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Compatibility between Continental Shelf Deposits and Sediments of Adjacent Beaches along Western Sardinia (Mediterranean Sea)

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Abstract: The compatibility of sediments in terms of grain size, composition and colour among beaches and strategic sediment deposits (SSD) along Western Sardinia (Western Mediterranean Sea) were assessed to explore management strategy in the protection and adaptation to counteract the beach erosion and the effect of sea level rise along sandy shores. Twelve beaches, mainly conditioned by geological control, due to the presence of extensive rocky outcrops in the sea, enclosed in seven sedimentary cells (defined by the continuity of sediment transport pathways and by identification of boundaries where there are discontinuities), were characterised in terms of sediment composition and grain size. One hundred ninety-three beach sediments and one hundred sediments from SSDs were collected and analysed for sediment grain size, carbonate content and sediment colour. The beach sediments are composed by gravel to fine sands (D_{50}: from 81 μm to 4986 μm) with siliciclastic and biogenic carbonate sediments mixed in different proportions (0–100% in $CaCO_3$). The SSDs sediments are gravels to medium-fine sand (D_{50}: from 96 μm to 1769 μm) composed by biogenic carbonate sands mixed with siliciclastic grains (0–100% in $CaCO_3$). To be able to evaluate the compatibility between the beaches and SSDs, a multivariate statistical procedure was applied to grain size dataset. Our results show that 8 beaches have strategic deposits of compatible grain size and composition, whereas only 2 beaches have compatible strategic deposits of both grain size and colour. This may be related to the different sediment sources and depositional processes of sediment along the coastal cells and the continental shelf.

Keywords: strategic sediment deposits; adaptation strategy; coastal erosion; sea level rise

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1. Introduction

Beach and barriers are complex systems that characterize about the 30% of the ice-free world shorelines [1]. They protect the landward areas from flooding and storms, they host precious ecosystems and can provide important income for recreational tourism economy [2,3]. Recent studies indicate that over a period of 33 years (1984–2016), 24% of the world's sandy beaches were eroded at rates exceeding 0.5 m yr^{-1}, while 28% were accreted and 48% were stable. On a global scale, the overall surface of eroded land is about 28,000 km^2, twice the surface of gained land in the same period [1,4].

Over a long-term perspective, the climate change can be considered the most important forcing that would have an impact on the coastal area. Thousands of kilometres of the world's sandy beaches could face severe erosion by the end of the century and millions of coastal inhabitants would be forced to move [5,6].

Among the climate change drivers, storms and sea level rise (SLR) are the most relevant from coastal hazard perspective [7]. In the Mediterranean Sea storminess is not expected to increase [8,9], instead the SLR can be one of the main forcing which will influence the coastal areas and in particular the coastal plains, including beach and barriers [6,10–12]. The SLR may imply a redistribution of the sediments of the coastal system leading to a shoreline retreat and a change on sediment budget of the littoral cells that can promote a reorganisation of the configuration of the coast [13]. A further factor which may influence the sediment budget of carbonate beaches is ocean acidification, both by affecting the ecosystems which provide biogenic sands and promoting dissolution of carbonates [14].

The prediction of beach evolution following climate change is of particular importance to develop long-term strategic adaptation plans [15]. The adaptation of coastal systems refers to an adjustment in natural or human systems as a means of moderating the adverse impacts and includes three basic approaches: (1) protect, (2) accommodate and (3) retreat [15,16]. The 'accommodate' option involves the continued occupancy and use of vulnerable zones by increasing the ability to cope with the effects of extreme events, also providing space for coastal processes [16,17]. In some case it could be possible to shift inland the artefacts which limits the accommodation space applying the 'retreat' option.

The soft protection of beaches is generally performed by sand nourishment, and this approach includes the availability of strategic sediment deposits (SDDs). The SSDs are supplies of sediment of appropriate characteristics that are available for replenishment of the coastal zone, either temporarily or in the long term [18]. Due to their importance SSDs have been mapped along the Mediterranean continental shelves to include the availability of sand in beach management plans [19–22].

A further aspect to be considered in sediment management plans is the compatibility between the materials of SSDs over the continental shelf and the sediments of the beaches facing the adjacent coastal sectors. Particularly, beach sediments of coastal areas characterised by high geomorphological variability may derive from multiple sources (small rivers, cliff erosion, coastal ecosystems) thus resulting extremely variable in grain size and composition [23–25]. The availability of compatible sediments is a key factor to implement the adaptation strategies of coastal systems with respect to long term scenarios related to the global change.

This study provides a new approach based on multivariate statistics apply to grain size dataset to assess the compatibility between the sediments of a large marine sand deposit over the continental shelf and the sediments of adjacent beaches. Then, results of the multivariate were used to point out the chromatic compatibility between the sets of samples. The study examined a coastal sector of the Western Sardinia (Western Mediterranean Sea), 100 km long, with 12 beaches partially geologically constrained [26], composed by various sediment types forming several coastal cells. The specific aim is to highlight a new approach to assess, for each coastal cell, the availability of compatible sediments from the sand deposits located in the continental shelf. In the future, this new approach might be applied to other beaches mainly conditioned by geological control.

2. Study Area

The study area is the coastal sector of the Central Western Sardinia Island (Western Mediterranean Sea) and extends from the Sinis Peninsula to the Gulf of Oristano (Figure 1). The Sinis Peninsula is a structural high, formed by a sequence of volcanic and sedimentary rocks (marls, sandstone, and limestone), dating from the Neogene to the Quaternary [27]. The Gulf of Oristano is bordered to the west by rocky capes and has a mostly sandy shoreline which also includes several marshes and lagoons. The Tirso River is the major source of terrigenous sediments [28], the mouth of which is in the north-eastern part of the Gulf (Figure 1). The geological setting of the basin draining into the gulf includes Palaeozoic crystalline basement, Oligocene-lower Miocene calco-alkaline volcanic formations, Miocene and Pliocene sedimentary formations and Pliocene and Quaternary basaltic deposits.

