Chapter 2. Pollution in a liquid world

Sources and impacts of pollution in Senegal and the implications for marine spatial planning

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Introduction

1 Historically, the ocean has been considered large enough to accommodate all kinds of waste produced by human societies without causing damage (GORMAN, 1993). This logic has been taken to extremes by industrial societies, which are only now becoming aware of the limits of this approach. The origin and nature of the waste discharged into the marine environment vary highly: waste from the operation of ships, civil and military nuclear activities, industrial and domestic wastewater, run-off from agricultural inputs, brine and contaminants from the desalination of seawater, discharge and leaks linked to the extraction of raw materials, etc. The ocean is also subject to accidental or unintentional pollution, often as a result of negligence: solid waste including macro and microplastics, oil spills, leaks of radioactive materials, etc.

2 Human disturbance of nature in general, including the ocean, is characterised by the introduction and diffusion of pollutants, i.e. agents of external origin: biological, physical or chemical. Above a certain threshold, and sometimes under certain conditions (potentiation), these pollutants cause negative impacts on all or part of an ecosystem. Human interest in marine pollution now mainly concerns the impacts it may have on exploited biomass, consumer health, occupation of the marine environment and conservation of biodiversity.

3 In Senegal, studies measuring pollution and its potential impacts are rare. Between 2000 and 2013, the Senegalese population increased by almost 40% (from 9.8 million in 2000 to 13.5 million in 2013, the date of the first census), an increase that is still accelerating, according to the 2013–2063 projection of the Senegalese National Agency

for Statistics and Demography (ANSD) (17.2 million in 2021), with the 30 million mark expected to be passed by 2040.[1] Combined with the rural exodus, this dynamic has increased the population of Dakar from 400,000 inhabitants in 1970 to 2.2 million in 2002 and 3.6 million in 2018. More generally, the number of those living in coastal areas is increasing; due to a combination of lack of awareness and inefficient waste collection systems, a growing amount of non-biodegradable waste is being dumped on beaches and in estuaries. The recent media coverage of the dumping of hospital waste on the beaches around Cape Manuel[2] is an example of this (fig. 1A).

Figure 1. Sedimentation of waste. A. Accumulation of hospital waste in strata on the beach of Cap Manuel

Source: Screenshot of the report “Medical waste on beaches: images of horror… a hospital caught in the act”

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Figure 1. Sedimentation of waste. B. Erosion of the coastline on the Djiffer oceanfront reveals a dumping ground of domestic waste and monofilament fishing nets

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4 In this chapter, we present the main sources of marine pollution emitted in Senegalese territory. We then discuss the risks and challenges this poses to the marine ecosystem, and the main physical processes affecting the transport and distribution of pollutants along the Senegalese coast. Finally, we offer recommendations for spatial planning of the marine environment.

Sources of marine pollution

When plastics become political

5 Plastic pollution is one of the most visible types of pollution, and is therefore at the centre of citizens and political initiatives to curb environmental degradation. Since 2008, but especially from 2015 onwards, the Senegalese government has adopted laws and policies related to plastic waste (NGAIDO, 2020). However, laws on other sources of pollution are more general, limited and out of date: recent initiatives for better waste management seem to pay little attention to these other sources of pollution. Although plastics make up the majority of marine litter recorded[3] (THIELE *et al.*, 2021), they account for "only" 12% of the litter generated.[4] In reality, there is a large diversity of pollutants released into the sea, and soluble pollutants are both less visible and often more dangerous. They are responsible for an increasingly serious health crisis despite early diagnosis and alarm bells sounded in the 1990s by Senegalese researchers (DIAW, 1993). In this section, we review the sources of agricultural, domestic and industrial pollution in Senegal.

Agricultural pollution

6 Marine pollution from agriculture is caused by the leaching of cultivated land during rainfall, which carries pesticides, herbicides and fertilisers to waterways and ultimately to the ocean. Fertilisers can cause eutrophication of coastal waters, while pesticides and herbicides have toxic effects on the wider ecosystem.

7 Although Senegal is increasingly importing fertilisers,[5] the quantities used per hectare of arable land remain an order of magnitude lower than in Europe.[6] Pesticide use is only partially documented in the country, particularly in the Niayes region,[7] which is a prime area for market gardening along the coast between Dakar and Saint-Louis, and where the water table is shallow. However, according to the Centre of Ecological Monitoring (CSE, 2015), most of the pesticides used are banned, and the recommended dosages are not respected. The passage of pollutants from the coastal water table to the ocean therefore seems likely, especially during the rainy season. The Petite Côte and the Casamance are a priori free of agricultural pollution, as they are areas with essentially small traditional farms that use few chemical inputs. In the Casamance River delta, mangrove swamp rice is traditionally grown in small areas. Groundnut crops in the Sine-Saloum watershed are not considered using large amounts of chemicals, but are responsible for deforestation and thus for reducing the soil's capacity to store rainwater, which is one of the key factors in soil salinisation, particularly in the delta (FAYE *et al.*, 2019). On the banks of the Senegal River, there are large farms with relatively heavy soils (75–90% clay) that drain chemical-laden water into Lake Guiers, which supplies Dakar with drinking water. The river thus potentially carries the chemicals used for the intensive crops present in the valley (rice, sugar cane, market gardening) to the sea.

Domestic pollution

8 In 2016, the Senegalese government estimated the annual production of solid waste at about 2.4 million tonnes, for a population of 15.4 million (KAZA *et al.*, 2018). Collected wastewater was estimated at 25 million m^3 per year in 2000. The spatial distribution of discharge correlates with that of the population, which is highly concentrated on the Cabo Verde peninsula. The Sine-Saloum estuary is exposed to discharge from more than 1.6 million inhabitants. In the north, the Senegal River is under pressure from more than 1.5 million inhabitants (if the populations of the cities from Saint-Louis to Matam are taken into account). In the south, the regions of Ziguinchor, Sédhiou and Kolda also have nearly 1.5 million inhabitants, mostly spread along the estuary of the Casamance River.[8]

9 Solid waste in the country is composed of 58% "fermentable" waste (organic waste, leather, paper and cardboard), 26% "combustible" waste (textiles, plastics and wood) and 13% "inert" waste (metals, glass, fine particles, stone and ceramics): 3% of waste is not classified. In 2016, an estimated 1.08 million tonnes of solid waste was not collected. It is difficult to estimate how much of this waste ends up in the marine environment, but it is often seen on beaches and in lagoons and estuaries (fig. 1B). In addition to domestic waste from residential areas, the influx of bathers on the beaches during the summer generates local pollution mainly consisting of disposable plastic objects (cups, straws, bags, bottles, etc.). Debris from fishing gear (nylon nets, polystyrene floats, etc.)

is commonly found in the sea and on the Senegalese coast. Moreover, the presence of hospital waste (syringes, plastic bottles and bags, etc.) is regularly reported on certain beaches in the capital (fig. 1A).

10 Wastewater discharge is difficult to estimate given the unquantified existence of direct discharge not connected to the stormwater network into the natural environment (CSE, 2013). Some wastewater seeps into the ground, or flows into the stormwater network and ends up in the sea. The storm drains collect a large amount of wastewater that is continuously discharged into the sea, but with peaks of discharge during heavy rainfall events.

