The Pantanal: A Seasonal Neotropical Wetland Under Threat

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Abstract

Although wetlands are associated with water, their conservation can be a challenge at present days: Wetlands can lose water and be water insecure. The

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Pantanal is the largest continuous wetlands in the world, highly regulated by precipitation. However, precipitation has been substantially reduced from the past years. The present text explains how this can happen to wetlands and it will show the chain of causality through a conceptual model. The reduction in precipitation, caused by the accretion of the deforestation in the Amazon, reduces the amount of water that is shared in the Pantanal. The construction of dams in the plateau of the Pantanal holds the water that flows to the plain, where the use of the rivers as waterway reduces the capability of the water overflow (from rivers to the floodplain). Drier soil, deforestation, introduction of new crops, intense fire, and even more pronounced lack of rainfall are of high concern for water security in the biome. The water security and the culture of the "pantaneiro" must be taken into account to reach the wetland sustainability. A systemic view can promote a regard on the interdependencies between social and environmental processes related to the production and impacts of water scarcity in this wetland, also encompassing the plain and plateau relationship and the territories management outside and beyond the catchment borders.

Keywords

Water security · Systemic view · Water shortage · Social impacts · Sustainability

1 A Brief Introduction to Wetlands

Wetlands are diverse ecosystems, corresponding to areas that are inundated or saturated by surface or groundwater, at a frequency and duration sufficient to support determined types of vegetation and soils. Their flora is typically adapted for life under these water-saturated conditions and depends on the degree of flooding (Lewis III 1990; Mitsch and Gosselink 2015; Campbell 2020).

Wetlands occur worldwide, and cover about 10% of North America, 20% of South America, 10% of Russia, 7% of China, 3% of tropical and subtropical Asia, 3% of Australia, 7% of Africa, and 5% of Europe (Junk et al. 2013, and see https://www2.cifor.org/global-wetlands/ for a distribution map of global wetlands). Wetlands can be roughly classified in two types: a) wetlands with fluctuations in their water level (also called "flood-pulsing"), including periodical water bodies that may dry up for several years, and b) wetlands which typically have a relatively stable water level (Junk et al. 2014). The sources of water in wetlands are variable, including groundwater, inundation, and backflooding from rivers and streams, and surface runoff (Junk and Wantzen 2004), while the residence time varies with evapotranspiration and substrate porosity. The composition of the water and climate-driven hydrodynamics are, along with the soil type, key factors that control most of the ecological processes. These features vary according to wetland type, which, in turn, have great importance for the hydrological buffering and the flood regime in the entire catchment, due to their "sponge effect" (Acreman and Holden 2013).

Wetlands provide several ecosystem services (supporting, provisioning, regulating, and cultural) related to water, climate, and biodiversity (Mitsch et al. 2015; Jähnig et al. 2021). Although wetlands cover $< 3\%$ of the globe surface, they contribute up to 40% of global annual renewable ecosystem services (Zedler and Kercher 2005), influencing landscape connectivity, rainfall, and biodiversity maintenance (Junk and Wantzen 2007).

In terms of global biochemical cycles, wetlands have a disproportionally important contribution compared to their extension, specifically for the carbon cycle (see Wantzen et al. 2022a, b for a recent review). Primary production by the vegetation, hydrology, and carbon cycle are closely connected. Although carbon (C) input in wetlands can be imported into the system (allochthonous – produced *ex situ*), most of it is produced by the autochthonous (produced *in situ*) vegetation, including phytoplankton, macrophytes, and woody plants (Kendall et al. 2001). The low oxygen concentration in the waterlogged sediment reduces the capacity of decomposition and mineralization of the C deposited (Reddy and DeLaune 2008), consequently being accumulated in the sediment for a long time (Gorham 1991; Reddy and DeBusk 1991). It is estimated that wetlands are responsible for roughly 30% of the total soil organic carbon (OC) pool in the world (Mitsch and Gosselink 2015). The duration of the waterlogging of the sediments acts as a switch between soil carbon storage or release (Vega et al. 2014), as drying up results in fast mineralization of carbon compounds. However, the release of gaseous carbon (mostly CO_2 and CH_4) also occurs in wet and rewetted sediments. The wet-and-dry cycle of flood-pulsing and seasonal wetlands result in an alternation of aquatic and terrestrial plant biomass and a high productivity (Junk et al. 1989; Junk and Wantzen 2004).

The high temperatures and moist climate in the tropics result in high vegetation biomass (Pan et al. 2013), especially in forested wetlands. Growth-related biochemical processes, such as phosphorus (P) and nitrogen (N) uptake are elevated tropical aquatic plants, especially by the fast-growing, free-floating vegetation (Petrucio and Esteves 2000; Jampeetong et al. 2012), which can absorb large amounts of CO_2 (Morison et al. 2000; Oliveira Junior et al. 2018, 2020). In fact, tropical ecosystems present more N accumulation in the soil and on plant biomass than temperate systems (Martinelli et al. 1999).

Wetlands suffer from direct and indirect human interventions worldwide (Mitsch and Gosselink 2015). Direct losses result from filling, draining, or diversion. A global assessment based on remote sensing data indicated an overall decline of wetland area of 6% between 1993 and 2007 (Prigent et al. 2012), mostly in tropical and subtropical South America and South Asia. Indirect effects such as inadequate land use, wood and peat extraction, fires, and invasion of exotic plants or animals result in degradation and a reduction of their ecosystem services (Light 2006; Steinke and Saito 2013; Hu et al. 2017).

The natural hydrological regime, which is the key element for the functionality and integrity of wetlands, is most often impacted. Global climate change and a permanently increasing human population with increasing per capita demands on energy, food, and water, they all account negatively on the water budget of continental hydrosystems, especially wetlands. As a case study for this chapter, the focus is on the largest contiguous wetland worldwide, the Pantanal in Central South America, known for its (still) rather harmonious coexistence of humans and nature (Wantzen et al. 2022a, b). A fast proceeding agroindustry and a hydropower boom in its catchments, land use change, and planned channelization in the floodplain, combined with climate change effects, are threatening this global wetland. The chain of causalities is analyzed through a conceptual model and it will also be shown how the combination of wise modern use and traditional ecological knowledge by the inhabitants ("*pantaneiros*") may contribute to sustainability of this wetland.

2 The Pantanal and Its Catchments: From the Plateau to the Plain

The Pantanal is a large transboundary wetland of about 160,000 km^2 in the center of the South American continent, encompassing territories of Bolivia, Brazil, and Paraguay (Junk and Nunes da Cunha 2005; Junk et al. 2011; Fig. 1).

The Paraguay River forms the main hydrographic basin of the Pantanal. This river basin represents the upper section of the La Plata Basin, which encompasses

Fig. 1 Location of the Brazilian portion of the Pantanal and the Upper Paraguay Basin. (Organized by the authors)

territories in Brazil, Bolivia, Paraguay, Argentina, and Uruguay. During the World Water Forum in 2018, the first three countries signed an unprecedented declaration that calls for sustainable development of the Pantanal with all respect to their inhabitants.