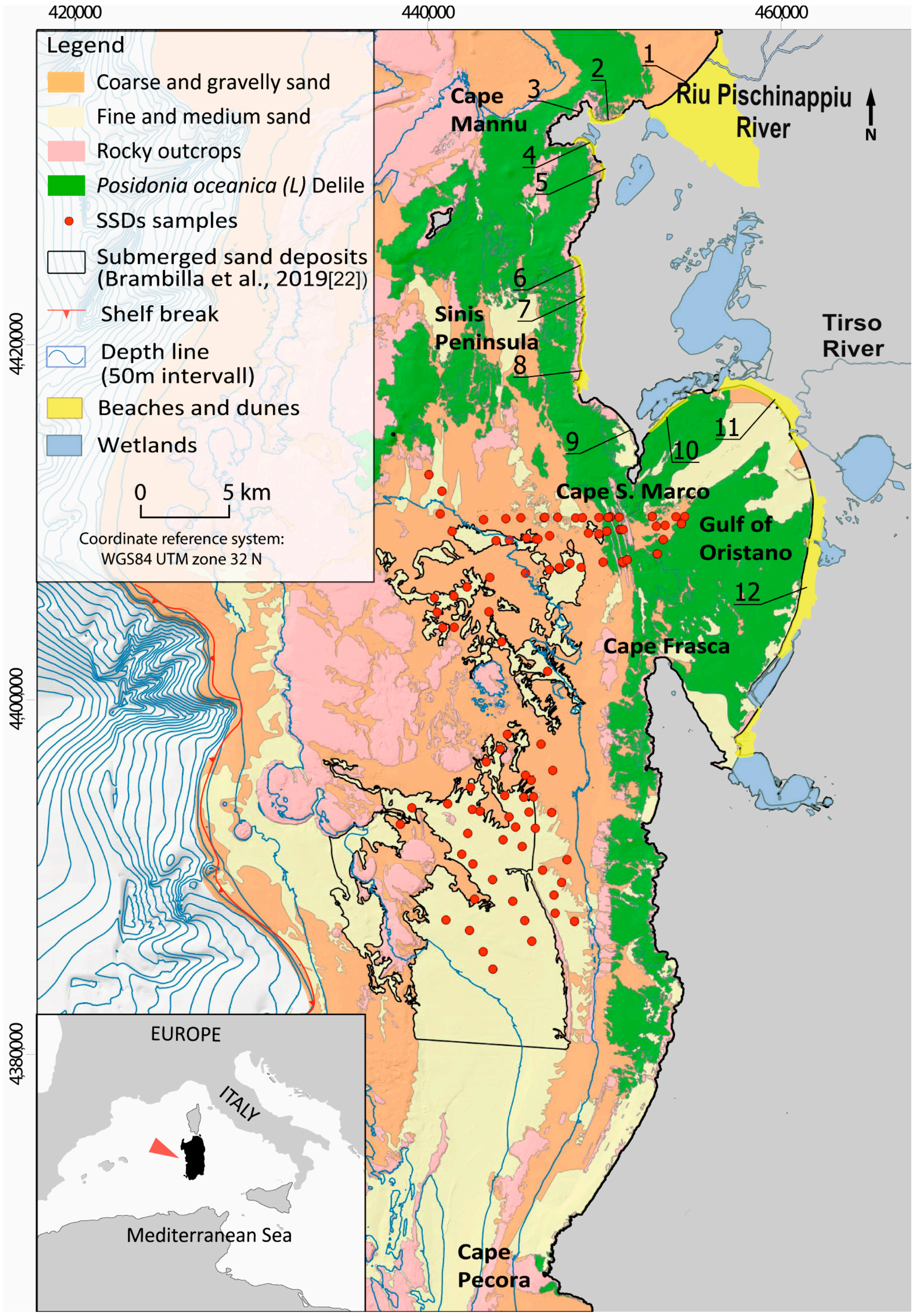

Figure 1. Map of the study area with localities and geomorphic features. Location of continental shelf with samples in the submerged sand deposits and beach areas (numbers from 1 to 12) analysed in this study are also shown.

The continental shelf is sediment-starved, with limited land-to-sea sedimentary run-off. The absence of sediment run-off allowed the colonisation of the seabed by extended *Posidonia oceanica* seagrass meadows (Figure 1). The transgressive deposits associated with the last post-glacial sea level rise are characterised by siliciclastic sands and calcareous bioclastic sands [29–33] along the inner shelf, as well as clays and calcareous mud along the outer shelf [34]. Along this area, several submerged sand deposits, from 25 to 140 m depth, were detected and characterised in terms of grain size, stratigraphy, composition, and available volume [22,30,31].

The Sinis Peninsula is partially included in a Marine Protected Area (MPA Penisola del Sinis and Isola di Mal di Ventre) and is characterised by a low degree of urbanizations, except for two small villages mainly occupied during summer season. Local hotspots of coastal erosion were highlighted in two beaches (Is Arutas, Su Pallosu, [35]). The shore of the Gulf of Oristano is characterised by the presence of a commercial port, two touristic marinas, a small village developed on the backshore along the northern side of the Gulf, cross-shore dikes and artificial lagoon inlets. The inland drainage system was modified during the last 100 years; a large part of the wetlands was reclaimed, and large dune fields were smoothed for agriculture and residential purposes.

The Gulf of Oristano is considered vulnerable with respect to sea level rise due to the low elevation of the Campidano plane [10,36].

Despite that some beaches of the studied area showed a shoreline retreat [35] no nourishment project was realised in the investigated area. Considering the Island of Sardinia two nourishments were realised in the last 40 years [37]. The first was fulfilled in Cala Gonone by using residual grains and cobbles from a limestone quarry and involved about 80,000 m^3; the second, more important was realised in Poetto Beach. In this nourishment ~ 400,000 m^3 of material was dredged from a depth of ~40 m and used to nourish the beach.

