10 reasons why the **Geomorphology of wetlands** is important

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with input from the **Wetlands in Drylands Research Network**

adapted from the booklet
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produced by **Stephen Tooth** and **Heather Viles**
for the **British Society for Geomorphology**

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Wetlands in Drylands RESEARCH NETWORK

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What is geomorphology?

Environmental change is currently one of the most topical global issues, having rapidly risen up scientific, social and political agendas. Against a backdrop of clear evidence for global warming, vigorous debate surrounds the nature and likely impacts of future climate change at local and regional scales, and how societies will manage these changes. Climate change poses huge threats to human wellbeing through impacts on many facets of the environment, including biodiversity loss, declining soil and water quality, and the spread of disease. Given that ecosystems and these related environmental processes depend upon heterogeneity in the physical structure of the Earth's surface, it is also important to understand how landforms and wider landscapes will respond to climate change.

Geomorphology is the science that studies the origin and development of landforms and landscapes such as mountains, valleys, river channels, wetlands and estuaries. Geomorphological studies include analyses of landform shapes, quantification of surface and near-surface processes (e.g. running water, groundwater, wind) that shape landforms, and the characterisation of landform and landscape changes that occur in response to factors such as tectonic activity, climate change, sea level fluctuations, and human activities. Investigations may be directed towards reconstructing past processes and landform changes, towards understanding present-day processes and landform changes, or towards anticipating future processes and landform changes.

Wetlands are key components of many landscapes worldwide, and increasingly are regarded as providing a wide range of direct and indirect benefits ('ecosystem services') that contribute to human wellbeing. These benefits may include enhancement of biodiversity, water quality improvement, food supply and recreational opportunities, and so influence human activities in and around wetlands. Understanding how the world's wetlands are structured, how they function, and how they may change is thus a key part of gaining a full understanding of the Earth system and enabling better environmental management. Nonetheless, many questions remain to be answered about wetland landscapes and our interactions with them:

- Where are wetlands most commonly found, and why do they form?
- Do wetlands change over time, and if so, why and how?
- How old are the world's wetlands?
- How sensitive are wetlands to environmental change and human impacts?
- How can we best manage wetlands to ensure 'wise' or 'sustainable' use of their ecosystem services?

As this booklet will demonstrate, geomorphology can make a critical contribution to answering these and many other questions about wetlands.

derived from Greek
geomorphology

ge - 'earth'
morphe - 'form'
logos - 'discourse'

What are wetlands?

'Wetland' can be defined in various ways but the term generally is taken to incorporate a variety of inland and coastal features (see box on p. 2). Excluding lakes, rivers and offshore coastal features, wetlands are typically considered to form in landscape settings that are transitional between fully terrestrial and fully aquatic (Figure 1). In these settings, the ground is saturated or flooding occurs to shallow depth (commonly less than 1 m) such that soils are seasonally or permanently starved of oxygen. Since all plants need oxygen in the root zone, many higher-order wetland plants (grasses, sedges, shrubs, trees) are adapted to pump oxygen from aerial parts into the root zone. With these adaptations, and given the abundant water supply, wetlands are among the Earth's most biologically diverse and productive ecosystems (ecological 'hotspots'), supporting a wide variety of plant and animal species. Nevertheless, while wetland plants fix large amounts of carbon from the atmosphere and incorporate it into biomass, plant tissue typically has a low nutrient content and commonly is neither palatable nor nutritious. Hence, although wetlands may harbour biodiversity, they do not necessarily support a high animal biomass.

Around wetland margins, variations in soil wetness typically result in a distinct vegetation zonation (Figure 1), which reflects the toler-ances of different plant species. Permanent saturation tends to inhibit the complete breakdown of dead plant matter, so that soils may become rich in organic content, possibly forming peat. Seasonal or temporary wetting and drying commonly encourages breakdown of dead plant matter, so organic content tends to be lower and instead produces mottled soil textures (e.g. yellow, brown and red colours) that result from fluctuations in soil oxygen content (Figure 1).

Globally, many wetlands form in broad valleys on low slopes, and experience slow, shallow water flow. Although some of these wetlands may be traversed and drained by river channels, the combination of high plant biomass, low animal biomass, and slow water flow means that they commonly act as long term stores of sediment and soils. Such sediments and soils may be largely inorganic, consisting mainly of clay, silt and sand particles, but as noted above, may also include a large component of organic matter that consists of the partially decayed remains of plants.

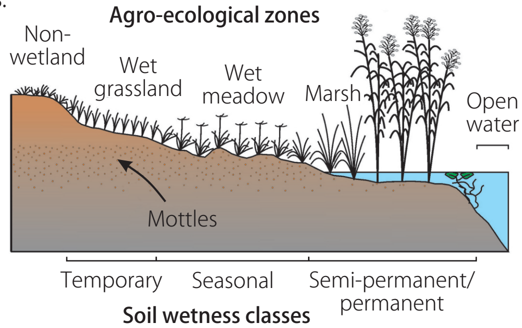

Figure 1. Around many wetlands, variations in the depth and duration of soil wetness typically lead to vegetation zonation. Soil textures such as mottles reflect hydrochemical processes related to variations in wetness and oxygen content (Source: Kotze, D.C. et al. 1994. The Development of a Wetland Soils Classification System For KwaZulu/Natal. WRC Report No 501/4/94. 32 pp.).

wetland

an area that is periodically or continuously inundated by shallow water or has saturated soils, and where plant growth and other biological activities are adapted to the wet conditions.

The Ramsar Convention on Wetlands is an intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. Given an historical emphasis on protecting wetland habitat for waterbirds, the Convention uses a very broad definition of wetlands that includes all lakes and rivers, underground aquifers, swamps and marshes, wet grasslands, peatlands, oases, estuaries, deltas and tidal flats, mangroves and other coastal areas, coral reefs, and all human-made sites such as fish ponds, rice paddies, reservoirs and salt pans. Other definitions of wetlands are narrower, and exclude underground features, offshore coastal features, open water bodies (rivers, lakes) and many human-made sites. Even then, a wide variety of other local and regional terms can be used to describe wetlands (e.g. billabong, bog, muskeg, vlei, dambo), while many more common terms (e.g. marsh, swamp) are rarely used in a standardised way.

Why is the geomorphology of wetlands important?

To gain a full understanding of the role and importance of wetlands in the Earth system and to support their effective management, it is vital to understand the factors controlling wetland formation and development.

Much previous wetland research has assumed hydrology to be the primary factor controlling wetland formation, particularly as the degree of wetness alters soil characteristics, which in turn influences vegetation distribution and wider ecosystem structure (Figure 1). Key questions, however, remain about the physical landscape characteristics that combine with regional or local hydrology to promote the characteristic wetness. For instance, what are the geomorphological processes that lead to the creation of broad, gently sloping valleys in which many wetlands are found?

Furthermore, much previous wetland research also has tended to focus largely on timescales relevant to ecological processes, such as rates of vegetation establishment or the life cycles of fish and birds. The emphasis is therefore typically on changes over seasonal, annual or multiannual timescales, and longer term changes to wetlands are less commonly considered. Studies of short-term ecological processes form an essential part of wetland research, but for a comprehensive understanding of wetlands, a longer term perspective is also required. Over many decades, centuries, millennia or longer, the physical landscape hosting and surrounding wetlands can develop as a result of ongoing erosional and depositional changes, commonly leading to changes in regional and local hydrology. Key questions can be posed. For instance, how dynamic are channels, levees and other landforms within floodplain wetlands (Figure 2)? How does this dynamism affect water flow, sediment distribution and ecological responses over these longer timescales?

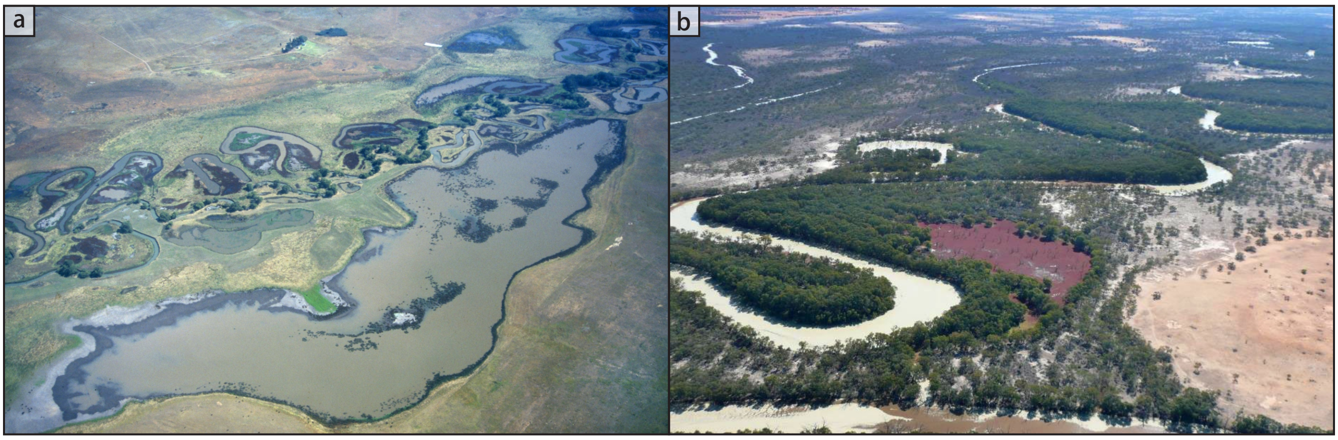

Figure 2. How dynamic are the meandering river channels in these floodplain wetlands? a) Klip River in eastern Free State, South Africa (Photo: Stephen Tooth); b) the Darling River in western New South Wales, Australia (Photo: Tim Ralph).

Effective wetland management needs to consider these and other geomorphological questions in order to understand how wetland landforms and landscapes have developed in the past, how they function at present, and how they are likely to change in the future. This is particularly important when flow or erosion control structures are built in wetlands, or where other human activities such as agriculture or settlement occur in or around wetlands. Unless geomorphology is considered, wetland structure and function, infrastructure stability, and the sustainability of human activities may be threatened. In extreme cases, such as where river and flood-plain adjustments lead to major, regional-scale changes in wetland flood patterns (Figure 3), even lives may be at risk.

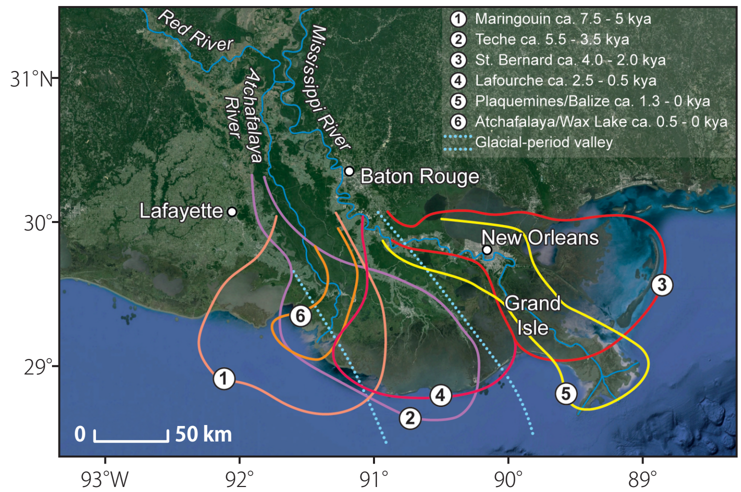

Figure 3. Wetland landscapes may undergo major changes over time, as shown shown by the shifting positions of the deltas of the Mississippi River as it enters the Gulf of Mexico. Major changes in delta position have occurred over the last 7500 years (lobes 1-6), with the city of New Orleans occupying a delta that was active up to 1000 years ago (lobe 3). Ongoing investment is required to ensure that the present course of the Mississippi River does not divert into, or significantly away from, the city (Source: redrawn after Roberts, H.H. 1997. Dynamic changes of the Holocene Mississippi River delta plain: the delta cycle. Journal of Coastal Research, 13: 605-627; Blum, M.D. and Roberts, H.H. 2012. The Mississippi delta region: past, present, and future. Annual Review of Earth and Planetary Sciences, 40: 655-683).