The drainage system of the Paraguay River is formed in a plateau, the Chapada dos Parecis, in the state of Mato Grosso, Brazil. Various tributaries to the Pantanal have their sources in this plateau with altitudes above 200 m. They coalesce in the Pantanal, which has originally developed as a deep trough resulting from subsidence processes associated with the uplift of the Andes around 2.5 million years ago (Ussami et al. 1999). This basin has been filled up with sediments (Assine et al. 2015), resulting a low slope with about 6–12 cm/km in the east-west direction and 1–2 cm/km in a north-south direction (Tricart 1982; Tucci et al. 1999). The soil of the Pantanal can be divided into 11 types, where the Gleyic Solonetz is the most present in the plain (22%) followed by Dystric plinthosols (20%) (Amaral Filho 1986). The soil type varies according to the region, flooding, and drainage potential, but the main characterization remains as hydromorphic or semi-hydromorphic (Weber and Couto 2008). Large areas remain waterlogged almost the whole year (Alho and Sabino 2012). During the wet season, where the Pantanal receives water in form of precipitation coming from the Amazon, the flooded area of the water mass reaches 21.409 km^2 and reduces to 3.358 km^2 in the dry season (Fig. 2).

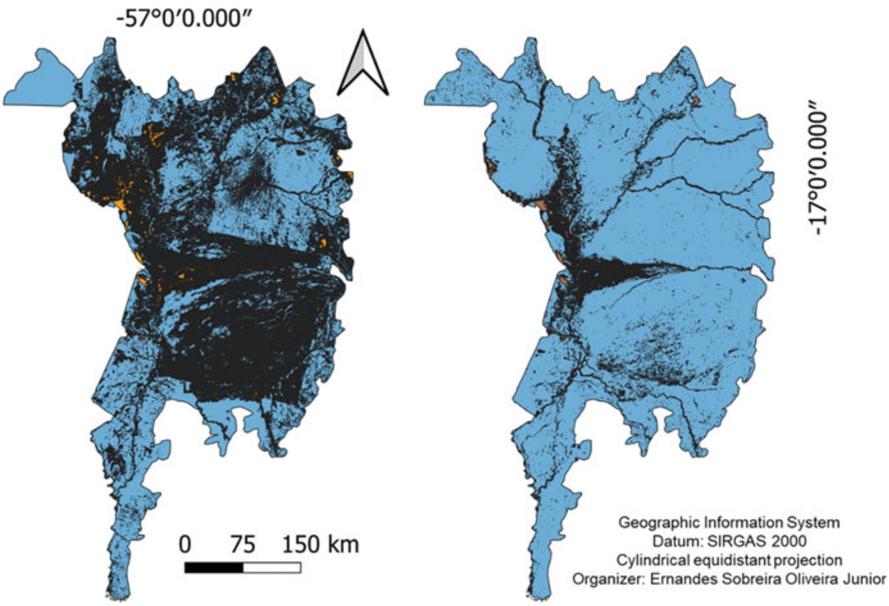

Fig. 2 Inundated areas (black) of the Pantanal (blue) during the dry season (September 2017) and the wet season (February 2018) based on Landsat 5 TM images. Orange areas indicate most expressive water mass. (Original graph)

The average annual rainfall in the Pantanal biome is 1400 mm, ranging between 800 and 1600 mm, and in some years it can reach 2000 mm, occurring seasonally between December and February with a dry season between June and August. In the dry period, the monthly rainfall ranges from 0 to 100 mm, with less year to year (Lázaro et al. 2020).

The annual inundations trigger the hydromorphological, biological, and functional diversity of the Pantanal, including the rhythm of its human inhabitants (Junk et al. 2006, 2011; Wantzen et al. 2022a, b). Flooding displays a north-south propagation. In the north, water levels rise soon after the onset of the rainy season (November–March) while in the drier central and southern parts, tributaries inundate due to backflooding at the mainstem rivers later in the year (Girard 2011; Hamilton 2002). Due to the minimal regional differences in altitude, floodplain channels and even lakes may become flown through in different directions (Wantzen et al. 2005).

Soil type and inundation pattern (determined by the nearness to rivers or lakes and by the elevation) produce a large diversity of landscape units, each with a specific vegetation (Wantzen et al. 2005; Junk et al. 2014). Distinct macrohabitats include floodable fields, so-called "*cordilheiras*" (strands of elevated soil with rarely flooded woody vegetation) and "*capão*" (circular or elliptical forest distributed on periodically flooded natural grassland matrix) (Scremin-Dias et al. 2011). The distribution of functional vegetation forms (grasslands, shrubs, and trees) is determined by the inundation gradient, cattle grazing, and fire. The plant and animal species diversity originates from the position of the Pantanal in the center of four large biomes – Amazonia, Chaco, Atlantic Forest, and the Cerrado (Pott and Pott [2004]; Junk et al. [2006]; and Alho et al. [2019] and see individual chapters on biota in Junk et al. [2011] for reviews). Thirty-six percent of the Pantanal plants are Cerrado species (Silva et al. 2000), and wooded and bush formations take the largest portion of the ten phyto-ecological regions (Pott et al. 2011). They also stated that there are 1863 plant species, including a high diversity of aquatic macrophytes. The diverse fauna also derives from diverse biomes; however, the fish fauna is clearly connected to the Plata basin and much less diverse than in Amazonia. The low degree of endemism is attributed to the relatively short existence of the Pantanal in its current physiographic status of less than 10,000 years (Junk et al. 2006).

The annual flood cycle has manifold effects on ecosystem functions and has triggered adaptive strategies by the biota. Most of these processes occur very fast and are locally restricted to "biotic hot spots and hot moments" (Wantzen and Junk 2006). At the end of the dry season, several fish species migrate upstream for spawning in predator-free headwater zones of Pantanal tributaries (*piracema* migration), and their offspring becomes drifted down into the recently flooded areas, in which macrophytes provide shelter and periphyton and invertebrates as food source (Fernandes et al. 2020). Other fish species perform local migrations and also spawn when the flood arrives (Resende 2008). Rising water levels drive terrestrial animals toward the nonflooded (terra firme) habitats and dissolve nutrients and soil-bound carbon. This results in an internal fertilization of the water bodies but also locally to fish kills due to lack of oxygen (Hamilton 2002). During high water levels, aquatic habitats become connected and partially homogenized (Thomaz et al. 2007), which has also effects on the use of territory by the traditional farmers and fishermen (Wantzen et al. 2022a, b). Falling waters isolate water bodies again (which finally dry up with the exception of permanent lakes and rivers), and terrestrial plants and scavenging animals profit by the nutrients of the decaying aquatic biota (Wantzen et al. 2002, 2016b). Large predatory fish await the return of young-of-the-year fish into the mainstem rivers, which therefore have a well-synchronized, multispecies migration during a new moon night ("*lufada*," Wantzen and Junk 2006). Fish-eating animals, including birds (storks, egrets, and herons, e.g.), the heraldic animal of the Pantanal, the Tuiuiu stork (*Jabiru mycteria*), and mammals such as the giant otter (*Pteronura brasiliensis*), reproduce during this period, and spectacled caymans (*Caiman crododylus yacare*) fill up their fat reserves. The dry-fallen river beaches become nesting sites for terns and skimmers.