11 The entire Cabo Verde peninsula is urbanised, covered by Dakar and its suburbs, with a population of almost 4 million inhabitants in 2020, almost double the 2.2 million inhabitants in 2000. Domestic pollution has become a large-scale issue there, especially as this is combined with industrial pollution (see the following sections). The increase in pollution, together with population growth, economic development and lack of infrastructure, has led to an explosion in pollution levels. The wastewater collected was estimated at 25 million m^3 per year in 2000, almost all of it (23,6 millions m^3) in Dakar. Less than 25% of this water is treated in wastewater treatment plants before being discharged into the sea.[9] This discharge results in the significant presence of coliforms (*Escherichia coli*) and enterococci and, more rarely, salmonella (SONKO *et al.*, 2016). The sources of the main discharge to the sea are listed in Table 1. Although historically concentrated on the western corniche, this discharge is now distributed all around the peninsula. Particularly critical points of emissions and accumulation of pollutants are observed (apart from the industrial zone of the autonomous port of Dakar) in Hann Bay, the southern part of the western corniche (in particular the accumulation in the bay of Soumbédioune), the bay of Carpes in Ngor and on the site of Cambérère (Fig. 2C). In addition to these critical sites where bathing and fishing activities are made impossible, there are many sites subject to emissions of lower intensity, but with a worrying increase, such as the site visible near the beaches of Virage and Yoff. It is also likely that the Mbeubeuss landfill, located less than 1.5 km from the coast, is responsible for indirect emissions to the sea, via rainwater run-off and/or underwater resurgence of the polluted water table, a process that has been demonstrated in other regions (BURNETT *et al.*, 2003). The increase in sources of pollution is making the Dakar coastline increasingly unfit for use, both for seafarers and for residents looking for places to relax.

Table 1. Types and quantities of soluble pollutant discharge around the Cabo Verde peninsula

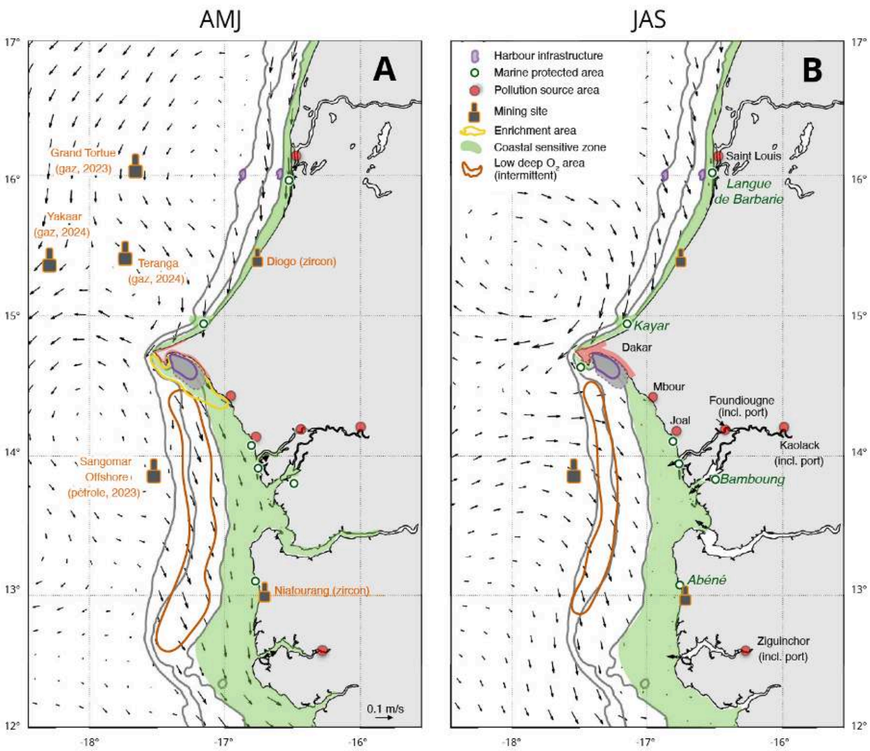
Origin of discharge at sea	**Quantity discharged into the marine environment (year)$^{-1}$**	**Date of the estimate***	**Main pollut identified**

Domestic wastewater from Dakar (of which less than 25% is treated before discharge)	24,000,000 m^3	2005 (ONAS)	Detergents, nutrients, microbes, plas parabens, nanoparticles (including plastics)
Domestic solid waste	~1,000,000 t**	2016 (DEEC)	Organic wa plastics, me glass, ceramics
Hann Bay industries	923,352 m^3	2013 (DEEC)	Hot wa chemical c hydrocarbons, solvents, an blood (slaughterhou organic ma and nutri (nitrogen phosphorus)
Diffusion via the water table under the Mbeubeuss landfill (especially in the rainy season)	No estimate	No estimate	Various he metals (espec iron, l cadmium aluminium)
Metal collection and sorting in the informal economy	Effluent mixed with domestic wastewater	No estimate known	Heavy me (lead, merc cadmium, e PCBs (polychlorinat biphenyls), aci
Dakar Port Authority	274,878 m^3	2000 (DEEC)	Hydrocarbons heavy me vegetable antifouling, phosphate, sulphur, attapulgite, c clinker, etc.

Mamelles desalination plant	50,405,000 m^3***	Max. discharge expected in 2035 (http://www.eau-assainissement.gouv.sn)	Brine (over-sa water) comb with t chemicals u for water treatment equipment protection (antifouling, e
Offshore oil and gas development	No estimate	No estimate known	Produced wa farm sludge, cargo

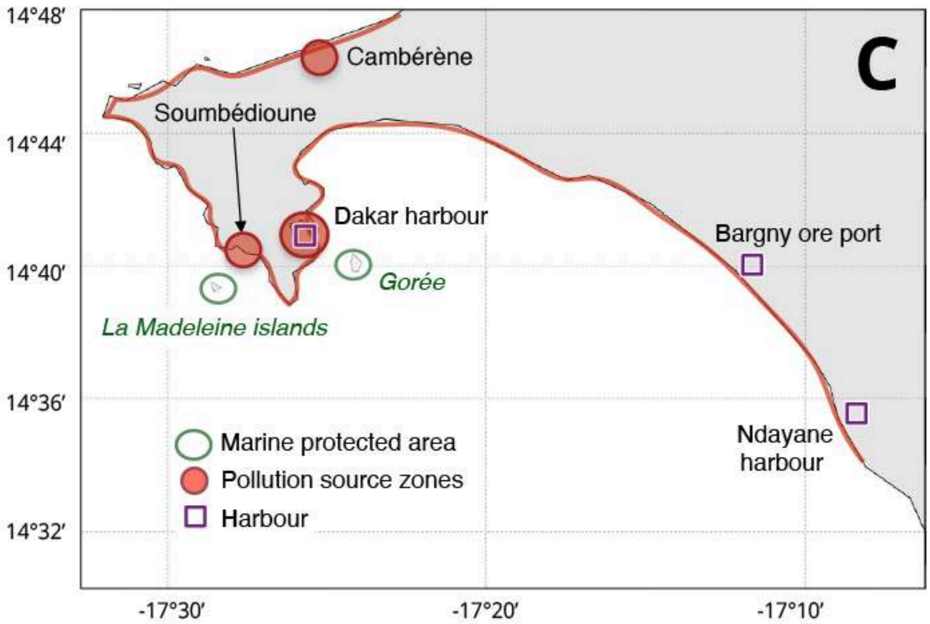
* Senegalese National Sanitation Office (ONAS)
Directorate for the Environment and Classified Establishments (DEEC)
** 1.08 million tonnes per year is not collected. Based on empirical observations, we estimate that the majority is disposed of in estuaries, lagoons or on beaches.
*** Assuming a recovery rate of 42%, which is the average rate for reverse osmosis on seawater.

Figure 2A and 2B. Main sources of pollution of coastal waters



Representation of elements relating to pollution and risks of damage to the Senegalese marine environment in two contrasting seasons: spring upwelling season (March–June; Map A) and monsoon period (July–September; Map B). The major specific point sources of pollution and the more diffuse pollution near Dakar are respectively indicated by red dots circled in brown and a red line along the coast.

Figure 2C. Main sources of pollution of coastal waters



Hann Bay and its vicinity (Map C) concentrate the impacts and risks due to the large amount of industrial and domestic pollution sources.
Source: E. Machu, T. Brochier, X. Capet, S. Ndoye, I. Sidiki Ba, L. Descroix

12 The ongoing construction of the multi-use port of Ndayane (which is intended to become the largest port in West Africa) and the mineral port of Bargny are expected to considerably expand the area of coastal ocean affected by port activities (figs. 2A and 2B, waiting area for ships, etc.; in purple with a solid line for the future situation and a dotted line for the current situation). Infrastructure is also under construction or planned at sea in connection with the exploitation of hydrocarbon deposits, such as off Saint-Louis. Maritime transport development projects also concern the Sine-Saloum estuaries (ports of Foundiougne and/or Kaolack) and the Casamance (port of Ziguinchor).

