diversity

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Supplementary Material

Salt marsh restoration for the provision of multiple ecosystem services

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Identification of priority sites for salt marsh restoration in specific South African estuaries

The available area for salt marsh restoration is considered for seven estuaries with the largest salt marsh extent; Groot Berg, Swartkops, Orange, Olifants, Gamtoos, Gourtiz and Klein Brak (Figure S1). Estuary characteristics are provided in Table S1 and dominant salt marsh species shown for each estuary in Table S2. The estuarine functional zone is the area covered by the floodplain, salt marshes and water surface area. Nine dominant species are listed for the intertidal and supratidal salt marsh habitats and occur in most of the seven estuaries (Table S2). The mapped land cover categories considered to have restoration potential were salt pans, agriculture and disturbed habitat. From early aerial photographs and historical knowledge of the estuaries it is considered that salt marsh previously occurred in these areas. Successful restoration will depend on hydrological connectivity influenced by elevation and therefore detailed elevation models would be needed to refine these data. For now, a percentage of each of the habitats is considered feasible for restoration i.e. 50% salt pan areas, 25% agriculture and 50% disturbed. This will be site specific and detailed studies would be needed to implement restoration plans. The current data set and habitat maps identify those estuaries that should be prioritised for restoration as they contain the largest extent of salt marsh.

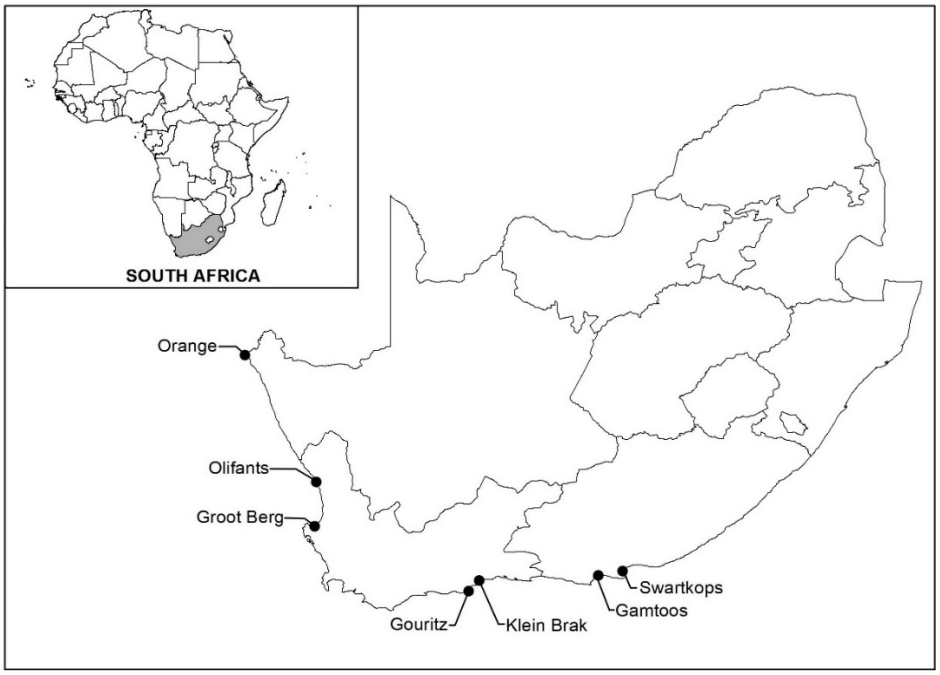


Figure S1. Location of the Orange, Olifants, Groot Berg, Gourtiz, Klein Brak, Gamtoos and Swartkops estuaries in South Africa.

Table S1. Characteristics of the Orange, Olifants, Groot Berg, Gourtiz, Klein Brak, Gamtoos and Swartkops estuaries (MAR = mean annual run-off).

	Estuary type	Estuarine Functional Zone (ha)	Catchment Area (km^2)	Present MAR ($x\ 10^6\ m^3$)	Estuary length (km)	Average Depth (m)
Orange	Large Fluvially Dominated	3647	601591	4143	12.9	2.5
Olifants	Predominantly Open	1424	49075	715	37.6	3
Groot Berg	Predominantly Open	7497	7635	520	55.0	3
Gouritz	Predominantly Open	363	45040	446	31.7	2
Klein Brak	Large Temporarily Closed	509	551	40	11.2	2
Gamtoos	Predominantly Open	501	34 805	265	22.6	3
Swartkops	Predominantly Open	909	1 392	80	17.3	3

Table S2. Salt marsh habitat, life form and dominant species in each estuary (* = present).

