



World wetlands classification: a new hierarchic hydro-ecological approach

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Received: 16 April 2024 / Accepted: 21 August 2024
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Abstract Many different approaches to classify wetlands at regional and global levels have been proposed, but their use of different classification parameters complicates comparisons of the results. Moreover, none of the international approaches cover global wetland variety with respect to size and environmental conditions. A comparison shows that hydrology is the only parameter that can be used for a hierarchic classification on a global scale. In the approach presented herein, differentiation between coastal, inland and anthropogenic wetlands is proposed. The use of higher classification units (systems, subsystems, orders, suborders and classes) is based on hydrological parameters. Wetlands are separated into small, simply structured types treated by all classification systems, and large wetscapes that, due to their complexity, are not. However, wetscapes represent well-defined landscape units, many of which are the focus of international organizations involved in wetland protection. They have to be treated using a holistic approach given the many interactions of their ecological subunits, their role in regional economies, their

targeting by legislation and their value to humans. Considering the large gaps in knowledge about wetlands at a global scale, the new approach is a powerful tool for its classification, because it is flexible enough to include additional classification units, as required. Local classification systems can eliminate higher categories, which do not occur in their regions. Classification at lower rankings (functional units, subclasses, macrohabitats) can be introduced using additional classification parameters such as vegetation, soils and water chemistry. Examples from Brazil are provided.

Keywords Wetlands worldwide · Wetscapes · Hydrology · Classification · Definition · Delimitation

Introduction

Wetlands cover large areas on all continents, except Antarctica. Worldwide estimates of their extent vary dramatically. Mitsch and Gosselink, in their standard textbook *Wetlands*, 5th edn. (2015), estimated that wetlands make up 4–6% of the Earth's land surface. A global review of wetland resources prepared for Ramsar COP7 in 1999, while affirming that *it is not possible to provide an acceptable figure of the areal extent of wetlands at a global scale*, indicated a “best” minimum global estimate of 7.48–7.78 million km², corresponding to 11.1–11.6%. The same report indicated that this “minimum” could be increased to

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9.99–44.62 million km², corresponding to 14.9–30%, if other sources of information are taken into account.

The reason for this ambiguity is the fact that the definition and delimitation of wetland areas have yet to be accurately elaborated. Wetlands appear in different hydrological, geological, geomorphological, and climatic conditions, are covered by different plant communities and are colonized by different animal species. Moreover, any definition must include areas in extreme environments, such as semiarid and arid regions, which become wet only every few years, as well as areas at high altitudes and latitudes, which are frost-free for short periods only. For example, large areas of the northern high latitudes are covered by permafrost soils, which during summer months are waterlogged and thus have to be considered as wetlands, but they are not included in many inventories. Recent estimates for some South American countries indicate that wetlands cover about 20% of the national territory of Brazil (Junk et al. 2011), 23% of that of Argentina (Kandus et al. 2008), and 27% of that of Colombia (Ricaurtre et al. 2019). This means that at least 20% of South America has to be considered as wetlands.

Wetland research requires the development of a uniform classification system that adopts a logical, hierarchical approach to the vast diversity of wetland types worldwide while recognizing their specific ecological peculiarities. However, under similar environmental conditions, similar wetland types in different regions may well show considerable differences with respect to soils, plant cover, animal colonization, interactions with the connected upland and deep-water ecosystems, and human impact. A broader application of the many proposed classification systems has thus been limited by three major problems: (1) their use of a mixture of different classification criteria, for example, soils, hydrology, geomorphology, geology, water chemistry, and vegetation, and the challenges in dealing with (2) wetlands differing in size and complexity and (3) wetlands in different climatic zones. Consequently, nearly every country has developed one or more wetland classification systems. This reflects the fact that: (1) scientists from different disciplines prioritize different parameters; (2) climatic zones influence wetland ecology and management and (3) local politicians prefer national or even regional definitions related to landscape units

described by local names and thus familiar to them and their constituents.

Definitions of wetlands can generally be divided into two groups. One exclusively considers scientific aspects and is important for scientific work, environmental protection measures and sustainable management. The other also takes political and socio-economic conditions into consideration and largely consists of regional approaches that omit scientific definitions and are frequently in conflict with the requirements of environmental protection, by favoring economic demands. This has been the case in Brazil, where scientific delimitations of wetlands are in sharp contrast to the definitions preferred by the agrobusiness. In the USA, state regulatory programs use specific wetland definitions that differ in nearly every state (Tiner 1999). Attempts at general approaches often provide an overview only of a specific region or country. For instance, the overview provided by Tiner (2018) delineates wetlands based only on examples in the US. Application of these different approaches in comparative international studies is accordingly difficult.

Finlayson and van der Valk (1995) noted the difficulties in determining general parameters that can be used on a worldwide scale to define and delimit wetland areas, and the need to resolve differences between already-existing regional wetland definitions and typologies. They also recommended a standardization of data collection and the dissemination of new technologies in order to establish ample international inventories. Ramsar's Scientific and Technical Review Panel likewise called for the *development and testing of a hydro-geomorphically-based system of wetland classification* (Davidson and Finlayson 2007).

In the following, a new hierarchic, hydro-ecological approach to the classification of the world's wetlands is presented. At higher rankings, it provides a uniform classification of major wetland types according to hydrological parameters, differentiating between small, simply structured wetlands and large, complex wetland systems (referred to as wetscapes) covering the entire hydrological gradient and requiring a holistic approach. At lower rankings, it allows local scientists to base their wetland classifications on local hydrological, soil- and water-chemical and vegetation peculiarities in the description of specific wetland types and their

subunits. The Brazilian wetland classification is used as an example of a classification to the lowest wetland unit (macrohabitat). The flexibility of the proposed system is essential for the inclusion of all wetlands and their subunits in all regions of the globe, since many of them are still not described and require additional studies.

Wetland definitions

At the international level, the Ramsar Convention, with 169 signatory countries, plays a leading role with respect to the conservation and wise use of wetlands. The Ramsar definition of wetlands states: *Wetlands are areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters* (Finlayson 2018a).

Semeniuk and Semeniuk (1995) defined wetlands as *areas of seasonally, intermittently or permanently waterlogged soils or inundated land, whether natural or otherwise, fresh or saline*. The authors called attention to Western Australia, where only the permanently inundated part of the wetland was traditionally considered as wetland area, and thus correctly extended the definition of peripheral wetlands.

At the national level, Cowardin et al. (1979) defined wetlands in the USA as ... *lands transitional between terrestrial and aquatic systems, where the water table is usually at or near the surface or the land is covered by shallow water. Wetlands must have one or more of the following three attributes: (1) at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained, hydric soil; and (3) the substrate is nonsoil and is saturated or covered by shallow water at some time during the growing season of each year*. In this definition, the inclusion of the growing season considers the annual change of the light/temperature pulse at high latitudes (see Sect. “Wetland size and complexity”). However, it is a concession to management interests, because the growing season considers crops in the respective areas, which is not ecologically justified. Furthermore, as noted above, state regulatory programs in the USA use specific wetland definitions that differ in nearly every state (Tiner 1999).

According to the Brazilian wetland definition, *Wetlands are ecosystems at the interface between aquatic and terrestrial environments; they may be continental or coastal, natural or artificial, permanently or periodically inundated by shallow water or consist of waterlogged soils. Their waters may be fresh or highly or mildly saline. Wetlands are home to specific plant and animal communities adapted to their hydrological dynamics*. (Junk et al. 2014). These examples show that wetland definitions agree in many general terms, but that problems arise when the details are considered, as exemplified by differences in wetland delineation.

Wetland delineation

Hydrological delineation

Determining the borders of a wetland would seem to be a simple task, assuming that the water level is relatively stable. Hydric soils with an accumulation of organic material and the presence of hydrophytes are good indicators of wetlands, and the transition zone to the upland is normally narrow. In wetlands with an oscillating water level, however, delimitation is difficult and scientific definitions often conflict with political and economic priorities.

There is general agreement that wetlands are ecosystems at the interface between terrestrial and deep-water ecosystems. Some classification systems include permanently deep-water habitats such as river channels and lakes as wetlands, e.g. Semeniuk and Semeniuk (1995) and Cowardin et al. (1979), but only the Brazilian classification considers permanently “terrestrial islands” within large wetland landscapes. Studies in the Brazilian Pantanal (Nunes da Cunha et al. 2023), the Okavango Delta (Ramberg 2018), and in other large wetlands, however, have shown that permanently terrestrial macrohabitats, such as paleo-fluvial levees and terraces, are of fundamental importance for biodiversity. The importance of the interaction between dry land and wetlands is exemplified by the prairie pothole area at the US/Canada border and by the playa wetlands of the semiarid Great Plains (USA) (Bartuszevige 2018). The accumulation of a large number of ephemeral wetlands in the semi-arid and arid landscape results in biodiversity hotspots

harboring many highly drought and wet-adapted plant and animal species.

Tiner (2018) provided an overview of wetland delineation, drawing on the US Army Corps of Engineers (2014) requirement in which “wetland hydrology indicators” were introduced. Hydrophytic vegetation and hydric soils are “common diagnostic features of wetlands” and should be found in all wetlands, except where “specific physiochemical, biotic or anthropogenic factors have removed them or prevent their development” (National Academy of Sciences 1995). This approach considers wetland conditions in the USA but it is not applicable at a worldwide scale, as shown in Sects. “Delineation by wetland soils” and “Delineation by wetland plants”.

The Brazilian definition considers the large water level fluctuations that affect most national wetlands. It states: *The extension of a wetland is determined by the border of permanent or periodic shallow flooding or waterlogging or in the case of areas subjected to flood pulses by the limit of mean maximum floods, including, if existent, permanently dry areas in its inner part, which are vital habitats for the maintenance of their functional integrity and their biodiversity. External borders are indicated by hydromorphic soils, and/or by the permanent or periodic presence of hydrophytes and/or woody plants adapted to grow in periodically waterlogged soils* (Junk et al. 2014). The innovation of this definition lies in its explicit reference to the mean maximum flood level as the external wetland border. Furthermore, it considers permanent dry areas as important habitats for the functional integrity and biodiversity of wetlands. The definition also incorporates ecological, social and economic aspects. For example, periodically flooded areas near urban centers are frequently inhabited during dry periods, but residents run the risk of losing their houses, home gardens and even their lives during periods of high floods. However, the wetland delineation proposed by Brazilian scientists has been rejected by Brazilian politicians and representatives of agrobusiness, who favor a definition of the wetland border at the “normal” (that is, low) water level, as it would allow them to make maximum use of floodplain areas. The problems with wetland delineation will become exacerbated in the future due to the increased frequency of extreme flood and drought events, as predicted by the Intergovernmental Panel on Climate Change (IPCC 2014).