This permanent turnover between aquatic and terrestrial life forms driven by the flood pulse is a strong driver for biodiversity (Junk and Wantzen 2004, 2007) and for the development of economic, social, and cultural activities of the human groups that inhabit the wetland (e.g., Neuburger and Da Silva 2011; Wantzen et al. 2022a, b). It is important to note that there are no two identical years in terms of hydrology. Variable local inundations and multiyear periods of drier and wetter conditions have a strong impact on ecological processes and patterns. For example, the tree species *Vochysia divergens* may cover huge grassy areas during wetter years and becomes strongly reduced by fire in drier phases (Nunes da Cunha and Junk 2004). Wetter periods favor the accumulation of carbon (Vega et al. 2014). In the past decades, dry phases have also been used for the conversion of native vegetation into more and more intensively used agricultural areas (Alho 2008; Junk et al. 2006; Schulz et al. 2019; Wantzen et al. 2022a, b).

The Brazilian Pantanal is recognized for its high diversity of flora and fauna, and for a long tradition of human inhabitants, that were living sustainably in the rhythm of the natural flood pulse, using the natural resources such as native plants, fish, and pastures (see Wantzen et al. 2022a, b for a recent review on flood-pulse-adapted Traditional Ecological Knowledge). The Pantanal has an important role as a hydrological buffer system for downstream areas, a regional climate regulator, a valuable water retention and purification area, and a biodiversity maintenance center (Lázaro et al. 2020). With its unique and universal value, it has been considered as National Heritage by the Brazilian Federal Constitution (1988) and as Biosphere Reserve by UNESCO (2000). Within its region, different portions of this territory have gained different protection status, and been nominated as Humanity Natural Heritage and Ramsar Sites, the Pantanal Matogrossense National Park (1992), the Natural Heritage Private Reserve SESC Pantanal (2003), the Natural Heritage Private Reserve Fazenda Rio Negro (2009), and Taiamã Ecological Station (2018).

3 Environmental Degradation in the Pantanal

Environmental degradation in the Pantanal is known for long (Alho et al. 1988), it has been studied in detail and frequently revised (e.g., Junk et al. 2006; Alho et al. 2019; Schulz et al. 2019; Wantzen et al. 2022a, b). Basically, the environmental impacts can be divided into those occurring in the uplands and those in the proper wetland. Both are tightly connected with each other, and they can result in negative impacts downstream, in the international waters in Paraguay, Bolivia, and Argentina (Tucci et al. 1999; Calheiros and Oliveira 2010). As the Pantanal is a huge sedimentation basin, the consequences of all inadequate landscape management accumulate in the wetland. These include huge amounts of sediments resulting from man-made erosion, pesticides, and water pollution (Laabs et al. 2002; Wantzen and Mol 2013), which derive from the diverse agroindustries (soy, cotton, corn, and cattle ranching) fast-growing "agrobusiness boom towns" (Zeilhofer et al. 2006; Wantzen et al. 2019) with insufficient wastewater treatment and heavy industries (the latter mostly in the southern part of the Pantanal). Massive deforestation of the native Cerrado vegetation in the uplands, often including the strictly protected gallery forests, also interrupts migration pathways for migratory species such as mane wolf and jaguar. Dams interrupt the essential spawning migration for many fish species to the headwaters, including all economically important ones (Medinas de Campos et al. 2020).

Inside the Pantanal, modifications of the landscape were moderate until the 1980s, including vegetation clearing for low-intensity cattle ranching and local gold mining causing mercury pollution. Dike roads, specifically the 140 km long "*Transpantaneira*" crossing the northern part of the wetland, and smaller dikes to access the farms, had a local influence on hydrology and, consequently, vegetation structure. In recent years, however, the face of the Pantanal has profoundly changed.

The vegetation in the Pantanal has strongly changed over the last years due to land clearing for an intensified pasture ranching (Miranda et al. 2018; Fig. 3). According to the same author, in the Pantanal plain, the reduction of areas occupied by dense vegetation increased more than 40% from 2008 to 2015. The sustainable, low-density cattle herding by local ranchers cannot compete economically with the high-intensity beef production in the high plains (Santos et al. 2011). Therefore, they either transform their farms into private reserves used for ecotourism, or they intensify their production by introducing exotic grass lineages (mostly African *Bracchiaria*) and adopting other practices such as nonlocal fodder and hormone treatment (Rossetto et al. 2020; Wantzen et al. 2022a, b). More recently, planting techniques that are incompatible with the natural flood regime, such as sugar cane and soy bean, are advancing from the outer margins of the floodplain toward its inner parts, which is very worrying as they represent of a tyranny of small decisions resulting in a complete change of the ecosocial structure of the Pantanal.

The most important human impact on the Pantanal, however, is the changing hydrological regime, which literally affects the wetland at its source (see next section).

