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Salt Marsh Restoration for the Provision of Multiple Ecosystem Services

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Abstract: Restoration of salt marsh is urgent, as these ecosystems provide natural coastal protection from sea-level rise impacts, contribute towards climate change mitigation, and provide multiple ecosystem services including supporting livelihoods. This study identified potential restoration sites for intervention where agricultural and degraded land could be returned to salt marsh at a national scale in South African estuaries. Overall, successful restoration of salt marsh in some estuaries will require addressing additional pressures such as freshwater inflow reduction and deterioration of water quality. Here, we present, a socio-ecological systems framework for salt marsh restoration that links salt marsh state and the well-being of people to guide meaningful and implementable management and restoration interventions. The framework is applied to a case study at the Swartkops Estuary where the primary restoration intervention intends to route stormwater run-off to abandoned salt works to re-create aquatic habitat for waterbirds, enhance carbon storage, and provide nutrient filtration. As the framework is generalized, while still allowing for site-specific pressures to be captured, there is potential for it to be applied at the national scale, with the largest degraded salt marsh areas set as priorities for such an initiative. It is estimated that ~1970 ha of salt marsh can be restored in this way, and this represents a 14% increase in the habitat cover for the country. Innovative approaches to restoring and improving condition are necessary for conserving salt marshes and the benefits they provide to society.

Keywords: socio-ecological system; salt pan; estuary; habitat loss; degradation; ecosystem health

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1. Introduction

Worldwide, salt marshes provide key ecosystem services to coastal communities such as carbon sequestration, coastal protection, wave attenuation, trophic enrichment of coastal waters, nursery areas for fish species, permanent or transient habitat for aquatic invertebrates, and resting areas for migratory birds [1]. The estimated total value of these ecosystem services is disproportionately high given that salt marshes cover less than 1% of Earth's surface [2]. Despite their ecological and socio-economic importance, these habitats are threatened by multiple anthropogenic pressures such as freshwater inflow reduction, land-use change, and development resulting in fragmentation and habitat loss, biological invasions, and pollution [3–6]. Furthermore, salt marshes are threatened by natural hazards such as sea storms, flooding, and sea-level rise, which are predicted to increase in intensity and frequency with climate change [7,8]. It is estimated that since the mid-20th century, the world's salt marshes are being lost at a rate of 1–2% annually [9], leading to substantial losses in ecosystem service provisioning. Global loss of salt marsh is estimated at between 25% and 50% [10]. In the near future, existing salt marshes will cross a threshold resulting in rapid losses as climate change-driven sea-level rise accelerates [11]. Current management approaches that are aimed at conserving coastal ecosystems have not been adequate, and ecological restoration of degraded areas is necessary to maintain the ecological integrity and service provision of these vital ecosystems [12,13].

Ecological restoration has become increasingly relevant across the world's ecosystems with this decade (2021–2030) being declared the "UN Decade on Ecological Restoration" by the United Nations General Assembly [14,15] calling for a "Decade of Socio-Ecological Restoration". Restoration is the process of assisting the recovery of damaged, degraded or destroyed systems. Ten guiding principles have been defined for the UN Decade on Ecosystem Restoration [16,17]. All of these apply to salt marshes; for example, Principle 3 refers to the continuum of restorative activities which includes reducing impacts, remediation, and rehabilitation moving towards ecological restoration (Figure 1). Impacts on salt marshes are variable and often need to be addressed with site-specific context, but common pressures include tidal restriction, encroaching development as well as trampling and grazing by livestock.

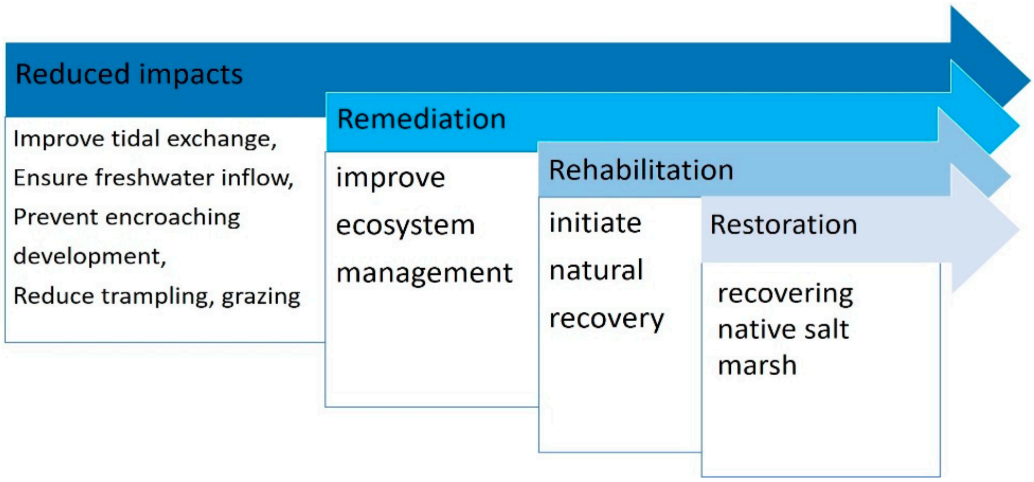


Figure 1. Restorative continuum to improve salt marsh biodiversity, health and ecosystem services (adapted from Society for Ecological Restoration, [16]).

Salt marsh management has shifted in response to calls for nature conservation and an appreciation of these ecosystems in delivering multiple services. Historically, salt marshes were managed for land reclamation, which focused on utilization, but there has since been a shift to protection and now restoration of these ecosystems is prioritized [18,19]. With high intrinsic ecological and economic value, ecological restoration has become recognized as critical for ecosystems like salt marshes that can provide multiple services (Figure 2; [20,21]). Restored salt marshes are valuable "blue carbon" ecosystems, as they can sequester and store carbon at efficient rates for centuries [22,23], thereby presenting important opportunities for climate change mitigation. Additionally, salt marshes provide nursery habitats and support fisheries which are crucial to food security and livelihoods around the world [24]. Salt marshes also reduce the costs associated with property damage by coastal flooding by millions of dollars [25], among various other ecosystem services. The ecological value of healthy salt marshes is recognized by the considerable investment in salt marsh restoration [26]. However, the human well-being domains of salt marsh are poorly understood and require further research [27].

