Scientific Reports of Port-Cros National Park, 39: 95-108 (2025)

Wastewater treatment in the Port-Cros National Park (Provence, France): a constructed wetland on the island of Porquerolles

Laurence BONNAMY[1], Christian BOTTAU[1],
Stéphane PENVERNE[1], Fabienne TANCHAUD[1],
Charles-François BOUDOURESQUE[2]*

[1]*Parc national de Port-Cros, 181 Allée du Castel Sainte-Claire, BP 70220, 83406 Hyères CEDEX, France.*
[2]*Aix-Marseille University and University of Toulon, MIO (Mediterranean Institute of Oceanography), CNRS, IRD, Campus de Luminy, 13009 Marseille, France.*
**Corresponding author: charles.boudouresque@mio.osupytheas.fr*

Abstract. Porquerolles Island, together with the Port-Cros Archipelago, constitutes the core area of the Port-Cros National Park. The wastewater of Porquerolles (4 500 Population-Equivalent, ~50 000 m³ per year), is treated in a wastewater treatment plant. The treated water is discharged in a constructed wetland with three shallow ponds. Maintenance of the ponds requires the mowing of part of the bank vegetation, the dredging of bottom sludge and removal of floating duckweed. At the outlet of the third pond, part of the treated water, the compliance of which with EU standards is monitored, is reused for drip irrigation of collections of varieties of fruit trees and olive trees, in the framework of organic farming. Another part of the treated water infiltrates into the ground and contributes to recharging the phreatic zone and preventing saltwater intrusion from the sea. Although the creation of a kind of wildlife park is not usually the purpose of a national park, the resident and migratory birds that frequent this wetland area provide an opportunity for education and raising public awareness, thanks to a specially constructed bird observatory. Overall, integrated water management in Porquerolles, in a context of water scarcity, global warming, and sustainable development, calls for nature-based solutions and trade-offs between the protection of natural habitats, the health and well-being of inhabitants, and the sustainability of a tourism-based economy.
Keywords: birds, constructed wetland, integrated management, nature-based solutions, Porquerolles Island, Port-Cros National Park, public awareness, wastewater, water reuse.

Résumé. **Épuration des eaux usées dans le Parc national de Port-Cros (Provence, France) : les bassins de lagunage de l'île de Porquerolles**. L'île de Porquerolles constitue, avec l'archipel de Port-Cros, le cœur du Parc national de Port-Cros. Les eaux usées de Porquerolles (4 500 équivalents-habitants, environ 50 000 m³/an), sont traitées dans une station d'épuration, puis l'eau traitée circule dans trois bassins de lagunage. Ces bassins, profonds de 30 cm à 1 m, nécessitent un entretien : faucardage partiel de la végétation des berges, curage des bassins et enlèvement de la végétation flottante en excès (lentilles d'eau). Une partie de l'eau issue du lagunage, dont la conformité aux normes européennes est suivie, est réutilisée pour irriguer (au goutte-à-goutte) une agriculture entièrement biologique et les collections de variétés arboricoles (oliviers et arbres fruitiers) méditerranéennes hébergées sur l'île par le Conservatoire botanique national méditerranéen (CBNM). Une autre partie de l'eau issue du lagunage s'infiltre dans le sol et participe à la recharge de la nappe phréatique, évitant l'intrusion du biseau salé. Les bassins de lagunage ont créé une niche écologique originale sur l'île, profitant à des espèces inféodées aux zones humides. Bien que la création d'une sorte de parc animalier ne

fasse pas partie des objectifs d'un parc national, les oiseaux résidents et migrateurs qui fréquentent les bassins de lagunage constituent une opportunité pour l'éducation et la sensibilisation du public, grâce à un observatoire à oiseaux construit spécialement. Au total, la gestion intégrée de l'eau à Porquerolles, dans un contexte de déficit en eau, de réchauffement climatique, et de développement durable, fait appel à des solutions basées sur la nature et à des compromis entre protection des habitats naturels, mise en valeur paysagère, santé et bien-être des habitants et durabilité d'une économie basée sur le tourisme.
Mots-clés : eaux usées, gestion intégrée, île de Porquerolles, lagunage, oiseaux, Parc national de Port-Cros, réutilisation de l'eau, sensibilisation du public, solutions basées sur la nature.