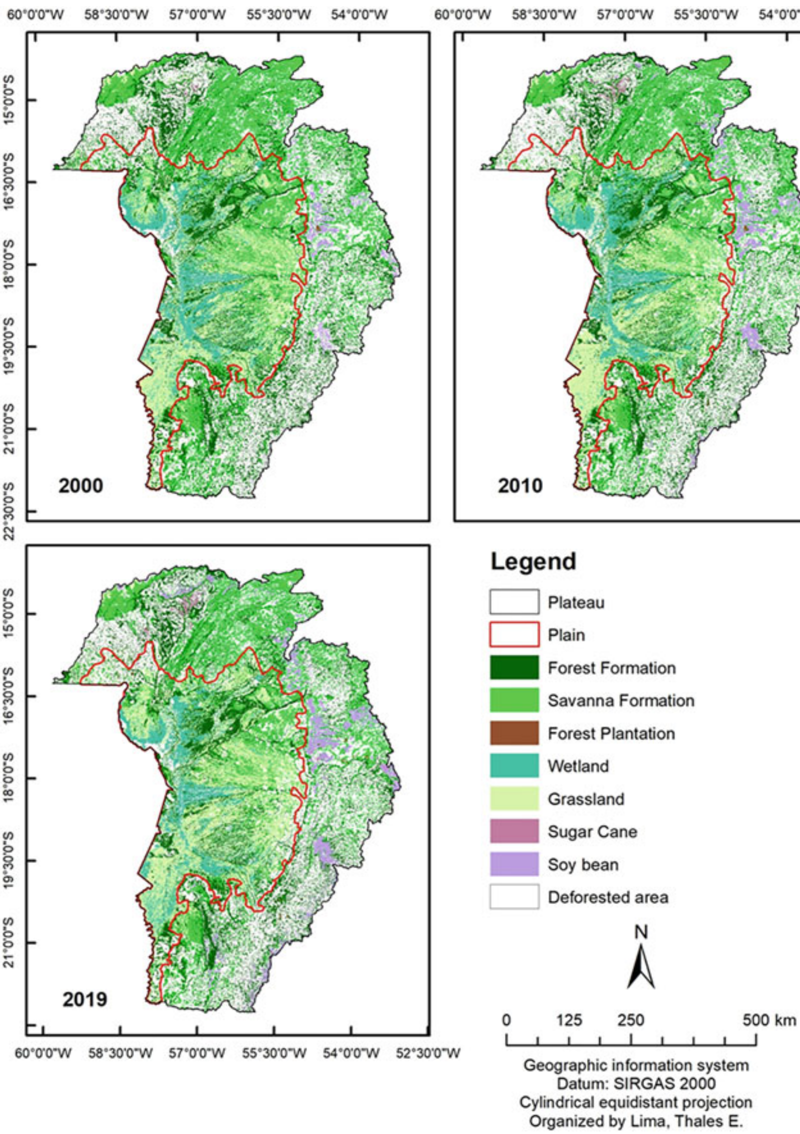

Fig. 3 Vegetation cover and economic activities of the Pantanal. Data acquired from MapBiomas 2019 Collection 5 https://mapbiomas.org/produtos

4 Causes for Water Shortage in the Pantanal

So far, all life in the Pantanal has been determined by the “rhythm of the waters” (Da Silva and Silva 1995; Wantzen et al. 2022a, b, c; Fig. 4), its floods are providing regional water security, nutrient cycling, sediment loads, and traditional livelihood. In the Northern Pantanal, the water levels reduce from May to September, and rise or remain high in the other months.

However, the hydrological heartbeat of this wetland becomes weaker and irregular. About 16% of the water mass in the Northern Pantanal was lost in the last 10 years (Lázaro et al. 2020). Causes for this trend can be seen in all elements of the hydrological budget, i.e., inflow, precipitation/evapotranspiration, and outflow (Rossetto et al. 2020).

Water input by inflow is originating from the tributaries in the high plains. Their discharge and their natural flow pattern are being impacted by the proliferation of hundreds of dams for small, medium, and large hydropower plants (there are 47 small hydroelectric plants installed in the Pantanal, 13 being built and 120 foreseen, totaling 180 enterprises; Fig. 5), which block rivers that form the Pantanal wetland (Da Silva et al. 2015; Crabb et al. 2017; Calheiros et al. 2018). The enormous quantity of dams previewed to be built in this region shows the magnitude of their potential impact. Apart from reducing discharge (especially during the highly important flood phase), the operation of hydropower dams also affects the pattern of the annual hydrodynamics, which counteracts the adaptations by fauna and flora to a predictable flood pulse (Junk and Wantzen 2004, 2007). Timely flooding has a very beneficial effect on fish yields, whereas reduced flood peaks reduce them (Resende 2008). Untimely floods resulting from increased discharge through the hydropower turbines during the hot dry season result in mass mortalities of bird fledglings and other terrestrial biota dwelling on beaches and the dry-fallen floodplain. Dams do not only impact water input to the wetland system (Crabb et al. 2017), but they may cause habitat fragmentation and isolation of populations,

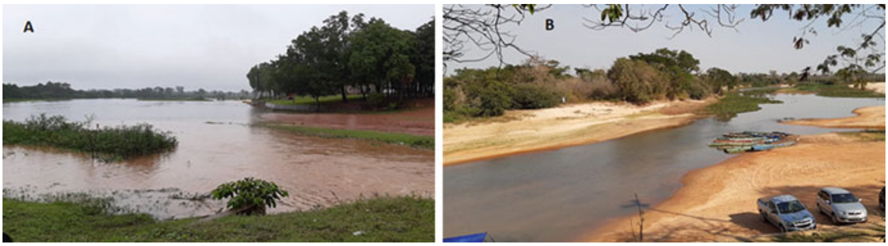

Fig. 4 Water levels during the wet (**a**) and the dry season (**b**). The pictures show a side bay that is located in front of the city of Cáceres – Northern Pantanal. In this city, 92,000 people depend on the water supply for daily use and usually go for fishing, recreation, and contemplation of the environment. Source authors

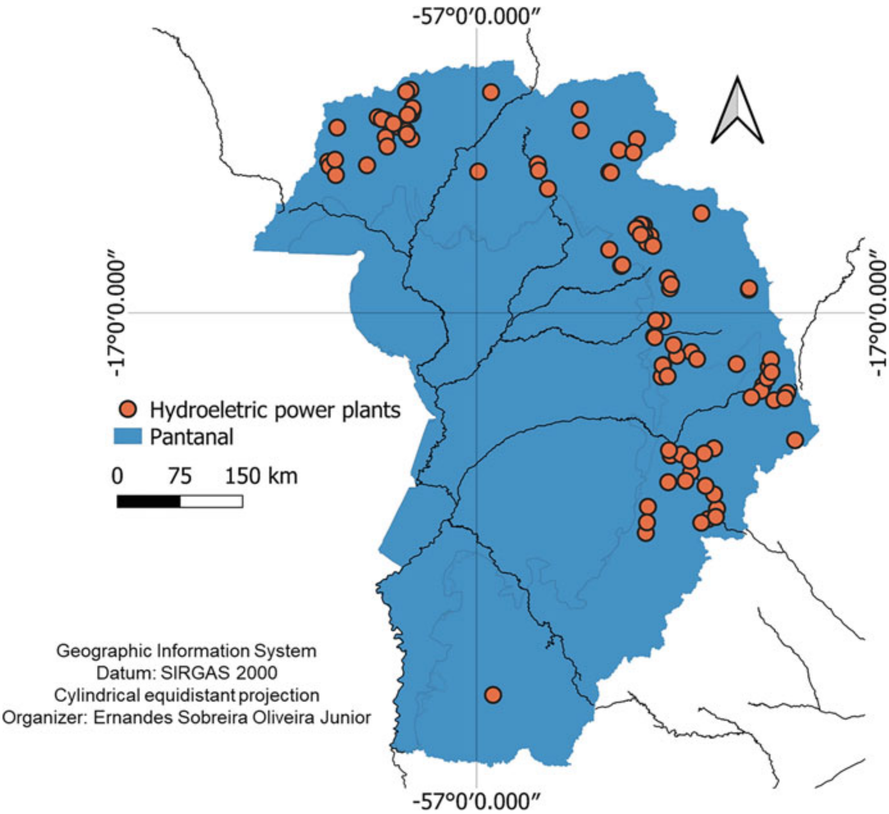

Fig. 5 Hydroeletric power plants in the Brazilian Pantanal. Data acquired from https://sigel.aneel.gov.br/Down/ in 2021. Organized by the authors

besides the social impacts associated with the loss of traditional lands, displacement, and livelihood impacts of a changing environment (Schulz et al. 2019).