Delineation by wetland soils

In the USA, wetland soils are classified into organic soils, characterized by an accumulation of organic material at the surface, and mineral soils, composed of a mixture of sand, silt and clay. A large list of indicators of hydric soils is provided by the US Army Corps of Engineers, summarized in Tiner (2018). Color is considered an important parameter for soil classification, and a standardized procedure for measuring and describing soil color is provided by the Munsell Color System (Schulze et al. 1993). However, soil color changes with soil wetness and is thus more difficult to describe in areas, where wetland soils are dry during the dry season. Furthermore, in many periodically drying tropical wetlands there is no accumulation of a layer of organic material, because high temperatures and oxygen availability lead to the rapid remineralization of organic matter. Many wetlands in semi-arid and arid regions are flooded only every few years. Their soils are poor in organic matter and characterized by an increase in salinity, because the rate of evaporation exceeds that of precipitation (Finlayson 2018a, b, c).

An important difference between soils in the tropics and those in temperate and northern regions is their age. Most wetlands in temperate regions developed after the retreat of the glaciers at the end of the last glacial period, about 10,000 years ago. In geologic terms, they are very young. Many large wetlands in the tropics and subtropics, however, are very old and have undergone several wetter and dryer periods that over geologically long periods altered their size and mineral composition, while maintaining their wetland characteristics. For instance, the Brazilian Pantanal is situated in a depression formed by the emergence of the Andes during the upper Pliocene–lower Pleistocene, about 2.5 million years ago. The majority of the depression is covered by leached fluvial and lacustrine sediments, which are partly consolidated and lateritic. Dramatic climatic changes during the Quaternary led to intermittent periods of large-scale flooding and drought. During the last glacial period, the Pantanal was almost dry while during the Holocene it passed through different climatic episodes: cool and dry between 40,000 and 8,000 BP, warm and wet between 8,000 and 3,500 BP, warm and dry between 3,500 and 1,500 BP and warm and

wet 1,500 BP to the present (Iriondo and Garcia 1993; Stevaux 2000). These long-term alternations between wet and dry periods in connection with annual dry and wet periods have affected the soils. Recent sediment depositions are found only along the river channels, which transport water and sediments to the floodplain.

Similar conditions are present in other Brazilian floodplains, e.g., in the Araguaia River floodplain. The differences in soils and hydrological conditions led Irion et al. (2016) to propose a subdivision of the large Brazilian floodplains into four categories: (1) a recent active floodplain, influenced by annual inundation and sedimentation as well as erosion processes; (2) an active paleo-floodplain, inundated by rainfall, subjected also to the push back-effect of the water of the parent river channel during floods, and engaged in an intensive exchange of plants and animals; (3) the higher-lying inactive paleo-floodplain built up by former ridges during wetter periods or by geological episodes and currently permanently dry; (4) the recent inactive floodplain, consisting of areas drained by humans. These examples show the limits of soil indicators for a worldwide classification system.

Delineation by wetland plants

Scientists working in wetlands recognized early on the difficulties in separating wetland plants from terrestrial plants. Warming (1909) stated *...there is no sharp limit between marsh plants and terrestrial plants...the boundary zone represents a gradual transition from terrestrial to aquatic conditions..and it is impossible to establish any sharp distinction between swamp-forests and forests on dry land.*

The simplest and most comprehensive definition remains that of Weaver and Clements (1938), who defined aquatic macrophytes as *plants that grow in water, in soil covered by water, or in soil that is usually saturated.* Dobenmire (1968) introduced oxygen deficiency into the definition: *A hydrophyte is any plant growing in a soil that is at least periodically deficient in oxygen as a result of excessive water content.*

In most cases, the definitions provided by botanists restrict aquatic macrophytes to herbaceous plants. However, in many wetlands shrubs and trees compete successfully with herbaceous plants for the same habitat, by excluding them by shading. For instance,

riparian wetlands along streams and rivers in the moist tropics and in temperate regions are covered by trees highly adapted to long-term flooding. The same is true for peat swamp forests in Southeast Asia. Therefore, Junk et al. (in press) propose that the definition of Weaver and Clements (1938) be amplified by the explicit citation of woody vegetation: *Hydrophytes are herbaceous and woody plants that grow in water, in soil covered by water, or in soil that is periodically saturated.*

The US Army Corps of Engineers characterizes hydrophytic vegetation on the basis of detailed species lists that divide the plants into obligate wetland plants (OBL), facultative wetland plants (FACW), plants that occur in wetlands but also in uplands (FACU), and upland plants that never occur in wetlands (UPL) (Lichwar et al. 2014). The Brazilian classification differentiates wetland plants into algae, herbaceous water and swamp plants, herbaceous plants growing in periodically flooded areas, herbaceous plants growing only on permanently terrestrial areas, woody plants growing in permanently or periodically flooded areas, woody plants growing in permanently terrestrial areas and epiphytes growing in the canopy of the floodplain forest (Junk et al., in press). Both classifications take into consideration the entire ecological gradient that exists in large wetlands and represents permanently aquatic environments as well as all transition zones up to permanently terrestrial habitats. The characterization of wetland vegetation in other regions is still in its early stages. The multiple adaptations of plants to periodic or long-term flooding require additional studies at the species level. Therefore, neither a classification of wetland plants at the level provided by the US classification nor an application of that approach to wetland delineation on a worldwide scale is possible. In the new classification system wetland vegetation enters at higher levels only as general descriptive element, such as peatlands at the suborder level or papyrus swamps, fen classes and sea grass beds and others at the class level.

Wetland classification systems

The diversity of wetlands is reflected in the many classification systems, put forward by nearly every country. Mitsch and Gosselink (2015) provide an overview of the classification systems in the USA and

compare them with the classification systems of Canada and of the Ramsar Convention. One of the most frequently cited classification systems is that for wetlands and deep-water habitats developed by the U.S. Fish and Wildlife Service (Cowardin et al. 1979). It distinguishes five major systems, ten subsystems and 56 classes. The major systems are marine (subtidal, intertidal subsystems), estuarine (subtidal, intertidal subsystems), riverine (tidal, lower perennial, upper perennial, intermittent subsystems), lacustrine (limnetic and littoral subsystems) and palustrine. Classes are described based on different attributes, such as rock bottom, emergent wetland, forested wetland, aquatic bed and unconsolidated shore.

The hydro-geomorphic classification of Brinson (1993) relies on geomorphic, physical and chemical parameters to provide a better understanding of the relationship between organisms and their environment. It groups wetlands into seven classes: depression, riverine, mineral soil wet flats, organic soil wet flats, estuarine (also referred to as tidal fringe), lacustrine (also referred to as lacustrine fringe) and slopes.

Several attempts at an international classification or typology system have also been made. The most frequently cited is the classification of the Ramsar Convention, which differentiates between 42 wetland types: marine and coastal wetlands (12 types), inland wetlands (20 types) and human-made wetlands (10 types). It uses a non-hierarchical mixture of criteria for the characterization of habitat types, including hydrological criteria (permanent, seasonal, intermittent), vegetation criteria (shrub-dominated, tree-dominated, marshes, peatlands, mangroves, etc.), geographical criteria (tundra/alpine wetlands, deltas, etc.), limnological criteria (rivers, streams, lakes, springs, etc.) and others (Finlayson 2018a).

Semeniuk and Semeniuk (1995) proposed a geomorphic-hydrologic approach to the global classification of inland wetlands that combines landform types with hydroperiod to distinguish 13 primary types of common wetlands: permanently inundated basin (lakes), seasonally inundated basin (sumpland), intermittently inundated basin (playa), seasonally waterlogged basin (dampland), permanently inundated channel (river), seasonally inundated channel (creek), intermittently inundated channel (wadi), seasonally waterlogged channel (trough), seasonally inundated flat (floodplain), intermittently inundated flat

(barlkarra), seasonally waterlogged flat (palusplain), seasonally waterlogged slope (paluslope) and seasonally waterlogged highlands (palusmont).

Scott and Jones (1995) and Gerbeaux et al. (2018) provided a global overview of the many approaches to the classification and inventory of wetlands. They also called for international standards to strengthen international agreements among partner countries regarding wetland protection. Finlayson and van der Valk (1995) noted the difficulties in determining general parameters for wetlands that can be applied on a worldwide scale to define and delimit wetland areas, and the need to resolve differences between regional wetland definitions and regional typologies. They also recommended a standardization of data collection and the dissemination of new technologies in order to establish ample international inventories. Ramsar's Scientific and Technical Review Panel likewise called for the *development and testing of a hydro-geomorphically-based system of wetland classification* (Davidson and Finlayson 2007).

The many wetland definitions and classification systems formulated decades ago for specific purposes clearly do not meet current scientific and regulatory requirements. However, there are several major problems in compiling a general wetlands classification. The first is that any classification system must encompass wetlands of different size and complexity, as discussed in the next section. The second is that most classification systems do not organize the hydrological, geomorphological, botanical or soil- and water-chemical parameters of wetlands hierarchically. While the large majority of scientists agree that hydrology is the main driver of wetlands worldwide, this is rarely reflected in classification systems. Furthermore, the terms used in a worldwide classification system have to be widely adopted by the international scientific community. The use of less familiar terms to describe wetland types, as in the classification developed by Semeniuk and Semeniuk (1995), hinders the formulation of an international wetland classification.

