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Research Article

Understanding sedimentary dynamics and bottom sediment characteristics in Bons Sinais Estuary – Mozambique: Insights from statistical analysis and Pejrup diagram

Cesar Antonio Mubango Hoguane[1], Jessica Mativane[2], Nacir Leitao da Cruz[2], Helder Arlindo Machaieie[2]

1 *Save University, Chongoene, Mozambique*
2 *Eduardo Mondlane University, Quelimane, Mozambique*
Corresponding author: Cesar Antonio Mubango Hoguane (cesarmubango@gmail.com)

Abstract

This article addresses the Bons Sinais Estuary sedimentary dynamics and bottom sediment characterization and its implication to pollution, based on bottom sediment grain size and statistical parameters. There were collected 15 bottom sediment samples with a Van veen sampler, which were further analysed by sieve and pipette methods. Sand was the most dominant textural class (51%), followed by silt (25%) and clay (24%). The sedimentary dynamics have varied from moderate to high. Both size of sediments and Pejrup diagram suggests that the hydrodynamics of this Estuary is high. Although the percentage of coarse sediments is higher, the estuary is susceptible to pollution, as the amount of thinner sediments is considerable regarding the values of skewness. These results may be useful to environmental management actions including pollutants tracking.

Key words: Bons Sinais Estuary, bottom sediments, grain size parameters, pollution, sediments statistics

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Introduction

Estuaries are coastal sedimentary environments whose evolution depends greatly on the interaction of hydrodynamics, sedimentary and morphological parameters. They are sediment receivers and their evolutionary processes occur rapidly, being important regions to investigate the morphodynamics and depositional facies of the recent geologic history (Frazão 2003).

In geological terms, estuaries are defined as the seaward portion of a drowned valley that receives sediment from both fluvial and marine sources, and which contains facies influenced by tide, wave and fluvial processes; the estuary is considered to extend from the landward limit of tidal facies at its head to the seaward limit of coastal facies at its mouth (Boyd et al. 1992).

Estuarine bottom sediments are a mixture of fluvial and marine materials. Their texture and composition reflects the origin and the geodynamic processes they were exposed to both at sea and on land, which gives them scientific and economic importance (Reading 1996).

According to Hedgpeth (1967) estuaries receive significant anthropogenic inputs from both point and nonpoint sources upstream and from metropolitan areas and industries located on or near estuaries.

Similarly to other estuaries located in urbanized areas, the Bons Sinais estuary presents a potential risk of receiving substances harmful to human health and aquatic organisms, coming from domestic and industrial sewage. Thus, understanding the natural susceptibility of this estuary to pollution may help decision makers improving environmental management actions to reduce the risks associated to pollution.

According to many authors (e.g. Jesus et al. 2014; Lima et al. 2019) bottom sediments are a compartment for the accumulation of pollutants from the water column and Lima et al. (2019) assert that pollutants accumulate mainly in thinner rather than in coarser sediments.

It is well established that grain size is one of the controlling factor affecting natural concentrations of trace metals in sediments (Çevik et al. 2008; Zhang et al. 2009). Karickhoff et al. (1979) documented in their study a more effective sorption in thinner sediments (<50 μm) than in larger ones. Ellis and Revitt (1982) stated that metals have a greater affinity for smaller sediments. Horowitz and Elrick (1987) investigated trace metals in different size fractions of sediments and found strong correlations between trace metals concentration and sediment grain size, with higher concentrations of metals in smaller sediments (i.e. <63 μm or < 125 μm). Smaller sediments tend to have relatively high metal concentrations due, in part, to specific surface area of the smaller particles, which enables surface adsorption and ionic attraction (Horowitz and Elrick 1987; Zhang et al. 2009).

Hence, study bottom sediments grain size distribution may bring important insights about the susceptibility of the estuary for pollutants retention.

Still is known that Bons Sinais Estuary has a high hydrodynamic pattern (Hoguane et al. 2020). However, the sedimentary dynamics, bottom sediment characteristics and its relation to the pollutant sorption were never explored. In this way, this study may give us valuable information on its susceptibility to pollution.

In this study, we aim to understand the sedimentary dynamics and bottom sediment characteristics and its influence in the vulnerability of pollutants retention in this estuary.

This study will bring advances in the field by bringing the relation of estuarine sedimentary dynamics, bottom sediment characteristics and the natural vulnerability of pollution and will benefit the society in general as it will be able to improve environmental management actions by the decision makers rising awareness in the need of adoption of pollutant treatment and preventing dumping of pollutants directly in the estuary, such as industrial or domestic wastes, as well as the dumping of fertilizers by agricultural activities upstream.