In addition to hydropower dams, small, earthen dams are built for maintaining drinking water for cattle in local ponds (*açudes*). They are numerous and hardly ever quantified, but they affect the environmental flows in several ways, by holding back discharge, by increasing transpiration, and by impacting the riparian wetlands in the headwaters, which have an important sponge effect to maintain flow during the dry season and reducing floods during the rainy season (Wantzen et al. 2006). The degradation of headwater zones is worsened by soil erosion (often caused by cattle trampling in headwaters), resulting in self-sustaining, deep erosion gullies (*voçorocas*) that tap groundwater throughout the year (Wantzen and Mol 2013). Another, yet unfathomed negative contribution to the hydrological budget of the Pantanal is the increasing abstraction of water by pumping it from groundwater or streams for irrigation of acres, industrial livestock farming (swine, poultry), or the ever-growing cities.

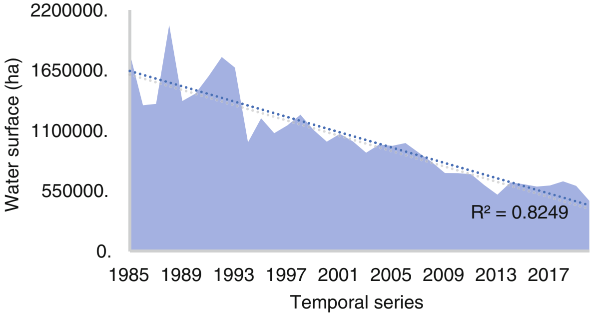

Fig. 6 Water mass reduction in the Pantanal. The historical series shows a significant reduction of the surface water in the region ($R^2 = 0.82$; $P < 0.05$). Figure made by the MapBiomas website (https://plataforma.brasil.mapbiomas.org/agua). Organized by the authors

A detailed water budget is yet lacking (i.e., losses from hydropower dams and abstraction for irrigation are not yet quantified), however a study on 24 dammed rivers has shown that 88 of the 256 hydrometrical indicators changed significantly, causing changes of 5–40%, compared to undammed reaches (Ely et al. 2020). Despite multiannual fluctuations, the trend of a continuous reduction in the past 45 years is evident (Fig. 6).

Precipitation and evapotranspiration affect the hydrology of the Pantanal at its surface. The effects of the massive change of the vegetation into diverse forms of land use and the increased diking on evapotranspiration deserve further studies. In the years 2019 and 2020, the Pantanal encountered its lowest precipitation (Marengo et al. 2021), and the highest incidence of natural and man-made bush fires ever recorded. Rainfall in the Pantanal during the rainy season was reduced by 50–60%, and the occasional precipitations during the dry season were even stronger affected (Marengo et al. 2021), but it was also reduced in the high plain areas, which deliver water to the Pantanal via the headwaters (Oliveira et al. 2021). It is also supposed that climate change affects the hydrological cycle in the Pantanal: According to Marengo et al. (2016), climate modeling results suggested that the Pantanal could become hotter and drier (an expected 5–7 °C increase in temperature and transpiration and a 30% reduction in rainfall).

Changing rainfall patterns may be associated with different potential causes. The Pantanal region is connected to the migration of the low-level jet that brings monsoonal precipitation modulated by the Amazonian forest (Bergier et al. 2018). In the past years, the Amazon rainforest has presented less evapotranspiration, which causes the reduction of the humidity in the air, consequently reducing the precipitation (Langenbrunner et al. 2019). Forests are responsible for the higher amount of evapotranspiration when compared to crops, for instance (Dias et al. 2015). That is why deforestation becomes an important factor in the understanding of water shortage in the Pantanal. Although Marengo et al. (2021) suggested that the local deforestation were influencing water shortage (addressing that the natural vegetation cover of the Pantanal fell from 92.65% in 1985 to 84.32% in 2019, with conversion values of natural areas for anthropic use in annual rate with an average of 0.33%), the low-level jet expands the picture to request a systemic view beyond the limits of the

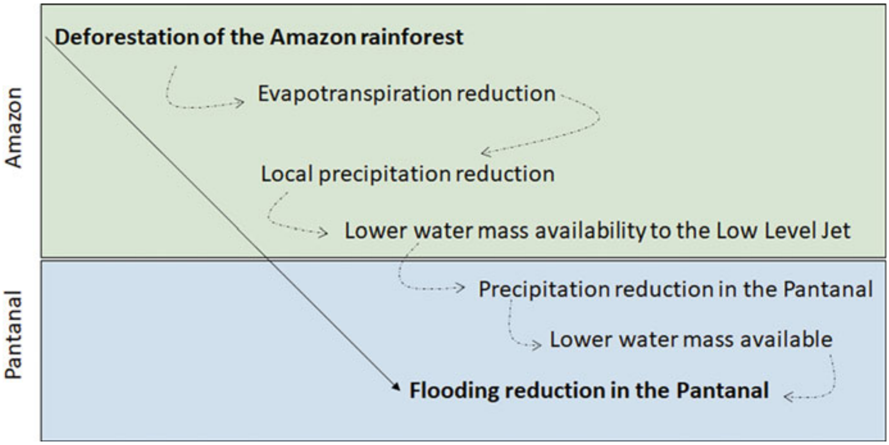

Fig. 7 Cascade effect of the water shortage in the Pantanal. (Original graph by the authors)

water basin to include distant Amazonian forest conservation to protect the Pantanal (Fig. 7).

The water shortage in Pantanal wetland is due to the dependence of the hydrological cycle on precipitation in the Northern Pantanal. The chain of interdependence starts from the north entrance of the water to the Pantanal (Da Silva and Girard 2004), where the runoff is resulted from the rainfall (Bravo et al. 2012). Marengo et al. (2021) believe that extended periods without rainfall tend to decrease the water level from the Paraguay River: The monthly levels of the Paraguay River at Ladário showed continuous decrease during the last 3 years with the strongest decrease of about 240 cm below normal in June 2020 (reaching 1.94 m, according to the Brazilian Navy Hydrographic Center).