Habitat	Dominant species	Life form	Orange	Olifants	Groot Berg	Gourits	Klein Brak	Gamtoos	Swartkops
Lower intertidal	***Salicornia tegetaria*** (S Steffen, Mucina & G Kadereit) Piirainen & G Kadereit	succulent	*	*	*	*	*	*	*
Lower intertidal	***Spartina maritima*** (Curtis) Fernald	grass		*	*	*	*	*	*
Lower intertidal	***Triglochin bulbosa*** L.	herb		*	*	*	*	*	*
Upper intertidal	***Cotula coronopifolia*** *L.*	herb	*	*	*	*		*	*
Upper intertidal	***Chenolea diffusa*** (Thunb.) Kuntze	succulent herb	*	*	*	*	*	*	*
Upper intertidal	***Juncus kraussii*** Hochst.	rush	*	*	*	*	*	*	*
Supratidal	***Sporobolus virginicus*** (L.) Kunth	grass	*	*	*	*	*	*	*
Supratidal	***Sarcocornia pillansii*** (Moss) A.J. Scott	succulent shrub	*	*	*	*	*	*	*
Supratidal	***Disphyma crassifolium*** (L.) L.Bolus	succulent			*	*	*	*	*

Groot Berg Estuary

Table S3. Potential area available for salt marsh restoration at the Groot Berg Estuary.

Salt pans 608.4 ha	50% available for restoration 304 ha
Agriculture 748 ha	Most > 2.5 m MSL, ~185 ha available for restoration consisting of supratidal salt marsh.
Degraded 225 ha	50% available for restoration 112.5 ha as mostly floodplain with bare dry areas, gravel roads and invasive plants

Salt production takes place in former salt marsh areas on the south bank of the lower /middle reaches of the Groot Berg Estuary (Figures S2 and S3) immediately adjacent to the Carinus road bridge east of the of the road bridge, and at Kliphoek approximately 6 km upstream from the road bridge [1]. The salt works produce ~ 55 000 tonnes of salt per year with a value of ~ R8.3 million per year, although operations are currently in state of transition [55]. Recently Cerebos (sites nearest to the Carinus bridge) sold the operation to Royal Salt. The total area covered by the salt works is 608.4 ha and has the potential to be restored back to salt marsh if hydrological connectivity with the main channel is restored. Erosion is occurring at the Cerebos saltworks levee, if this is allowed to erode naturally (a form of passive restoration) it could restore tidal connectivity with the main estuary channel. At least 50% of this area (304 ha) could be restored to functioning salt marsh if salts were removed from the sediment and hydrological connectivity with the main

estuary channel restored. Following hydrological connectivity and seed dispersal colonization by succulent species such as *Salicornia* spp. is expected.

Agriculture covers a large area (2250 ha) that mostly occurs above 2.5 m MSL (Figure S2) making hydrological connectivity and restoration of salt marsh difficult at this dry coast where mean annual rainfall is 520 mm per annum. Agriculture within the supratidal zone where restoration could take place covers 748 ha; it would be feasible to restore approximately 25% of this area (187 ha) back to supratidal salt marsh. Floodplain farming mainly consists of cattle and sheep grazing. Climate change (the area is becoming hotter and drier), prolonged drought conditions and lack of floodplain flooding (resulting from large dam developments) has resulted in farmers reducing their stock numbers by 30-60%. There are thirteen farms along the banks of the estuary and the floodplain contributes ~ R11.5 million per year to direct value added in the agricultural sector [1]. In the winter season of 2021 significant rains fell to replenish these areas. In terms of restoration little is known about the nature of these floodplain areas and further studies are needed to identify restoration interventions to allow salt marsh to return.

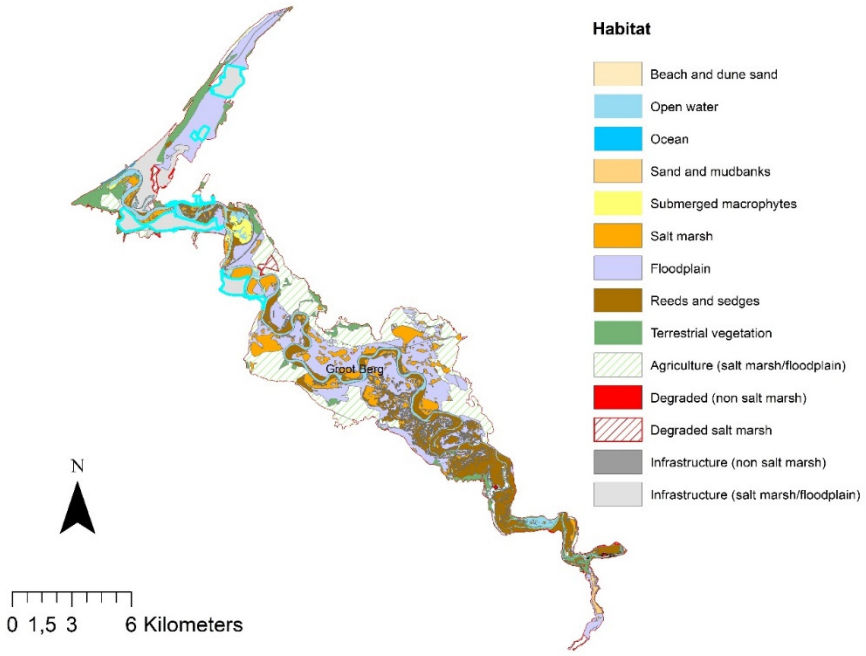


Figure S2. Distribution of habitats in the Groot Berg Estuary. Location and area cover of salt works indicated by light grey with blue outline.