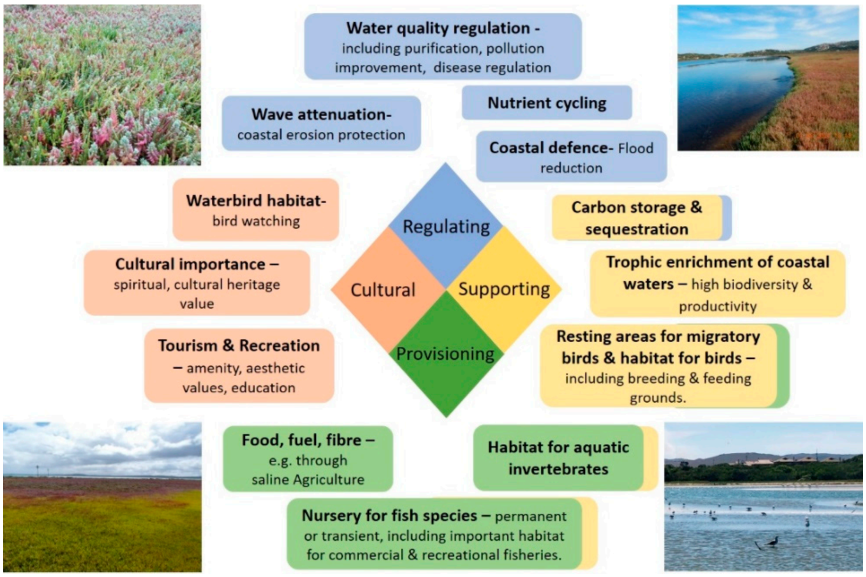


Figure 2. Ecosystem services provided by salt marshes.

Salt marsh restoration has received global attention particularly in the Northern Hemisphere, where these ecosystems are expansive but have been impacted by dikes, sea walls, and conversion to agricultural lands such as pasture for livestock grazing [28,29]. In comparison, the potential for salt marsh restoration in developing countries is less well-known due to the limited information on the extent and potential impacts. As salt marshes occur in dynamic coastal environments and are subjected to distinct ecological processes and local pressures [30,31], this paucity of research needs to be addressed through site- and context-specific studies to guide restoration.

In South Africa, salt marshes occur in sheltered estuaries, as the relatively straight coastline is subjected to high wave energy. The region is microtidal (tidal range < 2 m), with intertidal salt marsh occurring below the mean spring high water mark and supratidal salt marsh above this. Salt marsh includes herbs, grasses, and low shrubs. Lower intertidal salt marsh occurs between mean high water spring tide to mean high water neap tide with common species such as *Spartina maritima* (Curtis) Fernald and succulent halophytes *Salicornia meyeriana* Moss, *S. tegetaria* (S Steffen, Mucina and G Kadereit) Piirainen and G Kadereit, *S. natalensis* (Bunge ex Ung.-Sternb.) A. J. Scott, *Triglochin bulbosa* L., *T. buchenaui* Köcke, Mering, and Kadereit and *Cotula coronopofolia* L. [32,33]. Upper intertidal salt marsh occurs among extreme high waters spring tide to mean high water spring tide with common species such as *Salicornia decumbens* (Toelken) A.J. Scott, *Limonium scabrum* (Thunb.) Kuntze and *Chenolea diffusa* (Thunb.) Kuntze. Supratidal salt marsh typically occurs above 2.5 m MSL (> normal spring tide level) and species include *Stenotaphrum secundatum* (Walter) Kuntze, *Sporobolus virginicus* (L.) Kunth, *Salicornia pillansii* (Moss) A.J. Scott, *Disphyma crassifolium* (L.) L. Bolus, *Juncus* Society for Ecological Restoration *acutus* L., *J. kraussii* Hochst., and *Plantago crassifolia* Forssk.

It is estimated that nearly 45% of South Africa's salt marsh habitat has been lost due to the fact of development and agriculture in the past century [33]. Major pressures on estuaries in this region include altered freshwater inflows, pollution, land use and development, exploitation of living resources, and biological invasions [5,34]. The restoration of estuaries and associated habitats, including salt marshes, has been identified as a management priority in the latest South African National Biodiversity Assessment [35].

Although salt marsh restoration in South Africa has been quite limited, to date there is ample opportunity for such at the national scale. Restoration would enhance the provision of estuarine ecosystem services that are estimated to contribute R 4.2 billion to the national economy annually [36]. Most estuary restoration interventions have addressed hydrological or hydrodynamic issues such as the reconnection of the iMfolozi/uMsunduze and St. Lucia estuaries [37] and the active management of the Zandvlei Estuary mouth to maintain water quality [38]. Some physical habitat restoration has been carried out at the Knysna and Keurbooms estuaries by deploying artificial structures to prevent bank erosion, which, in turn, provides alternative habitats for estuarine fauna [39]. Targeted restoration against salt marsh loss was carried out to a limited extent at the Orange Estuary as part of a national payment for ecosystems services programme [40]. At the Groot Brak Estuary, removal of the alien invasive grass *Spartina alterniflora* Loiseleur resulted in re-growth of indigenous salt marsh [41].

A major shortcoming in previous estuary restoration attempts in South Africa has been the lack of a national framework—interventions have mostly been implemented ad hoc and in isolation. A strategic national framework is necessary to ensure restoration success [13,42]. In this study, a socio-ecological systems framework for salt marsh restoration is presented in which the extent of pressures is identified, and feasible restoration interventions are outlined. This framework is presented in the South African context but is composed of key elements derived from international restoration frameworks (e.g., [16,27,43,44]) and is thus globally relevant and applicable to salt marshes elsewhere. Restoration of salt marsh at the Swartkops Estuary is used as a case study to illustrate the site-specific application of this framework for the delivery of multiple ecosystem services. At this site, the proposed restoration approach will allow for stormwater run-off to be routed to an abandoned salt works with the aim to improve aquatic habitats for waterbirds, blue carbon storage, and nutrient filtration. This will provide cultural benefits and improve community well-being; thus, a single restoration intervention can provide multiple benefits.

2. Study Approach

Changes in the condition and extent of salt marsh habitat in South Africa were investigated in relation to identified pressures. The possibility of removing these pressures to potentially restore salt marsh was investigated in detail for seven priority estuaries. Global frameworks and restoration approaches were reviewed to develop a socio-ecological systems approach for salt marsh restoration. This framework was applied to the restoration of salt marsh at Swartkops Estuary.

2.1. Salt Marsh Extent and Distribution

Vegetation maps were created by manually digitizing salt marsh habitats in ArcGIS® (Version 10.2) using color orthorectified aerial photographs from the South African Chief Directorate: National Geo-Spatial Information (CD:NGI), which have a spatial resolution of 50 cm. These images are already orthorectified and have been corrected for lens, tilt, and height distortion. The coordinate reference system for the imagery is the Transverse Mercator Projection and the Ellipsoid is WGS84. Digitized polygons were then projected into the South African Albers Equal Area conical projection with the central meridian at 25°E, parallels at 24°S and 33°S, and the spheroid and datum the World Geodetic System of 1984 (WGS84). Differences in color and physiognomy were used to identify and classify different habitats based on site visits and field knowledge. Mapping was conducted at a scale of 1:2000. This fine scale mapping is preferred over the traditional supervised and unsupervised classification methods using satellite imagery because salt marsh habitat is often only a few m^2 in extent.

