Chemical Sedimentation as a Driver of Habitat Diversity in Dryland Wetlands

Marc Humphries (marchump@gmail.com)
University of the Witwatersrand https://orcid.org/0000-0002-4047-1451

Terence McCarthy
University of the Witwatersrand

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Author information:

Marc Humphries
School of Chemistry, University of the Witwatersrand, Johannesburg, Private Bag 3, Wits 2050, South Africa
Corresponding email: marchump@gmail.com
ORCID: 0000-0002-4047-1451

Terence McCarthy
School of Geosciences, University of the Witwatersrand, Johannesburg, Private Bag 3, Wits 2050, South Africa

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Marc Humphries and Terence McCarthy

Abstract

Freshwater wetlands located in dryland environments are characterised by high evapotranspiration rates and frequent periods of desiccation, which strongly influence the water chemistry and solute budgets of these systems. The transpiration of groundwater, especially by trees, is an important mechanism through which dryland wetlands can lose water. This process can lead to groundwater salinization and the precipitation of substantial quantities of mineral phases within the soil, the accumulation of which can have profound consequences for wetland structure and function. This paper aims to bring together current knowledge on the processes that result in solute accumulation and chemical sedimentation which assist in maintaining freshwater conditions in many seasonal dryland wetlands. Examples from central and southern Africa, Australia and South America are presented to illustrate the geomorphically diverse settings under which chemical sedimentation can occur, and the importance of these processes for the resilience and longevity of dryland wetlands. We show that the localised development of saline groundwater and subsurface precipitation of minerals within soils can play a key role in creating and maintaining the habitat diversity of dryland wetlands. Wetland vegetation focuses the accumulation of deleterious constituents, thereby preventing widespread salinization and playa-lake formation, and thus ensuring that the bulk of the surface water remains fresh. Although such processes remain widely understudied, we suggest that chemical sedimentation could be a common phenomenon in many dryland wetlands and have important implications for the future management of these ecosystems.

Keywords: Dryland wetlands, evapotranspiration, solute accumulation, groundwater salinization, mineral precipitation

Introduction

All wetlands can be described in terms of their inputs and outputs which fall into three categories: water, sediment and the atmosphere (Fig. 1). On the input side, water enters in the form of rain, surface

runoff and groundwater; sediment in the form of particulate material and solutes; and atmospheric gases in the form of CO_2 and O_2. On the output side, water is lost in the form of evaporation, transpiration, surface flow and groundwater flow; sediment in the form of solutes (particulate sediment is generally trapped within wetlands); and atmospheric gases in the form of CH_4 and CO_2. These inputs and outputs differ in their relative importance depending on the local climate, as indicated by the tick marks in Fig. 1.

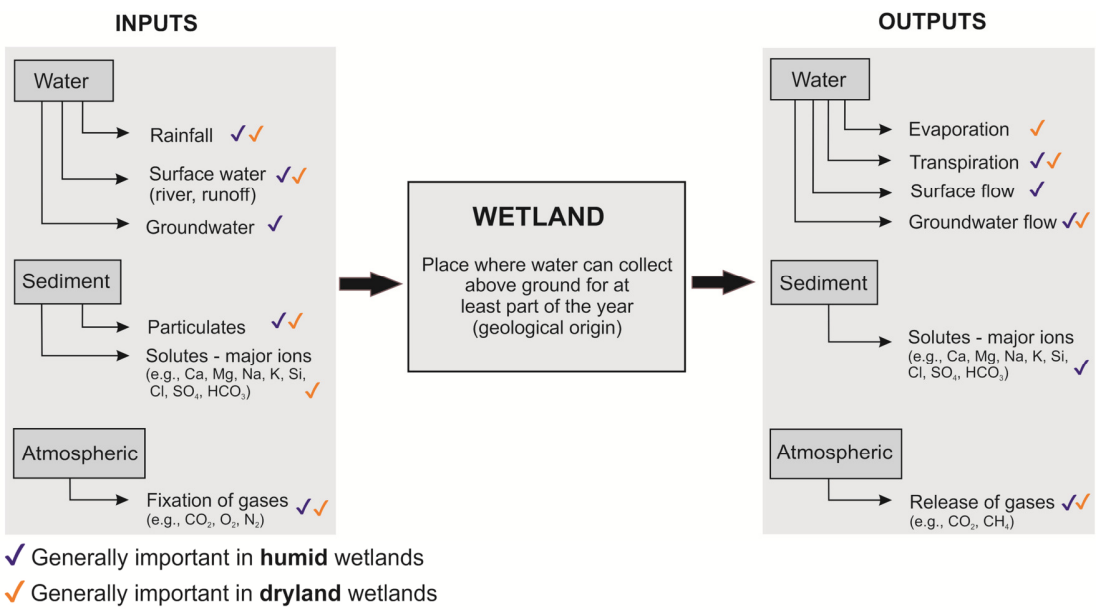

Fig. 1 A general framework describing the water, sediment and atmospheric gas budgets for wetlands.

The notion of a freshwater wetland in a dryland is somewhat of an oxymoron because wetlands can only exist where there is a positive water balance at or near the surface for at least some part of the year. Freshwater wetlands are thus most widespread in relatively humid and temperate regions of the world. Drylands are regions with sub-humid, semi-arid or arid climates, and cover ~45% of the Earth's land surface (Prăvălie 2016; Fig. 2). These environments are typically characterised by overall surface water deficits resulting from low ratios between precipitation and potential evapotranspiration. Perennial wetlands in dryland environments are usually supplied by groundwater sources and are invariably saline to hypersaline due to sustained evaporation. Despite the hydrological constraints, dryland regions host a surprisingly diverse range of perennial, seasonal and ephemeral freshwater wetlands (Tooth and McCarthy 2007). Although diverse in nature, wetlands in dryland settings are considered to share key functional characteristics that distinguish them from systems from more humid regions (Fig. 1; Tooth

and McCarthy 2007). Due to the relatively dry and variable climate that characterises dryland regions, most moderate to large wetlands are primarily dependent on fluvial surface flows and to a lesser extent on rainfall, with almost no input from groundwater. Flow regimes vary widely, but are typically characterised by strongly seasonal or episodic inflows. Thus, while perennial wetlands can exist in drylands (e.g., the Okavango) most wetlands are prone to extended periods of desiccation. Wetland ecosystems exhibit numerous strategies to cope with these dry periods which often involve biogeochemical transformations that play an important role in reducing the impacts of salinity increases.

Water availability in such systems is strongly influenced by both hydrological inputs and also by atmospheric demand. Evapotranspirational water loss can have a major impact on water chemistry, potentially resulting in localised to widespread surface and/or groundwater salinization. Pans and playa lakes provide an extreme example of this, being characterised by highly saline water and high salt concentrations in surface sediments. These systems have been fairly well documented in many dryland regions of the world (e.g., Etosha and Makgadikgadi pans in southern Africa, Lake Eyre in central Australia, Salar de Uyuni in Bolivia, and the Mojave Desert lakes, USA). Less well-recognised are the biological mechanisms that help to localise solutes in the groundwater of large freshwater wetland systems. Although knowledge of these processes is still largely limited to a few case studies, detailed investigations have shown that wetlands located in dryland regions are capable of effectively confining various non-nutrient solutes (e.g., Ca, Mg, Si, Na). Unlike nitrogen and phosphorus, these solutes are not taken up and incorporated into the biomass of plants in significant amounts and therefore tend to accumulate in the groundwater. This process can lead to groundwater salinization and the precipitation of various mineral phases within the soil (e.g., McCarthy et al. 1993; Humphries et al. 2010a). The accumulation of solutes and chemical sediments can have profound consequences for wetland structure and function.

Although drylands host some critically important wetland systems, the influence of chemical sedimentation on wetland structure and function remains poorly documented. This paper aims to bring together current knowledge on the processes that result in solute accumulation and chemical sedimentation which assist in maintaining freshwater conditions in many seasonal wetlands in dryland environments. Examples from central and southern Africa, Australia and South America (locations given in Fig. 1) are given to illustrate the different settings and processes under which chemical sedimentation can occur, and the implications of this for wetland structure and function. Our discussion is confined to

naturally occurring freshwater wetlands that are not subject to tidal influence or salinization induced by human activity. Although limited to a handful of reasonably well described case studies, it is expected that many of the concepts developed will apply to wetlands in other dryland regions of the world.

