.4%), followed by Annonaceae, Rubiaceae, Clusiaceae, Anacardiaceae, and Burseraceae (3–4% each). The 15 most important species (relative abundance + relative dominance + relative frequency) accounted for ~ 42% of the total importance. The most important species were *Calophyllum brasiliense* Cambess. (Clusiaceae), *Copaifera langsdorffii* Desf. (Fabaceae), *Talauma ovata* A. St.-Hil. (Magnoliaceae), *Tapirira guianensis* Aubl. (Anacardiaceae), *Casearia sylvestris* Sw. (Salicaceae), and *Protium spruceanum* (Benth.) Engl. (Burseraceae). Floristic composition, however, may vary considerably when mineral soils are replaced by organic material. This occurs in some headwater regions and in interfluvial depressions, both of which are permanently saturated with water.

A survey of the arboreal flora registered 2,453 species for all Brazilian wetlands (Wittmann et al., 2017). In the Cerrado, 846 species were determined at 50 sites, of which 292 species were restricted to this biome while the others occurred in at least one additional biome, mainly Atlantic rainforest and Amazonia (Wittmann et al., 2017). The mean alpha-diversity of the riparian forests of the Cerrado was slightly lower than that of the Amazonian wetlands but slightly higher than that of the Atlantic rainforest. Species richness in the riparian zone of the Cerrado was higher than that of the periodically flooded areas of the Pantanal (Wittmann, 2012). Many wetland tree species from other biomes become established in the riparian zones of the Cerrado, especially in the case of streams connected to large rivers that cross different Brazilian biomes.

Floristically, the riparian forests of the Caatinga share many tree species with the Cerrado, reflecting a South American belt of seasonally dry forest and savannas (Werneck, 2011). Only a few floristic inventories are available, but Wittmann et al. (2017) reported 223 tree species in the riparian forests of the Caatinga, 91 of which were exclusive to this biome while the majority were shared with the Cerrado. The most important tree species were *Caesalpinia pyramidalis* Tul. (Fabaceae), *Prosopis juliflora* (Sw.) DC. (Fabaceae), *Ziziphus joazeiro* Mart. (Rhamnaceae), *Copaifera martii* Hayne (Fabaceae), and *Anacardium occidentale* L. (Anacardiaceae).

Structure, floristic composition, and species richness in riparian forests of the Atlantic rainforest and Pampas

Riparian forests of the Atlantic Forest domain occur along the Paraiba do Sul, Pardo, Jequitinonha, and Doce Rivers in eastern and southeastern Brazil, together with thousands of small creeks that drain the interior and coastal mountains (Serra do Mar, Serra da Mantiqueira). Riparian forests are thus directly adjacent to semi-deciduous (at higher altitudes, mostly in the western zone) or evergreen (lowlands, mostly in the eastern zone) forests. Species richness and alpha-diversity are similar to that in riparian forests of the Cerrado, and most tree species are shared between these biomes (Wittmann et al., 2017). In the southern subtropical zone, riparian forests of the Atlantic rainforest additionally share many tree species with wetlands from the Pampas (Oliveira-Filho et al., 2013; Wittmann et al., 2017).

Although most riparian forests are heavily affected (i.e., fragmented) by human activities, those within the Atlantic Forest domain are rich in habitat and species diversity (i.e., Rolim et al., 2006). Numerous forest inventories are available for riparian forests across the Atlantic biome, especially its southern zone (i.e., Szutman & Rodrigues, 2002; Marques et al., 2003; Rolim & Chiarello, 2004; Rolim et al., 2006). However, inventories indicating the importance of single tree species per area are scarce, and comparisons with flooded forests of other biomes are restricted to the absence and/or occurrence of tree species. Common flood-tolerant tree species in riparian forests of the Atlantic Forest domain belong to the genera *Lithraea* and *Astronium* (Anacardiaceae), *Tabebuia* and *Jacaranda* (Bignoniaceae), *Cordia* (Boraginaceae), *Andira*, *Platymiscium* and *Inga* (Fabaceae), *Ocotea* (Lauraceae), *Maytenus* (Celastraceae), *Sloanea* (Elaeocarpaceae), *Alchornea* and *Sapium* (Euphorbiaceae), *Clidemia* (Melastomataceae), *Calyptranthes* and *Eugenia* (Myrtaceae), and *Annona* and *Rollinia* (Annonaceae). The most frequently cited tree species in the riparian forests of coastal areas in the States of São Paulo (Szutman & Rodrigues, 2002) and Rio de Janeiro (Carvalho et al., 2006) are *C. brasiliense* (Clusiaceae), *Lithraea brasiliensis* Marchand (Anacardiaceae), *Tabebuia cassinoides* (Lam.) DC. (Bignoniaceae), *Symphonia globulifera* (Clusiaceae), *Cordia sellowiana* Cham. (Boraginaceae), and *Astronium fraxinifolium* Schott (Anacardiaceae).