The new Brazilian classification system (Junk 2024) is an attempt to overcome these problems. It is hierarchical and based on hydrological parameters. Like most other classification systems, it distinguishes between three systems: coastal wetlands, inland wetlands and anthropogenic wetlands. Further categories of subsystems, orders, suborders and classes are based on hydrological parameters, with

vegetation and hydrochemical parameters used only at the subclass and macrohabitat levels. Moreover, the classification differentiates between small, simply structured wetlands and large, complex wetlands that cover the entire hydrological gradient from permanently aquatic to permanently terrestrial conditions. However, the system was developed for wetlands in Brazil; it does not consider the wetlands in other climatic and biogeographic zones worldwide.

Wetland size and complexity

General considerations

Wetlands can be small and simply structured, medium-sized or very large, covering areas up to many thousands of square kilometers. With increasing size, complexity increases as well. Complexity is reflected by the presence of different geomorphological subunits subjected to different hydrological and soil conditions and covered by different plant communities. For classification purposes, a separation into small to medium-sized, simply structured wetlands subjected to rather uniform hydrological conditions and large to very large wetlands with subunits subjected to different hydrological conditions is necessary. The first group is addressed by all classification systems. The second has not been adequately addressed because of its complexity.

The separation into two groups is essential not only for scientific purposes but also for management aspects and legal, administrative, cultural, and political reasons. The management and protection of large wetlands require specific legal frameworks, which in some cases, such as the Okavango Delta (Ramberg 2018) and the Indus River (Davidson 2018a), include multinational agreements. Many large tropical wetlands and northern peatlands are home to traditional communities. For instance, more than 12 million people live in and around the Sunderbans Delta of the Ganga–Brahmaputra–Meghna Rivers, of which about 2.5 million depend almost entirely upon the mangroves for their livelihood (Gopal and Chauhan 2018). The Mekong River Delta, divided between Cambodia and Vietnam, is one of the most populated rural areas in the world (Tran 2018). Some 200,000 people live within the Danube Delta, shared

by Romania and Ukraine (Baboianu 2018). All large river floodplains are used by local populations for fishing and crop production. The requirements of these populations have to be respected and adequately addressed by local authorities.

In 2024 a project started to map the wetlands of the Amazon basin, which covers an area of about 7.6 million square kilometers. Some of the eight countries, participating on the basin, have their own wetland definitions and classifications. Brazil owns about 77% of the area. Therefore Brazilian wetland specialists made a proposal to the Fórum Nacional de Comitês de Bacias Hidrográficas (FNCBH) to use the Brazilian classification approach and concentrate at the beginning on the mapping of wetscapes, because mapping of wetlands at lower classification levels would be very difficult and would require different methodological approaches at different scales.

Small, simply structured wetlands

Small, simply structured wetlands are highly diverse. In coastal areas they include different types of shores, including sandy and rocky beaches and mud flats, and isolated patches of mangroves and salt marshes. Examples of small inland wetlands are temporary wetlands in small depressions, isolated peat bogs and mires, wetlands around lakes and riparian wetlands along low-order streams and rivers. The small size of individual wetlands does not diminish their importance in the landscape. Depending on rainfall, small wetlands can be very numerous and, while often temporary, very important, as they maintain water in the landscape and provide habitats for many wetland plants and animals. For example, riparian wetlands along low-order streams typically form a drainage network, the density of which depends on precipitation, geomorphology, geology and vegetation cover. However, worldwide, there are only few inventories of small wetlands that also consider their density in the landscape.

In Brazil, an area of ~927 km² in the rainforest near Manaus, with an annual precipitation of 2,100 mm, was inventoried. A stream density of 800, 180, 42, 12 and 2 streams for first- to fifth-order streams was determined. Riparian wetlands, swamps and hydromorphic soils cover 48% of the area (Rodrigues et al. 1971). An inventory in the dryer Cerrado region found that 23.5% of the catchment of the fifth-order

Tenente Amaral River, comprising an area of ~875 km², consists of wetland of which roughly half is made up of riparian wetlands (Wantzen et al. 2006). A second inventory in the Cerrado indicated that 11.8% of the catchment of the fifth-order Quilombo River consists of wetland, extending over an area of ~1,669 km², with roughly 46% made up of riparian wetlands (Goncalves 2021). Overall, about 20% of the Amazonian lowlands and 5–10% of the Cerrado are covered by riparian wetlands of low-order streams (Junk et al. 2022). The total area is at least as large as the area covered by large wetlands, investigated by remote sensing approaches (Melack and Hess 2010).

At a regional scale, small, simply structured wetlands can be subdivided according to different parameters. For instance, streams can be classified in terms of their hydrology (perennial and ephemeral streams), climate (arctic streams, temperate region streams and subtropical/tropical streams), geomorphological parameters (lowland and mountainous streams) or the surrounding upland vegetation (streams in forested areas or in grasslands).

In the Brazilian classification system, small, simply structured wetlands enter at the level of subclasses and macrohabitats. Subclasses are defined as *small wetlands, respectively subunits of functional units in wetscapes, with specific hydrological conditions and a characteristic vegetation cover*. Macrohabitats are defined as *subunits of subclasses, characterized by specific indicator plants or groups of species, or, in their absence subjected to a similar terrestrial or aquatic environment* (Junk et al. 2015). This classification can be used for small, simply structured wetlands worldwide, but it is up to local wetland scientists to decide whether they want to use this or other approaches.

Small wetlands are more threatened than large ones to anthropogenic actions such as deforestation, agricultural activities, water withdrawal and pollution. As legislation dealing with small wetlands often differs from that aimed at large wetlands, small wetlands must be included in local classification systems to ensure their protection. To avoid overloading, an international wetland classification system should focus on classification units describing higher rankings. Classification of small wetlands allow the integration to lower rankings by local scientists, as shown by the Brazilian example.

Large and complex wetland landscapes, also called “wetscapes”

Thorslund et al. (2017) treat wetlands and the surrounding uplands at a catchment area level under hydrological aspects. They call these units wetlandscapes and define them as “*the hydrologically coupled system of multiple wetlands and their total hydrological catchment*”. Inherent water flux interactions between wetlands and the hydrological system are considered, including groundwater and evapotranspiration exchanges, which are naturally limited by the borders of entire interconnected hydrological catchments. Flow-paths through the wetlandscape and between individual wetlands are analyzed with hydrochemical parameters leading to hydrological models for the respective wetlandscapes including predictions of impacts of human water use and changes in global climate.

In the hydro-ecological classification system presented here, large and complex wetlands are called wetscapes. They combine hydrological parameters with ecological and socio-economical aspects and are defined as follows: *Wetscapes are large landscape units in which different wetland types closely interact with terrestrial and/or deep-water ecosystems, providing the environmental conditions required by specific plant and animal populations. Wetscapes are often recognized as political, economic, social and, in some cases, also as cultural units and have to be treated holistically as such.*

A large number of small, simply structured wetlands can together form a complex wetscape. For example, the prairie potholes at the US/Canada border consist of millions of depressional wetlands and cover a total area of ~770,000 km². The depressions receive water from snow melt and rain and constitute a large variety of temporary, seasonal, semipermanent and permanent wetlands. The complex wetland-grassland wetscape formed by the potholes harbor a high biodiversity that depends on the interactions of the different types of potholes with the surrounding terrestrial grasslands (Doherty et al. 2018). Similarly, the playa wetlands of the semi-arid western Great Plains (USA) are formed by many closed depressions that are filled during erratic precipitation events. Some receive water only every few years; large ones may contain water over several years and others may have multiple dry and wet periods in one year,

depending on the precipitation. This wetscape is a biodiversity hotspot that reflects the numerous adaptations to wet-dry changes as well as the interactions between the many small wetlands and the surrounding semi-arid upland (Bartuszevige 2018).

Other examples of wetscapes are the mires of the former Soviet Union (Masing et al. 2010), the northern peatlands of Canada (Warner and Asada 2006), the Everglades in North America (Brown et al. 2006), the Sundarbans mangrove ecosystem of the Indian subcontinent (Gopal and Chauhan 2006), the Okavango Delta in Africa (Ramberg et al. 2006; Ellery et al. 2000), Tonle Sap and connected wetlands in Southeast Asia (Campbell et al. 2006), the wetlands of the Kakadu National Park in Australia (Finlayson et al. 2006), the Pantanal (Nunes da Cunha et al. 2023), Amazonian large river floodplains (Junk et al. 2012, 2015) in South America and the large river deltas world-wide, such as the Yukon-Kuskokwim Delta, Alaska (USA) (Reid and Fehring 2018), the Amazon River Delta in Brazil, the Danube Delta in Europe (Baboianu 2018), the Paraná River Delta in Argentina (Kandus and Quintana 2018) and the Lena River Delta in Russia (Degtyarev 2018).

However, the inclusion of these wetscapes in existing classification systems is difficult. In *Wetland Indicators*, Tiner (1999) treated floodplain wetlands as hydrologically problematic, considered floodplain forests only briefly and called for additional studies. In the Ramsar Convention's typology of wetlands published by Finlayson (2018a, b, c), wetlands are listed independent of their size and complexity. Floodplains are not considered as a specific category because they are complex and include several wetland types. The hydro-geomorphic classification system of Semeniuk and Semeniuk (2018a, b) classifies floodplains as areas of seasonal inundation but, as shown above, floodplains include many different subunits. While Semeniuk and Semeniuk use these subunits as the basis for characterizing different wetland types, in wetscapes they are part of the same wetland system.

The Ramsar Convention addresses the conservation of wetlands and their flora and fauna, combining far-sighted national policies with coordinated international action. It designates 2400 large wetlands of international importance (Davidson 2018a). The Convention on Biological Diversity (CBD) and Wetland Management joins 193 parties with the aim of protecting biodiversity

(Coats 2018). The Convention on Migratory Species (CMS), or Bonn Convention, includes wetland management in the context of transboundary cooperation for the protection of migratory species (Roberts and Davidson 2018a, b). Wetlands International, a not-for-profit organization, is dedicated to the conservation and restoration of wetlands (Madgwick 2018). All of these international organizations and many others deal with wetscapes that do not appear in national and international classification systems.