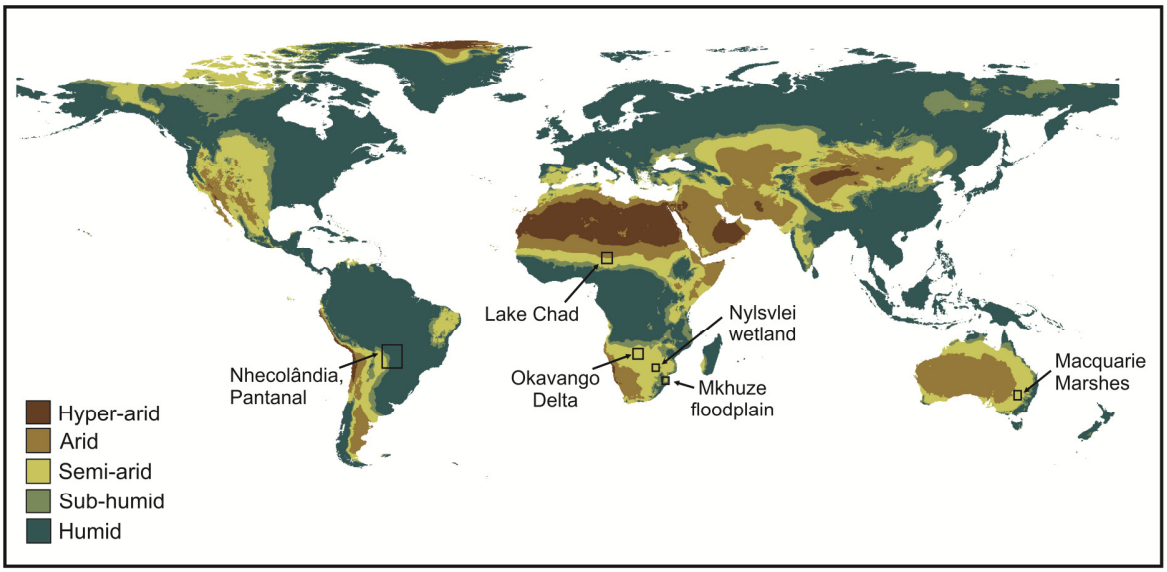

Fig. 2 Location of the wetland systems discussed in this paper and their relation to global climate zones. Climate classification based on United Nations Environmental Programme (UNEP) aridity index data and represents average yearly precipitation divided by average yearly potential evapotranspiration

Chemical precipitation under evaporative concentration

The progressive removal of water by evaporation causes solutes to increase in concentration ultimately to the point of saturation, resulting in mineral precipitation from solution. The evolution of water chemistry and the precipitation of minerals as a result of evaporation was originally studied by Hardie and Eugster (1970) who examined the evolution of surface water brines within closed basins. Saline lakes range from small ephemeral ponds to large perennial brine bodies and possess a remarkable variety of compositions and concentration ranges (Eugster and Hardie 1978). The chemical evolution of surface water bodies through evaporation was recognised to be largely determined by the chemical composition of the inflowing water, with the precipitation of a mineral phase having a profound effect on the subsequent evolution of the remaining brine. Subtle differences in the ratios of ions were shown to have profound effects on the final products of prolonged evaporation. This is shown in the evolutionary scheme of Eugster and Hardie (1978) and treats the chemistry of water undergoing

evaporation as a series of chemical divides (Fig. 3). A chemical divide is a critical branching point in brine evolution in which precipitation of a mineral depletes the water in certain cations and anions, causing further evaporation to move the solution along a distinct pathway. Variations in the relative proportions of Ca, Mg and bicarbonate are particularly influential in determining the initial chemical pathway followed.

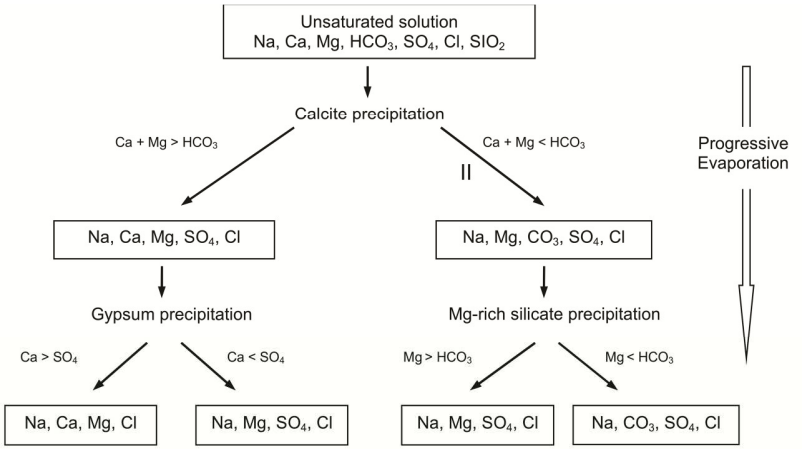

Fig. 3 The Hardie-Eugster model for the evolution of natural waters by evaporative concentration (based on milliequivalents of solute per litre, meq L^{-1}). Adapted from Drever (1997)

In most natural waters, $CaCO_3$ (calcite) is the first mineral to precipitate. The proportions of Ca + Mg and HCO_3 in the dilute parent solution then determine the subsequent evaporation pathway. If Ca + Mg are enriched relative to HCO_3, then the brine will follow pathway I after the initial $CaCO_3$ precipitation divide. Further evaporation of this type of brine will lead to gypsum ($CaSO_4$) precipitation because HCO_3 is consumed, leaving an excess of Ca. If HCO_3 is more abundant than Ca, brine evolution will follow pathway II. In this path, excess HCO_3 may combine with Mg and Na to produce a variety of carbonate-sulfate evaporite minerals. The precipitation of Mg-rich silicate (e.g., smectite or sepiolite) presents a second divide along this evolutionary pathway.

Although this model is clearly an oversimplification of complex sedimentary and geochemical processes, it nevertheless provides the underpinning for understanding chemical sedimentation in wetlands. The minerals deposited will largely be dependent on the chemistry of the water flowing into the wetland, no matter how dilute it may be, and the degree to which evaporative concentration proceeds.

Evapotranspiration-driven solute retention in wetlands

While an explanation for the chemical evolution of water under evaporative conditions and accumulation of mineral precipitates in closed-basins and playa-type lakes was described as early as 1970, pioneering efforts conducted in the Okavango Delta during the 1990s first drew attention to the potential importance of these processes for freshwater wetland systems. In particular, research in the Okavango Delta highlighted the vast quantity of solutes that may be retained within wetlands and the crucial role that shallow groundwater-vegetation interactions can play in creating sinks for the accumulation of solutes in the landscape.

Shallow groundwater is an important source of water for wetland vegetation, particularly during seasonal or episodic dry periods (Cooper et al. 2006; Sanderson and Cooper 2008). The transpiration of groundwater by plants is thus an important mechanism through which wetlands can lose water. Water can also move upward from the water table to relatively drier soil surface layers through capillary action. Quantifying the relative contribution of these fluxes is difficult and the term evapotranspiration is typically used to refer to water lost to the atmosphere through the combination of surface evaporation, capillary rise and plant transpiration. Although upward fluxes of groundwater into the root zone depend on many factors, including vegetation type, water table depth, soil hydraulic properties and atmospheric water demand, evapotranspiration is often the primary mechanism of water loss from dryland wetlands (Shah et al. 2007; Luo and Sophocleous 2010). Evapotranspiration can thus be a major control on the solute budget in these landscapes.

The Okavango research highlighted the importance of the relative proportions of evaporation versus transpiration. Evaporation in wetland settings leads to enrichment of dissolved solutes in surface waters, whereas transpiration leads to enrichment of solutes in the groundwater. If transpiration greatly exceeds evaporation then surface waters will remain fresh, while solutes will accumulate in the groundwater. The accumulation of solutes in surface water leads to salinization and is detrimental to aquatic diversity. In contrast, accumulation of salts in groundwater has a lower impact and this impact is further reduced by leaching of saline groundwater by infiltrating rainfall.