3. Materials and Methods

3.1. Sedimentological Data Set

A total 98 sediment samples were collected from 8 beaches (1, 2, 3, 4, 5, 10, 11, and 12, Figure 1 and Table 1) by using PVC pipes (10 cm length, 5 cm diameter) along transects normal to the shoreline in the backshore, foreshore, upper offshore. These samples were integrated with sediment data collected in previous studies in the remanent 4 beaches (6, 7, 8, and 9, Figure 1 and Table 1; [14,23,33]) to obtain a dataset composed by a total of 193 sediment samples. The whole dataset was processed in this study.

Sediment samples along the continental shelf were collected during the years 2007–2013 for a total of 100 samples and sediment data were already published in previous studies [30–32]. Table S1 (see Supplementary Materials) report the whole sedimentological data set for a total of 293 sediment samples.

Table 1. Characterisation of cells and sub-cells (beaches) of the study area morphology, textural proprieties, composition, and sources of sediments.

Cell	Sub-Cell	Beach Name	Morphology	Textural Description	Sediments	% Carbonate		D50 µm		% Gravel		% Sand		Sediment Source
A	1	Is Arenas	Beach–dune	Gravelly Sand/Slightly Gravelly Sand	Mean SD	47	4	833	380	11%	12%	89%	12%	Riverine and transgressive relict sediments; ecosystem carbonate-producers
					Min–Max	42	51	441	1514	3%	28%	72%	97%	
B	2	Sa Rocca Tunda	Embayed	Sand	Mean SD	57	13	421	334	0%	0%	100%	0%	Ecosystem carbonate-producers; cliff erosion
					Min–Max	34	72	177	1140	0%	0%	100%	100%	
	3	Sa Mesa Longa	Beach–dune	Slightly Gravelly Sand/Sandy Gravel	Mean SD	65	5	658	624	9%	18%	91%	18%	
					Min–Max	55	76	220	2449	0%	63%	37%	100%	
C	4	Putzu Idu	Barrier–lagoon	Slightly Gravelly Sand	Mean SD	32	4	371	167	1%	1%	99%	1%	Relict sediment; cliff erosion; ecosystem carbonate-producers
					Min–Max	27	40	182	597	0%	5%	95%	100%	
	5	S'Arena Scoada	Embayed	Slightly Gravelly Sand	Mean SD	25	14	185	7	1%	1%	99%	1%	
					Min–Max	2	43	178	195	0%	3%	97%	100%	
D	6	Mari Ermi	Barrier–lagoon	Gravel/Muddy Sandy Gravel	Mean SD	15	23	2289	1093	66%	26%	26%	17%	Transgressive relict sediments; ecosystem carbonate-producers [23,38,39]
					Min–Max	0	76	81	4986	0%	100%	0%	61%	
	7	Is Arutas	Embayed	Gravel/Sandy Gravel	Mean SD	0		2682	263	83%	13%	17%	13%	
					Min–Max			2094	3140	54%	100%	0%	46%	
	8	Maimoni	Beach–dune/barrier	Gravel/Sandy Gravel/Gravelly Sand/Slightly Gravelly Sand	Mean SD	9	21	1417	958	35%	35%	63%	34%	
					Min–Max	0	70	224	3063	0%	100%	0%	96%	
E	9	San Giovanni	Beach–dune	Slightly Gravelly Sand/Sand	Mean SD	62	22	506	219	1%	3%	99%	3%	Ecosystem carbonate-producers; transgressive relict sediments; [14,33]
					Min–Max	22	100	285	1069	0%	16%	84%	100%	
F	10	Mistras	Barrier–lagoon	Slightly Gravelly Sand	Mean SD	56	24	553	451	7%	13%	91%	13%	Ecosystem carbonate-producers; riverine sediments; [40,41]
					Min–Max	15	74	117	1331	0%	33%	67%	100%	
G	11	Torregrande	Beach–dune	Sandy Gravel/Gravelly Sand/Slightly Gravelly Sand/	Mean SD	0		996	563	0.10	0.17	0.90	0.17	Riverine sediments [28]
					Min–Max			209	2327	0%	62%	38%	100%	
	12	Arborea	Beach–dune	Slightly Gravelly Sand/Sand	Mean SD	6	6	381	196	1%	2%	99%	2%	Riverine and transgressive relict sediments [29]
					Min–Max	1	24	159	812	0%	7%	93%	100%	

All samples were processed with the same methodologies in the CNR-IAS laboratory. Specifically, gravelly sandy sediments were carefully washed to remove salt, and grain size distribution was measured using dry sieving for the gravel/sand fraction between >4000 and 90 μm at half-phi intervals; the finer fraction (<90 μm) was analysed using a Galai CIS 1 laser system at 0.5 μm intervals [42]. Statistical parameters of grain size data distributions were computed using the momentum method using the GRADISTAT spreadsheet [43]. The carbonate fraction of sediments is of biogenic origin [23,33]. The carbonate contents of both sets of sediments samples were determined by using the Dietrich-Fruhling calcimeter. The samples were classified into three groups based on biogenic carbonate contents: siliciclastic (carbonate 0–20%), mixed (20–60%) and biogenic carbonate (60–100%).

Sediment colour assessment was determined by the matching of each sediment sample with the closest Munsell Soil Colour Charts. The Munsell system is easy to use and respects the progressiveness with which we perceive colour differences. What is difficult is to measure these differences that are essential for expressing them objectively. The California Coastal Commission [44] refers to it for determining the colour of native and nourishment sands. The precision with which a colour can be visually characterised with the Munsell system is estimated at 0.5 Hue, 0.1 Value, and 0.4 Chroma (ASTM D1535) [45]. A more objective method to determine the compatibility between borrow and natural sediments is reported in [46] and [47]. In these studies, the CIEL*a*b* colour space appears to be the most reliable method and allows an exact quantification of the chromatic distance between two samples.

3.2. Littoral Cells

A littoral cell is a coastal compartment that contains a complete cycle of sedimentation including sources, transport paths, and sinks [48]. Cells and sub-cells can be defined examining the continuity of sediment transport pathways and by the identification of boundaries where discontinuity occurs [49]. Along urbanised areas the man-made boundaries can further separate a cell into sub-cells [50]. In this study the littoral cells were identified considering the longshore sediment transport direction, the presence of headlands causing discontinuity, and with the characterisation of the beach sediments [24].