Why is this booklet needed?

Despite the demonstrable importance of geomorphology for wetland studies, until now the discipline's contributions have tended to be limited. Hydrologists and ecologists have tended to focus on the local, short-term (decadal or less) process interactions between hydrology, soils and biota (Figure 4), essentially downplaying or ignoring the larger area, longer term geomorphological and climatic factors that shape wetlands. Geomorphologists have tended to neglect wetlands, perhaps because they are difficult to characterise and classify. As a consequence, the geomorphological essentials of wetland science are not widely appreciated or understood by wetland scientists, policy makers, land managers, or the general public. This is despite growing pressures for data to inform decisions about wetland conservation, rehabilitation and artificial construction, especially in an era characterised by rapid environmental change, a growing population, and increasing human activities in and around wetlands (Figure 4).

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The aim of this booklet is to illustrate a selection of key principles that underpin a geomorphological perspective on the world's wetlands. Drawing inspiration from the British Society for Geomorphology's related initiative to promote geomorphology[1], we highlight ten key points that everyone should know about the geomorphology of wetlands. We anticipate that the booklet will be particularly relevant to wetland researchers and managers, but it also may be of interest to other scientists and a wider public. The initial focus of the key points is on wetlands that remain in a dominantly natural or near-natural state, but consideration is then given to those wetlands that have been impacted by human activities. These ten key points are not exhaustive but simply provide an illustration of why geomorphology is an important part of developing a comprehensive approach to wetland science and management. The booklet concludes by providing sources of additional information.

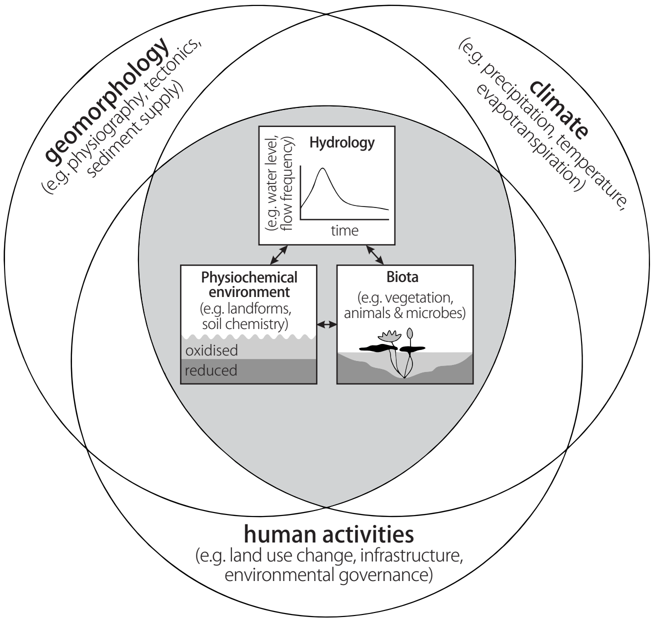

Figure 4. Local, short-term (a decade or less) wetland processes (shaded area) arise from interactions between geomorphology, climate, and possibly human activities, all of which tend to operate over larger areas and longer timescales. An example of such processes is when vigorous plant growth in wetlands helps to slow surface flows, thereby promoting sediment deposition and trapping of associated nutrients and any pollutants. Over time, these wetland processes may feed back to influence the geomorphology and climate of the broader landscape, such as by influencing downstream water, sediment and nutrient transfer, or through promoting evaporative cooling. Activities can have a key influence on wetlands, but through their supply of ecosystem services, wetlands also influence human activities in and around wetlands, including by providing favourable locations for cultivation and other forms of resource use (Source: modified after Mitsch, W.J. and Gosselink, J.G. 2007. Wetlands (4th ed.). John Wiley and Sons, New York).

1 Tooth, S. and Viles, H.A. (2014), 10 Reasons Why Geomorphology Is Important, Brochure produced on behalf of the British Society for Geomorphology. Available at: www.geomorphology.org.uk/what-geomorphology

The ten key points that everyone should know – the ten reasons why the geomorphology of wetlands is important – are summarised in Table 1, both in abridged and extended form.

Table 1. Summary of the ten key points

1	**Wetlands are shaped by movements of mass**	The physical structures of wetlands are shaped by geomorphological processes, which involve the movement of mass (rock, sediment, water, organic matter) across the Earth's surface
2	**Wetlands can form in a range of landscape and climatic settings, including drylands**	Wetlands can form in a wide range of landscape and climatic settings, including humid regions where surface water is abundant (high precipitation with low evapotranspiration) and dryland regions where there are overall surface water deficits (low precipitation with high evapotranspiration)
3	**Wetland processes result from interactions in the Earth system**	Wetland processes result from local-, regional- and global-scale interactions between the atmosphere, hydrosphere, geosphere and biosphere
4	**The Earth's wetlands are naturally dynamic**	Wetlands are not static and unchanging, but are dynamic and develop through time in response to changing external (tectonic, geological, climatic, sea level) conditions
5	**Wetland dynamics may be complex**	In addition to changing external conditions, wetland development can also be driven by changing ecological conditions (e.g. vegetation succession, animal activities) or internal geomorphological adjustments (e.g. channel abandonment, gully development)
6	**Wetlands are archives of past environmental change**	Wetlands contain histories of their development that potentially can be deciphered and reconstructed from study of their associated landforms, sediments and biological remains
7	**Global environmental change is influencing wetlands**	Ongoing global environmental change, which includes atmospheric warming and sea level rise, is currently driving changes in wetland structure and function, including through increased coastal erosion, desiccation, and gully development
8	**Human activities are influencing wetlands**	Increasingly, the direct and indirect effects of human activities (e.g. land use, infrastructure, environmental governance) are also driving changes in wetland structure and function
9	**Wetlands may be vulnerable to geohazards but may also buffer the wider landscape from their impacts**	Both global environmental change and human activities are increasing the magnitude and frequency of geohazards in wetlands (e.g. flash floods, coastal storm surges), which occur wherever and whenever land surface stability is affected and adverse socio-economic impacts are experienced
10	**Sustainable use of wetlands needs geomorphological knowledge**	Geomorphology can provide a key role in wetland management, including their conservation, restoration, and artificial construction, thereby helping to protect and enhance the delivery of wetland ecosystem services

1

Wetlands are shaped by movements of mass

The physical structures of wetlands are shaped by geomorphological processes, which involve the movement of mass (rock, sediment, water, organic matter) across the Earth's surface. The movement of mass associated with the shaping of wetlands can involve tectonic activity (uplift, subsidence), and the weathering, erosion, transportation and deposition of surface materials by surface water, groundwater, gravity, ice and wind. The movement of mass is predominantly downwards (from higher to lower elevations), such as through downslope sediment movement, although it can also be upwards (from lower to higher elevations), such as by tectonic uplift. Most wetlands form on those parts of the Earth's surface where surface and groundwater flow is concentrated and/or drainage is impeded as a result of the movements of mass. For instance, some of the world's major wetlands have formed where tectonic subsidence has created depressions in the Earth's surface, thereby providing foci for water and sediment supply by large rivers (Figure 5). Many other wetlands have formed within smaller depressions resulting from uneven bedrock scouring by past ice sheets and glaciers, or that are related to landslides, tributary fans, groundwater activity, and wind erosion and deposition (Figure 6). Consequently, it is vital to consider wetlands in the context of the wider landscape within which they occur, particularly their local catchment.

Within wetland landscapes, individual landforms can be classified as primarily depositional ('constructional'), with mass accumulating to create features such as river channel levees or bars, or as erosional ('degradational'), with mass being removed to create features such as gullies. Except where severe degradation is occurring, most wetlands tend to accumulate mass over time, leading to the formation of thick piles of sediment (Figure 5a). In some cases, these accumulated sediments may store large amounts of carbon (key point 3) and also represent important archives of past environmental change (key point 6).

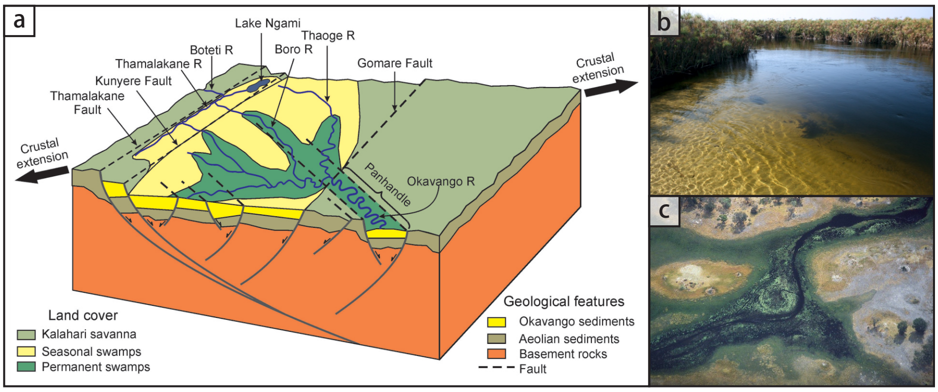

Figure 5. The Okavango Delta, located in the Kalahari Desert in Botswana, is a globally-significant wetland complex consisting of permanent and seasonal swamps: a) the overall physical structure of the wetland complex is controlled primarily by tectonic subsidence that is occurring as a result of rifting of this part of the Earth's crust. Water and sediment is supplied to the rift by the Okavango River and its distributaries, leading to accumulation of sediments ('Okavango sediments') that are many hundreds of metres thick (Source: redrawn and adapted from McCarthy, T.S. and Ellery, W.N. 1998. The Okavango Delta. Transactions of the Royal Society of South Africa, 53: 157-182); within the b) permanent and c) seasonal swamps, water flow, sediment movement, plant growth and animal activity create a range of depositional and erosional landforms, including river channels, backswamps, shallow lakes and islands (Photos: Stephen Tooth).

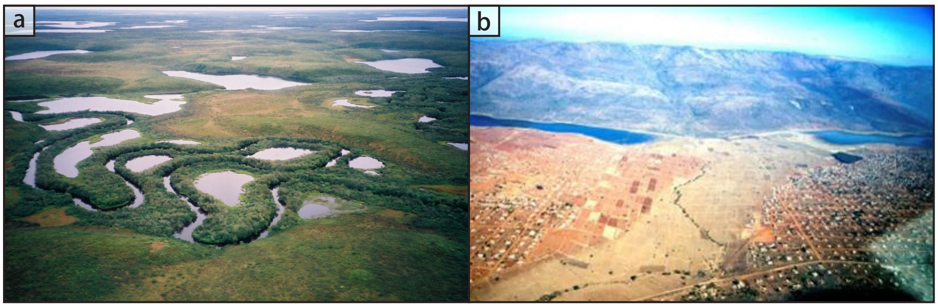

Figure 6. Oblique aerial views of wetlands in two contrasting landscapes: a) the northwest margin of the Canadian Shield near Inuvik, showing how numerous wetlands have formed along river valleys (flow from right to left) and in the ice-scoured terrain (Photo: Tristram Irvine-Fynn); b) shallow flooded depressions along the Nyl/Mogalakwena valley in northern South Africa (flow in the valley is from left to right). Such depressions are created by sediment inputs from tributaries. In this case, the Dorpspruit (flow from lower left to middle distance) has supplied abundant sediment, obstructing the seasonal flows along the Nyl/Mogalakwena. Numerous houses and roads provide scale, and illustrate the human activities that take place in close proximity to such wetlands (Photo: Spike McCarthy).