Materials and methods

Study area

The Bons Sinais Estuary is located in Central Mozambique, to the north of Zambezi Delta (17°54'S, 36°49'E; Fig. 1) adjacent to Sofala Bank, is the largest and the most productive of the eastern African coast. An updated and

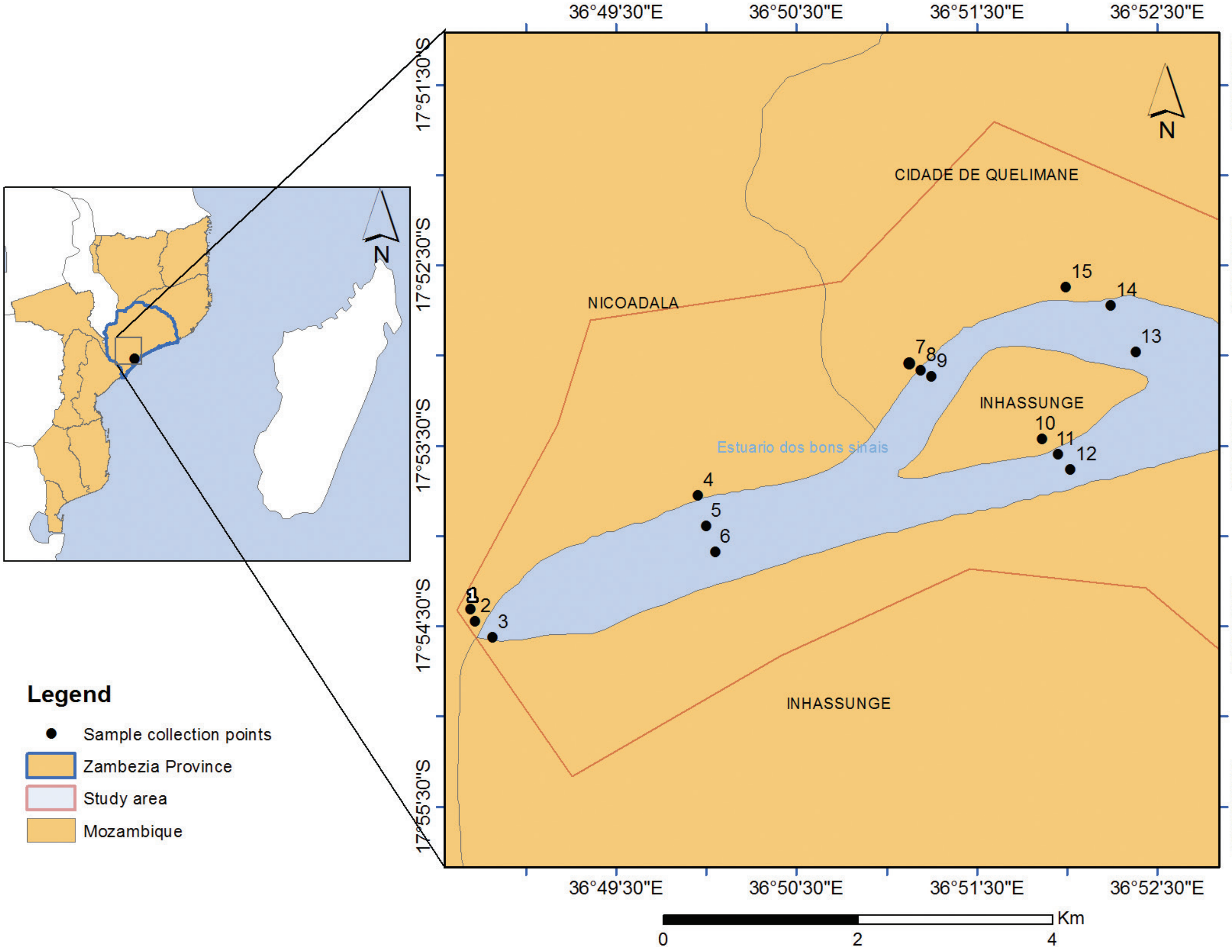

Figure 1. Study area – Bons Sinais Estuary.

more complete description of the Bons Sinais Estuary is given by Hoguane et al. (2020). It's a long (28 km) and shallow (10 m) estuary, with an extensive floodplain. It has a positive salinity gradient and is mostly well to partially mixed. The tides are semidiurnal, with amplitudes varying from 3.5 to 4.0 m, during the spring tide; therefore, it's classified as meso to macrotidal (Mazzilli 2015).

