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ENVIRONMENTAL ASSESSMENT OF PRE-DREDGING SEDIMENTS AND PROPOSALS FOR THEIR SUBSEQUENT MANAGEMENT IN THE PORT OF MAR DEL PLATA, BUENOS AIRES, ARGENTINA

Graciela Cuello[@ 1, 2, 3], P. Garzo[1, 2, 3], Ro Elias[1], Francisco Isla[1, 2, 3]

ABSTRACT: Nowadays, the discharge of sediments from dredging works into the sea is one of the most critical problems affecting coastal management. Therefore, the characterization, assessment and handling of the materials to be dredged is of utmost importance. Since its creation, the Port of Mar del Plata, Buenos Aires, Argentina, has presented a structural difficulty that affects its operation: the interruption of the strong littoral drift by its breakwaters generates an important sand sedimentation, blocking the access channel. This hampers the entry and maneuverability of large ships, while promoting sediment imbalances on a regional scale, causing coastal erosion on many beaches. At present, the administrative authorities of the port are proposing a new dredging work in order to restore adequate navigation depths. On this basis, the aim of this work was to assess the current sediment characteristics of the Port of Mar del Plata and compare it with previous results from 1996. Grain size, water content and organic matter were monitored at 12 stations. The results indicate that the external sector receives a larger share of sand than in 1996; silts and clays are preferentially deposited at the inner docks; organic matter, with increases compared to the previous study, accumulates in the inner docks with lower water renewal and higher contributions of waste-water. Based on these results, this work proposes beach nourishment as a management alternative for dredged sediments. Several urban beaches of Mar del Plata subject to regional-scale erosive processes could be the target sites. It is expected that this study will be used as a baseline for the improvement of the environmental quality of the port system as well as for pre- and post-dredging studies within the framework of an integrated coastal zone management.

Keywords: dredged material; particle settling; beach erosion; multivariate analysis; dumping zone.

RESUMO: *Nos dias de hoje a descarga no mar de sedimentos provenientes de obras de dragagem, é um dos problemas mais críticos que afetam a gestão costeira local. Assim, a caracterização, avaliação e manuseamento dos materiais a dragar é de extrema importância. Desde a sua criação, o Porto de Mar del Plata, em Buenos Aires, Argentina, têm apresentado uma dificuldade estrutural no que respeita ao seu funcionamento: nomeadamente a forte interrupção da deriva litoral pelos seus quebra-mares, acarretando sedimentação significativa local de areia e bloqueando o canal de acesso. A atual configuração dificulta a entrada e a manobrabilidade de navios de grande calado, enquanto incute desequilíbrios sedimentares à escala regional, proporcionando erosão costeira em praias adjacentes. Atualmente, as autoridades administrativas do porto equacionam uma nova operação de dragagem para restabelecer profundidades de navegação adequadas.*

O objectivo do corrente estudo foi o de avaliar as características actuais dos sedimentos do Porto de Mar del Plata e compará-las com características anteriores a 1996. Monitorizou-se o tamanho dos grãos, o teor de água e a matéria orgânica, em 12 estações. Os resultados indicam que o sector exterior recebe atualmente maior percentagem de areia do que em 1996; os siltes e argilas são preferencialmente depositados nas docas interiores; a matéria orgânica, registando aumento em conteúdo, em relação ao período de estudo anterior, acumula-se nas docas interiores com menor renovação de água e observando contribuições de águas residuais mais elevadas.

Com base nos resultados obtido, e alternativamente, este estudo propõe que se utilizem os sedimentos provenientes das dragagens em alimentação de praias. Várias praias urbanas de Mar del Plata sujeitas a processos erosivos de escala regional poderiam ser os locais de deposição dos dragados. Espera-se que este estudo seja utilizado como base de referência para a melhoria da qualidade ambiental do sistema portuário, bem como para suportar outros estudos de pré e pós-dragagem no âmbito de uma gestão integrada da zona costeira.

Palavras-chave: *material dragado; deposição sedimentar; erosão de praias; análise multivariada; zona de descarga.*

@ Corresponding author: gracielacuello@mdp.edu.ar

1 Instituto de Investigaciones Marinas y Costeras (IIMYC – UNMDP/CONICET), Mar del Plata, Buenos Aires, Argentina.
2 Consejo Nacional de Investigaciones Científicas y Técnicas, Argentina.
3 Instituto de Geología de Costas y del Cuaternario (IGCC – UNMDP/CIC), Mar del Plata, Buenos Aires, Argentina.

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1. INTRODUCTION

The coast of Argentina offers a wide variety of port and harbor facilities. Among the most outstanding are, on the one hand, the fluvial ports located on the coast of the Paraná River (ports of San Nicolás, San Pedro, Campana and Zárate) and the estuarine ports of the Rio de la Plata (Buenos Aires, Dock Sud and La Plata). The oceanic ports of Buenos Aires Province (Mar del Plata, Quequén, Coronel Rosales and Bahía Blanca) are used for the exportation of cereals and fish (Gualdoni and Errazti, 2006). The Patagonian region comprises several ports mostly concerned with fisheries activities (San Antonio Oeste Rawson, Puerto Madryn, Camarones, Caleta Córdova, and Caleta Olivia). Oil production is located offshore at Caleta Córdova, Caleta Olivia and San Sebastian Bay. Other activities of these ports include merchandise trade, storage, customs control, and ship construction and repair (Lasta, 2001; Costa, 2006).