Did you know?

In addition to the Okavango Delta (Figure 5), some other major wetlands worldwide occupy tectonic depressions created by subsidence of the Earth's crust. In the southwestern USA, spreading and fracturing of the Earth's crust along parallel faults has created the 'Basin and Range' geographic province, with the subsiding basins being supplied with water and sediment from uplifted neighbouring fault blocks. Subsidence tends to be faster than the rate of filling by water and sediment, so depressions persist and even deepen with time. At -85.5 m below sea level (bsl), Badwater Basin in Death Valley, California is the lowest point in the western hemisphere, and is characterised by playas (salt flats) that flood occasionally, which helps to maintain wetlands even in the dry climate. Other major tectonic depressions with playas include Lake Eyre, Australia (-15 m bsl), the Qattara Depression, Egypt (-133 m bsl) and Turfan Depression, China (-154 m bsl) (Source: USGS/National Parks).

Wetlands can form in a wide range of landscape and climatic settings, including humid regions where surface water is abundant (high precipitation with low evapotranspiration) and dryland regions where there are overall surface water deficits (low precipitation with high evapotranspiration). Figure 7 shows that the most extensive distributions of wetlands are in the middle to high latitude, temperate and boreal parts of the northern hemisphere, but wetlands are also widely distributed in the lower latitude tropics. In these humid regions, some wetlands can be sustained solely by local precipitation, local surface runoff, or groundwater (e.g. raised mires, high-altitude montane wetlands) but river inflows also may be important determinants of wetland hydrology, forming riverine wetlands, swamps and marshes. Despite overall surface water deficits, wetlands can also be found in many dryland regions (Figure 7), including some of the world's largest wetlands complexes, such as the Okavango in Botswana (Figure 5) and the Macquarie Marshes in Australia. In these hyperarid, arid, semiarid and dry subhumid settings, moderate to large wetlands usually can only exist where river inflows combine with factors that locally promote positive surface water balances, including tectonic subsidence, and ponding by tributary or wind-blown sediments (key point 1). In these wetlands in drylands, positive surface water balances may persist year round but more commonly are seasonal or ephemeral phenomena, possibly occurring only once every few years following above average rainfall and runoff. For instance, in the Okavango Delta, the flooded areas expand and contract annually, leading to the pattern of permanent and seasonal swamps (Figure 5).

Owing to the great diversity of wetlands worldwide and variable definitions (see box on p. 2), there is no universally-accepted classification of wetlands. Many individual countries and regions have developed their own classifications to account for the diversity of wetlands within their territories, some of which are based on a combination of geomorphological and hydrological characteristics (Figure 8).

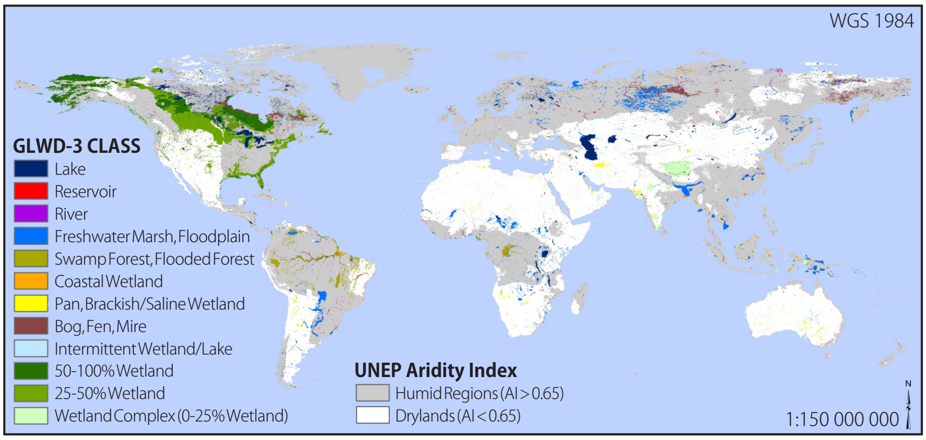

Figure 7. The global distribution of wetlands and other water bodies in relation to humid regions and drylands. Excluding rivers, lakes, reservoirs and offshore marine wetlands, the total wetland coverage is estimated to be about 6-8% of the terrestrial land surface (Source: map produced by Michael Grenfell using: i) Wetlands Data Source: Global Lakes and Wetlands Database Level 3 (Lehner, B. and Döll, P. 2004. Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology, 296: 1-22), available at: http://www.wwfus.org/science/data.cfm; ii) UNEP Aridity Index Data Source: CGIAR-CSA Global Aridity Index (Global-Aridity) geo-spatial dataset (Trabucco, A. and Zomer, R.J. 2009. Global Aridity Index (Global-Aridity) and Global Potential Evapo-Transpiration (Global-PET) Geospatial Database. CIGAR Consortium for Spatial Information), available at: http://www.csi.cgiar.org).

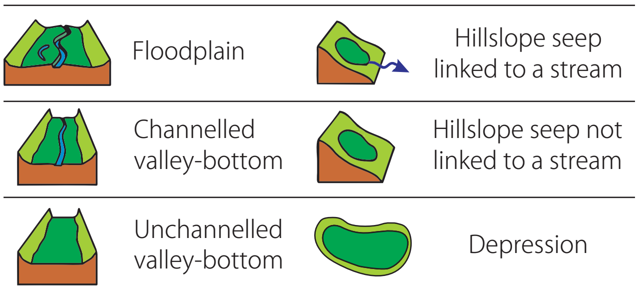

Figure 8. Classification illustrating the range of wetland hydrogeomorphic types in southern Africa. The classification system relates principally to the way water arrives at and flows through a wetland, as controlled by interactions between factors such as tectonic activity, geology, catchment size, landscape position, trunk-tributary channel relationships, and the source, volume and reliability of water and sediment supply. This classification illustrates a subset of the range of hydrogeomorphic wetland types that occur globally (Source: redrawn from Ollis, D.J. et al. 2013. Classification System for Wetlands and Other Aquatic Ecosystems in South Africa. User Manual: Inland Systems. SANBI Biodiversity Series 22. South African National Biodiversity Institute, Pretoria).

Did you know?

Although the term 'wetlands in drylands' sounds like a contradiction, many drylands in fact host a diverse range of ephemeral, seasonal or even perennial wetlands that collectively can cover significant areas (e.g. ~5% of the sub-Saharan African land surface). In detail, every wetland has a unique range of characteristics but by comparison with humid region wetlands, many wetlands in drylands are thought to be distinguished by: i) more frequent and/or longer periods of desiccation; ii) channels that commonly decrease in size and even disappear downstream; iii) higher levels of chemical sedimentation owing to greater evapotranspiration and non-biological and biological solute concentration mechanisms; iv) more frequent fires that reduce the potential for thick organic accumulations and promote wind erosion; and v) longer timescales of development that may extend back many tens of thousands of years (Source: Tooth, S. and McCarthy, T.S. 2007. Wetlands in drylands: key geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Progress in Physical Geography, 31: 3-41; Rebelo, L.-M. et al. 2010. Wetlands of sub-Saharan Africa: distribution and contribution of agriculture to livelihoods. Wetlands Ecology and Management, 18: 557-572).

Wetland processes result from local-, regional- and global-scale interactions between the atmosphere, hydrosphere, geosphere and biosphere. The overall physical structure and hydrology of wetlands is determined by geomorphological and climatic factors (key points 1 and 2), and as shown by Figure 4, this provides the framework for a multitude of processes that involve interactions between local hydrology (e.g. flood depth and duration), the physiochemical environment (e.g. soil pore space and oxygen content), and biota (e.g. plant establishment and levels of animal activity). For instance, in the Okavango Delta, surface water, groundwater, sediment and solutes interact with plant growth to create distinctive landforms, such as the numerous tree-fringed islands with saline interiors (Figure 9). These islands act as the kidneys of the wetland complex, locally concentrating salt compounds (e.g. sodium chloride) that would become toxic to plant and animal life if more widely dispersed in surface waters. Furthermore, accumulation of calcium-magnesium carbonate beneath islands provides a store for inorganic forms of carbon, preventing its oxidation and release to the atmosphere as carbon dioxide.

Similarly complex, subtle interactions characterise other wetlands globally. In many mid- and high-latitude northern hemisphere wetlands, water flows, vegetation growth and the activities of beaver can lead to the formation of numerous shallow lakes along river valleys. These lakes regulate down-stream water flows, particularly by helping to reduce flood peaks, and locally concentrate sediment, nutrients and organic matter such as dead plants. Under the typically cool, waterlogged, oxygen-starved conditions, breakdown of organic matter is slow, possibly leading to peat formation. Continued peat growth or its burial by sediment can help to store organic forms of carbon, also preventing its oxidation and release to the atmosphere.

Overall, wetlands exemplify in microcosm the complex interactions between the atmosphere, hydrosphere, geosphere and biosphere that are implicit in scientific concepts of the Earth as an integrated system. They support high biodiversity while playing key roles in hydrological, sedimentary and biogeochemical cycling that may be important on local, regional and global scales.

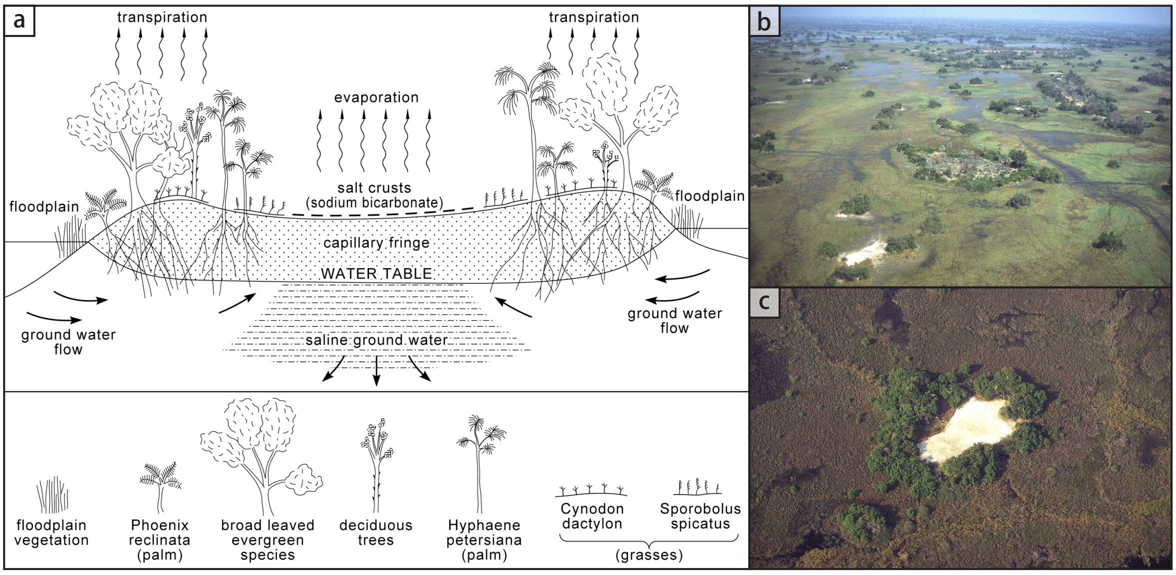

Figure 9. Example of a wetland landscape with landforms that contains a strong biological imprint: a) schematic illustration of the interactions between hydrology, soil geochemistry and plants that lead to the development of distinctive, tree-fringed islands with saline interiors in parts of the Okavango Delta, Botswana (Source: redrawn after Ellery, K. and Ellery, W.N. 1997. Plants of the Okavango Delta: A Field Guide. Tsaro Publishers, Durban); b) and c) aerial views of islands in the permanent swamps (Photos: Stephen Tooth).

