Habitat changes in response to pressures in the Verlorenvlei Estuarine Lake, South Africa

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Verlorenvlei is a globally important RAMSAR wetland on the arid west coast of South Africa. A prolonged drought between 2016 and 2021 and increasing competition for water from the agricultural sector resulted in extremely low water levels. We used historical aerial and satellite imagery from 1942 and rainfall and water level data for the past 50 years, to assess habitat changes within the estuarine functional zone of the Verlorenvlei Estuarine Lake. Prior to the drought, lake water levels and water surface area remained stable (1113 $\pm$ 27 ha (SE)). Since then, there has been a 64% decrease in open water area, exposing 193 ha of sandbanks, of which 190.9 ha were hyper-sulfidic pyrite-rich. The water in the lower lake was hypersaline ($>$100), and in the middle, it was acidic (pH$<$3). The low water level plus sediment and nutrient input from surrounding agriculture resulted in a localised increase in reeds. Additional pressures, such as fires, have reduced the above-ground biomass of reeds and sedges, potentially altering surface morphology and reducing stored carbon. Despite flooding and filling up in June 2023, the lake remained in an acidic state (3.9–4.3). Similar low-lake level, hypersaline and acidic conditions are predicted to become more common under future climate change scenarios where aridity and extreme weather events are anticipated. Inflow of fresh water into the estuary and control of farming practices are required to keep the Verlorenvlei in a functional state, with long-term monitoring necessary to assess the ecological condition in response to restoration actions.

Significance:

We assessed the habitat changes in Verlorenvlei, an estuarine lake on the arid west coast of South Africa. Estuarine lakes are scarce, and an extended drought greatly reduced the water surface area, exposing hyper-sulfidic pyrite-rich soils, leading to lake acidification and a negative response from biota. Competition for water from agribusiness and the burning of reeds are added pressures. Subsequent heavy rains have been slow to buffer lake acidity, and the impacts thereof serve as a warning for the management of similar ecosystems and their ecological water requirements, especially under climate change where extreme weather conditions, increased aridity and competition for water are realities.

Introduction

Estuarine lakes are particularly susceptible to anthropogenic pressures due to their shallow nature, large surface area, weak connectivity with the sea and low flushing rate.[1] Verlorenvlei is the only freshwater lake on the very arid west coast of South Africa, being fed by both rainfall and a large secondary aquifer.[2] It has historically been an important source of fresh water for early humans, later becoming the focal point of settlements, agriculture and, in the last few decades, an important agribusiness region.[3-5] Verlorenvlei is also an important bird area, providing feeding, nesting and resting facilities, for up to 20 000 birds at a time; for these reasons, it achieved RAMSAR status in 1991 (No. 525). It also represents an important national peatland, a rare wetland ecosystem in South Africa, due to the buildup of organic matter over centuries.[6] Ecologically, Verlorenvlei is located in an area that forms a transition between the Strandveld and Fynbos bioregions, supporting many rare and threatened species.[7,8] This collectively makes it an estuary of high conservation importance, albeit with no statutory protection.[1,6]

Only 4% of South African estuaries are estuarine lakes (of which there are 13), yet they cover more than 60% of the country's estuarine habitat area.[1] Their high water retention results in a sensitivity to the influence of in situ processes such as low flushing rates and slow remineralisation of nutrients more than other estuary types, making them less resilient to change and more vulnerable to catchment land use and development pressures, as well as climate change. This is particularly true in shallow estuarine lakes such as Verlorenvlei. Not surprisingly, more than 84% of South Africa's estuarine lake area is in a poor ecological state.[1] The Verlorenvlei is particularly important because, despite being small in comparison to other estuarine lakes, it is an ecological and socio-economic source of fresh water on an arid coastline.[9]

Estuarine habitats fluctuate naturally over time, and this is particularly evident at Verlorenvlei, where research has documented the changes that have taken place since the late Holocene.[4,10-12] Fossil pollen analysis conducted on sediments from Verlorenvlei shows that the dominant vegetation type within the vicinity of the lake shifted between drought-resistant woody shrubs and salt marsh vegetation.[4,5,10,11] These shifts took place on several occasions over the last *ca* 6000 years, largely in response to changing sea levels. The present ecotonal mix of Strandveld and Fynbos vegetation was established around 1900 BP in response to lowered sea levels.[4,10,11] A number of freshwater springs facilitated the proliferation of the current wetland species during this period of sea-level regression, and the permanence of the reed swamps resulted in the formation of large peat beds associated with Verlorenvlei, where peat is defined as "an area with or without vegetation with a naturally accumulated peat layer at the surface", where peat is "sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material with a depth of least 300 mm"[2,6].

Interwoven with global climatic drivers, human presence and their pressures are also at play locally. Archaeological studies from Elands Bay Cave, situated south of Verlorenvlei's mouth, show intermittent human presence over the last 20 000 years.[5,10,11,13] In the last 2000 years, pollen analysis shows a decline in grass species, probably due to the increased presence of grazers[10,11], further exacerbated by colonial occupation in the area in 1741 and the introduction of wheat and corn production, and cattle[3].

Given the importance of Verlorenvlei, this study describes the extent of changes in the macrophyte habitat and their drivers over the last 90 years, a period when anthropogenic pressure resulted in the greatest change. We make use of historical aerial and satellite imagery, repeated photography, and historical abiotic data in a data-poor environment to gain an understanding of these changes. The implications of these changes were evaluated under future climate change scenarios where rainfall patterns are expected to be more extreme, aridity increased and anthropogenic pressures more likely.[14,15] The present status assessment is a component of the estuarine health index needed for an evaluation of the ecological flow requirements of estuaries as specified by the South African Department of Water and Sanitation and will therefore support management at a regional and national scale.[16-18]

Materials and methods

Study site

Verlorenvlei lies approximately 180 km north of Cape Town with a surface area of approximately 198 000 ha and an average depth of between 2 m and 3 m.[1] Rainfall ranges from 537 mm/year in the catchment to about 210 mm/year at the mouth.[19] The lake can be divided into three distinct reaches: Lower, Middle and Upper (Figure 1).[9] The Lower reach near the mouth has a small, shallow channel (~2.6 km) that connects the larger lake basin (Middle reach) to the sea. There is very little free water exchange between the sea and the lake, mostly being closed by a sandbar during the dry summer months overlying a rocky sill. A migrating barrier dune has pushed the mouth progressively south. During the winter months, when rainfall is at its maximum, the sandbar is breached and limited tidal interaction occurs. Seawater can overtop the sandbar during high spring tides and stormy conditions. The Lower reach is separated from the main lake basin (Middle reach) via a causeway and rocky sill. The Middle reach has a lake basin with an average depth of between 2 m and 3 m and a maximum depth of 5 m.[20] In the shallow Upper reaches, the Verlorenvlei River feeds the lake through a series of wetlands at Redelinghuys (Figure 1). There is extensive agriculture in the catchment, being the largest and most intensively cultivated and fastest-growing agricultural area in the Sandveld.[9] The main crops are potatoes, wheat, corn, vegetables, rooibos, vineyards and citrus.

