FIG. 17.1 Piraputangas (*Brycon hilarii*; endemic to the basin) in Bodoquena Plateau Hills, Miranda Basin. *(Photos: José Sabino.)*

Chapter 17

Paraguay

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"No Pantanal ninguém pode passar régua.
Sobremuito quando chove.
A régua é existidura de limite.
E o Pantanal não tem limites."

Manoel de Barros (excerpt of the poem "mundo renovado," from the "Livro de Pré-Coisas")

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17.1 Introduction

The Paraguay River acts as a north-south axis in Central South America, and, connecting to the Paraná and La Plata rivers, it forms a ca. 3400-km long lifeline between the inner tropics in the north (the sources of the Paraguay River are at 14°S, in Brazil) and the temperate zone (34°S) in the south in Argentina and Uruguay. This makes it an important biogeographical corridor for aquatic, water-bound, and migratory biota (including nonnative species). The headwater area of the Paraguay River is very close to the geodetical center of South America in Brazil, i.e., the point with the greatest distance to the sea, and to some tributaries to the middle section of the Amazon River. Despite intertwined headwaters along the basin divide between Amazonia and Plata, most of the fauna is very distinct between both catchments. In the west, the Paraguay basin is bordered at some distance by the piedmonts of the Andean Mountains, from where tributaries flow across large plains (Chapter 18). The northern and eastern tributaries derive from the arenitic and—locally—calcareous high plains of the Brazilian Shield. This geophysical setting spans several gradients (land-sea, north-south, mountain-plain), which supports the high biological and cultural diversity in South America (Figs. 17.1 and 17.2).

The Paraguay River does not only connect biomes but also people. Many native ethnic groups colonized the river and its floodplains. Later, the river corridor served the Spanish and Portuguese as exploitation and transport routes in the central part of South America. The Paraguay River played an important role in the War of the Triple Alliance (see below). Much of the original native culture has been lost, but traditional uses of the river and cultural practices have evolved from a mixture of native, African, and European origins. These include rituals to cherish the river and a lifestyle in the rhythm of the waters that has been conserved until recent times due to the remoteness of the area and the harsh wet-and-dry regime of the floodplains (see Wantzen et al., 2023c, for a review).

The Paraguay River forms one of the largest continuous continental flood plains, extending through Brazil, Bolivia, and Paraguay, the Pantanal (~166,000 km^2), which is of extraordinary importance for biodiversity because it hosts large populations of species that have become rare in other parts of South America, such as hyacinth macaw, jabiru stork, and jaguar (Alho and Sabino, 2011; Junk et al., 2006, 2011) and an impressive flora (Damasceno-Junior and Pott, 2022). As discussed below, recent wildfires have threatened these species and their use of riparian forests as dispersal corridors (de Barros et al., 2022; Leal Filho et al., 2021).

Since the end of the 20th century, several development trends have disturbed the sustainable coexistence between humans and the river (Girard, 2012; Junk et al., 2011; Tomas et al., 2019). Most plain areas of the Paraguay basin with soils adequate for agriculture have been converted into an agroscape with high-intensity mono-cropping and cattle production. In the northern region, the hilly parts of the headwaters are being dammed for hydropower generation (Ely et al., 2020; Medinas de Campos et al., 2020), and the river is more and more transformed into a navigable channel to transport the crops produced in Brazil to the Atlantic harbors in the south via the "Hidrovía Paraguay-Paraná" project. This project aims to make the entire Paraguay River navigable for larger ships up to the city of Cáceres, and despite that hydrological models predict that navigation would not be possible during long periods of each year, it becomes further supported, resulting in enormous damage for nature and local societies (Hamilton, 2002a; Tortato et al., 2022; Wantzen et al., 2023a). Traditional groups in the Pantanal and along the banks of the Paraguay River have developed sustainable use forms and cultures, but these are currently overrun by a fast development toward short-term economic return without consideration for the carrying capacity of the socio-ecosystems. Additionally, climate change effects and insufficient protection of rivers and floodplains along with their biota currently put the ecological integrity of the Paraguay River at high risk (Lázaro et al., 2020; Thielen et al., 2020; Tomas et al., 2019).

17.2 Physiography, geology and relief

The Paraguay River, together with the Paraná and Uruguay rivers, make up the main tributaries to the Río de la Plata. The La Plata River basin with an area of ~3.1 million km^2 is the second-largest hydrographic watershed in South America and the fourth-largest in the world. The Paraguay River basin has an area of 1.3 million km^2, with 32% in Paraguayan territory, 31% in Brazil, 19% in Bolivia, and 18% in Argentina. The river marks the borders between Brazil-Bolivia, Brazil-Paraguay, and Paraguay-Argentina.

On a length of approximately 2630 km, the Paraguay River covers an altitude gradient from headwaters at ~430 m a.s.l. in the Serra dos Parecis (Mato Grosso State, Brazil) to its confluence with the Paraná River in Argentina, at 47 m a.s.l. (Fig. 17.3). In its first 250 km, the Paraguay River has a slope of about 84 cm/km, changing to 8 cm/km in the next 870 km, and from then on, it has a slope of approximately 2 cm/km down to its mouth. At its first 1190 km, the Paraguay River runs in Brazil, including a short section (~50 km) forming the border between Brazil and Bolivia, and, farther downstream, some 380 km along the Brazil-Paraguay border. Farther below, it crosses the entire State of Paraguay for about 600 km, reaching its capital, Asunción. It then flows along the Paraguay-Argentina border for about 460 km before reaching its confluence with the Paraná River in Paso de la Patria (Argentina).

FIG. 17.2 Paraguay River basin (1.3 million km^2). Land cover: Forests, 53%; pastures, 19%; open seasonally flooded savanna and wetlands, 11%; arbustive savanna, 11%; cropland, 5%; other, 1%. Population density, 4 ind/km^2. Largest city, Cuiabá/Várzea Grande (906,000). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

The Upper Paraguay stretches from the city of Diamantino, Mato Grosso State in Brazil to the confluence of the Apa River (Barros et al., 2004; Krepper et al., 2006), about 1600 km. The Middle Paraguay stretches from this point to close to Asunción (Barros et al., 2004), about 600 km. The Lower Paraguay River spans about a 400 km-long section from Asunción, Paraguay to the confluence with the Paraná River, near the locality of Isla del Cerrito (Barros et al., 2004; Blettler et al., 2012). It receives the sediment-loaded waters of two major Andean tributaries, the Pilcomayo and Bermejo (Drago et al., 2008a,b). Due to the hydrological effects of the Pantanal, the hydrographs of Paraguay and the Paraná rivers differ by 4–5 months (Drago et al., 2008a).

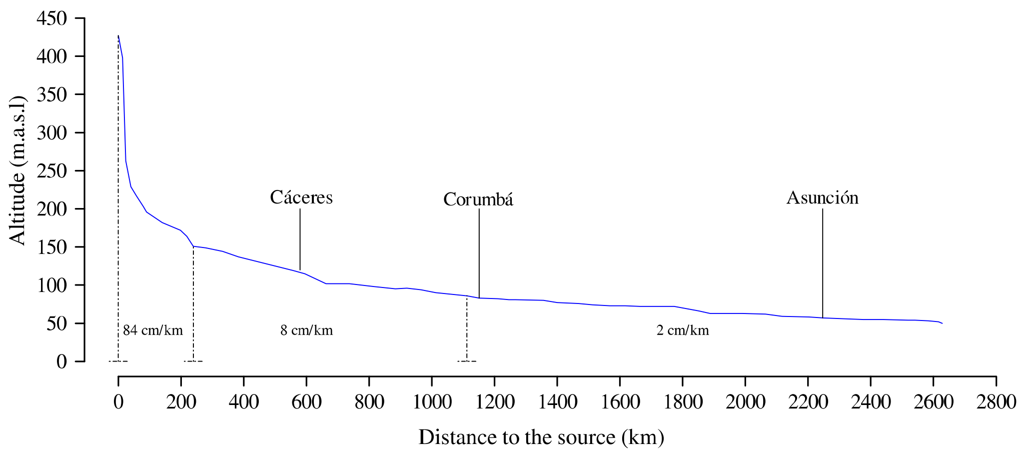

FIG. 17.3 Longitudinal elevation profile of the Paraguay River from its headwater to its confluence with the Paraná River (Argentina).

The Brazilian tributaries in the headwaters and left banks of the Paraguay River have a low altimetric variation and, originally, had a low erosive capability. Mining, deforestation, and agricultural activities have substantially increased erosion, and the bedload is deposited downstream in the Pantanal. The Taquari River is an extreme case of river braiding and avulsions, partly through faults and crevasses in natural levees, and a high propensity to erosion amplified by land use in the headwaters region (Assine et al., 2015; Bergier and Assine, 2022; Louzada et al., 2023).

The fluvial systems of the Paraguay River Basin have been shaped by tectonic phases such as the break-up of the Gondwanaland in the Jurassic-Cretaceous (~180 My ago) and later, by the Andean uplift (Ribeiro et al., 2018). The formation of the Andean chain caused important hydrological changes, particularly, the Cenozoic deformations of the headwaters in post-Cretaceous paleo-plateaus. The Paraguay flows over a basement composed of Paleoproterozoic cratons, such as the Amazonian and Rio Apa Cratons, Neoproterozoic covers and folds belts, and Phanerozoic and Mesozoic covers (Warren et al., 2014). In the Pantanal, a large depression in the upper section of the Paraguay River (see below), subsidence, intense fluvial dissection, and sedimentation began in the Eocene, synchronously with the epeirogenic uplift of the Phanerozoic/Mesozoic cover. Later in the Quaternary, a tectonic reactivation caused relief downcutting, basin subsidence, and sedimentation (Assine et al., 2015; Bergier, 2013). All these diverse geological formations, including rocks ranging from the Precambrian to the Quaternary, influence the compartmentalization, sediment morphology, and water chemistry of the present-day river system (Brea and Zucol, 2011).

17.3 Climate and seasonal variations

According to the Köppen-Geiger climatic classification, the Paraguay River basin falls within two categories: (1) Tropical savanna (*Aw*) mainly in the Upper Paraguay Basin, including all Brazilian tributaries, the lower basin in Bolivia and Paraguay down to the mouth of the Apa River. (2) Humid subtropical (*Cfa*) without a distinct dry season and with hot summer; this includes the Southeast of Paraguay (with a predominance of wet Chaco) and northeastern parts of the Argentinian portion of the basin with the lower Pilcomayo and Bermejo rivers (see Chapter 18), including the confluence with the Paraná River.

The annual mean precipitation in the Paraguay River basin follows altitudinal and latitudinal gradients, with rainfall maxima of ~2000 mm/year in the north-western boundary and >1600 mm/year along the eastern basin boundary (Figs. 17.4 and 17.5). From these boundaries, precipitation decreases toward ~400 mm in the center of the basin (Pantanal, Paraguay State) and ~200 mm in the high Andes (Bolivia). Rainfall in the basin can be divided into two regimes: In the north (upstream of the confluence of the Miranda River, 20°S), rainfall is concentrated mainly in the southern spring and summer (~74% of rain falling between November and April) in response to South Atlantic Convergence Zone that allows the arrival of humidity from Amazonia, while the middle and lower basin areas' rainfall seasonality is less pronounced (Caffera and Berbery, 2006). Climate change is currently disturbing seasonal patterns (Thielen et al., 2020).

The temperature follows the elevation and latitudinal gradients (Fig. 17.4) with the lowest average temperatures in the Andes and the highest in the northern part of the river basin (Vicente-Serrano et al., 2016). During the southern winter (mostly in June), cold air masses from the Antarctic can move northwards, resulting in air temperatures dropping from more than 30 to less than 10 degrees in a few hours and this decrease can last for a few days. Despite that these so-called friagens are buffered by the high thermal resistance of the water, they may represent a landscape-level filter effect for the aquatic biota.

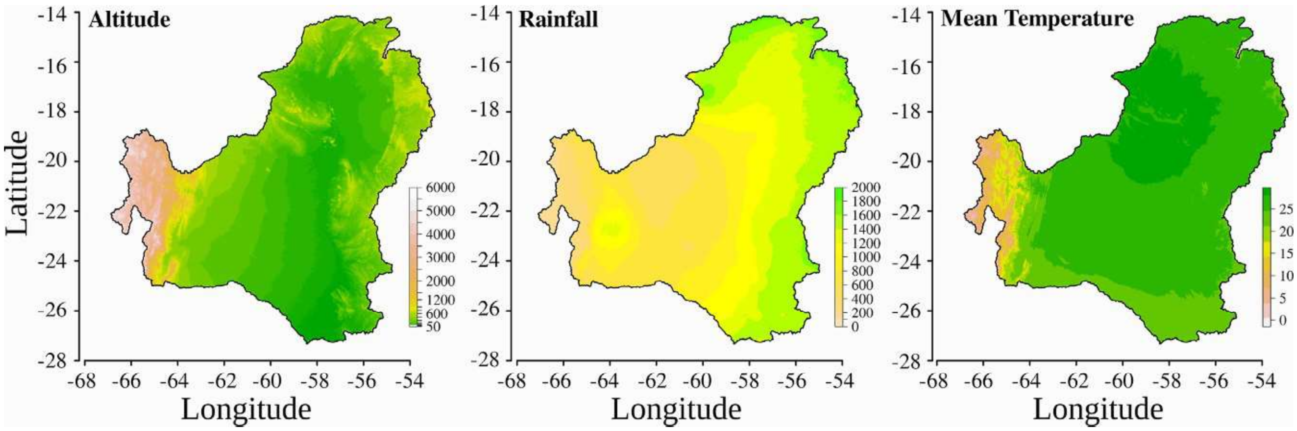

FIG. 17.4 Spatial variation in elevation (*left*), rainfall (*middle*), and mean annual temperature (*right*) in the Paraguay River basin. Data obtained from WorldClim from 1961 to 2019. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

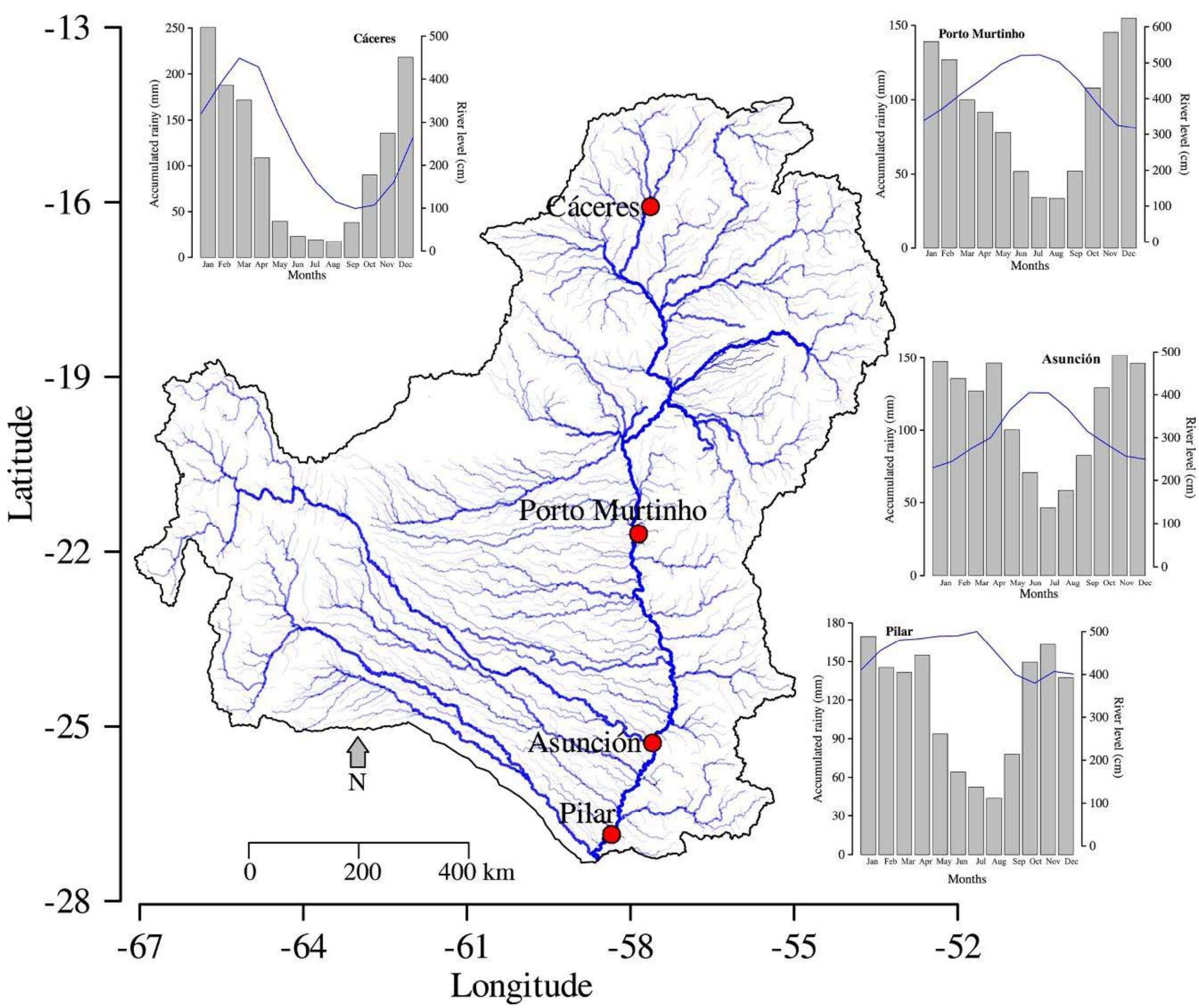

FIG. 17.5 Seasonality in long-term river level *(blue line)* and rain *(bars)* in different sections of Paraguay River basin. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

17.4 Biogeography, natural aspects and biotic regions

Due to its north-south extension, the Paraguay River connects the intertropical zone in its headwaters (14°S) to the tropical-temperate border at its confluence with the Paraná (27°S). Climatic gradients along the Paraguay River basin (Figs. 17.4 and 17.6) set up conditions for different life zones, biodiversity, and land use forms (Bergier, 2013; Fig. 17.7). The Paraguay River basin represents a freshwater ecoregion on its own (number 343, according to Abell et al., 2008). It acts as an interface between different ecoregions including Cerrado (Woody Savanna in Brazil), Amazonian savannas, the Pantanal, wet and dry Chaco, and the Andes (Fig. 17.6).

In the north-eastern part of the basin, an open tree Savanna (Cerrado) develops on sandy soils. This forest type is shared among Paraguay, Bolivia (e.g., Sierra de Chiquitos), and Brazil. Small stream systems with adjacent riparian wetlands (Junk et al., 2022; Wantzen et al., 2011b), including peat-stocking "veredas" develop here. Cerrado vegetation is fire-adapted and can be subdivided into different types according to soil type and water availability (Eiten, 1982). Some floristic elements of the Cerrado, e.g., *Curatella americana* or *Vochysia divergens*, can survive the temporal water-logging in the floodplains. Most Cerrado tree species, however, are restricted to unflooded elevations, such as paleo-levées and foothills of the sierras.

The Pantanal is considered a biome by the Brazilian Law, but it has a low degree of endemic plants due to its harsh conditions and the relatively young geological age of the current environmental features. The structures of 56 macrohabitats are determined by flood regimes and vegetation types (Nunes da Cunha et al., 2022). In the north-western part of the basin, the florae of Amazonia and the Cerrado form an ecotone (da Silva et al., 2015).

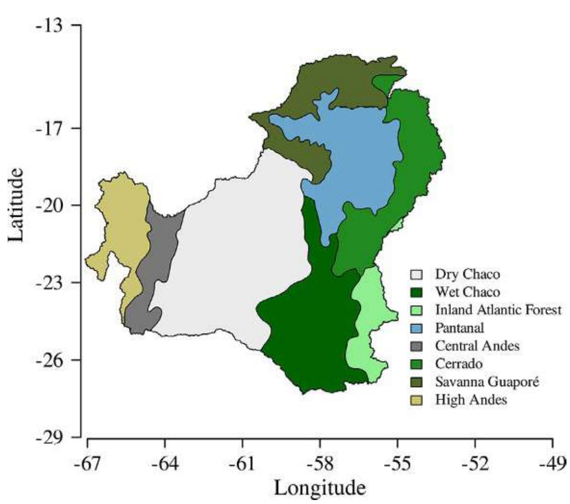

FIG. 17.6 Simplified ecoregions of Paraguay River basin based on Griffith et al. (1998). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

The Chaco ecoregion in Argentina and Paraguay borders the southern section of the Paraguay River downstream of the Pantanal (below 23°S). The subhumid and semideciduous forests of the Chaco occur alternating with hydromorphic savannas (Fig. 17.8 and Chapter 18). Farther to the west there are semiarid forests, with the predominance of *Schinopsis lorentzii*, *Aspidosperma quebracho-blanco*, *Ceiba insignis*, *Gonopterodendron sarmientoi*, *Salta triflora*, and *Cynophalla retusa*. These forests develop on clay soils of the Glysol and Luvisol types, which harden during the dry season and are water-logged in the wet season.

17.5 Human history and culture

17.5.1 People

At diverse archeological sites in the headwaters of the Paraguay River, there is evidence of different cultures originating from the Amazon, Chaco, and the Andes by 12,000–20,000 years BP. In the Pleistocene-Holocene transitional period, ecological transformations of the region facilitated human settlement (Bespalez, 2015). The Brazilian portion of the basin was apparently colonized from lowlands of large river valleys by rapid migrations over long distances, which may explain the almost simultaneous occurrence of sites with similar remains (Dias and Bueno, 2013). The Bolivian llanos (mainly in the Madeira River basin) are considered to have favored human dispersal in southern South America by connecting the East Andes with the Atlantic Coast and the Amazon River basin (Anderson and Gillam, 2000).

Evidence of episodical occupation in the Pantanal dates back to around 8100–8300 years before the present. In Ladário (Brazil), signs of continuous occupation occur much later (~3000 years ago) with a ceramic technique characteristic of the Pantanal (Oliveira, 2003). The main indigenous groups inhabiting the lower portion of the Paraguay basin were Guaicurus and Xaray, the latter exploiting the floodplains. The tribe's name is associated with the mythic name of the Pantanal floodplain ("Sea of Xararés").