In the hydro-geomorphological classification proposed in this article, individual wetscapes occupy the status of classes although their complex structure would require their subdivision into smaller, hydrologically well-defined subunits. In the Brazilian classification system, this problem has been resolved by the introduction of a specific category, the "functional unit," defined as a *large landscape unit in the wetscape, characterized by specific hydrological conditions*. The system differentiates between five functional units: permanently aquatic, periodically aquatic, periodically terrestrial, permanently waterlogged (palustric) and permanently terrestrial (Fig. 1). A sixth functional unit recognizes anthropogenic areas, independent of their hydrological characteristics. Based on a previous definition of wetland delimitation (Junk et al. 2014; Junk 2022), permanently terrestrial macrohabitats inside and at the edges of a wetland are included. The number of sub-classes and macrohabitats in different Brazilian wetscapes is shown in Table 1.

Subdivisions in different smaller landscape units are also available for wetscapes in other countries. Ramberg (2018) pointed out the importance of permanently terrestrial areas for the biodiversity of the Okavango Delta, which extends over an area of ~28,000 km². It consists of ~14,000 km² of permanently terrestrial areas in the form of ~150,000 island-like features and plains that were flooded during historic times (beginning in the 1850s): +820 km² belong to the panhandle, ~2,500 km² are permanently swamps, ~3,300 km² are seasonal swamps, and ~7,100 km² occasional swamps, flooded at least once every decade. The 45 habitat types are distributed among 500,000 habitat units that are, on average, about 5 ha in area. The Okavango Delta Ramsar Site covers ~68,640 km² that include adjacent areas as buffer zones, in

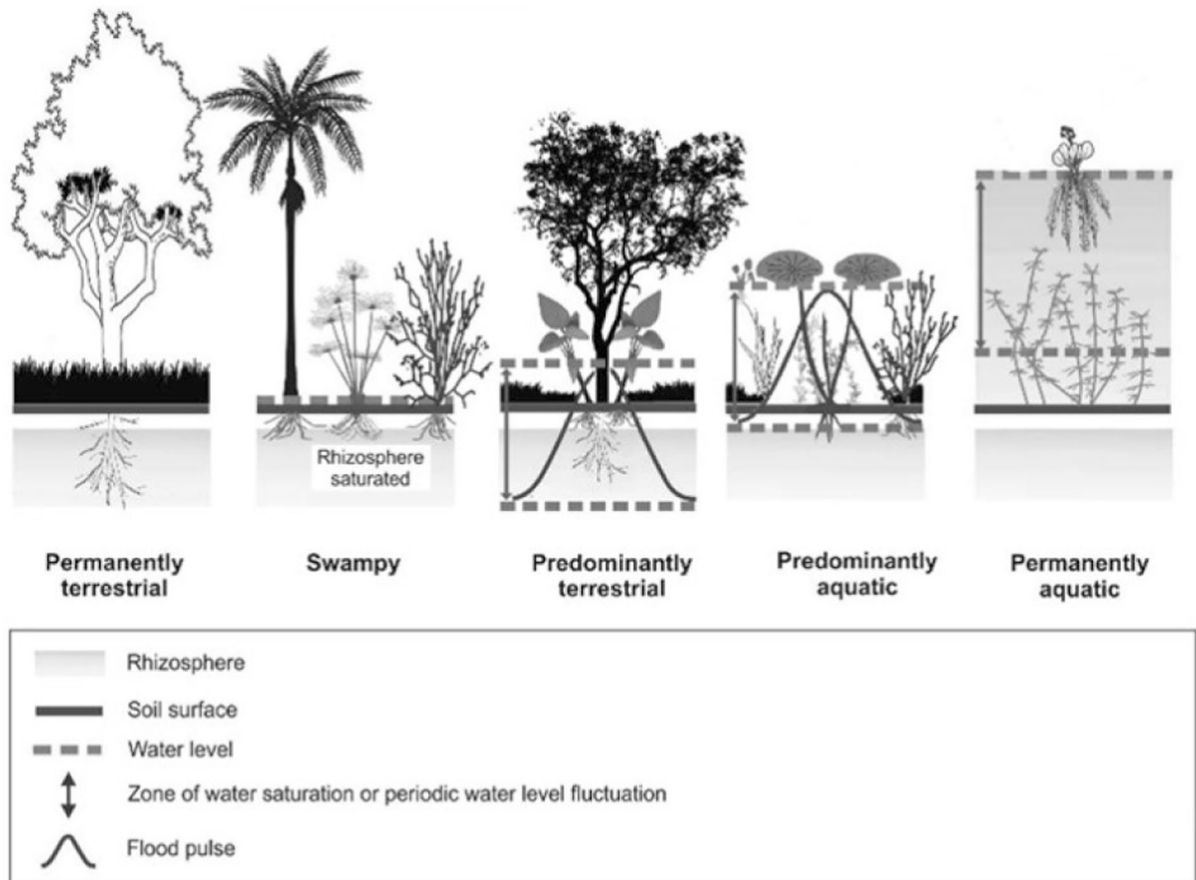


Fig. 1 Functional units in Brazilian wetscapes according to their hydrological status. (Adapted from Nunes da Cunha and Junk 2017)

Table 1 Number of macrohabitats in five large Brazilian floodplains belonging to the suborder of wetscapes with predictable monomodal flood pulses of low (Pantanal and Ara-

guaia River floodplains) and high (várzeas of Amazon River, igapós of the Negro River, floodplain of the Paraná River) amplitudes

Floodplain	Functional units	Subclasses	Macrohabitats	Source
Pantanal	6	16	74	Nunes da Cunha et al. 2023
Araguaia	6	13	43	Arruda et al. 2023
Várzeas	6	13	36	Junk et al. 2014
Igapós	6	12	25	Junk et al. 2015
Paraná River	6	13	23	Junk et al. 2021

recognition of the importance of terrestrial areas for wetland protection. The alluvial valley of the Mississippi River extends over an area of ~100,000 km² and was subdivided in the classification by Davis (2018) into riverine wetlands, palustrine emergent wetlands, bottomland hardwood forests, palustrine

shrub forests, lakes, reservoirs and aquaculture ponds, with many different subunits.

Wetland size and complexity and the relationship to biodiversity

There is general agreement that wetlands are centers of biodiversity but few definitions take this relationship into account. The most comprehensive one is that of Gopal and Junk (2001), which states that wetland organisms are *all those plants, animals, and microorganisms that live in a wetland permanently or periodically (including migrants from adjacent or distant habitats) or depend directly or indirectly on the wetland habitat or on other organisms, living in the wetland*. However, this definition highlights a conflict between wetland definition and delimitation. The position between permanently deep-water ecosystems, such as the oceans in coastal wetlands and lakes and river channels in inland wetlands, and adjacent permanently terrestrial ecosystems results in permanent or periodic invasions of species from both areas in addition to wetland-specific species.

For the Pantanal of Mato Grosso in Brazil, about 2,000 species of higher plants are listed (Pott and Pott 1996, 2000), of which 1,147 are herbaceous species, 756 are woody species. 247 species are considered herbaceous aquatic macrophytes “sensu strictu.” An analysis of the habitat preferences of 85 tree species showed that 18 species were restricted to habitats with long inundation periods; 45 species preferred terrestrial habitats or habitats with short inundation periods and 22 species were found along the entire flood gradient (Nunes da Cunha and Junk 2001). Extrapolating these numbers to the 756 woody species occurring in the Pantanal, about 160 would show a preference for habitats with long inundation periods, 195 would occur along the entire flood gradient and 401 would prefer permanently terrestrial habitats.

For the flora of the Okavango Delta, 1,256 species are listed. Plant species are ordinated along hydrological gradients ranging from permanently terrestrial to permanently aquatic conditions; 696 species occur in dryland settings, 43 in riverine woodlands, 86 in flooded grasslands, 36 in rainwater pans, 219 in seasonal swamps and 20 in permanent swamps. Many of the dryland species, however, are not present in the surrounding savanna habitats. Rather, they are intimately associated with the wetland environment, as they require a high groundwater table (Ellery et al. 2000).

Wetland animals can be classified into six main categories (Gopal and Junk 2000). The first includes residents of the wetlands proper. The second comprises regular migrants from deep-water habitats and thus mostly fishes. Juveniles of many fish species use the floodplains during the high-water period for hiding and feeding (Junk et al. 1997). In Amazonia, some turtle species and the manatee (*Trichechus inunguis*) migrate from deep-water habitats into the floodplains for feeding. In the third group are regular migrants from terrestrial habitats. This group covers a wide range of species and includes the well-known large migrations of ungulates between the African floodplains and adjacent savanna (Ramberg et al. 2006) and the bird populations in the prairie potholes in the USA (Doherty et al. 2018). In the fourth group are regular migrants from other wetlands, such as the extended migrations of waterfowl between South American wetlands depending on the water level of the respective areas. Some species from northern and southern high latitudes spend the winter in tropical and subtropical South American or African wetlands, but terrestrial birds may also use the floodplains as stopping points during their migrations (Junk et al. 2006). The fifth group comprises occasional visitors and in the sixth are animals that indirectly depend on wetland biota. This last group, which includes canopy invertebrates (Adis 1997) and also pathogens and parasites of wetland species, has hardly been studied but it contributes significantly to the overall species diversity of wetlands. This broad classification allows further subclassification of animal groups according to their adaptation and life-history traits.

The examples show that the characterization of vegetation and animal communities are useful for the description of lower classification units. However, their use for a world-wide classification is not recommendable, because it would overload the system with local information.

The importance of climate for wetland classification

The major driver of ecological processes world-wide is climate. At higher latitudes the annual light/temperature pulse (summer/winter pulse) influences all biological processes, including the life cycles of organisms, the velocity of biogeochemical processes,

and photosynthetic activity. It also influences hydrology by uncoupling precipitation from the water level in lakes, rivers and wetlands by storing rainwater in the form of snow and ice in the landscape and releasing it with increasing temperature, independent of the local precipitation pattern. Extended wetlands occur in the permafrost of arctic regions. In summer, the rise in temperature causes the upper soil layer to thaw, resulting in the formation of a waterlogged peatland (Minayeva et al. 2018).