13 Rainwater runoff during the monsoon period washes out the soil and probably increases the amount of pollutants discharged into the sea (thicker red line, fig. 2B), but this seasonal variability is to our knowledge not documented (see LEE *et al.*, 2004 and CHOW *et al.*, 2005 for other regions).

14 The marine area near Dakar plays a key role in the marine ecosystem. It is an area that benefits from the upwelling of nutrient-rich deep waters during the upwelling period (fig. 2A) and a spawning and nursery area for several species of small pelagic fish (NDOYE *et al.*, 2018).

15 The 20, 50 and 100 m isobaths are represented by shaded lines (fig. 2). The 100 m isobath, located furthest offshore, is the outer shelf boundary. The 20 m isobath, located closest to the coast, is the inner shelf boundary, within which most artisanal fishing takes place. Several key small pelagic species are known to be associated with the inner shelf (flat sardinella) as well as the estuaries (ethmalosa).

16 Given the lack of knowledge, the proposed delineation of the sensitive coastal zone (green in figs. 2A and 2B) is subjective and does not include all the Important Bird Areas

(IBAs) identified by BirdLife. The area further offshore contains a particularly rich offshore ecosystem, the exploitation of which is an important source of both income and protein, and also contains areas considered to be IBAs. However, we posit that the pressures on this ecosystem and the associated risks are significantly lower compared to the coastal hotspot. The IBA identified in Senegal[10] is in the sector of the median/external plateau, which is subject to episodes of deoxygenation of the bottom layer, with consequences on the ecosystem that are not yet understood.

17 The mean surface currents from numerical simulations (NDOYE *et al.*, 2017) are indicated by black arrows for both seasons (fig. 2A and 2B). They reveal the complexity of current circulation, in particular in the vicinity of the Cabo Verde peninsula (Dakar), which is very different from the traditional pattern expected in the spring upwelling area (see also fig. 5). A direct connection via the mean currents exists in the model between the deep Sangomar offshore oil exploitation area and the South Senegalese continental shelf, especially during the monsoon period. This connection is intermittent due to the variability of the currents, which is due both to intrinsic/turbulence factors and forced by wind fluctuations (e.g. on synoptic and intraseasonal scales).

Industrial pollution

Hann Bay

18 This is the largest industrial zone in West Africa. In 2013, 42 industrial units generating discharge into Hann Bay were listed by the Directorate of the Environment and Classified Establishments (DEEC). These are mainly fish processing plants, chemical fertiliser manufacturing plants, tanning plants and oil refineries. Hot water, chemical dyes, hydrocarbons, solvents, blood (from slaughterhouses), organic matter and nutrients (nitrogen and phosphorus) are discharged from these sites into Hann Bay. Agri-food industries are responsible for the bulk of the emissions (approximately 1200 m^3/d, see details in the final environmental and social assessment report of the Hann Bay depollution project).[11]

19 In principle, these industries are monitored and pose a low risk of chemical pollution by heavy metals. However, the vast majority of the Senegalese economy is informal, which means that a large proportion of the waste is not recorded (e.g. illegal connections to pipes normally reserved for rainwater drainage). For example, there are informal battery recycling industries, which have been blamed for causing massive lead poisoning (WHO, 2008), as well as the very common practice of artisanal recycling of transformers, which may contain PCBs (polychlorinated biphenyls[12]). Generally speaking, all industrial waste containing a proportion of reusable metal is collected by scrap dealers, either small-scale or industrial, via informal economic circuits without any real monitoring of effluents or measures to prevent the release of heavy metals or other toxic products. The recycling of metals recovered in this way nevertheless takes place in factories classified for environmental protection (P. Tastevin, French National Centre for Scientific Research [CNRS], pers. comm.). Studies of metal pollution in the country are rare, but moderate levels of lead (48 mg/kg) and significant levels of cadmium (15 mg/kg) have been measured in the sediment of Hann beach (DIANKHA, 2012).

Fishing and shipping

20 Artisanal fishing canoes, industrial fishing vessels of various sizes, as well as cargo ships transit and anchor in Senegalese coastal waters. Industrial bottom-trawling vessels destroy benthic habitats and resuspend sediments, including any accumulated pollutants. Industrial fishing vessels frequently discard their bycatch, which decomposes in the water column and on beaches. Fishing gear debris (nets, traps, plastic drums and polystyrene floats) also constitutes a significant part of the waste observed at sea and on beaches.

21 The autonomous port of Dakar, the second largest industrial port in Africa, is located in the middle of the city. It adjoins Hann Bay, but its right of way for the mooring of industrial ships covers a vast maritime zone that encompasses the whole of Hann Bay, from Cap Manuel in Dakar to Cap Rouge in Yenne. The associated traffic was estimated at 20 million tonnes in 2019. Among the port's activities that cause marine pollution are ship repair, the grain terminal, and the loading and unloading of oil through oil tanker pipelines (underground and overhead) and oil traffic, the landing for import-export of solid industrial bulk such as sulphur, coal and clinker (a component of cement consisting of about 80% of limestone and 20% of aluminosilicate), and the shipping of phosphate and attapulgite. The most commonly observed pollution is from accidental sulphur spills, the continuous presence of urban effluent outfall in the port, the mixing of hydrocarbons and floating waste of undetermined origin (degassing/discharge by ship). There are many industrial ships moored in the port or in the maritime part of the port, which additionally generate constant noise pollution as the engines run continuously to provide power to the ship.

22 Lastly, over the past 20 years, the West African coast has seen the installation of some 60 fishmeal factories which, in addition to causing overfishing, the plundering of fish resources and the disappearance of the highly productive fish smoking sector, also causes pollution through the discharge of toxic products into mangrove wetlands and rice fields as well as into the ocean (GRAND and DIOP, 2018; DESCROIX and MARUT, 2015).[13]

Offshore oil and gas extraction

23 Exploration off Senegal in recent years has revealed the presence of hydrocarbon wells (gas in the north of the Cabo Verde peninsula, oil and gas in the south). Concessions cover a large part of the Senegalese exclusive economic zone, from coastal areas to about 200 km off the north and south coasts, and about 100 km from the Cabo Verde peninsula (Dakar), typically to a depth of 4000 m (fig. 2A; all concessions can be found on Map 2C in LE TIXERANT *et al.*, 2020). Offshore oil extraction activities started in 2019.

24 This type of activity generates daily pollution linked to tanker traffic, transhipment activities, and chronic discharge of drilling fluids (or "drilling muds") and produced water. Drilling muds are recovered solids from drilling operations impregnated with hydrocarbons, as well as drilling oils that are added to fluidify the extracted materials. For a given production site, this mud waste represents thousands of tonnes, hence the environmental concern. In addition, water from oil or gas production, also known as "produced water", is brought to the surface, often as an emulsion in the crude oil. This water is separated from the hydrocarbons. Three levels of standards govern the treatment of these by-products and the risks associated with exploitation: international standards, those adopted by operators, and those adopted by the countries concerned.

In Senegal, the signing of the Abidjan Convention authorises produced water to be discharged into the sea or reinjected, but requires drilling mud to be transported onshore.[14] The long-term effects of offshore exploration and development is therefore generally related to chronic low-level discharge of drilling fluids and produced water. Of course, there is also a risk of accidents and the massive release of hydrocarbons in the event of blowouts during extraction or from spills during transportation.

Mineral extraction

25 The West African coastline has also seen the emergence of other types of potentially polluting extractive or primary activities. The coastline itself (beaches and dunes) locally contains not inconsequent levels of zircon, ilmenite and rutile (titanium); this has been exploited since 2010 in Sanyang in the Gambia, and since 2014 in Diogo on the Senegalese Grand Coast (fig. 2A). In the latter case, any pollution is not necessarily likely to reach the ocean, as the extraction site is located 4 km inland. It should be noted that at least two extraction sites (Kartung in the Gambia and Varela-Sucujaque in Guinea-Bissau) have been closed at the request of the local population, who complained about the harmful impacts of this exploitation: toxic discharge on land, toxic discharge at sea, and undesirable turbidity of the sea and mangrove swamps. A project linked to a small dune containing a deposit with a very high heavy metal content (12% compared to 2% on the other sites mentioned) has been blocked in the north of the Casamance coast, following the fears of the population concerning the possible impacts on rice fields, mangroves and fisheries (DESCROIX and MARUT, 2015).