The Mar del Plata Port construction was initiated in 1911 by the french Société Nationale de Travaux Public, and began its operation one year later. However, the formal inauguration took place in 1922. The military areas were constructed in 1926 as a Submarine Division by the National Law No 11378 (Cicalese, 1997). During the thirties, the port was totally completed in its design with maximum activities comprising commerce, military and touristic vessels (Miccio and Vellenich, 2002). The operation of the port depended on the Federal Government, through the Port Administration (currently Administración General de Puertos de la República Argentina) from its inauguration until 1991. Then, it was transferred to the Province of Buenos Aires by Decree No. 3572/00 as a regional consortium (Consorcio Portuario Regional Mar del Plata, CPRMDP) in charge of its administration and operation (Gualdoni & Erratzi 2006). This port is almost entirely oriented to fishing activities. Considering that it comprises small and long-distance vessels that generate much organic wastes, recreational and touristic activities are only concerned to the summer months (January and February, Villemur, 1988).

Given the economic and tourist importance of this port, it is necessary to have an updated environmental baseline that allows for the sustainable development of its activities, as well as the monitoring of those that could be detrimental to its environmental and operational quality.

1.2. The Mar Del Plata Port Setting

The city of Mar del Plata is located at the south eastern extreme of the province of Buenos Aires, Argentina (38º 01’ S; 57º 32’ W) (Figure 1), and is one of the most important coastal-maritime cities in the country given its tourist development (more than 8 million visitors annually) and its permanent population of approximately 650,000 people (https://www.mardelplata.gob.ar/MardelPlata). Mar del Plata port, occupying 220 ha, is emplaced between two capes composed of orthoquartzites of the Balcarce Formation (Corrientes Cape and Mogotes Point), at the outlet of the Del Barco creek (Cortelezzi *et al.*, 1971). Two breakwaters protect it: the southern one (Escollera Sur) with a NE orientation and 2,750 m longer; and the northern one (Escollera Norte) oriented to the SE with 1,099 m longer (Figure 1). At the same time, it is divided in two sectors: the northern one concentrates the military (submarines and vessels of the Argentinian Navy) and nautical club’s (recreational) activities; the southern one has several docks of different depths for the requirements of different fishing activities. Oil and gas transport facilities are located at the middle of the southern breakwater. The operative sector consists of five inland docks that act as a shelter for the various port activities and facilities (De Boer *et al.*, 1997).

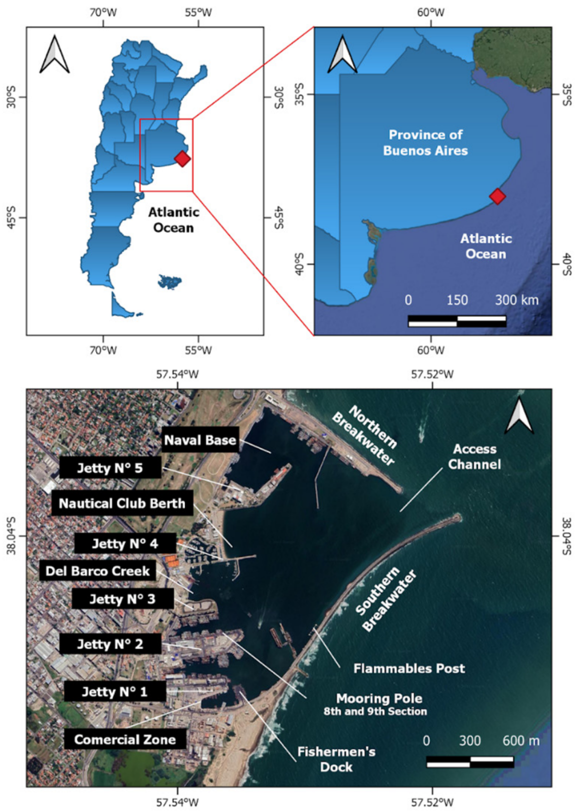

Figure 1. Up: location of the Mar del Plata Port in the Province of Buenos Aires, Argentina. Down: Mar del Plata Port’s docks, breakwaters and sectors.

In Mar del Plata, the wave regime is bimodal with prevailing SE and ENE directions; the mean wave significant height is of 1.5 m and the mean peak period of 7 s (Lanfredi *et al*., 1992; Isla, 2010; Figure 2). A potential northwards drift was estimated at 390,000 m^3/yr, according to the wave-energy statistics (Caviglia *et al*., 1992). Based on morphological variations, a minimum net drift of 100,000 m^3/yr was estimated (Isla, 2014). For sediment grain sizes of 0.2 to 0.5 mm a longshore drift of 300,000 m^3/yr to 500,000 m^3/yr was calculated (Van Rijn, 2008).

This strong littoral drift, together with structural deficiencies in the port's original design, have generated obstacles in the port operation since its origin. The disruption of this current with the harbor defense structure produced the accumulation and growth along the coast of a sandbar at the tip of the southern breakwater. This embankment is induced by the refraction of waves coming from the south. To the north, the beaches receive less sand and are therefore sedimentarily unbalanced. These processes have been repeatedly analyzed for the Mar del Plata Port (Sunrise Technical Consultants, 1971; Isla & Schnack, 1986; Lagrange, 1993; Isla, 2010; Cáceres & Castellano 2012; Gyssels *et al*. 2013; Pontrelli-Albisetti *et al*., 2015; Isla, 2015).