A recent study on the estuarine lakes of South Africa showed that Verlorenvlei alternates between four abiotic states in response to local climate and rainfall.[1] Historically, drought cycles occur every 10 to 20 years and the mouth breaches every 2 to 3 years, remaining open for 1–2 months after breaching. Under closed-mouth conditions, the estuarine lake can be in either a very low water level state (a drought state where water can either be brackish or progress to acidic), a low water level and fresh state, or a high water level and fresh state, fed by rainfall and a large groundwater recharge from a secondary aquifer.[2] During the closed-mouth state, back flooding of the floodplain during high inflow periods causes high water levels that inundate large parts of the wetlands in the upper reaches, which in turn can result in the illegal practice of artificial breaching, for example, in 2014. The fourth state is one where the mouth is open and water levels are declining due to outflow. At the time of this assessment in November 2021, the mouth was closed and the water level was below 0.5 m MSL with hypersaline conditions in the lower mouth region. Large parts of the main basin were exposed and acidic (pH in Lower reaches > 8, Middle reaches < 3, and

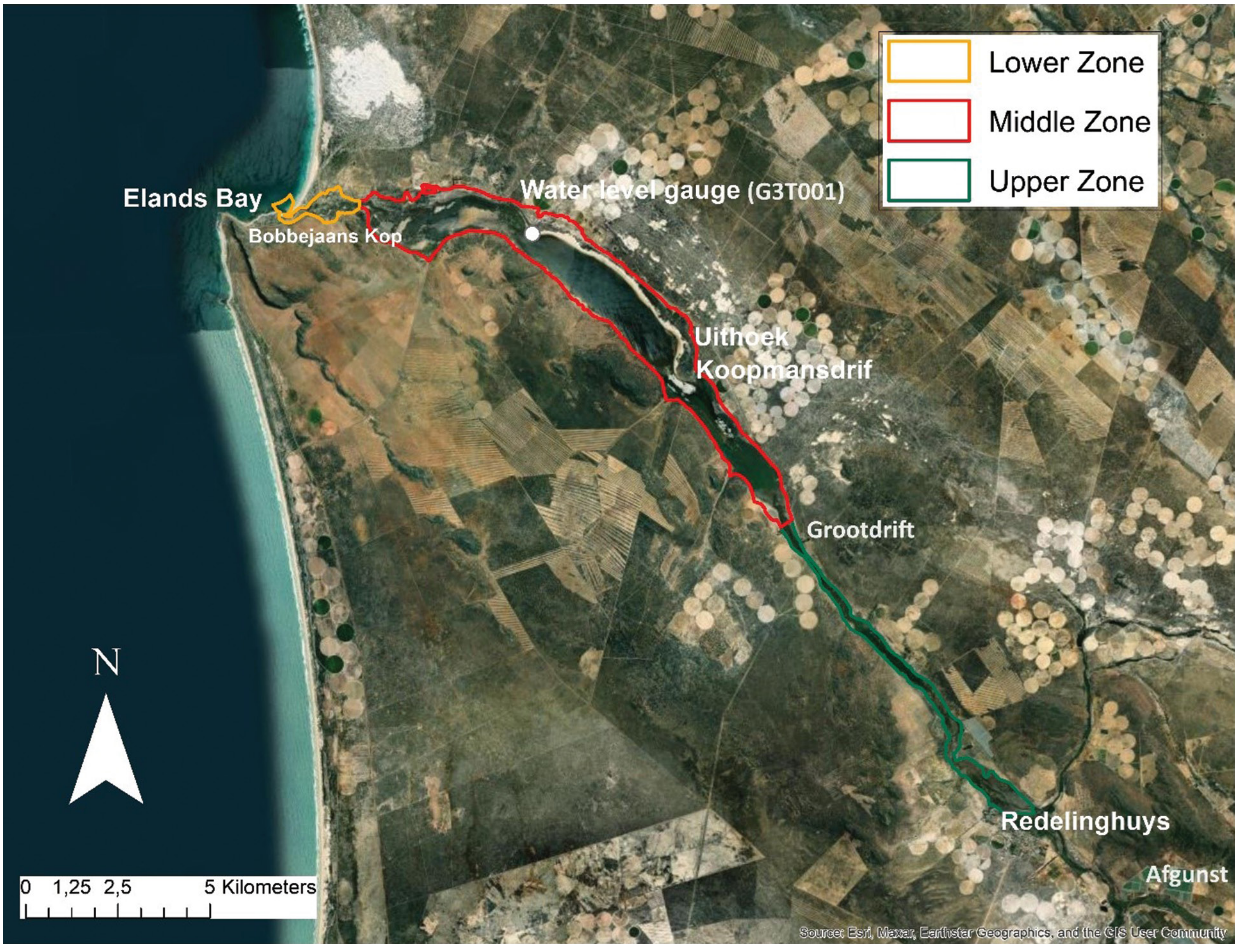

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Figure 1: Locality of the Verlorenvlei Estuarine Lake, along with places of interest mentioned in the text.

Upper reaches between 6 and 7.5)[9] and vegetation was dying back as a result (Figure 2).

Present and past habitat distribution

Habitat changes within the estuarine functional zone (EFZ) (represented by the 5 m contour) were mapped manually by digitising in ArcMap 10.6.1[21] aerial imagery obtained from the Chief Directorate National Geo-spatial Information (CDNGI) (http://www.cdngiportal.co.za/cdngiportal/)[22] (Table 1). The present habitat (2021) was compared to the habitat in past years (1942, 1978, 1998, 2003, 2013). These years were chosen to represent decadal changes based on the availability and quality of images. While recent orthorectified images are of 50 cm resolution, the older images are of relatively poor resolution, and they were used in conjunction with Google Earth imagery to map past areal extent. From