The mean wave energy flux (MWEF) directions coupled with the main headlands position were considered in first instance to delimitate the boundaries of the littoral cells. This because the longshore sediment transport is correlated to the wave exposure and longshore component of wave power. The MWEF for the whole Western Sardinian coast was determined by Atzeni et al. [51], whereas a more detailed description of the MWEF for the northern sector of the investigated area was provided by Sulis et al. [52]. The MWEF is mainly related to storms forced by the Mistral wind (coming from the 0northwest) along the Western Sardinia coastal sector [51]. In correspondence of main headlands, the Mistral storms can promote opposite directions of the MWEF which can be used to establish the boundaries of the littoral cells [51,52].

Furthermore, the beach sediment grain size and composition were used to infer the sediment source [23,53,54], thus providing additional information which were used to delimit the littoral cells and sub-cells.

3.3. Multivariate Statistics

The grain size fractions of the beach sediment sample (Table S1) were subjected to Entropy-Max analysis (EM) [48,49,55–57]. The software is designed to ensure optimal grouping, maximising the inequality between groups of samples and minimising the inequality within the groups, so that the distributions in each group have similar shapes, and the shapes of the distributions differ mainly between groups [56]. EM allows optimal classification of samples into self-similar groups.

Discriminant analysis (DA) was applied to grain size data of both beach sediments and SSDs. With an "a priori" criterion, i.e., the results of the EM, DA is employed to group the SSDs in relation to the variables that have greater discriminating power. Data were previously transformed, by using the ranking method, to avoid artifacts due to the closure to 100 of grain size data [58].

3.4. Assessment of the Availability of SSDs

To assess the availability of SSDs grouped by the DA, a partitioning of the area in which the deposits are located was realised. A square grid of 4 km on each side was considered. Each square includes an area of 16 km^2 which is equivalent to 1.6 10^7 m^3 of available sediment, with at least 1 m of thickness. The minimum thickness of 1 m was measured through the analysis of seismic surveys previously performed in the study area [22]. A specific type of sediment was assigned to each square based on the number of samples falling inside and on their statistical classification. SSDs were considered available if at least 5 stations fell into the square. Moreover, the assignment of single square to a specific DA group was carried out when at least half of the samples fell into a single group.

4. Results

4.1. Beach Geomorphology and Littoral Cells

A total of 7 littoral cells were identified (Figure 2 and Table 1). Each cell is separated by the adjacent one by the opposite ways of the longshore directions of the mean wave energy flux (MWEF). The MWEF directions (as they were reported by [51,52]) were showed in Figure 2. The MWEF diverges in correspondence of three headlands: Cape Mannu, Cape Sa Sturaggia and Cape San Marco. The other headlands (Cape Sali and Cape Seu, Figure 2) and lagoon inlets separate beaches which were characterised by sediments with different composition (Table 1).

Cell A include Is Arenas beach, a large beach characterised by a wide dune field. The MWEF and the related longshore sediment transport directions are oriented from SW to NE. A small river flows into the northern sector of the beach (Figure 2). Sediments are mixed gravelly sands and origins from the reworking of riverine sediments and biogenic sediments derive from coastal ecosystems facing the beach (Table 1). Sediment colours are light yellowish and pale brown (Table 2).

Table 2. Colours of the cells and sub-cell together with the colours of the SSDs groups identified by the DA.

Cell	Sub-Cell	Munsell Colour Description	Munsell Colour Code
A	1	Light Yellowish/Pale Brown	10YR6/4–10YR6/3
B	2	Light Grey/Pink	10YR7/2–7.5YR7/3
	3	Pink	7.5YR7/4
C	4	White/Light Grey	10YR8/1–10YR7/1
	5	Light Grey/White	10YR7/1–10YR8/1
D	6	Pinkish Grey/White	7.5YR7/2–7.5YR8/1
	7	Pinkish White/White	7.5YR8/2–5YR8/1
	8	Pinkish Grey/White	7.5YR7/1–7.5YR8/1
E	9	Pale Brown/Light Brownish Grey	10YR6/3–10YR6/2
F	10	Light Brownish Grey/Pale Brown	10YR6/2–10YR6/3
G	11	Ligth Grey/Pale Brown	10YR7/2–10YR6/3
	12	Grey/Ligth Grey	10YR6/1–10YR7/2
SSDs Groups			
	G1	Reddish Yellow/Very Pale Brown	7.5YR6/6–10YR7/4
	G2	Light Grey/Very Pale Brown	10YR7/2–10YR7/3–10YR6/2
	G3	Very Pale/Ligth Brown	10YR7/4–10YR7/3–10YR6/3
	G4	Reddish Yellow/Ligth Brown	7.5YR6/6–7.5YR6/4–10YR6/4