26 The Senegal, Gambia and Koliba/Corubal river basins have also been major gold mining sites for several years now, with large mines operated by South African or Brazilian multinationals, as well as more or less clandestine gold panning operations on land or in rivers. Is there not a risk that the waste from these activities, known to be highly toxic (including mercury, cyanide, etc.), will one day end up in the sea or in coastal mangrove forests?

Major coastal development projects

Desalination plant

27 The desalination plant project on the Mamelles site in Dakar plans an initial production of 50,000 m^3/d and eventually 100,000 m^3/d of drinking water. It will use reverse osmosis, which involves filtering water pumped from the sea at very high pressure through membranes: a very energy-intensive process. Local marine pollution, linked to the production of brine and the toxic chemicals used for water treatment and pipe cleaning (sulphuric acid, hydrochloric acid, caustic soda, citric acid, chlorine gas, etc.) is expected. Despite the validation of the environmental impact study by stakeholders, the pumping and discharge of treated water in the vicinity of the beaches and the artificial reef managed by the fishermen of Ouakam continues to raise various environmental concerns. For example, the lack of a baseline for the local ecosystem will make it difficult to assess the consequences of the alteration of the environment by brine discharge, or the impacts of the toxic chemicals used (the volumes of which were not quantified in the impact study). High salinity can cause a reduction in dissolved oxygen in the receiving waters, and ultimately have significant impacts on benthic organisms, which can have repercussions on the entire ecosystem. In addition, the

consequences of underwater noise pollution resulting from pumping installations are difficult to assess.

Industrial ports

28 Four new infrastructure projects are planned as part of the Plan for an Emerging Senegal (PSE[15]). In the mangrove ecosystems of the Sine-Saloum and Casamance, which are particularly sensitive to hydrocarbon pollution (DUKE, 2016), three hydrocarbon terminals (specialised landing stages, storage areas and loading/unloading systems: pipes, etc.) are to be built in Kaolack, Ndakhonga-Foundiougne (Sine-Saloum) and Ziguinchor (Casamance). The construction of this infrastructure would inevitably multiply the areas of potential pollution of the marine environment, both during their construction and throughout their operation. The risks of dispersing contaminants throughout these ecosystems are increased by the strong hydrological dynamics that characterise these regions, which are as yet largely unknown (see the section on the role of ocean dynamics in the trajectory of pollutants).

29 In the coastal region, the Bargny mineral and bulk port project and the Ndayane multipurpose port project, located in the extension of Hann Bay, could generate environmental damage comparable to that of the current port of Dakar. The relocation of existing industrial activities to these areas could reduce the sources of pollution in the current port of Dakar, but this could increase the vulnerability of mangrove ecosystems and the shallow continental shelf of the Petite Côte, which is a retention zone whose fragility and role in the reproduction of fisheries resources have been highlighted (e.g. TERASHIMA *et al.*, 2007; ECOUTIN *et al.*, 2010; MBAYE *et al.*, 2015; SADIO *et al.*, 2015; NDOYE *et al.*, 2017).

Ecosystem risks

30 The effects on a marine ecosystem resulting from exposure to a pollutant depend on the nature of the pollutant, the trajectory of the pollutant (in the environment and within the organism), the level of exposure and the organisms exposed. This section outlines the general principles of the consequences of exposure of marine organisms to pollutants, and presents examples of disturbance at different structural levels.

General principles

31 The response of organisms to pollution occurs at four levels of biological organisation: (1) biochemical and cellular; (2) the systemic physiological, biochemical and behavioural responses of the organism; (3) population, including changes in population dynamics; and (4) community, resulting in changes in community structure and dynamics (e.g. CAPUZZO, 1987)

32 Generally speaking, the first reactions of an organism to exposure to pollution consist of setting up mechanisms to resist or reduce the impact of toxic substances or stress. In the case of exposure to a toxic pollutant, for example, the response will be through the activation of toxic substance metabolism processes (at the biochemical level), or through the selection of toxic substance-resistant forms (at the population level). The biological effects of pollutants can manifest themselves at different levels before

disturbances are observed at the population level. Not all responses are harmful in nature and do not necessarily lead to degeneration at the next level of biological organisation. It is only when compensatory or adaptive mechanisms at one level begin to fail that deleterious effects manifest themselves at the next level (CAPUZZO, 1981). Adaptive processes are able to counteract disruptive processes until the system reaches a threshold of toxicity beyond which the adaptive potential is exceeded by the degeneration imposed on the system by the disturbance.

33 A pollutant can accumulate along a trophic chain, but it can also be resorbed by certain organisms, which thus mitigates this accumulation. Nevertheless, whatever the organism, the reactions caused by its exposure to pollution can disrupt its metabolism, modify its behaviour and induce energy costs that are often to the detriment of its maintenance, growth and/or reproduction. Differences in the adaptive capacity of different species can have significant consequences on the structure of communities.

Examples of disturbances and responses of organisms

34 In this section, we illustrate the responses of organisms at different levels of organisation using examples concerning species found in Senegal (or of close taxonomic rank) and of types of pollution affecting the region.

Biochemical disruption of cells: oysters and plastics

35 The presence of plastic debris in the ocean has been reported since the 1970s (CARPENTER and SMITH, 1972). Plastics are now ubiquitous and their presence in the waters of Senegal is reinforced by local pollution. Modern plastics are made up of a complex mixture of polymers, residual monomers and chemical additives. In the environment, the fragmentation of plastic debris by photo-oxidation, mechanical action or biodegradation generates small particles called microplastics (1 µm to 5 mm) or the even smaller nanoplastics (< 1 µm). This secondary waste represents between 97% and 99.9% of ocean contamination by plastics (TALLEC, 2019). The presence of nano-sized particles is important in an ecological context, as their small size allows them to cross biological barriers and penetrate cells. Several studies have highlighted the sensitivity of the early life stages of the oyster species *Crassostrea gigas* (the leading aquaculture species worldwide) to exposure to polystyrene nanospheres (SUSSARELLU *et al.*, 2016; TALLEC, 2019). TALLEC *et al.* (2020) found that 50 µm nanospheres induced acute toxicity on spermatozoa, oocytes, fertilisation and embryo-larval development of *C. gigas*. Given the absence of ingestion processes in oyster gametes and embryos, the toxicity of nanospheres is related to direct contact with the external barrier of these cells, i.e. their cell membrane. The latter is a complex and dynamic structure composed of two large families of macromolecules, the lipids forming the lipid bilayer, and the proteins inserted into this (transmembrane proteins) or attached to this (peripheral proteins). Transmembrane proteins play an essential role in homoeostasis (e.g. ion channels) and in communication with the intracellular environment. Their activity depends on their spatial configuration, which is directed by the state of the lipid bilayer (WEIL *et al.*, 2009). The WEIL *et al.* study shows that a modification of the physical properties of the membrane, linked to the adsorption of nanoplastics, can induce harmful effects in cell function.

Disturbance of organisms: marine birds, trace metals and oil

36 Early studies on the effects of pollutants on birds focused on direct mortality (BELLROSE, 1959), but later research has demonstrated a wide range of sublethal effects on the development, physiology and behaviour of individuals. Sublethal effects of pollutants on seabirds include reproductive deficits (AINLEY *et al.*, 1981), teratogenicity and embryotoxicity (HOFFMAN, 1990), eggshell thinning (RISEBROUGH, 1986), enzyme induction (FOSSI *et al.*, 1989; RONIS *et al.*, 1989), effects on endocrine function (PEAKALL *et al.*, 1973; PEAKALL, 1992) and behavioural abnormalities in adults and juveniles (BURGER and GOCHFELD, 1985, 2000; BURGER, 1990).