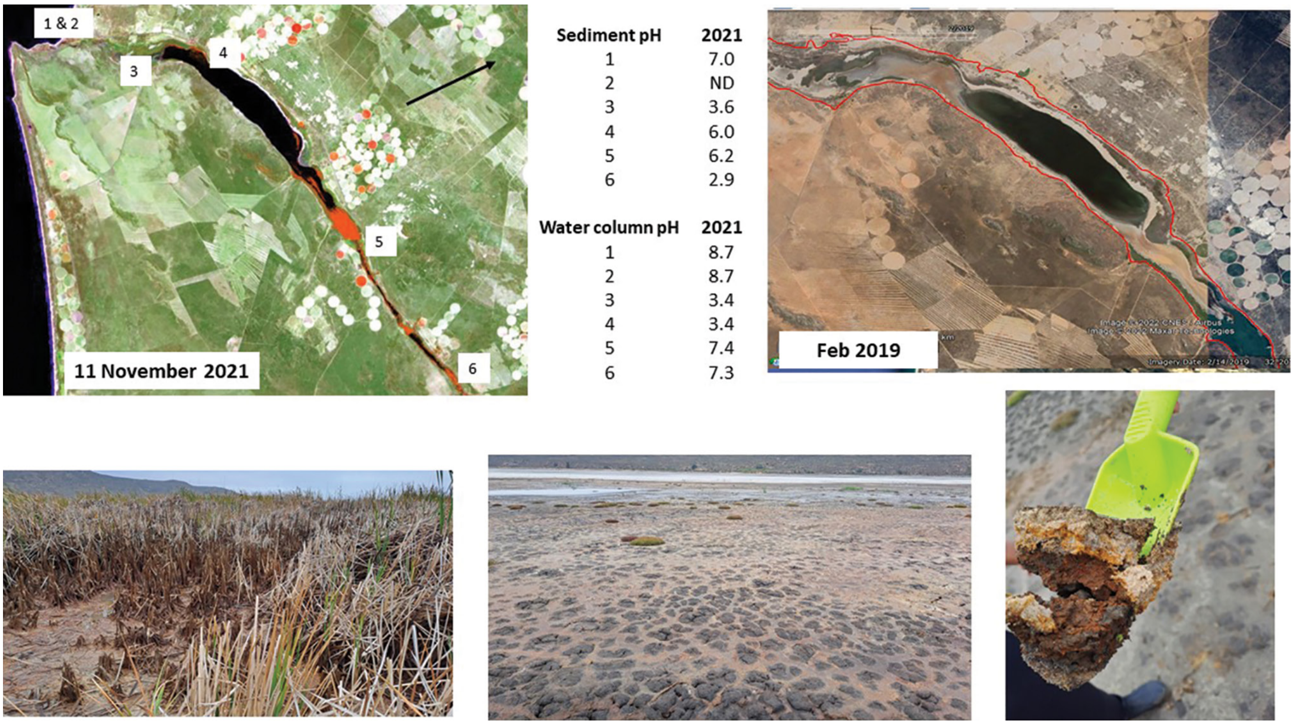

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Figure 2: Large exposed sandy areas appear orange as the water level recedes during low inflow. By November 2021, the exposed sands were oxidised, acid sulfate soils with yellow and orange mottling from jarosite and iron oxide minerals were present and resulted in the dieback of vegetation.

Table 1: Available data used in the assessment of habitat changes over time in Verlorenvlei

Data	Period	Source
Aerial imagery	1942, 1978, 1998, 2016	Historical aerial imagery available from the Department of Agriculture, Land Reform and Rural Development (http://www.cdngiportal.co.za/)[22]
	2013, 2021	Google Earth
Oblique imagery	1981, 2013, 2021	Jenny Day (written communication, 2023), Dimitri Veldkornet (written communication, 2013), this study
Rainfall data	Elands Bay, 1978–2021	South African Weather Service (https://www.weathersa.co.za/)[26]
	Redelinghuys, 2008–2021	Agricultural Research Council (ARC) (https://www.arc.agric.za/Pages/Home.aspx)[27]
	Afgunst, 1985–2004	
Water level data	1994–2017 (water level too low thereafter to record)	Department of Water and Sanitation station G3T001 (https://www.dws.gov.za/Hydrology/)[28]
Catchment land cover	1990, 2014, 2018, 2020	South African National Landcover Data (https://egis.environment.gov.za/sa_national_land_cover_datasets)[29]
Additional land-cover changes	Pre-colonial	Sinclair (1980)[30]
		Parkington (1976)[5]
Fire and peat	2013, 2016, 2017, 2018, 2019, 2010	Felicity Strange, Friends of Verlorenvlei personal records and photographs (https://www.facebook.com/groups/113047522058060/)
		Grundling et al. (2021)[6]; Grundling (written communication, 2023)

historical Google Earth imagery, the two states identified by Van Niekerk et al.[9] could be clearly identified: closed with very low water levels in 2021, and closed with high water levels in 2013/2014. Although colonial settlers have inhabited the area since the 1600s, the earliest images to assess vegetation distribution were only available in 1942 and represent a near-natural state with little human pressure. Historical oblique photos, unpublished literature, social media and local conservancy groups ('Friends of Verlorenvlei') were widely sourced to gain an understanding of the spatio-temporal changes of vegetation at the local scale (Table 1). Where available, repeated photography from previous research on the estuary was used (1981, 2013 and 2021). This method of historical ecological analysis provides an accurate, practical tool to document vegetation changes, especially when used together with other historical information like long-term rainfall data. It is also invaluable as a method of comparing predicted climate change scenarios with actual changes[3-25], especially in a data-poor environment such as this study site.

Estuarine habitat was categorised into the following subcategories: freshwater reeds and sedges, salt marsh, terrestrial vegetation, and open water, which represents microalgal habitat.[31] Often, an ecotone forms in places with an intermingling of habitat. Also mapped were degraded habitat (where some original vegetation and biodiversity remain) and developed habitat (where complete transformation has taken place, usually represented by hard structures like roads, railways and the built-up environment, along with agriculture). To verify these habitats, ground truthing took place on 8, 9 and 10 November 2021, during which time geotagged images assisted with the identification of habitat type. During the field trip, random depth to groundwater and groundwater salinity measurements were taken to understand the location and extent of habitats and their drivers. These data are mentioned in the text.

Drivers of macrophyte change (rainfall, water level, human pressure)

Two important drivers influence habitat extent in the Verlorenvlei Estuary, namely rainfall/water level and human pressure.[9] Monthly rainfall data from the South African Weather Service began only in 1967, and as late as 2008 for some sites in the catchment.[26] To supplement this rainfall data, data from the Agricultural Research Council[32] were sourced for the catchment (Afgunst) and within the EFZ (Figure 1). These data, along with historical aerial imagery, were used to identify when the different abiotic states identified by Van Niekerk[9] occurred and how this influenced habitat extent. The closed, very low water level state was clearly seen in the 2021 images, which represented the present state.

Water level data in the estuary were supplied by the Department of Water and Sanitation, station number G3T001.[28] The gauge is located near Uithoek Farm, 11 km from the mouth of the reed beds (Figure 1). Data were obtained for the period 1994–June 2017, after which the lakebed dried at the monitoring point and no further measurements could be recorded. Salinity is closely linked to vegetation distribution and species composition in estuaries[31,33], but as no historical data exist, known species tolerance ranges were used to assess temporal changes.

Historical accounts were used to assess the change in human pressures over time. Local knowledge regarding the fire history was sourced from the Friends of Verlorenvlei, a local conservancy group, and other available data such as the Estuary Management Plan.[7] Changes in the catchment were assessed using the South African National Landcover Data[22,29] and raster data on the rates and patterns of habitat loss, which cover four periods: 1990, 2014, 2018 and 2020.[34] These images were clipped using the catchment and the EFZ polygons of the Verlorenvlei.

Results

Present and past habitat distribution

The main habitats associated with the Verlorenvlei are open water, reeds and sedges, sand and mudflats, and floodplains (Figure 3). Due to a drought between 2016 and 2023, open water area decreased by 64% from a mean of 1113 $\pm$ 27 ha (SE) before the drought to 421 ha during the drought (Figure 4). This exposed large areas of sand (189 ha) in the main basin (Middle reaches) and Upper reaches with a total sandbank area of 193 ha. Prior to the drought, there were very few exposed sandbanks due to the high water level (<2 ha). On Google Earth imagery, these beds appeared orange in colour in places due to their pyrite-rich content (data presented in a separate article). Similar orange colouration was seen in February 2019 (190.9 ha) and in December 2020 (61.1 ha). These highly acidic soils resulted in the dieback of many of the emergent habitats (Figure 2) with the 2021 state representing a