Past salt marsh cover was mapped using the earliest available aerial photographs (1934–1937), while present-day cover was mapped using photographs captured between 2018–2021. The present salt marsh cover was also updated and verified using more recent satellite imagery (Google Earth™) and ground-truthing in the field using ArcPad® 10.1 loaded on a Trimble Juno® GPS. The intertidal and supratidal salt marsh zones were distinguished based on species composition recorded during field surveys and from available elevation data, with supratidal salt marsh occurring from approximately 1.5 m AMSL (above mean sea-level) [33]. Floodplain salt marsh occurs from approximately 2.5 m AMSL;

dominant halophytic plants here are *Salicornia pillansii* and *Salsola aphylla* L.f [45]. The past and present vegetation maps (Figures S2, S4 and S6–S10) were compared to determine the change in salt marsh cover over time. Only land-cover changes due to the development and other related direct human impacts were quantified, while changes due to the indirect pressures (e.g., water quality and freshwater input alterations) were qualitatively described. All spatial data for the habitat assessment are available from the National Botanical Database (Opus at SANBI: NBA 2018: Mapped estuarine habitat in South Africa [46]).

2.2. Identification of Pressures

Six categories of pressures have been identified for South African estuaries:

1. Coastal development and habitat degradation;
2. Freshwater inflow modification;
3. Pollution and changes in water quality;
4. Biological invasions by alien invasive species;
5. Manipulation of estuary mouths (influencing tidal connectivity);
6. Exploitation of living resources (fish and invertebrates);

Each estuary has been assessed and given a pressure rating (i.e., low, medium, and high to very high) in terms of severity and need for intervention [34]. Coastal development and habitat degradation are considered in Section 2.1. in terms of loss of salt marsh extent. The largest salt marsh areas are found in estuaries that remain open to the sea and, thus, manipulation of estuary mouths was not considered. There is little current understanding of responses of salt marshes to exploitation of living resources and, therefore, this pressure was not considered in this study. The other pressures (2, 3, 4) were identified for seven estuaries that had the largest potential for salt marsh restoration. While it is important to consider spatial scales impacted by pressures (e.g., [47,48]), the pressures identified in this study cannot all be directly represented spatially. However, these pressures each have the potential to impact salt marsh condition and the associated ecosystem services; therefore, the changes in salt marsh extent due to the fact of these pressures were indicated as needing to be addressed in order to ensure successful restoration. The focus of the study was restoration of salt marsh extent. Species composition was not a focus, but this will change in response to changes in elevation, inundation, and salinity.

The pressure ratings (i.e., low, medium, and high to very high) were obtained from the Estuary Health Index scores. The EHI has been applied on three occasions in South Africa to all estuaries to assess changes over time for reporting on the implementation of the National Biodiversity Act. Pressure ratings correspond to: low = $\geq$ 75% similar to natural (Categories A–B), medium = 75–60% (Category C), high = 60–40% (Category D), and very high = $\leq$ 40% (Categories E–F) [5]. For freshwater inflow modification, changes in low flow (60% of indicator rating) and floods (40% of indicator rating) were used. In the case of pollution, changes in nutrient inputs were used to estimate the degree of this pressure [5,35]. The percentage coverage of the estuarine area by alien invasive plants was used to indicate where this pressure was low = $\leq$ 5% cover, medium = 5–15%, and high = $\geq$ 15%. Alien invasive plants include both terrestrial species (e.g., *Acacia longifolia* (Andr.) Willd. E,T; *Lantana camara* L. E,T; *Solanum americanum* Mill.) and floating aquatic invasives (e.g., *Azolla filiculoides* Lam.; *Pontederia crassipes* (Mart. and Zucc.); *Pistia stratiotes* L.). Terrestrial species invade disturbed high-elevation salt marsh areas displacing indigenous species, and floating invasive aquatic plants are deposited onto salt marsh areas causing smothering and die-back.

2.3. Identification of Sites for Restoration

The historic disturbances in salt marshes were identified from past and present vegetation maps and other non-spatial records of area change available in the National Botanical Database. Areas denoted as “Developed” in the database were areas where natural land cover (i.e., salt marsh) had been completely removed and replaced with hard infrastructure. Areas classified as “Degraded” were those where revegetation or restoration to natural land cover was possible, i.e., grassed recreational areas that could be converted back to supratidal or floodplain salt marsh given the correct environmental conditions. Sea-level rise would accelerate this process in some systems, particularly if physical processes and substrates were still largely intact. Specific restoration actions were identified for the seven estuaries with the largest salt marsh areas.

2.4. Development of a Socio-Ecological Systems Framework for Salt Marsh Restoration

Ecosystem services, the benefits that people derive from nature (Figure 2), form a complex adaptive socio-ecological system (SES) whereby the ecological and socio-economic aspects interact with each other at multiple spatial and temporal scales [49]. A socio-ecological systems framework for salt marsh restoration has been developed to link the state of the ecosystem to the state of the societal system through ecosystem services (Figure 3). The SES framework presented by [50], based on [51], the millennium ecosystem assessment approach [52], and others was used to develop a salt marsh specific framework. Key ecosystem services that need to be considered when setting restoration objectives for salt marshes include fisheries and nursery habitats, carbon storage, erosion control and coastal protection, nutrient sequestration and cycling, habitat for invertebrates, and resting areas for migratory birds (Figures 2 and 3).

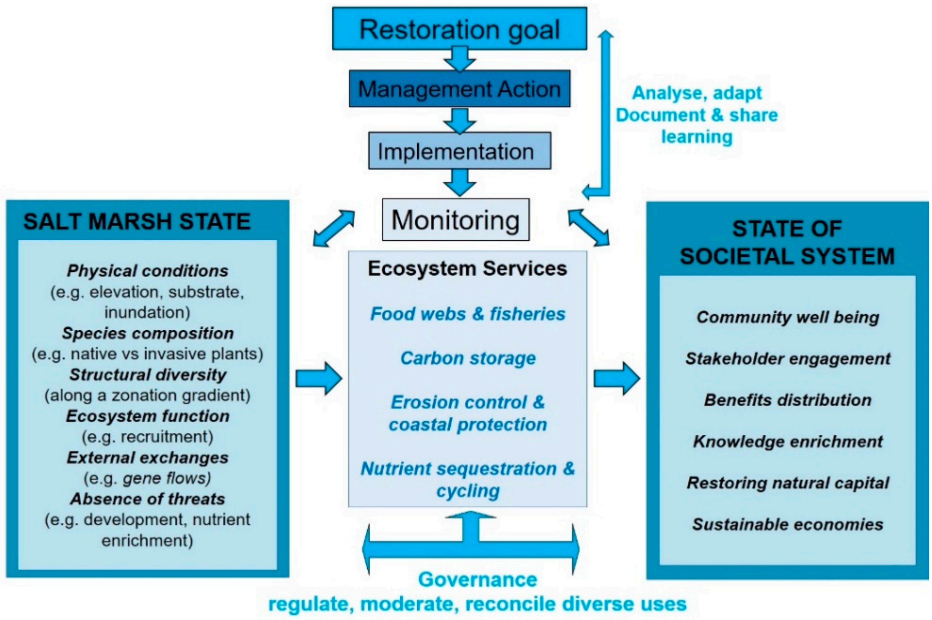


Figure 3. Socio-ecological systems framework for salt marsh restoration (adapted from [50]).