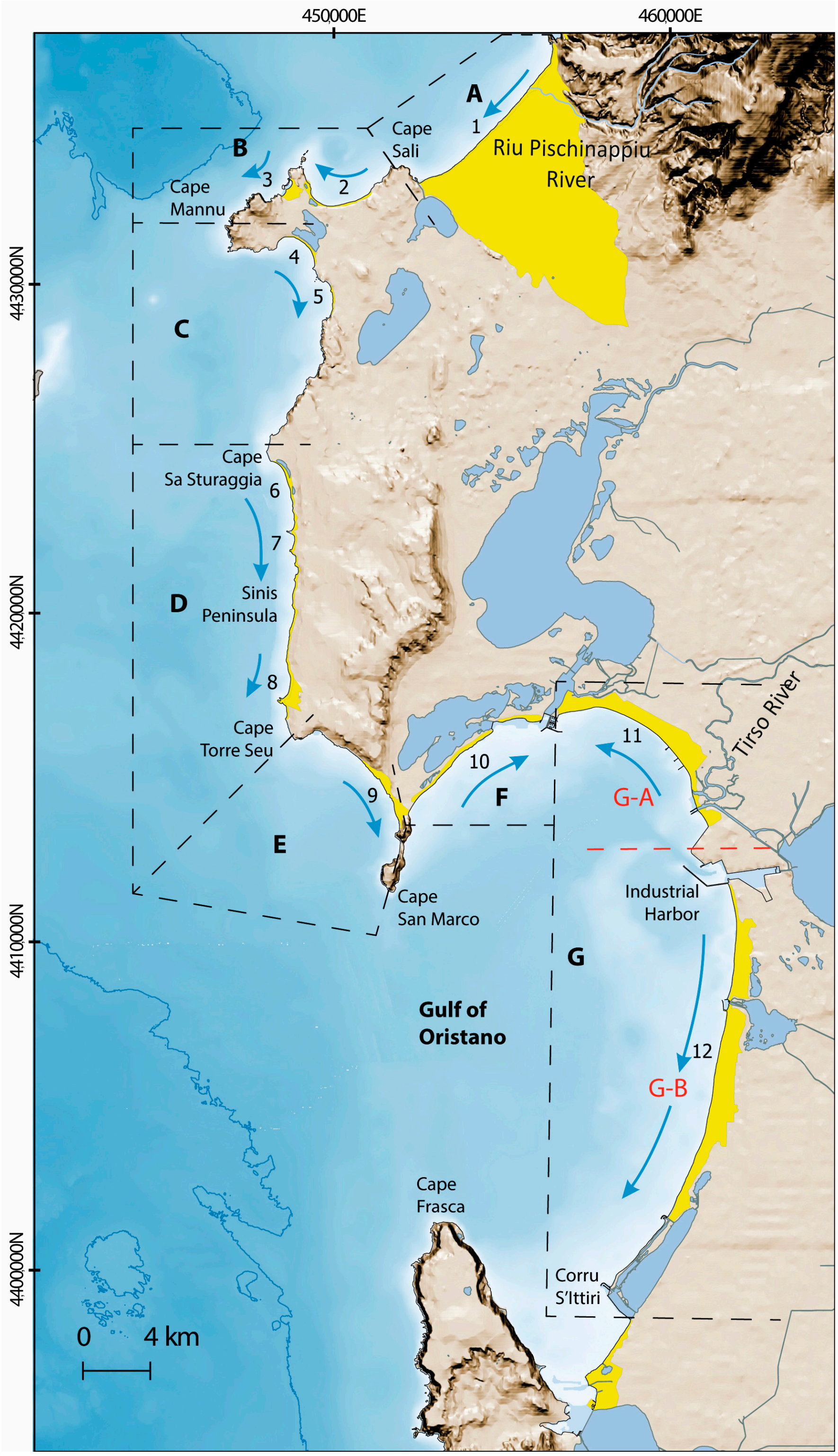

Figure 2. Coastal littoral cells as defined in the present study. (**A**–**G**): cells or primary compartments. 1–12: beach areas or sub-cells. Blue arrows: longshore sediment transport direction.

Cell B extends from Cape Sali to Cape Mannu (Figure 2). The MWEF is oriented from west to east [52]. Two beaches are enclosed in this cell (Sa Rocca Tunda and Sa Mesa Longa, Table 1; numbers 2 and 3 in Figure 2). Beach sediments are mixed sands, with a predominant biogenic carbonate component: they derive from ecosystems production and cliff erosion, while there is not any contribution from rivers (Table 1). Colour of sediments for these beaches are light grey to pink (Table 2).

Cell C extends from Cape Mannu to Cape Sa Sturaggia and enclose two beaches (Putzu Idu and S'Arena Scoada, Table 1; numbers 4 and 5 in Figure 2). The MWEF is oriented to the south. Putzu Idu Beach is a barrier–lagoon system while S'Arena Scoada beach is bordered by a cliff. Sediments are medium-fine sands with a dominant siliciclastic component. Sediment colour is light grey and white (Table 2).

Cape Sa Sturaggia is the boundary among Cells C and D. The MWEF flux is oriented to the south [51]. Cell D enclosed three beaches. Mari Ermi (Table 1, number 6 in Figure 2) is a barrier–lagoon system, Is Arutas (Table 1, number 7 in Figure 2) is an embayed beach and Maimoni (Table 1, number 8 in Figure 2) is a barrier/beach–dune system. The sediment composition deriving from the mixing of coarse siliciclastic sediments and finer bioclastic sediments (Table 1, [23]). The siliciclastic component of the sediments is formed by gravels and coarse sands, the biogenic components is formed by medium-fine sands. Sediment colours are pinkish, grey, and white (Table 2).

Cell E is located between Cape Seu and Cape San Marco. The MWEF flux is oriented to the south [51]. The San Giovanni beach (Table 1, number 9 in Figure 2), located in this cell, is a semi-constrained beach and dune system [33,54]. Sediments of this cell are mainly sand and slightly gravelly sand and are characterised by the prevalence of bioclastic components deriving from ecosystem carbonate-producers ([33], Table 1). Sediment colours are pale brown and light brownish grey (Table 2).

Two cells can be identified inside the Gulf of Oristano (Figure 2). Cell F extends between Capo San Marco and the inlet of the Cabras lagoon. The beach of Su Siccu, located in cell F (Table 1, number 10 in Figure 2), is a barrier enclosing a wide lagoon and is composed by fine mixed siliciclastic and carbonate biogenic sands (Table 1). Sediment colours are light brownish grey and pale brown (Table 2).

The inlet of Cabras lagoon marks a drastic change of sediment composition, separating cells F and G. Cell G is the main cell of the Gulf of Oristano. The system is characterised by a wide beach, running for several km from the north to the south of the Gulf. The cell is interrupted by the industrial Port of Oristano that subdivide the main cell in two sub cells: Ga and Gb. The mouth of the Tirso river is part of the southern area of the cell Ga (Figure 2). The flux is from SE to NW in cell Ga, whereas in Gb is from north to south [51]. Sediments of this cell range from gravelly sand to sand, they are siliciclastic, with lack of mixed and carbonate sediments and originate from river supply and reworking of alluvial deposits (Table 1 [29]). Sediment colours are light grey, grey, and pale brown (Table 2).