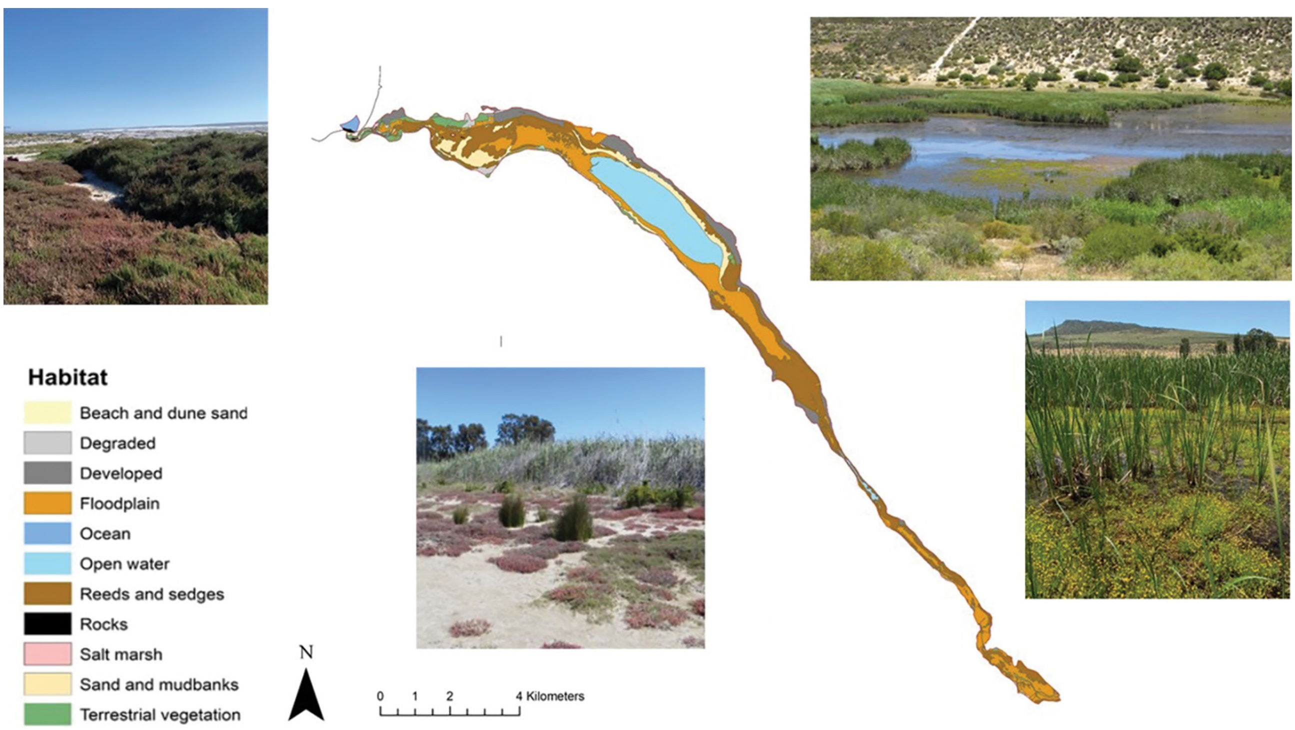
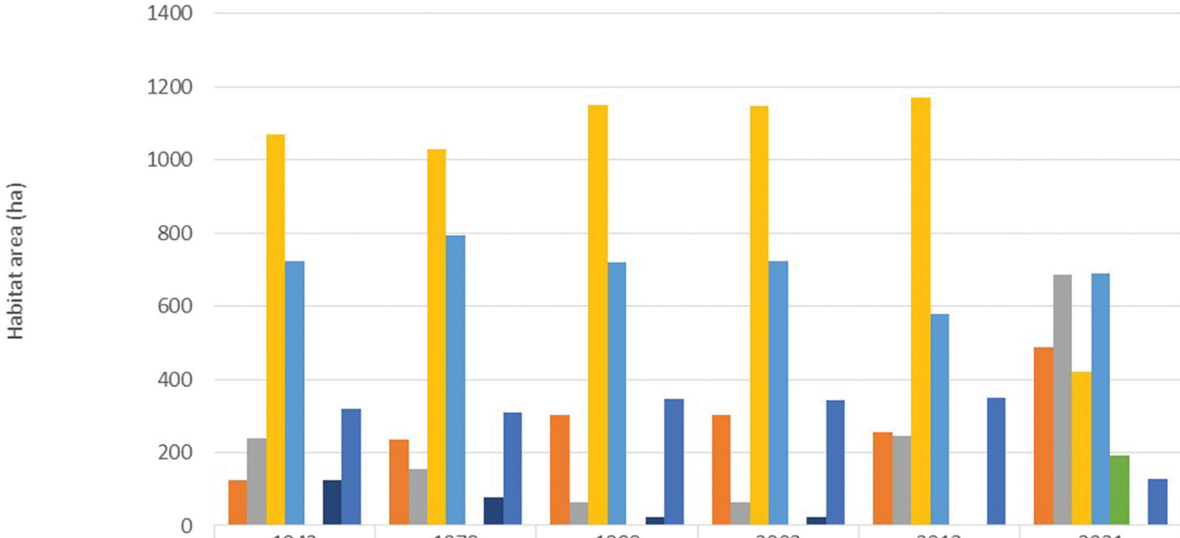


Figure 3: Present (2021) habitat of the Verlorenvlei with examples of habitat of salt marsh at the mouth; *Phragmites australis* stands in the middle with aquatic macrophytes, and ecotonal mixes of reeds, terrestrial and salt marsh species in places.



	1942	1978	1998	2003	2013	2021
Degraded / developed	124	236	304	304	254	487
Floodplain/ecotone/terrestrial	240	156	64	64	244	686
Open water	1069	1030	1150	1146	1170	421
Reeds and sedges	724	795	719	722	579	688
Sand and mudbanks	0	0	0	0	2	193
Salt marsh	125	77	22	22	4	3
Submerged macrophytes	321	309	345	344	351	126

Figure 4: Changes in habitat within the estuarine functional zone of the Verlorenvlei between 1942 and 2021.

closed, very low and acidic state (Supplementary figure 1).[1] The open water supports submerged and floating aquatic macrophytes, but this habitat could not be mapped or groundtruthed in November 2021 due to limited access as a result of the low water level. It was estimated that these macrophytes covered approximately 30% of the open surface water area (126 ha) (Figure 3). The open water in the Middle and Upper reaches was connected, but not in the Lower reaches. Submerged and floating aquatic macrophytes were represented by freshwater species. The naturalised exotic submerged aquatic *Myriophyllum spicatum* was not observed during the field trip nor in the satellite images, despite being prolific in the 1980s.[3] Its presence in the past was suggested to be in response to nutrient run-off from surrounding agricultural activities. However, large beds of floating *Crassula natans* occurred, together with *Cotula coronopifolia* and *Aponogeton distachyos*, in the Middle and Upper reaches in 2021.