Restoration of salt marsh habitats is important for rebuilding blue carbon storage and improving other ecosystem services. However, reduced freshwater inflow due to climate change and water abstraction as well as erosion threatens any planned activities. Degraded area (225 ha) consisted of bare dry areas; of which 50% could potentially be restored. Lateral erosion on outside bends due to channel movement is occurring in response to fluvial flows and wave action from wind and boats. Wind wave erosion was also observed at the road bridge closest to the mouth with the predominant wind direction from the southwest. Three designs to limit erosion were proposed [2]: regrading of the bank slope and planting with suitable indigenous vegetation; regrading of the bank slope and construction of a toe berm to prevent wash away of material into the channel and planting with suitable indigenous vegetation; and regrading of the bank slope and laying down of geo cells in which soil can be placed and suitable vegetation planted. Riprap was recommended for high energy locations.

Figure S3. Salt works in the lower reaches of the Groot Berg Estuary. Map source: Google, Maxar Technologies.

Orange Estuary

Table S4. Potential area available for salt marsh restoration at the Orange Estuary.

Agriculture 119 ha	25 % potentially available for restoration (29.6 ha)
Degraded 563 ha	50% of desertified salt marsh (281.5 ha) available for restoration after removal of causeway

The Orange River (including the estuary) is a Ramsar wetland of special concern and forms the boundary between South Africa and Namibia. It was placed on the Montreux Record in 1995 because 300 ha of salt marsh had become desertified. This loss was attributed to leakage of diamond mine water, the effect of windblown dried slimes dam sediment on the marsh vegetation, construction of flood protection structures and a beach access road, and the elimination of tidal exchange into the wetland due to a causeway constructed at the river mouth [3]. Due to the low rainfall on the west coast of South Africa and highly salinized nature of the desertified marsh area there has been little change in the salt marsh status over the last 10 years. However, revegetation can easily take place if hydrological connectivity is restored through removal of the causeway. This was seen when part of the causeway was removed, the area became tidally connected and was quickly vegetated by *Cotula coronopifolia* (Figure S5e & f).

Sites where culverts need to be placed on the old causeway (road to the beach) were identified by [4] to ensure connectivity of the main Orange River channel with the desertified (degraded) salt marsh (Figures S4 and S5). Freshwater inflow to the desertified salt marsh area would reduce salinity and transport salt marsh seeds for natural revegetation. Potentially 281.5 ha of salt marsh could be restored, and the process would be accelerated if the entire causeway was removed. Mouth closure provides another mechanism for back flooding freshwater into the marshes but can only occur if baseflows are restored to naturally low levels (these have been elevated mainly due to surplus agricultural releases). Restoration would result in the improvement of multiple ecosystem services such as carbon storage and biodiversity provision. The Orange River Estuary is a Ramsar site as it is a fresh/brackish water habitat in an arid environment. It is an important resting area for migratory birds providing breeding and feeding grounds.