Shatford (2018a, b) noted the importance of spring and summer floods on the extensive system of wetlands and small lakes situated above the normal river stage in the Peace-Athabasca Delta of the MacKenzie River Basin (Canada). The Yukon River has low flow, with small variations in the cold season (November to April), and high flow with large variations in the warm season (May to October) (Ge et al. 2013). Degtyarev (2018) reported an ice cover of 220–230 days for the Lena River Delta (Russia) in winter. After the spring break-up in late May, a flood-pulse affects the delta that reaches 15 m in the upper part and 6–9 m closer to the sea. The same report highlighted the importance of ice drift jams, which locally increase the floods. For the greater part of the Yenisey system, the eastern Siberian hydrologic regime prevails: violent spring floods are followed first by a rapid and then by a slower fall in the water level, with summer and autumn rain-induced floods punctuating the sequence. In winter, the runoff is sharply reduced, but water levels remain high, as ice jams are formed. About half of the Yenisey's water comes from snow, a little more than one-third from rainwater and the remainder from groundwater (Yang et al. 2004). The importance of climate is recognized by the North-American wetland definition (Cowardin et al. 1979), which considers the duration of waterlogging or shallow inundation during the growing season of the vegetation as an important parameter describing wetland status.

Towards the equator, the light-temperature pulse loses strength and the availability of water becomes the major ecological driver. The alternation between rainy and dry seasons determines the timing and intensity of ecological processes on land, in water and in wetlands. The subtropical climate of south Florida leads to a wet dry seasonality in the Everglades. In characterizing the ecological conditions in south Florida, Richardson (2018) postulated that, with respect

to vegetation composition, the flood pulse was more important than the winter/summer temperature pulse.

Large wetlands in the tropics and subtropics are subjected to monomodal, rather predictable flood pulses according to rainy and dry seasons. The flood pulse of large rivers may be as large as 15 m, as is the case in some Amazonian rivers (Fig. 3), the Nile River and the Mekong River. The extended floodplains are covered by a species-rich, flood adapted vegetation with high productivity rates throughout the year. The predictable flood pulses of the Nile River allowed agricultural use of the fertile floodplain and were the basis for the development of Egyptian high culture. In flat interfluvial areas, large floodplains subjected to a low predictable flood pulse can develop, usually in connection with large or medium-sized rivers. Many of them receive most of their water from local rainfall, but all of them show an intensive exchange of plants and animals with the connected rivers. Examples include the Everglades in the USA, the Pantanal, the Araguaia and Guapore River wetlands in Brazil, the Llanos baixos in Venezuela, the Llanos dos Moxos in Colombia, and the Sudd and the Okavango Delta in Africa. This aspect is considered in the hydrological classification presented in Sect. “[General considerations](#)”, Table 2.

Hydrology as a worldwide uniform classification parameter

General considerations

Among most scientists there is common agreement that hydrology is the best criterium for a world-wide uniform classification system. Nonetheless, hydrology has not been prioritized in the description of wetland systems. In its many chapters, the encyclopedic Wetland Book (Finlayson et al. 2018a, b) provides description of major wetlands around the globe, often with a specific section devoted to a description of the hydrology. However, the descriptions are often very vague and do not provide the information necessary to understand the ecological conditions in the respective wetlands and their subunits. For instance, reporting the mean discharge of a large river without reference to the amplitude, length and frequency of floods and droughts provides no information about the connected wetlands. All chapters indicate characteristic

Table 2 Hydrological regime and affected wetlands. Examples are provided in paragraphs 7.2, 7.3 and 8

1. Wetlands with rather stable water levels			
	Wet permafrost soils, northern peat bogs, freshwater swamps, wetlands around large lakes, tropical peat lands		
2. Wetlands with fluctuating water levels			
	Flood pulse variables		
Predictability	Frequency	Amplitude	Wetland type
Predictable	Monomodal	High	Large river floodplains in a) subtropical and tropical regions according to rainy and dry seasons b) high latitudes according to snow melt
		Low	Large interfluvial wetlands a) subtropical and tropical regions according to rainy and dry seasons b) high latitudes according to snow melt
Predictable	Bimodal	High	Magdalena River, upper Negro River
Predictable	Polymodal	Variable	Tidal wetlands
Unpredictable	Polymodal	Variable	Wetlands along streams and low-order rivers, wetlands in small depressions, (flooding by rain and/or snow melt)
Unpredictable	Multi-annual	Low	Wetlands in arid regions (dryland wetlands)
Variable (man-made)	Variable	Variable	Reservoirs, paddy fields

plant communities but only in some are they related to hydrological conditions.

A classification of the hydrological regime and examples of affected wetlands are given in Table 2. Most classification systems do not consider these hydrological differences. Many inland wetlands fall into the palustrine system proposed by Cowardin et al. (1979) and into the classes moss-lichen, emergent scrub-shrub or forested wetlands (Mitsch and Gosselink 2015). However, large river floodplains include subsystems of riverine, lacustrine and palustrine systems. The same is true for coastal wetlands. Large mangrove systems are composed of subunits that differ with respect to the length of the tidal pulses and the interaction with affluents from the upland. Modifications in the flood pattern result in changes in species composition and in extreme cases in species extinction, as shown in areas affected by human activities. Construction of the Balbina Reservoir in Central Amazonia changed the flood pulse below the dam and caused the wide-scale death of highly adapted floodplain trees along a river stretch of ~100 km below the reservoir (Schoengart et al. 2021).

Wetlands with a relatively stable water level

Many wetlands can be described as moist areas with a relatively stable water level, defined borders with the surrounding upland and, when connected to lakes and rivers, to adjacent deep-water habitats. The hydrologically stable conditions lead to permanently anoxic conditions in the soil that delay the decomposition of organic material, produced by mosses (*Sphagnum*), sedges, grasses, reed beds shrubs and trees. If more than 30% of the dry material of the soil is organic material, it is called peat; if the layer is deeper than 30 cm and not covered by mineral soil, the wetland is called peatland. Peatlands that receive their water from rainfall are nutrient-poor and also called ombrotrophic bogs or mires; those supplied by groundwater or surface water are richer in nutrients and are called minerotrophic fens (Joosten and Clarke 2002).

Peatlands cover huge areas mainly in the northern part of the globe, including in Russia (~1.376 million km²) and the USA and Canada (~1.86 million km²) (Vitt 2018), regions where the low temperature, the balanced relationship between precipitation and evapotranspiration and a flat landscape provide appropriate conditions for permanent water logging and

the accumulation of peat. The region can be divided into an arctic part, with permafrost soil, and northern boreal wetlands. Minayeva et al. (2018) examined the impact of permafrost processes for the variability of arctic peatlands, differentiating between “frozen” peatland types (polygon mires, peat plateaus and palsa mires), and “non-frozen” peatland types (patterned string fens, raised bogs, riparian mires, coastal tundra and some types of coastal marsh).

A classification of the North American boreal wetlands recognizes three classes of mineral wetlands and two classes of peat wetlands. Mineral wetlands include open water (three subunits), marsh (two subunits) and swamp (five subunits). Peat wetlands include a fen class, subdivided into poor fens (three subunits) and rich fens (three subunits), and a bog class (three subunits). The differentiation into subunits is based mostly on the species composition of higher vegetation (Gingras et al. 2018). Lindsay (2018) differentiates peatlands into minerotrophic mires (fens) with five subtypes and ombrotrophic mires (bogs) with four. In South America, major peatlands are located in the cold temperate humid zones of Chile (10,470–21,000 km²; Figueroa et al. 2018) and Argentina (~50,000 km²), mainly in Patagonia (Iturraspe 2018). With an area of ~44,000 km², the Magellanic tundra, also called the Magellanic moorland, is the largest peatland complex of the region.

In the tropics, peatlands are less frequent because high temperatures and fluctuating water levels hinder the accumulation of organic material. Data on peatlands in tropical South America are incomplete. Brazilian peatlands cover ~55,500 km² (Silva et al., in press). In Africa, papyrus marshes accumulate organic matter. Papyrus (*Cyperus papyrus*) is a large, highly productive wetland sedge that reaches a height of 5–6 m. Large stands occur in the Sudd, in the Nile River floodplain in South Sudan and around large African lakes, including Lake Victoria, Lake Albert, Lake Tanganyika and Lake Chad, and rivers, including the White Nile, Congo River and Zambezi River systems (Kipkemboi and van Dam (2018). Figures on the actual extent vary between ~20,000 km² (Thompson 1985) and ~85,000 km² (Chapman et al. 2001).

Tropical peatlands of Southeast Asia cover an estimated area of ~248,000 km² (56% of the global resource) (Page and Rieley 2018). Most are rain-fed, acidic and of very low nutrient status. Their

vegetation consists of tree species adapted to long-term water logging. The peat layer, composed of woody debris, may reach a depth of up to 20 m. The hummock-hollow structure of the peat dome surface leads to a mosaic of dryer, wetter and water-filled areas. Hydrologic stress is highest in the center of the peat dome. Vegetation changes from stunted, open-canopy pole forest in the center to tall, closed-canopy forest on shallow marginal peat. Streams and rivers draining from the peat domes are acidic, nutrient-poor and rich in tannins (black water).

Wetlands with fluctuating water levels

Many wetlands are subjected to water level fluctuations (Figs. 2 and 3), which affect the size of permanently and periodically wet areas and the ecological conditions. In regions with sufficient rainfall, the terrestrial phase of these wetlands can last from a few days (Fig. 2) to several months (Fig. 3) and in arid regions for several years. The change in hydrology results in a change from oxic to anoxic conditions and thus affects the biogeochemistry of the soil. Plant and animal species show many morphological, anatomical, physiological and ethological adaptations to the shift from wet to dry conditions, as described by the flood pulse concept (Junk et al. 1989), and, for example, for the Amazon floodplain forest (Junk et al. 2010) and Amazonian herbaceous plants (Piedade et al. 2019).