With an SES approach, restoration takes place in an adaptive management cycle, where objectives are set, actions are implemented, and then monitored. Restoration outcomes are analyzed, and objectives are adapted in a learning-by-doing approach (Figure 3). The success of restoration interventions is measured against restoration objectives, which should include ecological and social targets. In South Africa, the estuary state is measured using the national Estuarine Health Index [5,35], while the state of the social system can be measured through uses and values that contribute towards human wellbeing [50]. The Swartkops Estuary is a well-studied system; available information and local knowledge was used to show how the framework can be applied as a case study. The restoration intervention is to re-create aquatic habitat at an abandoned salt works by routing stormwater run-off from the Motherwell Canal to this site. A network of 14 stormwater drains transport litter, debris, and raw sewage (during infrastructure failures) down a 4.2 km long canal that services the large urbanized Motherwell Township [53]. Although some of the water from the canal enters an artificial wetland before entering the estuary, it is largely ineffective at coping with the high volume of stormwater that is received. The Motherwell

Canal is therefore a major point source of nitrogen (ammonium), trace metals, and fecal bacteria that contaminates the middle reaches of the estuary [53]. The area adjacent to the Motherwell Canal outlet is regularly used by church members for baptisms and as a fishing and boating site.

3. Results

3.1. Habitat Extent, Distribution, and Identification of Pressures

Historic changes for intertidal (Table 1) and supratidal (Table 2) salt marsh in South Africa are mostly represented by losses. For intertidal salt marsh, the largest losses have occurred at the Groot Berg, Swartkops, and Knysna estuaries. At the Groot Berg Estuary, 655 ha of intertidal salt marsh has been lost following conversion of the land for agricultural use and infrastructure development such as a marina and solar salt works. The Swartkops Estuary has had a long history of development and removal of intertidal salt marsh (344 ha) for bridges, roads, and houses. At the Knysna Estuary, 242 ha of intertidal salt marsh has been lost due to the fact of development including the placement of infrastructure such as marinas, jetties, and roads. Additionally, at Knysna the elevation of some intertidal areas was increased to allow for property development, including residential areas which have replaced salt marsh. Other widespread threats to intertidal salt marsh include salinization, disturbance, and grazing pressure from livestock.

Table 1. Changes in the largest intertidal salt marsh areas (ha) in South Africa (east to west) and the associated pressures and protection status of each estuary. Habitat trends are indicated by arrows (🡻 decreasing, 🡹 increasing, and 🡺 stable). Updated from [33] and [54].

Estuary	Historic Area (1937)	Present Area (2021)	Habitat Trend	Pressures	Protection Status
Kosi	58	58	🡺	Cattle browsing and grazing, trampling by people and cattle, fires.	National (iSimangaliso Wetland Park World Heritage Site)
Great Fish	144	133	🡻	Disturbance in lower reaches, flow reduction.	None
Kowie	83	27	🡻	Development—houses, marina. Eutrophication.	None
Swartkops	537	193	🡻	Development—industrial, infrastructure. Eutrophication.	None
Keurbooms	105	72	🡻	Development—houses, jetties.	Partial, Provincial (CapeNature)
Kromme	89	68	🡻	Development—houses, jetties, marina. Changes in freshwater inflow.	None
Knysna	537	295	🡻	Development—residential, infrastructure. Eutrophication.	Partial, National (SANParks).
Langebaan	806	806	🡺	Grazing pressure removed with establishment of protected area, potential for further expansion.	National (SANParks)
Groot Berg	1965	1310	🡻	Agriculture, development, marina.	Partial, Provincial (CapeNature)
Olifants	195	97	🡺	Salinization, flow reduction.	None
Orange	154	144	🡻	Mining, causeway, salinization, flow reduction.	Ramsar

Table 2. Changes in the largest supratidal salt marsh areas (ha) in South Africa (east to west) and the associated pressures and protection status of each estuary. Habitat trends are indicated by arrows (🡻 decreasing, 🡹 increasing, and 🡺 stable). Updated from [33] and [54].

Estuary	Historic Area (1937)	Present Area (2021)	Habitat Trend	Pressures	Protection Status
Kosi	229	229	🡺	Cattle browsing, trampling by people and cattle, fires.	iSimangaliso Wetland Park World Heritage Site
Keiskamma	312	181	🡻	Agriculture, cattle browsing.	None
Swartkops	643	359	🡻	Development—industrial, infrastructure.	None
Gamtoos	240	84	🡻	Agriculture, flow reduction.	None
Keurbooms	398	304	🡻	Development.	Partial, Cape Nature
Knysna	680	221	🡻	Development—residential, infrastructure.	Partial, Cape Nature
Klein Brak	594	333	🡻	Development, agriculture.	None
Gouritz	220	8	🡻	Agriculture, flow reduction.	None
Heuningnes	500	259	🡻	Agriculture, flow reduction.	Cape Nature/SANParks
Klein	208	206	🡺	Changes in response to water level and mouth condition	Cape Nature
Langebaan	1075	1132	🡹	Grazing pressure removed with establishment of protected area, potential for further expansion.	SANParks
Groot Berg	2926	2178	🡻	Agriculture, flow reduction.	Partial, Cape Nature
Olifants	1442.3	879	🡻	Development—saltworks. Salinization, flow reduction, agriculture (supratidal covers ~183 ha and floodplain 696 ha, mostly loss of floodplain).	None
Orange	1311	627	🡻	Flow reduction and salinization.	Ramsar

For supratidal salt marsh, significant losses have occurred in several estuaries (Table 2). As the supratidal marsh occurs above the high-water mark, these areas are more easily accessible to be developed, converted, or transformed for alternative uses. Large losses due to the fact of agriculture have occurred at the Groot Berg (748 ha), Gouritz (539 ha), Gamtoos (630 ha), and Klein Brak (351 ha) estuaries. These areas consist of a mixture of supratidal salt marsh and floodplain vegetation. Development and industrial pressures have replaced large areas of supratidal salt marsh in the Knysna (242 ha) and Swartkops (675 ha) estuaries. At the Orange and Olifants estuaries, 692 ha and 619 ha have been lost respectively due to the fact of reduced freshwater inflow and loss of major floods resulting in salinization. The only historic increase in salt marsh area has been reported from the Langebaan Estuary (57 ha), which has occurred over recent years following the establishment of a national protected area to remove the pressure of livestock grazing and agriculture.