Did you know?

Carbon (C) is a constituent of two of the most important greenhouse gases in the Earth's atmosphere, namely carbon dioxide (CO_2) and methane (CH_4). The world's wetlands have a strong influence on the storage and release of C, and so collectively exert an important influence on atmospheric composition and therefore global climate. In wetlands in humid regions, C is typically sequestered as a result of the long-term accumulation of plant material (e.g. as peat). By contrast, in wetlands in drylands, C is more commonly sequestered as carbonate compounds that precipitate in soils owing to evapotranspirational water losses. In the Okavango Delta alone, each year over 200000 tonnes of solutes precipitate in islands (Figure 9), many of which are carbonates. In both humid and dryland regions, however, wetlands may also release C, either as CO_2 (e.g. in peat fires, through microbial respiration, or by carbonate weathering) or as CH_4 (e.g. by microbial breakdown of organic matter in oxygen poor, waterlogged conditions). Estimates suggest, for instance, that the vast Amazonian floodplains each year release approximately 10 million tonnes of CH_4. The balance between storage and release of C determines whether individual wetlands are net sinks or sources of C. In their natural, un-disturbed state, most wetlands are net sinks but there is concern that with ongoing global warm-ing and increasing human pressures, more wet-lands worldwide may be prone to desiccation and combustion, and thus become net C sources (Source: McCarthy, T.S. and Ellery, W.N. 1998. The Okavango Delta. Transactions of the Royal Society of South Africa, 53: 157-182; Ramberg, L. and Wolski, P. 2008. Growing islands and sinking solutes: processes maintaining the endorheic Okavango Delta as a freshwater system. Plant Ecology, 196: 215-231; Devol, A.H. et al. 1988. Methane emissions to the troposphere from the Amazon flood-plain. Journal of Geophysical Research, 93: 1583-1592).

Wetlands are not static and unchanging, but are dynamic and develop through time in response to changing external (tectonic, geological, climatic, sea level) conditions. Changing external conditions influence the geomorphological processes that affect the movement of mass (key point 1), ultimately leading to changes in wetland landscapes.

In the absence of human activities (key point 8), such changes take place naturally over a range of temporal and spatial scales. Individual extreme weather events (e.g. intense rainstorms, coastal surges) can lead to rapid, commonly dramatic, changes to erosional and depositional patterns along river channels or tidal inlets. Channels may deepen or widen, or individual meander bends may be cut off, thereby affecting the subsequent distribution of water and sediment, both locally and regionally. Seasonal variations, multi-annual changes in weather patterns (e.g. flood and drought cycles occurring in association with El Niño/La Niña events), and climate change on timescales of decades to thousands of years can also drive progressive, but possibly still dramatic, changes. In places like the Macquarie Marshes, Australia, and the Okavango Delta, Botswana, many old channels preserved in and adjacent to the wetlands are larger than the present-day channels (Figure 10), suggesting long-term, climate-related changes in river inflows.

On longer timescales still (tens or hundreds of thousands of years), changes to climate and associated sea levels can lead to dramatic expansion and contraction of wetland landscapes in both inland and coastal settings. Over these timescales, geological factors also may be important. Progressive river erosion of weaker bedrock upstream of more resistant bedrock outcrop can cause valley widening and slope reduction, increasing the area within which floodplain wetlands can form (Figure 11a), but once the resistant outcrop is eroded through, deep river incision occurs and floodplain wetlands are abandoned (Figure 11b). Over these long timescales, tectonic activity can also drive wetland changes. In inland settings, subsidence may continue to provide a depression within which water and sediment accummulates (Figure 5), whereas in coastal settings, land subsidence can lead to relative sea level rise, beach erosion and wetland loss. In inland settings, uplifted fault blocks can form across river courses, thereby impeding drainage and promoting wetland formation, as is clear in satellite images of parts of the Amazon basin (Figure 12). In coastal settings, land uplift can lead to relative sea level fall and the loss or seaward migration of wetlands.

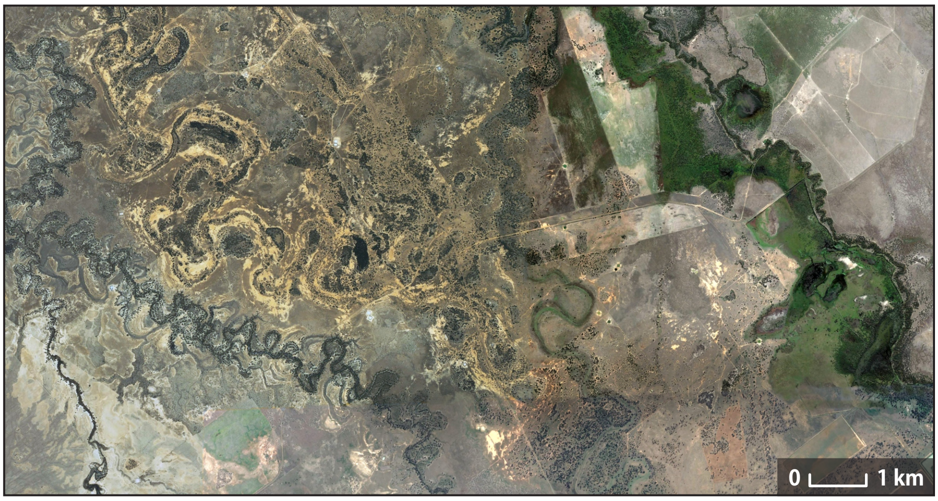

Figure 10. Aerial view showing the numerous old channels (left and centre of image) that are preserved adjacent to the modern lower Macquarie River and associated floodplain wetlands (right of image), southeastern Australia. Older channels have meander bends that are many times larger than bends along the modern river, implying past intervals with significantly enhanced flows (Source: Google Earth - Map Data from CNES/Astrium and Digital Globe, 2015).

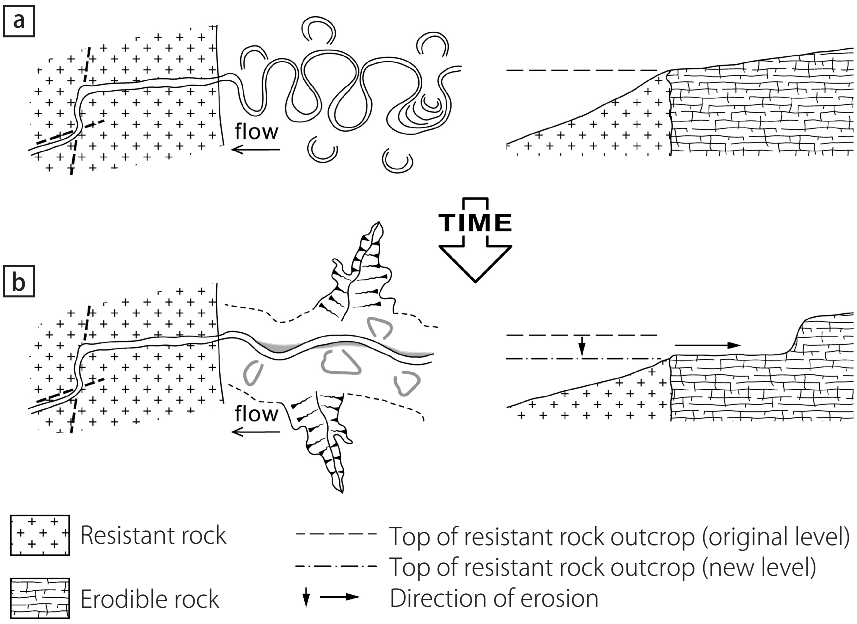

Figure 11. Schematic illustration to show a cycle of wetland formation and destruction: a) meandering channels and floodplain wetlands initially form atop more erodible rocks upstream of resistant outcrop; b) as the resistant bedrock is eroded, the channel straightens and deepens. This leads to wetland abandonment and desiccation, and commonly initiates the formation of large gullies. In the South African interior, many floodplain wetlands form atop mudstone and sandstone rocks upstream of resistant dolerite sills and dykes. The timescales over which these processes occur is poorly constrained but within the floodplain wetlands, channel changes (meander bend development, bend cutoff, avulsion) have been shown occur on timescales of years to many tens of thousands of years (Source: modified after Keen-Zebert, A. et al. 2013. Late Quaternary floodplain reworking and the preservation of alluvial sedimentary archives in unconfined and confined river valleys in the eastern interior of South Africa. Geomorphology, 185: 54-66).

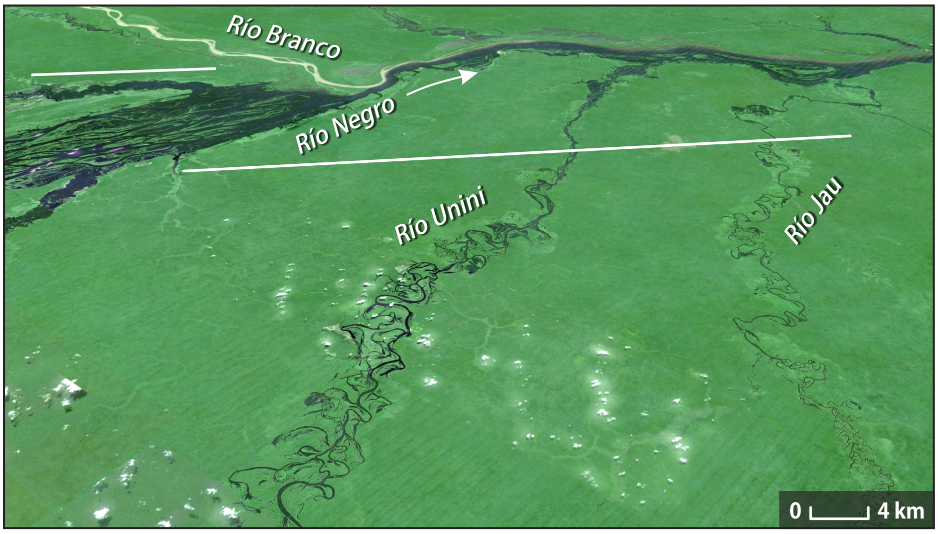

Figure 12. Oblique aerial view showing part of the central Amazon lowlands near to the junction of the Negro and Branco rivers (upper left of image). The Unini and Jau rivers join the Negro farther downstream. The white lines indicate the northern boundaries of extensive floodplain wetlands, boundaries which have been interpreted as controlled by tectonic faults (Source: Forsberg, B.R. et al. 2000. Tectonic fault control of wetland distributions in the Central Amazon revealed by JERS-1 radar imagery. Quaternary International, 72: 61-66; Google Earth - Map Data from Landsat, 2015).

Did you know?