According to Köppen's climatic classification (Köppen 1900), Mozambique's climate is classified as tropical with two seasons: summer or rainy season and winter or dry season (Kottek et al. 2006). The average monthly wind speeds vary between 3 and 5 m s^{-1}, with higher values, southeast winds, observed during the summer, between September and January (Hoguane 1999; Rodrigues et al. 2000; Mazzilli 2015). The average annual precipitation is about 1,140 mm, of which approximately 80% falls during the wet season. Average annual evaporation is estimated at 1,650 mm; therefore, evaporation exceeds precipitation by about 500 mm per year.

The Bons Sinais Estuary is relatively shallow, funnel shape, highly hydrodynamic, with muddy strata and high mobility of sediments, being responsible for building and destroying continuously islands and sandy banks in the mouth. The channel depth varies from <2 to > 20 m. The greater depths are found near the harbour and its surroundings. The estuary is sinuous, braided with four large islands (Mazzilli 2015).

Mazzilli (2015) estimated, based on historical data and modeling, that the estuary receives an average of 500–840 m^3s^{-1} of freshwater from the tributaries per year. Bons Sinais Estuary used to be connected to Zambezi River in the past. Nowadays the Estuary is independent of the Zambezi, and the flow it receives depends on the precipitation in its hydrographic basin.

Data collection and analysis

There were collected 15 bottom sediments samples in 15 stations (Table 1) along the estuary using a Van veen sampler. The sampling took place during the low tide of spring tides in October 2022. The samples were collected and stored in plastic bags. Each point was georeferenced with a GPS.

Table 1. Geographic coordinates of the sampling points.

	Sampling points	GPS Coordinates
Section A	A 1	17°54'24.48"S, 36°48'41.63"E
	A 2	17°54'28.55"S, 36°48'43.05"E
	A 3	17°54'33.65"S, 36°48'48.90"E
Section B	B 1	17°53'46.63"S, 36°49'57.20"E
	B 2	17°53'56.74"S, 36°49'59.92"E
	B 3	17°54'5.22"S, 36°50'3.02"E
Section C	C 1	17°53'2.76"S, 36°51'7.61"E
	C 2	17°53'4.93"S, 36°51'11.32"E
	C 3	17°53'6.97"S, 36°51'14.84"E
Section D	D 1	17°53'27.84"S, 36°51'51.62"E
	D 2	17°53'32.97"S, 36°51'56.92"E
	D 3	17°53'37.82"S, 36°52'1.20"E
Section E	E 1	17°52'58.92"S, 36°52'22.90"E
	E 2	17°52'43.45"S, 36°52'14.64"E
	E 3	17°52'37.22"S, 36°51'59.65"E

The samples were further analysed in the laboratory of civil engineering in Quelimane by conventional sieve and pipette methods. Data processing included the computation of statistical parameters (mean, sorting, skewness and kurtosis) and the plotting of Shepard and Pejrup diagrams in the software SYSGRAN 3.0 to infer about the facies distributions and sediment dynamics along the estuary.

Results

Textural distribution

Fig. 2, shows the relative abundance of the sediment classes in the Bons Sinais Estuary along the 15 sampling points. As seen in the figure, there are three textural classes in the Estuary, namely, Sand, Silt and Clay. Sand is the dominant class (51%), followed by Silt (25%) and clay (24%). Even though Sand is the dominant class, the abundance of thinner sediments is noteworthy.

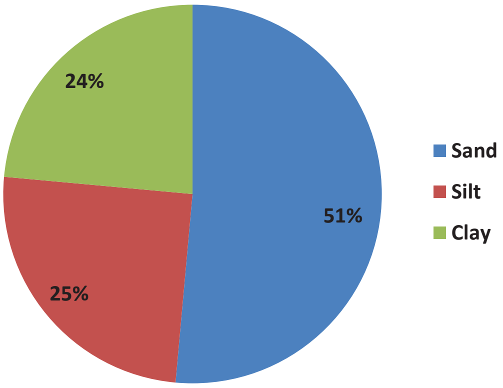

Figure 2. Textural distribution of Bons Sinais Estuary.

Statistical parameters

The values of the mean grain size (Fig. 3), varied from values as low as 2.50 ϕ (fine sand) – in station B3 – to values as high as 7.30 ϕ (very fine silt) – in station C2. Generally, the sediments of the sampled area are coarse, as in most stations (7 stations) the sediments are classified as very fine sand.