3.2. Identification of Sites for Restoration

Seven estuaries with the largest salt marsh area losses were identified for restoration (Table 3, Figure S1 and Tables S1 and S2). Vegetation maps were created for each of these systems (Figures S2, S4 and S6–S10). Specific restoration actions were identified for each estuary in relation to the current pressures (Table 4). Priority estuaries for restoration based on area cover and revertability of impacts include the Groot Berg, Swartkops, and Olifants estuaries with their expansive supratidal and floodplain marshes (Table 3, S3, S5 and S6). At the Groot Berg and Swartkops estuaries, there is the potential for salt extraction pans to be restored to estuarine habitat (Figure S3, Tables S3 and S7, [55–57]). It would be possible to restore 50% of this habitat to functional salt marsh (304 ha at Groot Berg and 314 ha at Swartkops) (Table 3). Hydrological connectivity would need to take place before salt marshes could establish here. Desertified salt marsh at the Orange Estuary mouth can also be restored through removal of the causeway (road to the beach) and re-establishment of hydrological connectivity with the main river channel (Table S4 and Figure S5). The Gamtoos, Gouritz, and Klein Brak estuaries have degraded supratidal salt marsh and floodplain areas that can be restored (Tables S7–S9). The Knysna Estuary has lost salt marsh due to the fact of infrastructure development and, therefore, there is little opportunity for restoration.

Table 3. Priority estuaries for salt marsh restoration. Area (ha) of salt marsh lost in specific estuaries due to the salt pan development, agriculture, and other (degraded) activities. The potential for restoration (gain in extent) assumes that it will be possible to restore 50% of the salt pan area, 25% of the agricultural area, and 50% of the degraded area.

Estuary	Salt Pan Area (ha)	50% Restored (ha)	Agriculture (ha)	25% Restored (ha)	Degraded Area (ha)	50% Restored (ha)	Total Potential Restoration Area
Groot Berg	608.4	304	748	187	225	112.5	603.5
Swartkops	628	314	n/a	n/a	175	87.5	401.5
Orange	n/a	n/a	119	29.6	563	281.5	311.1
Olifants	59	29.5	746	186.6	-	-	216.1
Gamtoos	n/a	n/a	215	53.8	242.4	121.2	175.0
Gouritz	n/a	n/a	540.8	136.5	2.6	1.3	137.8
Klein Brak	n/a	n/a	201.7	50.4	149.4	74.7	125.1
Total	1295	648	4073	643.9	1357	679	1970.1

Table 4. Pressures (VH = very high, H = high, and M = medium) that require attention in order to restore salt marsh in seven estuaries that have the largest potential for salt marsh restoration. Specific restoration actions are identified.

	Freshwater Inflow		Water Quality	Invasive Alien Plants	Restoration Actions
	Baseflow	Floods			
Groot Berg	H	H	VH	M	Remove agriculture, restore salt pans, ensure freshwater inflow, bank restoration, improve water quality, and remove alien invasive plants.
Swartkops	VH	VH	VH	H	Remove old berms and upstream barriers, re-establish riparian vegetation, remove alien invasive plants, and rehabilitate abandoned salt pans.
Orange	VH	VH	H	M	Remove causeway, ensure freshwater input to reduce salinization, and control dust input from surrounding mining.
Olifants	M	M	H	H	Remove agriculture, ensure freshwater inflow, and potential for salt pan rehabilitation.
Gamtoos	M	M	M	M	Remove agriculture, ensure baseflow input, and improve water quality.
Gouritz	VH	VH	M	M	Remove agriculture, ensure baseflow input, and improve water quality.
Klein Brak	H	H	M	H	Removal of old berms and upstream barriers to tidal action, remove alien invasive plants, remove agriculture, and improve water quality.

Agriculture has replaced large areas of supratidal salt marsh, and typically these lands have been elevated to allow for freshwater irrigation, which poses challenges for restoration. Within the seven estuaries identified as priorities for restoration (Table 3), it is estimated that approximately 25% of the area converted to agriculture (644 ha) could be restored to salt marsh, as the agricultural practices have been largely abandoned. For the areas identified as "degraded", 50% is considered feasible for restoration (679 ha). The degraded habitats consist of grassy disturbed areas that would take less effort than agriculture to restore to salt marsh. Restoration of salt pans (which occur in two of these estuaries) could return 648 ha of salt marsh (Table 3).

Other pressures that need to be addressed are flow modification, water quality improvement, and removal of invasive alien plants as indicated in Table 4 (medium, high and very high intensity pressures). These are increasing due to the growing population. For example, in the urbanized estuaries, such as Swartkops, freshwater inflow changes and water quality pressures are very high (Table 4). Restoration of salt marsh will not be effective unless freshwater inflow reduction and deterioration of water quality are improved.

3.3. *A Socio-Ecological Systems Framework for Salt Marsh Restoration*

The Swartkops Estuary was used as a case study to illustrate the application of the proposed restoration framework for the delivery of multiple ecosystem services. The details of the general salt marsh framework (Figure 3) were used to develop a specific framework for the restoration of the salt pans at Swartkops Estuary (Figure 4). Extensive salt marsh has been lost at this site due to development. To restore some of this habitat (~314 ha), stormwater run-off will be routed to an abandoned salt extraction pan (Figure 5) to improve aquatic habitat for waterbirds, carbon storage, and nutrient filtration; thus, a single restoration intervention will deliver multiple ecosystem services (Figure 4). As this estuary has cultural and religious significance to local communities, improving the ecological conditions (water quality in particular) will lead to multiple societal benefits. The abandoned salt pan will act as a stormwater detention pond, thereby improving water quality. The stormwater will reduce hypersalinity thus allowing for expansion of the salt marsh.