Introduction

The Port-Cros National Park (PCNP, eastern Provence, France, Mediterranean) is one of the oldest terrestrial and marine national parks in the Mediterranean area. It was established in December 1963 by a French decree (*Décret* 63-1235, 14 December 1963). It then encompassed the island of Port-Cros and the nearby island and islets (Bagaud Island, La Gabinière Islet and Le Rascas Islet), i.e., the Port-Cros Archipelago, situated about 8 km off the mainland coast of eastern Provence. In addition to the land areas of the islands and islets (675 ha), the PCNP included a 600-m wide belt of sea, corresponding to 1 300 ha in surface area, surrounding the Archipelago (Meinesz, 2019; Boudouresque *et al.,* 2020a, 2021).

Progressively, the PCNP has been entrusted with the management of an increasing number of territories outside its initial 1963 territory. A plot of land (~950 ha) situated on the neighbouring island of Porquerolles, bought by the French State in 1971, was handed over for management to the PCNP (Barcelo and Boudouresque, 2012).

Following the redefinition of the national parks by the French legislation of 2006, the territory of the PCNP was between 2012 and 2016 extensively redefined and extended; the new Port-Cros National Park (N-PCNP), established in 2016, includes the Port-Cros and Porquerolles Archipelagos as core areas (both terrestrial and marine: 30 km²), a vast Adjacent Marine Area (AMA – *Aire Maritime Adjacente*) including the Bay of Hyères and extending seawards to the edge of the continental shelf (1 186 km²), and a discontinuous continental area, the Adhesion Area (AA – *Aire d'Adhésion*: 113 km²). The AA includes five municipalities, namely La Garde, Carqueiranne, Hyères, La Croix-Valmer and Ramatuelle, which voluntarily joined the N-PCNP, through the signing of a charter defining the objectives of the national park regarding the conservation of the natural and cultural heritage, and sustainable development (**Fig. 1**) (Sellier, 2015; Boudouresque *et al.,* 2020a).

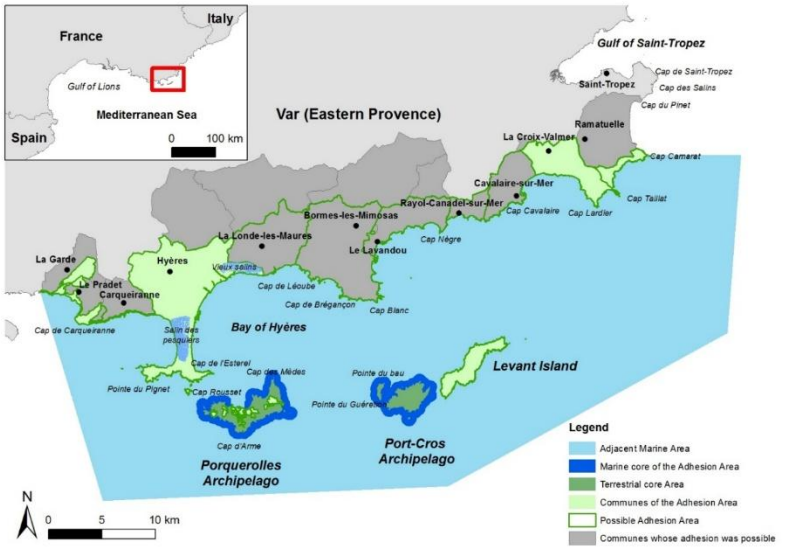

Figure 1. Map of the Port-Cros National Park with the Adhesion Area, the terrestrial and marine core areas and the Adjacent Marine Area.

Figure 2. Map of eastern Provence with the Island of Porquerolles and the location of the wastewater treatment plant and the constructed wetland. Base map from Géoportail (geoportail.gouv.fr/carte).