4.2. SSDs vs. Beach Sediments

The grain size data and carbonate content of sediment collected over the SSDs located in the central western continental shelf of Sardinia are reported in Table S1 (Supplementary Materials). Multivariate statistical techniques were applied to classify beach and SSDs sediment samples into sedimentary facies to distinguish sample groups both from grain size and compositional characteristics. Different steps of data analysis were applied due to the mixing nature of the sediments (siliciclastic and carbonate).

In order to better understand the role of grain size distributions rather than single grainsize intervals EM analysis was applied to the raw data of beach sediments samples (Figure 3). Eleven intervals per sample were used and the main result of this kind of statistical representation indicated the best grouping solution in four groups. The four groups of distributions resulting from the entropy analysis are displayed in Figure 3. The groups are numbered from 1 to 4, the standard deviation are 1.84 phi and 1.97 phi for groups 1 and 2, respectively; and 1.69 phi and 2.75 phi for groups 3 and 4. Skewness for groups 1 and 4 is negative (−0.54 and −1.70, respectively), whereas it is positive for groups 2 and 3 (0.82 and 0.34, respectively).

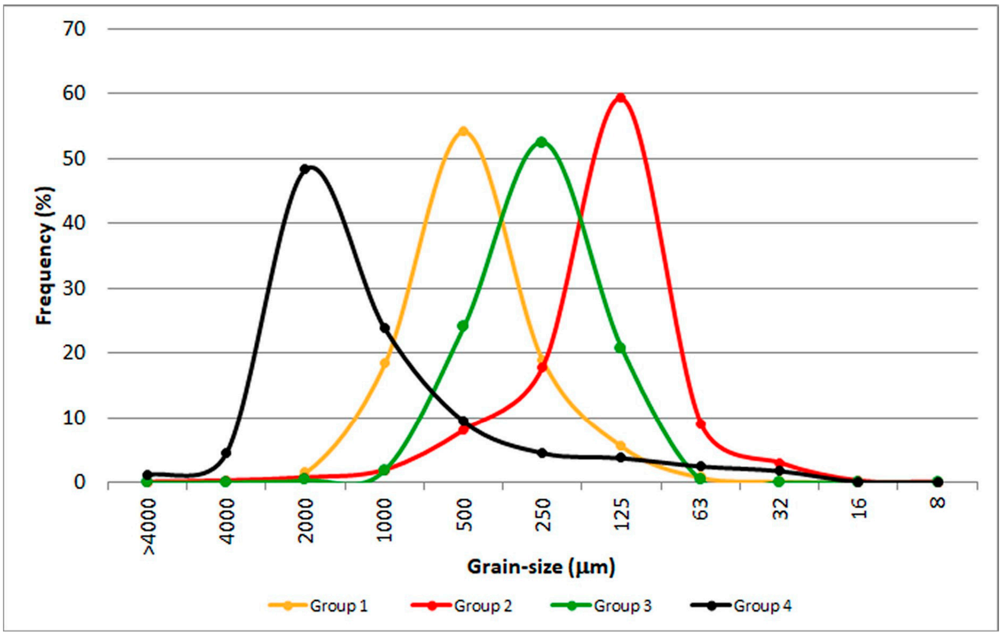

Figure 3. Mean grain size distribution groups (textural facies) in the beaches of the study area derived from EntropyMax.

The grain size characteristics corresponding to the four groups are as follows: (1) a slightly gravelly sand, with a mode at 500 µm (coarse sand); (2) a slightly gravelly sand, with a sand mode 125 µm (from medium to fine sand); (3) as lightly gravelly sand, sandy gravel and sand with a mode at 250 µm (medium sand); (4) a gravel, sandy gravel and gravelly sand with a mode at 2000 µm (from very fine gravel to very coarse sand).

To evaluate the similarity between the grain size of beach sediments and the grain size of submerged sediment deposits (SSDs) a Discriminant analysis (DA) was applied to the 4 groups pre-defined by the EM and to the grain size data of SSDs. The SSDs were initially included as unknow samples; the DA is a statistical procedure able to classifies unknown samples and the probability of their classification into a certain group. The results of DA for the 293 samples are summarised in Figure 4, in which discriminant scores are scatter-plotted for the two discriminant functions.