A third component of the hydrological budget is the outflow of water from the Pantanal into the mainstem of the Paraguay River. The flood water of the Pantanal is in slow, but permanent movement, driven by local differences in precipitation and the declivity of the landscape. Only locally, floodplain channels may have a high water velocity of more than 1 m s^{-1} (Wantzen et al. 2005). The flow between mainstem and floodplain is buffered by several factors, including the vegetation cover, massive debris dams, and backflooding effects from rivers and lakes. The Paraguay River itself represents a series of low, rocky outcrops on average every 50 km along its course through the Pantanal, which act as natural barriers for the water flow, but which also represent obstacles for transport vessels (Gottgens et al. 2001). Navigation on the rivers with small traditional boats has had no or minor impact on the ecological functions and represents an important element of its river culture (Wantzen et al. 1999, 2022a, b). However, to make the rivers navigable for commercial vessels with a deeper draft would require permanent dredging, local straightening of meanders, and riverbank fixation with riprap or concrete. Plans to do so are currently under way, by the resumption of the Paraguay-Parana waterway project (see Wantzen et al. 2022a, b for a review of the current situation) and current

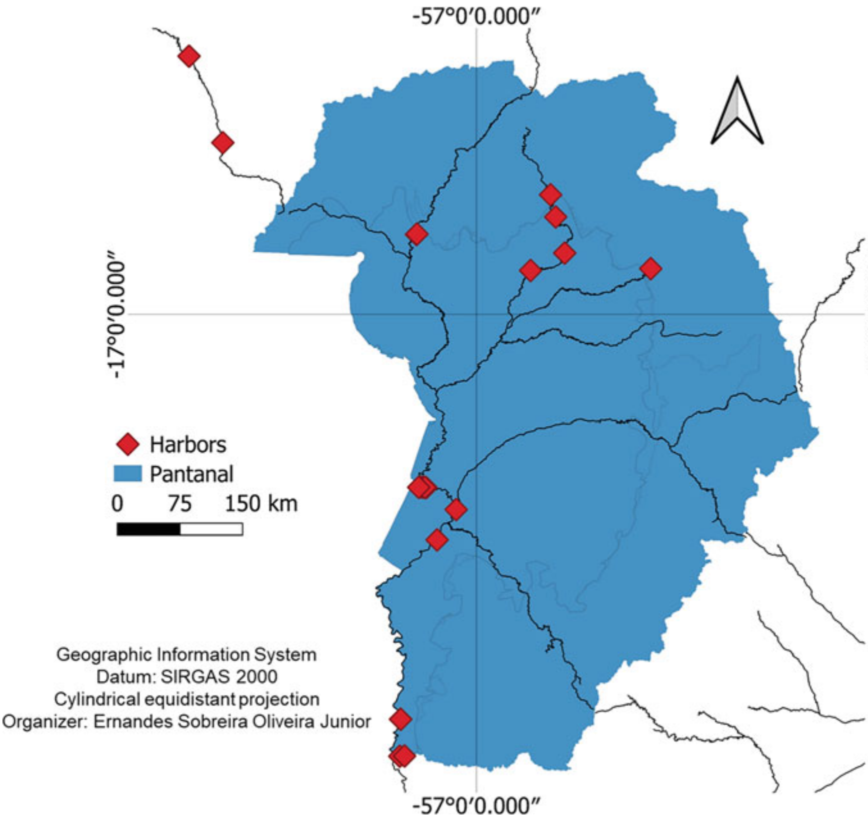

Fig. 8 Rivers of the Pantanal highlighting the respective harbors, indicating plans to regulate Pantanal rivers in favor of commercial navigation. Source: Brazilian Federal Government, Ministry of Infrastructure (https://www.gov.br/infraestrutura/pt-br/assuntos/dados-de-transportes/bit/bitmodosmapas#maphidro)

plans for enlarging existing traditional harbors several smaller rivers (Fig. 8). The consequences of such a project are well known. A lowering of the water level of the Paraguay River would result in an estimative reduction of its floodplain size of 1% per centimeter of riverbed incision (Hamilton 1999). The maximum height and duration of the floods as well as the residence time of the water in the floodplain would be reduced.

In summary, it can be said that water shortage in the Pantanal wetland has the meteorological component (a meteorological drought) causing less rainfall; and hydrological component directly related to water bodies, due to both reduced input upper streams by dams or accelerated output down streams by waterways. Local deforestation also produces impacts in double ways: less rainfall and less soil infiltration and groundwater recharge (Fig. 9).

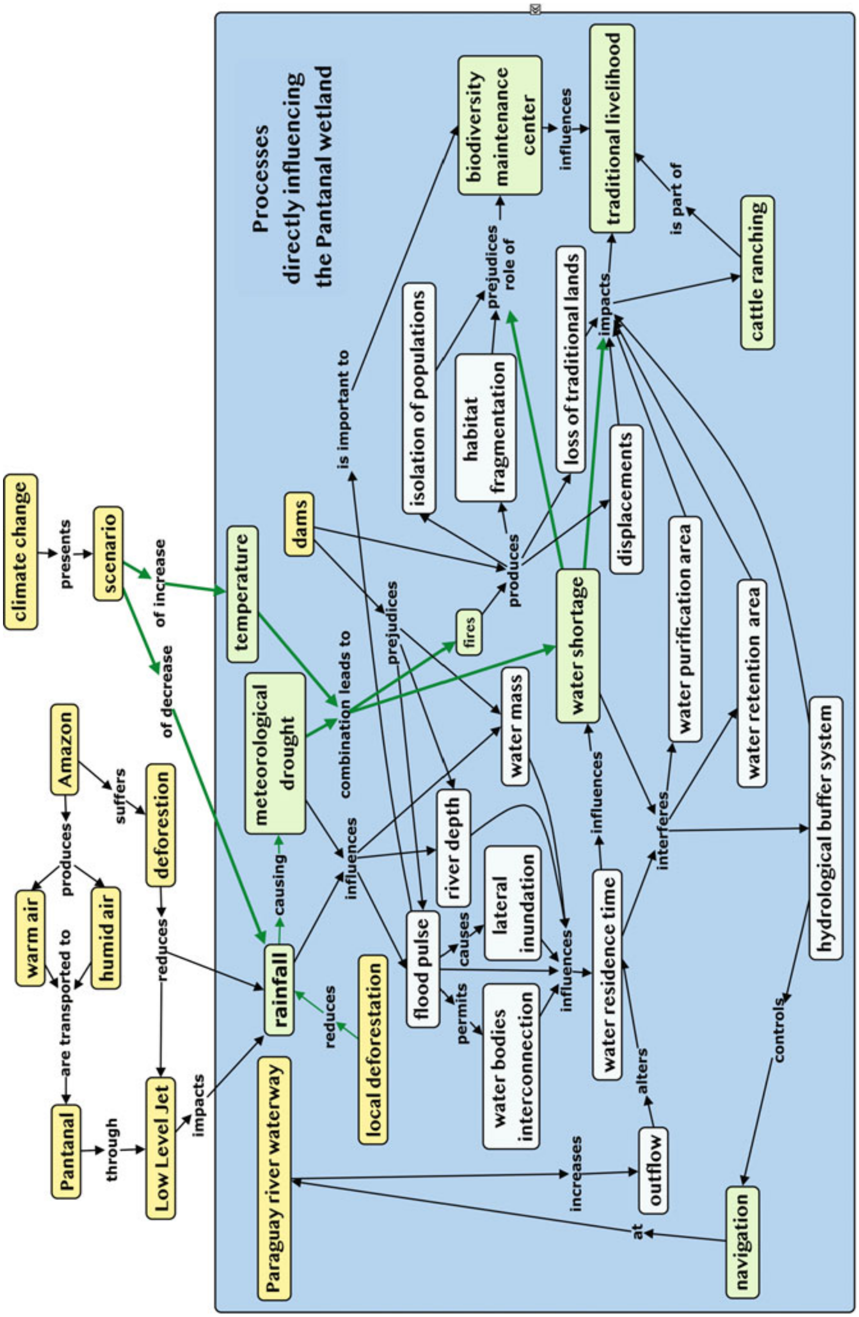

Fig. 9 Concept map about the water shortage in the Pantanal region. Yellow boxes represent the forces promoting impacts. Green boxes represent the produced impact or who/what suffers impacts. The light boxes represent intermediary steps of the chain of processes. The blue large box delimits all processes which occur inside the Pantanal region. (Original graph by the authors)

5 The Effects of Water Shortage on Biota and Stakeholders of the Pantanal

Experts alert that wetlands are particularly vulnerable to climate change and therefore deserve adequate policies (Moomaw et al. 2018). Abundance of water and of the rich natural resources resulting from the flood cycle can be seen historically as a foundational element for Mato Grosso's identity (Schulz and Ioris 2017). Conversely, water shortage, as it is currently developing, can be understood to have an opposite effect on the sense of place, which is essential for respectful use of the environment.