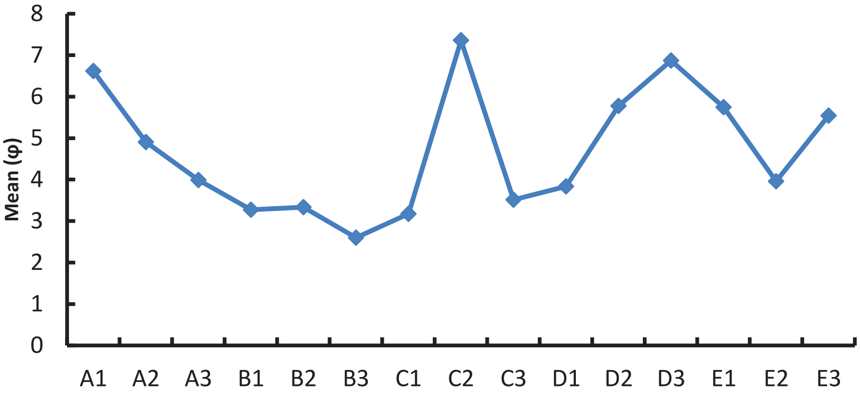

Figure 3. Mean, showing the trends of all the samples.

The values of sediment sorting (Fig. 4) varied from 0.70 to 1.90 ϕ, in stations D2 and E1, respectively. Generally, the sediment sorting is classified as poorly sorted, since most of the stations (12), showed this classification. The remaining stations were classified as moderately sorted.

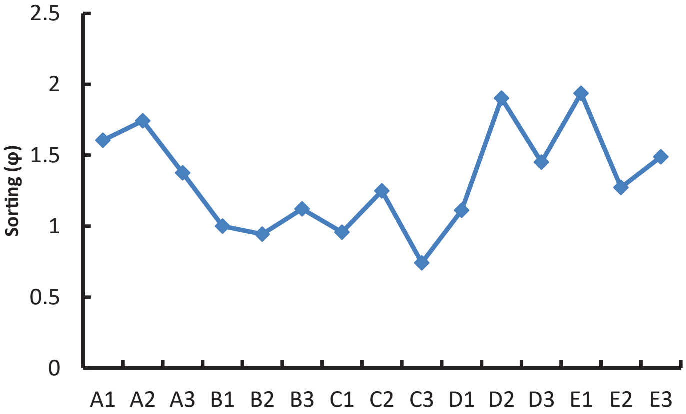

Figure 4. Sediment sorting, showing the trends of all the samples.

The values of skewness (Fig. 5), varied from -0.30 ϕ, in station C2 to 0.60 ϕ, in stations B3 and E2. The sediments were mostly classified as very fine skewed, as in most stations (9) were classified like this; three stations were classified as fine skewed, namely, E1, D2, and C3, the stations A1, C2, and D3 were classified as coarse skewed.

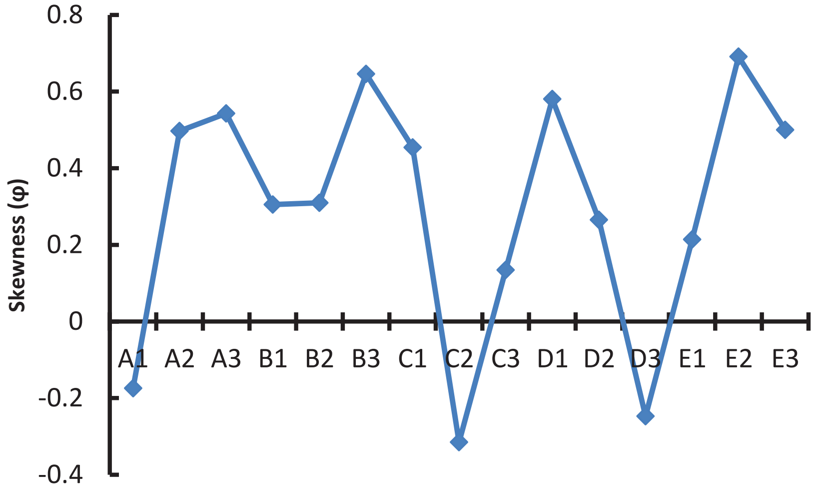

Figure 5. Sediment skewness, showing the trends of all the samples.

The sediment kurtosis (Fig. 6) varied from 0.60 ϕ, in stations A1, D2, and E1 to 3.70 ϕ, in station B2. Stations B1, B2, B3, and E2 were classified as extremely leptokurtic, stations A3, C1, C3, and D1, were classified as very leptokurtic, stations C2 and E3 were classified as mesokurtic, the stations A2 and D3 were classified as platkurtic and the stations A1, D2 and E1 were classified as very platkurtic.