37 DIANKHA *et al.* (2019) studied the level of trace metal element (TME) and polycyclic aromatic hydrocarbon (PAH) contamination in four Senegalese seabird species (Caspian tern *Sterna caspia*, royal tern *Sterna maxima*, slender-billed gull *Larus genei*, and grey-headed gull *Chroicocephalus cirrocephalus*). Eggs of these species were collected in the national parks of the Langue de Barbarie and the Saloum Delta (fig. 2B), two breeding sites of these species with marine protected area status that are located close to future hydrocarbon exploitation sites. All species were found to be contaminated with PAHs and TMEs. Benzo(a)pyrene, one of the most toxic PAHs, was the compound most present in the eggs of three of the four species analysed. The concentrations of benzo(a)pyrene in the eggs of the royal tern and the grey-headed gull were above the median lethal concentration (causing the death of 50% of the individuals in a population) defined for species such as the mallard duck.[16]

38 Of the TMEs, lead was the metal with the highest concentration in the eggs of the species studied. Lead pollution comes mainly from industrial processes, leaded gasoline combustion, runoff, agricultural practices, eroded lead paint and, to some extent, natural processes such as erosion and volcanism. For three decades, lead contamination levels and effects in seabirds breeding in the New York-New Jersey area have been studied in the laboratory and in the field. This research has shown that lead affects a wide range of behaviours in chicks, including locomotion, balance, begging, feeding, growth and cognitive ability, which in turn affect survival in the wild (BURGER, 1990; BURGER *et al.*, 1994; BURGER and GOCHFELD, 1997).

Population disturbance: copepods, sardinella and warming

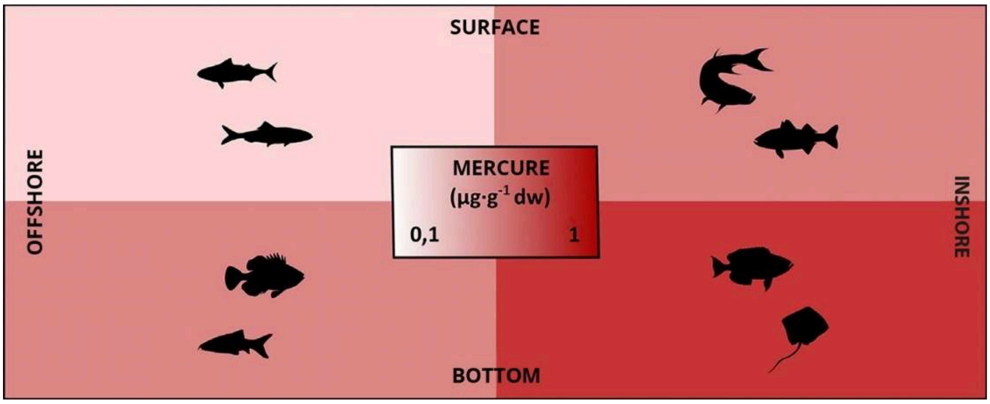
39 Studying the consequences of pollution at the population level of a species requires observation over a sufficiently long period of time. The number of documented examples of such impacts is therefore relatively limited. Using a zooplankton collection device installed on ships operating in the North Atlantic since the 1930s (continuous plankton recorder, WARNER and HAYS, [1994]), BEAUGRAND *et al.* (2002) were able to show that, in response to ocean warming, large-scale changes had occurred in the biogeography of calanoid copepod zooplankton organisms in the eastern North Atlantic Ocean and in the seas of the epicontinental shelf of Europe. Over a period of about 40 years (1960–1999), warm-water copepod species have moved up to 10° further north, an extension that has been associated with a decrease in the number of cold-water species. This type of shift is consistent with the general response observed and expected in response to climate change (HASTINGS *et al.*, 2020).

40 Several studies also suggest that the West African sardinella (*Sardinella aurita*) population is making increasingly northern migrations through the Canary Islands system (SARRÉ, 2017; KIFANI *et al.*, 2019). Using time series of independent observations, SARRÉ (2017) showed a northward shift in the distribution of *S. aurita* since 1995. These spatial changes observed over the last 20 years may be related to observed changes in surface temperatures, with warmer years associated with a more northerly population. However, KIFANI *et al.* (2018) point out that it is difficult to determine the relative contribution of climate change, natural variability and exploitation on the dynamics of this population over the last decades.

Community disturbance: fish and algae

41 For a TME such as mercury, for example, it has been shown that bioaccumulation can be highly variable in marine fish species found on the Senegalese shelf (LE CROIZIER *et al.*, 2019). The impact of trophic ecology and habitat on mercury accumulation was analysed through the total mercury concentration and stable carbon and nitrogen isotope ratios (which provide information on diet) in the muscle of fish belonging to 23 different species. Spatial occupation, both vertically and in terms of distance from the coast, seems to lead to differential mercury accumulation, with coastal and demersal fish being more contaminated than offshore and pelagic species (fig. 3). Proximity to the most anthropised urban sites is also a factor in amplifying the pollution of marine organisms (DIOP *et al.*, 2016, 2017). For individuals of the same species and from the same site, the variation in mercury content is mainly explained by the length of the fish, in line with the hypothesis that mercury bioaccumulates over time.

Figure 3. Mercury contamination of fish communities



Mercury contamination pattern for fish caught at sea during the AWA 2014 campaign. Vertical (i.e. distribution in the water column) and horizontal (i.e. distance from the coast) habitat resulted in differential mercury accumulation between species. Coastal and demersal fish were more contaminated than offshore and pelagic species.
Source: LE CROIZIER *et al.* (2019)

42 Data from laboratory and field studies support the hypothesis that mercury in the aquatic environment has a negative impact on the reproductive health of fish (CRUMP and TRUDEAU, 2009). In controlled feeding studies, consumption of diets containing mercury (e.g. methylmercury) at realistic concentrations resulted in a range of toxic effects in fish, including behavioural, neurochemical and hormonal changes (SCHEUHAMMER *et al.*, 2007). Some notable variations in response to mercury exposure

can be attributed to one or more of the following factors: species, life stage, gonadal developmental status, route of exposure, duration of exposure, mercury speciation and concentration. Although it is difficult to demonstrate these changes in the field, long-term exposure of fish to mercury is likely to affect the structure of fish communities.

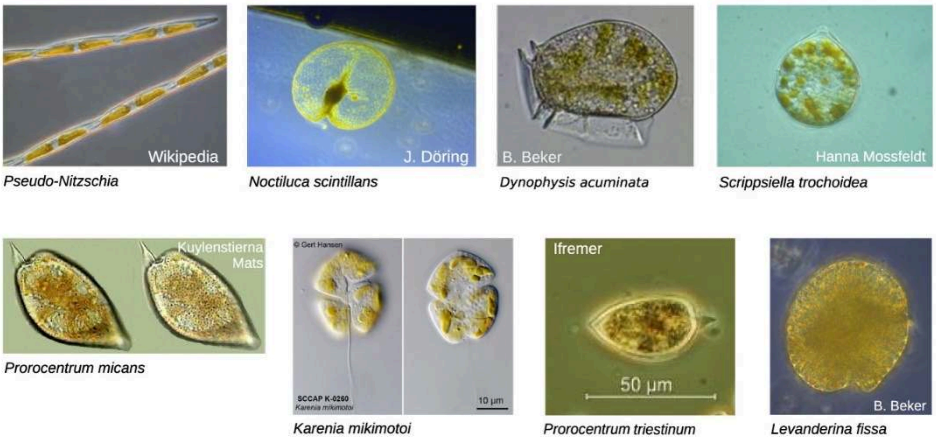
43 The consequences of anthropogenic disturbance on plankton communities have also been identified. Harmful algal blooms (HABs) are increasingly threatening the economic viability of fisheries and aquaculture, ecosystem health and diversity, and recreational activities in some areas. Among other things, these harmful algae can produce paralytic, diarrhoeal or amnesic toxins for humans who consume them indirectly through shellfish. Other toxins (e.g. ichthyotoxins, yessotoxins) can affect different components of marine ecosystems. These HABs can also have significant effects on ecosystems when the degradation of algae blooms leads to hypoxia or anoxia (COCKCROFT, 2001; GRANTHAM *et al.*, 2004; HERNÁNDEZ-MIRANDA *et al.*, 2010). In Senegal, hypoxic conditions are intermittently encountered in bottom waters along the middle and outer shelf (figs. 2A and 2B), likely related to the degradation of large blooms (MACHU *et al.*, 2019).