A key difference between wetlands in humid environments and those in arid environments relates to solute accumulation (Fig. 1). The most soluble constituents in natural waters are sodium, chloride, and

under certain circumstances carbonate and sulfate, which although not toxic in themselves, at high concentrations lead to osmotic stress and death through dehydration for most terrestrial plant species. If solutes accumulate in surface water the lifespan of a freshwater wetland will be very short and it will evolve into a saline lake. In contrast, accumulation in the groundwater creates opportunities for flushing and therefore prolonged wetland existence. Sodium and the other ions mentioned above may form a small component of the initial inflow into the wetland, but prolonged water loss by evapotranspiration will lead to the precipitation of less soluble salts and ultimately the formation of sodium-rich brines, as illustrated in Fig. 3. An important characteristic of the chemistry of wetland source water is the relative proportions of bicarbonate, chloride and sulfate. Excess bicarbonate results in the removal of many cations in the form of insoluble carbonates. However, if chloride is in excess, these cations form highly soluble chlorides and total salinity rises dramatically.

In the following sections, we draw on studies of wetlands in drylands to illustrate the manner in which feedback loops enable wetlands to accommodate the accumulation of solutes.

Okavango Delta, Botswana

The Okavango Delta remains the best described wetland system from a chemical sedimentation perspective and represents the clearest example of the fundamental role that chemical sedimentation can have on wetland structure and function. The Delta is a large (40,000 km^2) alluvial fan situated in a fault-bounded depression in semi-arid Botswana (Fig. 2). The fan receives water and sediment primarily via the Okavango River, which arises in the highlands of central Angola. Rainfall in the catchment averages approximately 1000 mm yr^{-1} and peaks in the late austral summer (January to March; Wilson and Dincer 1976). Rainfall over the Delta averages about 550 mm yr^{-1}. In the upper reaches of the Delta, the Okavango River is confined in a narrow (<12 km) depression known as the Panhandle, but divides into several distributary channels farther downstream on the edge of the graben, forming a large, gently sloping alluvial fan. The Okavango River discharges on average about 11×10^9 m^3 of water onto the fan each year, sustaining ~6000 km^2 of permanent swamp and up to 8000 km^2 of seasonal wetland (J. McCarthy et al. 2003). Water discharging onto fan rapidly infiltrates into the sandy soils and progress of the flood wave across the fan is slow, taking 4 – 5 months to reach the southern end of the Delta. Annual evaporation is three to four times rainfall and ~96% of the water that enters the Delta each year is lost to the atmosphere by evapotranspiration (Wilson and Dincer 1976; McCarthy 2013).

The catchment of the Okavango River is situated almost entirely on aeolian Kalahari sediments and fluvial sediment entering the Delta consists mainly of fine sand, transported primarily as bedload (McCarthy et al. 1991). The annual flux of bedload to the Delta is estimated to be about 170,000 t (McCarthy and Ellery 1998) with ~95% of this material deposited in the anastomosed reach of the Panhandle (McCarthy et al., 1991). Relatively little alluvial sediment is introduced onto the distal seasonally flooded areas of the fan and floodplain soils consist predominantly of fine quartz with minor clay minerals (McCarthy and Ellery 1995). Despite carrying a very low solute load (~40 mg L^{-1}), the large quantity of water transported by the Okavango River results in an estimated 360,000 t of solute being delivered to the Delta each year (McCarthy et al. 1998). The solute load is dominated by silica, and calcium and magnesium bicarbonates, whereas chloride and sulfate make up a very small proportion of the solute load. Even though most of the water that enters the Okavango is lost to the atmosphere, surface water in the Delta remains remarkably fresh and the development of saline brines is rare.

Fresh surface water conditions in the Delta are maintained through interactions and feedbacks between wetland vegetation, groundwater and microtopography. The topography of the fan surface is gently undulating, creating numerous irregularly-shaped islands that seldom rise more than 1 m above the surrounding swamp (Fig. 4a). While relatively few islands occur in the permanent swamps, they form an important component of the seasonal swamp where they vary in size from a few square metres in area to several thousand square metres (Gumbricht et al. 2004). Islands on the Okavango fan have been studied in detail and are considered to either represent abandoned channels or originate through termite activity (Ellery et al. 1993; McCarthy et al. 1998; 2012). These raised patches remain elevated above the surrounding swamp water level and support vegetation intolerant of flooding. Large trees on the fan are almost exclusively confined to islands and transpiration by deep-rooted woody species (e.g., *Ficus sycomorus* and *Acacia nigrescens*) plays an important role in lowering the water table beneath islands. This draw-down creates a hydraulic head, resulting in a net inflow of groundwater from the surrounding swamp to the islands (McCarthy et al. 1993). Plants selectively exclude salts when taking up water and transpiration thus leads to an increase in dissolved solute concentrations in the root zone. This results in the build-up of salinity in the groundwater beneath islands. Increasing solute concentration results in saturation and subsurface precipitation of silica and magnesian-calcite. This process has the effect of removing dissolved silica, calcium and magnesium from the water, leaving only sodium bicarbonate remaining in solution. The precipitation of minerals causes swelling resulting in a raised rim around the edges of islands. Although sodium bicarbonate is extremely soluble, capillary rise

draws saline groundwater to the surface where it evaporates, leaving behind efflorescent carbonate salt crusts on the surface of islands. Over time, island interiors become extensively salinized, creating barren centres (Fig. 4a). An increase in solute concentration beneath islands produces marked variations in vegetation composition that reflect tolerance to salinity (Ellery et al. 1993). Evergreen tree species are typically found on the outer fringes of islands, whereas grasses interspersed with sodium carbonate-encrusted bare soil dominate the island interiors. Ultimately, the salinity of the groundwater beneath the cores of islands rises to the point where density-driven subsidence occurs (Fig. 4b; McCarthy et al. 1991; Gieske 1996; McCarthy 2006; Bauer-Gottwein et al. 2007). The plumes meld with extremely saline groundwater which underlies the Okavango region as revealed by geophysical studies (Bauer-Gottwein et al. 2007). Islands, therefore, become sinks for groundwater solutes and play a fundamental role in maintaining the low salinity in surface water in the Okavango wetland (McCarthy 2006; Ramberg and Wolski 2008). These processes result in marked salinity gradients from island fringes to the interior. Groundwater around the fringes of islands may have conductivity as low as 0.05 mS cm^{-1}, which rises to 30 mS cm^{-1} over a lateral distance of typically not more than 100 m (McCarthy et al. 2006). Conductivities in excess of 30 mS cm^{-1} are rare suggesting this represents a cap which is maintaining by gravity-driven advection.

Chemical precipitation constitutes a major sedimentary process on the fan. Approximately 85% of the solute load is precipitated as amorphous silica and calcium carbonate, causing swelling and islands to grow. Over time, islands slowly enlarge and eventually start to coalesce, leading to a diverse range of island shapes and sizes (Gumbricht et al. 2004). Mineral volume calculations suggest that precipitated silica and magnesian calcite together account for ~30 – 40% of the volume of typical islands in the seasonal swamps (McCarthy et al. 2012), although this contribution is likely to vary depending on the size of the island and its stage of development. The implications of island formation and growth for ecosystem structure have been well documented (Ellery et al. 1993; Dangerfield et al. 1998; Ellery et al. 2000). Islands are the main source of habitat diversity on the Okavango fan. Not only do islands provide sites for the establishment of large woody plant species which are unable to grow on the surrounding floodplains, but also act as sites for the accumulation of nutrient-rich dust (Humphries et al. 2020). The entrapment of dust is facilitated by the interruption of airflow by trees and can amount as much as 60% of the volume of islands (Humphries et al. 2014).