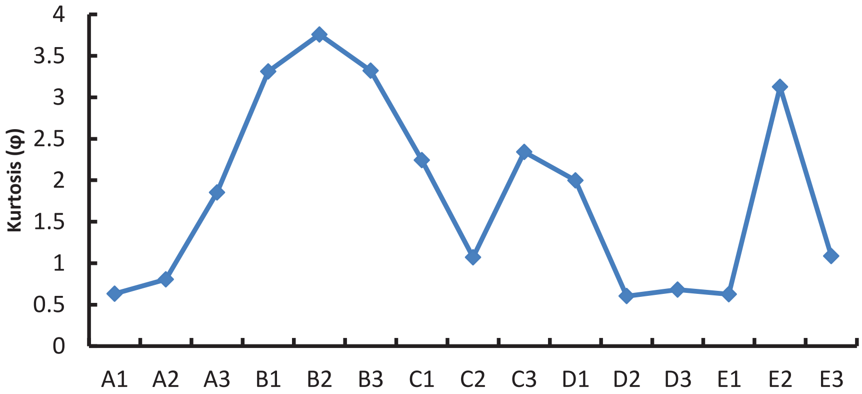

Figure 6. Sediment kurtosis, showing the trends of all the samples.

Sedimentary dynamic classification

The hydrodynamic of the Bons Sinais Estuary, as shown in the Pejrup Diagram (Fig. 7), varied from moderate to high. In the stations, A1, C2, and D3 are located in the band II-D, with a percentage of clay between 50 to 80%, and a percentage of sand between 0 to 10%. The Stations D2 and E1 were located in the band II-C with percentages of clay between 50 to 80% and percentages of sand between 10 to 50%. The stations A2, B2, B3, C1, E1, and E2, were located in the band II-B, with a percentage of clay between 50 to 80% and a percentage

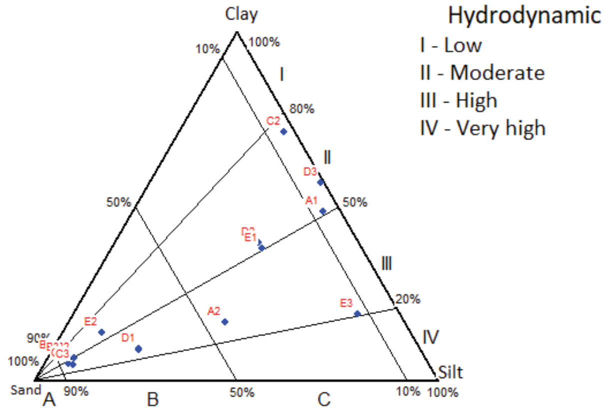

Figure 7. Sedimentary dynamics inferred by the Pejrup's diagram.

of sand between 50 to 90%. The stations A2 and E3 were located in band III-C, with a percentage of clay from 20 to 50% and a percentage of sand between 10 to 50%. The remaining stations were located in band III-B, with a percentage of clay from 20 to 50% and sand from 50 to 90%.

Textural composition

The textural composition, shown in the Shepard diagram (Fig. 8), varied considerably. The Stations A1, C2, and D3 are located in position 3 at Shepard's diagram, classified as Silty clay. The stations D2 and E1 are located in position 4, which is classified as Sandy silty clay. Station E3 is located in position 8 and is classified as Clayey silt. The stations B1, B2, B3, C1, C3, and E2 were located in position 9 and are classified as Sandy. The stations D2 and E1 are located in the position of Silty sand.

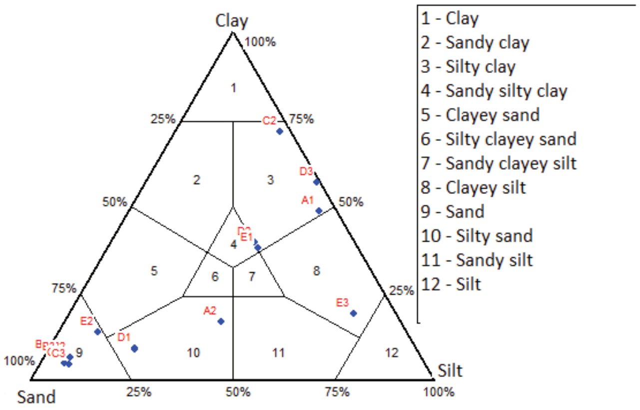

Figure 8. Bons Sinais Estuary textural composition.