44 The eutrophication[17] of coastal areas is one of the mechanisms put forward to explain the increase in the number of HABs worldwide (e.g. HEISLER *et al.*, 2008; GLIBERT *et al.*, 2005). Beyond this eutrophication phenomenon, phytoplankton biodiversity is altered by merchant ships introducing exotic microorganisms into all ecosystems of the world (e.g. BAX *et al.*, 2003). Changing environmental conditions in response to climate change also affect the mechanisms of competition between species (EDWARDS *et al.*, 2006; HEISLER *et al.*, 2008; FU *et al.*, 2012). Climate change is expected to have significant effects on the frequency and abundance of HABs due to the complex factors that may change and the combined effects that these factors (temperature, acidification, salinity, sunlight, stratification) may have on HAB growth or habitat (FU *et al.*, 2012).

45 In addition to encouraging harmful algae, these changes are likely to alter planktonic assemblages. One study documented this type of potential change in the northern Arabian Sea, which has experienced a dramatic change in the composition of winter phytoplankton blooms. These previously consisted mainly of diatoms, but are now replaced by blooms of the large dinoflagellate *Noctiluca scintillans* (DO ROSÁRIO GOMES *et al.*, 2014). These *N. scintillans* blooms are facilitated by an unprecedented influx of oxygen-depleted waters and the extraordinary ability of its endosymbiont, *Pedinomonas noctilucae,* to fix carbon more efficiently than other phytoplankton in oxygen-depleted conditions. Such changes have the potential to disrupt the traditional food chain maintained by diatoms to the detriment of regional fisheries and the long-term health of an ecosystem supporting a coastal population of nearly 120 million people.

46 In recent years, nine of the 28 potentially toxic algal species found in the eastern upwelling ecosystems have been sampled off Senegal (Fig. 4). To our knowledge, no monitoring of these algae has yet been implemented in Senegal, either in the context of food security or health.

Figure 4. **Potentially toxic algae of the 29 harmful algal species found in upwelling systems in coastal waters (TRAINER *et al.*, 2010)**



Nine species have been identified by microscopy in samples collected since 2013 in Senegalese coastal waters.
Source: E. Machu, T. Brochier, X. Capet, S. Ndoye, I. Sidiki Ba, L. Descroix

The role of ocean dynamics in the trajectory of pollutants

47 Marine pollution has so far received relatively little attention, particularly where it does not lead to major damage to the coastline. Despite the fact that sources of pollution are mainly concentrated in certain nearshore and coastal areas, the dispersive properties of the marine environment generally tend to limit local accumulation in the water column (although not necessarily in marine sediments, MARTIN *et al.*, 2017; LUOMA, 2018). The ocean would therefore appear to be a giant landfill capable of rapidly diluting large quantities of water-miscible pollutants. However, in the case of debris or material floating on the ocean surface, accumulation effects are possible and pose specific problems. Dilution/dispersion/accumulation of liquid or solid pollutants can result from a large number of physical processes, mainly of a turbulent nature. Different processes act at different spatial scales with their own intensity depending on the environmental conditions and the type of pollutant considered.

48 Coastal environments subject to an upwelling wind pattern, as is the case off the West African coast, are considered to be unlikely to be affected by marine pollution due to the general characteristics of their circulation. In the simplified “2D vertical” view of a coastal upwelling, coast to offshore circulation is mainly forced by the wind and takes the form shown in figure 5. Due to the rotation of the Earth, the effect of wind friction drives surface water offshore. This is replaced by deep water that ascends at the coast. In this context, coastal sources of pollution can contaminate the upwelling water, but these are systematically transported away and the accumulation of pollutants is therefore, in theory, greatly reduced. This is consistent with the global simulations of micro-plastic drift presented by ONINK *et al.* (2019). The mixing by the mesoscale and

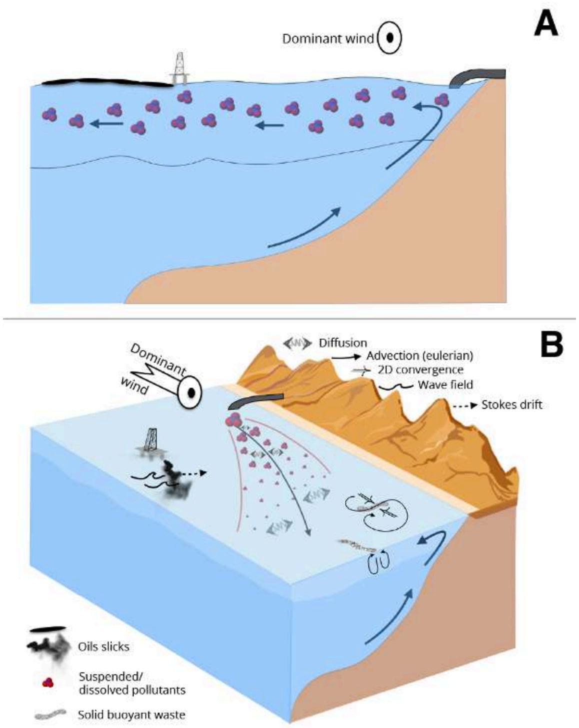
submesoscale eddies that accompanies the upwelling dynamics contributes to the rapid dilution of pollutants introduced into the environment.

49 The risk of oil spills reaching the coast is also considered limited due to circulation resulting from the wind. This, however, must be qualified. Oil slicks, which are frequently confined to the surface, and floating solid waste are transported separately from suspended or soluble waste in the water column. This is due to several factors:

- The prevailing dynamic balance between Coriolis force and wind friction on the ocean induces seaward (Ekman) velocity that is lower at the exact ocean surface than in the mixed layer maintained by the wind (typically 10 m to 30 m deep).
- Ocean wave fields are also responsible for the drift of substances and (micro-)objects trapped on the surface (Stokes drift, ARDHUIN *et al.*, 2009). Stokes drift can result in speeds of the same order of magnitude as Ekman velocity. Transport takes place in the direction of swell/wave propagation: generally towards the coast. Depending on the type of pollutant, a wind-borne effect (windage) can also contribute to its transport. In Senegal, the winds have a westerly component from February–March until October–November and also contribute to transport towards the coast.
- On horizontal scales of around a few tens of metres to ten kilometres, the convergence of surface currents is capable of aggregating pollutants trapped at the surface very efficiently along fronts that are clearly visible in calm weather (Langmuir cells, MCWILLIAMS *et al.*, 1997; sub-mesoscale circulation, CAPET *et al.*, 2008). The underlying processes are general, and their nature is turbulent. The partly random orientation of the fronts and their associated circulation can lead to the aggregation of polluting materials being moved closer to or further away from the coastline.