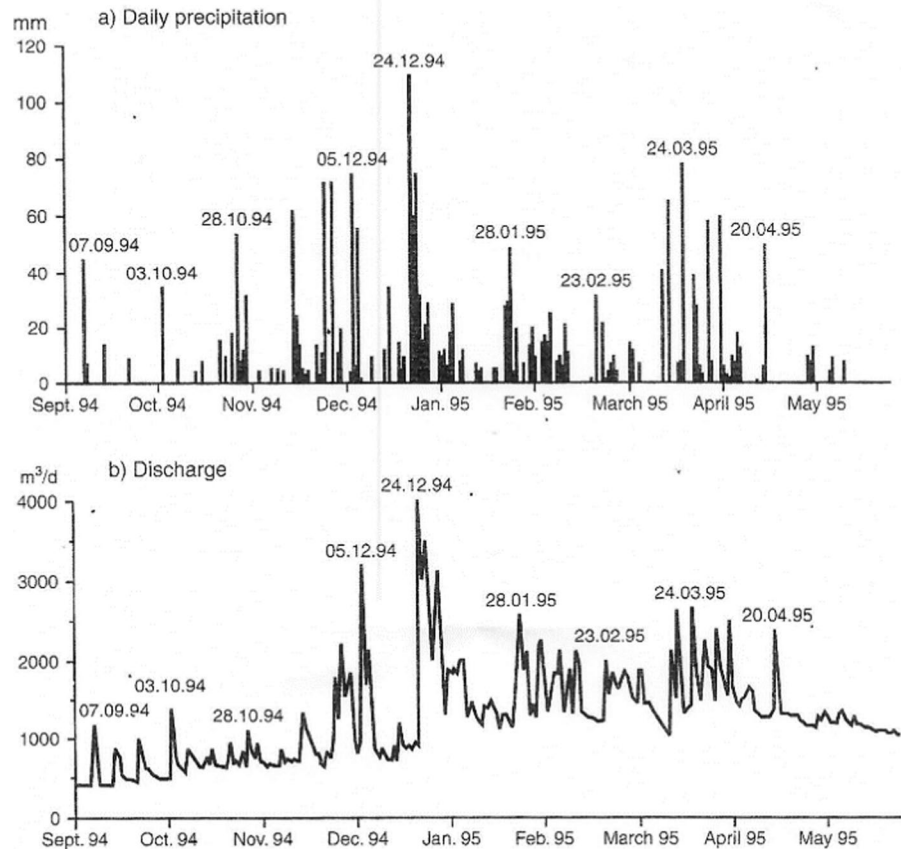
Along the coast many wetlands are subjected to polymodal, short, predictable pulses of different amplitude (tidal pulses). In the tropics and subtropics extended mangrove forests and in temperate regions large mud flats and salt marshes occur, which are colonized by highly adapted animal species. In the transition zone of coastal and inland ecosystems many wetlands are subjected to different types of flood pulses, resulting from the overlap of river discharge, local rainfall and tidal activities.

A proposal for an international hydro-ecological wetland classification system

General considerations

An international wetland classification system should be hierarchical, easily understandable and flexible

Fig. 2 Precipitation and discharge of the Tenente Amaral stream (data from Wantzen 2003)



enough to allow the introduction of additional major wetland units, because their characterization is far from complete. The hydro-ecological classification system presented here (Table 3), is a hierarchic system that bases at higher levels on hydrological parameters and relates them at lower levels with ecological parameters and differences in plant and animal communities. Wetland vegetation enters only as general descriptive element at higher levels, such as peatlands at the suborder level or papyrus swamps, fen classes and sea grass beds and others at the class level.

The system is an amplified version of the new Brazilian classification system (Junk 2024). At the system level it follows many other classifications and divides wetlands into coastal, inland and artificial wetlands. Higher rankings of subsystems, orders, suborders and classes are based on hydrological parameters. The classification differentiates between relatively small, simply structured wetlands and large, complex wetscapes, which enter at

the class level. Large river deltas are included in the coastal wetland system despite the fact that large areas in their upper parts could also be treated as inland wetlands. Examples of wetlands at the class level are provided. Considering their complexity, a subdivision of wetscapes into functional units is required before their entry at the subclass and macrohabitat levels. The Brazilian approach to the classification of smaller units is presented in Fig. 1. Artificial wetlands are summarized only at the class level and not discussed in detail. They should be treated by local scientists and included in regional or national classification systems.

The proposed classification system allows the inclusion of additional wetland types at higher rankings. It is up to local specialists to characterize the wetlands in their regions or countries, define their position in the classification system and subdivide them into lower units, if necessary. Given the large diversity of wetlands worldwide, the new classification system cannot deal with those at lower

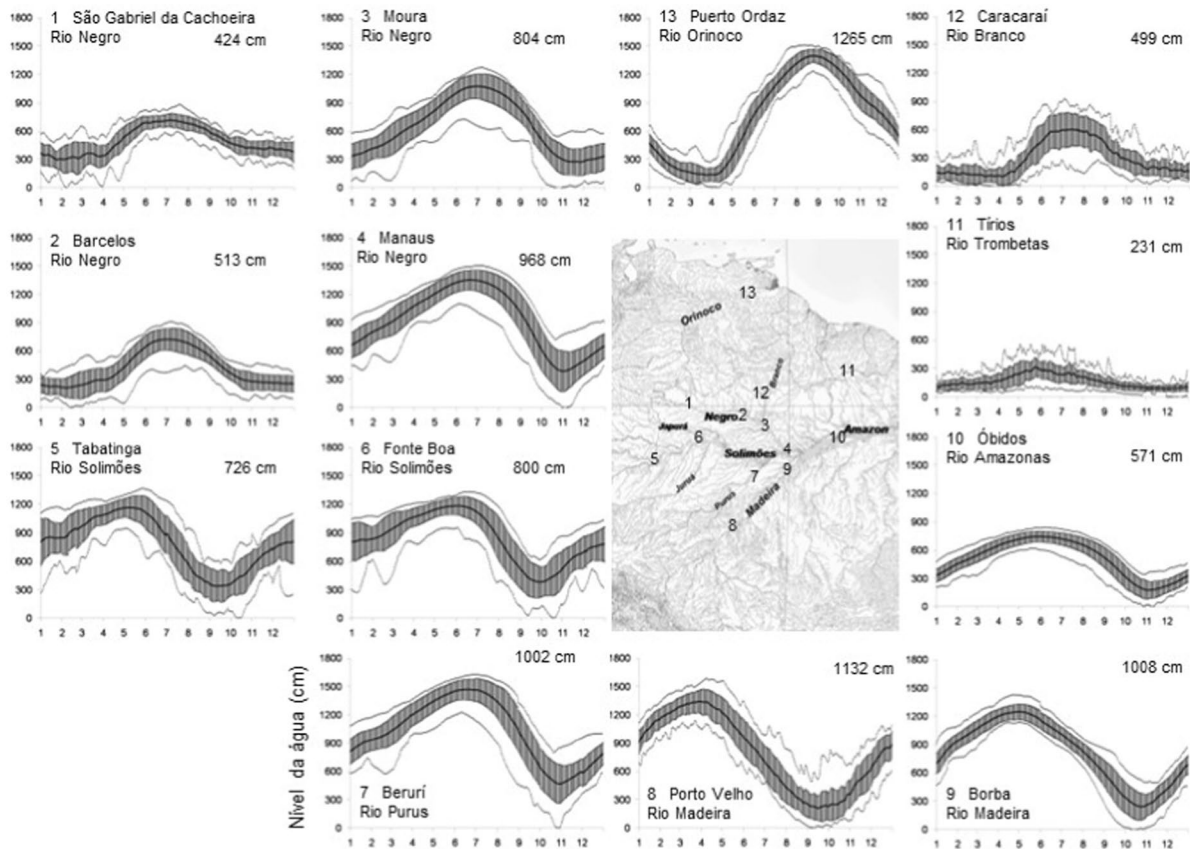


Fig. 3 Flood pulse pattern at 13 hydrological stations on the Amazon, Solimões, Negro, Branco, Trombetas, Purus and Madeira rivers. The geographic positions of the stations are indicated by the numbers in the map. The figures show the mean annual water level, the standard deviation and the minimum and maximum values between 1983 and 2005 ($n=23$).

levels (functional units, subclasses and macrohabitats). These should be classified by local scientists in national approaches based on local parameters such as vegetation, soils and hydrochemistry. Those approaches are of national interest because they provide the basis for wetland management, protection and rehabilitation.

The coastal wetland system

The five subsystems used to classify coastal wetland systems consider differences in the tidal area and the transition from the sea to inland waters (Table 3). The first subsystem covers marine wetlands. At the class level it includes sea-grass beds, which are widely distributed along temperate and tropical coastlines and

extend to depths of 90 m (Short et al. 2018). Another class includes different types of reefs, which are also found at great depths in the ocean. The new classification follows the Ramsar classification system which considers these ecosystems as wetlands only down to a depth of 6 m at low tide.

The second subsystem includes coastal wetlands subjected to predictable flood pulses of long duration. It is formed by one order, consisting of coastal-marine wetscapes, and by one suborder that includes wetscapes of large river deltas. They are situated at the interface between coastal and inland wetlands. Their hydrology is strongly influenced by the parent river but overlaps near the sea with tidal pulses. A classification of subunits requires the consideration of salinity gradients (Barendregt 2018). An example

Table 3 Proposal for a worldwide hydro-ecological classification system of wetlands at higher classification units

System	Subsystem	Order	Suborder	Class
System 1: Coastal wetlands				
	Subsystem 1.1: Marine wetlands			Classes:
Examples: Sea grass beds, reefs and others				
	Subsystem 1.2: Coastal-marine wetlands subjected to monomodal predictable flood pulses of long duration			
	Order 1.2.1: Coastal- marine wetscapes subjected to monomodal long pulses			
			Suborder 1.2.1.1: Wetscapes of large river deltas	Classes:
Examples: Deltas of Amazon River, Paraná River, Mississippi River, Mackenzie River, Lena River, Ganges/Brahmaputra River, Danube River and others				
	Subsystem 1.3: Coastal wetlands subjected to polymodal, short predictable pulses			
	Order 1.3.1: Coastal-marine wetscapes subjected to polymodal short predictable tidal pulses			Classes:
Examples: Large mud flats (Wadden Sea, Europe), large salt marshes, large coastal mangrove areas and others				
	Order 1.3.2: Small coastal wetlands			Classes:
Examples: Sandy beaches, rocky coasts, small coastal mangrove areas, small coastal salt marshes and others				
	Subsystem 1.4: Wetlands separated from the sea and with relatively stable water levels			Classes:
Examples: Freshwater lagoons, lagoons with saline water, forested swamps, herbaceous swamps and others				
	Subsystem 1.5: Wetlands separated from the sea and with fluctuating water levels			Classes:
Examples: Wetlands along coastal river channels, periodically flooded forests, periodically flooded grasslands, temporary lagoons and others				
			Suborder 1.5.0.1: Wetscapes near the coast	Classes:
Examples: Lenções maranhenses (Brazil) and others				
System 2: Inland wetlands				
	Subsystem 2.1: Wetlands with relatively stable water levels			
	Order 2.1.1: Wetscapes with relatively stable water levels			
			Suborder 2.1.1.1: Wetscapes in the permafrost arctic region	Classes:
Examples: Paludified shallow peatland (tundra), polygon mires with or without thermokarst ponds, peat plateau and palsa mires, and others				
			Suborder 2.1.1.2: Northern mineral wetscapes of North America	Classes:
Examples: Marshes, swamps and others				
			Suborder 2.1.1.3: Northern peatland wetscapes of North America	Classes:
Examples: Fen classes, bog classes				
			Suborder 2.1.1.4: Northern mineral wetscapes of Asia	
			Suborder 2.1.1.5: Northern peatland wetscapes of Asia	
			Suborder 2.1.1.6: Southern peatland wetscapes of South America	