Discussion

Textural sediment analysis

The sediments of Bons Sinais Estuary in the sampled area are in majority sandy (about 50%) and the muddy fraction makes up the remaining 50% (Fig. 2). This result is not much different by the results found by Corrêa (2005) in the Estuary of Marajó Bay where the bottom sediments were composed of medium to very thin sand that graded to coarse to thin silt in direction of the continental shelf and Oliveira (2015) that found in the study of Lagoa the Patos that the bottom sediments are composed by thin to very thin sand with presence of muddy material (silt). However, in Bons Sinais Estuary, different of these other estuaries, the presence of clay is noteworthy (24%). Corrêa (2005) and Oliveira (2015) associated the presence of sandy sediments with places with relatively high hydrodynamics and shallow depth. Therefore, the amount of sand in the Bons Sinais Estuary. is probably related to the estuary's high hydrodynamics as stated by many authors(e.g. Davis Jr. and Fitzgerald 2004; Corrêa 2005; Oliveira 2015). This aspect is reinforced by Hoguane et al. (2020) when they state that Bons Sinais Estuary has the highest tide amplitude (4 m) of the Western Indian Ocean, being therefore classified as meso to macro tide. According to Pinet (2009), most of the sediments in well-mixed estuaries are marine sediments. Therefore, probably most sediments found in this estuary are marine in origin, as this is well mixed, as argued by Hoguane et al. (2020). The concentrations of Silt and Clay in this estuary may be due to the local morphology or flocculation, as these sediments tend to be deposited at high depths or flocculate in the meeting of fresh and saltwater and due to the changes of pH, as Corrêa (2005) argues.

Although sandy sediments are dominant, muddy sediments concentrations are considerable, therefore the estuary may be considered susceptible to pollutants accumulation, as according to many authors (e.g. Karickhoff et al. 1979; Ellis and Revitt 1982; Horowitz and Elrick 1987; Singh et al. 1999; Krein and Schorer 2000; Ujević et al. 2000; Sutherland 2003; Çevik et al. 2008; Zhang et al. 2009; Zhao et al. 2010; Lima et al. 2019) pollutants tend to accumulate in thinner rather than coarser sediments.

Statistical parameters analysis

In most stations the sediments were coarse (Fig. 3), with values that varied from 2.50 to 7.30 ϕ. These results don't differ so much from those found by Oliveira (2015) that found sediment mean varying from thin sand to very thin silt. Haddout et al. (2022), in turn, found mean sediment values ranging from 3.07 to 9.80 ϕ and related his findings to the energy of the environment. Jesus and Andrade (2013) argue that environmental energy is closely related to the mean grain size, with coarser sediments revealing high energy conditions and thinner sediments revealing the opposite.

The sediments were generally poorly sorted (Fig. 4). Oliveira (2015) found, in his study that most of the samples collected varied from poorly to very poorly sorted and Haddout et al. (2022) found sorting varying form moderately poorly sorted to moderately well sorted. The bottom sediment sorting is related to the degree of reworking by waves and currents. Jesus and Andrade (2013) claim that with increased transport and hydrodynamics, the sediments tend to be sorted, on the contrary, occur a mixing of different sediment sizes, being therefore poorly sorted. According to Lima et al. (2019) sediments deposited near the source regions tend to be poorly sorted. Corrêa (2005) says that poor sorting is due to the existence of many depositional processes.

Generally, the sediments in the area of study were fine to very fine skewed (Fig. 5). Haddout et al. (2022) found, in their study, that the values of skewness have varied from coarse skewed to very fine skewed, and stated that the finer the skewness values, the thinner the sediments found in the environment. Therefore, even though the percentage of coarse sediments is high (Fig. 2) in Bons Sinais Estuary, skewness values reveal a relative abundance of thin sediments as many authors argue higher values of skewness are related to thin sediments (e.g. Jesus et al. 2014; Haddout et al. 2022). Hereupon, based on the values of skewness we can affirm that Bons Sinais Estuary is susceptible to pollutant retention.

The Kurtosis has varied from very platkurtic to extremely leptokurtic (Fig. 6). According to Jesus et al. (2014), variations in Kurtosis may be related to the degree of polymodality of the sediments. Thus, when there is only one source of sediments, the curve of sediments distribution tends to be unimodal, i.e., with kurtosis values closer to 1. When the curve of sediments has a second mode less expressive, the value of kurtosis will be higher than 1 and the curve will become more strongly leptokurtic. When there are different sources, each source will have a population that will represent a mode in the distribution curve. Thus, the value of kurtosis will decrease to values lower than 1 and the curve will tend to be bimodal or polymodal, i.e., platkurtic. It means that, although this estuary has both continental and marine sediments, one of these sources is dominant, which is probably the marine, due to its high tide amplitude as Hoguane et al. (2020) say. Haddout et al. (2022) associated mesokurtic to leptokurtic curves to the dominance of thin sediments. Jesus and Andrade (2013) state that very high and very low values of kurtosis mean that sediment may have been transported from its origin and deposited without losing its original characteristics.

The implications that thinner sediments have for the pollutions dynamics are the following: i) increasing pollutant retention, ii) reducing the mobility of pollutants, iii) interactions of the polluted sediments and the water column and iv) pollutants may affect living organisms through the trophic chain.

The findings of this study may contribute for understanding the Bons Sinais Estuarine Ecosystem since many estuarine processes; species distribution, pollutant transport and nutrient cycle are intrinsically linked to bottom sediment distributions influence.