Pampas occupy a small portion of southern Brazil that is covered by subtropical semi-deciduous forest (Oliveira-Filho et al., 2013). Riparian forests show a strong zonation of tree species associated with periodically to episodically flooded streams, with the highest species richness usually occurring where inundations are low and brief (Budke et al., 2008). A review of 13 floristic inventories in riparian forests of the Brazilian Pampas recorded 183 tree species, of which only 34 were exclusive, as the large majority was mainly shared with riparian forests of the Atlantic rainforest and, to lesser extent, with those of the Cerrado (Wittmann et al., 2017). The most important tree species identified in that review were *Sebastiania commersoniana* (Baill.) L.B. Sm. & Downs (Euphorbiaceae), *Eugenia uniflora* L. (Myrtaceae), *Allophylus edulis* (A. St.-Hil., A. Juss. & Cambess.) Hieron. ex Niederl., *Cupania vernalis* Cambess, (Sapindaceae), and *Casearia silvestris* Sw. (Salicaceae).

Human impact on riparian wetlands and streams

Humans interference with streams and riparian wetlands negatively affects their hydrology, water quality, sediment load, vegetation cover, and biodiversity, resulting in the elimination of species adapted to specific ecological niches and specific food items.

Anthropogenic modifications occur by:

1. direct destruction, such as by the construction of infrastructure, and by the occupation for house building,
2. water pollution by domestic and industrial wastes, by mining activities, as well as by fertilizers and agrotoxins from agricultural areas,
3. the construction of reservoirs, which modify the hydrological regime and interrupt longitudinal connectivity,
4. conversion of land for agriculture and animal ranching,
5. selective logging, the burning of vegetation in the catchment area, and other forms of destruction that result in:
    - modifications of surface run-off,
    - increases in sediment load by erosion and thus by depositions of sediment in the riparian zone,
    - increases in environmental and water temperatures,
    - homogenization of ecological niches in the streambed,
    - modification of food webs,
6. fish culture.

The direct destruction of riparian wetlands occurs mostly in urban areas, where space for construction is limited and population growth is rapid. Streams have been transformed into concrete canals and wetlands have been destroyed to make room for transportation infrastructure. Available wetland areas are often used as dumping grounds or they are inhabited by the poorest segments of the population. The frequent flooding of these areas places their inhabitants at high risk (Wantzen et al., 2019).

The impact of domestic wastewater on streams is shown in the area of Manaus. The non-polluted headwaters of the Tarumã-Açu, Quarenta, and Mindú Rivers are acidic, with low electrical conductivity, low concentrations of cations and anions, and high concentrations of dissolved oxygen. In the lower reaches, water pollution has raised the pH and increased both the electrical conductivity and the concentrations of cations and anions, in addition to reducing the concentration of dissolved oxygen (Melo et al., 2005). In the non-impacted headwater of a stream from Reserva Ducke, the pH is 4.47, the electrical conductivity 6.44 µS cm^{-1}, and the concentration of suspended material 1.25 mg l^{-1}. Outside the reserve, the pH is 6.84, the electrical conductivity 141.50 µS cm^{-1}, and the concentration of suspended material 9.50 mg l^{-1}, indicating anthropogenic pollution (Ferreira et al., 2012). In the urban area of Manaus, the water in the stream shows high levels of minerals, turbidity, and suspended material, a lower acidity, and lower levels of dissolved oxygen (Ferreira et al., 2021).

A general analysis of human impact on urban streams and wetlands in the tropics and efforts at their restoration was provided by Wantzen et al. (2019). The authors combined their ecological assessment with practical aspects, such as public healthcare and cultural linkages with a healthy ecosystem, and pointed out the need for the broad acceptance of environmental protection by the local population and public willingness to comply with the respective measures.

Mercury pollution due to gold mining activities affects both in-stream animals and human health, as shown in large rivers and wetlands (Nogueira & Junk, 2000; Callil & Junk, 2011). Moreover, in mining areas the increase in sediment load together with pollution can be disastrous for streams and the riparian zone. Minor impacts have not been registered, but several environmental disasters were a wake-up call for the public. In November 2015, a tailings dam in the municipality of Mariana (Minas Gerais) broke, destroying the City of Bento Rodrigues, with effects also involving the City of Paracatu de Baixo, and killing 19 people. Sediments contaminated with heavy metals polluted the Rio Doce and its riparian zone over a distance of ~ 700 km below the estuary of the Atlantic Ocean (Brasil & Pires, 2017; Carvalho et al., 2017). A similar accident occurred in 2019, in the City of Brumadinho in Minas Gerais, resulting in the death of some 300 people and polluting the Rio Paraopeba as well as its riparian wetlands over a distance of 250 km (Freitas et al., 2019).