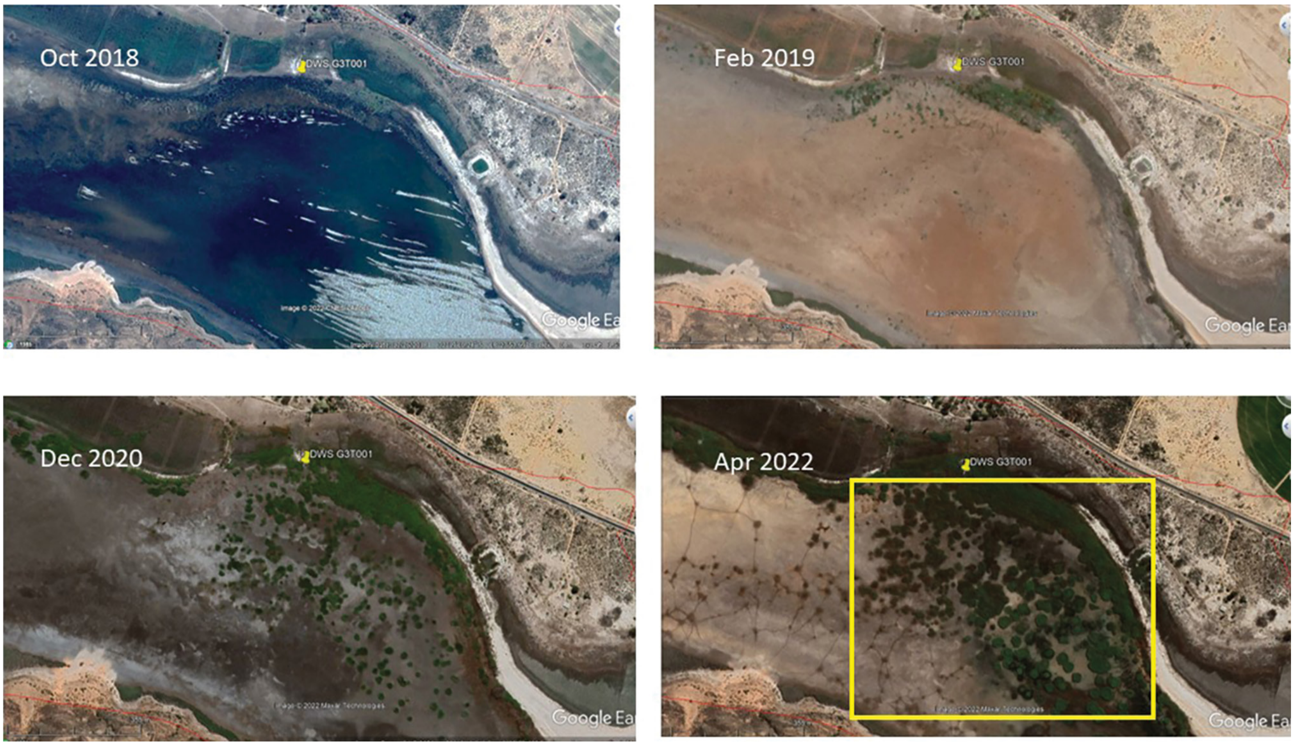
At the mouth, the water was hypersaline (>100), and no aquatic plants were observed. However, stands of reeds and sedges occur in the Lower and Middle reaches despite high surface salinity. Ad-hoc augured holes found the groundwater to be at 10–30-cm depths with a salinity of 10. These fresh water seepage areas maintain these plants in this area as they grow best at a salinity of below 15. This groundwater source is of significance as the water column salinity in the Lower reaches was hypersaline (mean 143). Most of the reeds and sedges (*Phragmites australis, Scirpus maritimus, Schoenoplectus scirpoides, Typha capensis* and various other *Cyperus* species) occur in the Middle and Upper reaches (688 ha) (Figure 3). Beds can either cover the width of the system (Middle and Upper reaches) or occur on the dry, exposed lakebed intermingled with salt marsh and terrestrial species, forming an ecotone (Figure 3). Despite the lack of physico-chemical data other than rainfall and estuary water level, it was possible to infer environmental conditions based on habitat and the salinity preferences of the dominant macrophytes. *Phragmites australis* indicates freshwater conditions even in the presence of hypersaline surface waters as was found in the Lower and Middle reaches[35] as the roots and rhizomes are located in fresher water. During the field trip, surface water salinity was found to be over 140 in the lower reaches, but at sediment depths between 30 cm and 1.5 m, groundwater was 10. Analysis of historical aerial imagery shows the presence of reeds and sedges in the exposed lakebed even under low water levels; fresh groundwater input would be important in maintaining these habitats. Reeds and sedges appear to be stable in extent over the last few years with only a 6% increase from 1942 to 2021 and a mean area of 704 $\pm$ 28.9 ha (SE) (Figure 4). Under very high water levels (2013), reed extent is reduced, probably due to depth limitations. Under very low water levels, there have been localised increases in reed and sedge extent in the Middle as well as in the Upper reaches into the exposed lake bed (Figure 5). The rate of expansion into the dry riverbeds was calculated at 1.4 ha/year. Where reeds have died due to high water levels and inundation, recovery to previous extents under lower water levels took about 14–19 months.

Cape arid estuarine salt marsh and saline grasses (3 ha) occur in the Lower reaches around the mouth with species such as *Salicornia* spp., *Bassia diffusa, Sporobolus virginicus, Cynodon dactylon, Paspalum vaginatum, Triglochin* spp., *Cotula* spp. and *Juncus kraussii*. Salt marsh remains relatively constant (3 to 4 ha) and on the large floodplain above 2.5 m MSL (168 to 588 ha) (Figure 4), terrestrial species such as *Mesembryanthemum crystallanum*, various Aizoaceae and other ecotonal terrestrial species intermingle with *Salicornia* spp., *Juncus* spp. and *Phragmites australis*. The large salt marsh area in the lower reaches in 1942 (125 ha) would be a mix of ecotonal species, terrestrial and salt marsh, as is the case in the intermediate years. It was difficult to delineate salt marsh from ecotonal habitat due to the poor resolution of the earlier images, and it is possible that the high extent in the early years may include floodplain habitat. Other habitats, like rocks (habitat for epipelic microalgae) and beach and dune sand also occur within the EFZ, but to minor extents. Terrestrial vegetation consists of Lambert's Bay Strandveld, Saldanha Flats Strandveld and Leipoldtville Sand Fynbos (99 ha) (Figure 3).[7]

Drivers of macrophyte change (rainfall, water level, human pressures)

Rainfall and lake water level

Analysis of rainfall data for the Elands' Bay area showed that over the last 43 years there have been alternate wet and dry cycles (Figure 6), with a duration of 3–10 years. Although patchy datasets hamper statistical analyses, estuarine habitat shifts between low- and high-water states



Source (maps 2018, 2019, 2020, 2022): Image Landsat/Copernicus, Image © 2024 Maxar Technologies; reproduced with permission

Figure 5: Reed encroachment in the Middle/Upper reaches of the Verlorenvlei due to low water levels. Images show the transistion from high-water level in October 2018 to low water level and the expansion of reeds in February 2019, December 2020 and April 2022.