50 Beyond these general processes, the local specificities of certain coastal sectors subject to upwelling can lead to circulation patterns that differ significantly from the typical situation presented in figure 5. This is particularly the case in the vicinity of bays and capes where meanders and quasi-permanent recirculation frequently exist (LARGIER, 2020). Along the Senegalese coast, the geomorphological obstacle of the Cabo Verde peninsula strongly structures the circulation, both to the north and to the south. As a result, the mean surface currents in the area just below the cape are preferentially directed towards the coast (fig. 2). Contrary to what might be expected based on the general knowledge of the circulation in the upwelling zone, possible oil leakage from wells planned to come on stream in the next few years could, even in the upwelling period, affect the continental shelf area north and south of Dakar, and in particular the coastline of Hann Bay and the Petite Côte (fig. 6). During the rainy season (July to September/October), the weaker prevailing westerly winds lead to substantial changes in the circulation on the continental shelf, characterised by a relatively direct connection from the slope to the shelf south of Dakar via transport by surface currents, and a stagnant circulation on the inner part of the shelf, which is necessarily detrimental to the dispersion of pollutants (fig. 6)

Figure 5. Physical processes and trajectory of pollutants



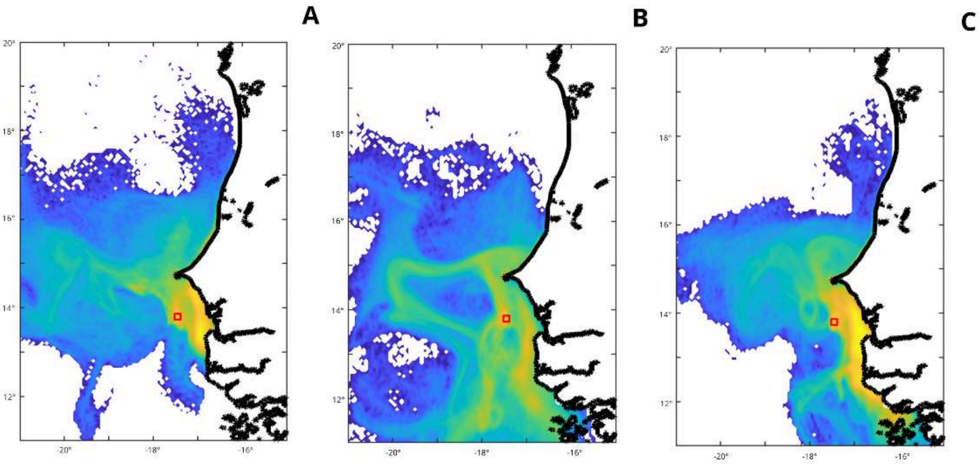
Representation of the typical circulation attributed to coastal areas subject to the upwelling process, under the action of a wind blowing parallel to the coast in the direction of the Equator for a coast oriented north-south

A. In the simplest setting, the cross-shore circulation consists of an Ekman cell that moves water from the open sea to the coast and transports surface water in the mixed layer to the open sea by the wind (Ekman transport). In this context, pollutants introduced to the ocean at the shore or at sea are carried offshore.

B. In a more realistic framework, seaward transport is accompanied by lateral dispersion/diffusion effects that affect all types of pollutants, as well as specific effects that affect pollutants confined to the surface (oil slicks, plastics, etc.). These effects are wave-driven drift (Stokes drift), which occurs in the direction of wave/swell propagation; horizontal convergence (2D) along fronts produced by meso/submeso-scale structures (MUNK *et al.*, 2000) or other forms of circulation involving vertical velocity (e.g. Langmuir cells, MCWILLIAMS *et al.*, 1997)

Source: E. Machu, T. Brochier, X. Capet, S. Ndoye, I. Sidiki Ba, L. Descroix

Figure 6. Oil spills



Simulation of the dispersion of hydrocarbons emitted continuously for 30 days (month of June) at the Sangomar offshore operation site (red rectangle)
Map A shows the average dispersion over the period 2001–2009. The interannual variability of the circulation, and thus of the dispersion, is illustrated by the maps for June 2004 (map B) and June 2005 (map C). These maps were generated based on Lagrangian transport of floating particles in the currents from a regional modelling experiment conducted with the ROMS model at a spatial resolution of 1/60.
Source: E. Machu, T. Brochier, X. Capet, S. Ndoye, I. Sidiki Ba, L. Descroix

51 Based on available knowledge of slope-shelf exchanges (NDOYE *et al.*, 2018), the dispersion study by MURAWSKI *et al.* (2019) and an ongoing study (fig. 6), Senegal's inner shelf is subject to significant pollution risks in the event of oil spills from Kayar, and especially the Sangomar offshore area (fig. 2) where deep oil exploitation is due to start in 2023. Potential long-range impacts were also identified as far north as the Banc d'Arguin marine protected area, and as far south as the Bijagos archipelago biodiversity sanctuary in Guinea-Bissau (fig. 6; figure 19.1.C in MURAWSKI *et al.*, 2019).

52 The typical circulation near and south of Dakar is also responsible for particularly favourable conditions for the reproduction of marine organisms with pelagic early life stages: upwelling water concentrated in Hann Bay (fig. 2; NDOYE *et al.*, 2018) and strong retention of upwelled water on the shelf. This allows the early life stages of many marine species to evolve in an enriched coastal environment (FRÉON, 1988; MBAYE *et al.*, 2015).[18]

53 All these inferences are made on the basis of simulations whose realism in terms of currentology needs to be assessed in more detail (but see NDOYE, 2016 and NDOYE *et al.*, 2017 for an encouraging general assessment of the model), which is not currently possible given the scarcity of existing current observations. Despite one-off measurements of varying duration since 2012 (CAPET *et al.*, 2017; MACHU *et al.*, 2019; TALL *et al.*, 2021), the reference circulation for the southern zone of the Senegalese continental shelf remains that of REBERT and PRIVÉ (1974), which has many limitations and probable bias, in particular due to the short duration of the stations and measurements (< 10 min per depth at each station) and the failure to take into account tidal currents, which we now know dominate the circulation perpendicular to the coast (CAPET *et al.*, 2017).

54 Modelling of oil dispersion clearly illustrates the importance of good in situ knowledge in the implementation of pollution risk management approaches in the coastal

environment and, more generally, in the spatial planning of marine areas. These remarks apply to the impact studies carried out recently with a view to oil exploitation (the Rufisque Offshore Profond block[19] and the AGC Profond block; cartographic atlas of marine environment law, Senegalese Oil and Gas Paddle), some of which were carried out using global circulation models, which are not very well suited to representing the dynamics of the continental shelf, and whose circulation on the Senegalese shelf differs markedly from that presented by REBERT and PRIVÉ (1974) or NDOYE *et al.* (2017).

55 The circulation in estuarine environments connected to the Senegalese plateau (Sine-Saloum, Casamance) and their fluid exchanges with it have been the subject of very few studies. Tidal currents here are intense and extraordinarily complex, and their residual (average over a complete cycle) is unknown. These estuaries are also evaporation basins for a large part of the year. This results in an additional component of estuarine (or gravitational) circulation similar in principle to that observed in the Mediterranean: inflow of water with relatively low salinity at the surface and outflow of dense/salty water at depth related to the existence of stratification despite the shallow depth (typically about 10 m, CAPET *et al.*, 2019). In view of this, oil intrusion as far as the southern Senegalese inner shelf (fig. 6) appears to be a risk that needs to be quantified (and, if necessary, prevented). The residence times of pollutants emitted within estuaries are also unknown, but are likely to be long (months to years). Recently initiated estuarine modelling work (B. NDOM and V. E CHEVIN, pers. comm.) will eventually provide valuable information to clarify these issues and guide possible prevention or remediation strategies.

Conclusion

56 The annual reviews written by the Emergency Response Division of the National Oceanic and Atmospheric Administration (NOAA) of the main publications that have studied the effects of pollution on marine organisms (e.g. MEARNS *et al.*, 2018, 2019, 2020) illustrate both the diversity of sources of pollution and the diversity of their effects depending on the organisms exposed to them. In Senegal, human activities generate various types of pollution, the composition of which is unknown and the volumes poorly quantified. These sources of pollution are added to the anthropogenic disturbances not described here that affect the entire globe, namely warming, acidification and deoxygenation of the oceans. Pollutants affect all levels of biological organisation, and Senegal is not spared from the many threats associated with this pollution. The effects of these pollutants can be significant and can act in concert. However, the combined effects on the species that make up the marine ecosystem remain unknown. Ocean circulation can also produce situations that are much more diverse than that generally envisaged in an area (i.e. through the dilution and rapid export of pollution to the open sea). For pollutants confined to the surface, there may be strong accumulation effects involving a combination of processes.

