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Nature-based solutions: the success story of the renaturing of the beach-dune-*banquette* and wetland ecosystems of Les Vieux Salins d'Hyères (Eastern Provence, France, Mediterranean)

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Abstract. The Les Vieux Salins lagoon was first transformed into salt evaporation ponds, for salt production, in the Middle-Ages. Its last owner, the *Compagnie des Salins du Midi*, in order to protect the site and the salt production against marine intrusions, artificialized the coast in the 1980s and 1990s using riprap. This management method has proven to be non-sustainable in the long term, with a negative impact on the dune-beach-*banquette* (accumulation of *Posidonia oceanica* seagrass dead leaves) ecosystem and the wetland corresponding to the ancient salt ponds, as well at the scale of the entire Bay of Hyères. After the cessation of salt production (in 1994), the site was acquired (in 2001) by the *Conservatoire du Littoral*, a French public sector organization whose role is to protect outstanding areas on the coast and the shores of great lakes. The renaturing of this space, through in-depth discussions with the various stakeholders, the removal of most of the riprap (in 2011, 2019 and 2020), dune reconstitution via sand supply, and the installation of wooden fences marking the coastal path, has made it possible to respond to the risk of submersion by giving the coastal strip a space for mobility and ensuring the functionality of the dune barrier. On this site, a soft nature-based strategy for the management of the coastline is a cost-effective solution from all points of view: ecological, landscape, economic, tourism and educational.
Keywords: beach erosion, *Conservatoire du Littoral*, dune, nature-based solutions, Port-Cros National Park, renaturing, riprap, salt evaporation ponds, wetland.

***Résumé*. Des solutions basées sur la nature : le succès de la renaturation des écosystèmes dune-plage-*banquette* et zone humide des Vieux Salins d'Hyères (Var, France, Méditerranée).** La lagune des Vieux Salins d'Hyères a été transformée en marais salants depuis le Moyen-Âge. Son dernier propriétaire, la *Compagnie des salins du midi*, afin de protéger le site et la production de sel contre les intrusions marines, a artificialisé la côte au moyen d'enrochements, dans les années 1980s et 1990s. Ce mode de gestion s'est révélé peu durable, avec des conséquences négatives aussi bien sur les écosystèmes dune-plage-banquette (accumulation de feuilles mortes de *Posidonia oceanica*) et zone humide qu'à l'échelle de la baie d'Hyères. Après l'arrêt de la production de sel (en 1994), le site a été acquis (en 2001)

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par le *Conservatoire du littoral*, un établissement public français qui assure la protection de sites remarquables le long des côtes et des berges de grands lacs. Après un dialogue approfondi avec les partenaires concernés, la renaturation de ce site grâce à l'enlèvement de la plus grande partie des enrochements (en 2011, 2019 et 2020), à la reconstitution dunaire par apport de sable et à l'installation de ganivelles le long du sentier littoral, a permis de répondre au risque de submersion en rétablissant la mobilité du trait de côte, en restaurant la dynamique sédimentaire naturelle et en assurant la fonctionnalité de la barrière dunaire. Aux Vieux Salins, la gestion souple du trait de côte, 'basée sur la nature', apparaît comme une solution efficace, aussi bien d'un point de vue écologique, paysager, économique et touristique que pédagogique.
Mots-clés : dunes, Conservatoire du littoral, enrochements, érosion des plages, marais salants, Parc national de Port-Cros, renaturation, solutions basées sur la nature, zone humide.

Introduction

In the 1960s-1990s, the artificialization of the coastline peaked in the French Mediterranean as well as in other Mediterranean areas: destruction of the back-beach and the dunes by roads and urbanization, over-frequentation and trampling of the dunes, the construction of marinas, reclamations, beach replenishment, etc. (Meinesz and Lefevre, 1978; Meinesz *et al.,* 1981; Bertozzi, 1990; Meinesz *et al.,* 1991; Anagnostou *et al.,* 2005). Along the whole length of the coasts of Occitania, Provence, French Riviera including the Principality of Monaco, and Corsica, 12% of the shoreline is artificialized; this percentage reaches 32% in French Riviera (Meinesz, 2021). Since the early 2000s, it has been relatively stable (Meinesz *et al.,* 2013; Meinesz, 2021).