Encounters between Native Americans and Europeans (Portuguese and Spanish explorers) occurred around CE 1540. European occupation included the establishment of Jesuit colonies in what is currently Paraguay and Bolivia. Portuguese descendants called "Bandeirantes" pioneered the territorial expansion of Europeans in Brazil, exploring new routes (often along rivers) for gold and silver prospecting. Bandeirantes usually established partnerships with some ethnic groups, taking advantage of rivalries between them to capture slaves.

In the first two centuries of European colonization, many indigenous cultures disappeared in the Paraguay basin and all over South America from diseases (mainly smallpox and influenza) and from their traditional lands being occupied by colonizers. The Guató, originally

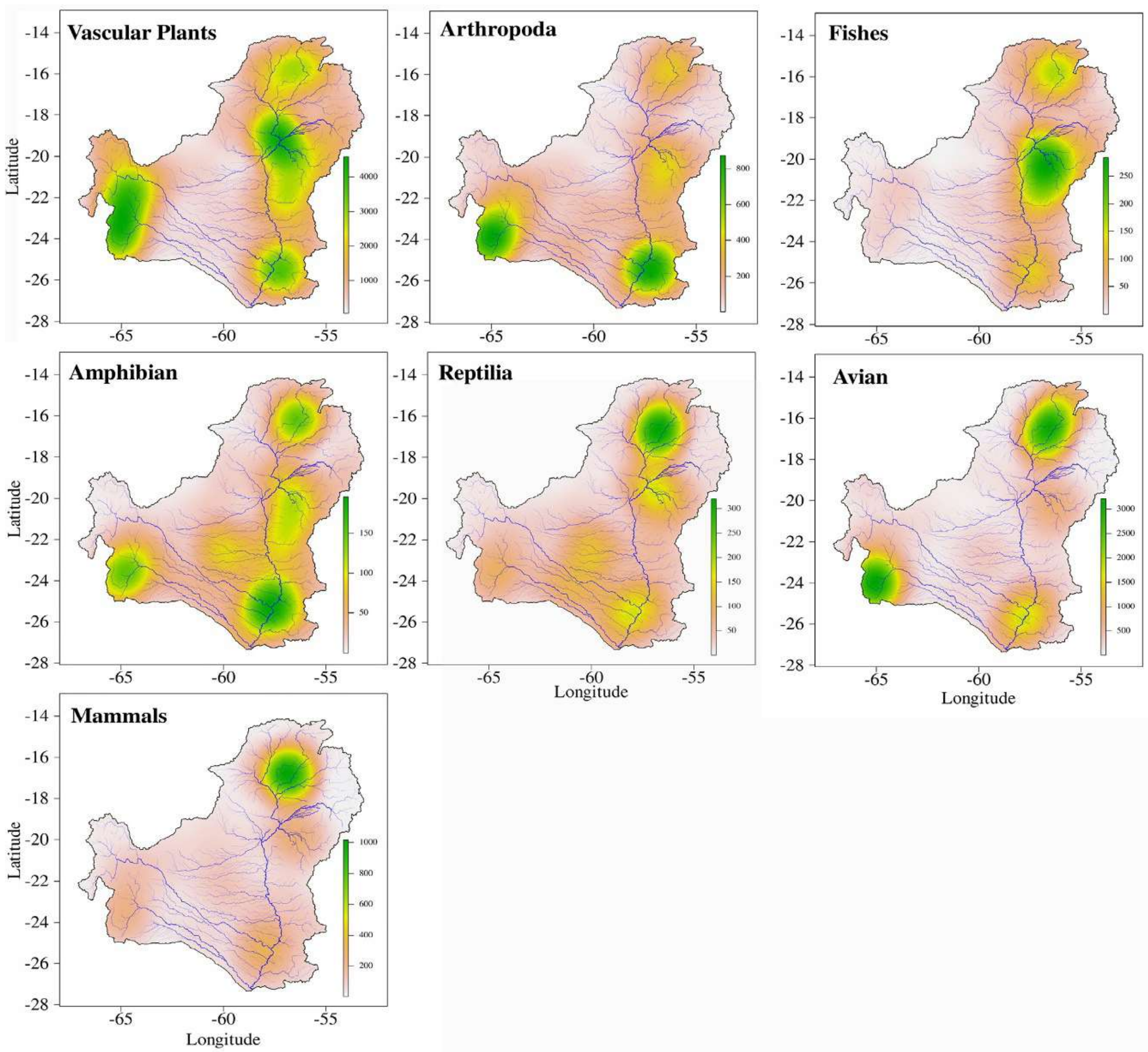

FIG. 17.7 Distribution of sampling effort (number of samples without repetition) for some biological groups at Paraguay River basin, based on available data on Global Biodiversity Information Facilities (GBIF). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

occupying the south-western Pantanal, are today reduced to less than 1000 people. Their original language (like that of other native people, such as Kinikinau, Chiquitano, Kadiwéu, Bororo, and Terena) is endangered (Grubits and Darrault-Harris, 2003). Along with these people and their cultures, traditional ecological knowledge, e.g., on the use of pharmaceutical plants or the life cycle of fish species, is being lost. "New traditional" cultural groups from European settlers, Native Americans, and African people that escaped or were freed from slavery developed local communities and flood-adapted cultures in the past two centuries, but these are today again threatened by modern, large-scale industrial and agribusiness projects (Wantzen et al., 2023b).

Despite the Treaty of Madrid (1750), which considered the Paraguay basin as Portuguese territory (except the high Andes), there were persistent disputes between Portugal and Spain, as evidenced by fortifications in this region. The War of the Triple Alliance (Brazil, Argentina, and Uruguay) against Paraguay (1864/65–70), the bloodiest conflict in Latin American history, caused ~440,000 casualties and left many settlements along the Paraguay River devastated.

In the Gran Chaco, one indigenous nation, the Payaguá (who called themselves Evueví, "people of the river," and who possibly contributed to the name of the Paraguay River) fought with rival tribes and European colonists. In contrast, the Guaraní people, who had occupied the

FIG. 17.8 Tuiuiu (*Jabiru mycteria*) and a flock of wood storks (*Mycteria americana*) in a lake of the Wet Chaco. The forest in the background is a carandazal (almost monospecific stand of *Copernicia alba*). *(Photo: Paulo R. Souza.)*

Paraguay region about 1500 years ago, had cordial relationships with Spaniards and served as guides for expeditions through the Río de la Plata basin. Today, less than 2% of the population is completely indigenous in Paraguay, however, nearly 75% identifies as at least partially indigenous. Guaraní and Spanish are the official languages in Paraguay, which currently has 17 ethnic groups, who speak 5 different languages.

Despite their variable ethnic origins, the diverse regions of the Paraguay basin currently are undergoing a similar trend of cultural homogenization and increasing commercialization of natural assets, which used to represent high ethical values for the native and traditional communities. The functional role of the Paraguay River as a cultural axis and as a site of cultural innovation (Wantzen et al., 2023b) is being suppressed by more "modern" uses of the river for hydropower generation in the headwaters (which reduces the rhythm of the waters (Wantzen, 2022)) and by the incompatibility of the traditional uses (small-scale navigation, fishing) with commercial shipping (the hidrovia Project; Wantzen et al., 2023a) and fishing tourism. The social groups that are impaired by these developments remain unheard or they even become actively suppressed, as evidenced by the current (2023) debate about a 5-year interruption of the fisheries (which would drive all traditional fishermen into poverty).

The current human population of the Paraguay Basin is roughly estimated to be 11 million people, most of whom live in cities, including (in an upstream-downstream sequence) Cáceres (95,000); Cuiabá/Várzea Grande (906,000); Corumbá/Ladário (137,000) (as of 2021, https://cidades.ibge.gov.br/); Concepción (89,000); Asunción (521,000); and Formosa (264,000). Outside these cities, the population density is very low, with about 4 people/km^2.

17.5.2 Land use

Nearly 41% of the Paraguay River basin is still forested, 26% is savanna (Cerrado and Chaco), 18% is used for agriculture, ~5% is in the Higher and Central Andes (see Chapter 18), and 10% are wetlands. Probably, the percentage of wetlands is higher, as the riparian wetlands of streams (which are not wide but extensive due to the dense net of streams) are not counted (Venticinque et al., 2016; Wantzen et al., 2006). Most areas of the Cerrado and Southern Amazonian vegetation in the plateaus of the Upper Paraguay Basin have been deforested or fragmented to produce cash and energy crops (such as soybean, corn, and sugarcane production), except for a few Indigenous Reserves and other conservation units (Roque et al., 2016; Siqueira et al., 2018).

Apart from the ironwork at Corumbá, the cities along the Paraguay River are more oriented toward administration and commerce. Production of cash and energy crops in the fertile high plains of the basin supports an intensive agribusiness. The fast-growing cities have an increased energy demand, which translates into a steady demand for the growth of hydropower dams, water supply, and transport infrastructure.

The main economic activity in the vast floodplains, where soils and the flood regime are inadequate for crop production, is cattle ranching. The expansion of cattle

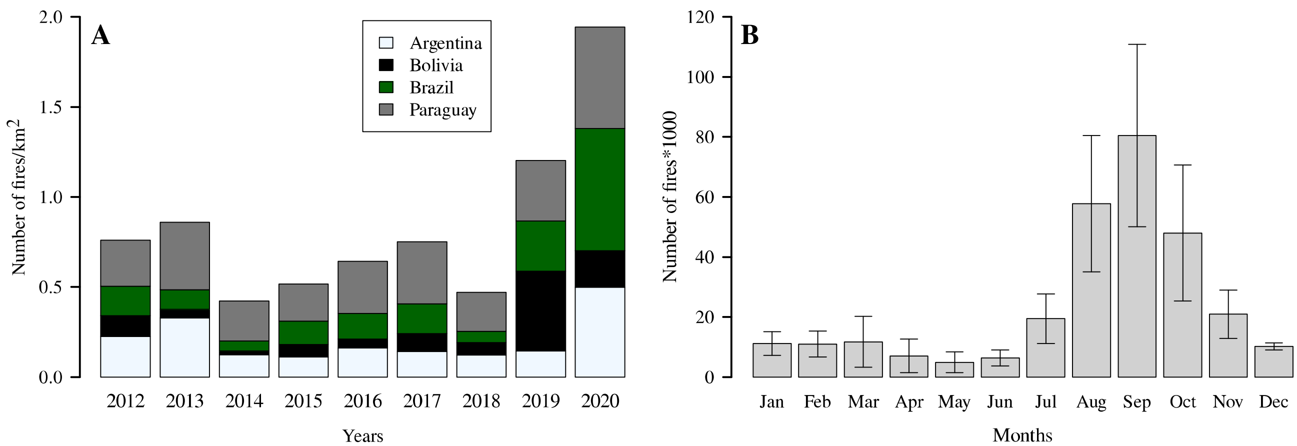

FIG. 17.9 Number of fires/km^2 by country (A) and monthly variation in the Paraguay River basin (95% confidence interval) from 2012 to 2020 (B) (from MODIS satellite).

ranches driven by increasing global demand for beef and dairy products is causing some of the world's fastest rates of deforestation, resulting in losses of nearly 2500 km^2 of forest cover annually between 2001 and 2014 (35,000 km^2 in total) in the highly diverse Chaco region of western Paraguay. These figures far exceed earlier land use changes for the plantation of mate tea plants (*Ilex paraguariensis*) in the 19th century and tannin-delivering plants (red and white quebracho (*Schinopsis balansae*, *A. quebracho-blanco*)) in the 20th century.

The production of cash crops in the plateaus and of cattle, poultry, and aquaculture (exotic fish and freshwater shrimp) in the piedmont and lowland areas satisfies the needs of a growing regional and global human population, but it reduces the native vegetation cover to small percentages (Siqueira et al., 2018; Roque et al., 2021). Moreover, it causes massive erosion in the high plains and excessive deposition of sediments just below the piedmont zone (Assine et al., 2015; Wantzen and Mol, 2013). The Pantanal wetland has not been the focus of intensive agriculture so far, but increasing demands, a recent phase of reduced floods, and inadequate conservation policies support a tendency to transform the classical, extensive cattle ranching (which is also a cultural brandmark of the Pantanal (Araujo et al., 2018; Santos et al., 2011; Wantzen et al., 2023b)) into intensive production systems with higher economic returns, to the detriment of its bio-cultural integrity.

Legal and illegal land clearing, combined with recent climate change effects, led to an increase in the number of fires in the entire Paraguay River basin. Neotropical savannas are fire-adapted ecosystems, and natural bushfires previously occurred regularly during the dry season (Coutinho, 1990). However, in the past decade, fires have occurred more frequently, out of season, and with a much higher intensity and extension than previously known, representing an important problem (Pivello et al., 2021). Fire densities have increased from ~0.63 fires/km^2 in the 2012–2018 period to ~1.94 fires/km^2 in 2019 (Fig. 17.9A). Most of these fires are human made, aiming mainly at pasture renovation and increased cattle production during the dry season (Fig. 17.9B), but increasingly, large fires are observed when the floodplain is expected to be wet during the rainy season. The wildfires in 2020 are estimated to have killed at least 17 million vertebrates in the Pantanal (Tomas et al., 2021; de Barros et al., 2022; dos Santos Ferreira et al., 2023; Leal Filho et al., 2021).

17.6 The rivers

17.6.1 Paraguay mainstem

17.6.1.1 Physiography, geomorphology and land use

Concerning declivity, the Upper Paraguay River can be divided into two sections (Fig. 17.3), a high-gradient zone (84 cm/km) upstream from Cáceres, and a low-gradient zone (8 cm/km) flowing across the Pantanal, receiving waters of diverse tributaries (see rivers Cuiabá, Miranda, and Apa below). The gradient of the middle and lower sections of the river in Paraguay and Argentina is even lower (2 cm/km). These sections are bordered by fringing floodplains in a semiarid region (Drago et al., 2008b).

Some hills and mountain ranges arise from the Pantanal floodplain, e.g., the Serra do Amolar at the Brazilian-Bolivian border, extending for ~80 km, with a maximum elevation of 960 m a.s.l. This highland location is one of the most isolated areas in the Pantanal and home to the indigenous Guató people. The area is also an important biological reserve protected by several conservation units, including the Pantanal Matogrossense National Park, in Brazil (Fig. 17.2). Another prominent elevation is the Maciço do Urucum mountain near Corumbá, Brazil, with a maximum elevation of ~1065 m a.s.l. The area has important iron and manganese deposits, which have been explored since 1930.

Different factors determine the physical habitats of the Paraguay River. The headwaters of the Paraguay and its largest tributary, the Cuiabá River are separated from low-gradient sections in the vast plains by steep hillslopes with rapids and waterfalls. This gradient (Figs. 17.3 and 17.4) corresponds to a change in average sediment size from a gravel-rich section and a long, sandy (and dynamic) section, which is interrupted by rocky outcrops that occur regularly along its course. The contribution of the recently eroded substrate is locally restricted; therefore, the river mostly reworks old sediment deposits. Steep clay banks on the outer sides of the meanders are quite solid, bank slumping occurs mostly after storm events or (more recently) due to navigation and dredging. The sandy bed sediments are highly dynamic, and sand bars and underwater dunes are permanently shifting. At the piedmonts of the surrounding elevations, deposition of sediments (recently increased by man-made erosion) gives rise to huge avulsive megafans and dynamic, braided alluvial plainforms (e.g., Bergier and Assine, 2022; Pupim et al., 2017; Stevaux et al., 2020). Floodplain lakes and secondary channels are also dynamic, and their flow speed and direction depend on local water-level differences, which may substantially change the life conditions for the aquatic biota (Wantzen et al., 2005, 2011a).

Floating aquatic macrophytes (mainly composed of *Pontederia azurea*) have a strong influence on the connectivity of floodplain water bodies and have even resulted in a shift of the main channel to a former anabranch upstream at Taiamã Island (Fig. 17.12). Wantzen et al. (2005) identified five functional sectors in the upper section based on the Fluvial Hydrosystem Concept (Petts and Amoros, 1996): (i) a headwater sector from the basin divide to the mouth of the Sepotuba River 3 km upstream of the city of Cáceres; (ii) a meandering floodplain sector (sinuosity $S = 2.2$), reaching from the Sepotuba River outlet to the mouth of the Jaurú River, about 70 km below Cáceres, with irregular meanders (length 500–1500 m, width 800–2000 m); (iii) a straight sector from the mouth of the Jaurú River to the Morro Pelado hills (sinuosity $S = 1.1$), with a well-developed floodplain on the right bank. Most alluvial lakes are located on long reaches of the former main channel, 2–4 km west from the present mainstem, while large sections of the left margin are steep, including the bedrock outcrops at Simão Nunes, Barranco Vermelho, and Descalvados; (iv) a transition sector from Morro Pelado to the upriver edge of Taiamã island, where the main channel shows irregular meanders and a slightly higher sinuosity ($S = 1.4$); and (v) a fluvio-lacustrine sector, beginning at the apex of the Taiamã island, with alternating reaches of irregular and tortuous meanders, strongly increased main channel sinuosity ($S = 2.1$) and a complex pattern of lentic water bodies, which is hardly penetrable by boat due to the shifting pattern of floating islands.

In the Pantanal floodplain, the annual floods generate a complex system of physical habitats interacting with diverse vegetation types (Nunes da Cunha and Junk, 2011; Nunes da Cunha et al., 2022). The Middle Paraguay River Basin is characterized by a floodplain between 5 and 10 km wide, which is larger on its right margin and corresponds mainly to the Occidental Region or Paraguayan Chaco (Takahashi, 2016).

On average, the main channel of the Lower Paraguay River is 575 m wide and 9 m deep and has a discharge of 4000 m^3/s. The river section is characterized by a meandering channel form and extensive alluvial floodplains, with sinuosities ranging from 1 to 1.6 and a floodplain extension of 1 to 8 km on each side. It has three important tributaries: the Bermejo, Pilcomayo, and Tebicuary Rivers. The first two have their headwater in Bolivia above 5000 m a.s.l. These tributaries carry substantial amounts of sediments, which have an important influence on the habitat structure and the biota of the Paraguay River (Blettler et al., 2015; Drago et al., 2008a,b; Chapter 18).

17.6.1.2 Hydrology

The nearness of Upper Paraguay to the equator and the shortness of periods with cold air ingressions from the south prevent strong variations in water temperature, which ranges from 21°C to 33°C near Cáceres (Heckman, 2013), but the variability is much higher in shallow floodplain water bodies.

The annual mean discharge (1950–98) of the Paraguay River is approximately 4200 m^3/s, which results from contributions from the Pantanal (30%), the upper and middle Paraguay basins (45%), and the lower Paraguay basin (25%); at Asunción, most of the peak of the major discharge occurs between May and July (Gonçalves et al., 2011). Climate forcing, with major discharge contributions from the upper and middle Paraguay basins, has been found in the autumn period following an El Niño year (Barros et al., 2004; Bravo et al., 2014).

In the low-order streams of the headwater areas of the upper section of the Paraguay River, higher discharges directly follow precipitation peaks, and the flood peak of the mainstem lacks only shortly behind the peak of the rains (Fantin-Cruz et al., 2011; Girard, 2011). The low slope of the Pantanal (~2 cm/km) in a north-south direction and several hydraulic bottlenecks (i.e., Serra do Amolar, Maciço do Urucum, and Fecho dos Morros region in Porto Murtinho city) are natural flow barriers (Ponce, 1995) that divert the flood water into the adjacent wetlands (Stevaux et al., 2020). Therefore, in the middle section of Paraguay, the rains of December in the headwaters take several months to arrive and define the flood levels in its tributaries, many of which inundate their floodplains by back flooding resulting from high water levels in the river mainstem rather than by runoff from local rainfall (Girard, 2011; Hamilton, 2002b). In the lower section of the Paraguay River near the mouth of the Paraná River, the seasonal flow variation is

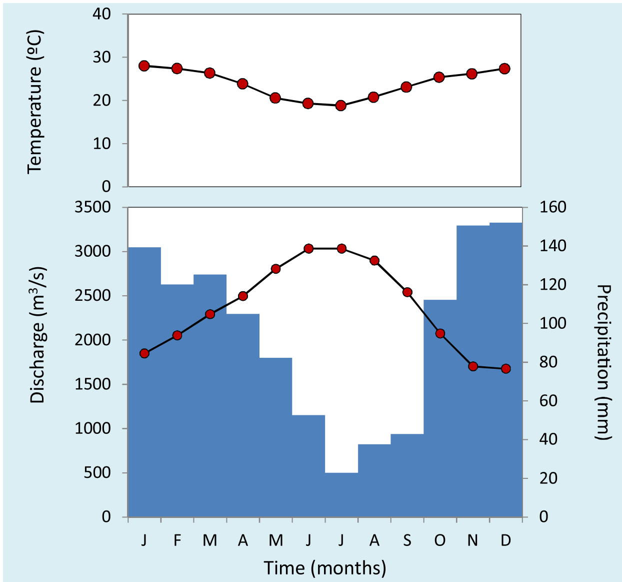

FIG. 17.10 Paraguay River basin. Temperature, precipitation (*bars*), and discharge at Porto Murtinho (21°41′49″S, 57°33′02″W). *(Source: Discharge and rainfall, www.snirh.gov.br/hidroweb/; temperature, https://climateknowledgeportal.worldbank.org/country/paraguay/climate-data-historical.)*

much lower (Barros et al., 2004) (Figs. 17.5 and 17.10). Due to the low declivity, minor differences in elevation and precipitation cause a differentiated pattern of flood levels and flow velocity at the local scale, and even multiple changes of flow direction in floodplain channels during one hydrological cycle, in addition to multiyear patterns of higher and lower average water levels. Despite its enormous size, the water balance deficit of the Pantanal due to evapotranspiration has been estimated to be only 11% (Oliveira et al., 2019).