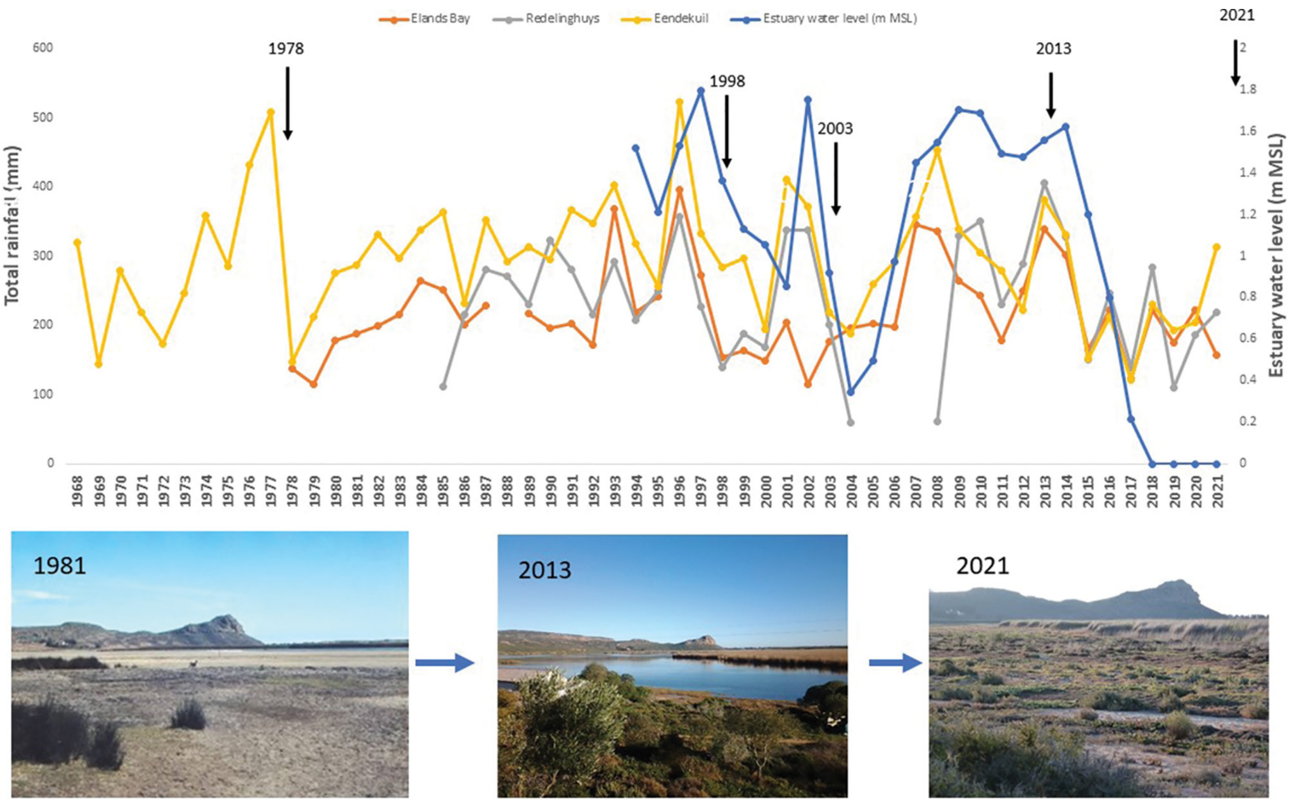


Figure 6: Annual rainfall for Elands Bay from 1978 to 2021 (South African Weather Service) and estuary water level as recorded at the Department of Water and Sanitation gauge G3T001 (blue = rainfall, grey = estuary water level, orange = expected annual rainfall). There are no water level data after July 2017 as the gauge site dried out. Arrows indicate the years used for mapping low- and high-water states.

as a result. Above average / wet years were experienced between 1993 and 1998, 2007 and 2011 and 2012 and 2015. Drought years occurred between 1978 and 1983, 1998 and 2006 and 2015 and 2020. Although the estuary water level gauge only began recording in 1994 and stopped in July 2017 due to exposure of the lakebed, it still shows the response of the water level to rainfall, especially the time lag between rainfall and increased water level at times only weeks later. Repeated photography has shown that variability in water surface area in the Verlorenvlei is part of a natural decadal cycle associated with rainfall and water level (Supplementary figure 1).

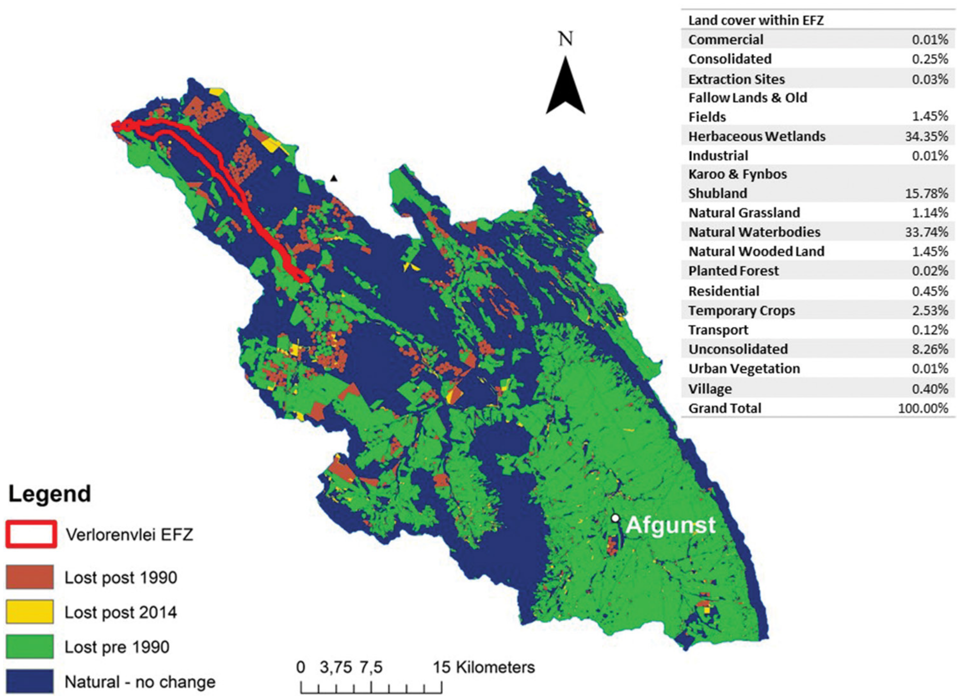
Human pressures: Fires and over-allocation of surface and groundwater

Development within the EFZ already covered 124 ha (5%) in the earliest aerial images of 1942 and has since increased to 12% (267 ha) in 2021 due to agriculture, roads, railway lines, gravel roads and various footpaths (Figure 4). As development increased, so did the presence of invasive species; for example, *Eucalyptus* stands occur around farmsteads planted for shade and wind protection. Cattle grazing, trampling, and footpaths have degraded habitat, mostly at the expense of floodplains and terrestrial vegetation. Almost 50% of the catchment has been transformed into either agriculture or development, most of which occurred prior to 1990 (44%) (Figure 7). Post-1990 changes account for 9% of the catchment. However, competition for water resources by farming and nutrient and sediment input arising from the various land-use practices in the catchment, particularly those related to fresh water abstraction, are serious pressures on the ecological health of the estuary. Hunter-gatherers and pastoralists have been intermittently present in the area over the last 20 000 years.[5,10,11,13] The presence and associated pressures intensified with the settling of European settlers around the Verlorenvlei since the early 1600s (Figure 8). Land-cover changes first took place in the early 1600s, when loans were granted by the governing Dutch East India Company for grazing and wheat production.[3] By the 1800s, settlements were well established in the area. Agricultural activities continued with further clearing of land, especially when the area became electrified in the 1960s, promoting the use of centre-pivot irrigation for the cultivation of seed potatoes. Vines and orchards are the other main forms of agriculture in the catchment. Since the 1960s, several major obstructions have altered tidal exchange in the Lower Zone.[3] A rocky sill at the mouth (that used to be a causeway); a causeway below the Sishen-Saldana railway bridge and the road crossing to Elands Bay. In addition to the constrictions in the lower estuary, there are also two causeways in the Upper Zone at Grootdrift and Redelinghuys that also pose a constraint on circulation, separating the zones and reducing biological connectivity.

Irregular fire practices have also impacted the Verlorenvlei habitats in the Lower to Middle reaches in the past 10 years. Some of these were due to lightning strikes (1 February 2020), others through illegal burning to clear the reeds by local farmers (13 May 2013, 6 April 2016, 8 March 2017, January 2018) (Figure 9). One such out-of-control fire at Bonteheuvel began on 6 April 2016 and continued to smoulder until 18 June. The fire residue was still evident on Google Earth imagery in October 2018. The most recent fire on 1 February 2020, caused by a double lightning strike, burned until 23 April 2023. However, the below-ground biomass (peat) continued to smoulder for a few months, finally being extinguished on 23 April 2020 (Grundling, personal communication).