Ever since the evolution of higher-order terrestrial plants, wetland landscapes have been a feature of the Earth's surface but over time they will have expanded and contracted in extent. For example, in the African drylands, river systems, lakes and wetlands have undergone profound changes over the last 10 million years owing to a combination of tectonic, geological, climatic and sea level changes. Such changes may have been an important factor driving biological diversification, and also probably played a role in early human origins by enabling survival and migration in marginal environments. In north Africa, radar images provide widespread evidence for large, former river channels buried at shallow depth beneath wind-blown sands. Although many details are disputed, it is thought that many rivers used to flow south to north across the Sahara. During wetter intervals in the past, such as the last interglacial (approximately 120 000 years ago), a dramatic expansion of rivers, lakes and wetlands may have provided humid corridors across what is now one of the driest parts of the continent, enabling migration and dispersal of early modern humans from sub-Saharan Africa to the Mediterranean and beyond (Source: Osborne, A.H. et al. 2008. A humid corridor across the Sahara for the migration of early modern humans out of Africa 120,000 years ago. Proceedings of the National Academy of Sciences, 105: 16444–16447; Paillou, P. et al. 2009. Mapping of a major paleodrainage system in eastern Libya using orbital imaging radar: The Kufrah River. Earth and Planetary Science Letters, 277: 327-333).

5 Wetland dynamics may be complex

In addition to changing external conditions, wetland development can also be driven by changing ecological conditions (e.g. vegetation succession, animal activities) or internal geomorphological adjustments (e.g. channel abandonment, gully development). In some wetlands, natural processes of vegetation succession can transform shallow open water bodies into peatlands and eventually woodlands. Even where such gradual terrestrialisation does not occur, major wetland changes can result from internal geomorphological adjustments. For example, in some floodplain wetlands, sedimentation along and adjacent to river channels can lead to the formation of alluvial ridges that become raised above the surrounding terrain (Figure 13). During successive flood events, increasing amounts of water are diverted away from the ridge and into the lower terrain, which promotes erosion of a new channel and abandonment of the channel on the ridge (Figure 13). Such channel switching ('avulsion') can occur on various scales, from the local to the regional (Figure 3), and can result in major ecological changes (Figure 14).

Although channel switching events can result from internal adjustments alone, commonly they are also influenced by externally-driven changes in water and sediment supply. The Okavango Delta in Botswana provides graphic illustration of the complexity of such wetland dynamics over a range of temporal and spatial scales (Figure 15). Seasonal and longer term fluctuations in river inflows lead to variations in flooding extent, duration and depth. Flow leaks through the grass- and sedge-lined

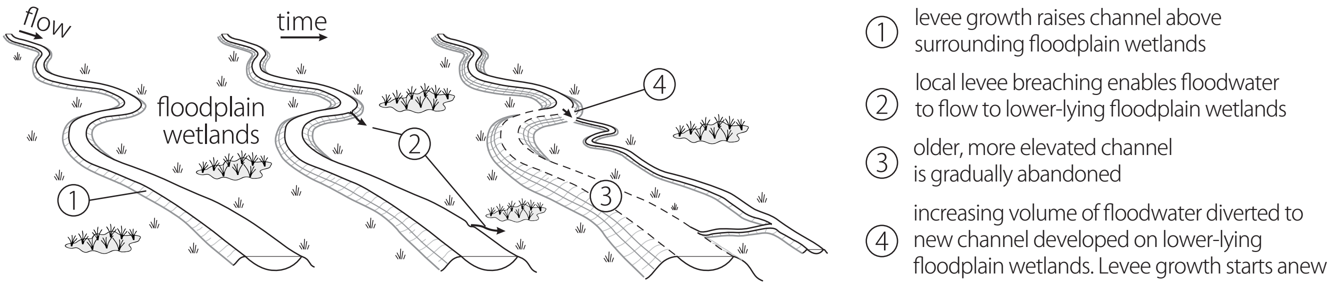

Figure 13. Illustration of the geomorphological processes leading to channel switching (avulsion). Deposition of sand, silt and clay along and adjacent to river channels can lead to the growth of levees and the raising of flow above the level of the surrounding floodplain. During floods, levee breaching can divert increasing amounts of flow to parts of the lower-lying floodplain. Eventually, a threshold is crossed whereby a newly-formed channel carries an increasing proportion of the flow, and the old, higher-elevation channel is gradually abandoned.

banks of the main distributary channels (Figure 15a), supplying vast areas of permanent and seasonal swamps. Channel flow losses lead to progressive sedimentation, which encourages further flow diversion. Over decades to centuries, these distributary channels become less efficient conduits for water and sediment dispersal, and are gradually abandoned. At the same time, increasing flow diversion means that new channels are eroded in areas of swamp, commonly by exploiting the trails created by hippopotami. Eventually, channel switching occurs, leading to desiccation of parts of the delta while new parts are flooded. On timescales of centuries, regional channel switching has led to major re-distributions of water and sediment, contributing to the fan-shaped form of the delta (Figure 15b). Some other wetland complexes globally, most notably the Pantanal in Brazil, are influenced by similar processes of channel switching.

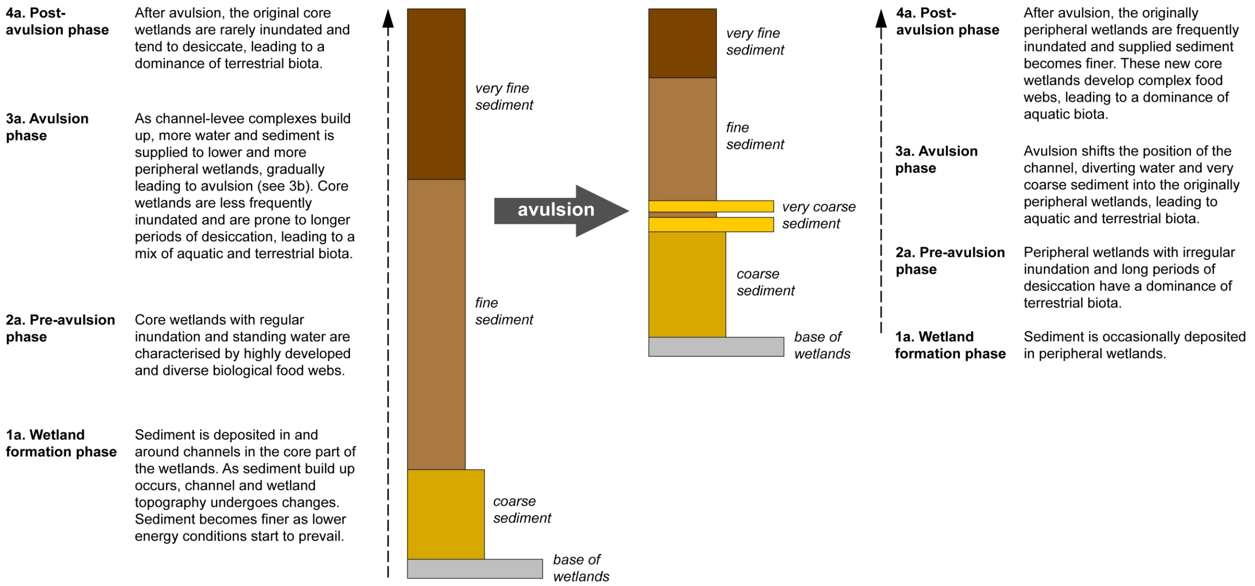

Figure 14. Illustration of the ecological consequences of avulsion, based on an example from the Macquarie Marshes, southeastern Australia (redrawn and adapted from Ralph, T. et al. 2011. Paleoecological responses to avulsion and floodplain evolution in a semiarid Australian freshwater wetland. Australian Journal of Earth Sciences, 58: 75-91).

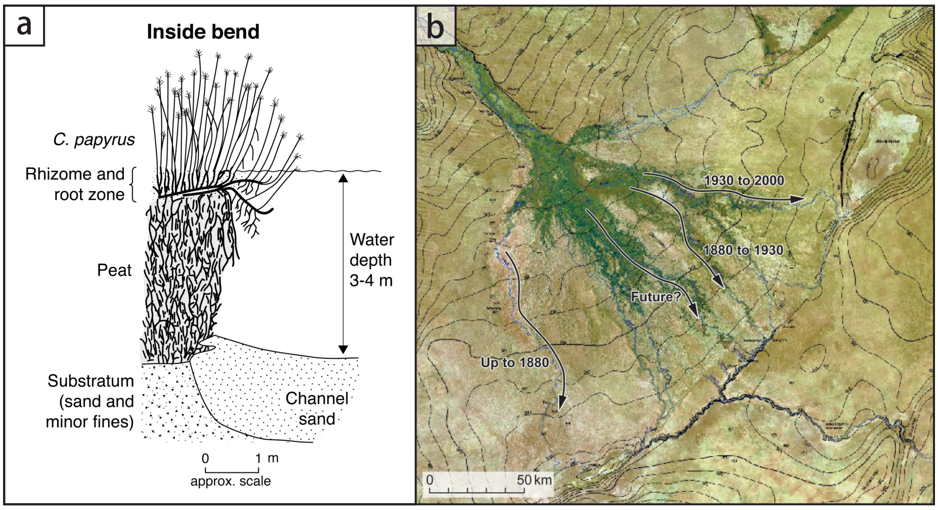

Figure 15. a) Schematic cross-section showing the typical bank composition on the inside of a meander bend in the Okavango Delta, Botswana. The active vegetation and peat layer is permeable, so water leaks through the banks but the sand stays within the channel and leads to progressive sedimentation (redrawn after McCarthy, T.S. et al., 1988. Features of channel margins in the Okavango Delta. Palaeoecology of Africa, 19: 3-14); b) Illustration of the century-scale changes in flow among the main distributary channels of the Okavango Delta. The dates (years AD) indicate the periods of time that each distributary was the main conduit for flow and sediment dispersal. Since about 2000, increasing flow has been going down the Jao/Boro distributary in the central part of the delta, suggesting that this will become the main conduit in future (Source: based on information in Ellery W.N. and McCarthy T.S. 1996. Wetland dynamics and conservation: identifying key factors in the Okavango Delta, Botswana. In: Beilfuss, R.D. et al. (Eds), Proceedings of the 1993 African Crane and Wetland Workshop. International Crane Foundation, Baraboo, Wisconsin, USA, pp. 323-332).

Did you know?

Many near-natural African wetlands host populations of hippopotami (hippos). Hippos spend daylight hours submerged in water bodies (rivers, lakes, ponds) but at night move to terrestrial grazing grounds. Adult hippos weigh between 1000 and 1500 kg and eat about 18 kg of grass (dry weight) per day. Hippos seldom travel more than 2-3 km from water to feed, and their repeated movement creates networks of trails along rivers, on banks and through floodplain wetlands. Many floodplain trails are oriented parallel to local valley slope and help to disperse flood flows more widely than would otherwise be the case, but also encourage localised erosion, particularly where increasing flow is being diverted from a nearby channel as a result of sedimentation. Headward erosion along a hippo trail towards a channel eventually can lead to channel switching (avulsion) such that the former channel is abandoned and the trail is enlarged to become the new channel. Hippos therefore have both hydrological and geomorphological impacts in wetlands that can contribute to radical changes in the distribution of water and sediment over timescales of decades, rivalling the impact of beavers in some northern hemisphere wetlands (Source: McCarthy, T.S. et al. 1998. Some observations of the geomorphological impact of hippopotamus (*Hippopotamus amphibious* L.). African Journal of Ecology, 36: 44–56).

6 Wetlands are archives of past environmental change

Wetlands contain histories of their development that potentially can be deciphered and reconstructed from study of their associated landforms, sediments and biological remains. For instance, preservation of former, larger river channels in and around wetlands can provide evidence for wetter past climates (Figure 10), while inactive wind-blown dunes surrounding wetlands can provide evidence of drier past climates. More commonly, reconstructions of past wetland changes focus on wetland sediments (Figure 16). Given their geomorphological and climatic settings (key point 2), most wetlands tend to accumulate clastic, chemical and organic sediments over time (key point 3). Commonly, these sediment accumulations are metres to tens of metres thick (Figure 16a), and locally may be hundreds of metres thick (Figure 5a). Biological matter may be preserved in organic wetland sediments, including pollen grains, leaf epidermis, faunal skeletons, and diatoms (Figure 16b). In rare instances, human remains have been recovered from wetland sediments (e.g. the 'bog bodies' preserved in western European peatlands). Biological evidence may provide detailed signatures of past environmental conditions (e.g. temperature, rainfall, water chemistry, local vegetation assemblages, food webs) and highlight major periods of past environmental change. Geochronological techniques such as radiocarbon and luminescence dating can help establish the age of sediment deposition, thereby enabling reconstruction of the timing and rates of past changes.