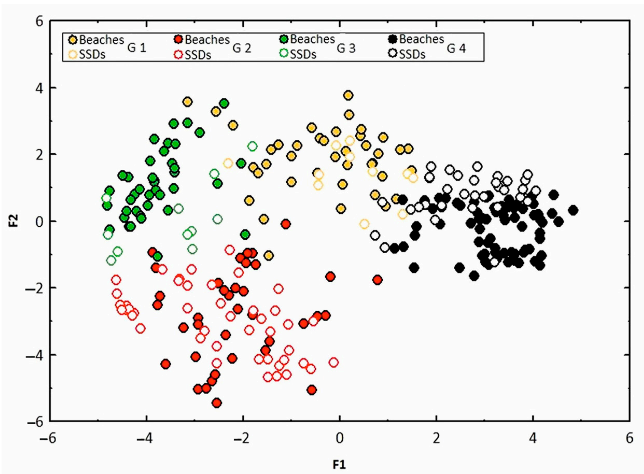

Figure 4. *Cont.*

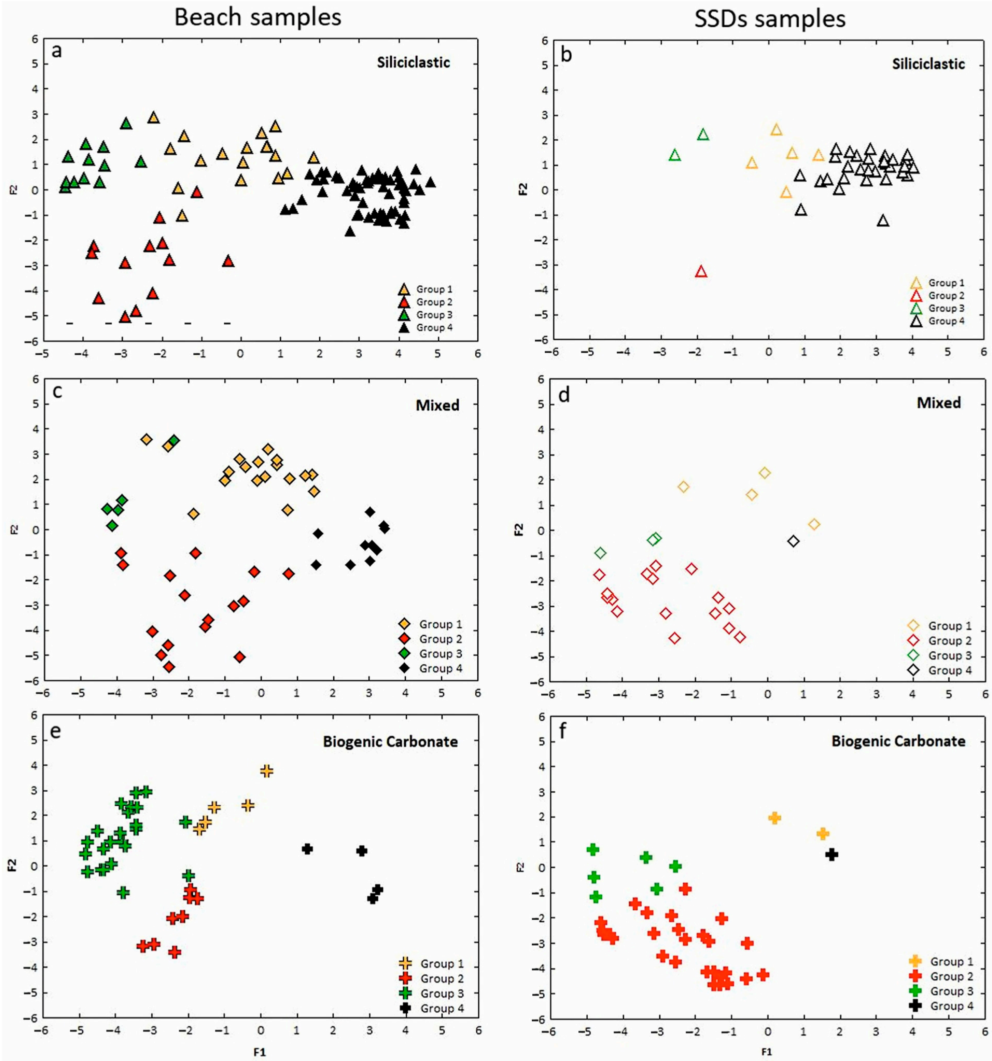

Figure 4. Discriminant score scatterplot for two discriminant functions: classification of 4 groups of sediment samples obtained by EM analysis (see Figure 2) and the unknown SSDs. Discriminant variables are: 4000 µm, 2000 µm, 500 µm, 250 µm, 125 µm, and 63 µm; (**a**) discriminant score scatterplot for two discriminant functions for siliciclastic beach sediments; (**b**) discriminant score scatterplot for two discriminant functions for siliciclastic SSD sediments; (**c**) discriminant score scatterplot for two discriminant functions for mixed beach sediments; (**d**) discriminant score scatterplot for two discriminant functions for mixed SSD sediments (**e**) discriminant score scatterplot for two discriminant functions for biogenic carbonate beach sediments; (**f**) discriminant score scatterplot for two discriminant functions for biogenic carbonate SSD sediments.

Six variables significantly contributed to the separation between the groups and two Discriminant functions explain 96% of the total variance of the samples. Function 1 explained 73% of the total variance and Function 2 explained 23% of the total variance.

The grain size fractions with greater discriminating power were: (a) the very fine gravel, the very coarse and fine sand fractions (4000–2000, 2000–1000, and 250–125 µm) for function 1, separating especially groups 4 from 2 and 3 and slightly from group 1; (b) the medium, very fine sand and coarse silt (500–250, 125–63, and 63–32 µm) for function 2, which clearly separates group 2 (negative values) from groups 1, 3, and 4 (positive values). Table 3 summarises the results.

Table 3. Group means of the discriminating elements for each function.

Group	4000 mm	2000 mm	500 mm	250 mm	125 mm	63 mm
1	3	5	44	20	6	1
2	0	1	6	18	54	18
3	0	0	20	50	28	1
4	6	31	15	10	8	2

In Figure 4, together with the result of the DA, the biogenic carbonate content for each group of beaches and SSDs samples is also shown (Figure 4a–f). The siliciclastic (0–20% carbonate) sediments are mostly concentrated in group 4 both in beaches and SSDs samples with prevailing fine gravel and very coarse sands. Siliciclastic sediments are also present in beaches of groups 1, 2, and 3. Only few samples from the SSDs sediments are reached in siliciclastic components in groups 1, 2, and 3 (Figure 4a,b). The mixed (20–60% carbonate) carbonate/siliciclastic sediments in beach samples are scattered in groups 1 and 2 with prevailing medium and very fine sand few samples are accounted also in groups 3 and 4. Mixed sediments include several SSDs samples of group 2, while there are only few in groups 1, 3, and 4 (Figure 4c,d). The biogenic carbonate (60–100% carbonate) sediments are mainly present in beaches and SSDs sediment samples in groups 2 and 3 with prevailing the finer fractions, whereas there are few samples of both beaches and SSDs clustered in groups 1 and 4 with high biogenic carbonate contents (Figure 4e,f).

The compatibility analysis between beaches and SSDs sediments Is shown in Figure 5. The Figure 5 (Panels 1-A, 2-A, and 3-A) shows the location of the beach sediment samples split into 4 grain size groups identified by the multivariate statistical analysis (G1, G2, G3, and G4) and belonging to the three compositional groups based on the calcium carbonate content (siliciclastic: 0–20%, mixed: 20–60%, and biogenic carbonate: 60–100%). Figure 5 (Panels 1-B, 2-B, and 3-B) shows the location of the SDDs samples divided into the 4 grain size groups (G1, G2, G3, and G4) and their belonging to compositional groups described above. In Panels 1-B, 2-B, and 3-B, a grid of 4 km of side was superimposed to the map, and this was useful to assess the availability of SSDs to a specific group based on the number of samples falling inside each square of the grid (see Section 3 for the description of the criteria used).