The Island of Porquerolles (1 260 ha) is home to around 350 permanent residents (**Fig. 2**). In summer the resident population can be estimated, based on water consumption, as around 5 000 people. They are also many day visitors, disembarking in the port of Porquerolles from shuttles from a number of mainland ports: mainly from La Tour-Fondue (Giens Peninsula, Hyères municipality),

but also from Bandol, Cavalaire-sur-Mer, La Croix-Valmer, La Londe-les Maures, La Seyne-sur-Mer, Le Lavandou, Saint-Mandrier, Saint-Raphaël, Saint-Tropez, Sainte-Maxime, Sanary-sur-Mer and Toulon. The total number of visitors increased from 500 000 in 1980 to 1 000 000 in the 2010s. On some days, attendance reached 12 000 visitors. Since 2023, after a two-year experimentation, the number of visitors has been capped at 6 000 per day, in July and August (Baillet, 1997; Cadoret, 2021; Rabisse, 2021; Cadoret, 2023), as part of the governance partnership between the *Métropole Toulon-Provence-Méditerranée* (MTPM), the municipality of Hyères and the PCNP, a strategy resulting from consultation with users (Barcelo *et al.,* 2018; Michel *et al.,* 2023).

The Island of Porquerolles has some small-scale agricultural activity, entirely organic, on 200 ha, including 28 ha of orchards and 75 ha of vineyards. Since 1979, the *Conservatoire Botanique National Méditerranéen* (CBNM) has been located in Porquerolles; attached to the Ministry of the Environment, it is managed by the PCNP. The CBNM is in charge of safeguarding Mediterranean wild flora and manages Mediterranean collections of fruit trees and olive trees (Manche *et al.,* 1980; Peirache *et al.,* 2023; Le Nouveau *et al.,* 2024); the strains come from all the regions bordering the Mediterranean (Garnier *et al.,* 2021). These collections of trees require irrigation, at least in summer (Le Nouveau *et al.,* 2024).

Water consumption in Porquerolles, for domestic, touristic, industrial (port) and agricultural uses, amounts to approximately 100 000 – 110 000 m³/year (De Marco, 2024). About 40 000 m³/year is extracted from groundwater; this is the maximum that can be extracted sustainably, preventing saltwater intrusion from the sea into the groundwater. Since 2004, the remaining 60 000 m³/year is brought from the mainland by a tanker, the *Saint-Christophe* (De Marco, 2024; Le Nouveau *et al.,* 2024). From summer 2024, an underwater pipeline brings freshwater directly from the mainland and therefore has replaced the tanker; this pipeline should not increase the island's water consumption, which ought to remain restricted and water-efficient (Creocean, 2024; De Marco, 2024; Le Nouveau *et al.,* 2024).

Wastewater from Porquerolles (68 000 m³ in 2023; Le Nouveau *et al.*, 2024) is treated in a wastewater treatment plant (WTP) supplemented by a constructed wetland. A constructed wetland is an artificial wetland to treat sewage wastewater. They are engineered systems that use the natural functions of vegetation, soil, and organisms, to provide tertiary treatment of wastewater.

In the present work, we describe the Porquerolles constructed wetland and its inclusion within an integrated and virtuous approach

to the management of an island belonging to the core area of a national park. The management approach must reconcile the protection of natural heritage and the limitation of the impact on water resources with respect for the lifestyle of resident inhabitants, the reception of tourists and agricultural activities benefiting from the 'organic farming' label.

The Porquerolles constructed wetland

Before 1975, the Porquerolles wastewater was discharged at sea on the northern coast, near the port. A biological WTP was commissioned in 1975 in the southern part of the island (**Fig. 2**). The activated sludge process is used for treating up to 4 500 population-equivalent (PE) sewage (De Marco, 2024; Le Nouveau *et al.,* 2024). This plant does not use any chemical treatment: the bacteria directly degrade organic matter. In 2026, this WTP will be replaced by a new one, with improved water processing, a sludge drying unit and a capacity increased to 6 500 PE (De Marco, 2024; Le Nouveau *et al.,* 2024). Until 1979, the treated water was discharged into the sea, in the Gorges du Loup Cove (Augier *et al.,* 1979). No data on the quality of the discharged water was found.