Due to the strong sedimentation in the access area to the port, successive dredging operations were carried out in the access channel. It was projected with a width of 100 m and a draft of 12 m deep; however, a width of 45 m and a depth of 9 m have been identified (De Boer *et al*. 1997). By 2021, the channel had an orientation to the SSW (238°39') with a width of 100 m and 11 m depth. In the last years, dredging efforts are needed to permit depths of 12 m for the operability of large fishing vessels, touristic ships and containers (Miccio & Vellenich, 2002).

The construction of the port of Mar del Plata changed the sediment balance on all the city's beaches, and even in neighboring counties. The subsaturation of the sedimentary flow of the coastal drift current promoted erosive processes towards the north of the harbor (Isla *et al*., 2005). Sediment imbalance induced by the construction of the port breakwaters has resulted in approximately half of the incoming sediment accumulating at the port entrance (Pontrelli-Albisetti *et al*., 2015).

The response to this lack of sand was to systematically implement breakwaters, jetties and groins, shifting the erosion problem in the same direction as the advance of the littoral drift current and promoting the construction of more coastal defense infrastructure northwards (Isla, 2006). The influence of these works and their relationship with coastal erosion has been extensively studied, mainly in the sector between the towns of Miramar and Parque Atlántico Mar Chiquita (Merlotto & Bértola, 2007; Bunicontro *et al*., 2013; San Martín *et al*., 2014; Bunicontro *et al*., 2015; Isla *et al*., 2015; Isla *et al*., 2018).

Other coastal erosion management tools have been less used

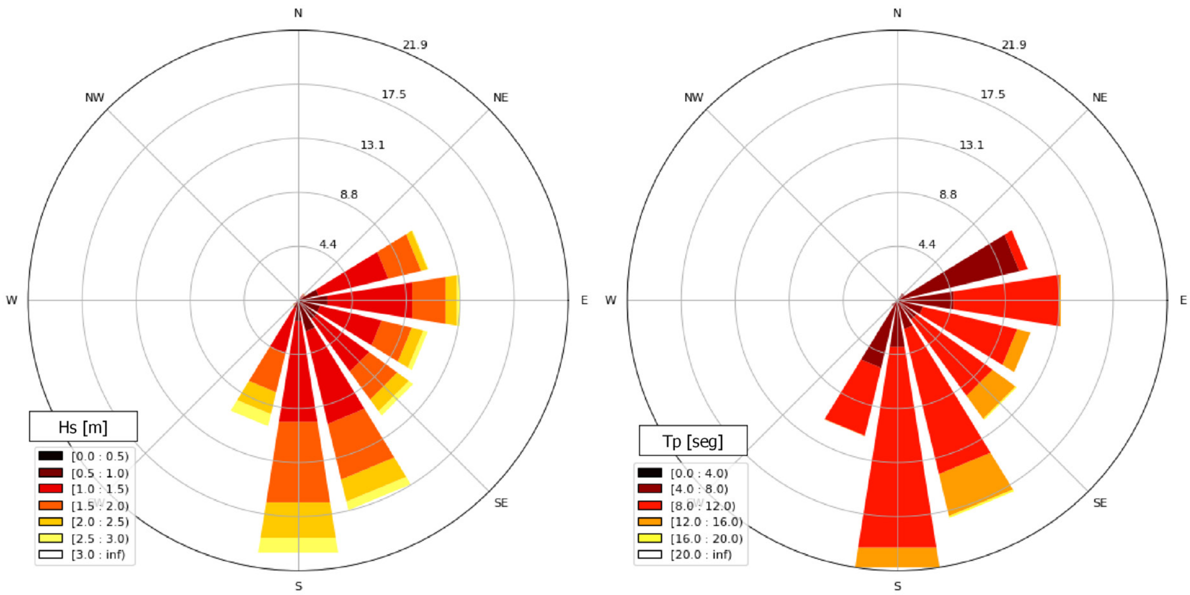

Figure 2. Wave roses for the significant wave height (Hs) [m] and peak wave period (Ts) [s]. Data calculated by Instituto Nacional del Agua (INA).

in Argentina. The beach nourishment method was proposed in the 1980s (Isla & Schnack, 1986) and carried out for only one time in 1998 on three beaches in Mar del Plata (Bértola, 2001; Marcomini & López, 2004). Detached breakwaters were also proposed taking into account its effectiveness in reducing cliff retreat while not interrupting coastal drift. These structures are external, not linked to the beach and parallel to the coastline, reducing wave energy towards the coast and even ensuring the normal flow of the littoral drift current. This wave energy reduction promotes beach replenishment by sediment deposition (Gyssels *et al*., 2007). In 2007, the Coastal Protection Plan (*Plan Director de Protección de Costas*) for Mar del Plata, proposed the construction of sixteen of these structures at a distance of about 250 m from the coast. However, due to some resistance of non-governmental organizations and some financial issues, only three of them were constructed by 2012 (Isla *et al*., 2018).

Thus, hard defense structures perpendicular and linked to the coast, continue to be the most used structure for the resolution of erosion problems at local and micro-local scales in the province of Buenos Aires. Isla (2015) estimated the flow of the littoral drift current at the Mar del Plata Port entrance as 220,000 m^3/yr. However, De Boer *et al*., (1997) identified that at least half of the incoming sediment supply is retained at the southern breakwater. This led for decades to a systematic implementation of groins, jetties and breakwaters northwards, promoting a regional scale erosion problem. In addition, the drift flow was calculated as 60,000 m^3/yr in the neighboring county of Mar Chiquita (Figure 3). This evidence suggests that the availability of sediments resulting from port dredging could represent an important potential for beach nourishment plans within the framework of coastal management plans and programs.