The long-term annual discharge averages of the Paraguay River show remarkable multiannual periods of higher and lower water levels (Fig. 17.11), with important consequences for the expansion and duration of floods. During the pre-1973 dry phase, large parts of the previously almost pristine Pantanal were occupied by large farms. Some of these projects were pushed back by the subsequent high-flow period. Potential causes of these periodical changes include climate change, land use change, and the increasing dam construction (Bravo et al., 2014; Ely et al., 2020; Jardim et al., 2020). These multiyear periods have great importance on the habitat structure and carbon storage (Wantzen et al., 2005) as well as on the fire regime and distribution of different plant associations (Nunes da Cunha and Junk, 2004; Damasceno-Junior et al., 2022).

17.6.1.3 *Water chemistry*

The base rocks of the headwaters of the Paraguay River vary between weathered arenitic rocks (releasing hardly any ions, resulting in less-buffered, low-conductivity waters with calcium values below the detection level), local granite formations, and limestone (including some karstic areas with caves). This has tremendous consequences for the aquatic fauna and flora. The water chemistry of the main stem of the Paraguay River results from a mixture of these sources. In the higher stretch of Upper Paraguay from Cáceres to Amolar, turbidity varied from 13 to 32 NTU, pH from 6.1 to 8.3, conductivity from 22 to 441 μS/cm, dissolved oxygen from 1.4 to 8.0 mg/L, suspended solids from 52 to 152 mg/L, dissolved organic carbon from 3.3 to 8.1 mg/L, and chromium (Cr) from 0.04 to 0.97 mg/L (Hylander et al., 2000; Pimenta et al., 2013). In the city of Cáceres, the influence of urban water pollution is

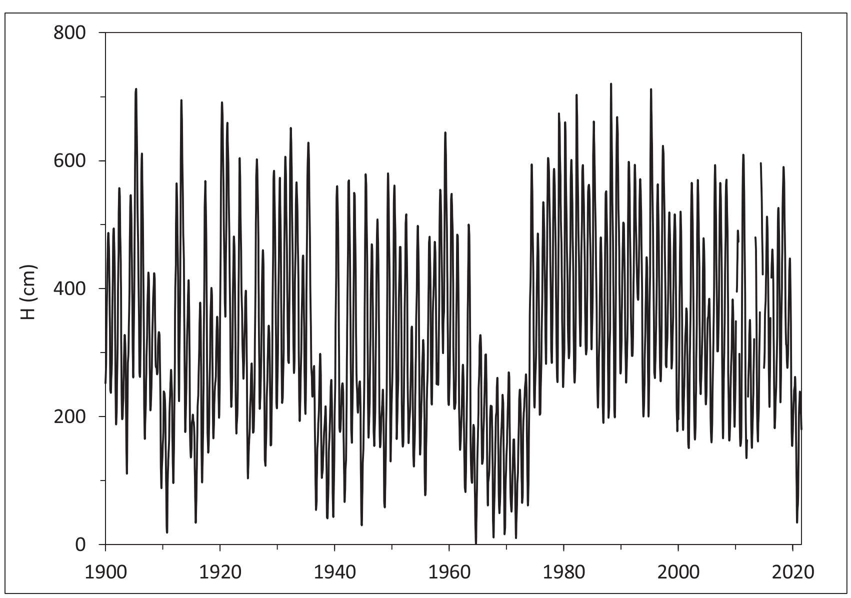

FIG. 17.11 Long-term minima and maxima of water levels of the Paraguay River.

evidenced by low dissolved oxygen, high conductivity, and a 10-fold higher Cr concentration compared with sites a few kilometers downriver (Pimenta et al., 2013). Mass balances for major solutes, nutrients, and particulate matter of the Paraguay mainstem and individual tributaries to the Pantanal have been obtained by Oliveira et al. (2019). They report average concentrations (in μM) for total nitrogen (30.2), dissolved nitrogen (7.1), total phosphorus (1.4), and dissolved phosphorus (0.4) for the Paraguay mainstem (upstream of the Pantanal). Moreover, they conclude from the apparent balance between inputs and outflow for most solutes that either the biogeochemical processes in the floodplain do not have major effects on transport or that losses and gains are in approximate equilibrium at the landscape scale in waters of the Pantanal.

In the shallow floodplain lakes, especially in the Pantanal, dissolved carbon may reach critically high values when the first rains strip organic matter from the terrestrial vegetation and anoxic events occur. Natural fish kills, the so-called dequada result from this (Hamilton et al., 1997; Calheiros et al., 2000). Similarly, feces from caimans or piscivorous birds can accumulate on the dry ground during the dry season and can cause eutrophic states in lakes when washed into the water by the first rains (Nogueira et al., 2011), with characteristic changes in the "isotopic landscape," i.e., the N isotope signature of primary producers and consumers varies along with the connectivity of the bird-influenced lakes with the river mainstem (Wantzen et al., 2011b).

17.6.1.4 Biodiversity

Vegetation

The main habitat types vary along the dynamic gradients of inundation level, sediment deposition, and hydrogeomorphological characteristics, acting as environmental filters to the variable tolerance of the species to inundation, anoxic conditions, drought, fire, nutrients, and soil pH. While the habitats of the mainstem and the active floodplain are clearly shaped by hydrology (Drago et al., 2008b; Wantzen et al., 2005, 2014), the vast floodplain areas with relatively small differences in the relief are locally determined by specific vegetation units, that are often defined by one or few monodominant plant species (Junk et al., 2014; Nunes da Cunha et al., 2022). With few exceptions, the faunal and floral assemblages in the Upper Paraguay and Cuiabá rivers are very similar, especially those of the Northern Pantanal (see also below).

Riparian vegetation and macrophytes

The structure of the riparian zone is alternately dominated by localized floodplain forests (at sites with at least a minimum of soil drainage) and herbaceous, flood-tolerant vegetation. Along the riverbanks and lake shores, floating macrophytes (mostly *Pontederia* (formerly: *Eichhornia*) *azurea* and *Pontederia crassipes*) form a fringing carpet. *Pontederia azurea* (Fig. 17.12) remains rooted in the soil regardless of water levels and shifts from a rooted-floating plant to an emergent plant. In contrast, *P. crassipes* is rooted in the soil when the plants are growing in moderately dry environments and shifts to free-floating plants when the water levels rise during floods in the Pantanal (Leandro et al., 2021). They can also detach and drift downriver. The rhizosphere of these floating islands ("batumes") represents an important habitat for aquatic invertebrates and fish, and, recently, invasive mussels (Marçal and Callil, 2008; Carvalho et al., 2019). The macrophyte flora of the floodplains is especially species-rich, with about 280 species registered within the Pantanal floodplain (Pott and Pott, 2011).

In the book by Damasceno-Junior and Pott (2022) on the vegetation of the Pantanal, Vali Pott and coworkers recently presented a list of 2567 plant species (all habitats and growth forms confounded), of which 2272 are native, 166 naturalized, and 130 cultivated, with 149 families, the most numerous being Fabaceae (344 species), Poaceae (302), Asteraceae (136), and Cyperaceae (117). Out of the total of 937 genera, the species richest are *Paspalum* (53), *Cyperus* (48), *Ipomoea* (32), *Mimosa* (32), *Croton* (28), *Eugenia* (28), *Ludwigia* (26), and *Arachis* (21). Only 244 species reported from the Pantanal wetland are endemic to Brazil.

Macroscopic algae are composed mainly of 16 Charophyceae species (*Chara* spp. and *Nitella* spp.) (Bueno et al., 2018) that occur in floodplain lagoons and mainly in rivers with higher dissolved carbonates (e.g., in the Bodoquena Plateau).

The woody riparian vegetation gradually shifts from north to south. In the lower sections, riparian forests include other species such as *Erythrina crista-galli*, *Phyllanthus chacoensis*, *Enterolobium contortisiliquum*, *Bauhinia bauhinioides*, *Triplaris gardneriana*, *Crateva tapia*, *Terminalia triflora*, or *Croton urucurana*. One of the characteristic formations of the lower section of the Paraguay River is the hydromorphic savannas of *Copernicia alba* palms, which alternate with forests and open savannas.

Between 2008 and 2018, the number of rainfall events decreased, while species richness of aquatic macrophyte communities increased, with increases in grasses and amphibious life forms, showing a trend that favors species that are more adapted to drought conditions (de Morais et al., 2022).

Terrestrial insects of recently flooded meadows, or fruits and flowers falling from inundated trees (e.g., *Erythrina fusca, Albizia niopoides, Acrocomia aculeata, Ficus gardneriana, Inga* sp.*, Spondias lutea, Cecropia* sp.*,* and *Triplaris americana* in the upper sections of the river), are an important food source for fish (Wantzen et al., 2002, 2005).

FIG. 17.12 Iconic animals/plants of the Cuiabá River. (A) Capivara, *Hydrochoerus hydrochaeris*; (B) *Pontederia azurea* with feeding marks of the semiaquatic grasshopper, *Cornops aquaticum*; (C) Tiger heron, *Tigrisoma lineatum*; (D) Curimbatá (*Prochilodus lineatus*).

Phytoplankton

Information on the phytoplankton assemblages of the Paraguay River is restricted to individual recordings. The phytoplankton assemblages of the Castelo lake in the nearby floodplain of the Paraguay River near the city of Corumbá revealed 82 taxa (at species or genus level), distributed in 9 classes with Chlorophyceae (23), Euglenophyceae (22), Nostocophyceae (10), and Zygnemaphyceae (7) being the most diverse (Oliveira and Calheiros, 2000). In terms of abundance, both the flooded area and the river were dominated by Cryptophyceae (*Cryptomonas brasiliensis, Chroomonas* sp.), while during falling water levels Bacillariophyceae (*Aulacoseira distans, Aulacoseira granulata*) and Cyanophyceae (*Merismopedia punctata, Oscillatoria* sp.) were most abundant.

Zooplankton

One hundred and twenty planktonic and benthic cladoceran species were recorded in Mato Grosso (Brito et al., 2020), with a remarkable faunistic overlap between the Paraguay and the Amazon basin, e.g., *Macrothrix elegans* Sars, 1901, *Chydorus eurynotus* (Sars, 1901) and *Karualona muelleri* (Richard, 1897). The cladocerans belonged to 8 families: Bosminidae, Chydoridae, Daphniidae, Ilyocryptidae, Macrothricidae, Moinidae, Holopedidae, and Sididae, with 17 new species records found in Pantanal lakes, such as *Coronatella paulinae* (Sousa, Elmoor-Loureiro & Santos, 2015), *Dunhevedia crassa* (King, 1853), *D. odontoplax* (Sars, 1901), *D. colombiensis* (Stingelin, 1913), *Nicsmirnovius paggii* (Sousa & Elmoor-Loureiro, 2017), and *Pseudochydorus globosus* (Baird, 1850).

Macroinvertebrates

The benthic invertebrate fauna of the Paraguay mainstem shows a distinct pattern shift between the gravellish section upstream of the city of Cáceres and the sandy section below it. The upstream section benefits from streams draining local calcareous outcrops, enabling the development of a diverse mussel fauna in the streambed, along with a rich insect diversity, mostly chironomid larvae (34 species identified so far, Aburaya and Callil (2007)), caddisflies (especially hydropsychids), mayflies (*Leptohyphes, Tricorythodes*, diverse baetids), stoneflies (*Anacroneuria* sp.), and huge *Corydalis* dobson flies.

The dragonfly fauna of the entire Paraguay basin is remarkable, concerning species diversity, variety of forms, and local assemblages. Rodrigues and de Oliveira Roque (2017) registered 198 species of Odonata in the State of Mato Grosso do Sul alone, distributed in 10 families: Calopterygidae (6 spp.), Coenagrionidae (58 spp.), Dicteriadidae (1 sp.), Lestidae (5 spp.), Protoneuridae (10 spp.), Pseudostigmatidae (1 sp.), Aeshnidae (8 spp.), Corduliidae (1 sp.), Gomphidae (13 spp.), and Libellulidae (95 spp.). Huge swarms of *Pantala flavescens* form seasonally.

Downstream Cáceres, Paraguay enters the Pantanal plain. Apart from gravel inputs from the tributaries and local rocky outcrops, the bed sediments are fine and often run in sand dunes, with a remarkably homogeneous fauna of few taxa highly adapted to the mobile substratum. The assemblage of *Narapa bonettoi*, *Myoretronectes paranaensis, Tobrilus* sp., *Parachironomus* sp., and *Lopescladius* sp. occurs along the entire Paraguay-Paraná continuum and is morphologically and taxonomically similar to that of other sandy river sections (Ezcurra de Drago et al., 2004; Marchese et al., 2005; Wantzen et al., 2014).

Large mussel species can be found in floodplain lakes or backwaters downstream of sand bars and islands, mostly Hyriidae (*Castalia, Diplopon*), Etheriidae (*Batlettia, Haasica*), and Mycetopodidae (*Anodontites, Fossula, Mycepoda*) (Pereira et al., 2014; Wantzen et al., 2011a). Between Cáceres and Taiamã, Marchese et al. (2005) identified a total of 69 species or morphospecies, dominated by oligochaetes (22 species) and chironomids (20 morphospecies).

Along the entire Paraguay River, the fauna of the adjacent floodplain water bodies (lakes, oxbows, abandoned anabranches) is significantly different and has a much higher alpha, beta, and gamma diversity (mostly by chironomids and oligochaetes) than the mainstem. Connectivity, variable oxygen saturation, organic matter content, and depth are key drivers for the distribution of benthic invertebrates. The primary floodplain channels that receive inflowing water from the river have the highest density of invertebrates, whereas the organisms on the bottom sediments of the shallow lakes often have to cope with low oxygen concentration, resulting in a depauperate fauna (Marchese et al., 2005; Wantzen et al., 2011a). Sediment-rich tributaries (such as the Bermejo River) lower abundances and modify benthic assemblages (Blettler et al., 2015; Ezcurra de Drago et al., 2004). However, the rare wooden logs, gravel sections, and patches of river weeds (Podostemaceae) are biotic hot spots concerning diversity, abundance, and biomass of invertebrates (Wantzen and Junk, 2006).

The surfaces of the solid clay banks are apparently void of macroinvertebrates, but they are mined by filter-feeding polymitarcid mayfly larvae (*Campsurus* sp.) and trichodactylid crabs. This primary interstitial space becomes secondarily colonized by filter-feeding hydropsychids, and, since the late 1990s, by the invasive mytilid, *Limnoperna fortunei*. It is remarkable how fast this mussel species propagated from the Paraná and Lower Paraguay Rivers to Upper Paraguay, and how the fish fauna lagged behind in learning how to prey upon them (Ezcurra de Drago et al., 2004; Marchese et al., 2005; Oliveira et al., 2010). In a study on the benthos of Lower Paraguay in 2001, *L. fortunei* was restricted to crevices in the lower (longer colonized) section, preyed upon by a number of fish species, but still grew on open surfaces in the (recently invaded) upper section. In 2000, we could not yet detect *L. fortunei* larvae on the 200 km downstream Cáceres (Marchese et al., 2005). Since then, the invasive "golden mussel" has spread and even colonized the floodplain water bodies, using roots of floating *P. crassipes* as a substratum (Marçal and Callil, 2008). Water-level fluctuations during the natural flood pulse and periodic anoxic events in the floodplain lakes may locally reduce their densities, but this will not eliminate *L. fortunei* in the long term, rather, it is predicted to conquer and engineer habitats in entire South America, potentially with as deleterious effects for this biodiversity hotspot of native, unionid, river mussels as is already the case with *Dreissena polymorpha* in Europe and North America (Darrigran and Damborenea, 2011; Oliveira et al., 2010). Both species fix themselves with byssus threads to solid surfaces and can act as "biofouling agents." When colonizing the shells of larger native mussels, they starve them of food competition. Other highly competitive mussels originating from Asia, the clams *Corbicula fluminea* and *Corbicula largillierti*, have spread across the Paraguay River and the Pantanal at about the same time as *L. fortunei* (Callil and Dreher-Mansur, 2002).

Fishes

There is yet no complete checklist for the entire river basin. Koerber et al. (2017) confirmed 307 fish species, with 12 orders and 39 families for the Paraguay River basin in Paraguay country, however, new explorations regularly enlarge the species list. In a recent update of the detailed book by Britski et al. (2007), a photographic guide of fish in the Pantanal and its surroundings (including habitat descriptions, recommendations for conservation, and a list of introduced species), 386 species are listed (Gimenes Junior and Rech, 2022). Two-thirds of the species belong to the Characiformes and Siluriformes. Comparing the geographical position of the Paraguay River with other watersheds, the northern portion of the basin is inhabited by some Amazonian fish species/groups (e.g., small trichomycterid catfish), mainly in response to headwater capture with Amazon subbasins (as Madeira, Tapajós, and Araguaia) (Ribeiro et al., 2018), but with few exceptions, larger river species have only recently be transferred from the Amazonian to the Paraguay basin (see below).

The main stem of the Paraguay River, the principal rivers and floodplains of the Pantanal have a higher fish species diversity than the headwaters of their tributaries, as rapids and waterfalls limit distribution in the latter. Isolation and physical-chemical habitat diversity favor taxonomic and phylogenetic diversity between tributary fish communities (Nakamura et al., 2021). The large floodplain water bodies are dominated by species occurring in the whole basin, such as smaller Cheirodontinae (e.g., *Serrapinnus* spp. and *Odontostilbe* spp.), smaller (e.g., *Xenurobrycon macropus*), and larger Characiformes (e.g., *Salminus brasiliensis* and *Piaractus mesopotamicus*).

Large, migratory fish species are widely distributed in the Paraguay River (e.g., *Salminus brasiliensis*, *P. mesopotamicus*, *Pseudoplatystoma reticulatum*, *Pseudoplatystoma corruscans,* and *Zungaro jahu*). The pimelodid catfish species *P. corruscans* (with ~170 cm and ~100 kg) and *Z. jahu* (with ~150 cm and 150 kg) are the largest species in the basin. Migratory species use different habitats along their life cycles; fertile adults perform a reproductive migration to headwaters of tributaries at the end of the dry season and hatching juveniles return to the floodplain during their growth phase (Ferraz de Lima, 1987; Resende, 2011). Only a few data are available about the migration routes. *Prochilodus lineatus* (known as curimbatá in Brazil, or as sábalo in Argentina and Paraguay; Fig. 17.12) occur (and migrate) in the entire Paraguay-Paraná River system. Recent dam constructions and navigation fragment these migratory pathways (Medinas de Campos et al., 2020; Peluso et al., 2022 and see below).

Some fish species are particularly interesting, such as *Lepidosiren paradoxa* (locally called pirambóia). This species is one of the few (six) lungfish species in the world and occurs in the Amazon, Paraguay, and the lower Paraná rivers. It has several peculiar characteristics, such as the longest genome among vertebrates and the capacity to aestivate in the anoxic mud during the dry season (Almeida-Val et al., 2010). Reproduction occurs in the wet season and males take care of the offspring during their early development.

Another characteristics species is *Laetacara dorsigera* (Cichlidae), one of the few fish species that occur naturally in both the Plata and Amazon River basins. This species occurs mainly in lakes and lagoons. When threatened by an aquatic predator (usually other fish), they jump over floating vegetation and stay out of the water for a few minutes until the predator leaves. In this case, probably aquatic predation is more intense when compared to aerial predators such as birds. *Paravandelia oxyptera* is a small, hematophagous catfish that feeds on the gills of larger fish. New species are regularly described, such as the endemic freshwater stingray *Potamotrygon pantanensis* (Loboda and Carvalho, 2013). Compared with the Paraná River, the fish fauna of Paraguay is still better preserved, despite that stocks of some commercial fish are seriously overexploited and released game fish species from Amazonia (*Cichla* sp.) begin to invade the basin (Resende et al., 2008; and see discussion in Wantzen et al., 2023b). Recently, the open-cage aquaculture of African tilapias is debated. Records on amphibians and reptiles are yet poorly published for the Paraguay mainstem, therefore see Section 17.6.2.

Birds

Bird species richness is very high in the Upper Paraguay River, as the bird fauna is formed by species from savanna-like ecosystems and the Amazon. About 450 bird species, which is comparable to species-rich sites in the Amazonian rainforest, were identified in the municipality of Cáceres including typical Cerrado savanna species such as *Penelope ochrogaster* and *Heliactin bilophus*, while *Phaethornis subochraceus* and *Thamnophilus sticturus* are related to the Chiquitano dry forests, and *Gymnoderus foetidus* can be found in the riparian forests of the Paraguay River (Lopes et al., 2016). Acoustic recordings reveal that the Pantanal is a highly important stepping stone for bird migration (de Oliveira et al., 2015) with so far 617 recorded species (Nunes et al., 2021).

The most conspicuous avifauna is the diverse, piscivorous species of kingfishers, ibises, egrets, herons, storks, many birds of prey (hawks, eagles, falcons, vultures), and the huge (and noisy) southern screamer (*Chauna torquata*). During the dry season (when fish are constrained in low-water bodies) or at the beginning of the wet season (when estivating crabs and apple snails reappear at the surface), predatory birds like jabirus, wood stork, or snail kites perform feeding migrations to these "biotic hot spots" (Wantzen and Junk, 2006). The "tuiuiu" stork, *Jabiru mycteria* (Fig. 17.8), is emblematic of the Paraguay basin and one of the largest flying birds of South America, reaching 1.5 m in height and a ~3-m wingspan. Apart from the review by Alho et al. (2011) and on mammals of the Pantanal, studies along the Paraguay River mainstem are scarce (but see Cuiabá River, below).

17.6.1.5 Environmental problems

Both the ecology and the traditional use forms of the entire river basin depend on the natural hydrological regime, the flood pulse, which reorganizes habitat structures, and the availability of nutrients and food for all biota in the floodplains and triggers cultural and economic development (Hamilton, 2002b; Junk et al., 2011; Wantzen et al., 2023c). This environmental flow pattern is impacted by damming tributaries in the uplands (Ely et al., 2020; Medinas de Campos et al., 2020) that lower the flood height and duration of the flood period, while the release of water for hydropower generation during the drought period causes untimely floods (Zeilhofer and de Moura, 2009). More than 150 small power plants have been built in the last years in the Upper Paraguay River Basin. Furthermore, dam development in the Upper Paraguay River Basin modifies the nutrient transport (Oliveira et al., 2020) and reduces the sediment transport (Fantin-Cruz et al., 2020) to the Pantanal wetland, impacting biodiversity and the provisioning of ecosystem services (Medinas de Campos et al., 2020; Peluso et al., 2022; Tortato et al., 2022 and Section 17.2, Cuiabá River).