From these findings, we propose to prevent dumping of pollutants direct in the estuary, and that pollution treatment plan be established in the city of Quelimane.

Dynamic and facies classification

The hydrodynamics of the sampled region in Bons Sinais Estuary varied from moderate to high (Fig. 7) and most of the points are located in position 9 of the Shepard diagram (Fig. 8). The hydrodynamic regime showed in the Pejrup diagram, may be due to: i) the tide regime of about 4 m of amplitude, and ii) the shallowness of the estuary, with a mean depth of 10 m as mentioned by Hoguane et al. (2020). Corrêa (2005) in its turn associated the deposition of sandy sediments to shallow and high-energy locations in the Baia de Marajó Estuary. This observation reinforces our thesis that the Bons Sinais hydrodynamics and shallowness deeply control the sedimentation and consequently its susceptibility to pollutant accumulation. We can also assert that the factors above mentioned, also control the type of sediments found in the estuary as illustrated in the Shepard diagram (Fig. 8).

A feature that can be noticed through the detailed analysis of Fig. 7 is that the higher hydrodynamics, the lower the concentration of finer sediments. Therefore, we may affirm that the hydrodynamics plays a significant role in pollutants retention that is the higher the hydrodynamics, the lower the vulnerability to pollutants accumulation.

Conclusions

From the present study we can conclude that:

- Sand is the dominant textural class, suggesting relatively high hydrodynamics. However, the thinner sediment amount is noteworthy, and might be associated to the local morphology and flocculation.
- Mean values also suggest that the sediments are coarse in general, as in most stations the sediments are classified as very fine sand, this reinforces that the estuary has a high energy condition.
- The sediments of the studied area are poorly sorted, revealing poor reworking by waves and currents or that the source of the sediments is relatively close or even the existence of many depositional processes.
- Skewness values suggest that despite there is a relative high abundance of coarse sediments, the amount of thin sediments is considerable. Therefore, the estuary is susceptible to pollutants retention.
- Kurtosis values suggest that although there are more than one source of sediments in the estuary, one of them is dominant.
- The hydrodynamic varied from moderate to high, and it is probably due to high tidal regime and the shallowness of the estuary, this reinforces that the estuary is tide dominated, hence, the sediments are mostly marine in origin.

Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Funding

No funding was reported.

Author contributions

Conceptualization: HAM. Data curation: JM, NLC, CAMAMH. Formal analysis: JM. Investigation: NLC, CAMAMH, HAM, JM. Methodology: JM, CAMAMH, NLC. Supervision: HAM, CAMAMH. Writing - original draft: HAM, JM, CAMAMH.

Data availability

All of the data that support the findings of this study are available in the main text.

References

Boyd R, Darlymple R, Zaitlin BA (1992) Classification of clastic coastal depositional environments. Sedimentary Geology 80: 139–150. https://doi.org/10.1016/0037-0738(92)90037-R

Çevik F, Göksu MZL, Derici OB, Findik Ö (2008) An assessment of metal pollution in surface sediments of Seyhan dam by using enrichment factor, geoaccumulation index and statistical analyses. Environmental Monitoring and Assessment 152: 309–317. https://doi.org/10.1007/s10661-008-0317-3

Corrêa ICS (2005) Aplicação do Diagrama de Pejrup na Interpretação da Sedimentação e da Dinâmica do Estuário da Baía de Marajó-PA. Pesquisas em Geociências 32(2): 109–118. https://doi.org/10.22456/1807-9806.19551

Davis Jr RA, Fitzgerald DM (2004) Beaches and Coasts. Texas: Blackwell Publishing.

De Oliveira AdeO (2015) Caracterização Sedimentar e Aplicação do Diagrama de Pejrup para Interpretação da Dinâmica em uma Enseada Estuarina na Lagoa dos Patos/Brasil. Geographia Meridionalis 1(2): 363–383. https://doi.org/10.15210/gm.v1i2.6232

Ellis JB, Revitt DM (1982) Incidence of heavy metals in street surface sediments: Solubility and grain size studies. Water, Air, and Soil Pollution 17: 87–100. https://doi.org/10.1007/BF00164094

Frazão EP (2003) Caracterização Hidrodinâmica e Morfosedimentar do Estuário Potengi e Áreas Adjacentes: Subsídios para controle e recuperação ambiental no caso de derrames de Hidrocarbonetos . Rio Grande do Norte- Brasil. Master Degree Dissertation. Universidade Federal do Rio Grande do Norte.