The recent and prospected hydrological changes described above affect practically all aspects of the Pantanal as a socio-ecosystem. The most obvious effect was the occurrence of enormous fires in the past years (mainly in 2020), which resulted from dryness and high temperatures (Marengo et al. 2021) and were locally facilitated by human activities. Fires are a natural phenomenon in seasonal savannas, and the biota and humans show remarkable adaptations to fire, including dependence of some plant seeds on fire to germinate. The recent fires, however, were exceptional in several ways: They occurred for the first time during the period thus far known as the rainy and flooding season, they had yet unfathomed dimensions and duration, and they impacted so-far protected areas such as the Pantanal National Park and many indigenous reserves. The fires have killed many organisms (including fast-running species such as jaguar or swamp deer), and have left behind unhabitable space without food. For example, the extremely rare hyacinth macaws are, among the last stable populations in the Pantanal, dependent on palm nuts from *Scheelea phalerata* as their most important food source, but most of them are burnt. The function of the Pantanal as a highly important stepping stone of many bird migration routes has also been impacted.

Decreasing flood maxima and prolonged low water phases (which now even occur during the months that commonly represent the flood period) affect the ecosystems, their ecological functions and biodiversity, as well as human populations that depend on the waters (see above) in many ways. Both, seasonal lateral inundation processes (Lázaro et al. 2020) and interconnection between water bodies (Gonçalves et al. 2011), are interrupted, and important habitats such as lakes and small water bodies are strongly isolated or fully vanish. Many species just survive in this extreme and nutrient-poor environment, which changes from flooding to drought, by remarkable adaptations of their life cycle strategies. A further expansion of environmental stressors may exceed their physiological limits. For example, as floodplain water bodies will now exist for a shorter period, heat up faster, and reach higher temperatures, so that many fish and invertebrate species will not be able to complete their life cycle anymore. Reproduction, phenology, dispersal recruitment, and growth patterns of most floodplain species are affected (e.g., Alho 2008; Leuchtenberger et al. 2013; Alho et al. 2019). Fruits of genipa trees (*Genipa americana* L.) are less and less often found in the Pantanal, but they are equally important for the fauna and for indigenous people who use them to make black ink for body paintings and as a phytomedicine (Libonati et al. 2020). Areas that do not undergo the flood cycle anymore will encounter a reduction of their productivity, resulting in a reduction of fish yields and areas suitable for planting. Thus, the food security of traditional communities is affected (Rossetto 2021). Vulnerable communities, which depend directly on secured environmental health for their livelihoods, are the most affected. Besides, the local economy and social life are extremely dependent on the regularity of the hydrological cycle. Thus, the consequences may also influence the economy of the whole region.

The population of municipalities located in the Brazilian Pantanal, estimated for 2020, totals 496,466 inhabitants (IBGE 2021). In addition to the inhabitants of urban areas, there is a traditional Pantanal population, which resides in the rural areas of the biome (Rossetto 2009; Wantzen et al. 2022a, b). These last ones are represented by 15,108 indigenous people of different ethnicities (IBGE 2010), traditional rural communities that practice professional artisanal fishing and subsistence cultivation, peasant family farmers who reside in small areas called rural settlements resulting

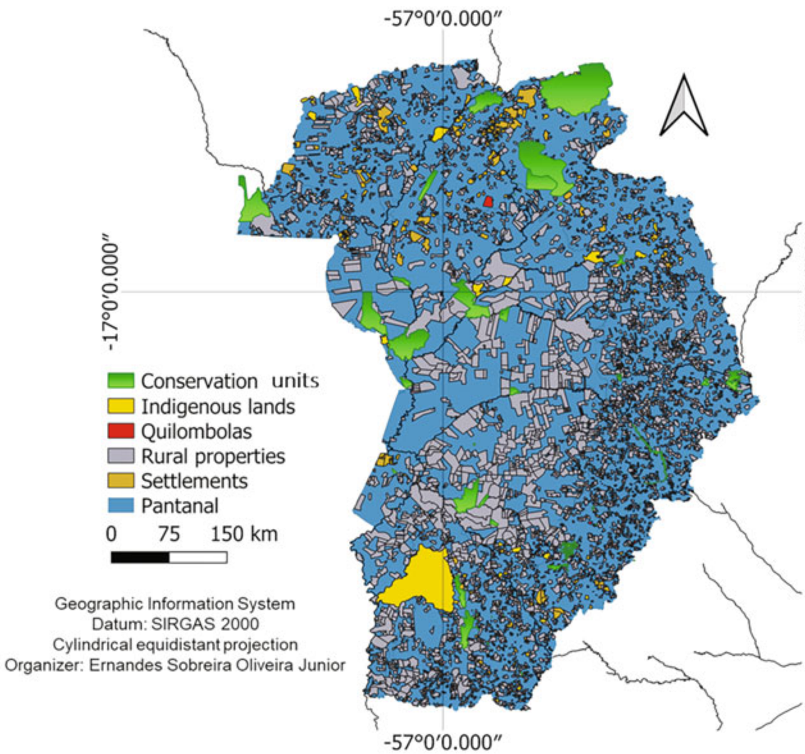

Fig. 10 Characterization of the Pantanal based on distinct properties owned by indigenous peoples, Quilombolas (settlements of enslaved Africans who escaped from plantations), conservation units, settlements, and farmers. Data was acquired from https://forest-gis.com/download-de-shapefiles/. Organized by the authors

from the National Agrarian Reform Program, and families that own large tracts of land inherited by successive generations, the Pantanal farmers (Fig. 10).