Inside the floodplains, dikes for road construction change the flood regime, favoring the growth of invasive plant species. The greatest threat, however, is the hidrovia project to enable navigation upstream of Corumbá. The project has recently been approved and dredging is ongoing. The hidrovia waterway project and the above-described "death by a thousand cuts" from the increasing damming of many small and important large tributaries threaten to eliminate the ecological heartbeat of the Paraguay River and its floodplains, the flood pulse (see, e.g., Junk et al. 2011 or Wantzen et al., 2023a,b). The removal of the rocky outcrops and permanent dredging (to maintain the river channel deep enough for navigation) will result in a dramatic reduction in floodplain space (approximately 1% loss per centimeter lowering of the main channel; lowering of up to 50 cm is planned) and a strongly reduced water retention time (Hamilton, 1999). Navigation causes a series of impacts on habitat structure and the biota, including habitat loss, increased fire frequency in the wetland, and the spread of inadequate pastures and intensive agriculture (Wantzen et al., 1999, 2023a). Inside the wetland, the increasing number of dike roads influences the hydrology in a less obvious but nevertheless effective way. The human made hydrological changes resulting in lower and shorter floods during the rainy season (resulting in shorter inundation, and disjunct floodplain patches) are coinciding with climate change. The most recent climate forecasts indicate that the Cerrado, Pantanal, and Chaco will become hotter and drier, extremes of rainfall are expected to become more frequent in the plateau, while more prolonged and severe droughts will be more common in the Pantanal plain, with deep impacts on the region's ecological and economical dynamics (Thielen et al., 2020). It can be anticipated that these changed environmental rhythms will also cause mismatches of life cycle strategies and extinction of some species.

The migration of fish, birds, and mammals in the Paraguay River is understudied, but it is evident that the dams cut off the migratory species routes from their reproduction zone, and hardly any tributary to Paraguay River (i.e., the breeding sites) and the Pantanal wetland (i.e., the feeding site for these fish) remains undammed (Ely et al., 2020; Medinas de Campos et al., 2020).

Other environmental problems include deforestation, mining, and road construction in headwaters (which release enormous amounts of sediments), as well as overfishing. A study on land use change in the State of Mato Grosso (including Amazonian headwaters) has revealed that the area covered by native vegetation classes has been halved (on average) between 1969 and 2007 and that the number of remaining patches (as a result of habitat fragmentation) has increased by several thousand percent. This tendency is recently decreasing, as the remaining patches are also being clearcut, resulting in a "consolidation" of the agroscape (Siqueira et al., 2018). Models estimate the use of pesticides in the Upper Paraguay catchment to be 55,000 L/year (with increasing trends) and suggest tremendous losses of soil quality due to sheet erosion (Roque et al., 2021). Recently, the combined effects of climate change (Thielen et al., 2020) and land conversion are increasing fire incidences (Fig. 17.9) (Tomas et al., 2021).

17.6.2 Cuiabá

17.6.2.1 *Physiography, river geomorphology and land use*

The Cuiabá River runs in two distinct domains, the upper catchment area dominated by bedrock substrates and lower course in the Pantanal alluvial plain (Fig. 17.13). The headwater region in the Serra Azul and the Guimarães Plateau elevates to 500 m a.s.l., then the river crosses the geomorphological units of the Cuiabá Lowlands, Paranatinga Inter planaltic Lowlands, and Província Serrana (Chiaranda et al., 2016). The catchment mainly consists of low-grade metamorphic rocks, such as phyllites, quartzites, and some limestone areas, all of which are the source material for the fine-grained sediments deposited in the alluvial zone of the Pantanal (Pupim et al., 2017). As with other rivers, there are conflicting estimates in the literature about the length of the Cuiabá River, varying from 1080 km (Pupim et al., 2017) to 820 km according to the National Water Agency of Brazil (ANA, https://www.gov.br/ana/pt-br). According to the latter, the confluences of the main tributaries occur after 621 km, where it receives the waters of the São Lourenço (645 km long) and further 76 km downstream, the Itiquira (509 km long) rivers.

The catchment has a total area of 117,714 km^2, of which 41,551 km^2 (35%) is in the Pantanal lowland. Most of the basin is influenced by tropical savanna or tropical wet and dry climate (*Aw*). Nearly 53% of the land cover is Cerrado savannas (e.g., parkland savanna, woody grassland savanna, seasonally flooded grassy-woody savanna) and 22% is forest (e.g., seasonal semideciduous and seasonal deciduous forests, seasonally flooded evergreen forest). However, human land use covers ~24% of the basin (urbanization, agriculture, livestock, and mining).

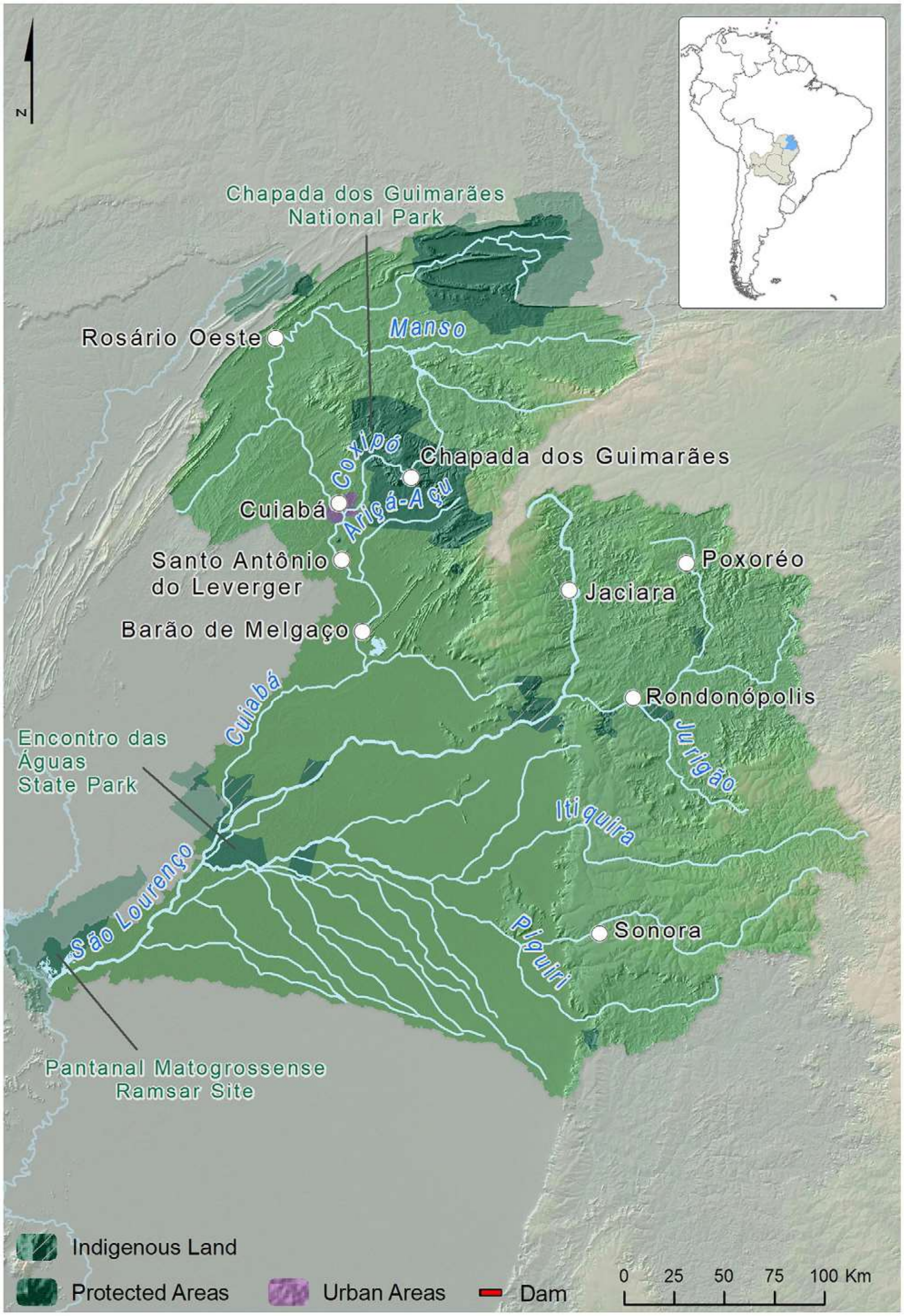

FIG. 17.13 Cuiabá-São Lourenço River basin (117,714 km^2). Land cover: Savanna, 36%; forests, 22%; wetlands, 20%; agriculture and pasture mosaics, 17%; native grasslands, 1%; urban areas, <1. Average catchment elevation, 850 m a.s.l. Population density: urban areas, 1482 ind/km^2; rural areas, 1.9 ind/km^2. Largest city, Cuiabá/Várzea Grande (906,000). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

Rains are markedly seasonal, ranging from 1300 to 1700 mm/year, concentrated from September to March (~84%). In the headwaters, annual rainfall can reach 2000 mm, while in the floodplain, at the confluence with the Paraguay River, it ranges between 1000 and 1100 mm annually (Thielen et al., 2020). From April onwards, rain events fade out, causing a water deficit in the dry season from May to August/September. The mean annual temperature on the border of the floodplain in Cuiabá city is ~26.3°C (https://en.climate-data.org/). A recent review on land use, biodiversity, cultural practices, and conservation of the Cuiabá River (including maps and species lists) has been delivered by Figueiredo et al. (2018b).

17.6.2.2 Hydrology

The mean annual discharge of the Cuiabá River (1997–2003) is 1.76 million m^3, 72% of which occurs in the wet season (December to April; Fig. 17.14). The monthly average discharge at the Cuiabá decreases from 590 m^3/s in the wet season to 162 m^3/s in the dry season (Pupim et al., 2017). Annual variation in water temperature upstream of Cuiabá city ranges from 19°C to 33°C, while downstream it ranges from 23°C to 38°C. The sediment load is about 50 mg/L, rarely attaining 100 mg/L (Fantin-Cruz et al., 2020; Oliveira et al., 2019). The sediment transport was estimated at ∼758 t/day near Cuiabá city, with the largest contribution from the upper part of the basin and, before damming, from the subbasin of the Manso River (Fantin-Cruz et al., 2020). Since the construction of the Manso Hydroelectric Power Plant in 2002, much of the sediment is retained in the reservoir. However, considering the current silting potential from the intensification of land use close to the river, the concentration of suspended sediments still tends to increase, especially during the wet season.

The closing of the Manso dam coincided with a change in the hydrological regime of the Cuiabá River including (i) a 40% increase in discharge during the dry season, (ii) a decrease in discharge at the beginning of the rainy season (November, 10% decrease; December, 24% decrease), and (iii) a decrease in discharge at the end of the flooding period (March, 8%; April, 12%) (Zeilhofer and de Moura, 2009). As a further consequence, the lateral connectivity between the Cuiabá River mainstream and its floodplain is strongly reduced (Jardim et al., 2020).

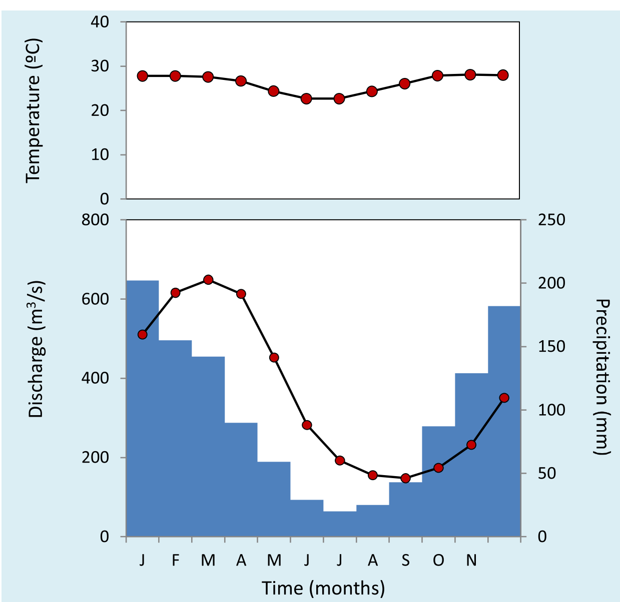

FIG. 17.14 Cuiabá River basin. Temperature and precipitation (*bars*) at the river mouth (17°18′16″S, 56°43′10″W) and discharge at Porto Cercado (16°30′59″S, 56°22′37″W). *(Source: Discharge and rainfall, www.snirh.gov.br/hidroweb/; temperature and precipitation, https://www.worldclim.org/.)*

17.6.2.3 Water chemistry

A long-term monitoring program on the water quality of the Cuiabá River between 1995 and 2017 has revealed significant variations between high and low water seasons, e.g., an increase of pH from 7.2 to 7.6, conductivity from 60 to 80 μS/cm, and a decrease in total phosphorous (with a wide variation between years but a clear increase in the 2015–2017 period during both seasons) (Figueiredo et al., 2018a,b). The main source of pollution in the Cuiabá River is the sewage of domestic and industrial origin (nitrate, nitrite, phosphate) (Lima, 2002; Zeilhofer et al., 2006). The release of insufficiently treated wastewater by nearly 1 million inhabitants of the metropolitan area of Cuiabá/Várzea Grande results in a significant change in the concentrations of coliform bacteria. Mean dissolved oxygen changes from 6.4 to 7.5 mg/L upstream of Cuiabá city to 3.6 to 5.9 mg/L downstream (Lima, 2002).

Average ranges and concentrations of dissolved solids (mg/L) in the Cuiabá River were total nitrogen (0.4–0.5), total dissolved nitrogen (0.02–0.12), total phosphorus (0.03–0.05), total dissolved phosphorus (0.005–0.012), Ca^{2+} (5.66), Mg^{2+} (2.46), Na^+ (1.68), K^+ (1.46), HCO_3^- (35.03), Cl^- (0.64), SO_4^{2-} (4.24), dissolved solutes (51.16), Si (2.09), dissolved organic carbon (7.56), and total Fe (0.81) (Oliveira et al., 2019).

Water color is under 8 mg Pt/L in the Manso River upstream and inside the Manso reservoir, and 27 downstream of the reservoir (Tuomola et al., 2008). One tributary, the Mutum, carries black water. Before reaching the Cuiabá River, it flows through a floodplain lake (Baía Sinhá Mariana), which is often back-flooded by the main river, resulting in a "moving front" of black vs white water in the lake visible from space (Nogueira et al., 2011).

In the Pantanal, flooded forest net nitrogen mineralization is positive during the flood season while immobilization takes place in the dry season as compared to the upland forest. In contrast, season does not affect nitrogen mineralization in upland forests. The phosphorus mineralization pattern was similar in upland and floodplain forests and was not affected by flooding (Vourlitis et al., 2017). The duration of the annual wetted period (longer or shorter than 250 days) has been identified as a switch between storage or mineralization of organic carbon in seasonal floodplain wetlands such as the Pantanal (Vega et al., 2014), and multiyear periods of higher water levels may keep riparian zones permanently wetted, resulting in higher carbon storage (Wantzen et al., 2005).

Pesticides in sediments have been detected at low concentrations (5.7–79.3 μg/kg) and frequency (5% of samples) both in the uplands and lowlands (Possavatz et al., 2014). Transport of pesticides from the high plains to the Pantanal is mediated by river discharge but also by air and rainfall (Laabs et al., 2002).

17.6.2.4 Biodiversity

Riparian habitats, wetlands and floodplain forests

Despite (or because of) its harsh conditions including flooding, severe drought, and even fire, the Pantanal is known to harbor large populations of animal and plant species that have become rare elsewhere, especially birds and mammals. The diversity of the most prominent taxa and the ecological patterns of the Pantanal have been detailed in several books (Bergier and Assine, 2015; Heckman, 2013; Junk et al., 2011) and checklists (e.g., Graciolli et al., 2017, and Section 17.3).

Like the Paraguay mainstem, the habitat patterns of the Cuiabá/São Lourenço catchments are strongly influenced by the physiographical structure of high and low plains. Tributaries in the Cerrado are bordered by gallery forests or more extended riparian wetlands (stream floodplains, hillslope campo wetlands, swamp forests), which interact with the streams in terms of water, nutrient, and biotic exchanges (Junk et al., 2022; Wantzen et al., 2006, 2011c). Permanent swamps (helocrenes) with stands of *Mauritia flexuosa* palms (called vereda in Portuguese, cananguchales in Spanish) have a high ecological and social value, e.g., due to the highest recorded diversity of copepods (Reid, 1984) and diverse use forms all over the Neotropics (Ricaurte et al., 2012). The steep escarpments have a specific microclimate, allowing the development of dense forest vegetation, while in the piedmont zone, habitat features overlap with the subsequent plains.

The vegetation of the lower section of the Cuiabá River is characterized by floodplain forests with, e.g., *Alchornea castaneifolia, Inga vera, Attalea phalerata, Ficus insipida,* and *T. americana* (Nunes da Cunha and Junk, 2011). These are more prominent downstream of the city of Cuiabá and become sparse further downstream. Most of the riparian habitats are similar to those of the Paraguay River, with steep clay banks on the outer side of the meanders, sand banks on the inner side, islands, and oxbow lakes (Wantzen et al., 2005).

The large, shallow lakes of the Baías de Chacororé and Sinhá Mariana are interconnected to the Cuiabá and the Mutum rivers, forming a complex system (da Silva Nunes et al., 2020). The gentle slope in the Pantanal alluvial plain favors the formation of numerous habitat types (local names in parentheses), such as paleo channels (corixos), channels with periodically flowing water covered with herbaceous plants (vazante) or woody plants (landi), natural grasslands with variable levels of flood duration (up to 6 months), savanna flooded for several weeks with termite mounds (campos de murundum), woodlands flooded from less than 3 up to 6 months, including monospecific systems of floodable savanna (paratudal with *Tabebuia aurea*, carandazal with *C. alba*) or evergreen forests (cambarazal with *V. divergens*, pimental *Licania parvifolia*, abobral with *E. fusca*), floodable shrubland (espinheiral with *Mimosa pellita*, canjiqueiral with *Byrsonima cydoniifolia*, pombeiral stands with *Combretum lanceolatum* and *Combretum laxum*), and several types of swamps on long-term inundated areas (Nunes da Cunha et al., 2022), whereas the rarely flooded, elevated zones harbor stands of "ipé" trees (*T. aurea, Handroanthus heptaphyllus*, Bignoniaceae family) whose yellow, pink, or white flowers are very conspicuous in the dry season when most tree species shed their leaves.

Macrophytes and bryophytes

The Northern Pantanal with the Cuiabá River and its tributaries (São Lourenço, Piquiri/Itiquira rivers) are known for about 280 species of aquatic and semiaquatic macrophyte species (Pott et al., 2011a) and, compiling records, there are about 750 plant species along the Cuiabá River basin. Endemism is low. Along the riverbanks and lake shores, the rooted *Pontederia azurea* dominates. Protruding into the open water from the banks, it provides a habitat for floating water plants such as *Pontederia crassipes*, *Pistia stratiotes,* or ferns (*Azolla caroliniana* and *Salvinia auriculata*). Secondary floodplain channels and lakes are also fringed by *P. azurea*, but their aquatic-terrestrial transition zone is highly diverse (da Silva Nunes et al., 2020). In permanently or long-term wetted areas of the floodplain, monodominant macrophyte stands of *Cyperus giganteus, Thalia geniculata,* or *Typha domingensis* develop. Many species are well adapted to surviving extensive drought phases in the floodplain, either by producing seeds or by developing hard-leaved, terrestrial dwarf forms, and display species-specific germination patterns after rewetting (Pagotto et al., 2011; Rebellato et al., 2012). This large range of adaptive strategies makes some species efficient invaders in other biogeographic areas (e.g., *P. crassipes* and *P. stratiotes* in tropical rivers worldwide, *Ludwigia grandiflora* in Europe).

Microorganisms, algae

One hundred and eighty-two species of cyanobacteria and microalgae were inventoried in the upper Cuiabá River basin, with no endemism acknowledged (Assis et al., 2018). A more extensive survey, which also included samples taken from the Paraguay River floodplain, in Cáceres, found 337 species (De-Lamonica-Freire and Heckman, 1996). Species include free-living phytoplankton (e.g., *A. granulata*, *Planktolyngbya* sp., *Microcystis aeruginosa*, *Merismopedia tenuissima*, *Crucigenia tetrapedia*) and periphyton (Bacillariophyceae: *A. granulata*, *Cyclotella* sp., and *Diatoma* sp.) associated with submerged roots and leaves of aquatic macrophytes (e.g., *P. azurea*), both living or dead organic matter (Loverde-Oliveira et al., 2011). A survey on protozoans listed 97, mostly cosmopolitan, free-living species (Sarcodina and Ciliata) (Hardoim and Heckman, 1996).

Macroinvertebrates

In the headwaters of the Cerrado, the invertebrate assemblages show distinct patterns due to the presence of dissolved calcium or its virtual absence (concentrations below the detection limit). In the latter case, shelled crustaceans and mollusks are lacking. Despite the low conductivity (in some cases, below 5 μS/cm), the diversity of aquatic insects (especially chironomids and other dipterans) is high (Wantzen et al., 2011a). Except for large dobsonflies (*Corydalis*) and predatory stoneflies (*Anacroneuria*), the life cycles of the winged aquatic insects are very short (Wantzen, unpublished data).