Haddout S, Azidane H, Hoguane AM, Priya KL, Casila JCC, Ljubenkov I (2022) Grain size distribution and fluvial environmental implications of Sebou estuary (Morocco). Marine Georesources & Geotechnology 41(10): 1132–1141. https://doi.org/10.1080/1064119X.2022.2121235

Hedgpeth JW (1967) The sense of the meeting. In: Lauff GH (Ed.) Estuaries. American Association for the Advancement of Science, Washington, DC, 707–710.

Hoguane AM (1999) Sea level measurement and analysis in the Western Indian Ocean. National report: Mozambique. UNESCO IOC, Maputo. https://doi.org/10.13140/RG.2.2.27361.97128

Hoguane AM, Gammelsrød T, Mazzilli S, Antonio MH, Da Silva NBF (2020) The hydrodynamics of the Bons Sinais Estuary: The value of simple hydrodynamic tidal models in understanding circulation in estuaries of central Mozambique. Regional Studies in Marine Science 37: 2–11. https://doi.org/10.1016/j.rsma.2020.101352

Horowitz AJ, Elrick KA (1987) The relation of stream sediment surface area, grain size and composition to trace element chemistry. Applied Geochemistry 2: 437–451. https://doi.org/10.1016/0883-2927(87)90027-8

Jesus LV, Andrade ACS (2013) Parâmetros Granulométricos dos sedimentos da praia dos Artistas-Aracaju-SE. Scientia Plena 9(5): 1–11.

Jesus LV, Andrade ACS, Silva MG, Rodrigues TK (2014) Distribuição espacial das características granulométricas, morfoscópicas e composicionais dos sedimentos das praia de Aracajú-Sergipe. Aracajú-Sergipe. Scientia Plena 10(04): 1–15.

Karickhoff SW, Brown DS, Scott TA (1979) Sorption of Hydrophobic Pollutants on Natural Sediments. Water Research 13: 241–248. https://doi.org/10.1016/0043-1354(79)90201-X

Köppen W (1900) Versuch einer Klassifikation der Klimate, vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. Geographic Zeitschrift 6: 593–611.

Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Koppen- Geiger climate classification updated. Meteorologische Zeitschrift 15: 259–263. https://doi.org/10.1127/0941-2948/2006/0130

Krein A, Schorer M (2000) Road Runoff Pollution by Polycyclic Aromatic Hydrocarbons and its Contribution to River Sediments. Water Research 34(16): 4110–4115. https://doi.org/10.1016/S0043-1354(00)00156-1

Lima LdaS, Bertoni F, Da Fonseca EM (2019) A importância da caracterização dos sedimentos em ambientes estuarinos - complexo estuarino de paranaguá-pr. Paper presented at the XVIII Simpósio Brasileiro de Geografia Fisica Aplicada, Fortaleza, Brasil.

Mazzilli S (2015) Understanding estuarine hydrodynamics for decision making in data-poor coastal environments. PhD Thesis. University of Cambridge.

Pinet PR (2009) Invitation to Oceanography. 5th Ed. Jones and Bartlett Publishers, 626 pp.

Reading HG (1996) Sedimentary environments: processes, facies and stratigraphy. Blackwell Science, Oxford.

Rodrigues MJ, Motta H, Whittington MH, Schleyer MH (2000) Coral reefs of Mozambique. In: McClanahan T, Sheppard C, Obura D (Eds) The handbook of Coral reefs of the Indian Ocean: Their ecology and conservation. Oxford, New York: University Press, 107–129. https://doi.org/10.1093/oso/9780195125962.003.0004

Singh AK, Hasnain SI, Banerjee DK (1999) Grain size and geochemical partitioning of heavy metals in sediments of the Damodar River – a tributary of the lower Ganga, India. Environmental Geology 39(1): 90–98. https://doi.org/10.1007/s002540050439

Sutherland RA (2003) Lead in grain size fractions of road-deposited sediment. Environmental Pollution 121: 229–237. https://doi.org/10.1016/S0269-7491(02)00219-1

Ujević I, Odžak N, Barić A (2000) Trace metal accumulation in different grain size fractions of the sediments from a semi-enclosed bay heavily contaminated by urban and industrial wastewaters. Water Research 34(11): 3055–3061. https://doi.org/10.1016/S0043-1354(99)00376-0

Zhang W, Feng H, Chang J, Qu J, Xie H, Yu L (2009) Heavy metal contamination in surface sediments of Yangtze River intertidal zone: An assessment from different indexes.Environmental Pollution 157: 1533–1543. https://doi.org/10.1016/j.envpol.2009.01.007

Zhao H, Li X, Wang X, Tian D (2010) Grain size distribution of road-deposited sediment and its contribution to heavy metal pollution in urban runoff in Beijing, China. Journal of Hazarduos Materials 183: 203–210. https://doi.org/10.1016/j.jhazmat.2010.07.012