Discussion

This article serves as a collation of available knowledge and published data on the Verlorenvlei Estuary so that its present habitat status (2021) and changes over time could be assessed. Unfortunately, for many of South Africa's estuaries, long-term data are lacking and any local sources of information are invaluable in understanding changes over time. For this reason, we have made use of a variety of data sources – aerial photographs, repeated photography, rainfall records and anecdotal data – to gain an understanding of macrophyte changes in Verlorenvlei. This information can be used in ecological water requirement studies, which are marked with low, medium or high confidence depending on the available data. From this monitoring, data requirements are specified in the study to improve future assessments. These ecological water requirement studies by the Department of Water Affairs and Sanitation are a national requirement in the management of South African estuaries and encompass ecohydrological and ecosystem-based concepts.[36] To date, the study approach has been applied to 40% of South Africa's estuaries with the majority (68%) of studies being completed as low confidence desktop or rapid level assessments.[18,37]



Land cover within EFZ	
Commercial	0.01%
Consolidated	0.25%
Extraction Sites	0.03%
Fallow Lands & Old Fields	1.45%
Herbaceous Wetlands	34.35%
Industrial	0.01%
Karoo & Fynbos Shubland	15.78%
Natural Grassland	1.14%
Natural Waterbodies	33.74%
Natural Wooded Land	1.45%
Planted Forest	0.02%
Residential	0.45%
Temporary Crops	2.53%
Transport	0.12%
Unconsolidated	8.26%
Urban Vegetation	0.01%
Village	0.40%
Grand Total	100.00%

Figure 7: Almost 50% of the Verlorenvlei catchment has been transformed into agriculture, most of which has occurred since the 1990s. The rainfall station Afgunst is shown in the catchment.

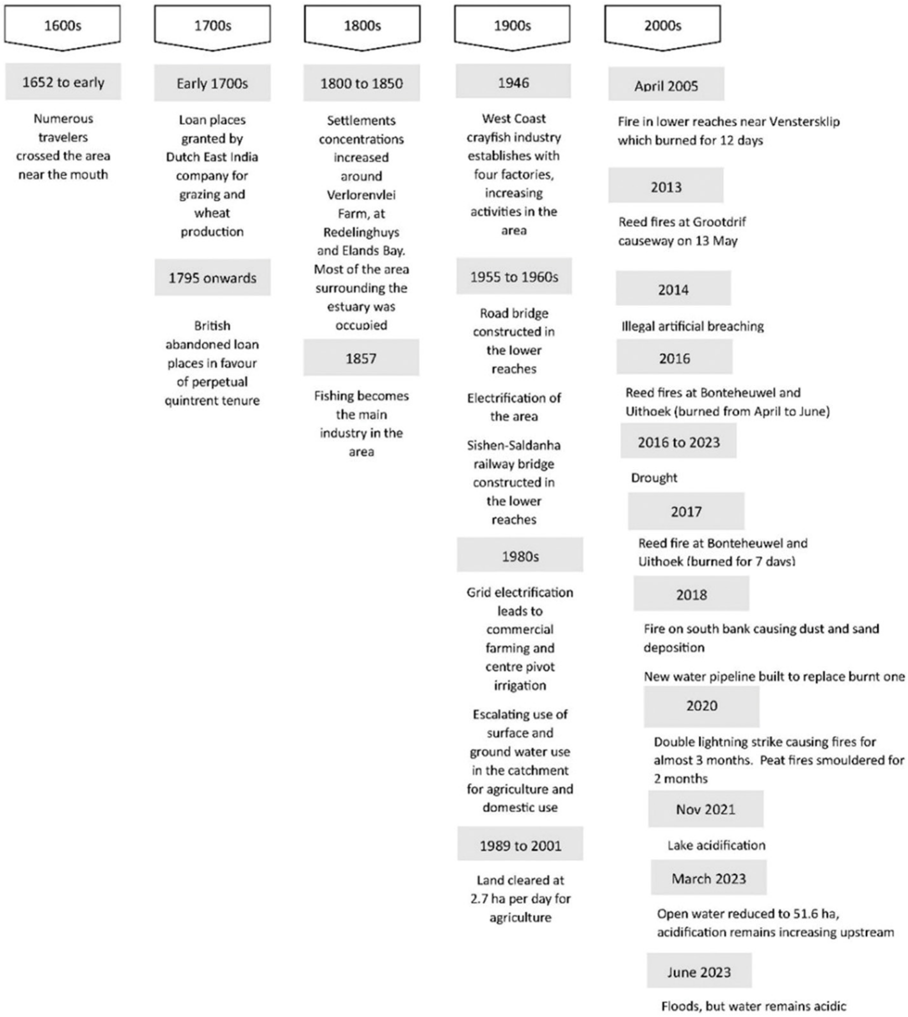


Figure 8: Timeline of changes in the Verlorenvlei area from 1652 until 2023.

Images: (left) Sara Louw; (right) Tiaan Carstens; with permission

Figure 9: Uithoek fire in 2017 (left) and the after-effects of the prolonged burn at Koopmansdrif 2020; (right). The black square indicates the area in which reeds burned.

In this study, we found large changes in habitat area, in particular open water, over the last decade. The open water area has been reduced by 64% from a mean high-water area of 1113 $\pm$ 27 ha (SE) (1942–2013) in response to a prolonged drought beginning in 2016. The reduced open water has led to large exposed sandbanks (increasing from 2 ha under high water levels to 193 ha under low water levels). The reduced open water reduces habitat availability for associated submerged and floating aquatic macrophytes. At the time of sampling in November 2021, the mouth was closed, the water level was below 0.5 m MSL, the Lower reaches were hypersaline and there were large, exposed areas in the Middle reaches with acidic soils (<3) and a dieback of reed habitat in some places. These orange-coloured sands suggest pyrite-rich sediments. Natural sulfate reduction processes in organic-rich aquatic sediments can result in the accumulation of sulfide minerals such as pyrite (FeS_2). Upon exposure to air, pyrite can oxidise to produce sulfuric acid, dissolved ferrous iron and jarosite mottling.[38] Thus, strongly acidic conditions can form upon rewetting (by rainfall or lake refill) of the exposed organic-rich sediments.[39] Sediment and water analysis showed this is now a persistent and ongoing process in Verlorenvlei (article in preparation) with negative effects on the overlying vegetation (Figure 2). A similar process of lake acidification occurred in the Murray-Darling Basin of Australia, where a 2-year drought resulted in the exposure of more than 200 km^2.[39] Upon rewetting of the sediments, surface water had a pH of between 2 and 3, and high concentrations of dissolved metals were mobilised.[39] This acidity persisted in the lake sediment and the water for several years after the drought broke, and surface water management was a long and costly process to return water pH levels to biologically acceptable levels. In the case of Verlorenvlei, partial rewetting from small rainfall events has produced standing pools of water with a pH below 3 in the Middle reaches. This has not changed much despite the increased inflow of fresh river water following the recent heavy rains of 2023 (1:20 year flood) along with water introduced from a burst dam in the catchment, adding another 150 000 m^3 of water to the lake. The mottling of these hyper-sulfidic organic-rich soils by jarosites often occurs along *Phragmites australis* roots and cracks[38] and was similarly found in this study in areas previously vegetated by *Phragmites australis*. These jarosites can retain acidity for many years, even decades, leading to continued low pH in the sediment and overlying water.[38] Drought conditions also potentially increase salinity, which in a predominantly freshwater habitat, can have severe consequences. The Verlorenvlei ecological water requirement study found that before the drought in 2016, salinity mostly fluctuated between 1 and 3, while after 2017, the system showed a marked increase in salinity due to evaporation, with 12.6 (2018), 17.5 (2019), and values as high as 25.8 (2020) observed, before a decline to 5.9 (2021).[9] These values are the highest on record for the system. While this is a predominantly freshwater ecosystem, salt marsh does occur in the Lower reaches but to a small extent. On the floodplain, it intermingles with terrestrial species to form an ecotone.