Among the functional feeding groups, shredders are scarce, represented either by miners in freshly fallen, soft leaves (*Stenochironomus* sp.) or by shredding caddis flies (*Phylloicus*) that are found in riparian ponds or humid zones aside the stream. This phenomenon has been attributed to the high concentrations of plant phenolics, the leaf hardness of most tree species, and the high dynamics of leaf litter in the streams (Wantzen and Wagner, 2006). Twenty-six genera of caddisflies (Trichoptera) were identified in the basin, most of them in the Leptoceridae, Hydropsychidae, Hydroptilidae, and Polycentropodidae family, being the most common genera *Smicridea* (Hydropsychidae), and *Nectopsyche* (Leptoceridae). While *Setodes* and *Synoestropsis* occur only in limestone streams, *Triplectides, Triaenodes, Oxyethira,* and *Atopsyche* are present in sandstone streams (Massoli and Callil, 2014). The section of the Cuiabá River flowing through the Pantanal displays similar, habitat-specific community patterns (and species) as those described for the Paraguay River, with a higher abundance and diversity on solid substrates (see taxa and literature cited above).

The river-connected Chacororé-Sinhá Mariana lake complex near Barão de Melgaço reveals specific invertebrate communities depending on local and seasonal types of connectivity (Wantzen et al., 2011a). During the rainy season, blackwater inflow from the Mutum River carries along large amounts of harpacticoid copepods, whereas during the low-water season, hardly any benthic invertebrates (apart from nematodes) can be found in the lake center. The connection canals between the two lakes and the Cuiabá River display the highest abundance and diversity of invertebrates, specifically filter-feeding mayflies (*Campsurus*) and mussels (e.g., *Castalia inflata*).

The hydrological seasons of rising and falling waters reveal season-specific invertebrate communities in the floodplain water bodies (Heckman, 1998), with high abundances of oligochaetes, nematodes, cladocerans, copepods, chironomids, hydrophilids, dysticids, and ampullariids.

Adaptations of aquatic invertebrates to cope with seasonal drought include estivation, lateral migration, mass emergence, drifting, and long-distance flight (reviewed by Wantzen et al., 2016). For example, mussels and large ampullariid snails like *Pomacea lineata, Pomacea scalaris,* and *Marisa planogyra*, seek the lowermost points of floodplain lakes before they dry up completely. Trichodactylid crabs (six species, *Dilocarcinus pagei* being the most common) have large brood pouches to carry their offspring between water bodies. The chironomid *Apedilum elachistum* has extremely short life cycles, allowing it to finish the larval stages in drying puddles (Nolte, 1995). The mayfly *Cloeodes hydation* can molt repeatedly after drying and rewetting. Freshwater sponges (*Drulia brownii*) live attached to floodplain trees and survive drought and extreme heat for several years when their habitat falls dry. Conversely, terrestrial invertebrates migrate (ants) or survive underwater (tiger beetle larvae, millipedes) during the flood period, while army ants and tarantulas profit from the rising water borderline for hunting fleeing animals (Wantzen et al., 2016). Annually at the beginning of the rainy season, adult Polymitarcid mayflies and giant water bugs (Belostomatidae, six species) perform mass migrations (Wantzen and Junk, 2006).

The flood cycle also determines the shell structure and reproductive strategies of bivalves (Callil and Mansur, 2005, 2007; Santos et al., 2021). Twenty-eight species are recognized for the Cuiabá, most of them are of the family Mycetopodidae (14 spp.), Hyriidae (5 spp.), and Sphaeriidae (2 spp.). *Bartlettia stefanensis* and *Haasica balzani* are endemic in this basin. Three bivalve species (*C. largillierti*, *C. fluminea,* and *L. fortunei*) are exotic and highly tolerant to environmental degradation (Oliveira et al., 2010). Like in the Paraguay mainstem, these invasive bivalves severely threaten the native species. *L. fortunei* can reach densities up to 145,000 ind./m^2 and have a high potential to affect ecosystem functioning in the Pantanal (Callil and Santos, 2018). Large ampullariid snails like *P. lineata*, *P. scalaris*, and *M. planogyra* are native to the Pantanal and are an important food source for wading birds and snail kites (especially when they return from their estivation habitats), but their congeners are invasive in other parts of the world. Organic pollution is causing changes in the composition of benthic invertebrate assemblages (Callil and Santos, 2018; Wantzen et al., 2011a), with clear differences above and below the city of Cuiabá (Lima, 2002).

Despite efforts such as the book series on *Aquatic Diversity in Latin America* (ABLA, e.g., Dominguez et al., 2006), the invertebrate fauna in Central South

America is still understudied (Fig. 17.7) and species descriptions and species trait analyses, such as the development of palaemonid shrimp *Macrobrachium amazonicum* (Anger and Hayd, 2010), are urgently needed. The timing of studies often does not match with the periodicity of population dynamics of many species (see Wantzen and Junk, 2006 for a discussion), so many field observations remain anecdotal.

Fishes

There are ~314 fish species in the Cuiabá River basin, with sizes ranging from a few centimeters (e.g., *Odontostilbe* spp., *Trichomycterus* spp., *Characidium* spp.) to catfishes larger than 1 m (e.g., *P. corruscans*, and *Z. jahu*, see Paraguay mainstem). Although most species are widely distributed, there are some endemic species, such as *Ancistrus claro* and *Ancistrus cuiabae,* two armored catfishes (Loricariidae). These and many others (e.g., *Hyphessobrycon eques*, *Gymnocorymbus ternetzi, Mesonauta festivus, Astronotus crassipinnis*) are sought-after species for aquariophilia. The knife fish (*Gymnotus* ssp.) and freshwater crabs become systematically captured from the roots of the floating macrophytes or holes in the clayish river banks and used as bait for anglers, resulting in population decline (Marques, 2017).

Floating macrophytes such as *Pontederia* provide food and shelter from predators for smaller fish species (Pacheco and Da-Silva, 2009; Teixeira-de Mello et al., 2016). When floodplain water bodies begin to dry out, these perform mass migrations back to the mainstem rivers. These multispecies migrations (locally called lufada) are strictly timed according to lunar phases to oversaturate the larger predators awaiting them in deeper waters (Wantzen and Junk, 2006). On the other hand, many commercially important fish species migrate upstream to spawn (locally called piracema) at the end of the dry season so that their offspring can make optimum use of the resources in the recently flooded wetlands (Ferraz de Lima, 1987).

Most fish species display a wide range of food items and shift their diets between the variable resource offered by the hydrological seasons, but others, e.g., scale-eating piranhas (*Serrasalmus marginatus*), are highly specialized (Wantzen et al., 2002). Other piranha species (*Serrasalmus maculatus, Pygocentrus. nattereri*, Sazima and Machado, 1990, *Hoplias malabaricus*, *Hoplerythrinus unitaeniatus*, and *Acestrorhynchus pantaneiro*) are common predators in the floodplains, while the larger predators (catfish and Dourado, *Salminus brasiliensis*, see above) mostly remain in the permanent water bodies.

The Cuiabá River floodplain supports a high richness and abundance of frugivorous fishes dispersing seeds of over 77 fruit morphospecies (Araujo et al., 2021). Frugivorous fishes are ubiquitous in this river and include iconic species such as the Pacu *P. mesopotamicus*, the Piraputanga *Brycon hilarii*, the Piavuçu *Megaleporinus macrocephalus,* and the Pacupeva *Mylossoma duriventre*, all of which are very appreciated in the local cuisine.

Commercial fishing also targets larger catfishes (*P. corruscans*, *P. reticulatum*, and *Pinirampus pirinampu*) and Pacu (*P. mesopotamicus*). There is no recent systematic stock assessment available for fisheries. Stock assessment for some species did not detect signals of overexploitation in the early 2000s, except for Pacu (*P. mesopotamicus*) and Barbado (*P. pirinampu*) (Mateus et al., 2011), but the few existing data on fish landings at the Cuiabá fish marked indicate a marked decline the 1980s (1500 t/year) to the early 2000s (100 t/year) (Mateus and Penha, 2009). Cuiabá River basin supports the highest population of active fishermen, and the highest harvesting (2074 t, 42% of total) but the lowest capture per unit effort (6.4 kg fish/fisher per) among the rivers of the Upper Paraguay River Basin, in Brazil.

Recreational fishing activities result in a strong impact on fish populations near cities, a phenomenon recently recognized as "defaunation shadow" (Tregidgo et al., 2017). Near the urban agglomeration of Cuiabá city (~1 million inhabitants), recreational fish catches have been estimated to 194–775 t/year (Massaroli et al., 2021). Fishing to meet one's daily protein needs is still common in rural areas and catches near cities or villages were very high until the 1980s. Today, artisanal (subsistence and commercial) and recreational fishers complain that they need to travel long distances to catch fish. Fishing restrictions to preserve the overfished populations are currently debated, as they limit the rights of traditional and indigenous communities (see (Wantzen et al., 2023c) for discussion).

Amphibians and reptiles

There are 64 amphibian species described, with 5 species considered endemic to the basin (Dorado-Rodrigues et al., 2018), including one species of a burrowing limbless amphibian, the caecilian *Siphonops paulensis*. *Allobates brunneus* is a critically endangered tree frog species that lays eggs on curled leaves fallen to the ground or at leaves 10–60 cm high. Other species such as the cururu toad (*Rhinella diptycha*) and the Chaco tree frog (*Boana raniceps*) are common in the basin.

A recent review of reptiles indicates 151 species, including 3 caimans, 5 turtles, 13 amphisbaenians, 38 lizards, and 93 snakes (Dorado-Rodrigues et al., 2018). A remarkable species turnover of amphibians and reptiles from headwaters to the floodplain indicates the complementarity of habitats between upland and lowland areas (see Strüssmann et al., 2011 for a detailed review of the Upper Paraguay River Basin).

The most conspicuous reptile species at the banks of the rivers and the floodplains is the spectacled caiman (*Caiman yacare*). After severe declines due to poaching in the 1980s, populations have recovered, and large crowds of them can be seen on the remaining water bodies at the end of the dry season. They consume fish and concentrate nutrients, especially phosphorous, at their resting sites in the form of feces deposits, which cause periods of hypertrophic conditions when these are washed into floodplain lakes with the first rains (Nogueira et al., 2011). Other, typical water-bound species are iguanas (*Iguana iguana*) that drop from trees into the water when disturbed, the false water cobra (*Hydrodynastes gigas*), and the Southern Anaconda (*Eunectes notaeus*). Among several species of Teiidae, the endemic Paraguay caiman lizard (*Dracaena paraguayensis*) is best adapted to water. It feeds mostly on ampullariid snails. Large quantities of terrestrial species seek shelter in the limited, nonflooded areas during the high-water season.

A larger portion of reptile species (135) is considered Least Concern. However, one species (*Kentropyx vanzoi*), a lizard associated with sandy areas in lowland rivers is of concern, considering the high deforestation rate in its distribution area. Many vertebrates, especially snakes, become victims of nocturnal road kills.

Birds

There are ~570 species from 68 bird families in the Cuiabá River basin (Oliveira, 2009). This high diversity results from various features such as (i) the Pantanal acts as a turntable between different biomes so that their faunae overlap here, (ii) ombrophilous species can use riparian zones of tributaries as microclimatic corridors, (iii) it is an important resting place for migratory birds, and (iv) the high diversity of habitats makes it attractive for diverse functional groups, ranging from purely water-bound (about 90 species, plus about 40 wetland-dependent species) to dryland species (see Petermann, 2011 for a review of the pre-2010 literature). Recent bioacoustic logging and computerized data analysis have enabled deeper insight into behavioral patterns and ecology of the bird, mammal, and anuran fauna of the Pantanal (de Deus et al., 2020; Jahn et al., 2017; Pérez Granados and Schuchmann, 2021; Pérez Granados et al., 2019).

The openness of the park-like landscape and the alternating and periodically abundant food sources favor especially bird species that are feeding on fish and larger invertebrates. During the dry season, low water levels and low oxygen concentrations urge fish to concentrate near the surface of shallow, remaining water bodies, making them easy prey for wading birds such as wood storks (*Mycteria americana*), jabirus (*J. mycteria*; Fig. 17.8), 13 species of herons and egrets, 5 species of ibises, roseate spoonbill (*Platalea ajaja*), as well as plunge divers (5 species of kingfishers, diverse terns), or diving predators such as olivaceous cormorant (*Phalacrocorax brasilianus*), or anhinga (*Anhinga anhinga*).

Some of these species gather in huge breeding sites (ninhais) that have a "black phase" (during deeper water levels), when cormorants, anhingas, and white-necked heron (*Ardea cocoi*) breed, followed by a "white" phase (breeding of wood storks and herons that have a lighter-colored plumage than the dark cormorants) when shallow water favors piercing hunters (Petermann, 2011). When estivating snails and crabs return to the water bodies at the beginning of the flood period, snail kites (*Rosthramus sociabilis*), which are territorial during the high water season, gather by the hundreds to feast upon the abundant prey (Wantzen and Junk, 2006). Bank slumping at the clayish river banks regularly provides new (and parasite-free) space for birds that breed in caves such as bank and cliff swallows (*Riparia riparia*, *Petrochelidon pyrrhonota*) and king fishers (genus *Chloroceryle* and *Megaceryle*). Ducks such as whistling ducks *Dendrocygna* spp., Brazilian teal *Amazonetta brasiliensis*, or muscovy duck *Cairina moschata* breed at the peak of the flood season (Petermann, 2011). During low water, diverse bird species breed on dry sandbars (large-billed tern *Phaetusa simplex*, yellow-billed tern *Sternula superciliaris*, black skimmer *Rynchops niger*, collared plover *Charadrius collaris*), undergoing the risk of being flushed by untimely floods from the hydropower dams upstream.

Mammals

Tomas et al. (2011) have revised the mammal species recorded in the Upper Paraguay River Basin ($n = 236$ sites) and found 152 species in the Pantanal (45 medium to large-sized mammals, 34 small mammals, and 73 bats) in 104 genera, 30 families, and 9 orders; the list by Alho et al. (2011), including the Paraguay portion of the Pantanal, sums up 174 species. A recent study on bats revealed 65 species in the floodplain, and 90 in the whole region, including the fishing bat *Noctilio leporinus* (Fischer et al., 2018). Due to the low density of forests, there are only four primate species in the Pantanal, the black howler monkey (*Alouatta caraya*) being the most prominent.

The most water-related mammals are the giant otter *Pteronura brasiliensis*, the freshwater otter *Lontra longicaudis,* and the capybara (*H. hydrochaeris*, the world's largest rodent), but also the marsh deer *Blastoceros dichotomus* and jaguar *Panthera onca* remain near water bodies. Capybaras live in socially organized clans that share work, i.e., several animals watch out for predators such as the jaguar and alarm the crowd by whistling if needed so that all animals can dive into the water.

Tapirs (*Tapirus terrestris*) and the rare bush dog (*Speothos venaticus*) migrate along gallery forests between the Pantanal and the high plains. All larger mammal species are threatened by road kills, poaching, illegal pet trade, and cross-infection with bred mammals and—more recently—by fire (Tomas et al., 2021), resulting in about 12% of the mammal species within the Pantanal being considered globally endangered and 8% at national level in Brazil (Tomas et al., 2011). Recently, Asian water buffaloes (*Bubalus bubalis*) and European wild boars (*Sus scrofa*) have become feral in the Pantanal, where they cause considerable damage to habitats and other biota.

Ecosystem processes

Ecosystem processes in the Pantanal are often triggered by "windows of opportunity" during which a large part of the turnover or phenological events such as reproduction occurs during a very limited time and at limited sites, the "biotic hot spots and hot moments" (Wantzen and Junk, 2006). For example, terrestrial plant litter remains "mummified" (dry) for a long time, and decomposition in the early rainy season occurs very fast, locally resulting in the above-mentioned "dequada" fish kills. The extreme drought conditions during the low-water season represent a strong selective pressure and often result in periodical population decline of aquatic organisms. Plant succession is controlled by water level, the duration of inundation during the high water period, and drought and fire during low water levels (Nunes da Cunha and Junk, 2004).

Annual rates of aboveground net primary production for the basin were estimated at 380–550 t C/km^2 per year for a seasonally flooded cerrado forest and 160–460 t C/km^2 per year for an upland mixed forest at the alluvial plain. For non-forested habitats, net primary production peaks at the beginning of raining season for native grasslands (5.1 g dry weight/m^2 per day (Pozer and Nogueira, 2004)) and some semiaquatic macrophytes (e.g. *Pontederia lanceolata*, 1126 t dry weight/km^2 per year (Penha et al., 1999)). Most dissolved organic matter (or carbon) in the water of a seasonally floodable area comes from terrestrial organic matter in the form of humic and/or fulvic constituents. Carbon dioxide, methane emissions, dissolved organic matter, and carbon concentration vary according to the flood cycle, with higher dissolved organic carbon concentration at the beginning and end of the flooding cycle (Dalmagro et al., 2018). Several studies corroborate that seasonally flooded and upland forests of the Pantanal alluvial plain of the Cuiabá River can act as aboveground C sinks (Schongart et al., 2011; Vourlitis et al., 2019).

17.6.2.5 Environmental problems

As with all rivers of the Paraguay basin, the problems affecting the biological and cultural diversities arise from different types of land use changes in the headwaters and the lowlands. However, the main threat is the current dramatical change of the environmental flow pattern, the flood pulse, due to upstream damming and the hídrovia project in the main course of the Paraguay River (see Section 17.6.1.5, Box 17.1 and Wantzen et al., 2023a,b), combined with climate change effects, which cause increased intermittency in streams, prolonged drought periods, fire incidents, etc. (Ikeda-Castrillon et al., 2022; Marengo et al., 2016; Thielen et al., 2020). Specifically, the fish fauna is affected by the combined effects of damming and climate change, with a predicted reduction of the local species richness by about 85% in the basin (Peluso et al., 2022).

Natural erosion in the headwater zones is very low, but these systems are susceptible to erosion caused by inadequate agriculture, road construction, and mining (Wantzen and Mol, 2013). Headwaters have been largely deforested since the 1970s and are intensively used for agriculture (soybeans, cotton, corn, sugar cane), in some cases even in the protected areas. Gallery forests and riparian wetlands, which retain sediments from land use, are dramatically declining (Siqueira et al., 2018). The São Lourenço River receives most of the eroded reddish soils from the intensively used catchment (one of its tributaries is even named "Rio Vermelho" or "red river"). Its suspended load increased by 67% between 1977 and 2002, causing substantial morphological changes in its alluvial fan (Corradini, 2011).

Gold mining was important in the colonial period, but a few gold mines are still active. Problems associated with mercury (used to amalgamate gold particles) and erosion from ancient mine tailings continue to be a problem (Callil and Junk, 2001; Tuomola et al., 2008). Biomagnification of mercury along the food chain is highly evident. The maximum recorded content of Hg was $2010.4 \pm 150.5\,\mu g\,g^{-1}$, the highest level ever recorded in a wild animal. The data indicate that mercury is an important threat to jaguars within at-risk regions of the Pantanal (May Junior et al., 2018).

Another evident but unfathomed mining activity is the extraction of sand and gravel directly from the riverbed, which results in riverbed incision, disturbing the hydro-sedimentological dynamics and disconnecting floodplains.

About 24 hydroelectric dams are operating, 5 are under construction, and 14 are planned to be built in the Cuiabá River basin (not including São Lourenço and Itiquira rivers, data from 2020). Hydroelectric dams change the pulsing flow regime, a crucial ecosystem process in the basin sustaining the high biodiversity of the basin. The dam on the Manso River (which contributes about 25% of the discharge of the Cuiabá River) increased low flows by ~80% (from 93 to 170 m^3/s), while maximum flows were reduced from 47% to 66% (from 1390–2617 to <1723 m^3/s) and occasionally as low as 650 m^3/s in Cuiabá city, 300 km downstream of the dam (Jardim et al., 2020). These dams interrupt access of migratory fishes to their spawning habitat despite their socio economic importance in the region (Medinas de Campos et al., 2020). Before closing the Manso dam in 1999, thousands of migratory *B. hilarii* and other species were seen jumping up the rapids at night during the spawning migration (KMW, JP pers. obs.), but these are flooded today by a 60-m high dam wall. It follows that the populations of all larger characids and catfish will encounter a dramatic decline in the next future even if fisheries were under strict control (Peluso et al., 2022), which is not the case (see above). The combined effects of dams and long-term overfishing will further reduce their populations and their ecological role as seed dispersers (Araujo et al., 2021).

Despite that dissolved oxygen and nutrient concentrations are within the limits allowed by legislation, one of the major problems of the Cuiabá River is untreated sewage from urban areas and the increasing stock-breeding. There were an estimated number of 1,700,000 heads of cattle, 65,000 pigs, and 3,200,000 chickens (in strong expansion) in 2014 (Sallo et al., 2018). Three hundred and sixteen fish farms were installed in the hydrographic basin in 2018. As a result of animal husbandry and deficient sewage treatment plants, water quality is low in several sections of the basin. The density of *Escherichia coli* is beyond the maximum limit of 1000 NMP/100 mL, reaching values above 25,000 NMP/100 mL. Other parameters, such as ammoniacal nitrogen, turbidity, and phosphorus (Figueiredo et al., 2018a), or copper and lead are elevated near urban centers (Magalhães et al., 2016). Pesticides and their biotic effects are not monitored regularly (de Carvalho Dores, 2016). The urban streams are severely polluted and channelized (Wantzen et al., 2019). Microplastics are a recent problem in the Cuiabá River, with concentrations of ~2 particles/L (average particle size ~200 μm) in urban streams in Cuiabá city; this amount is reduced by 75% in the floodplains downstream (Faria et al., 2021).

There is no systematic survey on endangered habitats or species for the Cuiabá River. In the red book of endangered species of Brazil (IUCN-Red List), and the National Plan for Conservation for birds of the Cerrado and the Pantanal, *Tigrisoma fasciatum*, *P. ochrogaster*, and *Alectrurus tricolor* (birds) and the frog *A. brunneus* are listed as Vulnerable in this basin. Due to the lack of systematic monitoring, so far, only a few species invasions have been documented in the Cuiabá River, including the mollusks *L. fortunei*, *C. largillierti*, *C. fluminea*, and *Melanoides tuberculatus*, Amazonian tucunaré perches (*Cichla piquiti* and *C. kelberi*), released as game fish, and other fish species escaping from aquaculture such as African tilapias (*Oreochromis niloticus* and *Coptodon rendalli*), and the hybrid tambacú (♀ *Colossoma macropomum* × ♂ *P. mesopotamicus*). The African catfish (*Clarias gariepinus*) is illegally bred (Box 17.1).