57 Figure 2 shows key areas for the ecosystem, either for vulnerable phases of the fish lifecycle (larvae, juveniles) and/or as biodiversity hotspots. The southern Senegalese inner shelf is generally an ecologically important area due to the physical conditions discussed in the section on the role of ocean dynamics in the trajectory of pollutants. From north to south, the estuaries of the Senegal River, the Sine-Saloum, the Gambia River and the Casamance also represent key sites for shellfish (see chapter 6) or certain

fish species (BAINBRIDGE, 1963; SIMIER *et al.*, 2004; ECOUTIN *et al.*, 2010; SLOTERDIJK *et al.*, 2017; DÖRING *et al.*, 2017). In terms of conservation, these estuarine areas are home to a high level of biodiversity (DIA, 2012), including some marine mammal species (VAN WAEREBEEK *et al.*, 1997; PERRIN and VAN WAEREBEEK, 2007; KEITH-DIAGNE *et al.*, 2021), and represent sensitive sites[20] for many bird species[21].

58 The key areas identified in figure 2 also concentrate a large number of human activities: small-scale fishing, tourism, and maritime transport linked to port infrastructure. They are also subject to local pollution, either because of the scale and chronicity of the sources of pollutants (Hann Bay and Petite Côte) or because of the length of residence time (estuaries). To this must be added the existence of delocalised risks, in particular linked to oil spills, which can affect the entire marine region and have a particularly significant impact in coastal areas. Figures 5 and 6 illustrate that circulation and dynamic processes connect areas of pollution to sensitive ecological areas and are therefore likely to pose risks to them. The seasonality of hydrodynamic conditions along the Senegalese coast is also an important element to take into account in the role that circulation can play in the transport and dispersion of pollutants (fig. 2).

59 From a marine spatial planning perspective, these different elements argue for the identification of sensitive areas on the basis of ecological criteria, risks linked to sources of pollution, and their socio-economic and cultural role. Given current knowledge, it seems legitimate to consider the entire inner shelf and estuaries as critical areas. In practice, these areas are places of conflicts of use between fishing, tourism and industrial activities. Numerous factors complicate the implementation of a spatial planning process for the marine environment (EHLER *et al.*, 2019), as many development projects show a strong tendency towards a top-down approach (e.g. the Ndayane multifunctional port project)[22] and are part of the weak regulation of polluting industries or artisanal fishing (unsatisfactory status of marine protected areas, CORMIER-SALEM, 2015). Failing that, and pending hypothetical conditions that are more favourable, the following recommendations can be made.

- *Prioritise work on pollution sources (upstream):* anticipate the risks linked to the installation of new infrastructure (desalination plant, port of Ndayane), ensure that a substantial budget and permanent human resources are allocated to monitoring and maintaining strict pollution prevention standards and implementing emergency responses. The project to clean up Hann Bay is one of the essential tools for reducing sources of pollution from the megalopolis of Dakar and is in line with this strategy.
- *Develop strategies and actions to mitigate pollution and its risks in concertation (co-construction):* marine spatial planning must resolve conflicts of use. It thus needs to be closely linked to a co-construction/co-development approach, which is essential whatever the level of aims. For example, the "What a Waste 2.0" project financed by the World Bank tackles the problem of plastic pollution by including local populations as well as government agencies and private stakeholders (see also the project *Ensemble Contre Les Ordures* [ECO] 'Together against rubbish').[23]
- *Advance scientific understanding:* given the rise in combined risks (local and global disturbance), it is urgent to better quantify pollution in Senegal, both in terms of the diversity and the quantity of pollutants entering the ocean. The consequences of this pollution also need to be anticipated. Understanding ocean circulation allows us to spatialise the risks linked to the different sources of pollution. The experimental study of the response

of every species in an ecosystem to disturbances, including the current and future variability to which they are/will be subjected, remains utopian. However, it is essential to identify the key species at risk, to understand their lifecycle in order to protect sensitive phases/areas, and to shed light on the mechanisms underlying all types of disturbance (Dupont and Pörtner, 2013). It is difficult to assess the toxic effects of contaminants on populations with long life spans consisting of many overlapping generations. Establishing a causal link requires multiple steps, including both laboratory experiments and field observations.

60 Scientists and the rest of society must adopt a humbler attitude towards the relationship between humanity and our environment, as science is not advanced enough to anticipate all the consequences of global and local disturbances on the marine environment. In Senegal, as in many places around the world, the sources of environmental degradation seem to be accumulating faster than the state of knowledge is progressing. By advocating for marine protected areas or similar types of zones, marine spatial planning could reduce some, but not all, of the pressures on the environment. Yet an important unresolved question is whether it perpetuates a cultural relationship with life that may be at the root of human-induced ecological problems. This was highlighted at a recent symposium[24] that raised the question: “Is the protection of the marine environment part of the activities understood as ‘uses’ of the sea and its resources or should it be distinguished from them?” This reasoning is also found in the work of P. Descola (2005) about the naturalism that characterises Western societies. Spatial planning, a tool for managing the marine environment, only attempts to organise the distribution of human activities at sea in order to optimise yields (for humans) and limit conflicts of use (between humans). That this results in areas where marine organisms can live relatively protected from human activities is only an unintended consequence. Is this enough to create truly sustainable conditions for coexistence between human societies and other species? The disproportionate share of human and financial resources invested in the forms of development that destroy nature rather than protect it, in Senegal as elsewhere in the world, unfortunately gives little cause for optimism.

Acknowledgements

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NOTES

1. See the figures of the National Agency of Statistics and Demography of the Republic of Senegal: https://www.ansd.sn/index.php?option=com_ansd&view=titrepublication&id=30
2. https://www.seneweb.com/news/Video/dechets-medicaux-sur-des-plages-les-imag_n_308080.html
3. According to several studies, between 60% and 80% of floating marine debris on beaches or on the seabed is plastic.
4. World Bank Infographic: *Waste, a global picture of household waste management to 2050*, Sept 2018: https://www.banquemondiale.org/fr/news/infographic/2018/09/20/what-a-waste-20-a-global-snapshot-of-solid-waste-management-to-2050
5. From about 40,000 t in 2010 to 150,000 t in 2016, according to the Senegalese Ministry of Agriculture.
6. In 2016, 16 kg/ha in Senegal vs 290 kg/ha in the Netherlands. https://donnees.banquemondiale.org/
7. The officially recorded use of these pesticides and herbicides varies between 700 and 800 t of active product per year (2012 to 2014, source: Plant Protection Directorate).
8. ANSD, 2013 Census.
9. See *the Yearbook on the Environment and Natural Resources of Senegal* 3rd edition (CSE).
10. IBAs can be consulted on a global scale at http://datazone.birdlife.org/site/mapsearch
11. https://www.onas.sn/sites/default/files/etudes/baiedehann_l3_volume_1_eies_v2_1.pdf
12. Organochlorine aromatic compounds are among the most ubiquitous and persistent toxic, ecotoxic and reprotoxic pollutants and are endocrine disruptors at low doses.
13. Informal report for DEEC, 2015.
14. Articles 10 to 13 of the Protocol to the Abidjan Convention ratified by Senegal.
15. https://www.un-page.org/files/public/plan_senegal_emergent.pdf
16. Species for which the experiment could be conducted.

17. Eutrophication of aquatic environments is an imbalance in the environment caused by an increase in the concentration of nitrogen and phosphorus.

18. For similar reasons, the Banc d'Arguin in Mauritania is another preferred spawning site for the *Sardinella aurita* population (CONAND, 1977; BOELY *et al.*, 1978, 1982; FRÉON, 1988).

19. A block in this context refers to a hydrocarbon exploration and production-sharing contract (BONNIN and LY, 2019).

20. *Important Bird Areas (IBAs) and biodiversity areas:* http://datazone.birdlife.org/site/ibacriteria

21. See all sensitive bird sites in Senegal: http://datazone.birdlife.org/site/mapsearch

22. http://www.big.gouv.sn/index.php/2019/05/09/le-port-de-ndayane-au-nom-de-la-competitivite

23. https://pfongue.org/Projet-Ensemble-Contre-les-Ordures.html

24. Colloquium "Conflicts of use at sea and European Union law", Aix-Marseille University, 19–20 November 2020. https://univ-droit.fr/actualites-de-la-recherche/appels/34550-conflits-d-usages-en-mer-et-droit-de-l-union-europeenne

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