There have been no studies of the impact of reservoir construction on low-order streams and their riparian zones, but the change in hydrology can be expected to alter the vegetation cover. Highway construction in the central Amazon basin modified the hydrology of the areas upstream of the roads, resulting in considerable changes in vegetation cover (Junk, personal observation). These changes, while significant, are only of local importance. The larger impact is that of large reservoirs. More than 35 years after the implementation of the hydroelectric Balbina Dam at the Uatumã River near Manaus, the riparian zone over a distance of > 125 km downriver continues to be heavily impacted. The operational period of the dam led to the suppression of the aquatic phase at higher floodplain elevations and to an encroachment of secondary tree species from upland forests. The permanent flooding conditions at low topographical elevations have resulted in the massive mortality of highly flood-adapted trees. The effects have probably cascaded down to the entire food web of the riparian zone (Schöngart et al., 2021).

Forest destruction in catchment areas strongly impacts streams and riparian wetlands. In-stream areas drained for soybean plantations, the mean annual discharge is about three times larger and the mean discharge amplitude two times higher than in forested catchments (Dias et al., 2015). A simulation study showed 39% less annual evaporation in pasture areas and soybean plantations than in areas of tropical forests and Cerrado vegetation. The increased stream discharge in agricultural and pasture areas also increases the loads of suspended and dissolved material, due to soil erosion (Chaves et al., 2008).

Destruction of the natural vegetation cover by agriculture and cattle ranching, the construction of roads, trampling by cattle, and insufficient erosion control can lead to the formation of large erosion gullies. After heavy rains, the sediment-loaded surface runoff enters the gullies in pulses and then is further transported into streams. The formation of a series of gullies can destabilize the river bed, by transporting the sandy bedload into the riparian zone, killing the vegetation and thus promoting the erosion of unprotected lateral shores. This has occurred in the transition zone between the Cerrado high planes and the Pantanal depression (Wantzen, personal observation) and along the highway from Cuiabá to Porto Velho (Junk personal observation). In many cases, the increased sediment load will finally be deposited in reservoirs constructed for water storage and hydro energy production, thus drastically reducing their longevity.

Several studies have shown the direct and indirect negative impacts of sediment mobilization by anthropogenically induced erosion on habitat structure, biodiversity, and ecosystem functions in the streams and riparian wetlands of the Cerrado in Mato Grosso (Wantzen, 1998, 2006; Wantzen et al., 2006, 2011a, b; Wantzen & Mol, 2013). Downstream of erosion gullies, the abundance of aquatic invertebrates is strongly reduced because the increased sediment load reduces habitat quality, including food availability (Wantzen, 2006; Wantzen & Mol, 2013). The results of experiments in which artificial substrates were subjected to varying amounts of sediments confirmed these observations (Wantzen & Pinto-Silva, 2006).

The destruction of the natural riparian vegetation leads to an increase in light intensity, which favors the growth of algae and aquatic macrophytes, thus increasing aquatic autochthonous primary production (Bleich et al., 2015). On the other hand, it modifies the quality and quantity of leaf litter and woody debris, such that habitat diversity for aquatic organisms, including fish, is reduced, which causes a loss of specialized species (Bordignon et al., 2015; Leitão et al., 2018). The elimination of the natural riparian vegetation along pasture streams near Manaus led to a significantly lower level of aquatic insect richness as well as the specific richness of Ephemeroptera, Plecoptera, and Trichoptera in comparison with streams in forested areas. In addition, the taxonomic composition of aquatic insects at these two habitat types differed significantly (Nessimian et al., 2008). It was the combination of rainfall-driven flood pulses and increased load of suspended particles from erosion which caused the decline of the benthic colonization in these streams rather than the hydrological disturbance alone.

Site-to-site comparisons revealed a highly significant reduction in density, biomass and taxon richness of the benthic invertebrates caused by siltation. All benthic insect taxa studied showed the same pattern, indicating a general impact of erosion on habitat quality and food sources. Semi-aquatic insects adapted to shifting habitat conditions, terrestrial food sources and aerial respiration were the most resistant invertebrate group.