BOX 17.1 Arrhythmia in the hydrological heartbeat of the Pantanal wetland

Near the geodetical center of South America, covering an area of approximatively 180,000 km^2 in Brazil, Bolivia, and Paraguay, the Pantanal is considered the largest contiguous wetland in the world. It is a natural depository for sediments, resulting in a very low declivity of the landscape, and a series of rocky outcrops in the Paraguay River causes a delay of the flood crest of about 3 months. The seasonal savanna floodplain receives waters from the Paraguay River and its tributaries during and after the rainy period (from November to March-April in the headwater regions), with a north-south propagating flood pulse and nearly arid conditions during the dry season. During the expansion-contraction cycle, approximately 60% of all the waters coming from the plateau are lost through evaporation. At Cáceres, in the upper end of the Pantanal, discharges vary from 200 (September) to 1000 (March) m^3/s (annual avg. 537 m^3/s), while at downstream of the wetland at Porto Murtinho (annual avg. 2376 m^3/s) the lowest discharges occur in December (1700) and highest in July (2800 m^3/s) (Gonçalves et al., 2011). The shallow inundations between some centimeters and few meters depth, lasting from weeks to several months, and the landscape with open seasonal savannas and regional forested elevations make the Pantanal a transition zone of different biogeographic regions, in which the occurrence of species is filtered by the strongly alternating environmental conditions. These changes act as a turntable for the organic matter between aquatic and terrestrial food webs and increase productivity during the change between the hydrological seasons. Approximately 500 bird, 400 fish, and 200 aquatic macrophyte species display remarkable adaptive features to this hydrological rhythm. Many migratory fish species, mostly of the characid and pimelodid families, perform risky upstream migrations at the end of the dry season so that their offspring can fully profit from the freshly flooded areas (flood-pulse advantage). The Pantanal still harbors large populations of bird, mammal, and reptile species that have become rare elsewhere in South America (e.g., hyacinth macaw, jabiru, wood stork, jaguar, marsh deer, southern anaconda, spectacled caimans), making it a naturalists' paradise. Likewise, the native and the traditional human communities have developed flood-pulse adapted cultural practices in cattle ranching and fishing (Wantzen et al., 2023b).

But the scenic beauty and the biological and cultural diversities of the Pantanal are at stake. Its position between headwater high plains undergoing massive transformations for agro-industrial soybean and other cash crop cultivations and the middle section of the Paraguay River, which is already in use as a waterway, triggers the construction of dams and waterways in the Upper Paraguay. While the dams currently produce a "death by a thousand cuts," i.e., stepwise decharacterization of the environmental flows and a fragmentation of spawning areas of the tributaries (Medinas de Campos et al., 2020), the planned hidrovia project would be the deathblow to the Pantanal. This waterway project intends to make the Upper Paraguay navigable for large barge convoys that could transport cash crops from yet-to-built harbors to the lower sections of the Paraguay River and finally to the oceanic hubs in the estuary of the Paraná River (Coelho-Junior et al., 2022). The envisaged deepening of the riverbed by dredging and rock-blasting, and the artificialization of river banks would result in a reduction of the natural river channel dynamics (Wantzen et al., 2005), a disconnection and drying out of most of the floodplain (Hamilton, 1999), and facilitate the currently increasing bush fires and land conversion in the wetland. Due to the undeniable, dramatic ecological, economic, and cultural consequences for the entire region, the project had already been stopped in 2000, but it has now returned to the planning phase. Hopefully, the decision-makers will reconsider the case and save one of the last ecological paradises on Earth.

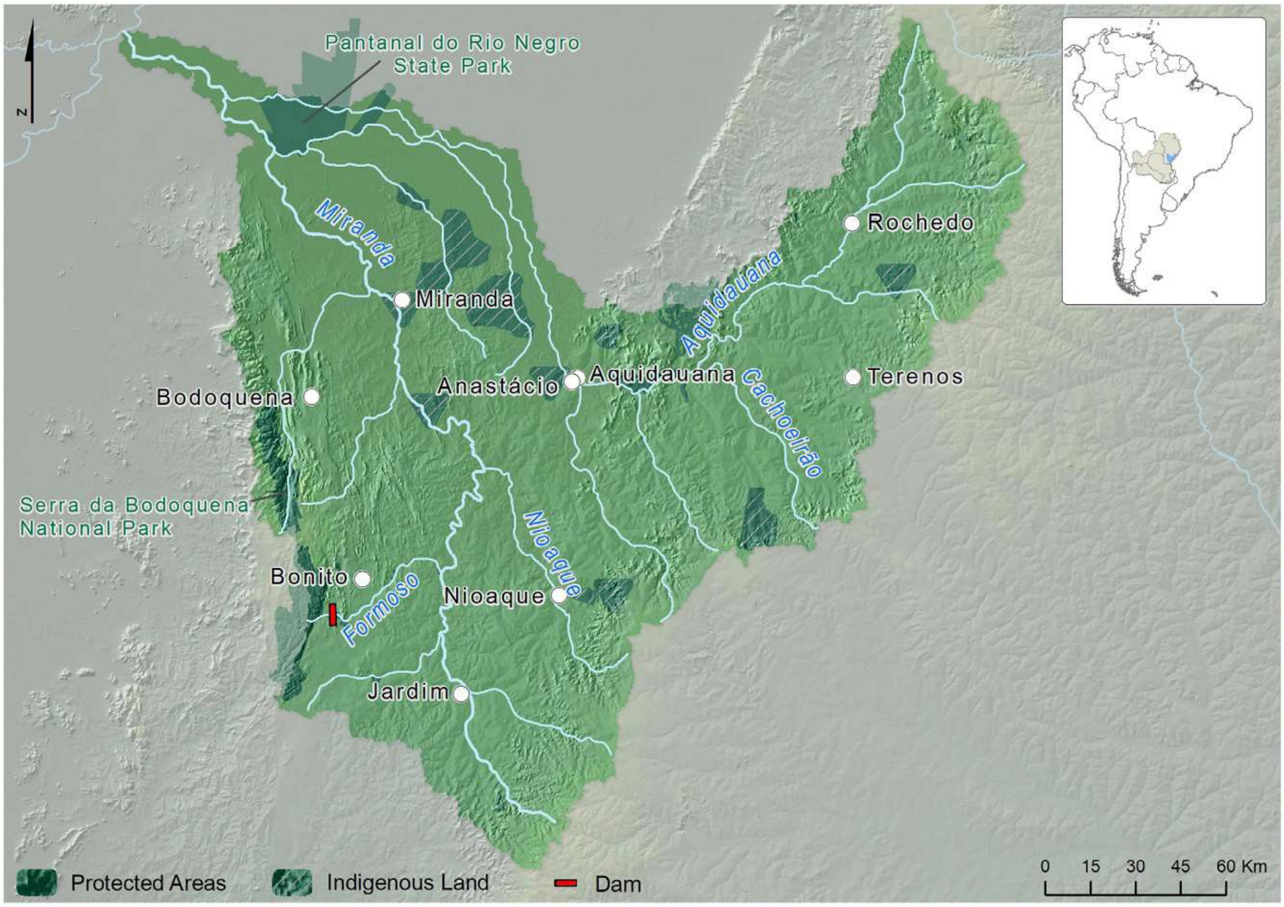

FIG. 17.15 Miranda River basin (45,548 km^2). Land cover: Croplands, 47%; forests, 31%; grasslands, 17%; wetlands, 5%. Average catchment elevation, 810 m a.s.l. Population density, 5.7 ind/km^2. Largest city, Aquidauana (48,184). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

17.6.3 Miranda

17.6.3.1 *Physiography, geomorphology and land use*

The headwaters of the Miranda River are located in the Serra de Maracaju at ~640 m a.s.l. and its mouth in Paraguay River near the city of Corumbá is at ~83 m a.s.l. (Fig. 17.15). The river is 798-km long, with a basin area of ~42,994 km^2. The main tributary of the Miranda River is the 658-km long Aquidauana River, which covers ~47% of the basin area.

The Miranda River flows across the Paraguay Belt, a limestone region characterized by a typical fold-and-thrust pattern. The geological evolution of this portion of the belt started in the Precambrian with rifting processes evolving to a restricted sea and marine transgression, forming calcareous sediments. At the beginning of the Cambrian, a collisional process associated with deformation and metamorphism occurred, followed by postcollisional magmatism in the Upper Cambrian (Campanha et al., 2011).

The Aquidauana River crosses through a predominantly rocky region, with many rapids and a well-fitted bed in the rocks, with little-developed floodplains above the confluence with the Miranda River. The lower Miranda River is dendritic, with more recent meanders, oxbow lakes, and a larger floodplain, which merge with those of the Paraguay River. The area below the confluence of the Miranda River (Nabileque region) is an ecotone between Pantanal and the Chaco region.

Due to calcite coprecipitation, the rivers of the Miranda catchment carry a low concentration of suspended material, resulting in transparent waters (Nunes et al., 2020). This scenic beauty makes it one of the most visited areas of the southern Pantanal, attracting anglers in the Miranda and Aquidauana rivers and ecotourists in the Bonito region (Figs. 17.1 and 17.16).

The climate of the entire Miranda basin belongs to the tropical zone with dry winter (*Aw* according to Köppen's classification), without periods of hydric deficit in the upper sections (rainfall ~1400 mm/year) and a smaller hydric deficit from June to September in the lower section (rainfall ~1180 mm/year). The Lower Miranda and Aquidauana Rivers are classified as hot, subhumid regions with rainfall concentrated from September to March (~70%).

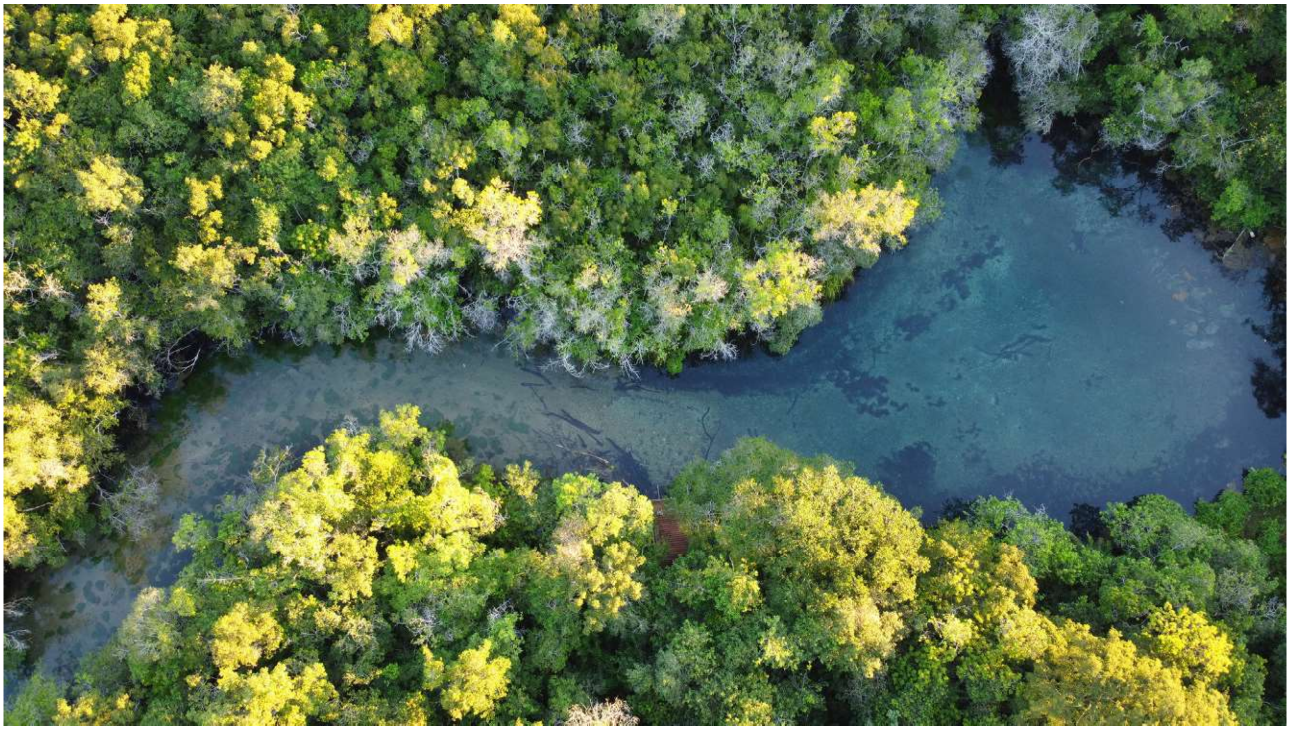

FIG. 17.16 Aerial view of OlhoD'água river. *(Photo: José Sabino.)*

From 1973 to 2006, human land use increased from 28% to 64%, mainly due to the conversion of native forests to pasture for cattle ranching. Deforestation increased by ~129% and livestock production by ~324%. This conversion occurred first in lowlands and foothills, leaving only terrains with high slopes unchanged (Ferraz, 2006). In the past three decades, ecotourism growth has allowed the valorization of areas with preserved vegetation, and legislation preventing deforestation has reduced the rate of conversion of native vegetation into pasture or agriculture.

17.6.3.2 Hydrology

The upper sections of the Miranda and Aquidauana rivers have high declivity (126.3 and 226.7 cm/km, respectively) changing to nearly 6.6 cm/km in the final section of the river, resulting in a downstream increase in floodplain extension. The headwaters of the Miranda River run over impermeable rocks of the Bodoquena Plateau, favoring surface runoff and increasing the flashiness of river flows. The Aquidauana River and the middle and lower Miranda River display better hydrological buffering. Above the confluence, the discharge of the Miranda River is estimated at 88–92 m^3/s and that of the Aquidauana River at 113–116 m^3/s (Gonçalves et al., 2011). The discharges of both rivers display pluriannual variations (Oliveira and Ferreira, 2003). The flood pulse in the lower Miranda River is bimodal with a large peak in January/February (driven by rainfall in the headwaters) and a second, smaller peak in May/June (caused by back flooding from the high water levels in the Paraguay River) (Hamilton, 2002b) (Fig. 17.17).

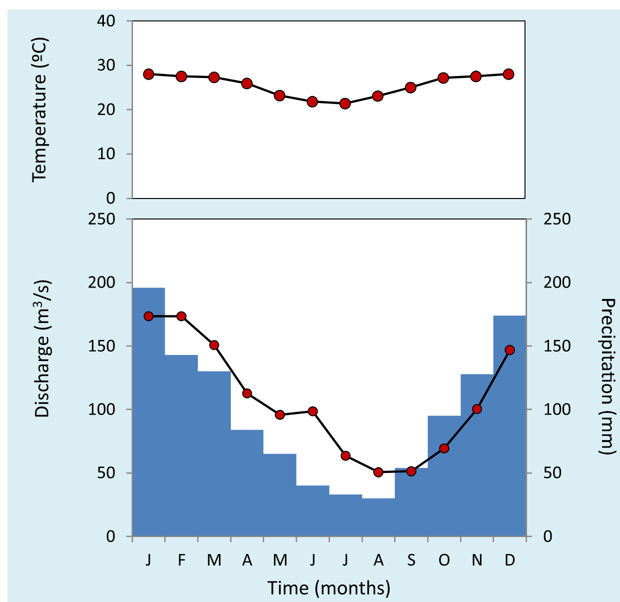

FIG. 17.17 Miranda River basin. Temperature and precipitation (*bars*) at the river mouth (19°24′54″S, 57°19′54″W) and discharge at Miranda station (20°14′19″S, 56°23′03″W). *(Source: Discharge and rainfall, www.snirh.gov.br/hidroweb/; temperature and precipitation, https://www.worldclim.org/.)*

The lower Miranda River has higher suspended sediment concentrations (206 mg/L) than the Aquidauana River (127 mg/L), but both have the same turbidity (32 NTU). Water transparency of the Miranda River decreases from headwater to mouth, with higher values in the rainy season due to higher sediment load. Tributaries of the Miranda River in the Serra da Bodoquena have lower sediment loads and higher transparency (Turbidity <5 NTU). In the Miranda floodplain, the suspended sediments increase again (189 mg/L), while turbidity reaches 16 NTU (Súarez, pers. obs., 2018–2020 averages).

17.6.3.3 Water chemistry

Water temperatures vary strongly between summer (~30°C in January) and winter (19°C in July; Oliveira and Ferreira, 2003). Air temperatures average 24–26°C. Above the confluence with the Aquidauana, the Miranda River has higher total nitrogen (0.54 ± 0.44 mg/L) and total phosphorus (0.25 ± 0.27 mg/L) concentrations than the Aquidauana River (nitrogen 0.38 ± 0.15 and phosphorus 0.11 ± 0.06 mg/L), resulting in intermediate nutrient concentrations in the lower section of the Miranda River (total nitrogen = 0.37 ± 0.14 mg/L; and phosphorus = 0.10 ± 0.04 mg/L) (Oliveira and Ferreira, 2003; Oliveira et al., 2019). In general, these values are ~9.8% (nitrogen) and 15.4% (total phosphorus) higher than in other watersheds in Pantanal, and the total phosphorus concentrations are close to or slightly above the 0.1 mg/L limits for waters adequate for biodiversity conservation and human use (with conventional treatment) (Resolution CONAMA 357/2005). Cattle ranching and agriculture are considered responsible for these elevated values (Moreschi et al., 2015).

The headwaters of the streams originating on the Serra de Bodoquena, a ca. 250-km-long carbonate strip expanding in the north-south direction (almost parallel to the Paraguay River, at a distance of ca. 120 km) are strongly influenced by dissolved calcium carbonate (Corrêa et al., 2018). Limestone caves and cave streams are common in this region.

As a result, despite the Miranda River contributing only 10% of the discharge of the Paraguay River, it is responsible for 29% of its dissolved load in terms of bicarbonate ions (HCO_3^-) (Oliveira et al., 2019). Aquidauana waters have lower electrolyte concentrations, mostly alkaline earth metals (Na^+ and K^+) in response to the sandy soils that predominate in the catchment. The Miranda River is slightly more alkaline due to larger magnesium concentrations from Bodoquena Plateau. Along the upper and middle sections of the Miranda River, nutrient concentrations (ammonium, nitrite, and phosphorus) increase, but chlorophyll values of the phytoplankton vary irregularly due to the influence of local tributaries, whereas in the lower (floodplain-connected) section of the basin, limnological variables are more stable (Oliveira et al., 2019).

As with the floodplain water bodies of the Paraguay mainstem, the rapid decomposition of accumulated plant litter at the beginning of the flood period lowers the values of dissolved oxygen from January to May (~2.1 mg/L) compared to the rest of the year (~ 5.2 mg/L), with the lowest concentrations of dissolved oxygen (~0.3 mg/L) and the highest concentrations of free carbon dioxide (>100 mg/L) floodplain channels (during "dequada" events, see above). Organic pollution on the Miranda River by the human population in the basin (~270,000 inhabitants) is estimated to be 4500 tm of BOD per year, most of which are concentrated in urban agglomerations (18% from Aquidauana and 11% from Anastácio cities) (Moreschi et al., 2015).

17.6.3.4 Biodiversity

Vegetation

The headwaters of the Miranda River basin are mostly within the Cerrado (Woody Savanna) biome with semideciduous forest and contain some pockets of inland Atlantic forest in the upper Bodoquena Plateau. The lower sections are divided between the seasonal floodplain savanna of the Pantanal wetland and the seasonal dry tropical forests of the Chaco biomes. The southwestern portion of the basin displays large monodominant stands of *C. alba* (Carandá; Fig. 17.8) and *T. aurea* (Paratudo), both highly adapted to the specific soil and flood conditions. Stands of *T. aurea* are species-poor with only 13 arboreal and 65 herbaceous species. A rapid assessment of the flora of the headwaters of the Negro, Aquidauana, and Miranda rivers revealed 431 species from 111 families (Damasceno-Júnior et al., 2000). These authors estimate a threefold number of taxa if detailed analyses were made.

Riparian vegetation

Woody vegetation assemblages of floodplain forests in a studied transect of the lower section of the Miranda River comprise 46 species, with 2 predominant families Meliaceae and Fabaceae (Battilani et al., 2005), and 4 dominant species (*I. vera, Ocotea suaveolens, Handroanthus heptaphylla,* and *Cecropia pachystachya*); the seasonal flooding for >2 months determines the species composition, with low diversity in locations with high number of flooding days (Wittmann et al., 2008). A rapid assessment of the Lower Negro and Taboco rivers revealed 239 plant species from 81 families (Foster et al., 2000), with typical riparian tree species such as *A. castaneifolia, I. vera, A. phalerata, F. insipida, T. americana,* and large stands of the flood-resistant Cambará (*V. divergens*).

Macrophytes

From the swift and often-shaded headwaters of the Miranda and Negro Rivers to the lower sections and lagoons, the

FIG. 17.18 *Victoria cruziana*. (*Photos: Yzel R. Súarez.*)

composition and dominance of aquatic macrophyte assemblages change from current-adapted species (e.g., *Potamogeton illinoensis*) to species restricted to slow-moving waters and high light incidence (e.g., *Victoria cruziana*; Fig. 17.18) (Catian et al., 2018; Pott et al., 2011b), while on the river banks, *P. azurea* is dominating. The crystal-clear waters of the limestone-influenced waters of the Serra de Bodoquena region harbor an extraordinarily high diversity of subaquatic plant species such as algae, bryophytes (e.g., *Riccia fluitans*), and more than 50 vascular macrophytes (e.g., genus *Echinodorus* (6 species), *Ludwigia* (2 species)), including several carbonate-precipitating species (*Isoëtes pedersenii* in lakes, *Chara fibrosa, Chara rusbyana* in streams), making these "submerged gardens" favorite sites for ecotourism (Scremin-Dias et al., 1999; Carvalho et al., 2019).