Most studies of wetland histories have focused on inland and coastal wetlands in mid latitudes of the northern hemisphere. Many of these wetlands have relatively short histories, having developed within the last 10–15 000 years following the retreat of ice sheets after the Last Glacial Maximum. Many wetlands formed on de-glaciated terrain (Figure 6a) or in response to sea level rise, and the records of past palaeoenvironmental conditions may be detailed but relatively short. In parts of the world that escaped the direct effects of glaciation, wetlands may preserve far longer records. Peat deposits as old as 45 000 years have been found in some tropical wetlands, while some southern African and Australian wetlands preserve evidence of changing channel and floodplain dynamics over timescales in excess of 50 000 years.

Reconstructing wetland developmental histories is important, for several reasons. First, it provides the context for assessing the nature, rates and patterns of recent changes to wetland structure and function, and the basis for assessment of the likely external and/or internal factors driving these changes (key points 4 and 5). Second, it provides a guide as to how wetlands may change in the future under global climate change scenarios (key point 7). Third, by providing a long-term perspective on natural wetland changes, it helps to evaluate the extent to which human activities are impacting on wetlands (key point 8).

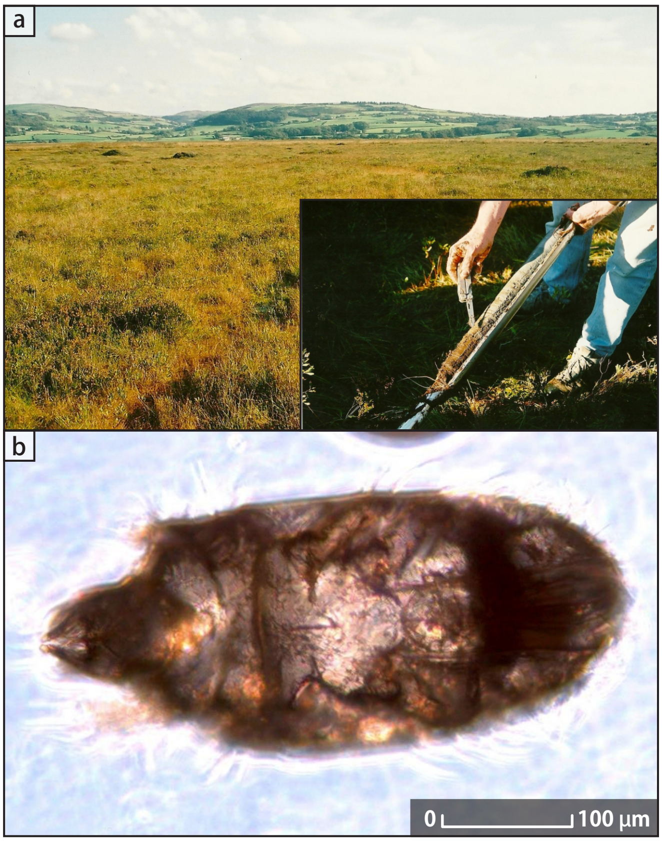

Figure 16. Examples of wetland sediments and associated biological features that can provide information about wetland histories: a) Borth Bog (Cors Fochno), west Wales, one of the largest surviving raised estuarine bogs in western Europe. The inset shows a core recovered from the margins of the bog at 5-6 m depth, showing the sharp transition from grey estuarine clays (lower part of core on upper right) to brown peat (upper part of core on lower left) that occurred about 6000 years ago in response to sea level rise (Photos: Stephen Tooth); b) water mite recovered from a core in the Macquarie Marshes, western New South Wales, Australia (scale at lower right, with 100 µm equal to 0.1 mm). The presence of this predatory invertebrate suggests the existence of a relatively well-developed food web about 5000 years ago (Image: Yoshi Kobayashi).

Did you know?

Although detailed studies are limited, available evidence indicates that many wetlands in the southern African drylands have histories that may stretch back many tens or even hundreds of thousands of years. During major periods of past environmental change, marked adjustments in channel and floodplain landforms may have occurred but the host wetlands have persisted as landscape features nonetheless. This long-term persistence provides stark contrast with present-day changes, with some wetlands in the southern African drylands currently undergoing a phase of severe degradation that threatens their existence. The causes of this degradation are debated, but may be resulting from a combination of natural geological factors (Figure 11), climatic changes, internal adjustments, and human impacts (Source: Tooth, S. and McCarthy, T.S. 2007. Wetlands in drylands: key geomorphological and sedimentological characteristics, with emphasis on examples from southern Africa. Progress in Physical Geography, 31:3-41).

7 Global environmental change is influencing wetlands

Ongoing global environmental change, which includes atmospheric warming and sea level rise, is currently driving changes in wetland structure and function, including through increased coastal erosion, desiccation and gully development. Although the response of wetland landforms and landscapes to external environmental changes may be complicated by changing ecological conditions or internal geomorphological adjustments (key point 5), some types of wetlands may be particularly vulnerable to dramatic and irreversible changes. Vulnerable wetlands include those located in landscape positions that are particularly sensitive to sea level rise, such as mangrove swamps and coastal freshwater wetlands. Other vulnerable wetlands are those located in marginal climatic settings, where even small variations in rainfall, evapotranspiration or river inflow may lead to large wetland changes, such as many wetlands in drylands and those wetlands in mountainous regions that are dependent on declining water supplies from shrinking glaciers. Furthermore, the physical structure of some wetlands means that they may function close to thresholds, whereby even small changes in wetland slope or area can lead to dramatic geomorphological changes (Figure 17). Wetland changes can feed back to drive further environmental change (key point 3), particularly where wetland degradation leads to the oxidation and release of stored carbon, so contributing to the ever-increasing burden of atmospheric greenhouse gases.

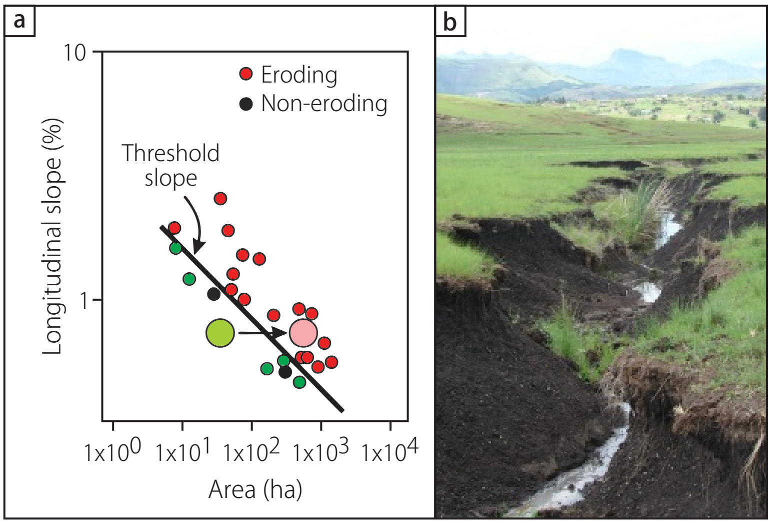

Figure 17. a) Relationship between wetland slope and wetland area, illustrating a threshold between non-eroding wetlands (channels absent or shallow, no gullies) and eroding wetlands (deep channels, gullies). For some wetlands, even small increases in wetland slope (i.e. faster flows) or wetland area (i.e. larger flow volumes) can change the balance between erosion and deposition, pushing the system across the threshold (see large circles). Data from South Africa shows that many floodplain or valley bottom wetlands have undergone dramatic geomor-phological changes over the last century, with some changing from eroding to non-eroding systems but many more changing from non-eroding to deeply eroding systems. These changes have been driven by a still poorly understood combination of natural geological factors, climatic changes, internal adjustments and human impacts (Source: redrawn and adapted after Ellery, W.N. et al. 2009. WET-Origins: Controls on the Distribution and Dynamics of Wetlands in South Africa. WRC Report No TT334/09, Pretoria); b) Example of a large gully in a rural South African wetland (Photo: Fred Ellery).

Considering the broader definitions of wetlands (see box on p. 2), many offshore wetlands are also undergoing profound change in response to global environmental change. Coral reefs are particularly vulnerable owing to a toxic combination of ocean warming and rapid sea level rise, ocean acidification, and increased sediment supply to coastal waters. Even in the context of major changes to the structure and function of other wetland types, coral reefs provide a particularly stark example of wetlands where both landforms and significant reservoirs of biodiversity are under threat.

Did you know?

Many landscapes worldwide are at risk from rising sea level, but the state of Florida in the southern USA is one of the most threatened. Studies show that more than half of Florida's 825 miles (1328 km) of sandy beaches are already eroding, and mapping of projected future sea levels shows that with a 5 ft (1.5 m) rise by 2100, nearly one million of the homes near the present-day coastline will be below the average day's high tide limit. For every 1 ft (0.3 m) of sea level rise, the shoreline will move inland by 500-2000 ft (152-610 m). This will lead to increasing saltwater incursion, radically altering the distribution of saline, brackish and freshwater wetlands in the Everglades (Source: National Geographic, February 2015).

8 Human activities are influencing wetlands

Increasingly, the direct and indirect effects of human activities (e.g. land use, infrastructure, environmental governance) are also driving changes in wetland structure and function. Many wetlands have been lost entirely owing to land use changes that include conversion for agriculture, grazing, forestry and urban developments, and as a result of drainage modifications such as flow diversion and regulation, channelisation, and groundwater abstraction. Wetland losses have occurred throughout human civilisation, but in western Europe these losses increased following the Industrial Revolution in the mid-18th century. European colonisation led to wetland losses in many parts of the 'New World', and globally many wetland losses have occurred with the 'Great Acceleration' in development after World War II. Some estimates suggest that at least half of all pre-development wetlands worldwide have been lost as a result of human activities. In addition, the structure and function of many other remaining wetlands have been degraded to varying degrees by these and other human activities, including by the introduction of exotic invasive riparian vegetation (e.g. willows in South African and Australian wetlands). With ongoing environmental change (key point 7), more wetlands are likely to come under pressure, particularly in drylands where growing populations look to these moist, productive landscape for water, food and other resources (key point 10).

In recent decades, however, there has also been greater awareness of the need to conserve and manage those wetlands that remain, for there has been increasing recognition that the ecosystem services provided by wetlands are essential to human wellbeing (key point 10). Various forms of regional, national and international legislation provide a framework for environmental governance, including wetlands. For instance, the Ramsar Convention (see box on p. 2) is an intergovernmental agreement to protect wetlands considered to be of international importance, while other wetlands are afforded protection by their incorporation within regional or national parks (Figure 18a). Some parks are even designated largely on the basis of wetland habitats, with a prime example being the Everglades National Park, which incorporates a complex of subtropical swamps in the southern USA. Other examples include Etosha National Park, northern Namibia, and Makgadikgadi Pans National Park, northeastern Botswana, which are based around large, seasonally-flooded salt lakes. Alongside conservation measures, there are also efforts to rehabilitate those wetlands that have been degraded by human activities. For instance, South Africa's Working for Wetlands programme employs impoverished, rural people to undertake rehabilitation work that may include flow restoration, plugging of gullies, and removal of invasive species. In some countries, most notably the USA, legislation even exists to artificially create, restore or enhance wetlands as compensation for those that have been lost by agricultural and urban developments. In some urban areas, artificial wetlands are also being created as part of sustainable urban drainage systems (Figure 18b), thereby helping to protect protect people and infrastructure against growing threats from geohazards such as flash floods (key point 9).