In 1979, the wastewater treatment plant was supplemented by a tertiary treatment: a constructed wetland (**Fig. 3**, **4**). The constructed wetland is managed by the PCNP, while the WTP was initially managed by the municipality of Hyères, then since 2007 by the MTPM. The constructed wetland encompasses three water bodies (ponds) from 30 cm to 1 m deep, with a total surface area of 1 ha (Tanchaud, 2024) (**Table 1**). The water from the WTP travels by the force of gravity successively through the water bodies, from No 1 to No 3; the cumulated residence time of the water in the ponds is about 1 month in summer (Le Nouveau *et al.,* 2024). There is certainly a significant portion of the water that has left the system by evapotranspiration; The annual volume of water that evaporates is estimated at 12 400 m³ (Le Nouveau *et al.,* 2024).

Table 1. Characteristics of the three ponds of the constructed wetland of Porquerolles Island. From SCP (Société du canal de Provence and Le Nouveau *et al.,* 2024).

Water bodies (ponds)	Plants	Surface area	Depth	Mean volume
No1	Microphytes	4 000 m²	1 m	4 000 m³
No2	Macrophytes (65%) and microphytes (35%)	2 000 m²	30 cm to 1 m	1 500 m³
No3	Macrophytes	4 000 m²	30 cm	1 300 m³

The water bodies of the constructed wetland require maintenance. The vegetation of the banks (reeds

Phragmites australis and cattails *Typha latifolia*) tends to progress towards the centre of the ponds and thus would ultimately fill them up. About every 6 years, this helophyte vegetation of the banks is partially mowed. However, a belt of vegetation is preserved in order to allow waterfowl to take shelter and nest there (**Fig. 5**).

Furthermore, the ponds tend to fill up with sediment. It is necessary to dredge this sediment every 4 to 10 years. The cost of a dredging operation is between 30 000 and 50 000 euros. The removed sediment was not used until early 2025, when it was used to restore soils degraded by human activities. The occasional renewal of sand filters, damaged by corrosive water, costs around 30 000 euros (Le Nouveau *et al.,* 2024).

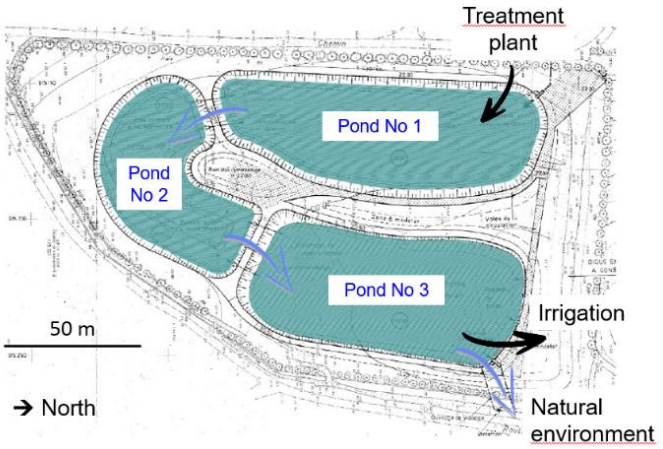

Figure 3. Map of the constructed wetland of Porquerolles Island, with water circulation between ponds and the fate of the treated water.

The duckweed *Lemna* sp.*,* which floats in ponds No 2 and 3, participates in the water purification process (Rahmani and Sternberg, 1999; Ater *et al.,* 2006; Ozengin and Elmaci, 2007). However, when it proliferates to the point of covering 90 to 100% of the pond surface, whatever the season (**Fig. 6**), it hinders the effectiveness of the purification process by intercepting light, including UV rays (Arden and Ma, 2018; Tanchaud, 2024). The waterfowl consumption of duckweed is not sufficient, and its abundance must be reduced; removal is done using a vacuum cleaning system (**Fig. 7**). In total, in 2023, 10 metric tons (wet mass) of duckweed were harvested; it is temporarily stored pending future valorisation, with green waste and other biowaste collected in Porquerolles. It is worth noting that possible valorisation of duckweed

is hindered by their storing of trace metals and antibiotics (Rahmani and Sternberg, 1999; Iatrou *et al.,* 2015).

Figure 4. One of the three water bodies [pond No 2] of the constructed wetland of Porquerolles Island. Photo © Charles-François Boudouresque.

Figure 5. Bank of a water body, with a preserved belt of reeds (*Phragmites australis*). A bird (the common coot *Fulica atra*) can be seen. Photo © Charles-François Boudouresque.