A study of the impact of changes in the riparian vegetation on fish fauna, conducted in the State of São Paulo, divided fish species into two groups. One group consisted of specialized species dependent on specific substrates but also on hydraulic variability, allochthonous food items, high dissolved oxygen concentrations, and low turbidity, and the other group of species with opportunistic and generalist habits, detritivores, and species able to tolerate low oxygen concentrations. Members of the first group colonized preserved streams with a forested riparian vegetation whereas those of the second group dominated in-streams that had suffered anthropogenic degradation and the advancement of aquatic macrophytes, such as cattails, into in-stream habitats (Casatti et al., 2012).

Higher water temperatures were measured in 12 streams draining sub-basins of the upper Xingu catchment, which is covered by grasslands and soybean plantations. Maximum daily temperatures of > 48°C and > 38°C, respectively, were recorded (Lorion & Kennedy, 2009). The impact of a rise in temperature was examined in experiments that included 13 fish species of the Amazonian rain forest. In the natural habitats of those species, water temperatures vary between 28 and 31°C (Jung et al., 2020). Two species did not survive 4 weeks at a water temperature of 33°C and nine species did not survive 35°C. Moreover, the tolerance of hypoxia decreased after exposure of the fish to higher temperatures. The authors concluded that many Amazonian fish species are at risk of extinction, due to increasing water temperatures and the accompanying hypoxia that occurs after large-scale deforestation.

Aquaculture is potentially polluting because the effluents, which contain industrialized food items, are released directly into streams (Affonso et al., 2012; Santos et al., 2015). Attention should thus be paid to the rising number of in-stream fish culture stations, such as near the City of Manaus (Fim et al., 2009; Pantoja-Lima et al., 2015; Rocha et al. 2015). Negative impacts on the local fish fauna derive from the higher water temperatures in fish ponds, the transfer of diseases, and the escape of genetically modified specimens and exotic species. Recently, escaped or released fish species caused ecological problems at the river basin level in the Paraguay–Paraná River system (Espínola et al., 2022).

Discussion and recommendations

Recent studies carried out as part of the project MapBiomas (Água) (2021) estimated 16.63 million ha of surface waters in Brazil, corresponding to 2% of the national territory. However, during the last 30 years, there has been an alarming reduction of 3.1 million ha, corresponding to 15.7% of the total area. These numbers do not consider the large areas covered by wetlands.

The remote-sensing inventory of Melack & Hess (2010), with a spatial resolution of 100 m, determined a wetland area of about 800,000 km^2 across the entire Amazonian lowlands below 500 m asl, corresponding to 14% of the area. An analysis of 29 inundation datasets for the Amazon basin by Fleischmann et al. (2022) indicated a mean long-term maximum inundation area of 490,300 $km^2 \pm 204{,}800$ km^2 and a mean long-term minimum inundation area 112,392 $km^2 \pm 79{,}300$ km^2. According to at least one dataset, 31% of the lowland basin (elevation below 500 m) is subjected to inundation, although the authors of that study acknowledged the considerable discrepancies between datasets, well evidenced also by the different numbers obtained in other studies.

The inventories mentioned above did not consider the small wetlands distributed over the entire landscape. Thus far, there have been too few inventories to allow precise determinations of the area covered by riparian wetlands of low-order streams and small interfluvial wetlands in different regions of Brazil. The participation of 48% of these wetlands in the inventory near Manaus seems to be very high and requires comparative studies in other regions of Central Amazonia. Realistic numbers may be 25% for the Amazonian rain forest biome, 10% for small wetlands in the Cerrado, including 5% riparian wetlands and 5% of other types of small connected wetland areas, and 3% in the semi-arid Caatinga region, with many of those wetlands being periodically dry. To these numbers the areas have to be added, which are covered by the large river floodplains and interfluvial wetlands. Junk et al. (2011) estimate, that about 30% of the Amazon basin is covered by different types of wetlands. For the national territory of Brazil, the estimates reach about 20%. In Argentina estimates are 23% (Kandus et al., 2008), and in Columbia 27% (Ricaurte et al., 2019). Thus, about 20% of South America can be considered as wetland.

The first to appreciate the relationship between the vegetation cover of the landscape and water availability was Dom Pedro II, who reigned as the last Emperor of Brazil between 1831 and 1889. He declared the protection of the headwaters of rivers in the mountains of the City of Rio de Janeiro and ordered, between 1862 and 1874, the planting of some 72,000 exotic and native fruit trees. Today, the forest of the Barra da Tijuca is a national park, famous for its biodiversity and abundant water resources. Unfortunately, this example of leadership has been abandoned by the politicians and planners who rule the country today. In Mato Grosso, formerly perennial streams and rivers are becoming ephemeral, with dramatic consequences for biodiversity and the local population. Over the long-term, the destruction and overexploitation of superficial water resources will result in a lowering of the groundwater table. The Brazilian Cerrado runs the risk of suffering the same problems as California, where the overexploitation of water resources has led to serious economic, ecological, and social problems for the population and has threatened the state's agriculture.