In the marine realm, sand may come from three sources. **(i)** The first is the terrestrial sand washed down by rivers. However, the artificial development of rivers, in particular with the construction of dams trapping sediments, has considerably reduced the sediment input into the sea since the 19th century: from 79 to 97% for the Rhône (France), the Ebro (Spain) and the Nile (Egypt) (Poulos and Collins, 2002; Sabatier and Provensal, 2002; Syvitski *et al.,* 2005; Collins and Poulos, 2006; Bouhmadouche and Hemdane, 2016; Sadaoui *et al.,* 2016). **(ii)** The second source of sediment is provided by marine ecosystems such as the *Posidonia oceanica* seagrass meadow, the 'sand factories'; this biogenic sediment comes from the fragmentation of the calcareous skeletons of the organisms living there: calcified algae, bryozoans, echinoderms, molluscs, foraminiferas, etc. (Basterretxea *et al.,* 2004; López *et al.,* 2016; De Falco *et al.,* 2017; Monnier *et al.,* 2019; De Luca *et al.,* 2020; Boudouresque *et al.,* 2022; Pikelj *et al.,* 2022). **(iii)** Finally, sand can come from mechanical and especially biological erosion of midlittoral rocks: they lose a layer of 0.3 to 1.3 mm per year (Laborel *et al.,*1999).

On the beaches and off the beaches, the sand circulates parallel to the shore, with the longshore drift due to wave action, and perpendicular to the shore, from the dune where it accumulates in calm weather, to the fore-beach, where it returns during storms. Anything that hinders these sand movements (e.g. road, wall, constructions, erosion of the dune) contributes to beach erosion (Paskoff, 1985, 1993; Ramoge, 2002; Serra-Raventós, 2003; Maiolo *et al.,* 2020). Other factors contribute to beach erosion, such as sand mining in front of the beaches, sea level rise, removal of the *banquettes* of *Posidonia oceanica*, and the decline in sediment supply via rivers and marine 'sand factories' (Serra-Raventós, 2003; Boudouresque *et al.,* 2017, 2022; Boudouresque and Perret-Boudouresque, 2023; Oudin and Boudouresque, 2023).

Faced with beach erosion, the solution adopted by the local authorities has often been, in the Mediterranean Sea, beach replenishment. Half of the municipalities in Provence and French Riviera nourish their beaches with sand, usually quarry sand (Coudrillier, 2015); between 2003 and 2015, over 35 000 m^3 of sand was dumped along the eastern tombolo of the Giens Peninsula (Vu, 2018). The problem with beach replenishment is that, coupled with the removal of the *banquettes* of dead *Posidonia oceanica* leaves, it destroys the rich Dune-Beach-*Banquette* ecosystem (DBB) and its ecosystem services; in addition, the sand from beach replenishment is rapidly washed out to sea, and contributes to the destruction by burial of the seagrass meadows. Destroying the seagrass meadows, which help to protect the beaches against erosion, as well as being the sand factory, is a remedy worse than the ailment (De Falco *et al.,* 2002; Simeone, 2008; Boudouresque *et al.,* 2017; Cantasano, 2021; Roig-Munar *et al.,* 2021; Oudin and Boudouresque, 2023; Boudouresque *et al.,* 2024).

Another solution, for the local authorities, has often been the installation of rocky structures: groynes (perpendicular to the coast), jetties (parallel to the coast) and ripraps (directly on the beach) (Paskoff, 1993; Anagnostou *et al*., 2005; Heurtefeux *et al.,* 2007; Bouhmadouche and Hemdane, 2016; Saïdi *et al.,* 2024). Although sometimes effective, at least in the short term (see e.g. Bouhmadouche and Hemdane, 2016; Saïdi *et al.,* 2024), this strategy of artificializing the coast is now questioned, as a long-term solution, for its poor cost-benefit ratio, and for its ecological impact (Heurtefeux *et al*., 2007: Sedano *et al.,* 2019, 2021), and alternative nature-based solutions are today proposed in a variety of habitat contexts (Dutoit *et al.,* 2023; Guarino *et al.,* 2024; Motta-Zanin *et al.,* 2024; UNEA, 2024).