Figure 6. A pond completely covered with the duckweed *Lemna minor*, in November 2023. Photo © Fabienne Tanchaud.

The constructed wetland in a context of integrated management

The constructed wetland, just like natural wetlands, attracts many species of waterfowl, such as the mallard *Anas platyrynchos*, the common coot *Fulica atra*, the moorhen *Gallinula chloropus,* the Squacco heron *Ardeola ralloides,* the little bittern *Ixobrychus minutus* and the little grebe *Trachybaptus ruficollis*. Many other bird species are attracted by insects that live above or near the ponds, such as the barn swallow *Hirundo rustica*, the house martin *Delichon urbicum,* the sedge warbler *Acrocephalus schoenobaenus* and the common kingfisher *Alcedo atthis*. Finally, the constructed wetland is a stopover site for migratory birds, such as *Hirundo rustica*, the common chiffchaff *Phylloscopus collybita* and the whinchat *Saxicola rubetra* (Beauvallet *et al.,* 2019; Tanchaud, 2024; Élodie Debize, pers. comm.). The PCNP, as part of its policy of welcoming the public and providing environmental education, seized the opportunity to promote this landscape. It carried out development operations intended to secure the surroundings of the ponds, to revegetate the hedges, to open up views of the wetland, to create information platforms, and it built a bird observatory for visitors to observe the constructed wetland and its flora and fauna (**Fig. 8**).

It is worth noting that the construction of this bird observatory is not part of a strategy for creating a sort of open-air zoo or wildlife park, which might be open to criticism (Boudouresque *et al.,* 2020b). A simplistic approach to the concept of biodiversity leads certain specialists of a taxon (e.g. birds, sea turtles, marine mammals, bats) to consider as 'positive' anything which increases the numbers of their beloved taxon (Boudouresque *et al.,* 2014, 2020a, 2020b, 2021;

Boudouresque, 2024). This is not at all the objective of the PCNP (Barcelo *et al.,* 2013; Boudouresque *et al.,* 2020a; Peirache *et al.,* 2023). The constructed wetland was created with the virtuous goal of purifying wastewater; although by nature artificial, and without adhering to the simplistic ideas of certain bird worshipers, this site has acquired an interesting range of biological diversity over time, and it is therefore quite legitimate to use it for public education.

Figure 7. Vacuum device for removal by suction of the duckweed *Lemna* sp., which is discharged into a container. Photo © Fabienne Tanchaud.

At the outlet of the third pond, 10 000 m³ of water are directed towards an irrigation network (called the 'red network') intended for watering agricultural plots, in particular the CBNM's collections of varieties of fruit tree.

Another part of the water infiltrates into the ground and contributes to recharging the phreatic zone and preventing saltwater intrusion from the sea. Unused treated water, when there is any, is

discharged into the Garonne, a tiny intermittently flowing stream; in practice, there is no open water in the Garonne during the summer period.

The reuse of wastewater, after purification, is an important goal in a context of water shortage (Faby, 1998; Bixio *et al.,* 2006; Angelakis and Snyder, 2015; Kesari *et al.,* 2021). The rate of reuse is 80-90% in Israel, 14% in Spain and 10% in Porquerolles Island; for the whole of France, it is only 1% (Mizyed and Mays, 2020). The reuse of water, after its passage through the constructed wetland, for agricultural purposes, began in 1985. The PCNP aims to develop and increase this reuse within the framework of the new regulations.

Figure 8. The observatory built by the PCNP near pond No 2, so that visitors can view its bird fauna. Built of wood, partly hidden by vegetation, it is almost invisible (in the centre of the yellow circle). Photo © Charles-François Boudouresque.

The reuse of treated wastewater requires a water quality which is defined by French and European Union (EU) regulations. Before 2023, these waters corresponded to classes C or D required by the French decree of 2010 amended in 2014; since June 23, 2023, the EU regulation relating to the minimum requirements applicable to water reuse requires a class B or C (Le Nouveau *et al.,* 2024). To check the usability of this water, analyses are carried out at the outlet of pond No 3 by an accredited independent laboratory, under the control of the *Agence Régionale de la Santé* (**Table 2**); the cost of the analyses is about 15 000 euros per year. In Porquerolles, treated

water is used for drip irrigation, either above ground or subsurface (70 cm depth) irrigation; for practical, ecological and economic reasons, the latter is preferred.