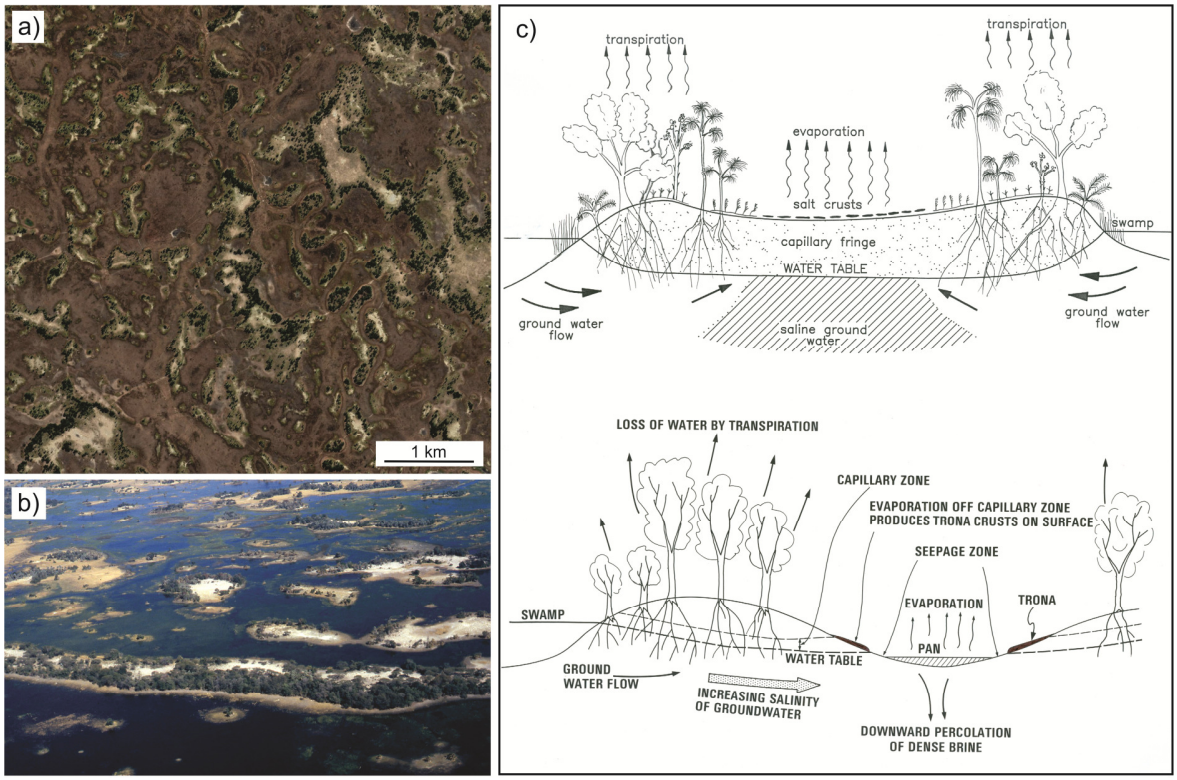

Fig. 4 a) Google Earth image of islands located the seasonal swamps of the Okavango Delta, b) aerial photo showing the tree fringe and barren interiors that characterise islands, and c) Schematic cross-section of an island illustrating the hydrogeochemical processes that contribute to observed variations in groundwater and soil chemistry.

The salinity of the inflow is 40 mg L^{-1} whereas the outflow contains ~80 mg L^{-1} despite the fact that 96% of the water that enters the Delta is lost to evapotranspiration each year. Saline surface water is extremely rare in the wetland. These figures underscore the difficulties of establishing salt and water balances in wetlands in semi-arid environments. It is often tempting to balance the water budget by inflating the proportion of water lost from the system to groundwater infiltration. In the case of the Okavango, there is evidence to indicate that large scale groundwater outflow from the Okavango Basin does not occur (McCarthy 2013).

Lake Chad, central Africa

Lake Chad is located in a large tectonic depression in the centre of West Africa (Burke and Gunnell 2008). The lake occupies some 20,000 km^2. It is fed by two main rivers, the Chari and the Logone, which

arise in the highlands along the south-eastern margin of the basin where rainfall exceeds 1600 mm yr^{-1}. The rivers drain granitic rock and contain less than 100 mg L^{-1} of dissolved solids in which Ca, Mg, HCO_3 and SiO_2 make up ~90% of the total solute load (Gac et al. 1977). Rainfall over Lake Chad is 300 mm yr^{-1} and evaporation exceeds 2,200 mm yr^{-1}. The northern part of the lake borders on the Sahara Desert with mean temperatures of over 30 °C and annual precipitation as low as 17.5 mm. An extensive barchanoid dune field forms the northern shore of the lake (Fig. 5a).

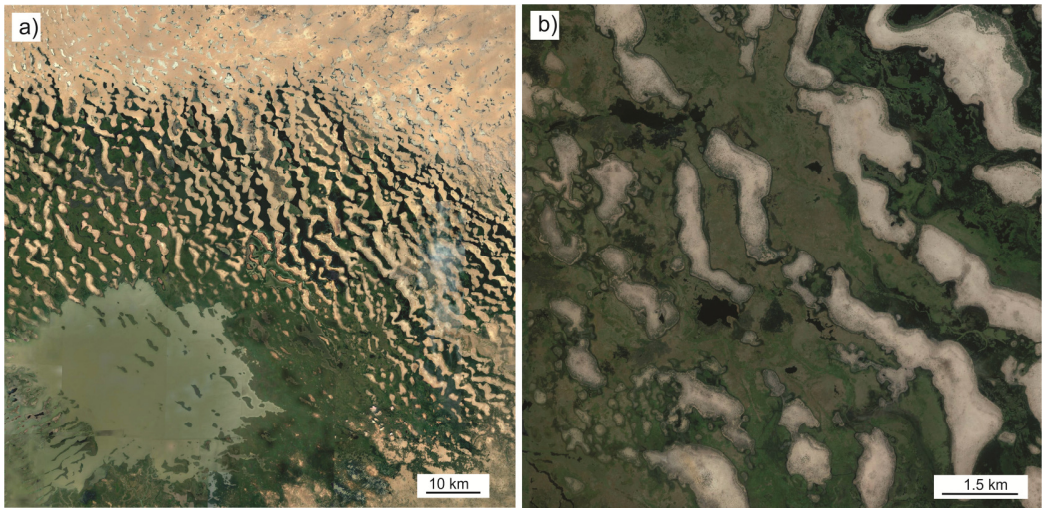

Fig. 5 a) A wide-field view of the dune field along the north-eastern shore line of Lake Chad, and b) close up view showing the various amoeboid island forms in the archipelago.

Along the north-eastern shore, lake waters have flooded the dune field creating a vast archipelago of elongated islands and submerged sand banks, oriented in a NW-SE direction (Fig. 5a). The dunes consist of quartz sand, while the depressions are covered by a veneer of clays and carbonates. The levels of the interdunal lakes near the shore of Lake Chad respond to the annual rise and fall of the lake, which can be as much as 1 m (Eugster and Maglione, 1979). Although the lake has no visible outlet and surface evaporation is intense, the lake water remains fresh. However, water that collects in shallow depressions between the dunes and in depressions on low sand dunes is saline and takes the form of playa lakes, which are covered by efflorescent crusts consisting mainly of trona ($Na_3H(CO_3)_2.2H_2O$; Eugster and Maglione, 1979). Trona makes up ~20% of the solute load, the bulk consisting of SiO_2, $CaCO_3$ and $MgCO_3$. The precipitation of trona has therefore been preceded by a significant quantify of silica, magnesian-calcite and magnesian silicate (Gac et al. 1978). The form of islands in the archipelago suggests that they have been significantly modified by the subsurface precipitation of solutes, leading to

various amoeboid forms (Fig. 5b) reminiscent of those described by Gumbricht et al. (2004) in the Okavango Delta. Like those in the Okavango, the islands in the archipelago are fringed by trees, whereas the interiors are largely devoid of vegetation (Fig. 5b).