Dredging of seaports is required to maintain navigational depth in harbors but removed sediments are often heavily contaminated, resulting in a serious waste management problem (Caplat *et al*., 2005). The dredged material has different physical and chemical characteristics from the sediment at the dumping zone, causing increments in the nutrients and turbidity, enrichment of contaminants and organic matter, changes in sediment dynamics or particle size, food chains, on the benthic communities (Lee *et al*, 2010; Fang *et al*., 2013; Dauvin *et al*.,2022). In turn, the final effects depend on a number of factors such as the form, duration and method of dumping, physical and chemical characteristics of the dredged sediment, oceanographic conditions and the dispersal around the dumping sites (Palanques *et al*., 2022).

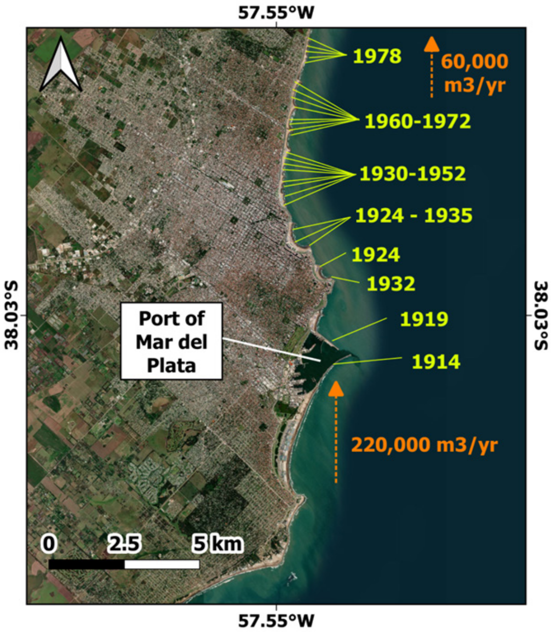

Figure 3. Magnitude of the littoral drift current at the entrance channel of the port and to the north (orange arrows); date of the original construction of groins, jetties and breakwaters (yellow). Source: modified after De Boer *et al.* (1997) & Isla (2015).

Pollutants, in such port sediments, may be remobilized due to bioturbation and resuspension, constituting a potential hazard (Zoumis *et al*., 2001). The concentration of pollutants in the water column can exhibit significant temporal and spatial variability, which causes problems in obtaining representative samples (Binning & Baird, 2001). However, sediment samples are in constant flux with the water column and incorporate pollutants over time. Thus, temporal analysis of sedimentary samples allows the detection of changes that may be absent or in low proportions in the water column (Davies *et al*., 1991). Therefore, laboratory analysis of samples has historically been the most widely used tool for monitoring sediment quality (Sany *et al*., 2013).

De Boer *et al*. (1997) carried out a study in the port of Mar del Plata with the objective of evaluating possible solutions to the lack of accessibility to the entrance channel, the presence of contaminated waste in the inner docks and port management strategies. Sediment characteristics and concentrations of various contaminants were analyzed. The results indicated a sediment distribution dominated by mud (silt and clay) and high organic-matter content in the dock areas. A total of approximately 200,000 m^3 of highly contaminated waste was also estimated to be removed from the port of Mar del Plata in future dredging works. In 2021, the CPRMDP in charge of the port's operation estimated to dredge 600,000 m^3 of sediment in 150 days to ensure the port's performance. The access channel and the flammables post sector were the preferential areas to dredge (Figure 1).

Based on this, the objective of the present study was to assess the current sediment characteristics in different sectors of the Port of Mar del Plata before dredging and to compare the results with those obtained in 1996 (De Boer *et al*., 1997). In this way, it is intended to generate an environmental baseline to support possible future dredged material management activities, in view of the recent actions promoted by the CPRMDP in the Port of Mar del Plata.

This paper is organized in five sections as follows. Section 2 presents the data acquisition, the sampling procedure and the methods carried out in order to assess the sediment characteristics. Section 3 shows the results of the proposed analysis and its comparison with those obtained in 1996. Section 4 discusses these results and aims to propose recommendations for the sustainable management of dredging works. Finally, section 5 presents the main conclusions of this paper.

2. METHODS

Surface sediment was sampled at 12 sites in the Mar del Plata Harbor. Replicates (2) were performed using a Snapper dredge and excavation devices employed by divers with 24 samples (Figure 4). The samples were placed in plastic bags and kept cold, in order to be transported to the laboratory for further analysis. These samples were analyzed to be compared to the samplings performed in 1996 (De Boer *et al*., 1997).

Sediment samples were dried and burned to estimate organic matter by loss of ignition (LOI) during 4 hours at 550°C (Heiri *et al*., 2001). Water content was estimated by drying 20 g during 24 hours. The organic matter was eliminated with peroxide of hydrogen (H_2O_2). Later, carbonates were eliminated by clorhidric acid (HCl) (Reeuwijk, 2003). Sand was separated from muds, washed to eliminate salts and sieved each 0.5 phi units using a sieve shaker. The percentages of silt and clay were estimated by the pipette method suggested by (Folk, 1974).

Multivariate analysis is a useful tool for the characterization and management of pre- and post-dredging sediments. It could be applied for exploratory data analysis (*e.g.*, to determine similarities and dissimilarities between sampling stations and sampling areas and to identify data structure characteristics), reducing the cost of investigations without reducing confidence in the final assessment (Casado-Martínez *et al*., 2009; Cesar *et al*., 2014).