Plankton

Data on phytoplankton assemblages in the Miranda River are scarce, with 37 genera reported, dominated by Cyanobacteria and Chlorophyceae (11 genera each) in a small reservoir at Córrego Alegre (Miranda River) (Vieira et al., 2009). Thirteen Cladoceran species were referred to in the Miranda River basin and 13 Ostracoda in the lower basin (Higuti et al., 2017; Zanata et al., 2017).

Macroinvertebrates

Nearly 200 benthic and semiaquatic macroinvertebrate taxa were inventoried for the basin, including permanent and intermittent streams in the karstic headwaters (Roque et al., 2017; Valente-Neto et al., 2020). At the genus level, the macroinvertebrate assemblages are similar to those described above for the headwaters of the Paraguay and Cuiabá rivers, with typical genera of Ephemeroptera (*Microphlebia, Traverella, Farrodes, Ulmeritoides, Hexagenia, Camelobaetidius, Cloeodes, Caenis, Leptohyphes*), Plecoptera (*Anacroneuria*), and Trichoptera (*Leptonema, Smicridia, Macronema, Chimarra, Polycentropus, Helicopsyche, Xiphocentron, Phylloicus, Triplectides, Oecetis*). Intermittent streams, however, have a higher contribution to beta diversity with some species of Coleoptera (*Derallus, Hexacylloepus, Tropisternus*), while three chironomid genera (*Endotribelos*, *Stenochironomus*, and *Tanytarsus*) are associated with perennial streams (Valente-Neto et al., 2020).

A study on dragonflies from Bodoquena Plateau registered 111 species with the highest number of species in the Libellulidae family (50 species), followed by Coenagrionidae (43 species) and Gomphidae (12 species) with a first record of *Phyllogomphoides suspectus* (Koroiva et al., 2017).

In the Middle and Lower Negro River and adjacent floodplain lakes, benthic invertebrates were sampled with Petersen grabs and detailed lists provided for oligochaetes (28 taxa), water mites (10 taxa), and mayfly larvae (7 taxa) (Takeda et al., 2000). Mayfly larvae of the genus *Campsurus* are known to migrate from the margins toward the center of lakes to avoid desiccation when water levels fall (Takeda and Grzybkowska, 1996). Decapod crustaceans include palaemonid shrimps (*Macrobrachium amazonicum, Macrobrachium brasiliense, Macrobrachium* *jelskii, Palaemonetes ivonicus, Pseudopalaemon* spp.) and trichodactylid crabs (*Dilocarcinus pagei, Silviocarcinus australis, Trichodactylus borellianus, Valdivia camerani*) (Magalhães, 2001).

Fishes

The Miranda River has a high diversity of fish species. In the Lower Miranda, 101 species were recorded, while in small tributaries in the upper section, the number reaches 145 species (Ferreira et al., 2017a and citations therein). In a long-term study (21 years) in a single marginal lake in the lower Miranda, 97 fish species were recorded, representing ~40% of the ichthyofauna known for the Pantanal (Severo-Neto et al., 2015). The total estimated number of species for the Miranda River is 185 species for the entire river basin, with a predominance of Characiformes (92 species), followed by Siluriformes (59 species) and Cichliformes (16 species). Most of these species are considered Least Concern (170 species), and 3 commercially important species are Near Threatened (by damming and overfishing): *Piaractus mesopotamicus*, *Pseudoplatystoma corruscans*, and *Zungaro jahu*.

The 1.3-m-long redtail catfish *Phractocephalus hemioliopterus*, a long-distance migrator from Amazonia, has been registered in the Aquidauana River since 2009 as non-native species and it is yet unknown how it got to the Paraguay River or how it possibly interferes with the native fauna. The crystal-clear waters of the Serra de Bodoquena streams, with large schools of *B. hilarii* and other larger characids (Nunes et al., 2020), and the high diversity of fish species known from aquaria, such as tetras (*H. eques, G. ternetzi*) or loricariids (*Hypostomus* spp., *Farlowella* sp.), are very attractive for ecotourism (Scremin-Dias et al., 1999) and allow detailed studies on habitat use and community structures (Nunes et al., 2020; Severo-Neto et al., 2023).

The Miranda River alone contributes 24% of recreational fisheries in the entire Paraguay basin (compared to 65% in the mainstem (Catella et al., 2020)). Recreational catches have decreased in the 1994–2016 period (in the Miranda: ~13 to 1.7 t and Aquidauana: ~74 to 1.4 t). In the Aquidauana River, the professional catches decreased from 44 t in 1996 to 2 t in 2006. Recreational and professional fisheries target different species. Piau (*M. macrocephalus*) is the main recreational species (~25%), followed by Pacu (*P. mesopotamicus*; with ~15%) and Spotted Sorubim (*P. corruscans*; ~10%). Professional fisheries are more focused on larger species with higher commercial value, e.g., *P. corruscans,* 32%; *M. macrocephalus,* 15%; and *P. reticulatum,* 14% (Fig. 17.19).

Amphibians and reptiles

Amphibian studies targeted mainly the Bodoquena Plateau and the Miranda River floodplain (Melo et al., 2021), with 103 amphibian species registered (102 Anura and 1 Gymnophiona). Most of the amphibians (80 species) are considered Least Concerned; the remainder of 23 species are data-deficient. Only 1 species occurred exclusively in the floodplain (*Rhinella paraguayensis*); 41 species occurred only in the highlands and 61 species in both environments. Comparative multisite studies such as the AquaRap suggest that the habitat (and species) diversity of the high plains is higher but the abundance is lower than in the Pantanal (Strüssmann et al., 2001).

Common aquatic reptiles are similar to those described in the Cuiabá River, (Strüssmann et al., 2011). At the EMBRAPA research station Fazenda Nhumirim, among the 172 snake species, 33% were considered fossorial or cryptozoic, with *Typhlops brongersmianus* being the most common species (Wang et al., 2005). In the piedmont zone, Schneider's dwarf caiman (*Paleosuchus trigonatus*) has their southernmost expansion.

Birds

Water-bound bird and mammal species of the Miranda catchment are very similar to those already described for the Paraguay and Cuiabá rivers (see above). Many piscivorous bird species (herons, egrets, cormorants, anhingas) use collective nests in trees at the river nearshore (ninhais, see Section 17.6.2.4). The occurrence of bird-feeding guilds is spatially and temporally structured by the inundation gradient, e.g., the period of receding waters is characterized by an increase in the number of species in guilds that consume nectar, invertebrates, vertebrates, and (or) plant parts obtained or captured in the drying landscape and terrestrial habitats (Figueira et al., 2011). Godoi et al. (2016) provides a detailed analysis of the habitat relationships of 156 bird species in the Bodoquena Mountains, including riparian zones of headwaters, which had lower bird abundance and richness than woodland savannas, seasonal forests and arboreal savannas.

Mammals

The Southern Pantanal tends to have more mammal species per square kilometer than any other type of tropical ecosystem, which is influenced by the heterogeneity of habitats interacting with other ecosystems surrounding the Pantanal (Tomas et al., 2011). Endangered deer species such as marsh deer (*B. dichotomus*) and pampas deer (*Ozotoceros bezoarticus leucogaster*) still occur in the Miranda catchment (Tomas et al., 2001a,b). Giant otters (*P. brasiliensis*) appear to be recovering from the severe population decline due to poaching in the 1960s and are currently estimated to 0.54 ± 0.15 individuals per kilometer of rivers and creeks in the Pantanal (Tomas et al., 2015). The capybara (*H. hydrochaeris*) is the most abundant larger mammal species occurring in groups varying from 6.5 to 14.8 ind/km^2 (Alho et al., 2011). Flood

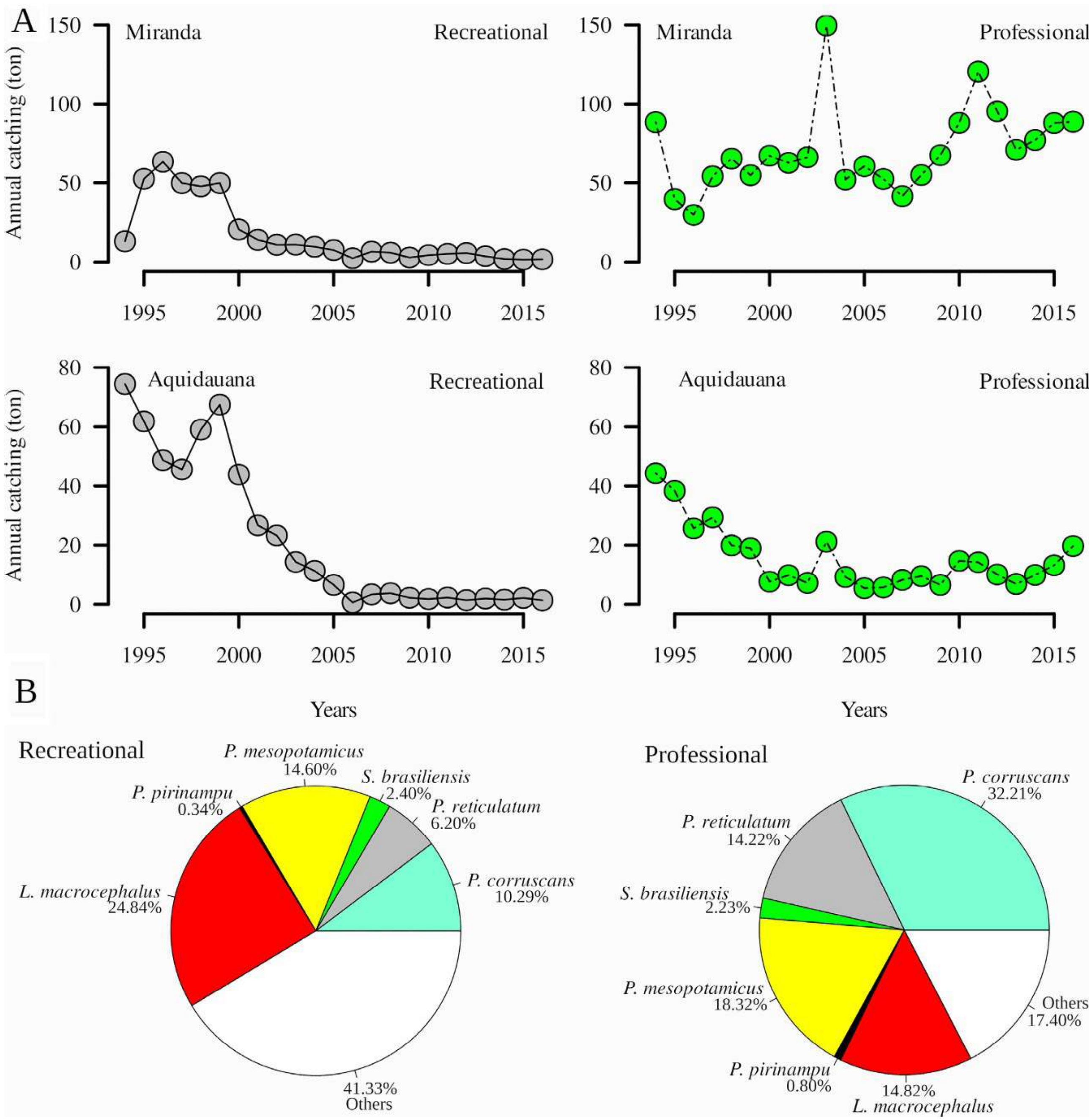

FIG. 17.19 (A) Development of fisheries (recreational fisheries in Miranda and Aquidauana, professional catches in the Aquidauana) in the 1994–2016 period. (B) Recreational and professional fisheries catches of different species in the Miranda River basin.

periods soften the termite mounds and make them more vulnerable to attacks by Giant Anteaters (*Myrmecophaga tridactyla*) (Möcklinghoff et al., 2018).

17.6.3.5 Environmental problems

Compared with the previously described Paraguay and Cuiabá headwaters, the problems caused by damming in the southern tributaries to the Pantanal wetland are so far somewhat lower, however, the erosion problem is regionally higher. The Taquari River, a left-hand tributary to the Paraguay north of the Negro and Miranda rivers, has become a symbol for excessive erosion in the highlands and deposition of sediments in alluvial fans in the transition zone between uplands and Pantanal, resulting in siltation and fast braiding rivers in alluvial fans, locally called “taquarization” of rivers (Assine, 2005; Buehler et al., 2011; Hamilton et al., 1998).

Nearly 55% of the Miranda River basin was deforested to provide agricultural areas (for cattle raising, soy bean, corn, or sugar cane), resulting in erosion and changes in the flood regime by reducing the catchment's water storage and buffering capacity (Bergier, 2013; Roque et al., 2016; Corrêa and Utz, 2023). The water quality is still considered good in most of the whole basin (Roche et al., 2022), but locally, e.g., in the Aquadauana river, nutrient concentrations (phosphorus), but also those of toxic metals (Al, As, Cd, Cu, Pb), exceed the legally permitted limits (Viana et al., 2022).

The seasonal floodplain meadows in the Miranda River basin are still relatively well preserved because of the traditional, extensive cattle breeding on near-natural pastures (Santos et al., 2011). The headwater area of the Aquidauana River is more deforested for cattle breeding than the Bodoquena region. Headwater zones for tourist-used streams are strictly protected.

By the beginning of the 21st century, sport fishing activities increased in the lower section of the Miranda River, often affecting the riparian forests (which are preserved by federal law) from deforestation; littering (sports fishers can become a major source of plastic deposits in remote areas (Garello et al., 2021)). The impacts of ecotourists can also affect the benthic invertebrates (Escarpinati et al., 2011) and fish. The release of untreated sewage from hostels to the rivers has impacted some sections of the karstic streams (Escarpinati et al., 2011).

Water-bound ecotourism (snorkeling, diving, cave-tourism) focuses on the clearwater streams and lakes near Bonito (Scremin-Dias et al., 1999), resulting in social inequalities, rapid changes in the traditional use forms (see the debate in Wantzen et al., 2023c), and locally, organic pollution of the water (Lima et al., 2014). But ecotourism also provides options for payment for ecosystem services (Pelicice et al., 2022).

Recommendations to improve conservation include (i) reinforcing current environmental legislation, (ii) implementing more legal reserves (Guerra et al., 2020a), (iii) reforesting illegally deforested areas with native species, (iv) adapting agricultural practices and pesticide use, (v) to protect vereda-like headwater wetlands, and (vi) to encourage the implementation of private reserves (Damasceno-Júnior et al., 2000).

17.6.4 Apa River

17.6.4.1 Physiography, geomorphology and land use

The Apa River is located at the frontier between Brazil and Paraguay in the southern section of the Upper Paraguay River Basin. Compared with the previously described rivers, it has a smaller floodplain area, with a higher natural sediment load and higher flow velocity due to its high declivity. The river originates in the Serranía de Mbaracayú ~670 m a.s.l. near the city of Ponta Porã, Brazil, and it is known for its great scenic beauty. The Apa discharges into the Paraguay River at Porto Murtinho at ~72 m a.s.l. Its length is ~500 km (Fig. 17.20). The total area of the basin is 15,617 km^2, of which nearly 80% is in Brazil and 20% in Paraguay. The headwater region is predominantly composed of basaltic rocks. In contrast, the headwaters of its main tributary, the Perdido River, are karstic limestone rocks, which result in crystal-clear waters that flow through caves in some stream reaches. This subterranean flow is the basis for its name, as the river temporarily "gets lost," to reappear farther downstream. The headwaters of Perdido River are protected by the Serra da Bodoquena National Park and some small Private Reserves of Natural Heritage (RPPN in Portuguese).

Geologically, the rock formations of the Apa River are part of the Rio Apa Block, which comprises a Paleoproterozoic crustal segment limited to the east by pelitic-carbonatic rocks of the Corumbá Group (Serra da Bodoquena) and to the west by Cenozoic sediments of the Pantanal Basin. The Rio Apa Block is further subdivided into Eastern and Western domains, limited by a suture zone with a predominant N-S direction. The Western Domain is represented by the Porto Murtinho Complex, the Morro do Triunfo Complex, the Serra da Alegria Suite, the Alumiador Intrusive Suite, the Serra da Bocaina Formation, and the metasedimentary rocks of the San Luís Group. The Eastern Domain is made up of the Caracol Gneiss, the Alto Tererê Group, and the Paso Bravo Complex (Lima et al., 2017).

The Apa River is in the transition zone between tropical and subtropical climates, however, the tropical zone has no dry season (*Af*) (Alvares et al., 2013; Souza et al., 2022). Rainfall is higher at the headwaters (1300–1500 mm/year) than in the area that drains into the river mouth (~1150 mm/year) with a rainy season from September to March (~67% of accumulated rainfall) and a hydric deficit in the lowland portions from July to August.

Approximately 35.5% of the basin area is used for agriculture (mostly, planted pasture for cattle breeding), nearly 3.5% is natural grasslands, and ~0.1% as urban areas, resulting in approximately ~39% of the basin being affected by human activities. The remaining area is occupied by Cerrado vegetation (~31%) and Inland Atlantic Forest formations (30%) (Sousa et al., 2020). The influence of the Chaco on the Apa River subbasin is minimal on the left bank (Paraguay). The sandy sediments dragged by the water in periods of flooding inundate a large part of the coast and penetrate up to 500 m or more, for a short time. These river-borne sediments strongly influence the vegetation in this periodical floodplain.

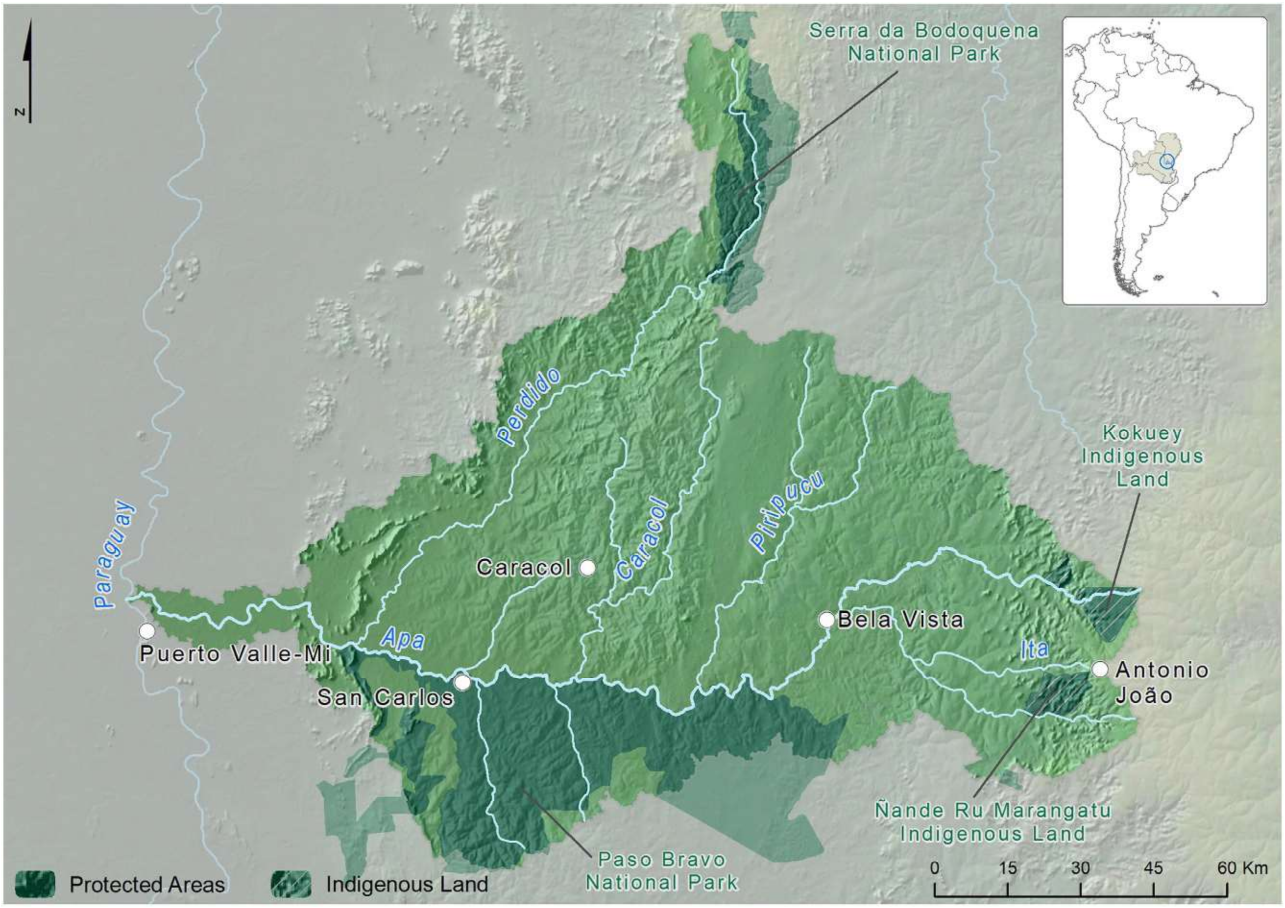

FIG. 17.20 Apa River basin (15,617 km^2; 80% in Brazil and 20% in Paraguay). Land cover: Agriculture, 35%; grasslands, 35%; forests, 30%. Average catchment elevation, 236 m a.s.l. (72–700 m a.s.l. range). Population density, 3.6 inh/km^2. Largest city, Bela Vista (24,842). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

There are only a few small urban areas in the upper portion of the Apa River Basin, which do not cause substantial changes in the water quality of the river, but the urban waters of Porto Murtinho flow directly into the Paraguay River. As of 2007, three-quarters of the about 52,000 inhabitants of the Brazilian part lived in urban areas (Terra et al., 2014).

17.6.4.2 Hydrology

In the lower Apa River and its tributaries, the water temperature varies from 24°C in the dry (winter) to 28°C in the wet (summer) season. The estimated discharge (near the Caracol and Perdido Rivers confluence) is 81.3 m^3/s (1971–2002 period) (Gonçalves et al., 2011; Fig. 17.21). The average discharge of the Perdido River was ~18.6 m^3/s in the wet season from October to March 2017–2019 (Suarez, pers. obs.).