A playa-lake developed on an island near the north shore described by Eugster and Maglione (1979) showed remarkable subsurface groundwater salinity gradients. On the lake shoreline of the island, the water was fresh enough to drink, while near the centre some 200 m away, it contained over 3000 g L^{-1} TDS and had a pH of 10.3. This gradient is maintained by intense capillary evaporation, which produced thick crusts of trona surrounding the playa-lake. A similar situation was described in a small playa-lake on an island in the Okavango Delta by McCarthy et al. (1991) and subsequently studied using geoelectrical imaging by Bauer et al. (2006). Bauer et al.'s results showed that dense surface brines formed by evapotranspiration were subsiding in form of high density brine fingers into a deeper saline aquifer (Fig. 4b). A similar process may be taking place in the Lake Chad region.

Nhecolândia, Brazil

The Nhecolândia (27,000 km^2, Fig. 1) is a large sub-region of the Pantanal located on the south-eastern portion of the Taquari River megafan. The wetland is an active alluvial plain, partially inundated by seasonal flooding (November to March). Although the prevailing climate is dominantly humid, mean annual evapotranspiration (1400 mm) exceeds mean annual rainfall (1100 mm), resulting in a small regional hydrological deficit of 300 mm (Por 1995). Examination of the drainage system of Nhecolândia indicates that it is largely disconnected from the Taquari River system in the north-west, but discharges into the Negro River in the south-east and south. The drainage appears to be primarily fed by runoff and groundwater seepage. The soils consist of quartz sand with minor silt and generally have a high permeability, although certain horizons are relatively impervious and may act as aquitards (silcrete and green sandy loam layers; Barbiero et al. 2002). Surface water has very low salinity with TDS of about 110 mg L^{-1} (Barbiero et al. 2002) and is dominated by calcium, bicarbonate and silica, with minor sodium and potassium.

A distinctive feature of the Nhecolândia landscape is the presence of numerous shallow lakes (Fig. 6a). The majority (~7000 in number) of these are freshwater lakes (locally called "baías"), with the remainder (~1500) being alkaline-saline lakes (locally called "salinas"). The salinas are surrounded by vegetated

sandy ridges (locally called ''cordilheiras''), whereas the baías are depressions hydrologically linked to the grasslands and the regional drainage system (Fig. 6b). Salinas are topographically closed and remain isolated during flooding during the wet season, whereas the grasslands become inundated during the seasonal flood (Guerreiro et al. 2018). In the rainy season, the water levels in the baías rise and they may connect with the flooded grassland. However they frequently desiccate fully in the dry season (de Santos et al. 2012). Baías are characterised by moderate pH values (5 – 8), low electrical conductivity (<2 mS cm^{-1}) and are covered by macrophytes (Barbiero et al. 2002; Bergier et al. 2014). In contrast, salinas rarely desiccate completely in the dry season, have pH values ranging from 9 – 10.5, electrical conductivity values from 4 to 65 mS cm^{-1}, and are devoid of aquatic macrophytes (Guerreiro et al., 2018). Although the origin of the lakes remains debated, they are thought to be the products of wind deflation during an extremely arid period in the early to middle Holocene (McGlue et al. 2017).

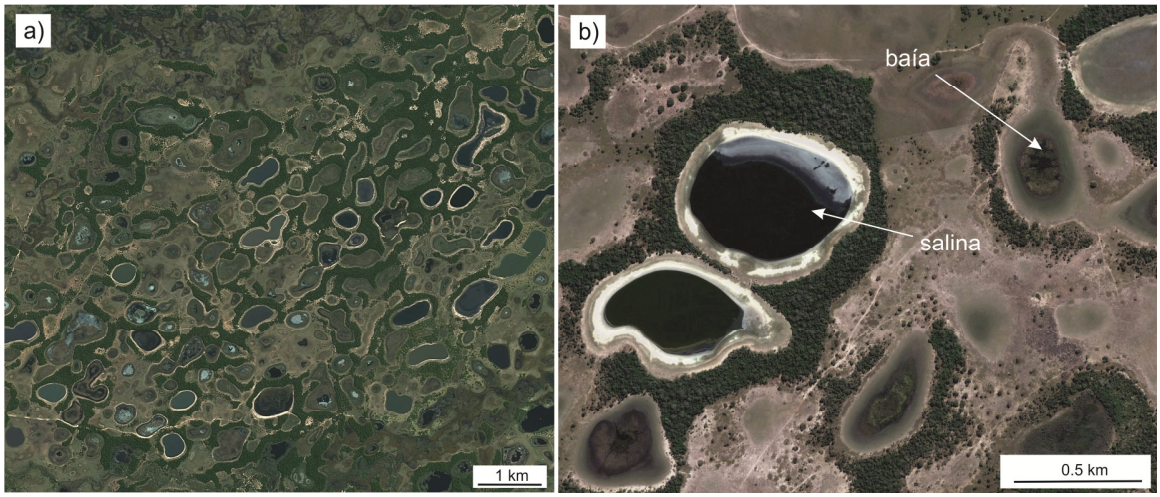

Fig. 6 a) A wide-field view of the Nhecolândia terrain, and b) close up view showing salinas surrounded by forested cordilheiras rising between 2 and 6 m above the floodplains, which are connected to baías.

The large variability in surface water chemistry is believed to result from the evaporation of surface water and the capillary fringe surrounding the salinas, which promotes the precipitation of authigenic mineral phases, including Mg-calcite, Mg-smectites and micas (Barbiero et al. 2002; Barbiero et al. 2008; Furquim et al. 2010; Furian et al. 2013). Evapoconcentration is thus an important process that drives transformations in the clay mineral assemblage and alters the permeability of subsurface soils around the lakes. Paleoecological studies suggest that saline lakes evolve from freshwater precursors, a process that appears to be driven by climatic controls on water chemistry (Guerreiro et al. 2018). The formation

of shallow chemically-cemented sediments restricts subsurface drainage and renders evaporation the sole mechanism through which water can leave the lake basin (Furian et al. 2013). Over time, this process is believed that have resulted in the diversified lake ecosystems that characterise the Nhecolândia landscape.

Although much has been written about the effect of evaporation as the determining factor in the development of the saline lakes in Nhecolândia, the moisture deficit is extremely small and unlikely to have caused evaporative conditions as postulated. Apparently, no consideration has been given to the powerful effect of transpiration by trees in lowering groundwater levels and thus establishing groundwater hydraulic gradients (e.g., McCarthy and Ellery 1994; Blight 2003; Tóth et al. 2014). We suggest that the available water chemistry data for the salinas and their local environment is more consistent with a lowering of the water table by the surrounding forest vegetation, resulting in a net flux of groundwater from the regularly replenished floodplains to the sinks provided by the salinas. Precipitation of minerals, particularly calcium carbonate and silica, leads to soil expansion, creating the elevated ridges surrounding the salinas. We are of the opinion that the Nhecolândia wetland is a site of extensive chemical sedimentation, similar to that observed on the floodplains of the Okavango.

Macquarie Marshes, Australia

The Macquarie Marshes are located towards the distal end of the Macquarie River Basin. The river arises in the Great Dividing Range with rainfall up to 1000 mm yr^{-1} and then flows north-westwards to the Macquarie Marshes where the average annual rainfall is ~400 mm (Hesse et al. 2018). Mean annual evaporation is ~1,800 mm, exceeding precipitation by a factor of around four (Kingsford and Auld 2005). The Macquarie River is characterised by perennial, although highly variable discharge (Ralph and Hesse 2010). Like many dryland river systems, discharge decreases downstream, accompanied by a reduction in channel dimensions, leading to the eventual cessation of channelised flow and the formation of floodouts and wetlands. The Macquarie River is prone to periodic massive floods in which suspended load is widely distributed across the floodplain. This sediment, which consists mainly of silt and clay, tends to dominate the clastic material in the marshes (Ralph et al. 2016) .

Ralph and Hesse (2010) suggest that 85% of inflow is lost across the marshes. Tim Hosking of the local Macquarie Water Authority suggested a figure as high as 90% (*pers. comm*. to TSM 2017). However,

water conductivity measurements reported by Kobayashi et al. (2011) show that salinity rises by only ~40% (220 to 360 mg L^{-1}), which implies an evaporative loss of about 40% of the water in the main channel system. Evaporation loss in the distributary channels is not recorded in the main channel measurements because these remain isolated. Combined discharge and salinity data imply that somewhere between 75 and 80% of the solutes entering the Macquarie wetland are lost in the marshes. Water is lost by evapotranspiration but the solutes are unaccounted for. Analyses of samples of "deep" ground water (80 to 100 m below surface) indicate that this water is extremely saline (TDS > 30,000 mg L^{-1}; Hollins et al. 2009) and may be fed by salt-enriched waters from the wetland above.