Table 3 (continued)

System	Subsystem	Order	Suborder	Class
				Classes:
Examples:	Magellanic tundra		Suborder 2.1.1.7: Tropical peatland wetscapes	Classes:
Examples:	Large peat swamp forests in Southeast Asia, large Andean peat lands, large papyrus marshes in Africa and others		Suborder 2.1.1.8: Wetscapes of tectonic activity	Classes:
Examples:	Yellowstone wetscapes	Order 2.1.2: Small, simply structured wetlands	Suborder 2.1.2.1: Forested wetlands	Classes:
Examples:	Palm swamps (Brazil), cypress swamps (USA) and others		Suborder 2.1.2.2: Grassy-herbaceous wetlands	Classes:
Examples:	Veredas (Brazil), small papyrus swamps (Africa), small peatlands (worldwide) and others	Subsystem 2.2: Wetlands with fluctuating water levels	Order 2.2.1: Wetlands subjected to predictable, long-lasting monomodal or bimodal flood pulses	Classes:
			Suborder 2.2.1.1: Wetscapes with flood pulses of high amplitude along large rivers	Classes:
Examples:	Várzeas and igapós of large Amazonian rivers (Brazil), Mississippi River floodplain (USA) and others		Suborder 2.2.1.2: Wetscapes with pulses of low amplitude	Classes:
Examples:	Prairie pothole area (USA-Canada border), playa wetlands of the semiarid western Great Plains (USA), Pantanal of Mato Grosso (Brazil), Everglades (USA), Okavango Delta (Botswana), Tonle Sap wetlands (Cambodia), Kafue flats (Zambia), and others		Suborder 2.2.1.3: Smaller wetlands subjected to predictable long-lasting monomodal flood pulses	Classes:
Examples:	Small floodplains along medium-sized rivers and others	Order 2.2.2: Wetlands subjected to unpredictable flood pulses	Suborder 2.2.2.1: Wetlands subjected to unpredictable, annual, polymodal, short flood pulses	Classes:
Examples:	Riparian wetlands along small to medium-sized streams, small wetlands in depressions inundated by rain or groundwater, subterranean wetlands and others		Suborder 2.2.2.2: Wetlands subjected to unpredictable pluriannual flood pulses	Classes:
Examples:	Dryland wetlands, salt pans and salt lakes in semi-arid and arid regions worldwide			Classes:
System 3:	Anthropogenic wetlands (no subsystems, orders or suborders)			Classes:
Examples:	Paddy rice plantations, aquaculture areas, water reservoirs, irrigation and drainage systems, areas for salt production, areas around large reservoirs for hydroelectric power generation and others			Classes:

of a class-level entry is the Yukon-Kuskokwim Delta, Alaska (USA), which covers $\sim 110,000 \text{ km}^2$ and includes a large variety of wetland habitats, ranging from lakes to herbaceous wetlands and peat lands. Along river shores are low and tall shrublands, large intertidal mudflats and dwarf shrub lichen peatlands. Near the coast, coastal dwarf shrub and coastal salt marsh communities are found (Reid and Fehring 2018). The Zambesi River Delta of Mozambique covers an area of $\sim 12,000 \text{ km}^2$ with three major vegetation types: floodplain savanna communities (three subtypes), floodplain grassland and swamp communities (five subtypes) and mangrove and swamp forest communities (three subtypes) (Beilfuss 2018). The latter study makes note of changes in flooding patterns resulting from the construction of the large Kariba and Cahora Bassa dams. The Sundarbans Delta of the Ganga-Brahmaputra-Meghna Rivers, situated in India and Bangladesh, covers $\sim 10,000 \text{ km}^2$ and is the world's largest contiguous mangroves wetland system. It contains a large variety of habitats along the gradient from freshwater to highly saline conditions, and different plant communities (Gopal and Chauhan 2018). The Danube Delta covers an area of $\sim 4,455 \text{ km}^2$ and is classified as water bodies (four subtypes), marginal vegetation (three subtypes), forests, shrubs and herbaceous vegetation (four subtypes), (4) open places with little or no vegetation (three subtypes) and anthropogenic ecosystems (Baboianu 2018).

The third subsystem covers wetlands subjected to polymodal short predictable pulses (tidal pulses). It includes two orders that divide these wetlands according to their size and complexity. The first order includes, at the class level, coastal wetscapes such as large mangroves, large salt marshes and large mud flats. Mangroves are restricted to tropical and subtropical coastlines and cover an area of $\sim 137,760 \text{ km}^2$. Floristically, they have been divided into a diverse Indo-West Pacific flora and a far less diverse Atlantic East Pacific flora. Large mangrove areas are found in tropical river deltas (Finlayson 2018b). Salt marshes cover $\sim 67,580 \text{ km}^2$ (Tiner and Milton 2018). Davidson (2018b) differentiates between four main general types of tidal salt marshes in western and northern Europe across increasing intertidal elevation, i.e., pioneer marsh, low marsh, upper (high) marsh and transitional (drift line) marsh, and recognizes over 60 habitat types/subtypes. The total area of mud flats is unknown but the Wadden Sea in Europe

covers $\sim 15,000 \text{ km}^2$ across a strip 10–30 km wide and more than 500 km long that borders the coasts of the Netherlands, Germany and Denmark (Laursen and Frikke 2018). The second order includes less complex coastal wetlands at the class level, such as sandy beaches, rocky shores, small patches of mangroves, small salt marshes and others.

The fourth subsystem covers wetlands separated from the sea by a relatively stable water level. Class-level entries include relatively small wetlands, such as freshwater lagoons, lagoons with saline water, swamp forests and herbaceous swamps.

The fifth subsystem consists of wetlands separated from the sea with a fluctuating water level. Class-level entries include wetlands along coastal rivers, periodically flooded forests and grasslands, temporary lagoons and others. Most of them are relatively small, but there is also a suborder that accounts for wetscapes near the coast. An example at the class level in Brazil is the *lenções maranhenses*, an area of $\sim 1,550 \text{ km}^2$ that is covered by sand dunes, permanent and temporary shallow waterbodies and different types of wetland vegetation. Ecological conditions in subsystems four and five were described by Barendregt (2018).

The inland wetland system

The inland wetland system encompasses a wide variety of wetlands differing in size, hydrological conditions and complexity such that a more sophisticated classification is required (Table 3). These wetlands are described by two subsystems. The first subsystem covers wetlands with a relatively stable water level and is subdivided into three orders. The first includes large hydrologically complex wetscapes with seven suborders: (1) wetscapes in the permafrost arctic region, with class-level entries of paludified shallow peatland (tundra), polygon mires with or without thermokarst ponds, peat plateaus and palsa mires, and others (Minayeva et al. 2018); (2) northern mineral wetscapes of North America (three classes and 10 minor units) and (3) northern peatland wetscapes of North America, (two classes and nine minor units) (Gingras et al. 2018); (4) northern mineral wetscapes of Asia; (5) northern peatland wetscapes of Asia; (6) tropical peatland wetscapes, including at the class level peat swamp forests in Southeast Asia and large papyrus marshes in Africa, and (7) large wetlands of

tectonic activity. Together, the USA and Canada contain ~1.86 million km² of peatland, corresponding to 40–45% of the world's ~4 million km² of peatland (Vitt 2018). There are differences in the vegetation cover of peatlands and the mineral wetlands of northern North America, Siberia and Fennoscandia (Gore 1983; Wieder and Vitt 2006). The total number of classes must still be determined by specialists.

The second order comprises small to medium-sized, simply structured wetlands and is divided into two suborders. The first includes forested wetlands with several classes, such as palm swamps in Brazil and Cypress swamps in the USA, and the second grassy-herbaceous wetlands at the class level such as veredas in Brazil (Nunes da Cunha et al., in press), the small papyrus swamps in Africa (Kipkemboi and van Dam 2018), and small peatlands and swamps in Europe (Cízková et al. 2013).

The second subsystem covers wetlands with an oscillating water level and is thus the most complex one. It also comprises two orders. The first deals with wetlands subjected to a monomodal or bimodal predictable pulse of long duration. The first suborder includes wetscapes subjected to flood pulse of high amplitude. Class-level entries are large river floodplains and freshwater deltas. Large river floodplains receive most of their water from the connected large rivers, which are subject to high water level fluctuations that intensify the exchange of dissolved and particular matter between the river and the floodplain or inland delta and transfer the strong hydrological dynamics of the river channel to a major part of the connected floodplain. Several Brazilian large river floodplains have already been classified at the macrohabitat level, such as the Amazon, Negro and Paraná River floodplains (Junk et al. 2012, 2015, 2021). The large Peace-Athabasca Inland Delta of the Mackenzie River Basin (Canada), with an area of >4,000 km², also belongs to this category. Some parts of its wetlands are connected to the river channels whereas other parts are situated above the normal river stage and are flooded only during the spring and midsummer floods. The complex hydrological conditions result in many different subunits (Shatford 2018a, b). Bimodal predictable flood pulses have been described for the Magdalena River (Ricaurte et al. 2019) and the upper Negro River.