Here, we describe the setting up of ripraps along the beach of Les Vieux Salins (Hyères, Eastern Provence, France), their limited

efficacy, then their removal, as well as the encouraging results of this removal, as part of the trend towards nature-based solutions.

The era of coastal artificialization: the installation of riprap

The site of Les Vieux Salins d'Hyères was acquired by the *Conservatoire du Littoral* (CL) in 2001 (Conservatoire du Littoral, 2022). The *Conservatoire du Littoral* (Coastal protection agency - official name: *Conservatoire de l'Espace Littoral et des Rivages Lacustres*) is a French public organization created in 1975 to ensure the protection of outstanding natural areas on the coast, the shores of lakes and stretches of water of 10 km² or more. Its creation was inspired by the British National Trust. The CL acquires land by private agreement, pre-emption, expropriation, donation or legacy, then entrusts the management of its lands to local authorities or local organizations (Letourneux, 1994; Kalaora, 2010; Legrain, 2000; Mornet, 2006; Bazin and Binet, 2015; Anonymous, 2024). As of 2023, the CL was managing an area of 2 183 km² (Conservatoire du Littoral, 2024).

The site of Les Vieux Salins, 365 ha in surface area, is part of the Hyères municipality, within the Adhesion Area of the Port-Cros National Park (Boudouresque *et al.,* 2020a, 2021) (**Fig. 1**). It includes a wetland and a lido (dune and beach) which separates it from the sea (Bay of Hyères) (**Fig. 2**). Les Vieux Salins harboured a salt production industry, which played an important role in the economic activity of the area since the Middle-Ages, but which ceased in 1994 (Astruch *et al.,* 2020; Faget *et al.,* 2021; Conservatoire du Littoral, 2022).

The Les Vieux Salins site, similarly to the neighbouring Pesquiers site, is mainly managed by Métropole Toulon Provence Méditerranée (TPM) for the conservation of its rich waterfowl fauna: water pumping, water circulation in the canals, water level in the ponds, installation of platforms suitable for the nesting of some bird species, etc. Many other species occur within and around the ponds, and along the dunes and the beach, including plants, fish and turtles (e.g. Lascève, 2014; Perrot *et al.,* 2016; Le Diréach *et al.,* 2018; Astruch *et al.,* 2019, 2020; Boudouresque *et al.,* 2020b; Le Diréach *et al.,* 2020; Massinnelli *et al*., 2020; Conservatoire du Littoral, 2022). Along the dunes and the beach, a coastal path is used by around 150 000 walkers each year (Conservatoire du Littoral, 2022). Finally, at sea, there is an extensive *Posidonia oceanica* seagrass meadow in the Bay of Hyères; close to the shoreline, a string of barrier-reefs have been built by *P. oceanica* (Andromede Oceanologie, 2014; Bonhomme *et al.,* 2015; Boudouresque *et al.,* 2019) (**Fig. 2**).

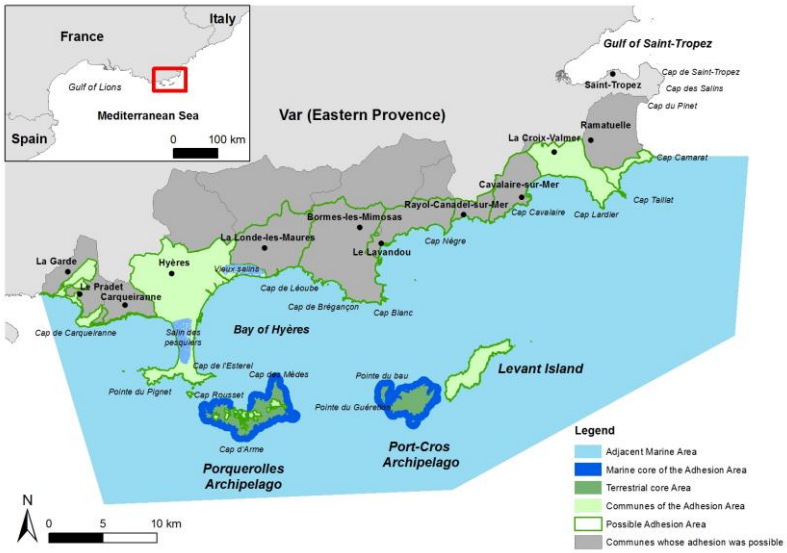

Figure 1. Map of the new Port-Cros National Park (N-PCNP). In the municipalities (*communes*) which joined, or not, the N-PCNP, part of the municipality's area is located outside the Possible Adhesion Area. From Boudouresque *et al.* (2020a).