The streams in the Macquarie Marshes terminate in dendritic arrays of distributary channels separated by distinctive geomorphic features, known as 'gilgai' mounds. These mounds are highly variable in terms of their spatial density, distribution and morphology (Fig. 7a). Mounds range in size from a few meters to more than 50 m, and are associated with low relief, seldom rising more than 50 cm above the surrounding floodplain. Some mounds are fully vegetated by grasses and woody shrub species, while others are characterised by distinct rings of woody vegetation around their margins with bare or sparsely vegetated centres (Fig. 7a). The origin of gilgai has long been speculated upon (e.g., Dixon 2009). The majority of models attribute the origin to the very pronounced shrink-swell behaviour of the soils in the distal regions of the wetland. It is believed that cracks become filled with material derived from the surrounding areas during the dry periods. When the soil expands during the wet season, they heave upwards to form mounds.

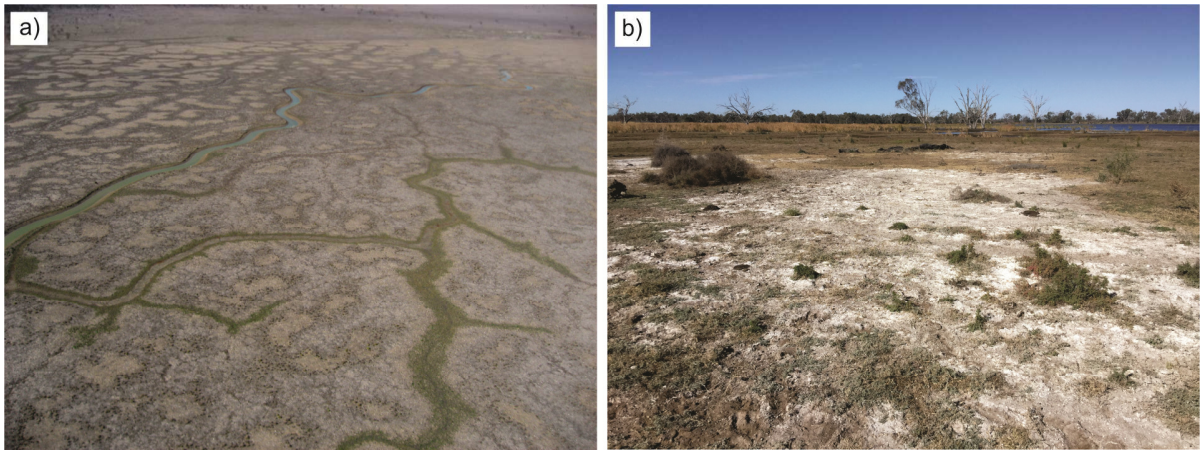

Fig. 7 a) Aerial view of distributary channels discharging into gilgai terrain, and b) efflorescent salt crusts in gilgai terrain

In contrast, recent geochemical investigations have revealed that mounds on the Macquarie floodplain are associated with chemical sedimentation. Helander (2021) carried out physical, mineralogical and geochemical studies on cores collected along a traverse across a large gilgai mound. Sediment porewater beneath the centre of the mound was saline with concentrations up to 25 times relative to porewater beneath inter-mound depressions. Capillary rise of the saline water, followed by evaporation, leads to the development of saline surface crusts which are frequently encountered in the gilgai (Fig. 7b). Localised solute accumulation beneath mounds leads to the precipitation of calcite ($CaCO_3$) and gypsum ($CaSO_4$), with preliminary estimates suggesting that chemical precipitates may account for up to 15% of the sediment mass beneath mounds (Helander 2021). The focussing of solutes beneath mounds appears to be driven by evapotranspiration, likely resulting from the upward movement of water through capillary action, followed by surface evaporation, as well as by transpiration by vegetation. While the influence of chemical sedimentation on mound formation and growth in the Macquarie Marshes is yet to be fully investigated, initial observations suggest that mineral precipitation could be a significant factor driving changes in wetland micro-topography and vegetation distribution.

While solute build-up beneath gilgai mounds appears to occur as a result of similar evapotranspiration processes that characterise Okavango islands, there are important differences. In the Okavango, groundwater from the surrounding swamp moves towards the island centre as a result of hydraulic gradients induced by transpiration losses from woody species growing around the island margin. By contrast, in the Macquarie wetlands, silt-rich floodplain sediments limit the infiltration of surface floodwaters, with plants probably accessing water rising under capillary action. It is likely that plants growing on islands consisting of clay-rich sediment create negative porewater pressure within the mound which draws water from the surrounding, more saturated sediment, unlike the Okavango where groundwater flows under the influence of a hydraulic head.

Nylsvlei wetland, South Africa

The Nyl River arises in the Waterberg Range in central South Africa. Rainfall averages about 450 mm yr^{-1}. The tributary streams carry a mixed sediment load consisting of fine gravel, coarse sand, silt and mud, but the sediment calibre decreases downstream so that only silt and mud deposit on the floodplain (McCarthy et al. 2011). The Nyl floodplain is unusual in that it acts as a localised sedimentary basin and very little of the clastic sediment delivered to the floodplain leaves the surface (Tooth et al. 2002;

McCarthy et al. 2011). The floodplain is prone to periodic extensive sheet-flooding. The upper mud-rich sedimentary layer has a very low permeability, but is underlain by more sandy deposits that form an aquifer which is locally artesian.

The floodplain consists of a flat, grass-covered plain dotted with islands, which rise 30-40 cm. The islands typically have barren centres with a ring of trees around the outer fringe (Fig. 8a). Soil geochemical studies have indicated that the porewater in the centres of islands is very saline (Fig. 8b). Soil chloride concentrations exceed 2000 ppm (Tooth et al. 2002), which translates into 2% chloride in the porewater (assuming 10% water content), approximately the same as sea water. This high salinity is evidently responsibly for the absence of vegetation on island centres. Studies revealed the presence of $CaCO_3$ accumulations within island soils (up to ~12%) but not obviously linked to island topography. Nevertheless, it is clear from the accumulation of chloride that islands are the focus of some form of chemical sedimentation.

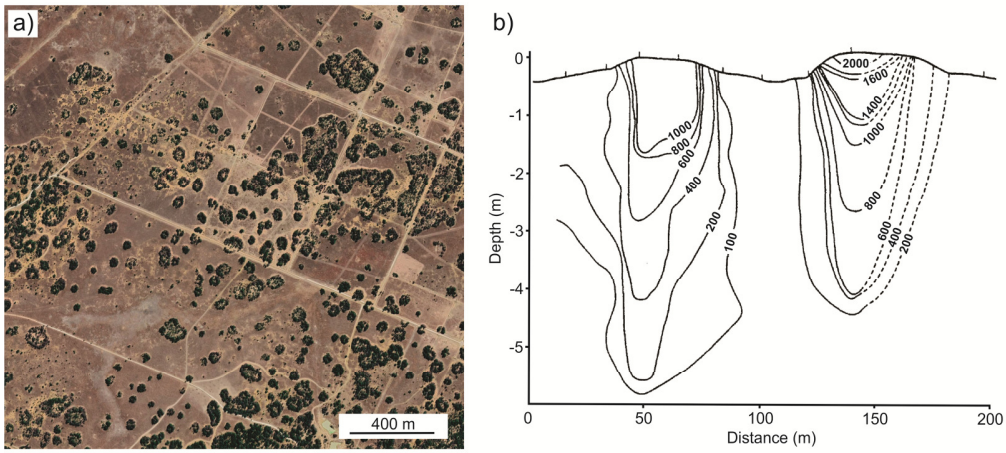

Fig. 8 a) Portion of the Nyl River floodplain grassland dotted showing islands characterised by a ring of trees with a relatively barren interior, b) Isopleth map showing the variation in chloride content (ppm) of subsurface soils (Tooth et al. 2002).