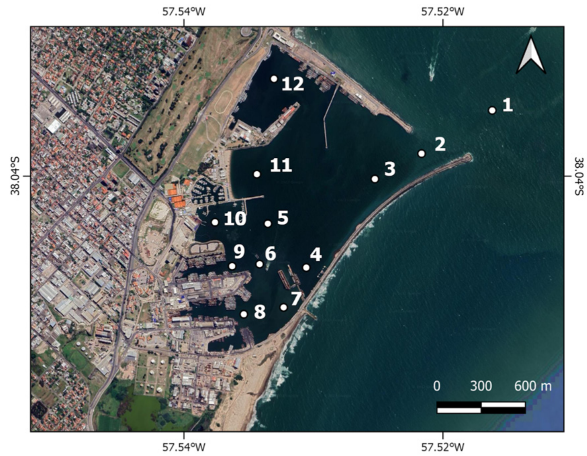

Figure 4. Location of the 12 surface sediments sampling sites in the Mar del Plata Harbor.

With the purpose of recognizing significant differences between both samplings (1996 and 2021) a cluster analysis was performed. Dendrograms were constructed using the Euclidean distance as distance parameter and Ward's method as linkage method (Aitchison, 1992; Martín-Fernández *et al*., 1998 y Aitchison *et al*., 2000).

The results obtained from the current sampling sites and those carried out in 1996 (De Boer *et al*., 1997) were spatially interpolated in order to recognize spatio-temporal variations. This interpolation was carried out using the IDW method (Mitas & Mitasova, 1999).

Finally, data was standardized to a common scale, previous procedure for an ordination process (Legendre & Birks, 2012). A Principal Component Analysis (PCA) test was performed to reduce factors of variability, which allows us to interpret the data and explain its structure. The PCA analysis was used for descriptive and/or exploratory purposes; therefore, it is not necessary to meet the multinormality criterion (Joliffe 2002). Dendrograms were drawn with the R software 4.1.0 (R Core Team, 2021); the PCA was tested Past (v 4.09; Hammer *et al*., 2001); the interpolation method was carried out with the software QGIS (v 3.22; QGIS, 2022).

3. RESULTS

3.1. Sediment characteristics

Dendrograms performed with the 2021 sampling data showed 3 groups, with subgroups according to sediment characteristics (Figure 5). The first group was associated with samples from sites 1 and 2 near to the port entrance. The second group was associated with samples from site 11, near the Nautical Club. The third group includes sampling sites 3, 4, 5, 6, 7, 8, 9, 10, and 12.

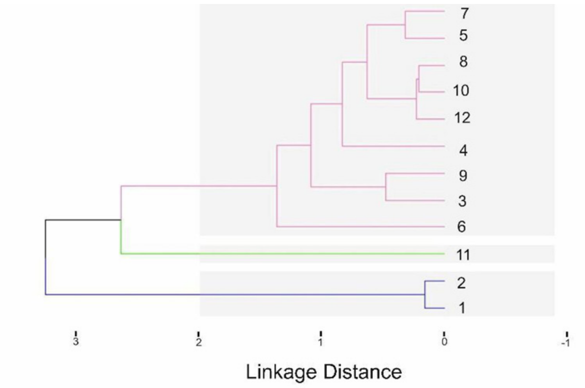

Figure 5. Euclidean distance dendrograms for the 2021 surface sediment-sampling sites.

Based on the sampling carried out in 1996, three groups can be distinguished, with slight differences compared to that of 2021 (Figure 6). The first group includes sampling sites 1 and 4 (close to the port entrance channel). The second group comprised sites 2 and 3 (entrance channel). The third group comprised sites 5, 6, 7, 8, 9 and 10, all located at the interior docks vicinities.

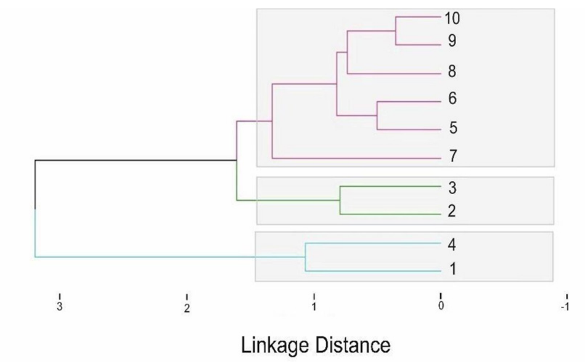

Figure 6. Euclidean distance dendrograms for the 1996 surface sediment-sampling sites. Data collected by De Boer *et al.*, (1997).

PCA analyses were performed with two samplings in order to compare the results. The analysis indicated that five components were able to explain the total variance (Figure 7). First component explained 62% gathering the sand percentage and the water content. On that axis, a spatial pattern was observed, where higher water contents were measured in 1996 in the docks area; an opposite pattern with higher sand content was estimated at the channel areas in 2021. The second component explained only 22% of the total variance comprising silt, total organic matter, and clay contents. In this axis, a temporal pattern was observed. Silt and organic matter (OM) were higher in 1996 in the docks areas and the Nautical Club in 2021; instead, clay is higher in 2021 at the same areas.

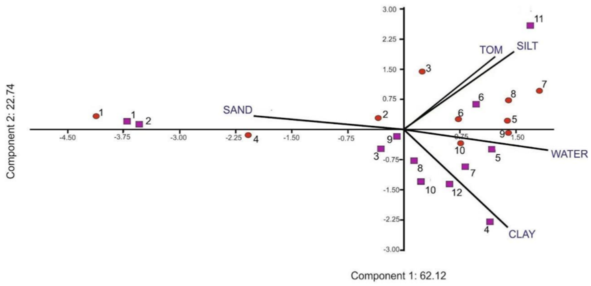

Figure 7. PCA of the stations sampled. Circles correspond to the 1996 sampling, and squares to that performed in 2021.