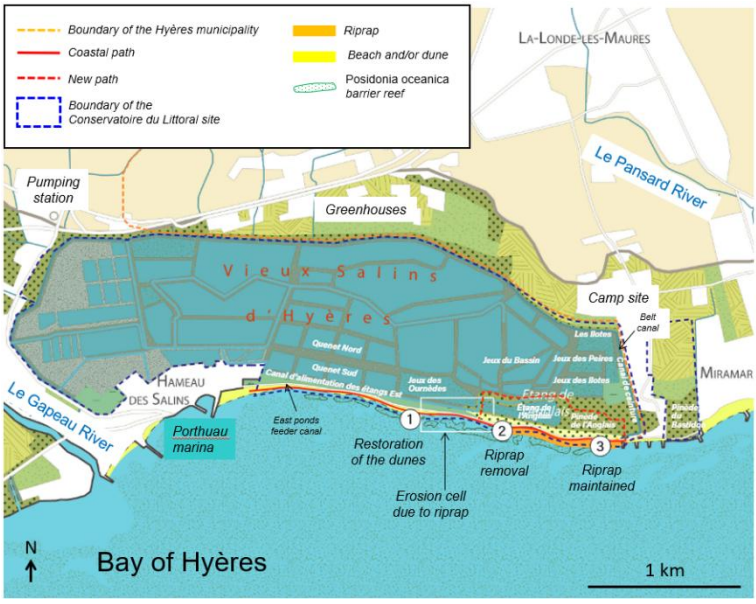

Figure 2. The Les Vieux Salins site of the Conservatoire du Littoral (CL). For the description of terrestrial plant communities, see Conservatoire du Littoral (2022). From Conservatoire du Littoral (2022), simplified and translated from French.

Although the coast of Les Vieux Salins is relatively sheltered from the swell by Giens Peninsula, Porquerolles and Port-Cros Archipelagos and Levant Island, the Compagnie des Salins du Midi, then owner of the site, installed riprap between 1985 and 1998. In all, large blocks of limestone, in an area where natural rocks are siliceous, were deposited along 850 m of beach (**Fig. 2**). The objective was to prevent the intrusion of marine water into the East pond's feeder canal, otherwise a natural phenomenon, with the aim of protecting the salt marshes and the salt production. However, the riprap causes the sand to be washed away at its offshore base, amplifies the beach erosion downstream of the sediment transit, amplifies the risk of marine water intrusion into the salt marshes and disrupts the hydro-sedimentary functioning at the scale of the Bay of Hyères, in addition to strongly artificializing the environment. In the long term, and counter-intuitively, instead of protecting the beach against erosion, the riprap causes and accelerates its erosion. Finally, the dunes, a major element of the Dune-Beach-*Banquette* ecosystem which characterises the Mediterranean, were disappearing (Vu, 2018; Conservatoire du Littoral, 2022).

The era of nature-based solutions: the removal of riprap

Today, climate change and the sea level rise mean that we can no longer have recourse to a rigid defence of the current shoreline (Schuerch *et al.,* 2018). More importance must be given to natural processes to mitigate the effect of coastal hazards (e.g. storms, erosion, submersion). Preserving and valuing natural processes in coastal areas constitutes an effective and inexpensive solution to mitigate the effects of climate change (Conservatoire du Littoral, 2022).

Several studies, commissioned by Métropole Toulon Provence Méditerranée (TPM), and carried out by Artelia and the BRGM (*Bureau de Recherches Géologiques et Minières*), showed that the Les Vieux Salins wetland was a favourable place for the implementation of a nature-based approach. From these studies, through in-depth discussions with the various stakeholders, and with European Union, French (*Agence de l'Eau Rhône Méditerranée Corse*), Regional (*Région Sud*) and local (*Département du Var* – Eastern Provence) financial support, a renaturing project has been designed, aiming at restoring natural dynamics for the dune-beach system, at the interface between the sea and the wetland (Conservatoire du Littoral, 2022; Hilbert, 2022).