Mkhuze Wetland System, South Africa

The Mkhuze River floodplain in eastern South Africa (Fig. 2) provides a good example of vegetation-induced chemical sedimentation. The lower reaches of the floodplain are associated with an extensive (450 km^2) freshwater wetland system that consists of a variety of different wetland types ranging from

seasonally flooded swamps and riparian floodplains to permanent wetlands and shallow lakes (Ellery et al. 2012). Inflow from the Mkhuze River represents the primary hydrological input into the wetland system, but annual discharge is highly variable, ranging from 200 to 326 x 10^6 m^3 (Stormanns 1987). The climate is dominantly sub-humid with rainfall varying between 600 and 1000 mm yr^{-1}. Most rainfall occurs during the summer months (Nov – Feb) and heavy rainfall events cause the Mkhuze River to overtop its banks and inundate the floodplain. Overbank flooding of the Mkhuze River is the primary input of clastic sediment onto the silt-dominated floodplain, with flood waters recharging floodplain lakes and local groundwater. Transmission losses through channel banks also play an important role in recharging local groundwater and losses to groundwater result in marked reductions in downstream channel dimensions (Humphries et al. 2010b). During drier periods, the Mkhuze River is characterised by low to no flow and the floodplain is prone to prolonged periods of desiccation. Annual evaporation is high (~1800 mm) and, together with transpiration losses, results in a large annual moisture deficit (Schulze 1997).

Mkhuze River water is characterised by TDS typically around 400 mg L^{-1}, about half of which consists of sodium, chloride and bicarbonate, with silica, calcium and magnesium constituting about 25% of the total. Electrical conductivity is typically about 0.7 mS cm^{-1}. Variable surface inflow and high evapotranspiration rates result in saline groundwater with conductivities exceeding 20 mS cm^{-1} on the Mkhuze floodplain (Humphries et al., 2011a). Isotopic data indicate that transpiration predominates over evaporation (Humphries et al. 2011a) and large, deep-rooted riparian trees (*Acacia xanthophloea*) appear to be particularly effective in drawing down the water table and concentrating solutes in the groundwater (Fig. 9a; Humphries et al. 2011b). The lowering of the water table adjacent to the Mkhuze River can exceed 2 m. The clay-rich floodplain sediments retard lateral recharge and therefore promote enrichment of solutes in the groundwater. Progressive solute enrichment causes sediment porewaters to become saturated in various solutes, leading to the precipitation of Mg-calcite and silica-bearing phases such as amorphous silica and Fe-smectite (Humphries et al. 2010a). In areas of significant chemical accumulation, concentrations of up to 13% $CaCO_3$ and 15% Fe-smectite may be found (Humphries et al. 2010a). Isolated floodplain lakes are also important sites for solute precipitation and are associated with extensive $CaCO_3$ accumulations (Humphries et al. 2019).

Marked groundwater salinity gradients (30-fold increase in salinity over a horizontal distance of ~200 m) result in distinct vegetation zonation on the floodplain. Grassland, scattered palms and microphyllous

savanna characterise much of the floodplain, while areas of chemical sedimentation are dominated by large *Acacia xanthophloea* (Fig. 9b) with a limited understory. Variations in groundwater chemical composition and geochemical modelling suggest that mineral precipitation is spatially extensive on the Mkhuze River floodplain (Humphries et al. 2011a).

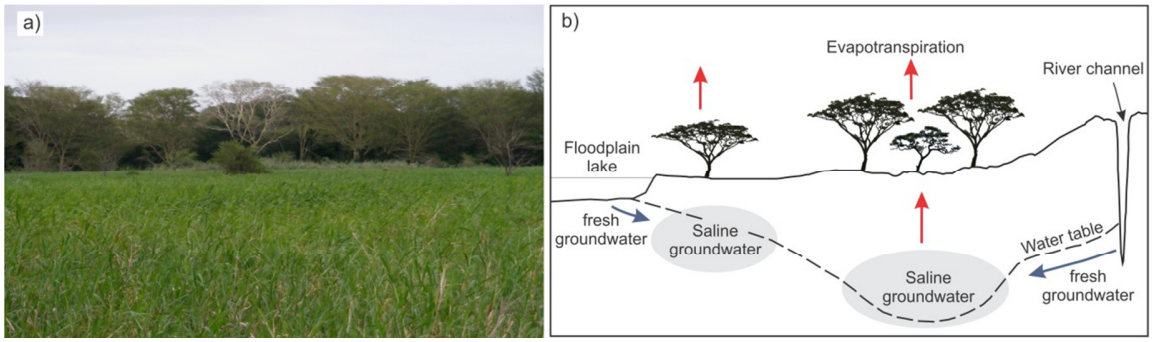

Fig. 9 a) Band of *Acacia xanthophloea* on the Mkhuze River floodplain associated with chemical sedimentation, and b) schematic cross-section of the floodplain illustrating the hydrogeochemical processes that contribute to observed variations in groundwater and soil chemistry.

Controls on chemical sedimentation

The case studies presented in this paper demonstrate that chemical precipitation driven by evapotranspiration can be a major mechanism driving solute accumulation in dryland wetlands thereby influencing the physiography. These examples also illustrate the diverse geomorphic settings under which chemical sedimentation takes place. In all cases, evapotranspiration strongly influences hydrology and is the principal driver of chemical sedimentation. It is extremely important to differentiate between evaporation and transpiration. Evaporation causes enrichment of solutes in surface water, whereas transpiration causes enrichment in groundwater. The latter is therefore far less obvious than the former and can go completely undetected as has probably happened in the studies of Nhecolândia and Lake Chad. Transpiration of groundwater, especially by trees, is invariably accompanied by precipitation of relatively insoluble components, such as silica and magnesian-calcite in the root zone, which causes expansion of the soil, creating topographic effects as have been well-documented in the case of the Okavango. These substances are benign and have no impact on the vegetation. The process also modifies pre-existing topographic features such as the dunes in the archipelago on the north-eastern shore of Lake Chad accentuating low relief basin-and-swell topography. We are of the opinion that gilgai

is a similar topographic expression of chemical sedimentation, although the exact nature of the processes involved has not yet been established.

Subsurface precipitation can produce islands with raised toroidal rims and internal depressions (e.g., Okavango and possibly Nhecolândia). Trees growing around the rim cause a depression in the water table beneath the island, resulting in centripetal flow and focussing the saline groundwater toward the centre of the island. This process causes very marked lateral gradients in groundwater salinity, typically up to three orders of magnitude increase in conductivity (from 0.05 to 50 mS cm^{-1}) over a lateral distance of a few tens of metres. Groundwater beneath the raised rim is fresh, whereas that beneath the central depression can be extremely saline. The accumulation of saline groundwater beneath the depression impacts on the vegetation and eventually causes vegetation zonation, usually with only grasses or bare soil surviving in the very saline soils of the island centre. Capillary rise brings saline groundwater to surface where it evaporates producing surface crusts of soluble salts such as sodium carbonates and sodium chloride. These are leached back into the soil during rain storms, only to be returned to surface later. This process results in further increase in salinity in the shallow groundwater which is accompanied by an increase in density. Ultimately density-driven plumes of saline water descend from beneath the island centre into the deeper groundwater (Gieske 1996; Bauer-Gottwein et al. 2007). This process seems to limit the maximum salinity to about 20 mS cm^{-1} (McCarthy et al. 1993). Seasonal flooding will cause a rise in the general water table and the depressions in the interior of islands may form transient saline lakes. The process of chemical sedimentation results in the localisation of salt accumulation, so that water in the bulk of the wetland remains fresh notwithstanding the very high evapotranspirational water loss. In cases where evaporation is in excess of transpiration, surface water becomes salinized and the end result is a saline lake.