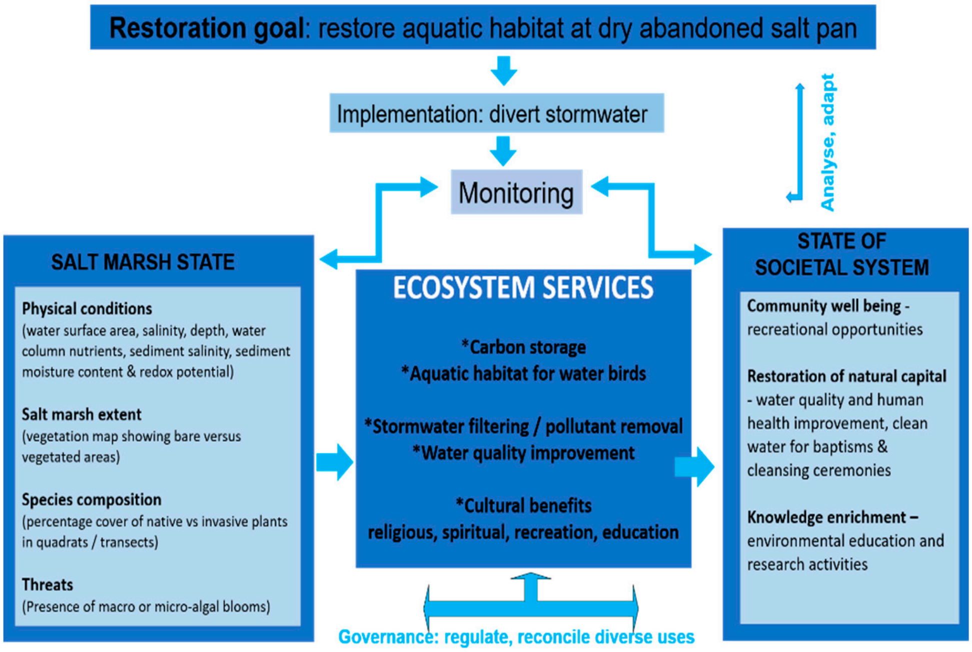
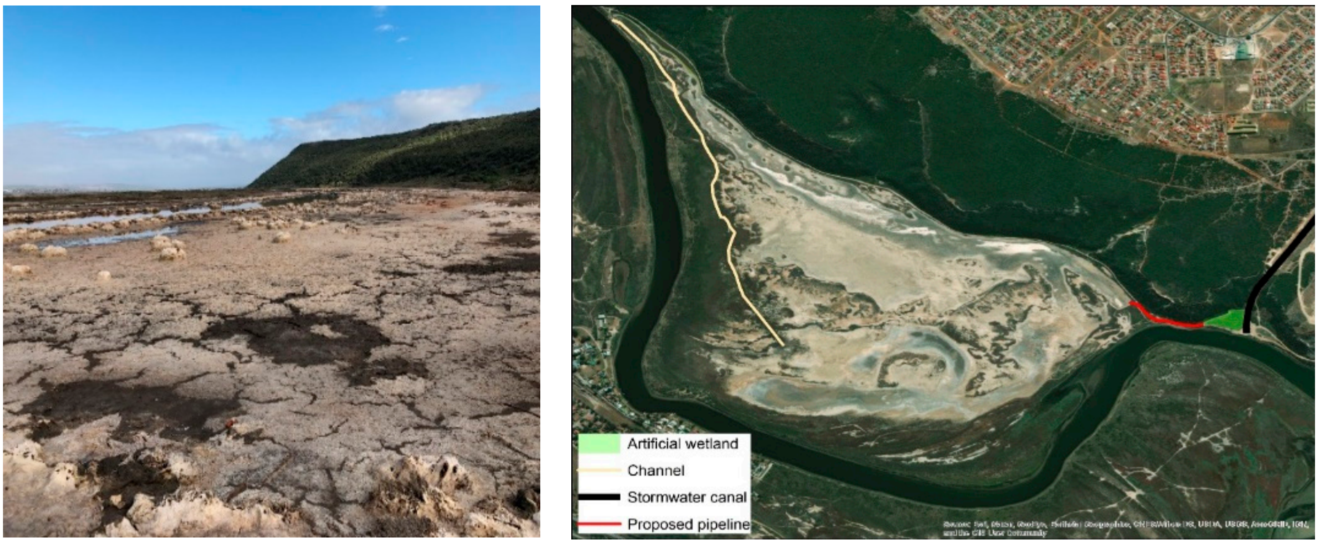


Figure 4. Socio-ecological systems framework for salt marsh restoration at the Swartkops Estuary salt pan.



(**a**) (**b**)

Figure 5. Restoration of salt marsh at an abandoned salt pan, Swartkops Estuary, South Africa, showing (**a**) the bare salinized pan and (**b**) the proposed location of a pipe that is intended to deliver stormwater from the Motherwell canal. Map source: Esri, Maxar, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN and the GIS User Community.

The relationships between salt marsh state, ecosystem services, and state of the societal system (Figure 4) were compiled based on available information for the Swartkops Estuary. Here, the restoration intervention was to route stormwater run-off from the Motherwell Canal to an abandoned salt works to recreate an aquatic habitat. The Motherwell Canal is a source of nutrients, trace metals, and fecal bacteria. This poses a risk to human health and, thus, any improvement in water quality will provide a safer environment for church baptisms and recreational activities such as fishing, boating, and swimming. Restoration of regulating services (water quality and nutrient cycling) are therefore directly linked to improving the ability of the site to provide cultural services (Figure 4). This restoration activity will also enhance supporting services, as one of the main aims was to restore aquatic habitat for migratory birds. Restoration of the aquatic habitat will improve birdlife thus providing birdwatching and ecotourism opportunities if the area is aesthetically pleasing. Additional cultural services that could be derived from the restored site include opportunities for educational programs and ongoing research (Figure 4).

Monitoring of restoration activities needs to take place in a strategic adaptive management cycle (Figure 4) to track the expansion of the salt marsh and improvement of the ecosystem services and related societal benefits. Salt marsh extent and species composition should be measured annually to monitor plant growth and expansion. Threats to the success of the restoration initiative may include the expansion of invasive plants such as *Atriplex lindleyi* Moq. subsp. *inflata* (F.Muell.) Paul G. Wilson as well as algal blooms in response to eutrophication. Ongoing monitoring of summer and winter bird counts for the area will provide evidence of a change in habitat utilization by key species that have been targeted by this restoration approach [57]. Water quality conditions in the salt pan, as well as the estuary, will need to be measured to see if there is an improvement. The number of people utilizing the area and benefitting from the improvement in terms of water quality, birding, and educational opportunities would provide proximate measure of societal benefits.

4. Discussion

Salt marshes and the ecosystem services they provide are rapidly being lost globally. Conservation efforts have not sufficiently prevented these losses, and ecological restoration has become a necessity to preserve these ecosystems. The need for salt marsh restoration is becoming increasingly urgent, particularly in the light of climate change impacts, such as sea-level rise and freshwater flow modification, driving habitat loss and coastal squeeze. The importance of salt marsh restoration is globally recognized, but national strategic frameworks are necessary for successful restoration, as pressures on these ecosystems can be regionally variable as well as site-specific. At present, restoration activities are guided by the UN Principles for Ecosystem Restoration, but examples of national-level frameworks are not readily available for application. In this study, a salt marsh restoration framework is outlined and conceptually applied to a case study in South Africa. This framework is composed of components from various international restoration frameworks and applied to salt marsh restoration globally. Large areas of salt marsh have been lost in South Africa and seven estuaries are recommended as high priority for restoration. Specific restoration actions were identified based on the pressures known to occur at these estuaries and salt marsh sites. The next step would be to apply the SES restoration framework to the seven estuaries identified as priorities for salt marsh.