Reeds and sedges cover 704 $\pm$ 29 ha (SE) with little variation over time. However, there have been localised increases in the Upper (probably in response to sediment and nutrient input from agriculture) and Middle reaches (due to low water levels), with the latter taking place at a rate of 1.4 ha/year (Figure 5). Although reeds are an effective nutrient and sediment filter, especially in the Upper reaches, the increased organic plant matter could cause an increase in inorganic nutrients through remineralisation. Cyanobacterial blooms in the basin (Middle reaches) and also at times in the Upper reaches (especially during spring and summer when temperatures are higher and residence times are longest) support this hypothesis.[1] Reeds in the Upper reaches rely on the Verlorenvlei River (which feeds the system through a series of wetlands at Redelinghuys) and freshwater springs and appear to have persisted since 1942, despite the absence of water at times. These freshwater springs also support stands of freshwater habitat in the Lower reaches, where hypersaline conditions occur in this closed, low and acidic state.

Palaeoenvironmental reconstruction of the Verlorenvlei area has provided insight into the climatic changes, sea-level fluctuations, vegetation changes and human activity in this coastal region.[10,11] Around 4300 BP, marine and more xeric conditions disappeared and were replaced by freshwater-dominant hydrology and ecology. The decline in grass pollen from 1900 BP in sediment cores suggests the impacts of pastoralists, colonial and post-colonial disturbances of the vegetation. In the 350 years of colonial occupation, disturbance has been the greatest in the last few decades due to agri-business. Anthropogenic pressures have intensified over the last 100 years as agriculture, road and rail development have increased. These have led to competition for water resources, and land practices such as burning and clearing of reed swamps, which have fast-tracked land-cover change in the area. This increased abstraction has led to a reduction of 50% in baseflow, and together with a reduction in mean annual rainfall in the last 90 years, has led to a reduction in lake water level by 33 cm.[9] These natural and anthropogenic pressures pose a serious threat to the ecological health of the Verlorenvlei and, therefore, to its current RAMSAR status. Agricultural activities occupied over 50% of the catchment prior to the 1990s. Commercial agricultural activities include potato farming, rooibos plantations (*Aspalathus linearis*), vineyards and orchards. Centre-pivot irrigation, a method that uses rotational cropping and the clearing of large areas, the use of fertilisers to enhance nutrient-poor soils and groundwater abstraction have all increased to boost production.[9,14] Agriculture accounts for more than 90% of the total registered groundwater use in the Sandveld, with potato farming accounting for 20% of the annual groundwater recharge.[14,40] Over abstraction of groundwater not only threatens the deep baseflows of the large secondary aquifer that feeds and sustains the wetlands of Verlorenvlei, particularly during the dry seasons, but also increases salinisation of groundwater resources.[41] While there is a disagreement amongst groundwater specialists as to the degree to which Verlorenvlei is dependent on groundwater versus surface water to maintain lake levels[40-42], both ultimately contribute to the total flow into Verlorenvlei and lake levels.

The peat resources are also at risk due to the occurrence of regular fires. Although the above-ground biomass only burns for a few days, the below-ground biomass can continue to smoulder for a few months as happened in 2016 and 2020. In the nearby Wadrif Estuary, a reed and sedge swamp similar to those in the Verlorenvlei existed for many years. The original swamps and resulting thick peat layers were fed by a freshwater spring.[42] However, these springs were targeted as a water source by the government. As a result, the water table lowered, saline water intrusion occurred, and vegetation began to dry out and die. An electrical fire in the late 1990s resulted in a fire that continued to smoulder for 2 years due to the 2-m-thick desiccated peat layer. These peat swamps cannot be recovered, nor can their ecological service of acting as nutrient filters and carbon stores.[43] Peatlands are among the world's largest carbon sources, and the loss of potentially 688 ha of reed swamps in the Verlorenvlei could have serious local ecological consequences, along with the release of carbon into the atmosphere, which would have a wider impact. Clearing of peatlands by fire has an estimated release of 88 t C/ha.[44] The clearing of land through fires and low lake levels also exposes large sand areas. This can lead to the buildup of sand through wind erosion, which can alter morphology, further restricting water flow and connectivity. A recent dust study showed that the main source of windblown sediment in the area was the exposed lakebed, Verlorenvlei catchment and surrounding agriculture sector.[45]

Future outlook

With the recent extreme low water level in Verlorenvlei, exposure to acidic soils and dieback of vegetation, what does the future hold for Verlorenvlei in the context of climate change predications of more extreme weather events (greater droughts and floods), increased temperatures, greater aridity and sea level rise? Since this study in 2021, the lake water level has declined further by 88% to 52 ha in May 2023 with water only occurring in the Middle reaches. Despite a 1:20-year flood in June 2023, which raised the lake water level, both sediment and water showed continued acidic conditions (article in preparation). This acidic state has had cascading effects on the lake biota as well as on surrounding livestock and farm animals. In the past, freshwater invertebrates were present throughout the lake, but under this new acidic state, no life occurs in the Lower and Middle reaches.[9] Partial drying out and flooding are natural cycles in lakes due to their large surface area and shallow nature, and this study has reported on these fluctuations. Under climate change, this cycling is expected to occur more frequently with greater extremes. Increased aridity, increased extreme weather events (droughts, floods), increased temperatures, increased wind, decreased rainfall (especially during critical growing months for agriculture), increased mouth closure and increased evaporation will result in lower lake levels and increased acidification[9,14,15,46], with the buildup of hyper-sulfidic sediment potentially remaining for decades[47]. What effects this will have on the long-term storage of seeds in the sediment, as well as the recovery of vegetation and aquatic communities, is unknown due to limited literature.[48] The mean annual run-off has been predicted to further decrease from the current 30% to 50%[9], putting more pressure on groundwater abstraction for commercial agriculture irrigation in particular. The additional pressure of land-use practices and existing human pressures needs to be considered if Verlorenvlei is to maintain its current RAMSAR status. This can be achieved through compulsory water use licensing, a reduction in water abstraction, a reduction in inorganic nutrient input from the catchment, prevention of illegal artificial breaching of the mouth, restoration of hydrological connectivity, protection of resources and buffer zones (reduced reed burning, grazing of salt marsh), and promulgation as a formally protected area with agreements on the fresh water requirements of the downstream estuarine lake.[9]

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Data availability

Data are available upon request to the corresponding author.

Declaration of AI use

No AI-generated content was used in this work.

Authors' contributions

T.R.: Conceptualisation, methodology, data collection, sample analysis, data analysis, validation, data curation, writing – the initial draft. L.v.N.: Conceptualisation, data collection, validation, writing – revisions, project leadership. F.S.: Data collection, writing – revisions. J.B.A.: Conceptualisation, data collection, validation, writing – revisions, project leadership, funding.

Competing interests

We have no competing interests to declare.

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