From the point of view of the natural functioning of terrestrial and marine ecosystems, this perfect water purification system is open to criticism. The supply of nutrients (e.g. nitrates and phosphates) and organic matter to the sea, *via* rivers, plays a major role in coastal ecosystems; the nutrients provided by rivers are the basis of photosynthesis; the organic matter brought by rivers is the basis of certain marine food webs and of some fisheries, such as that of sole (Darnaude, 2005; Ockowski *et al.,* 2009; Ourgaud *et al.,* 2013, 2015; Boudouresque *et al.,* 2022, 2025). The role of rivers' contributions of nutrients and organic matter to the sea surprises some green activists, sometimes even certain ecologists.

Table 2. Some parameters of water quality at the outlet of the constructed wetland of Porquerolles Island. Maximum, minimum and (mean) values. Na: not available.

Parameter/year	2018	2019	2023	2024
Suspended solids (mg/L)	9-47 (16)	2-140 (26)	2-12 (5)	2-43 (6)
COD – Chemical demand in oxygen (mg/L)	36-115 (57)	34-158 (79)	41-287 (89)	37-206 (106)
BOD5 – Biological demand in oxygen (mg/L)	Na	Na	1-28 (5)	1-31 (10)
Escherichia coli (UFC/100 mL)	15-46 (21)	15-1 372 (323)	1-8 000 (686)	1-8 000 (593)

Conclusion

Management in a national park core area is required to be exemplary, and to hint at what could be done outside the park's boundaries. This management approach must take into account the natural, architectural and cultural heritage, human health, the sustainable development of the territory, as well as the scientific strategy (Barcelo *et al.,* 2013; Peirache *et al.,* 2023).

The management of water by the PCNP, at Porquerolles, where the treatment of wastewater by a treatment plant is supplemented by a constructed wetland, with the still partial water reuse for drip irrigation of a Mediterranean collection of fruit and olive trees and entirely organic crops, a reuse process which the PCNP intends to develop further, clearly illustrates the trend towards an integrated system of management.

This integrated management is taking place in the context of a small island, with the possible increase in drought episodes and the ongoing rise in air and water temperature (IPCC, 2022). It constitutes

a trade-off between **(i)** the legitimate water needs of inhabitants, **(ii)** the reception of a sustainable number of tourists, **(iii)** the maintenance of fully organic agriculture, **(iv)** the conservation of unique collections of Mediterranean tree varieties, **(v)** the scarcity of water and **(vi)** its reuse.

This integrated management also illustrates the trade-off linked to sustainable development, between **(i)** the conservation of natural heritage, **(ii)** the health and well-being of inhabitants, and **(iii)** an economy linked to tourism. Obviously, the setting up of artificial ponds was not intended to 'improve or increase biodiversity'. Biodiversity does not mean 'How many species?', and an increase linked to humans has as negative an impact for the ecosystems as a decrease (Boudouresque, 2014, 2024). Nor was it intended to create a sort of bird wildlife park for tourists. However, education and public awareness are part of the missions of a national park, and it would have been a pity not to take advantage of the opportunities offered by the constructed wetland of Porquerolles Island.

Overall, the case study of the constructed wetland of Porquerolles highlights the way in which a set of nature-based solutions facilitates the compromises essential to integrated management.

Acknowledgements. The authors thank Nathalie Le Nouveau, Catherine Franck-Neel and Clélie Verna (Cerema) for providing them with an upcoming document entitled '*Utiliser les eaux usées traitées en contexte insulaire. L'exemple précurseur de Porquerolles*'. They also thank André De Marco for kind permission to cite an unpublished document developed with the *Comité Insulaire de Porquerolles*. They are grateful to all the PCNP staff and departments, who have provided the data here presented (in particular Élodie Debize), to the stakeholders, users and inhabitants of Porquerolles, whose involvement in the sustainable development policy is significant, to two reviewers whose valuable suggestions have contributed to improving the conclusions, and to Michael Paul, a native English speaker, for proofreading the text.

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