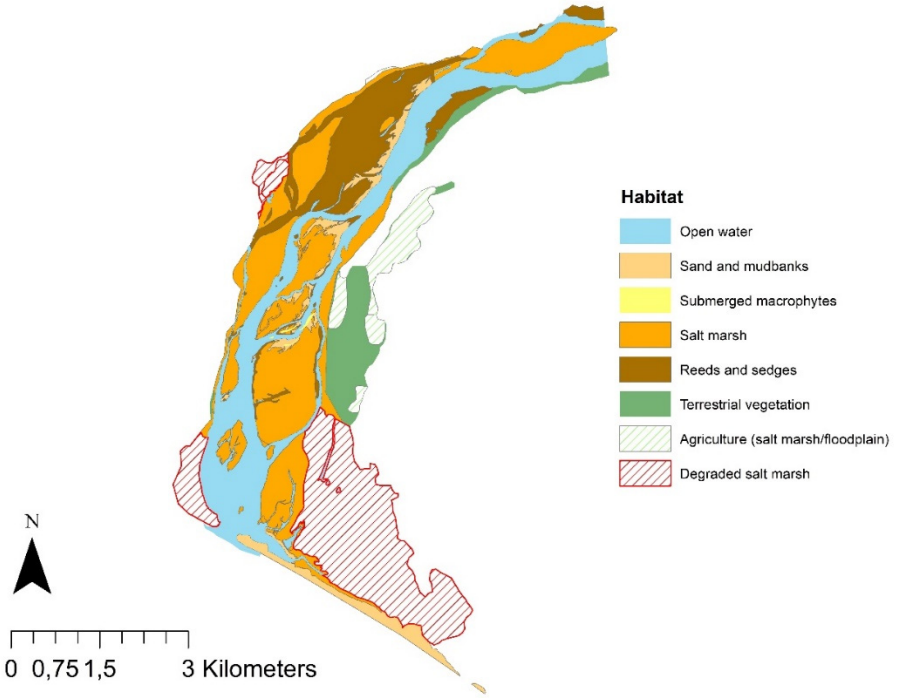
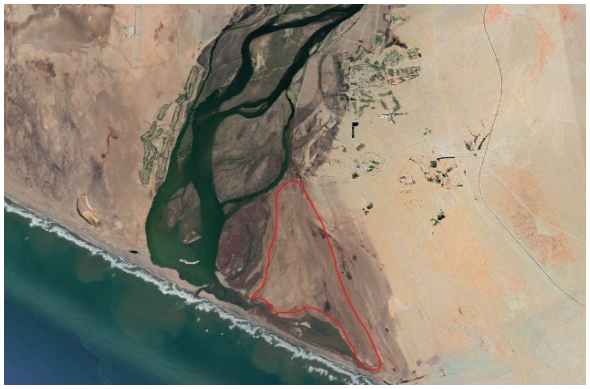
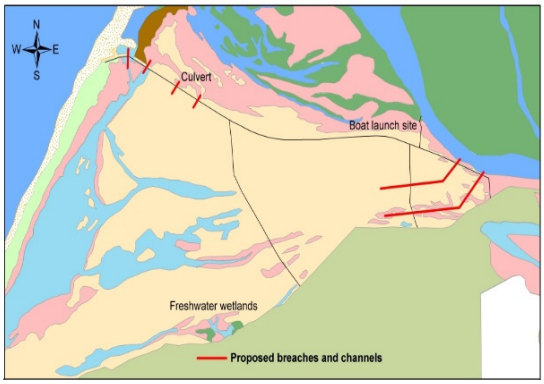


Figure S4. Distribution of habitats in the Orange River Estuary. Location and area cover of degraded salt marsh indicated.



(a) Orange River mouth indicating desertified salt marsh area (red polygon).

Wind blow dust covering *Salicornia pillansii* in the desertified salt marsh area.



(c) Restoration activity – to remove causeway (black line) at identified breach sites (red lines).

Working for Water activities to remove the causeway.

(e) Salt marsh grows (green) where hydrological connectivity has taken place. Estuary connection with sea: channel bottom right of photo.

Regrowth of *Cotula coronopifolia*. The green re-establishing salt marsh is shown in photo (e).

Figure S5. Restoration of salt marsh at the Orange River mouth, showing (**a**) and (**b**) the desertified salt marsh, (**c**) the proposed breaches and channels in the old causeway to ensure connectivity of the main Orange River channel with the desertified salt marsh [5], (**d**) the restoration activities, and (**e**) and (**f**) the re-establishment of salt marsh.

Olifants Estuary

Table S5. Potential area available for salt marsh restoration at the Olifants Estuary.

Salt pans 59 ha	50% available for restoration 29.5 ha
Agriculture 746 ha	Most occurs > 2.5 m MSL, ~25 % (186.5 ha) available for restoration consisting of supratidal salt marsh

Floodplain salt marsh is dominant in the Olifants Estuary; this consists of monospecific stands of the succulent *Salicornia pillansii* interspersed with a high percentage of bare ground. 143 ha of supratidal salt marsh and 797.1 ha of floodplain salt marsh has been mapped by [6]. The latter is a specific habitat type that is dominant on the west coast, it is naturally dry, sparsely vegetated and very difficult to restore once degraded as the bare areas become hypersaline. The supratidal zone is flooded during spring tides and extreme events such as river floods and storm events at sea. The floodplain is elevated above the supratidal zone and is only covered with water during large flood events. An impact of the extensive water abstraction in the catchment of the Olifants Estuary is that low base flows occur for longer periods at present compared to natural conditions and seawater now extends further upstream. The estuary is tidal for approximately 32 km upstream from the mouth. In addition to baseflow the occurrence of major floods (> 100 m^3 s^{-1}) has been reduced from 54 to 41% [6]; these would be important in flushing salts and reducing salinity in elevated areas.