The second suborder includes wetscapes subjected to a low-amplitude flood pulse that receive their water

mostly from local precipitation. The height of the inundation is limited from a few decimeters to a few meters. These floodplains are often connected to rivers that impact only small areas near the river channel but nonetheless influence the hydrology of the floodplain, by controlling rainwater drainage. Many of the floodplains have already been subdivided in studies that used hydrology, geomorphology, soils, hydrochemistry and vegetation as parameters, exemplified by the Brazilian Pantanal (Nunes da Cunha et al. 2023), Araguaia River wetscapes (Arruda et al. 2023), the Okavango Delta (Ramberg et al. 2006), the Everglades (Brown et al. 2006), the prairie pot-hole region at the USA-Canada Border (Doherty et al. 2018) and the playa wetlands of the semiarid western Great Plains (USA) (Bartuszevige 2018). Many others, however, are not recognized as such and have yet to be subdivided. A third suborder provides a class-level treatment of wetlands along medium-sized rivers that are smaller and do not reach the complexity of wetscapes.

The second order encompasses wetlands subjected to unpredictable pulses of short duration, including a large variety of small to medium-sized, simply structured wetlands. The first suborder deals with wetlands subjected to unpredictable, annual, polymodal short flood pulses. At the class level these include wetlands along streams and low-order rivers and wetlands in depressions. Each class can be subdivided into subclasses and macrohabitats. Despite their small size, these wetlands are very important for the hydrology and biodiversity of the respective landscapes. There are no quantitative data regarding the area covered by these wetlands. According to estimates, riparian wetlands of low-order streams and other small associated wetlands cover at least 25% of the forested part of the Amazon basin and up to 10% of the cerrado region (Junk et al. 2022). These wetland types are among the most threatened ones, because in many countries they are not covered by environmental legislation. A third class includes subterranean wetlands characterized by a species-poor fauna but very rich in endemic, highly adapted species (Sket 2018). The second suborder addresses wetlands subjected to unpredictable pluri-annual flood pulses. Class-level entries include dryland wetlands in semi-arid and arid regions worldwide, where evapotranspiration surpasses precipitation. Many of the wetlands are characterized by a high salinity. They commonly include salt lakes, such

as the Soda Lakes in the East African Rift Valley (Agembe et al. 2018) and the large salt lakes in the high Andes. When dry, salt crusts are seen across the surface of the lake beds (Finlayson 2018c). In most cases sodium chloride (NaCl) is the dominant component, but in some cases magnesium (Mg^{2+}), calcium (Ca^{2+}) and sulfate (SO_4^{2-}) occur in high concentrations. These wetlands are often dry for several years and receive water only during periods of strong rainfall. Species diversity is low, but the fauna and flora have a high level of endemism, with many adaptations to harsh environmental conditions.

The third system deals with anthropogenic wetlands and is not subdivided. At the class level it includes rice plantations, aquaculture areas, water reservoirs, irrigation and drainage systems, areas for salt production, the wetlands around reservoirs for hydroelectric power generation, etc. The hydrological status depends on management aspects.

Discussion and conclusions

Classifications of complex systems confer order and transparency, whether for accumulations of similar systems or for collections of disorganized data. The enormous number of wetlands of different size and complexity occurring on different continents and in different climatic zones can be better understood and thus protected by their classification. There are already many different national, regional and worldwide classification approaches, as discussed earlier in the text. All of them use hydrology, soils and vegetation as major parameters, with some also adding hydrochemical, geographic and geomorphological aspects, such as the position on the globe (e.g. tundra/alpine wetlands, deltas, dryland wetlands, mangroves, etc.), connection with permanent water bodies, origin of the water (rainwater, groundwater, or floodwater from connected streams and rivers) (U.S. Fish and Wildlife Service, Cowardin et al. 1979) or the position within the landscape, such as in depressions or on hill slopes (Semeniuk and Semeniuk 1995). However, these parameters are not applied hierarchically, as demonstrated by the classification of the Ramsar Convention (Finlayson 2018a), and many are only of regional value, such as the quality of the soils and the species composition of the vegetation. Furthermore, the various classifications are tailored to the

achievement of different goals, such as environmental protection, management or political interests. None of the existing classification systems, excepting the Brazilian wetland classification, address large and complex wetlands; hence the call for a wetland classification system that is applicable worldwide. Such a system requires a hierarchical structure, with higher rankings based on generally accepted key parameters and lower rankings enabling adaptation and the inclusion of already existing regional classification systems. A universal wetland classification system should also ensure transparency regarding the tremendous number of different wetland types and facilitate inclusion of the scientific information both from the innumerable already-existing regional studies and as obtained in future classification efforts.

A major obstacle is the delimitation of wetland borders. In existing wetland classifications, this is accomplished based on a combination of local or regional parameters, such as hydrology, soil sciences and vegetation. However, for wetlands worldwide and thus for their classification, the importance of these parameters varies dramatically between regions, as shown above. Hydrology is the only general parameter for a worldwide applicable wetland delimitation, but this approach must consider, that many wetlands are subjected to water level fluctuations. This leads to large fluctuations in their extent and complicates delimitation of their areas. The mean maximum inundation can be a worldwide acceptable parameter for wetland delimitation, with parameters describing soils and vegetation providing additional criteria for regional definitions.

Most wetland classifications start with a differentiation between inland, coastal and man-made wetlands. This approach can be applied at a global scale. Nonetheless, a peculiar situation exists with respect to river deltas. In the proposed classification system, they are included in the coastal wetlands category, but large parts of deltas belong to inland wetlands, as shown by Barendregt (2018). Therefore, a subdivision of these wetlands into minor units should consider not only hydrological but also salinity gradients.

The proposed hydro-ecological classification separates wetlands into two large groups: wetlands with a rather stable water level and wetlands subjected to fluctuating water levels. For both, the classification has to deal with the fact that the limits of these and other hydrological units at lower rankings are not

fixed, resulting in transitions among different classification units. For instance, peat bogs are considered as wetlands with a relatively stable water level, but in dry years the water level decreases and the bogs can suffer the impact of wild fires, which destroy part of the superficial layer of organic material. The variability of hydrological conditions is a general problem of all classification systems, one that requires flexibility by the scientists and managers using them. Moreover, in the future, the hydrological pattern in many wetlands will change because of changes in global climate, changes in the regulation of the discharge of connected rivers, the increased use of water and changes in land use.

At the next level the proposed classification separates wetlands into small to medium-sized, simply structured wetlands and large, complex wetscapes. This differentiation is also fluent. Even the largest river starts as a small stream, accompanied by simply structured, small riparian wetlands, such that in its upper and middle segments it belongs to the hydrological category of wetlands with an unpredictable and frequently fluctuating water level. Only at the lower course does the water level become predictable and monomodal, with the floodplain then reaching the level of a wetcape. Although wetscapes play a major role as geographic, ecological, political, economic and sociologic units for all national and international wetland organizations, they are not considered in any classification system. This is in part because they are composed of subunits with either stable or fluctuating water levels, often covering the entire ecological gradient from permanently terrestrial to permanently aquatic conditions.

The classification of wetscapes follows the example of the new Brazilian classification system and differentiates five hydrological categories: permanently aquatic, predominantly aquatic, predominantly terrestrial, permanently waterlogged (palustric) and permanently terrestrial as well as a sixth that covers anthropogenic areas independent of their hydrological characteristics. In Brazil, 15 coastal wetscapes and 10 inland wetscapes have been denominated thus far, of which one coastal and five inland wetscapes have already been classified at the macrohabitat level. The denomination of other wetscapes awaits sufficient data (Junk 2024). Some descriptions of wetscapes in other regions already use similar approaches, as shown for the Okavango Delta (Ramberg et al. 2006;

Ramberg 2018) and the Everglades (Brown et al. 2006). It is up to local scientists to denominate and describe wetscapes in their regions.

Small, simply structured wetlands follow a shortcut to lower levels in the new classification system. Because of their tremendous variability they are not addressed in the international approach. At a regional scale, they can be subdivided according to their hydrology together with other parameters, such as vegetation, soils and water chemistry. In the Brazilian classification system, they enter at the level of functional units, subclasses and macrohabitats, as shown in Fig. 1 and Table 1. The classification of minor units is essential for regional scientific research, management and protection purposes. Major changes in environmental conditions, for instance, in response to global climate changes and large-scale changes in vegetation cover by agroindustry or mining activities, are first detectable at the macrohabitat level, because they result in changes in hydrology and in sensitive plant communities, as shown for Brazilian wetscapes. Large wild fires have affected macrohabitats in the Pantanal of Mato Grosso (Brazil) with different intensity. Macrohabitats of the predominantly terrestrial functional unit exhibited the greatest resilience against the intense drought and large wild fires of 2021 and 2022, because they harbor many plant species of the fire-adapted savanna vegetation. Agroindustry activities in the catchment of the Pantanal first affected some macrohabitats of the permanently aquatic functional unit, because of the increased inputs of sediments in streams and rivers. Macrohabitats of the functional units of permanently terrestrial and swampy areas are also at existential risk from cattle ranchers who seek to convert these units into pasture areas.

From its higher rankings down to the class level, the general classification system represents a worldwide applicable, uniform approach that satisfies calls for the development of a hydro-geomorphically based system of wetland classification, such as that by Davidson and Finlayson (2007). It is up to local scientists to adapt it for the needs of their regions. For instance, countries without coastlines can delete the part which deals with the classification of coastal wetlands, and tropical countries delete that of the suborders, which deal with wetscapes in permafrost regions and northern peatlands. For lower rankings, including functional units, subclasses and macrohabitats, the

proposed system provides a framework for the inclusion of information of importance for national wetland management and protection. This information is often already available, but it is up to local scientists to organize it in a transparent and logical way such that it can be added to the general classification system. Worldwide, many small wetlands are likewise seriously threatened by agriculture, cattle ranching, mining activities and civil construction. These threats can only be counteracted by environmental legislation that regulates activities at the local level.

Acknowledgements The author acknowledges the technical support of the library and the computer center of the Max Planck Institute for Evolutionary Biology, Plön.

Author contribution No other authors.

Funding Open Access funding enabled and organized by Projekt DEAL. The author declares that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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