3.2. Changes in sediment 1996-2021

Mar del Plata port presented several changes between 1996 and 2021. In 1996, silts dominated at the docks and sand at the outlet (De Boer *et al.*, 1997). In the 2021 sampling, clay percentages increase towards the docks (Figure 8). The heterogeneous distribution of sediments is conditioned to hydrodynamic processes as tidal, wave and pluvial effects. The interior of the port (docks) have more percentage of clay, suggesting flocculation and settling effects and presence of nepheloid layers. The energy fluctuations at the port entrance are induced by waves, conditioning the sand transport. The results of this work show significant variability in sediment properties between sampling sites.

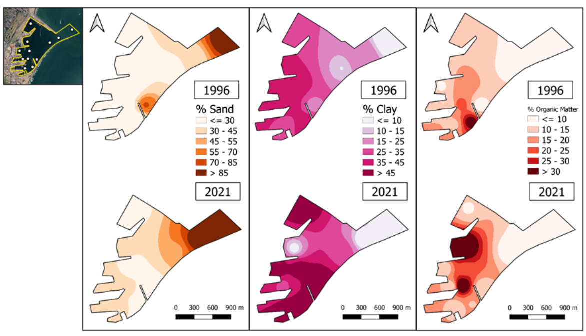

Figure 8. Spatio-temporal variation of the results obtained. IDW interpolation and comparison between the sampling carried out in 2021 and 1996 (De Boer *et al.*, 1997).

4. DISCUSSION

4.1. Future dredging works

The results of this study demonstrate that the application of multivariate analysis was particularly useful for evaluating and interpreting the results in an integrated way, especially when there is a large number of parameters analyzed in an environmental assessment. The use of multivariate statistical techniques applied to these data provides a useful tool for pre- and post-dredging studies (Casado-Martínez *et al*.,2009).

In pre-dredging studies, it is important to determine the particularities of the port environment in the so-called normal conditions of maritime traffic and establish a monitoring procedure that will be carried out during operations, like was done in the port of Genova (Italy). Dredging must consider the proximity to areas that must be protected from the negative effects of sediment movement (bathing beaches, mammals setting). On the other hand, dredging operations need constant bypassing of large volumes of sand across the port entrance (Capello *et al*., 2010).

The results of this study lead the authors to take special care about the sediments that should be extracted in future dredging works. Multiple anthropogenic stressors are likely to affect the environmental health of the entire ecosystem. A large part of the harbor waste comes from berthing and storage sites, administrative offices and recreational clubs activities; a small percentage is distributed among waste from ships, canteens, and workshops, among others (Valverde-Enciso, 2018). The silt-clay sediments and their high organic matter content found in the inner docks of the port, related to the extensive use of hydrocarbons (*e.g.*, fuels, motor oils, maritime traffic, moorings for pleasure craft, the shipyard, etc.), residual discharges from Del Barco creek, and the historical use of biocides in antifouling paints, can have ecological and environmental consequences related to resident biota and the deposition of contaminant particles.

Del Barco creek acts as an important piped storm-drain channel across the City of Mar del Plata. It benefits 14 neighborhoods in the port area and the south of the city and is intended to channel all the rainwater that may flow through this zone (Figure 9). In addition, few industries have any kind of primary treatment system, while most of them discharge their saturated liquid waste directly into the sewers or storm drains. The wastewater discharge without prior treatment saturates the drainage network and generates a significant increase in organic matter in the confined waters of the port, specifically those housed in the sector of the offshore dock where the creek discharges (Figure 9; Yurkievich, 2013). In addition, silt-clay sediments act as traps for toxic substances, which could be easily suspended by maritime traffic and storms, eventually making them more available to benthic biota (Yebra *et al*., 2004; Muniz *et al*., 2015; D` Alessandro *et al*., 2020).

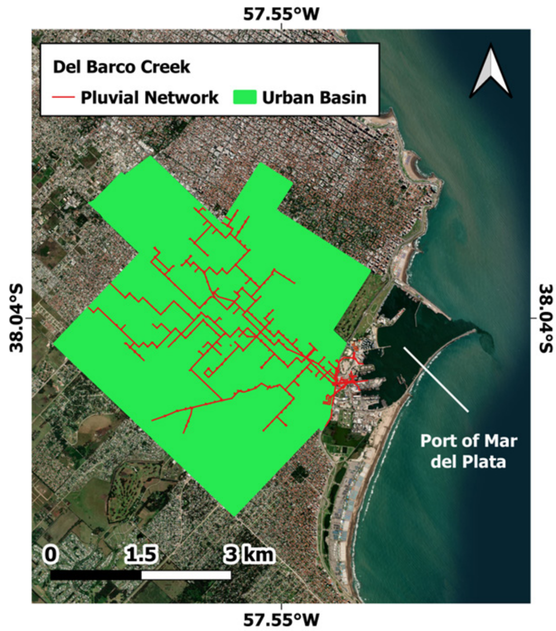

Figure 9. Del Barco creek urban basin and its pluvial network. It supports 14 neighborhoods in the southern area of Mar del Plata, discharging in the port. Source: open access database of the General Pueyrredon County (https://datos.mardelplata.gob.ar/)

Studies in the internal sectors of the port of Quequén (Necochea, Buenos Aires) show very high values of organic contamination due to the management of cereals in the port area, which confirm that grain size and total organic carbon (TOC) affect the habitat, diet and survival of benthic organisms (Godoy *et al*.,2011). Caplat *et al*. (2005) have identified Total Organic Carbon (TOC) levels between 5% and 10% in dredged sediments from the harbor of Port-en-Bessin, northwest of France. Those sediments are characterized by a high proportion of reducing materials (oxides, oxyhydroxides) that can give rise to metallic sulfides through diagenetic processes, and therefore are sinks for trace metals (Douglas & Adeney, 2000).