6 Perspectives for a Sustainable Use of Water Resources in the Pantanal and Its Catchment

The recent fire events have highlighted that most current water use practices in the Pantanal and its catchments are inadequate and that synergetic climate change and telescoping deforestation effects in Amazonia make action-taking in favor of sustainability an extremely urgent issue. The identified causes on the individual terms of the hydrological budget (see above) already deliver the approaches for achieving sustainability by securing environmental flow patterns (Arthington et al. 2018). A DPSIR (drivers-pressures-state-impact-response) analysis (e.g., Da Silva et al. 2015) may deliver detailed elements. These need to include an intermission of further dam constructions, a revision of the dam management to make it more compatible with the flood regime (see, e.g., Zeilhofer and Moura 2009), local dam removal for the restoration of fish migration pathways, and a definitive abandonment of the *Hidrovia* (waterway) project. A moratorium for deforestation as it has been in place in Amazonia is urgently needed. After decades of intensification of land use for the profit of individual stakeholders in the entire catchment, a water-centered land use policy needs to be prioritized that protects especially the headwater zones of all tributaries and the natural hydrological buffering effect of all ecosystems. Elements of traditional ecological knowledge that have been proven to be sustainable should be integrated into the management concepts (see Wantzen et al. 2022a, b). All land use techniques that are too water consuming or that require permanently dry soils by damming or drainage (such as soy bean cultivation) should be abolished within the floodplain. Legal statements need to define the wetland perimeter at its maximum extension (and not at the lowest water level, as it is currently debated). A major political issue will be to define the entire catchment as one political territory, so that those people who become impacted by inadequate use forms can debate directly with those who profit by them, in a "basin of responsibility" (Wantzen et al. 2016a). In the sense of multispecies justice, the nonhuman dwellers of the Pantanal and its rivers deserve special protection by law.

On the local scale, techniques to reuse water and to improve water use efficiency may support these actions. For example, a report from 2021 showed that some settled people left their land because of the lack of water to grow crops or livestock in the frontier between Brazil and Bolivia. The region was settled at the end of the last century with 36 families, and nowadays only 14 families remain from the initial group. In 2008, a project for keeping waters and supplying their wells started, making the land more attractive and productive. The project consisted in the installation of small dams (regionally called "*barraginha*"; Fig. 11), which is filled with rainwater, together with the water from the road that is diverted to the dams. Once filled, the dams keep the water for a few months which is drained through the soil supplying the underground water, consequently the main well of settlement. The

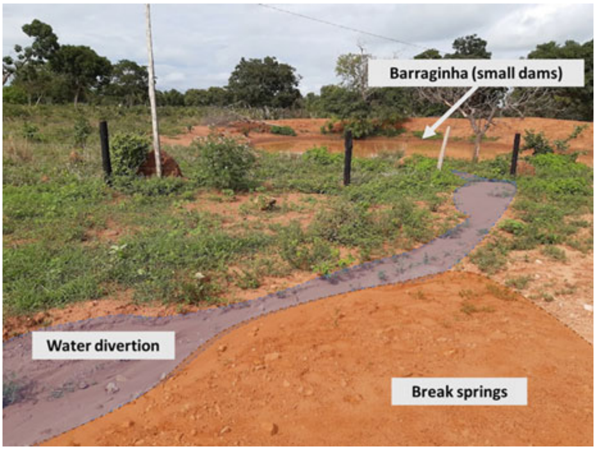

Fig. 11 Dams constructed in a small farm to keep rainwater to supply the underground water. Source: authors

Fig. 12 Rainwater collection in rural school as an alternative to reduce stress due to lack of water. Source: authors

project was twice awarded by the Brazilian government for land reform, in 2018 and 2021, because of the best practices for sustainability. The use of the small dams in the small farms enabled the families to prosper and aim for a better future (Silva et al. 2021).

Other alternatives for water supply have been used in the Northern Pantanal, such as the cisterns in schools (Fig. 12) and best practices for water usage (multiple usage lakes) or water cleaning (e.g., biopits). Social technologies are important alternatives for water supply, and in the Pantanal, they may be a solution for small farmers and traditional communities that are facing the severe drought from the world climatic change.

7 Conclusion

Water scarcity is something more and more evident, and each year the water masses must be reduced in the Pantanal region. Thus, its effect will be severely felt every year, with changes in environmental management, changes in the routine of life, and consequently, in the culture of people who have lived in this region for hundreds of years. The introduction of new species and new land use practices are also important disturbances to take into account with regard to the impact on the population that lives there. In fact, the water scarcity in the Pantanal has impacted different social groups with the reduction of fish and loss of native and cultivated plants in recent years, which cause changes in habits and lack of water and food security in the communities of the wetland. However, few studies have been developed in the scope of the impact of climate change and the consequent environmental transformations that culminate in water scarcity affecting the different social actors in the Pantanal, as shown in this text. Their challenges deserve to be better understood so that they can be solved. Thus, it is expected that further work will be carried out in the region demonstrating the effect of climate change and environmental transformations caused by human beings in the water scarcity that affects the different stakeholders in the Pantanal.

Social technologies can be guiding instruments for improving environmental and social quality in the Pantanal, and should be taken into account for use and promotion in places with a risk of severe drought in the near future. It seems surprising that cisterns are necessary among communities located in a wetland, but this reinforces the necessity to promote wetlands conservation: Wetlands can also lose water and present water shortage, especially in seasonal wetlands presenting a distinct drought phase such as the Pantanal.

It is important to highlight that the adoption of social technologies is only a mitigation strategy. The core origin of the problem should be faced: maintaining the sources of their rivers. The tributary rivers of the Pantanal are drying up. Their springs are being severely degraded by deforestation, and eroded or covered by sand. These waters are extremely important for the maintenance of the Pantanal and of great need for the maintenance of the biome’s ecosystem services.

This is the main lesson that the Pantanal can offer to wetlands all over the world. Wetlands are fragile, wetlands can lose water. Sustainability of wetlands should be a worldwide concern.

8 Cross-References

- ▶ Background on Economic Development
- ▶ Community Engagement
- ▶ Culture and Sustainability
- ▶ Ecosystems Services
- ▶ Ecotourism
- ▶ Environmental Education
- ▶ Environmental Law
- ▶ Fish and Fisheries
- ▶ Global Energy Use, Hydroelectric Power and Sustainability
- ▶ Global Water Use
- ▶ Green Economic Incentives
- ▶ History of the Environmental Movement
- ▶ Indigenous Sustainable Development: Shaping our Future, Environmental Justice in Latin America and the Caribbean
- ▶ Informal Education and Sustainability
- ▶ Introduction to Environmental Regulations
- ▶ Low-Consumption Lifestyle and Well-Being
- ▶ Mapping, GIS and Remote Sensing
- ▶ Protecting People
- ▶ Protecting Water and Wetlands
- ▶ Regional Planning
- ▶ Resiliency
- ▶ Stakeholders Engagement for Sustainable Communities
- ▶ Sustainability in Latin America and the Caribbean
- ▶ The Science of Climate Change. The Evidence for Climate Change on our Planet
- ▶ The State of Sustainability in Developing World
- ▶ The State of the World's Natural Resources
- ▶ The Sustainable Development Goals
- ▶ Water Management
- ▶ Water Resources: Aquifers, Reservoirs, Lakes, and Rivers
- ▶ Water Pollution

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