As a general rule, if the salinities of the inflow and outflow water of a wetland are known and the respective discharges are also known, then the proportion of water loss by evapotranspiration and groundwater outflow can be calculated as can the total amount of solutes lost. These solutes were either carried out in groundwater or were precipitated in the wetland, or both. For example, in the Macquarie Marshes between 75 – 80% of the solutes entering the wetland are unaccounted for. It is for this reason that we surmise that chemical sedimentation may play an important role in the geomorphology of the Marshes and perhaps gilgai is a surface expression of this process.

Most large wetlands in dryland environments can only exist when connected to a river system, which supplies not only the majority of water, but also sediment and solutes. Lower ratios between precipitation and potential evapotranspiration as well as frequent periods of desiccation often result in solutes accumulating to high levels. The strength of this coupling and the development of salinity are dependent on the balance between evapotranspiration rates and frequency of recharge. The extent to which chemical processes play a role in the structure and function of wetlands thus varies between individual wetlands, but is observed to occur in both sandy (e.g., Okavango Delta and Nhecolândia) and silt-dominated (e.g., Mkhuze and Nyl floodplains and Macquarie Marshes) systems.

Similarities in the geochemical processes across the wide range of wetlands described here are in stark contrast with characteristics typical of wetlands from more humid settings. Many large, humid-region wetlands are perennial features, often remaining flooded or saturated throughout the year. Although river inflow may be an important hydrological input, these systems are often sustained by groundwater or local precipitation alone. Lower rates of evapotranspiration and regular inundation means that solutes do not accumulate but instead are leached from sediments. Groundwater concentration and chemical sedimentation processes are thus typically not important in these systems, as saturation and precipitation thresholds are not reached.

Broader implications of chemical sedimentation

Solute concentration and precipitation of minerals within wetlands has several important implications for ecosystem function, wetland management and potentially global climate. Over short timescales (decades) evapotranspirational water loss results in the localised development of saline groundwater. This creates a local chemical gradient which may influence vegetation distribution based on tolerance to variation in soil salinity and pH (e.g., Ellery et al. 2000). The concentration and immobilisation of solutes within subsurface soils also regulates water quality. In such cases, salinity build-up is mediated by the strong coupling between vegetation and groundwater dynamics, preventing the widespread salinization of surface soils.

Landscape salinisation is a common phenomenon in drylands and vegetation-soil salinity feedbacks thus have important implications for wetland management in these regions, notably Australia (e.g., Salama et al. 1999; Scanlon et al. 2007). Changes in vegetation cover can impact water quality by modifying the

partitioning between evaporation and transpiration, potentially mobilizing salts accumulated in subsurface soils. The lower Murray River floodplains of Australia provides an excellent example illustrating how changes in land use may adversely impact salinity dynamics in dryland wetlands. The widespread conversion of native vegetation (largely deep-rooted *Eucalyptus* species) to shallow-rooted crops resulted in a rise in the water table, causing the mobilisation of salts within the vadose zone (Allison et al. 1990; Lamontagne et al. 2005; Jolly et al. 2008). Prior to tree clearance, salts accumulated beneath the root zone, where they remained largely immobile and thus did not constrain plant productivity. Mobilisation of these salts was further exacerbated by river regulation, which reduced the frequency and duration of large floods, leading to less frequent leaching of accumulated salt in floodplain soils (Jolly et al. 1993). Land use change has resulted in similar salinization problems in the semi-arid regions of south-western USA (Scanlon et al. 2015) and northern Africa (Leduc et al. 2001). Studies on the Okavango Delta and Mkhuze floodplain highlight the important role that deep-rooted tree species can play in driving chemical sedimentation in wetlands. In these systems, trees provide a salt removal mechanism and changes in vegetation cover would likely induce changes in local hydrological conditions and the distribution of salt accumulation within the soil profile. In the same way, deforestation in the areas around salinas in the Nhecolândia may have serious detrimental effects on their long-term survival.

Although salinization is often viewed as a threat to freshwater wetlands, responsible for inducing physiological stress in wetland biota and disrupting ecosystem function (e.g., Herbert et al. 2015), it is often a natural process in dryland wetlands that has important implications for long-term structure and functioning of these systems. Over longer timescales (centuries to millennia) chemical sedimentation can result in changes to the chemical and physical properties of wetland sediments. Chemically cemented soils reduce hydraulic conductivity and alter hydrological flows. The precipitation of swelling clay minerals (e.g., smectite), as documented on the Mkhuze floodplain and in Nhecolândia lakes, is likely to be particularly influential on wetland ecohydrology. Localised chemical precipitation in soils may also lead to swelling and the creation of topographic relief, which influences the response of wetland vegetation to flooding and inundation. Although chemical accumulation may result in relatively small changes in local elevation, this can translate to large changes in duration of inundation and thus vegetation distribution. Tree islands on the Okavango Fan probably provide the best documented example of topographic relief development as a result of localised chemical accumulation. These raised patches of land also support plants and animals that would otherwise not exist within a relatively

homogenous landscape. In this way, chemical sedimentation can result in the autogenous development of habitat heterogeneity and contribute to the spatial complexity of wetland landscapes.

Dryland wetlands have a low capacity to sequester organic carbon due to extended periods of desiccation and oxidising soil conditions. Even when organic accumulation does occur (e.g., permanent swamps of the Okavango), these deposits are vulnerable to peat fires and thus do not represent a long-term carbon sink. The sequestration of inorganic carbon (in the form of carbonate) within dryland wetland soils may have significant implications for terrestrial carbon budgets. Carbonate precipitated in wetland soils is permanent and therefore represents a potential long-term carbon sink. Mass balance calculations indicate that ~127,000 t of $CaCO_3$ accumulate annually within the Okavango Delta alone (McCarthy and Ellery 1998). Although the capacity of dryland wetlands to sequester inorganic forms of carbon has been given little attention and is poorly quantified, this process could have potential feedbacks to global climate.

Conclusions and future research directions

Although the existing literature on chemical sedimentation in wetlands is geographically limited and restricted to a few individual case studies, it is clear that chemical sedimentation processes can play a key role in creating and maintaining the biological and habitat diversity of dryland wetlands. The case studies examined in this paper represent some of the most biodiverse wetland ecosystems on Earth and chemical sedimentation is likely a key process contributing to the spatial complexity and biodiversity of these systems. In all cases, evapotranspiration is thought to be the primary driver of solute accumulation. Transpiration can be a particularly important hydrological driver, strongly influencing groundwater chemistry and soil composition. However, there are other important controls that influence the occurrence and extent of chemical sedimentation, which remain less well understood. While not all dryland wetlands are likely predisposed to accumulating large quantities of solutes, these processes are yet to be assessed in many systems. One of the challenges on this front is that chemical sedimentation can be difficult to detect, particularly in clay-silt dominated systems. Wetlands are complex sedimentary environments and the identification of amorphous and silicate precipitates typically requires detailed mineralogical and geochemical analysis. Clay minerals, such as smectite, may have authigenic or detrital origins, potentially confounding interpretations. The extent of chemical

sedimentation in dryland wetlands thus remains poorly quantified on a global scale, but could be a common phenomenon, particularly in wetlands fed by large distributary fluvial systems.

Even when there is clear evidence of chemical sedimentation, determining the rate at which solutes accumulate in wetland soils is difficult. Calculated age estimates for two islands in the seasonal swamps of the Okavango Delta suggest that these features are the products of long-term aggradation processes (on the order of 10,000 – 100,000 years), with $CaCO_3$ accumulation rates beneath individual islands ranging between 100 and 2500 kg yr^{-1} (McCarthy et al. 2012). However, accumulation rates are likely to be strongly influenced by solute inputs and internal water fluxes, and are thus expected to vary substantially both within wetlands and between wetlands. Such estimates remain elusive but are particularly important for assessing the long-term carbon storage potential of dryland wetlands.

Despite the importance of surface-groundwater interactions in dryland wetlands with respect to water fluxes, solute budgets and ecology, such processes remain widely understudied in these systems (e.g., Jolly et al. 2008). There is a clear need to develop hydrological models to simulate the movement of solutes within wetlands and assess ecosystem outcomes under different hydrological and climate scenarios. The ability to predict how human alterations to hydrology and land use may affect key biogeochemical processes will be a vital tool for the future management of dryland wetlands.

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