Against this backdrop, Figure 4 reflects the fact that, alongside geomorphological and climatic factors, human activities also have a key influence on wetland structure and function. Historically, these activities have tended to have mainly negative consequences but there are also some examples illustrating more positive trends.

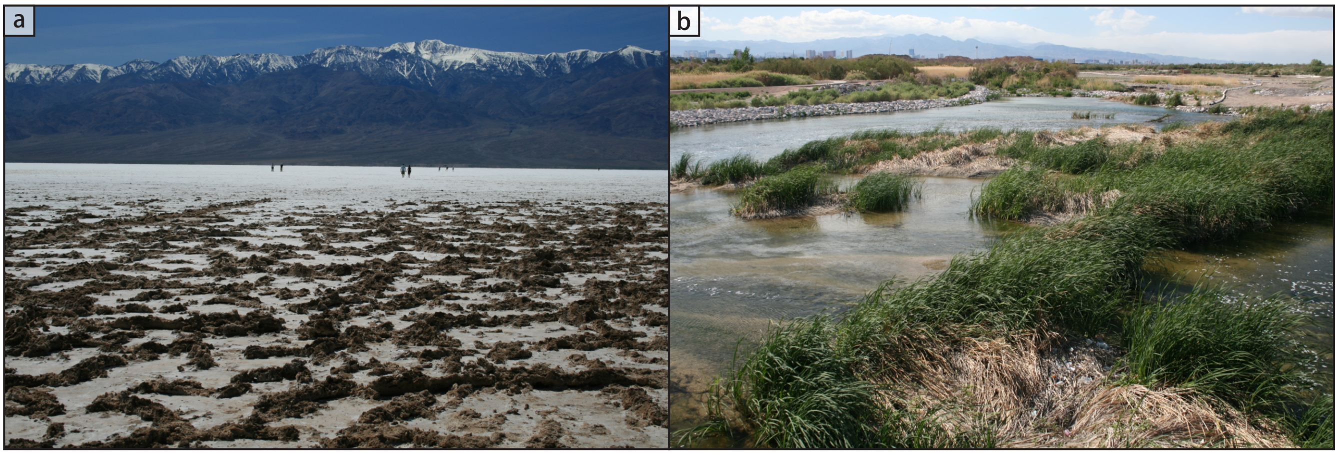

Figure 18. a) The salt-encrusted playa surface at Badwater, California is a major drawcard for visitors to Death Valley National Park. Snowmelt, rainfall, and sediment from the surrounding mountains is supplied to the tectonically-subsiding depression, leading to occasional flooding of the playa. Much of the water evaporates in the intense heat, resulting in growth of salt crystals (e.g. halite, calcite, gypsum and borax) and disruption of near-surface sediments. Careful management of the increasing visitor numbers is needed to avoid widespread damage to these unusual but delicate wetland surface features (Photo: Stephen Tooth); b) The Wetlands Park Nature Preserve is located adjacent to Las Vegas, one of the USA's fastest growing cities, and consists of a series of constructed wetlands that are being actively managed using surface runoff, reclaimed water, and water level control structures. The streams, ponds and plants help restrict erosion and provide habitat for wildlife, while trails and overlooks provide nature viewing and other recreational opportunities. High rise buildings along The Strip in Las Vegas are visible in the far distance (Photo: Stephen Tooth).

Did you know?

Throughout history, the hydrology of many wetlands worldwide has been radically altered by a combination of flow control, flow diversion, and drainage schemes. These schemes have been carried out for a variety of reasons. From the 16th century onwards, increasingly sophisticated flow control and drainage operations converted many western European wetlands to fertile agricultural land (e.g. the Fenlands of eastern England, and large areas of the Netherlands). These lands continue to be protected from floods by systems of ditches, dykes, levees, and pumps. In the 1930s, Benito Mussolini initiated extensive drainage works in the wetlands of the Pontina, located west of Rome, Italy. Once considered one of the most malarious places in the world (among other incidents, malaria was held to be responsible for the untimely deaths of several popes), the Pontina eventually became fit for human habitation. And in the late 1980s and 1990s, southern Iraq's Mesopotamian Marshes – the largest wetland in the Middle East and home to the Marsh Arabs for many thousands of years – was subject to a major flow diversion project that led to widespread desiccation. The former Saddam Hussein regime claimed that flow diversion and drainage was necessary for agricultural purposes but most commentators believed that the scheme was part of a campaign to crush Shia insurgents operating from the marshes. Since the fall of the Hussein regime, efforts have been made to restore the Marshes to their former ecological status (Source: Desowitz, R.S. 1991. The Malaria Capers: Tales of Parasites and People. Norton, New York; Purseglove, J. 1989. Taming the Flood, OUP, Oxford; Richardson, C.J. et al. 2005. The restoration potential of the Mesopotamian marshes of Iraq. Science, 307: 1307-1311).

9 Wetlands may be vulnerable to geohazards but may also buffer the wider landscape from their impacts

Both global environmental change and human activities are increasing the magnitude and frequency of geohazards in wetlands (e.g. flash floods, coastal storm surges), which occur wherever and whenever land surface stability is affected and adverse socio-economic impacts are experienced. Mounting evidence suggests that atmospheric warming and sea level rise is likely to be associated with increases in the magnitude and frequency of extreme weather events (e.g. convective thunderstorms, hurricanes, cyclones) and associated geohazards. In addition to flash floods and coastal storm surges, other geohazards include droughts and wildfires. Such events may drive rapid, dramatic changes in patterns and rates of geomorphological processes, possibly impacting negatively on the structure and function of inland and coastal wetlands (Figure 19a), and affecting associated human activities. Other hazards may be slower acting and less visible, such as soil salinisation that results from gradual groundwater rise or the spread of waterborne pollutants or disease, but may also lead to major changes in wetland structure and function, also with implications for human activities.

Although some wetlands may be vulnerable to geohazards, they may also buffer the wider landscape from their impacts. For instance, coastal wetlands can help to absorb the impacts of storm surges, providing protection for landscapes and human activities farther inland. Indeed, it is widely believed that the impacts of Hurricane Katrina (August 2005) on New Orleans, southern USA, would have been less severe had there been greater efforts to prevent the loss and degradation of coastal wetlands in the decades preceding the event. Inland, low gradient floodplain wetlands may attenuate flash flood peaks and help to trap associated sediments and pollutants, thereby providing protection for areas downstream. In South Africa, wetlands to the south of Johannesburg trap a wide range of pollutants associated with gold mining, helping to improve water quality for downstream users (Figure 19b).

Given the burgeoning human population, more and more human activities are taking place in areas that are increasingly vulnerable to weather extremes and other geohazards, including many low-lying coastal areas and river valleys. Wetlands may therefore play a key role in land management approaches that form part of wider climate change adaptation strategies, both in rural and urban areas.

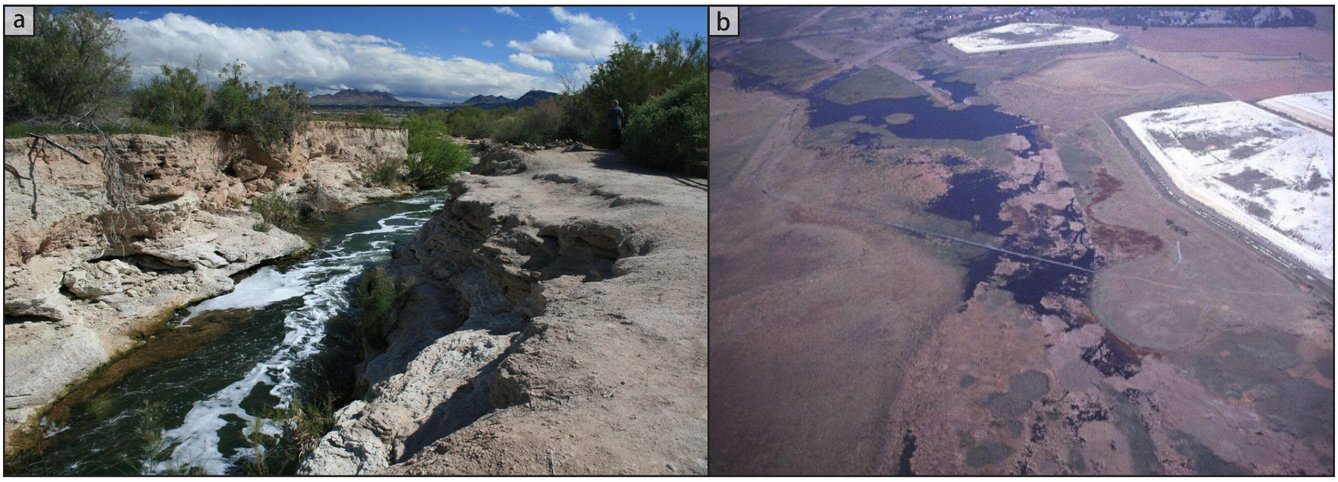

Figure 19. Examples of wetlands impacted by geohazards: a) the Las Vegas Wash (view looking downstream) showing the deep (4-5 m) erosion resulting from flash floods in the 1980s and 1990s. Subsequent design and construction of The Wetlands Park Nature Preserve adjacent to the Wash (Figure 18b) was partly in response to the impacts of this particular geohazard (Photo: Stephen Tooth); b) one of the numerous wetlands located adjacent to gold mining dumps (white areas on right of image) south of Johannesburg, South Africa. The wetlands trap a wide range of pollutants emanating from the dumps, thereby preventing more widespread contamination of surface flows and groundwater (Photo: Stephen Tooth).

Did you know?

The Las Vegas Wash (Figure 19a) drains past one of the USA's fastest growing cities, typically conveying 150 million US gallons (567 million litres) of water per day, including urban runoff, reclaimed water, shallow groundwater and natural thunderstorm runoff. In the 1980s and 1990s, major flash floods caused severe erosion along the Wash and its associated wetlands, causing damage to wildlife habitat and threatening homes. At downstream Lake Mead, sediment deposition led to the formation of a delta, forcing relocation of the marina at Las Vegas Bay. In one flash flood in 1999, 4.5 billion US gallons (17 billion litres) of water surged along the Wash in a 24 hour period, providing enough water to fill an Olympic-size swimming pool roughly every 3.5 seconds. Subsequent engineering and construction of The Wetlands Park Nature Preserve (Figure 18b) was partly in response to acknowledgement of the need to manage these flash floods, and was achieved using funds from a state wildlife bond (Source: information from Parks and Recreation, Clark County, Nevada).

Geomorphology can provide a key role in wetland management, including their conservation, restoration, and artificial construction, thereby helping to protect and enhance the delivery of wetland ecosystem services. Ecosystem services are defined as the benefits from ecosystems that contribute to human wellbeing, and can be categorised into provisioning, regulating, supporting, and cultural services. Table 2 illustrates some of the many ecosystem services provided by the world's wetlands, including their influence on local, regional and global scales.