Along the southern breakwater of the Mar del Plata harbor there is a colony of sea lions with normally more than 100 specimens (Rodríguez & Bastida, 1998). At the same time, a population of seahorses (*Hippocampus patagonicus*) is stable along the northern breakwater (Pujol, 2014). Future dredging plans should also take into account the presence of these communities.

The sediment characterization of the inner docks showed a shift from higher TOM concentrations at the vicinity of the fishermen's docks towards the nautical club berth and the mooring pole between 1996 and 2021. Mar del Plata's population grew from 532,000 to 620,000 inhabitants between 1991 and 2010. Moreover, a total population of 670,000 inhabitants is forecasted for 2025 (http://www.estadistica.ec.gba.gov.ar/). This demographic increase together with a growth in the tourist inflow and in the industrial activities could have led to an intensification in the disposal use of the aforementioned urban basin. In addition, the recreational club's activities have also been increased; the Mar del Plata Nautical Club showed a 25% increase in their memberships between 2019 and 2022, representing a record for the last 30 years (https://www.cnmp.org.ar/). This intensification in the waste disposal could have promoted higher TOM levels at the inner docks. Moreover, this section of the port is characterized by a very low water renewal, which could have generated proper conditions for organic matter accumulation. Finally, a decrease in the clay concentration and a growth in the sand content was observed in the nautical club berth by 2021. This could be linked to beach nourishment works carried out by the club's administration in order to promote the touristic use of this area.

4.2. Post-dredging dumping

Large volumes of polluted sediments from dredging efforts make remediation difficult. Any remediation strategy must include simultaneous programs to identify and reduce inputs of these pollutants to the marine environment, and hence to the bottom sediments (Birch & Taylor, 1999). Therefore, for the regulation of massive, long-lasting and intense dumping activities at landfills, a number of specific actions should be considered. Dump-induced shock waves to estimate the dispersion of dumped material must be assessed; spatial and temporal evolution of turbidity characteristics, even beyond the landfill boundaries, during and after the disposal of the dredged material must be monitored. With more emphasis on low dispersion environment, hydrodynamic processes do not allow a rapid dilution of the dumped material (Palanques *et al*., 2022).

Considering the results of this study, recommendations can be proposed for the sustainable management of the dumping zone. Mar del Plata port needs a dumping site zone for submerging the accumulated wastes and today attached at some docks (mostly abandoned ships). These types of dumping sites zones are necessary for a port of great activity generating great volumes of waste (Chin & Ota, 2000; Karl *et al*., 2001; Bolam & Rees, 2003; Dufour & Van Lancker, 2008). However, for these purposes it is necessary to locate this type of dumpling site at a certain location either at the province jurisdiction (3 nautical miles) or at the national domain (offshore from 3 nautical miles).

4.3. Beach management as an alternative

Hydrodynamics, sediment sources, and the compartments between docks conditioned the sediment dispersal. The port was constructed when the volume of littoral drift was not known nor the engineering alternatives to avoid the sand accumulation (*e.g.* sand traps or sand bypassing). Other ports on the Argentine-Uruguayan coastal plain have presented similar results in relation to sedimentation problems. The Montevideo port (Uruguay), at the outlet of the Río de la Plata, received important volumes of silt from the episodic inputs of the Río de la Plata discharge (Muniz *et al*., 2015, Venturini *et al*., 2004). The Quequén Port (Buenos Aires) is also conditioned by higher inputs of sand transported by longshore drift and causing a huge amount of sand at the extreme of its dock (Godoy *et al*., 1988).

In Mar del Plata, the obstruction of the longshore drift current has increased the erosion problem over the last 100 years, affecting the operation and economy of the port, as well as the degradation of the tourist resource and the bathing quality of the beaches. The beach of the Punta Mogotes tourist Complex, located immediately south of the port, is artificial. The sedimentary accumulation was caused by the construction of the southern breakwater and has become the most crowded tourist beach in Argentina (Isla, 2001). However, all the tourist beaches to the north of the port have suffered significant erosion processes. In order to solve this problem, the National Government invested in dredging and replenishment works at the end of 1998. The dredging of the sand bank at the extreme of the southern dock was analyzed in terms of the grain sizes and the nourishment of the beach of Playa Grande (Isla & Schnack, 1986). Sediments were pumped from the sand bank in the port access channel to three important tourist beaches located north of the port. It is estimated that about 1.6 million m^3 of sand was redistributed along these three beaches (Bértola, 2001; Marcomini & Lopez, 2006). These works permitted the increase of 300% of the beach's surface (Bértola, 2001; Marcomini & Lopez, 2006; Padilla & Eraso, 2012). However, the nourished sand presented a fine texture that caused a rapid loss during the first stages post-nourishment (Isla, 2006).

Coastal protection systems have undergone a major change on a global scale in recent decades; "hard" techniques, such as groins, jetties and breakwaters, have gradually been replaced by "soft" works. Artificial beach nourishment and sedimentary by-pass are now considered as two very effective soft methods for beach protection and restoration (Pontrelli-Albisetti *et al*., 2015).