Salt works at the mouth have removed approximately 59 ha of salt marsh habitat (Figure S6). Half of this area could be potentially restored. Agriculture (746 ha) occurs in the supratidal salt marsh and floodplain areas and approximately 25% (186.5 ha) of this would be available for restoration. The aridity of the area restricts agricultural activity to sheep and goat grazing except in the upper estuary / river reaches, where irrigation with water from the lower Olifants River Irrigation Scheme is possible. In the middle to upper reaches a large area of habitat (~50 ha) was removed for the construction of a dam. Because

of the aridity of this area restoration is completely dependent on wet years and freshwater inflow to the estuary from the upstream river. Freshwater input and flooding are important as this lowers the salinity of the water column and raises the depth to the water table in the floodplain so that this is accessible to the halophytic plants. If flooding does not occur the plants die, leading to desertification, similar to what occurred at the Orange River Estuary [7]. [8] showed that the cover abundance of *Salicornia pillansii* was visibly reduced where the water table was deeper than 1.5 m and where the electrical conductivity was > 80 mS cm^{-1}. Loss of vegetation cover leads to bare, dry salt pans that are easily eroded by wind and water.

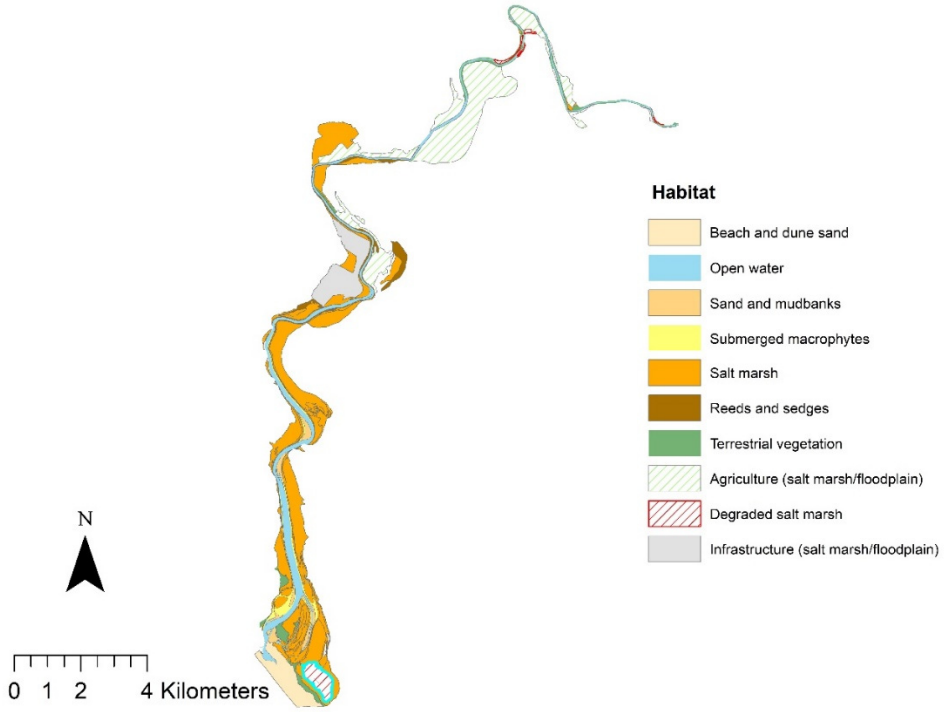


Figure S6. Habitat map for the Olifants Estuary indicating degraded and agricultural areas available for restoration. Salt works indicated by light grey with blue outline.

Swartkops Estuary

Table S6. Potential area available for salt marsh restoration at the Swartlops Estuary.

Salt pans 628 ha	50% available for restoration 314 ha
Degraded 174.8 ha	50% available for restoration 87.4 ha

At Swartkops Estuary there is the potential for restoration of 314 ha of salt pan habitat if there is tidal exchange; currently most of this area occurs above 2.5 m MSL (Figure S7). These saltworks were abandoned by Cerebos Ltd in 2018 after over 50 years of salt production [9]. The site now consists of hypersaline sediment with sparse patches of halophytic vegetation and hypersaline pools. Dominant salt marsh species are *Salicornia pillansii*, *Disphyma crassifolium* and *Suaeda fruticosa*. The once abundant and diverse birdlife of the site has all but disappeared. Zwartkops Conservancy has a plan to fill the salt pans with water from the adjacent estuary and nearby Motherwell canal. The Redhouse pan will be used to treat the urban stormwater that is currently impacting water quality in the Swartkops Estuary and estuary water will be used to fill the Bar None saltpan (Figure 5, main article). Recreating a wetland at the saltworks would provide a regionally important breeding site for resident waterbird species and stopover sites for migratory species.

These activities will not only improve aquatic habitat for waterbirds, but also improve blue carbon storage and nutrient filtration.

When water levels were high the islands within this saltpan provided safe breeding areas for waterbirds isolated from egg poachers and small mammalian predators. This saltpan was considered the most important mainland breeding ground in the Eastern Cape for various resident waterbird species including the Caspian tern, white-breasted cormorant, kelp gull, grey-headed gull and sacred ibis [9]. Summer months saw a large influx of Palearctic migrant waterbirds, especially waders, which would feed at the saltpans as water levels would decrease to expose wet mudflats providing feeding areas.