Globally, few wetlands remain entirely untouched by the direct and indirect effects of human activities (key point 8), and it is widely acknowledged that various degrees of management are needed to ensure 'wise' or 'sustainable' use that maximises wetland ecosystem services while also preserving them for future generations. Given the many natural and human pressures on wetlands, however, future wetland management will need to identify trade-offs between different ecosystem services, as maximising some services inevitably compromises some others. Should wetlands be managed primarily for provisioning services (e.g. food production), perhaps involving varying degrees of conversion for agriculture and inevitably compromising aspects of the regulating, supporting and cultural services? Should maximising the regulating services take precedence (e.g. by enhancing carbon storage or through flow manipulation for the benefit of downsteam users - Figure 20a)? Or in a world where access to nature is increasingly highly valued, should many wetlands be managed primarily for the preservation of cultural services (e.g. aesthetic appeal or recreational opportunities – Figure 20b), with any provisioning, regulating or supporting services simply being a welcome but essentially unmanaged spin off?

These are not easy questions to answer, but as this booklet illustrates, geomorphology underpins many wetland ecosystem services, and so needs to be taken into account when debating and devising wetland management strategies. Geomorphological processes shape the physical structure of wetlands, thereby influencing movement of water, sediment and nutrients, and providing the template upon which wetland ecological processes take place (key points 1, 2 and 3). An understanding of geomorphology, especially the drivers, rates and nature of past river, floodplain or delta changes (key points 4, 5 and 6), can help to anticipate undesirable future changes to wetlands (key points 7 and 8) and informs the use of wetlands for buffering the wider landscape against climatic extremes and other geohazards (key point 9). In these ways, geomorphology can be used proactively to protect and enhance the delivery of wetland ecosystem services as part of integrated rural land management strategies and sustainable urban drainage systems. Ideally, management should be based on allowing

Table 2. Ecosystem services and functions in the world's wetlands (Source: adapted from Costanza, R. et al. 1997. The value of the world's ecosystem services and natural capital. Nature, 387: 253-260; Aber, J.S. et al. 2012. Wetland Environments: A Global Perspective. Wiley-Blackwell, Chichester. Ecosystem service categories follow the Millennium Ecosystem Assessment 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, D.C.).

Ecosystem services	Wetland functions (L= local, R = Regional, G = Global influence)	Examples of influence
Provisioning		
Water supply	Storage and retention (L, R)	Soil moisture, aquifers, rivers, ponds, lakes
Food production	Gross primary production for food (L, R)	Crops, fish, game, livestock
Raw materials	Gross primary production for materials (L, R)	Timber, fibre, fuel, fodder
Genetic services	Unique biological materials and products (L, R, G)	Medicines, plant and animal varieties, ornamental species
Regulating		
Gases	Atmospheric chemical composition (G)	Carbon storage (organic, inorganic)
Climate	Weather and climate (L, R, G)	Evaporative cooling, cloud formation, greenhouse gas emissions (carbon dioxide, methane)
Disturbances	Absorbing and damping landscape and ecological responses to geohazards (L, R)	Storm surge protection, flood control, drought recovery
Water	Hydrological flows (L, R)	Irrigation, transportation, industrial applications
Erosion, sedimentation	Retention of soil and sediment (L, R)	Prevention of soil loss and siltation in ponds, lakes and reservoirs
Ecology	Floral and faunal population controls (L, R)	Predator control of prey
Supporting		
Soil formation	Soil-forming processes (L)	Rock weathering, organic matter accumulation
Nutrient cycling	Storage, processing and transfer of nutrients (L, R)	Nitrogen, potassium and phosphorous
Waste treatment	Nutrient recovery, removal of harmful substances (L, R)	Pollution control, detoxification
Pollination	Movement of floral gametes (L, R)	Pollinators for plant reproduction
Refugia	Habitat for resident and migratory populations (L, R, G)	Nurseries, regional habitats, migratory routes
Cultural		
Recreation	Recreational opportunities (L, R, G)	Ecotourism, bird watching, sport fishing, hunting
Cultural	Non-commercial uses (L, R, G)	Artistic, aesthetic, spiritual, religious, or scientific values

natural geomorphological processes to operate, but even where this is not possible and some degree of management is deemed necessary (Figure 20), geomorphological considerations should underpin direct interventions. For example, in the case of wetlands that exist just to the left of the non-eroding/eroding threshold (Figure 17a), intervention may be required to limit or prevent erosion taking place upvalley. Any such erosion may lead to increased sediment supply and deposition in the wetland, locally increasing wetland slope and pushing the system across the threshold into an eroding condition, with loss of many regulating services for downstream users.

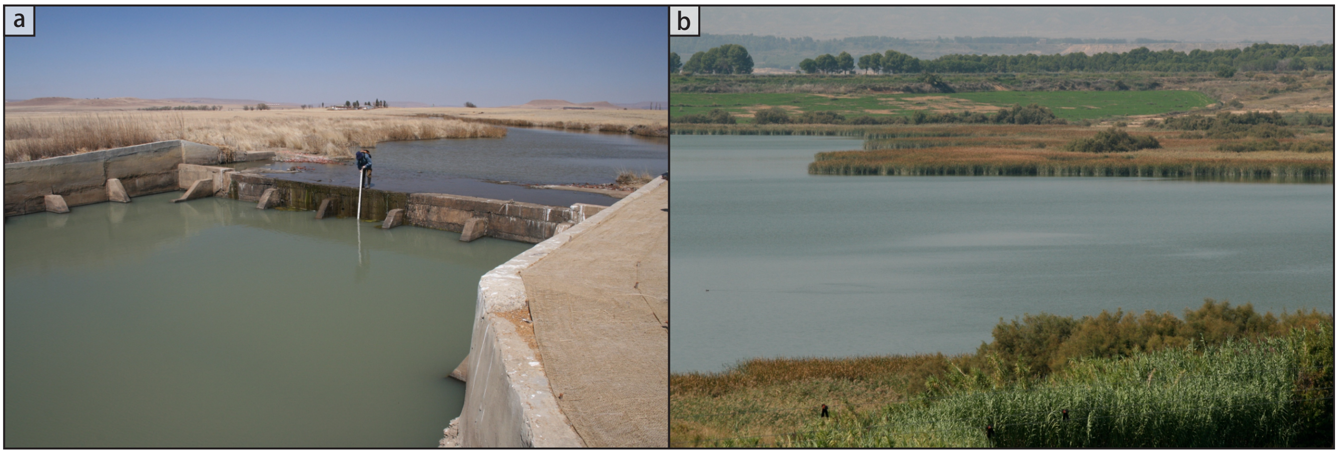

Figure 20. Photographs illustrating wetlands that are subject to different forms of flow manipulation: a) Klip River, eastern Free State, South Africa, showing one of the weirs that has been installed to control channel erosion and raise water levels in the channel and surrounding floodplain wetlands. Such weirs interfere with the natural processes of flow and sediment transport but play a vital role in enhancing the quality of water entering the Vaal River downvalley, which in turn supplies the important agricultural, mining, industrial, and urban centres of Gauteng Province (Photo: Stephen Tooth); b) La Laguna de Sariñena, Monegros region, northeast Spain. In the arid climate, water in the lake is derived largely from irrigation runoff, and the level is artificially maintained for the benefit of biodiversity and associated recreational opportunities (Photo: Stephen Tooth).

Did you know?

La Laguna de Sariñena (Figure 20b) is located on the drainage divide between the Alcanadre and Flumen rivers in the Monegros region, northeast Spain. Formerly, it was an ephemerally-flooded salt lake (playa) but from the 1960s onwards, irrigation developments on the surrounding land meant that it became a sink for excess water, leading to permanently-flooded conditions and a reduction in salinity. A drainage canal was built to maintain a regular water level (maximum 2.35 m deep) and aerial extent (about 204 hectares) by draining off excess water. With permanent water, vegetation established around the margins and fish colonised, and this managed wetland has since become magnet for resident and migratory waterbirds. In 1995, La Laguna was given status as a Wildlife Refuge and in 2001 was declared a Special Protection Area for Birds. In recent years, La Laguna has gained importance for its large population of bitterns (Source: information brochures from Ayuntamiento de Sariñena, Diputación Provincial de Huesca).

Are there any real life case studies where knowledge of the geomorphology of wetlands has proven topical or useful?

Although the terms ‘geomorphology’ and ‘wetlands’ are commonly not used explicitly, geomorphology sometimes underpins the coverage of wetland topics in online media articles. A selection from the BBC includes:

2015

Panama protects wetlands from construction boom
www.bbc.co.uk/news/world-latin-america-31351625

Norfolk and Suffolk Broads to be renamed 'national park'
www.bbc.co.uk/news/uk-england-30952369

Waiting for the sea (Aral Sea immersive website)
www.bbc.co.uk/news/magazine-31588720

2014 & older

Virginia's dying marshes and climate change denial
www.bbc.co.uk/news/magazine-17915958

West Sussex river re-routed to create wetland habitat
www.bbc.co.uk/news/uk-england-sussex-11642278

Mangroves offer win-win opportunity
news.bbc.co.uk/2/hi/science/nature/8893767.stm

Call for regeneration of wetlands to fight climate change
news.bbc.co.uk/1/hi/uk/7492056.stm

Where can I go for further information?

The Wetlands in Drylands Research Network comprises a group of international scientists who recognise that the geomorphology of wetlands is an important study topic, particularly given the many threats faced by wetlands and their ecosystem services.

wetlandsindrylands.net

The Society of Wetland Scientists is an international organization of more than 3000 wetland professionals dedicated to fostering sound wetland science, education, and management.

www.sws.org

The Ramsar Convention on Wetlands is the oldest of the modern global intergovernmental environmental agreements, and provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. Currently, there are 168 contracting parties with 2186 Ramsar sites designated worldwide, details of which can be obtained through the interactive site map (www.ramsar.org/sites-countries/the-ramsar-sites).

www.ramsar.org

Many national and international organizations are dedicated to the support and promotion of geomorphology, including the British Society for Geomorphology (BSG), the Southern African Association of Geomorphologists (SAAG), the Australian and New Zealand Geomorphology Group (ANZGG), and the International Association of Geomorphologists (IAG).

What would you recommend as further introductory reading?

The following books provide very good introductions to wetland science and management issues, although in many cases the emphasis tends to be on short-term hydrological, soil chemical and ecological processes, rather than the longer term geomorphological or climatic processes influencing wetland development:

Aber, J.S., Pavri, F. and Aber, S. 2012. *Wetland Environments: A Global Perspective*. Wiley-Blackwell, Chichester, 437 pp.

Mitsch, W.J. and Gosselink, J.G. 2015. *Wetlands* (5th ed). Wiley, New York. 744 pp.

Mitsch, W.J., Gosselink, J.G., Zhang, L. and Anderson, C.J. 2009. *Wetland Ecosystems*. Wiley, Chichester, 256 pp.

And what about online resources?

These Vignettes are stand-alone electronic case studies that teach about geomorphology and related topics. A word search on 'wetlands' will reveal many case studies that illustrate the importance of geomorphology for an understanding of wetland structure, function and dynamics, e.g.:

Vignettes: Key Concepts in Geomorphology
http://serc.carleton.edu/vignettes/index.html
[Last access date: 15th May 2015]

Artesian blister wetlands, the intersection of geomorphology and hydrogeology
http://serc.carleton.edu/60239

Beneath the surface of coastal lowlands: archives of mid- to late-Holocene subduction zone earthquakes
http://serc.carleton.edu/42738

Floodouts, drainage breakdown and wetland formation in a losing river in Eastern Australia
http://serc.carleton.edu/35887

Floodplain chronology of the Stillerust Vlei, Mooi River floodplain wetland, in western KwaZulu-Natal, South Africa
http://serc.carleton.edu/60232

How is Everglades geomorphology like that of arid Australian rivers and boreal bogs?
http://serc.carleton.edu/69109

Natural and anthropogenic impacts on a freshwater wetland, Lake Bogoria, Kenya
http://serc.carleton.edu/60230