In practical terms, the project involved **(i)** the reconstruction of the dunes, **(ii)** the channelling of pedestrian traffic on a well-marked path (between wooden fences) (**Fig. 3**), in order to avoid trampling on the dunes, **(iii)** sand trapping by the above-mentioned fences, and **(iv)** the removal of part of the riprap.

The first riprap removal operation, on a 110 m stretch of shoreline, to the west of the beach, took place in 2011. In 2019 and 2020, riprap was further removed on 340 m and 275 m stretches, respectively. In these same years, the dunes were restored, with the supply of 3 200 m^3 of sand in Spring 2019, the coastal path was marked out by means of wooden fences (‘*ganivelle*s’ in French) (**Fig. 3**), and an alternative path was created between L’Ėtang de l’Anglais and Pinède de l’Anglais (a pine-tree forest) (**Fig. 2**) (Conservatoire du Littoral, 2022).

The positive results came sooner than expected. Between 2019 and 2021, GPS surveys have established that the beach widened by between 5 and 10 m (**Fig. 4**); this expansion has been maintained ever since. In addition, natural vegetation, characteristic of Mediterranean dunes, began to colonize the restored dunes (e.g. *Elytrigia juncea, Eryngium maritimum, Pancratium maritimum*), and a naturally formed *banquette* of *Posidonia oceanica* dead leaves occurred on the naturally reconstituted beach. Relatively severe storms, which occurred towards and after the end of the restoration work, from 2019 to 2023, offered an opportunity to assess the effectiveness of the nature-base restoration strategy (Conservatoire du Littoral, 2022; Girardier and Noble, 2022).

Figure 3. A wooden fence (in French ‘*ganivelle*’) along the coastal path, to channel pedestrian traffic, and avoid trampling of the dune. Photo © Conservatoire du littoral.

Before the beginning of the restoration work, 63% of the people questioned were worried about the consequences of the work, while finding the ripraps unsightly. After the work, 75% of them were

satisfied with the work, and 53% trusted the nature-based solutions (Hilbert, 2022).

A cost-benefit analysis compared two scenarios, by 2050: **(i)** resisting, *via* an increase in the artificialization of the shoreline, and **(ii)** adapting, *via* nature-based solutions. The second scenario is obviously the cheapest (**Table 1**), in addition to being the most effective, from an ecological, landscape, economic, tourism and educational point of view (Farhangi and Long, 2022).

Table 1. Cost-benefit analysis of two scenarios, by 2050: resisting vs. adapting. From Farhangi and Long (2022).

Scenario	Studies and investment	Maintenance	Total
Resisting (*via* increased artificialization)	2.4 – 16.8 M€	3.1 – 21.7 M€	5.5 – 38.5 M€
Adapting (*via* nature-based solutions)	0.8 M€	0.8 M€	1.7 M€

Conclusions

The Les Vieux Salins d'Hyères site represents a successful example of sustainable management of the shoreline, based upon nature-base solutions. The renaturing of this space, artificialized by the installation of riprap in the 1980s and 1990s for the requirements of the salt industry, through the removal of the riprap, made it possible to respond to the risk of submersion by giving the coastal strip a space for mobility and ensuring the proper functioning of the dune barrier. Furthermore, the addition of sand and the installation of wooden fences against trampling allowed the reconstitution of the dune. At this site, nature-based management of the coastline is a cost-effective solution from all points of view: ecological, landscape, economic, tourism and educational.

Obviously, 5 years is not enough to conclude on long-term success. In addition, the rising of the sea level, which is accelerating, will require that management takes into account the long-term dynamics of the beach, the dune, and the adjacent wetland.

It should also be noted that the very particular localization of the site, with a *Posidonia oceanica* meadow acting as a wave and swell attenuator, and *P. oceanica* dead leaves (*banquette*) coating and protecting the beach, contribute to the success of this management method. The site's response to the successive storms of 2019 and 2023 confirms the success of this operation.

Figure 4. Before and after the riprap removal. **Top left**: Riprap on Les Vieux Salins beach, before removal, in September 2019. **Top right**: After removal, May 2020. **Bottom left**: May 2021. **Bottom right**: September 2022. Photos © Matthieu Lascève, TPM.

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