Low-order streams, riparian wetlands, and uplands are ecologically closely connected. Riparian forests are as species-rich as the upland forests in Amazonia, and richer than the upland communities in the Cerrado. They are major contributors to beta-diversity, as shown in many local examples from the Cerrado and for Brazil in general (Wittmann et al., 2017). The abundance and diversity of herbaceous plants depend strongly on light availability, which is reduced in both the forest and in black-water streams. The mineral content of the water is of relatively little importance for the aquatic vegetation, as a species-rich herbaceous flora can develop even in-streams in which the specific conductivity of the water is < 10 µS cm^{-1}. It affects, however, primary production, which is very high in species growing in nutrient-rich white-water.

The diversity of invertebrates is large but few data on their different groups are available. Species requiring calcium, such as mollusks and shrimps of the Family Palemonidae, are absent in calcium-deficient streams. Most of the invertebrate species are very small, and many have a short reproductive cycle (a few weeks), most likely a response to the high predation pressure and because these traits favor colonization of the ephemeral waterbodies that develop in the riparian zone after strong rainfall events. In-stream food webs are strongly linked to organic matter provided by the riparian forest.

The alpha-diversity of fish species in low-order streams is between 10 and 50 species, but beta-diversity is high. Many species depend on an intact riparian zone. Soares et al. (2020) estimated that half of the richness of Amazonian fish fauna occurs in large rivers and their floodplains, and the other half in low-order rivers and streams. This observation points to the need for a network of protected watersheds to maintain fish species diversity (Mendonça et al., 2005).

The unpredictable flash floods and droughts common to the semi-arid Caatinga are heavy stressors for the flora and fauna in-streams and riparian wetlands, but they have favored evolutionary processes allowing adaptations to this environment (Matias et al., 2021). The few riparian wetlands in the Caatinga require strict protection because they are of fundamental importance for the maintenance of biodiversity.

The biodiversity of riparian zones goes far beyond the aquatic and semiaquatic life forms discussed in this article. Brazilian riparia serve as habitats for terrestrial species that require shade and buffered temperature regimes (e.g., ombrophilous bird, monkey, or deer species), neither of which is available in the almost completely deforested agricultural areas surrounding these habitats. Moreover, riparian zones provide migration and dispersal corridors for rare and endangered species that have large territories, such as wildcats (jaguar, puma, ocelot) and canids (e.g., mane wolf, bush dog). Due to their dendritic shape, riparian zones also connect habitats and conservation areas across biomes and political territories (Wantzen & Junk, 2000).

Brazilian riparian wetlands are protected by the law that covers Areas of Permanent Protection (APP). Its aim is "to protect water resources, the landscape, geologic stability, and biodiversity, facilitating genetic fluxes of flora and fauna, protecting the soil, and securing the well-being of populations." The 1965 law (N° 4.771/1965) that was part of the old Forest Code defined protected areas starting from the highest water level of the stream, thus comprehensively protecting riparian wetlands. However, the new Forest Code, formulated in 2012 (N° 12. 651/2012), defines the protected area starting from the stream bed, and thus the area occupied at the low-water level. This definition drastically shrinks the area of riparian zone protection (Campagnolo et al., 2017) and does not consider the impact of very large changes in-stream discharge in semi-arid regions (Andrade, 2015).

A quantification of riparian wetlands along low-order streams and other small wetlands is essential for the development and implementation of management and protection measures. Of the 79,250 basins of 4th- to 5th-order rivers, quantitative information on riparian and associated small wetlands is available for only three. The risk of losing these areas is certainly high, given the rapid expansion of agriculture, cattle ranching, selective logging, mining activities, and infrastructure building. Global climate change necessitates the protection of these areas for Brazil, because they maintain water in the landscape and hinder surface runoff and its related side effects, such as erosion and sediment transport. Furthermore, riparian and small wetlands store considerable amounts of carbon in their soils and living biomass, a capability that must be taken into account in calculations related to the greenhouse effect.

The enormous deficit of information should be addressed by implementing a national inventory, together with a temporal analysis of wetland degradation, including the responsible factors and actors, as such measures will enable targeted conservation programs (Wantzen et al., 2012). This can be done along major highways, that cross different landscapes and climatic zones. In addition, local studies can be embedded, to provide the detailed picture needed to elaborate a national restoration and conservation program for the Brazilian riparia.

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Declarations

Conflict of interest We declare that there are no potential conflicts of interest.

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