The rehabilitation of the saltworks as a waterbird habitat aligns with Section 56e (principles for mine closure) in the Mineral and Petroleum Resources Development Act (Act No 28 of 2002), which states that "the land is rehabilitated, as far as is practicable, to its natural state, or to a predetermined and agreed standard or land use which conforms with the concept of sustainable development". The rehabilitation of mines in South Africa is now governed by the Regulations for Financial Provision for Prospecting, Exploration, Mining and Production Operations issued in Government Notice R1147 (GNR 1147) and promulgated under the National Environmental Management Act (Act No 107 of 1998). The regulations also stipulate that any holder of mining rights or permits must develop plans for rehabilitating any decommissioned mining sites and financial provision for said rehabilitation [9]. Thus, Cerebos have an obligation to restore the abandoned salt pans at Swartkops Estuary.

Besides the salt pan areas, salt marsh and floodplain have been disturbed by housing, bridge and railway construction since 1817. These developments resulted in the loss of intertidal but mostly supratidal habitat. The banks of the estuary in the middle and upper reaches are also disturbed by the presence of alien plants. These need to be removed to improve the health and ecological integrity of the estuary. Disturbed (degraded) habitat that has the potential for restoration is approximately 87 ha. This is in a degraded state due to trampling, footpaths and general disturbance (Figure S7). When these pressures are removed surrounding salt marsh species (Table S2) will naturally colonize the area by seed or vegetatively. In the upper reaches water hyacinth has spread due to nutrient rich river input from upstream wastewater treatment plants.

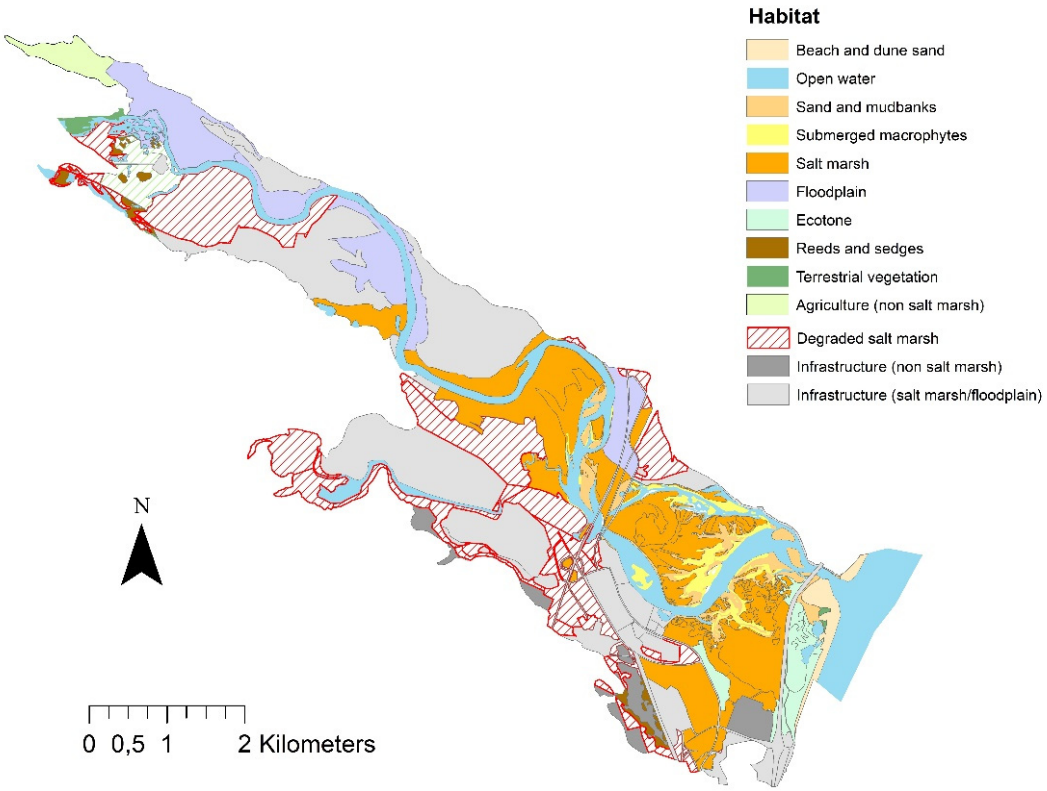


Figure S7. Habitat map for the Swartkops Estuary indicating degraded and agricultural areas available for restoration. Salt works indicated by light grey with blue outline.

Gamtoos Estuary

Table S7. Potential area available for salt marsh restoration at the Gamtoos Estuary.