4.1. Abiotic Pressures and Salt Marsh Restoration in South African Estuaries

The area covered by salt marsh in South Africa is relatively small; however, these ecosystems form a critical biodiversity component and provide several unique and irreplaceable ecosystem services [33]. Identifying areas for potential restoration requires spatial and ecological data. Restoration aims to return an ecosystem into a natural or near-natural state by reversing degradation, which can be carried out by reducing or removing pressures as well as through active habitat reconstruction. When setting a restoration goal, the desired ecological state can be based on the historic condition of the site (before any impacts) or to a comparable undisturbed site [58]. Historical ecological and spatial data can therefore provide important insight to guide restoration goals.

In this study, historic site conditions were compared to the present-day salt marsh extent and ecological state to identify disturbances and pressures. We found that while some pressures were widespread, those that varied regionally could also be linked to changes in climatic conditions such as droughts. For example, dam construction and water abstraction in combination with changes in rainfall patterns have caused salinization of large salt marsh areas on the arid west coast at the Orange and Olifants estuaries [59,60]. Droughts are predicted to intensify in this region as global temperatures continue to rise, therefore posing significant challenges if restoration activities require diversion of increasingly scarce freshwater resources. Although South African legislation recognizes that sensitive environments have required environmental flow allocations, in practice these allocations are not provided during drought conditions [61,62].

Freshwater inflow modifications are also related to a deterioration in water quality [50]. For some estuaries, treated effluent from WWTW are the only sources of inflow during low flow periods. Restoration activities that focus on improving water quality in these systems must also consider the effect of effluent on freshwater volume inputs. Improving water quality is complicated by WWTW infrastructure exceeding capacity or failures, resulting in the release of untreated effluent. This can lead to macroalgal blooms that smother intertidal salt marsh, particularly in closed estuaries that provide the calm sheltered conditions for rapid growth. Eutrophication has also increased the extent of invasive alien aquatic plants such as water hyacinth (*Pontederia crassipes*) [63]. Many of these floating plants in fresher upper reaches of estuaries are transported downstream onto salt marsh during high flow conditions causing smothering and die-back. Changes to hydrological regimes (particularly salinity intrusion) and the proliferation of invasive plants are widespread pressures leading to salt marsh deterioration that are being exacerbated by climate change, especially in tropical regions including parts of Australia, Asia and the Americas [64–68].

Restoration of salt marsh will be dependent on elevation, freshwater inflow, and restoring hydrological connectivity as many of these areas are currently dry and salinized. Conversion of these areas back to salt marsh would be facilitated by an increase in sea-level rise. This would increase tidal and saline conditions facilitating the growth and expansion of salt marsh [69,70]. Studies on estuarine ecotone habitats in South Africa have shown sediment characteristics to be conducive for salt marsh establishment given the correct hydrological processes [71]. However, while seagrass and intertidal salt marsh can expand into supratidal habitats there may be an overall loss of supratidal salt marsh due to the fact of coastal squeeze [33,72].

4.2. Opportunities for Restoration Following Land-Use Change

Salt marsh habitats that have been lost due to the fact of development of hard infrastructure cannot be restored, but there is scope for restoration of areas that have undergone certain types of land-use change. For example, sites that have been modified for salt works that are no longer operational could be restored to salt marsh habitat by removing tidal barriers and re-establishing tidal flows. This has been successful at impounded areas [23,73]. The potential to establish tidal connectivity to the salt pan area at Swartkops Estuary was considered as a restoration approach [70]. However, as the site had been elevated for the construction of the salt works, this limits the potential for tidal exchange. Establishing tidal connectivity to desiccated salt marsh areas has the potential to improve blue carbon storage and increase sediment stabilization, enhance nitrogen removal, and provide support to fisheries through increasing biodiversity and nursery habitats. Restoration actions to restore these ecosystem services would take place along a restorative continuum that includes reducing impacts, remediation, and rehabilitation, moving towards ecological restoration (Figure 1). It will not always be possible to restore salt marshes to a natural state, instead restoration targets can be set that would achieve the most beneficial ecosystem services (Figure 3).

For areas classified as "degraded", it was considered that 50% of this area could potentially be restored to salt marsh (total of 679 ha) by removal of barriers to ensure tidal exchange or increasing freshwater inflow (baseflow and floods) (Table 4). Facilitation of tidal exchange to restore degraded marshes could consist of a single permanent action, e.g., breaching a sea wall/embankment, installing, or widening culverts or excavating tidal creeks. Thereafter, tidal exchange raises moisture levels, reduces salinity, increases sediment supply and plant propagules. Certain species, such as the *Salicornia* succulents, will germinate rapidly from an available seedbank when conditions are suitable [74,75].

Salt marsh habitats that were modified into agricultural lands that have since been abandoned also provide opportunities for restoration. We found that in South Africa, if 25% of the current agricultural area which would naturally be salt marsh is restored, this would add ~644 ha to the total salt marsh cover. However, little is known about the feasibility of restoring agricultural lands to salt marsh and site-specific studies are needed as growth will depend on salinity, elevation changes, sea-level rise, and storm events [76]. Elevation in relation to tidal level is the most important environmental factor affecting salt-marsh species establishment [77]. Early studies established that soil salinity [78], waterlogging [79], wave action [80], and soil aeration [81] are the main determinants of the seaward limit of a species, and interspecific competition for light [82] and nutrients [83] influence the landward limit [77]. A favorable environment for salt marsh establishment will be provided through interaction of these factors. However, site-specific alterations in the environment could influence the successful establishment and only restoring hydrology might not achieve the desired effect. For example, [84] found that changes in soil structure and compaction due to the previous agricultural activities at restoration sites reduced groundwater dynamics, potentially altering the subsurface fluxes of water and nutrients thus affecting the development of marsh vegetation. In Europe, 140 managed realignment projects have been completed to provide sustainable flood risk management and ecological habitat [85]. The potential for managed realignment as a viable salt marsh restoration approach has been identified in regions like Australia [86] and much scope remains to adopt this approach globally.