It is very important to evaluate the material to be used for beach fill; natural selection processes act on it, redistributing the finer part offshore and the coarser debris to the surf zone, which does not provide a functional use in controlling beach erosion. One option is the case study known as Guardialfiera Reservoir, southern Italy, which used sand dredged from reservoirs instead of marine sand. Using marine sand could alter the bathymetry, inducing a variation in wave climate and exposing marine life to serious risks (De Vincenzo *et al*., 2018).

However, these approximations can only be applied to the sandbank accumulated at the access channel of the port, and not to the sediments inside the port, as these sediments contain not only high values of organic matter, but also many trapped contaminants, whose dredging can spoil environmental conditions. Benthic indicators, most used ecological indicators, also showed very poor environmental conditions in docks at the central part of the Mar del Plata port, while better conditions were present in the mouth (Rivero *et al*., 2005). In addition to benthic organisms, which are directly related to sediment quality, there are other species to be taken into account in the environment of the Port of Mar del Plata.

Based on the results of this work, those sand embankments located on the entrance channel and even those retained in the southern breakwater could be proposed as nourishing sediments for unbalanced beaches located northwards (Figure 10). Assuming that these sediments are in a well environmental condition, their textural characteristics must be taken into account. James (1975) proposed a method for verifying the aptitude of a nourishing sediment in order to feed a natural beach and it is based on sand granulometric characteristics of both sites. In this way, the dynamic behavior of the supplied sand and the time span between successive nourishments can be estimated (Mojica *et al*., 2022).

In addition to the proposed beach nourishment, the dredged material, after adequate treatment, can be reused in a positive way by depositing it on land for construction, public works, building materials (such as bricks, blocks without structural purposes and in combination with construction waste) and dike rehabilitation, among others (Mymrin *et al*., 2016). The industrial utilization of this type of waste can replace traditional raw materials, minimizing the extraction of natural resources and ultimately reducing the degradation of coastal areas by reducing the current practice of these discharges into the marine environment.

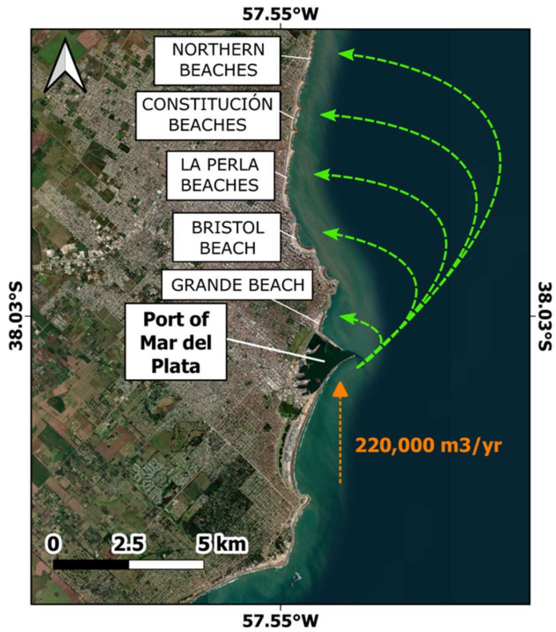

Figure 10. Schematic representation of a potential beach nourishment in the city of Mar del Plata, taking into account those sand embankments at the port entrance and the southern breakwater as loan zones.

5. CONCLUSIONS

The results of this study revealed important differences between the 12 sampling sites within the port of Mar del Plata. Sand currently dominates at the access channel while silt towards the inner docks (Nautical Club, Del Barco creek discharge zone and southern breakwater area). Organic matter accumulates in the compartments of the inner docks with lower water renewal, higher runoff and pluvial discharges and higher contributions of waste from different recreational, administrative and operational activities. Thus, sediment distribution is highly conditioned by hydrodynamic processes as tidal, wave and pluvial effects.

The current port sediment characteristics also present differences with those estimated for 1996. It was observed a shift from higher organic matter concentrations at the vicinity of the fishermen's docks towards the nautical club berth and the mooring pole. The demographic increase in Mar del Plata, the growth in the touristic inflow and industrial activities, the recreational clubs development and the intensification of the disposal use of the Del Barco creek urban basin could explain these results. In addition, a decrease in the clay concentration and growth in the sand content could be linked to beach nourishment works.

The obstruction of the longshore drift current at the southern breakwater has promoted regional-scale erosion problems over the last 100 years. It affects the operation of the port as well as the environmental quality of tourist beaches of Mar del Plata. Coastal defense structures have been systematically implemented in order to protect these beaches. However, artificial beach nourishment or sedimentary by-pass methods have not been implemented yet. This work proposes a beach nourishment process by taking into account dredged sediments from the sand embankments located at the entrance channel as loan sites. Unbalanced urban beaches located northwards could be the target sites. Textural characteristics of the sediments must be taken into account. At this point, it is necessary to obtain a larger number of samples at each station and mainly in the vicinity of the access channel and adjacent to the breakwaters, as this is where most dredging activity takes place.

The results of this work reinforce the usefulness of multivariate analysis for an environmental assessment of a large number of parameters in pre-dredging works. It is expected that this study will be used as an important monitoring tool for the improvement of the environmental quality of the port system as well as a baseline for pre- and post-dredging studies. Future dredging plans should take into account their impact on the quality of Mar del Plata's tourist beaches as well as proper post-dredging treatments in order to guarantee an adequate sediment dumping.

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CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

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