Agriculture 215 ha	~25 % (54 ha) available for restoration consisting of supratidal salt marsh
Degraded 242.4 ha	50% available for restoration 121.2 ha currently bare and saline

Gamtoos Estuary has 215 ha of agricultural and 242 ha of degraded habitat (Figure S8). Approximately 25% (54 ha) and 50% (121.2 ha) of this area has the potential for restoration. This would have originally consisted of large supratidal salt marsh and floodplain areas. *Salicornia pillansii* is the dominant species in the remaining areas (Figure S8). The remaining areas. Agriculture consisting of mostly vegetable cultivation and cattle grazing takes place. The degraded areas are dry and saline and will require hydrological connectivity and freshwater inflow to restore. Poor water quality due to agricultural drains is also a concern.

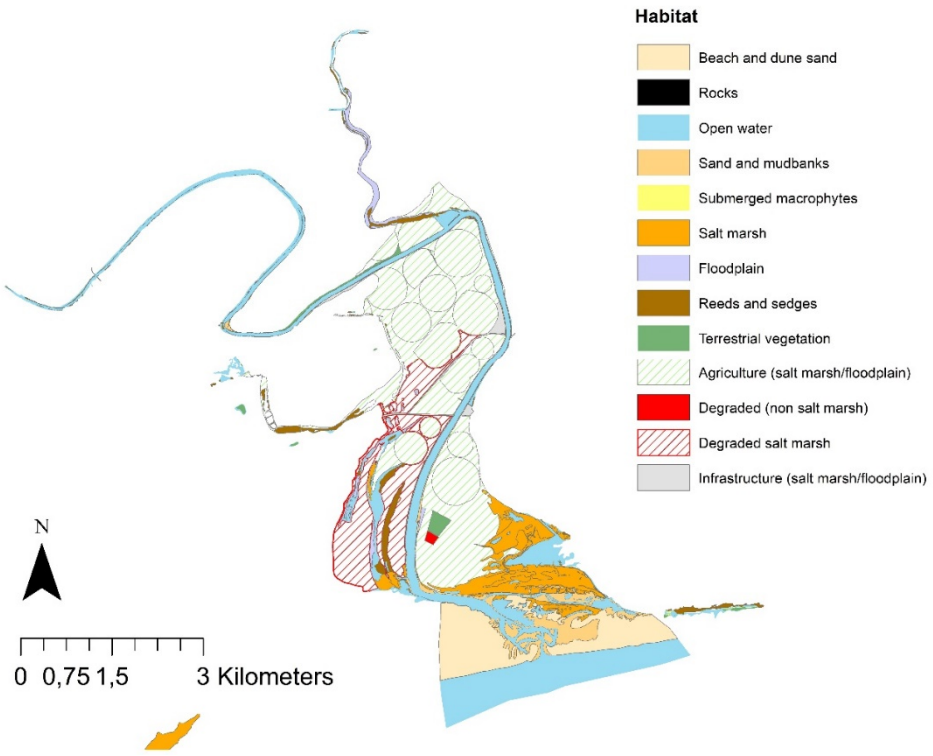


Figure S8. Habitat map for the Gamtoos Estuary indicating degraded and agricultural areas available for restoration.

Gouritz Estuary

Table S8. Potential area available for salt marsh restoration at the Gouritz Estuary.

Agriculture 540.8 ha	Most > 2.5 m MSL, ~25 % (135.2 ha) available for restoration consisting of supratidal salt marsh
Degraded 2.6 ha	50% available for restoration, 1.3 ha

Agriculture covers a large area of the Gouritz Estuary floodplain (540.8 ha, Figure S9). Approximately 25% of this could be restored (135.2 ha). In 2013 only 138 ha was mapped as intact supratidal salt marsh where *Salicornia pillansii* was the dominant species. A small natural floodplain area (27 ha) was covered by the grass *Stenotraphrum secundatum*. Agricultural drainage has also disturbed the water table and resulted in poor estuary water quality.