Salt marsh may recover on its own, without any active intervention, if human activities are stopped. Such passive recovery can be cheaper than active intervention and provide better outcomes. If the proper site conditions are created, then the salt marsh areas are likely to revegetate naturally. Sometimes, plant colonization may also not occur at all or, if it does, occur slowly or be dominated by invasive species [87]. Restoration sites may differ in plant cover but still provide habitat for aquatic wildlife [88]. Passive restoration depends on the availability of target species and the presence of favorable environmental conditions that allow the species to germinate and establish [77]. Research at the Orange River mouth showed successful passive restoration in intertidal areas. There was rapid seed germination once hydrological connectivity was restored [89,90]. However, passive restoration was less successful in restoring floodplain marsh in this arid environment. Active restoration of supratidal salt marsh has been carried out at the Knysna Estuary (on Thesen Island). In this case, plants were grown from vegetated sediment cores as a condition of the marina development between 2000–2007 to ensure that there was no net loss of salt marsh. Much research is still needed to identify specific restoration methods at the identified seven estuaries.

4.3. Application of the Socio-Ecological Systems Framework

In this study, a socio-ecological systems framework for salt marsh restoration was presented that links ecosystem functioning and the well-being of humans to guide meaningful and implementable management and restoration interventions. As the framework is guided by tangible ecosystem services, it is generalized and can therefore be applied at different sites and at different spatial scales depending on the available data. A socio-ecological systems approach is important for restoration, as it connects ecologists, social scientists, and practitioners. There is future scope for a living labs transdisciplinary research approach to analyze the ecological and social effects of restoration activities as they occur [15].

The Swartkops Estuary case study shows that with a single restoration intervention, multiple ecosystem services would be gained. Application of the framework requires identifying the ecosystem services that have been lost or those that could be enhanced through holistic restoration (both social and ecological aspects). These are context-dependent, based on whether the restoration site is in an urban, semi-urban, or rural setting. Ecosystem service provisioning also depends on ecological conditions that control habitat type and distribution. For example, provisioning services in the form of species that are harvested for food, fuel, and fiber can only be provided at sites that are ecologically suitable, i.e., reeds and sedges that are associated with freshwater seepage, or fish and invertebrate species that require specific salinity regimes.

Recognizing the economic value of salt marshes will accelerate restoration activities, but this should be used to leverage for holistic SES approaches to restoration. For example, protecting salt marshes for carbon storage provides important opportunities for climate change mitigation (IPCC 2021). Restoration and creation of salt marsh can act as a mechanism to offset national GHG emissions. Preventing the loss or degradation of salt marshes leads to avoided GHG emissions, as these ecosystems store large quantities of C that can be released as CO_2 following disturbance or destruction of the habitat [91,92]. The authors of [93] estimated that a 1 ha increase of salt marsh in South Africa could potentially sequester between 4.7–26.1 t CO_2eq in one year. Ecosystem service provision (e.g., carbon sequestration and recreational benefits) has also been used to prioritize sites for salt marsh realignment [94]. Managed realignment is implemented in developed countries to compensate for the loss of natural salt marsh habitat due to sea-level rise and anthropogenic pressures.

Effective SES restoration can only be carried out at national scales under suitable legislation and proper implementation. In the South African context, restoration at the national level directed at priority estuaries can be coordinated by the lead department mandated with estuary management (i.e., Department of Forestry, Fisheries and Environment). Additionally, as will be the case in many other countries, there is also scope for NGOs, and provincial and local authorities to participate in restoration. In many cases, restoration activities can be carried out by leveraging existing policies, particularly those that guide integrated coastal management. These approaches will ensure coordination among various stakeholders including private landowners, the local community, government and NGOs. Socio-ecological frameworks are useful in engaging stakeholders in decision making [27]. This is important as participation of local communities ensures that social benefits are achieved [95]. In South Africa, the Expanded Public Works Programmes have played an important role in freshwater wetland restoration in a way that has created jobs to reduce local unemployment, particularly in rural areas. However, a new policy is urgently needed that addresses estuary restoration to coordinate efforts and link to existing programs. Similar to Australia, in South Africa marine and coastal restoration is regulated through a framework designed to limit environmental impacts from development rather than through a tailored framework meant to achieve net environmental benefits [96]. Well-structured national restoration programs will allow for large-scale actions to be approved once-off in a strategic manner to fast track actions. Globally, legislation that addresses restoration of estuaries include the Clean Water Act and the Estuary Restoration Acts in the USA, and the Water Framework Directive and the Marine Strategy Framework Directive in the European Union. The economic impact of estuary and salt marsh degradation can be used as an incentive to protect and restore the resources they provide. Positive restoration results communicated through an SES approach will promote public awareness and participation.

5. Conclusions

This study presented a framework for salt marsh restoration in which the extent of degradation and the responsible pressures were discerned and feasible restoration interventions were outlined. The framework included adaptive management and monitoring, which were crucial for informing future restoration projects. This framework was presented in the South African context but shares key elements that are presented in international restoration frameworks and is, thus, globally relevant and applicable to salt marshes elsewhere. Critical knowledge gaps in the restoration of coastal ecosystems include the identification of areas suitable for restoration, appropriate restoration interventions, and funding opportunities [13]. This study addressed some of those gaps. Innovative approaches are needed to restore and improve salt marsh condition and the benefits they provide to society. A National Estuary Restoration Programme is needed to prioritize key sites and allocate resources. Site- and context-specific research studies (living laboratories) will guide restoration. In the South African context this can be done through the implementation of Estuary Management Plans. Restoration provides opportunities for transdisciplinary studies and action research, as these projects can be treated as adaptive management experiments.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/d13120680/s1, 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), Table S2: Salt marsh habitat, life form and dominant species in each estuary (* = present), Table S3: Potential area available for salt marsh restoration at the Groot Berg Estuary, Figure S2: Distribution of habitats in the Groot Berg Estuary. Location and area cover of salt works indicated by light grey with blue outline, Figure S3: Salt works in the lower reaches of the Groot Berg Estuary. Map source: Google, Maxar Technologies., Table S4: Potential area available for salt marsh restoration at the Orange Estuary, Figure S4, Distribution of habitats in the Orange River Estuary. Location and area cover of degraded salt marsh indicated, 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, Table S5: Potential area available for salt marsh restoration at the Olifants Estuary, 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, Table S6: Potential area available for salt marsh restoration at the Swartlops Estuary, 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, Table S7: Potential area available for salt marsh restoration at the Gamtoos Estuary, Figure S8: Habitat map for the Gamtoos Estuary indicating degraded and agricultural areas available for restoration, Table S8: Potential area available for salt marsh restoration at the Gouritz Estuary, Figure S9: Habitat map for the Gourtiz Estuary indicating degraded and agricultural areas available for restoration, Table S9: Potential area available for salt marsh restoration at the Klein Brak Estuary, Figure S10: Habitat map for the Klein Brak Estuary indicating degraded and agricultural areas available for restoration.

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