Due to the karstic bedrock, turbidity in the Perdido is much lower (22 NTU) than in the Apa River (144 NTU), making the former, along with its scenic waterfalls and abundant submersed vegetation, a prime site for ecotourism (Fig. 17.22). The suspended solids in the Apa River increase from headwaters (169 mg/L) to the middle section at the confluence of the Caracol River (407 mg/L), but they decrease to 123 mg/L in the floodplain section near the river mouth when the suspended sediments of the Caracol have settled out (Suarez, pers. obs.).

17.6.4.3 Water chemistry

The waters of the Apa River are slightly basic (average pH 7.3, range 5–8.9), with oxygen concentrations ranging from 1.9 to 8.8 mg/L, turbidity 7.2–746 NTU, low conductivity (7–303 μS/cm), displaying an increase of turbidity (indicating erosion in the catchment) in the period from 1999 to 2015 (dos Santos et al., 2017), and total nitrogen varying from 0.2 to 0.5 mg/L (values as of 2020 above the city of Bela Vista, IMASUL, 2020). The total phosphorus concentration in the Apa River is low (headwater, 0.13; middle section, 0.17; lower section, 0.14 μg/L) despite the middle section being cleared for pastures (nearly 60%).

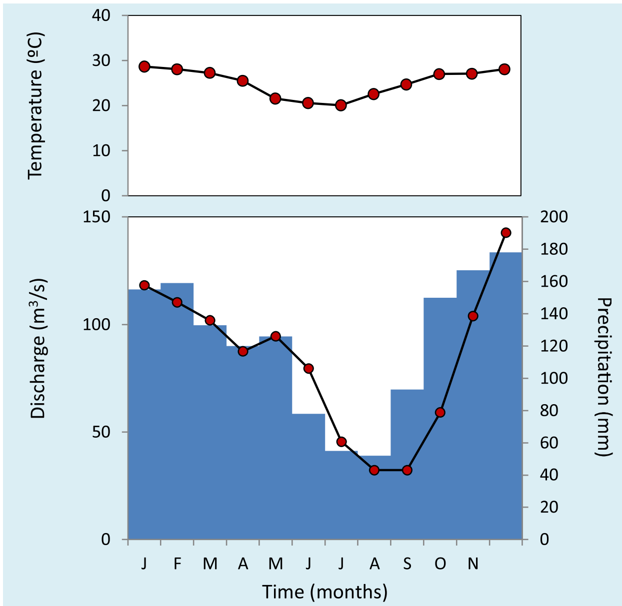

FIG. 17.21 Apa River basin. Temperature and precipitation (*bars*) at the Apa River mouth (22°5′41″S, 57°59′38″W) and discharge at São Carlos (22°13′25″S, 57°18′14″W). *(Source: Discharge www.snirh.gov.br/hidroweb/; temperature and precipitation, https://en.climate-data.org.)*

17.6.4.4 Biodiversity

Vegetation

In the humid Chaco savanna on the Brazilian side, the diversity of angiosperms is high with 377–388 species identified and 439–585 species estimated, with a predominance of Leguminosae (Sartori et al., 2018; Castuera-Oliveira et al., 2020; NeoTropTree, http://www.neotroptree.info) (Fig. 17.7). In the Cerrado portion of the Apa basin, large trees such as *Anadenanthera peregrina*, *Samanea tubulosa*, *Myrocarpus frondosus*, *Psidium grandifolium*, and palms (Arecaceae, with a dominance of *Attalea phalerata*) are common (Castuera-Oliveira et al., 2020). The Apa River harbors one of the few areas with a Chaco vegetation in Brazil, including four subclasses: Tall trees, with *A. quebracho-blanco*, Hawthorn and cacti (e.g., *Echinopsis rhodotricha*), Caranda palm stands (*C. alba*), and shrubs and open fields, where grasses and few shrubs predominate (Pott et al., 2008).

Macrophytes

In the headwaters of the Perdido River, similar aquatic and semiaquatic macrophyte species assemblages can occur as in the limestone areas of the Miranda system, including *P. illinoensis*, *Myriophyllum aquaticum*, or *Ludwigia peruviana* (see above and Scremin-Dias et al., 2018). In the Apa River, macrophytes such as *Hydrocotyle ranunculoides*, *Eleocharis debilis*, *Rhynchospora corymbosa*, *Phyllanthus fluitans*, *Pontederia cordata* var. *cordata*, and *Hygrophila guianensis* are common (Chernoff et al., 2001). The limestone rocks of waterfalls harbor charophytes (macro-algae) and wild petunias (*Ruellia angustiflora*) (Pott et al., 2008).

Algae, plankton and macroinvertebrates

To our knowledge, there are no specific studies on the periphytic or planktonic algae, or benthic invertebrates of the Apa River yet; however, similar species assemblages as in the previous subbasins can be expected (see also Zalocar de Domitrovic, 2002). To our current knowledge, there are no published records or ecological studies on zooplankton and benthic invertebrates of the Apa River.

Fishes

The fish fauna of the Apa is relatively well known, with 135 identified species, mostly Characiformes (51%) and Siluriformes (37%) (Y. Súarez, *unpublished data*). Considering that the recent checklist of fish in Pantanal (Upper Paraguay River Basin) includes 269 species (Britski et al., 2007), the Apa River represents ~50% of its species richness. New descriptions and new occurrences are regularly reported.

Two large, migratory fish species are considered Near Threatened (NT) in the Apa River, *P. mesopotamicus* and *P. corruscans*; their stocks are impacted by damming, deforesting, and excessive fishing. Commercial fisheries are prohibited in the whole Perdido River (CECA 006/2000), and recreational fishery is only permitted as catch and release. For local populations, fisheries are authorized to subsistence practiced by artisanal fishermen, except during reproductive migration season (from October to February). In the Apa River, nearly 7.1 t of fish (~1.9% of the catch in Pantanal) were caught in 2016 and nearly 6.14 t were caught (and released) by sports fishers (Fig. 17.23). The Pacu (*P. mesopotamicus*) is preferentially caught by recreational fishers (~31%), while Pintado (*Pseudoplatystoma corruscans*, ~34%) and Dourado (*Salminus brasiliensis*, ~22.6%) are preferred for professional fishing.

Amphibians and reptiles

Currently available, published information on amphibia of the Apa River basin has registered 32 species (Santos et al., 2019). However, field records suggest 46 anuran species (Y. Suarez, *pers. observation*), including *Lepidobatrachus asper*, considered Near Threatened by the IUCN red list. In the Paraguayan part, 88 species of amphibians were recorded (Brusquetti and Lavilla, 2006), and considering that nearly 90% of Paraguay territory is included in the Paraguay River basin it is probable that all of these species occur in the Paraguay River basin. Amphibians of Paraguay include three species Near Threatened (NT: *Crossodactylus schmidti*, *Leptodactylus*

FIG. 17.22 Perdido (A) and Apa River (B) in the Paraguay River basin. *(Photos: Yzel R. Súarez.)*

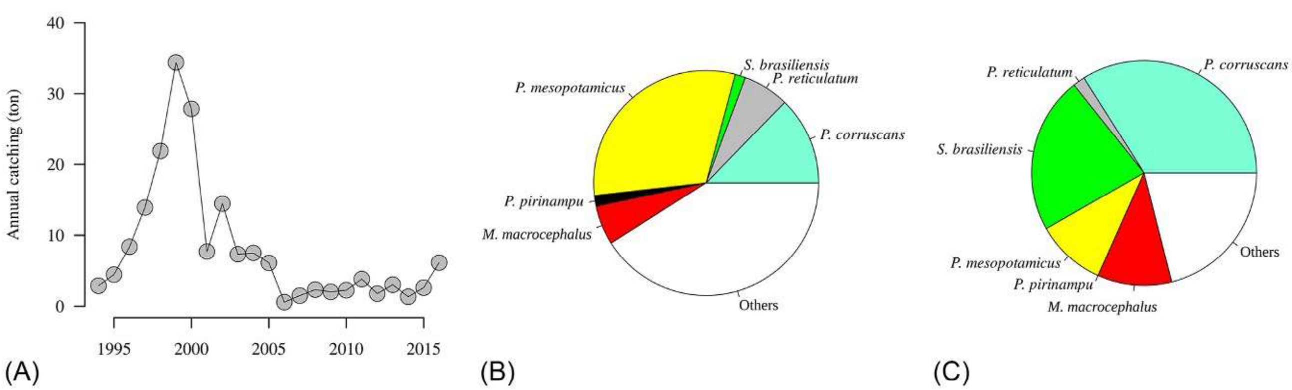

FIG. 17.23 Total fish yields along the years (A) and for species by different groups recreational (B) and professional (C) fisheries in the Apa River in the 1993–2017 period.

laticeps, and *L. asper*) and one species considered endangered (EN: *Melanophryniscus devincenzii*).

In the lower Apa River Basin, on the Brazilian part of the Chaco, a total of 34 amphibian and 39 reptile species were identified (Souza et al., 2010), while for the entire Chaco region of Mato Grosso do Sul State 118 species have been recorded (Ferreira et al., 2017b). In addition to typical water-bound reptile species described for the previous subbasins, two species of side-necked turtles (*Acanthochelys macrocephala, Phrynops geoffroanus*) are present.

Birds and mammals

Avian richness included 630 species for Mato Grosso do Sul State and 412 species for hills of the western Pantanal (Nunes et al., 2021 and citations therein). The only available studies on avian species diversity in the Apa River and parts of the Paraguay River listed 282 species (Straube et al., 2007), indicating a decreasing bird diversity with increasing distance from the river channel. In addition to the typical water-bound species mentioned above, 10 species of herons, including *Syrigma sibilatrix, Pilherodius pileatus,* and *Butorides striata*, and migratory shorebirds such as *Pluvialis dominica, Bartramia longicauda,* and *Calidris melanotos* were observed. The mammal study nearest to the Apa River has been performed in the Bodoquena mountains, citing 56 species (including 14% rare or endangered species), with *Artibeus jamaicensis, Cerdocyon thous,* and *Procyon cancrivorus* being the commonest species at gallery forests (Cáceres et al., 2007).

17.6.4.5 Environmental problems

The fast growth of agriculture in the Apa region triggered a substantial conversion of natural vegetation into acres. Larger parts of the Perdido River basin are protected in the Serra da Bodoquena National Park and two municipal parks, but in the unprotected parts, deforestation and land conversion for cattle ranching and culture of soy and dry rice have increased since 1970. The rapid land conversion in the Chaco (near to 1 ha/min from 2008 to 2018, as estimated by the NGO Guyra Paraguay, https://guyra.org.py), affects especially the flora, e.g., the tree species *Prosopis rubriflora* is considered endangered in Paraguay by the IUCN red list.

The upper Apa River and middle to lower Perdido River basins (~13% of the basin) have high erosion rates because of steep slopes, urbanization (Antônio João and Ponta Porã), and the sandy texture of soils (Barbosa et al., 2016). The excessive release of sediments into the tributaries results in habitat siltation, abrasion of food sources, increased turbidity, and die-back of gallery forest (Wantzen and Mol, 2013 and Section 17.6.2).

Apart from direct habitat losses, the need for irrigation results in water conflicts and international treaties between Brazil and Paraguay for shared management of the basin (Broch, 2008). These water conflicts are worsened by climate change and the fast-growing trend for small hydroelectric power plants (Pequenas Centrais Hidrelétricas), which are currently being built or planned in the Apa River basin, specifically at the Perdido River. Apart from the effects on large migrators (as discussed for the Cuiabá River basin, above), many smaller fish and invertebrate species will lose access to their spawning grounds, and water-bound species including freshwater turtles and amphibia will lose their habitats. The regional increase in small dams is altering sediment transport and water quality (Fantin-Cruz et al., 2020; da Cruz et al., 2921). Karst systems are specifically sensitive to hydrological changes and pollution (Filipović Marijić et al., 2018). The stepwise modification of the seasonal flood pulse will affect the natural dynamics (and size) of the floodplains in the lower sections. The planned construction of a Transoceanic Road may accelerate land use changes in the region, mainly from pasture to soy bean plantations.

17.7 Management and conservation

Despite its high biodiversity, the Paraguay River basin is still underrepresented in scientific studies, in terms of both geographical and taxonomical coverage. Sampling effort data (Fig. 17.7) reveal that biodiversity records rather follow the nearness to academic centers than the distribution of characteristic habitats. Initiatives such as AquaRAP rapid-assessment expeditions to the less-studied southern regions of the Paraguay River and its tributaries (Chernoff et al., 2001; Magalhães, 2000, 2001; Willink et al., 2000), and permanent efforts by federal and state universities (e.g., the diverse PELD (programa de pesquisas ecológicas de longa duração) sites for long-term ecological studies), and the EMBRAPA research center and museums are very important (see, e.g., the book by Junk et al., 2011 for reviews on diverse taxa in the Pantanal, or the ABLA book series, e.g., Dominguez et al., 2006). However, more systematic (and permanent) monitoring is urgently needed, especially for species groups that are sensitive to overexploitation (e.g., commercial fish species), habitat fragmentation (migratory fish), hydrological changes (wetland vegetation), and habitat overuse (flora and fauna of terra firme habitats). Impacts, e.g., by invasive species, remain undescribed. Red lists are incomplete.

Studies of the transformation of natural landscapes into intensively used agroscapes in the watershed of the Paraguay River began following the use of satellite imagery of the entire country (RADAMBRASIL, 1973–1983). These studies included the mapping of adequate soils for agriculture, and the subsequent implementation of sponsoring programs by the federal government to appeal to farmers from already-colonized regions (e.g., in the south of Brazil) to settle in the states of Mato Grosso and Mato Grosso do Sul (Guerra et al., 2020b; Siqueira et al., 2018). Modifications of the river course and the floodplain wetlands are more recent, as these have a lower potential to yield an economic return from intensive agriculture (Roque et al., 2021; Tomas et al., 2019; Wantzen et al., 2023a,b).

In Brazil, the National Agencies of Waters (ANA) and Electric Energy (ANEEL) provide monitoring of the hydrometric stations, and state environmental agencies (FEMA, SEMA) are responsible for the enforcement of the laws and the environmental monitoring, while the federal agency for biodiversity conservation (Chico Mendes Institute, in Portuguese: Instituto Chico Mendes de Conservação da Biodiversidade, ICMBio) is in charge of overseeing the conservation laws and the protected areas. Decisions about national and international waterways are made by the federal government, whereas permissions for hydropower dam constructions depend on their size. The smaller power plants require only limited environmental impact assessments, thus their expansion is difficult to control. In Paraguay, decisions are made by the central government regardless of their size, and are executed by the Ministry of Public Works.

In the 1990s, a conservation plan for the Upper Paraguay River Basin (PCBAP, Plano de Conservação da Bacia do Alto Paraguai) was set up by the state agencies and later published (PCBAP, 1997), with the main focus to preserve the water resources. Conservation areas (see Fig. 17.2 for the most important ones) exist at different levels (Harris et al., 2005), ranging from national parks state parks to permanently protected areas (APPs, corresponding to Fauna-Flora-Habitat sites in Europe). There are also Legal Reserves (percentages of private ground in which deforestation is forbidden or limited (Guerra et al., 2020a; Siqueira et al., 2018)) and Private Reserves (RPPN), in which the owner dedicates a part of the terrain to conservation and is compensated by a tax exemption. A special type of conservation area is the "Estrada Parque," which protects sections of a road crossing the Pantanal wetland (and serves as an observation site for its fauna and flora today). The pros and cons of ecotourism (mostly for birdwatching and fishing) concerning environmental conservation and cultural development are currently being debated (Arts et al., 2018; Wantzen et al., 2023b).

However, general management targets by national and regional institutions mainly focus on the progress of hydropower, navigation, intensive agriculture, and tourism, and their respective economic return. Programs to establish and support sustainable development, ecosystem functioning, and conservation of biological and cultural diversities exist, but despite early warnings and precise suggestions by scientists (e.g., Alho et al., 1988; Hamilton, 1999; Tomas et al., 2019; Wantzen et al., 2008), they do not correspond to the magnitude and the increasing tendencies of the environmental problems described above. Moreover, conservation efforts are still not sufficiently targeted to the entire river basin, resulting in conservation areas that are fragmented and commercial interests in single-use environmental assets (soil fertility, hydropower, etc.) are valued higher than the environmental conditions for the functioning of the entire ecosystem. Specifically, the maintenance of the natural hydrological pattern of the flood pulse and environmental flows.

Fish stock monitoring for the entire river basin has been claimed since Ferraz de Lima's early paper (Ferraz de Lima, 1987) but is still incomplete (Mato Grosso do Sul State) or virtually absent (Mato Grosso State) so that the real impacts of fragmentation and overfishing can only be roughly estimated. The early 2020s dramatic increase in fire incidences (Fig. 17.9) compared to the natural fire cycles can be attributed to illegal land conversion, climate change, dam construction, and inadequate management of plant biomass, which may serve as fuel when accumulating (Correa et al., 2022; Leal Filho et al., 2021; Pivello et al., 2021).

In addition to the subbasin-specific issues mentioned above, several management challenges are common to the entire river basin, including (1) large infrastructure projects affecting the overall, natural flow pattern and thereby the essential ecosystem functions and biological patterns of the entire river system, such as the Paraguay-Paraná waterway (hídrovia) project, hydroelectric power plants, roads and railway tracks. (2) Land-use change (deforestation), which is driven by cash-crop agriculture and by the intensification of cattle ranching both on the high plains and in the lowlands, resulting in massive habitat loss, increasing intermittency in streams, erosion, and siltation. (3) Mining for metals (in the catchment) and sand (in the river), toxic pollutants, and disturbing the hydrogeomorphology by excess or lack of bed sediments. (4) Climate change and associated water and energy demands by a growing population as well as incidences of human made bush fires that devastate ever larger areas, even during the wet season. The implementation of a plan for climate change mitigation and adaptation, as well as integrating fire management initiatives at a large scale is an urgent need. (5) Control of fisheries, currently lacking a systematic monitoring of fish populations, reinforcement of conservation measures, and a harmonization of those with traditional and indigenous fishers. (6) The insufficient monitoring of biodiversity (specifically sensitive species, invasive exotic species, and novel diseases harming the native fauna and flora), control of direct killing of animals by poaching, bait fishing, and roadkills. (7) Poor knowledge of biodiversity and lack of strategic planning in conservation to restore networks of sufficiently sized habitats. (8) Insufficient urban planning, resulting in the disconnection of urbanized subcatchments, a transformation of urban streams and wetlands into sewers and built space, and the increasing pollution with untreated sewage, plastics, and toxic substances. (9) Maintenance of traditional ecological knowledge and cultural diversity and their valuation for sustainable management concepts, and the reinforcement of socio-ecological conditions, in which these cultures may thrive and evolve. (10) Legal reinforcement of the existing laws and better legislation for the conservation of floodplain wetlands, including an integration of the established typology and boundaries of wetlands into conservation planning. (11) Economic initiatives and alternatives to the present, exploitation-oriented, nonsustainable commerce, and management, such as an improvement of value chains based on the strictly controlled and sustainable use of native species, incentives for bioeconomy, payments for ecological services, carbon markets, and One Health programs. (12) Transboundary cooperation across state and national borders. Moreover, due to climate change and the synergetic effects and dimensions of the human impacts, an overarching planning considering all these processes synchronously is needed.

Agendas and suggestions have been continuously produced by academia, native and traditional communities, NGOs, and state agencies (e.g., Alho and Sabino, 2011; Junk et al., 2006; Roque et al., 2018; Tomas et al., 2019; Wantzen et al., 2023c). Informed decision-making is critical to support sustainable development. As with all types of restoration and conservation projects, adequate communication among the different interest groups, and a match between bottom-up (participative) and top-down (governmental) initiatives is decisive for success (see, e.g., Wantzen et al., 2019; Yousry et al., 2022). The current efforts taken in the context of the PELD program (the Brazilian Long-Term-Ecological Study program, with two sites in the Pantanal), the National Institute for Wetlands at the Federal University of Mato Grosso (implementing a standardized wetland typology for Latin America (Junk et al., 2014; Nunes da Cunha et al., 2022)), combined remote sensing and geostatistical approaches to assess the vegetation (Arieira et al., 2011), and overall biodiversity (e.g., by acoustics, see https://cobra.ic.ufmt.br) need to be further supported. For an analysis of the published research and active research groups, see da Silva et al. (2022).

Despite the large conservation units such as the Pantanal National Park, the UNESCO World Heritage Site, and diverse private reserves such as SESC Pantanal, the connectivity among these sites, the conservation of species diversity on nonprotected sites, and the integration of legal reserves (Guerra et al., 2020a; Siqueira et al., 2018; Tomas et al., 2019) need to be improved and the protected area increased under bio-strategical aspects (i.e., to maintain the evolutionary potential of populations). This need includes the full protection of rivers from the headwaters to the mouth to maintain migratory fish populations, the defragmentation of habitats by establishing vegetated corridors across landscapes, and most importantly, the recovery of the natural flow regime by a strict limitation of further dam constructions and the nonrealization of the currently planned transformation of the Paraguay River into a navigation channel (hidrovia, Wantzen et al., 2023a,b), which would put the entire Pantanal, considered a biome by the Brazilian Government, at stake.

17.8 Web pages of interest

National (Brazilian) Institute for Wetland Science INAU—https://www.inau.org.br/site/.

Pantanal Research Center—https://www.cppantanal.org.br/.

Upper Paraguay Catchment Conservation Plan—https://www.imasul.ms.gov.br/plano-de-bacia-do-alto-paraguai-2/.

University work groups—https://www.ecologia.ufmt.br/, http://www.lemarpe.wix.com/lemarpe, https://coexistenciaufms.wixsite.com/index.

COBRA research unit on computational bioacoustics—https://cobra.ic.ufmt.br.

Catálogo de Plantas Vasculares del Cono Sur—http://www.darwin.edu.ar/Proyectos/FloraArgentina/Generos.asp.

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