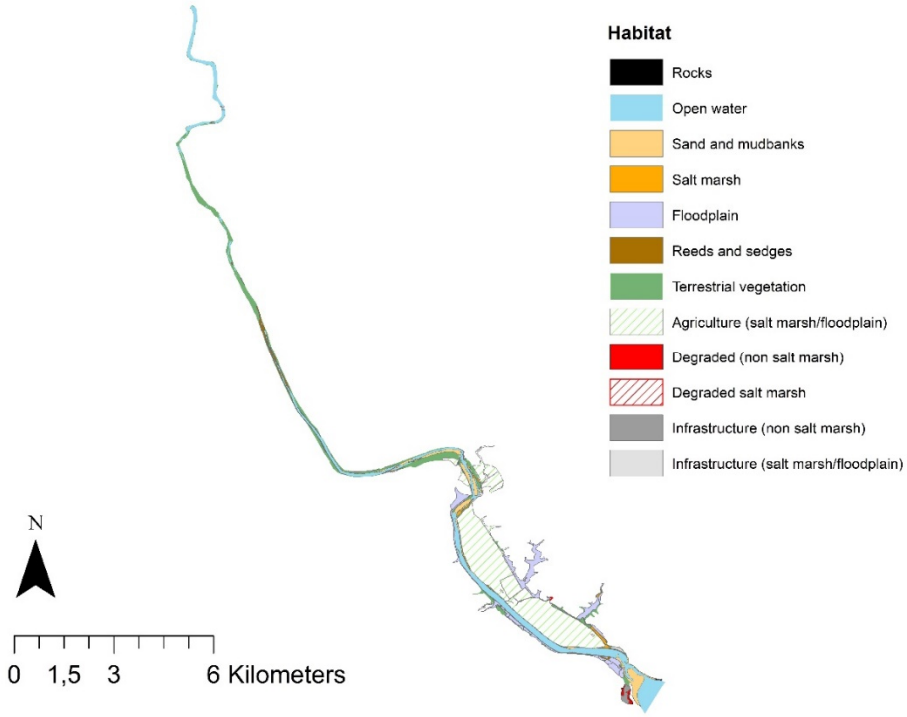


Figure S9. Habitat map for the Gourtiz Estuary indicating degraded and agricultural areas available for restoration.

Klein Brak Estuary

Table S9. Potential area available for salt marsh restoration at the Klein Brak Estuary.

Agriculture 201.7 ha	Most > 2.5 m MSL, ~25 % (50.4 ha) available for restoration consisting of supratidal salt marsh and floodplain
Degraded 149.4 ha	50% available for restoration, 74.7 ha

There have been significant reductions in freshwater inflow (26% decrease in mean annual runoff from 50.7 to 37.66 million m^3) and a decline in water quality from the catchment of the Klein Brak Estuary. This has negatively impacted estuary and salt marsh health. There are extensive formal and informal settlements on the floodplain of the Klein Brak Estuary (526 ha) mostly above 2.5 m MSL. Sections of the riparian area have been stabilised and hardened, resulting in loss of tidal connectivity. Many of these activities have been carried out illegally. In addition, barriers have been erected in both arms in the upper estuary to prevent salinity creep, further reducing tidal flows and leading to degradation of marshes. Trampling by grazing cattle also occurs in the supratidal and floodplain area. This reduces vegetation cover, increases the potential for land erosion and sediment input into the estuary. Existing salt marsh vegetation (333 ha) is represented by *Salicornia meyeriana, Disphyma crassifolium, Salicornia decumbens, Salicornia pillansii*, and various saline grasses (Figure S10). These same species would colonise the restored areas once the pressures were removed.

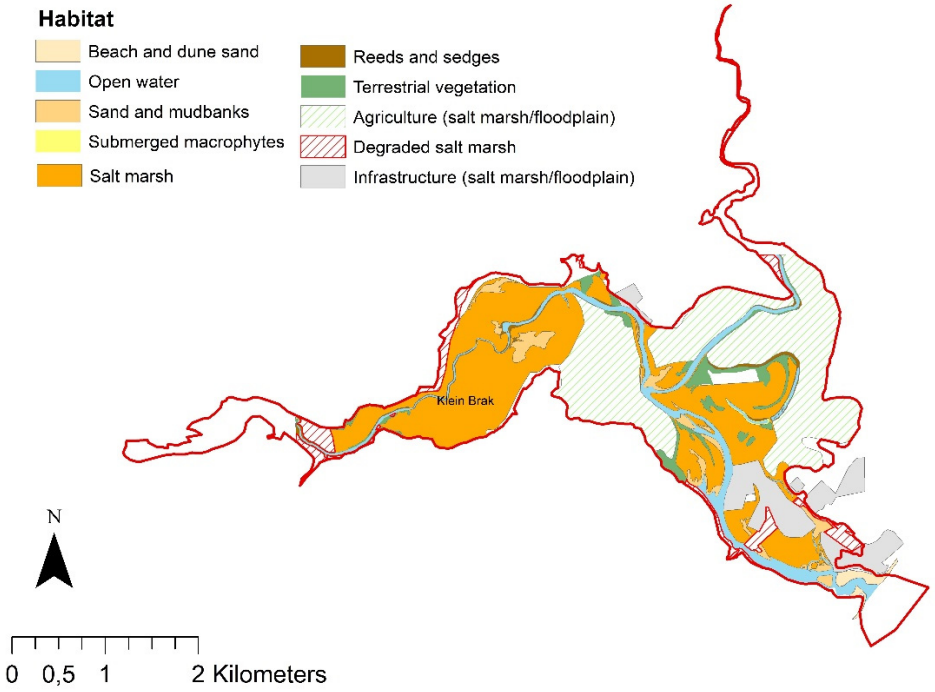


Figure S10. Habitat map for the Klein Brak Estuary indicating degraded and agricultural areas available for restoration.

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