The beaches characterised by siliciclastic sediments (0–20%) are mainly located in cells D, western sector of the Sinis Peninsula and G, Gulf of Oristano (Figure 5, Panel 1-A). Sediments of cell D fall predominantly in group G4 and partially in group G1 (sub-cell 8). Sediments of cell G are heterogeneous: all the four groups are present in sub-cell 11, while 3 groups (G1, G2, and G3) are present in sub-cell 12. The SSDs characterised by siliciclastic deposits fall almost exclusively in group G1 (Figure 5, Panel 1-B). Two squares grid (Figure 5, Panel 1-B) contain 5 stations belonging mainly to group G4. With regard to grain size and compositional compatibility, it was highlighted that beaches of cell D (sub-cells 6, 7, and 8) and one beach of cell G (sub-cell 11) have a deposit of sediment equivalent in size and composition located in the SDDs.

Beaches characterised by mixed sediments (20–60%) are mainly located in cells A, B, C, and E (Figures 2 and 5, Panel 2-A) in the Sinis Peninsula. Some mixed sediment samples are also present in cell D. The mixed sediments of the beaches are quite heterogeneous and fall into the four groups (G1, G2, G3, and G4, Figure 5, Panel 2-A). The SSDs of mixed sediment fall almost exclusively in group G2 (square highlighted in Figure 5, Panel 2-B). One square grid (Figure 5, Panel 2-B) contains 5 stations belonging mainly to group G2. Concerning grain size and compositional compatibility, it was highlighted that sub-cells 2, 4, and 5 have an equivalent sediment in marine deposits, while sub-cells 1, and 9 have no sediment reserves at sea.

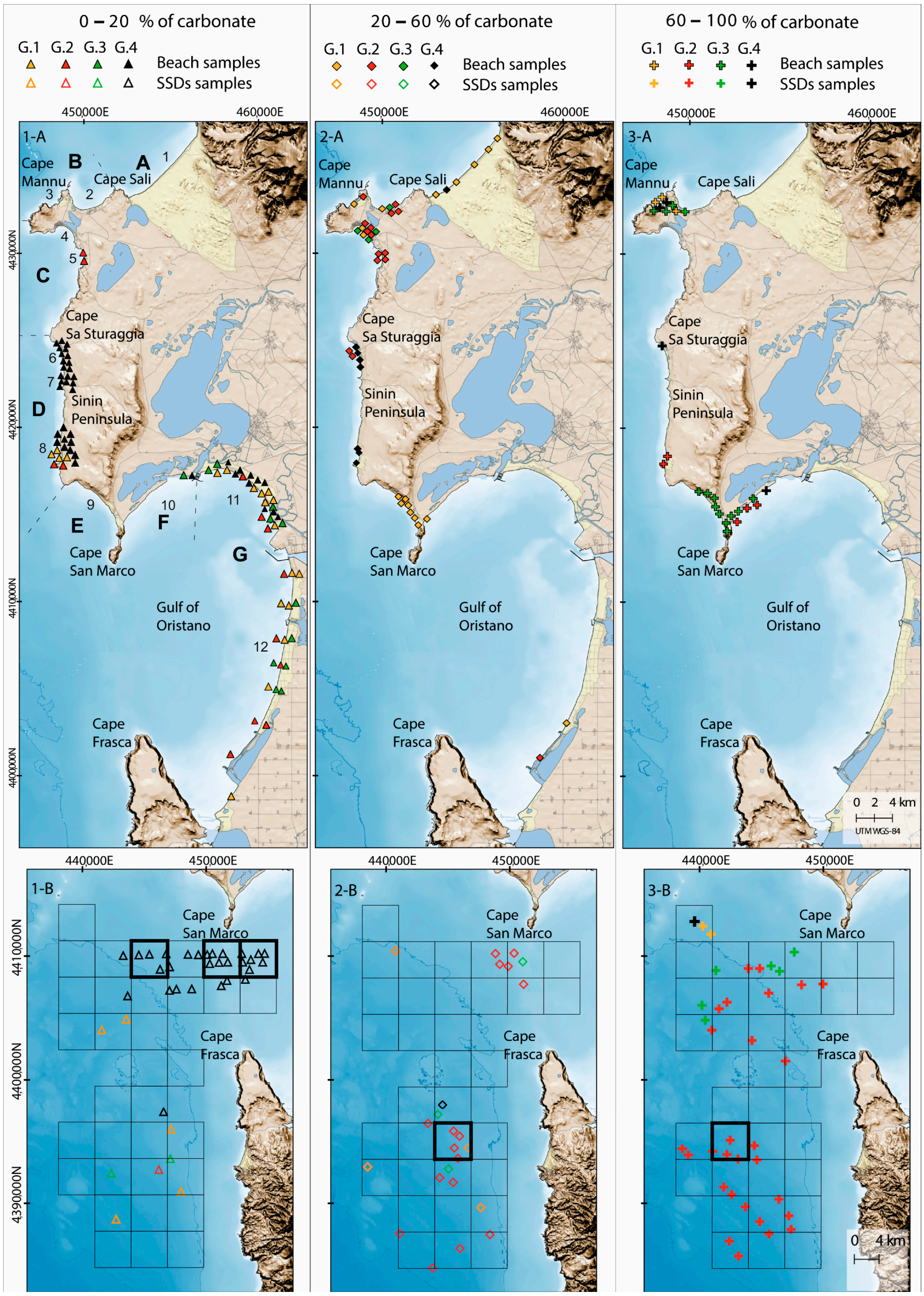

Figure 5. Spatial distribution of both beaches and SSDs sediment samples defined by Discriminant analysis and carbonates content. G1, G2, G3, and G4: Groups identified by Discriminant analysis; 0–20% carbonate: siliciclastic sediments; 20–60% carbonate: mixed sediments; 60–100% carbonate: biogenic carbonate sediments. Square (in bold): to assess the availability of SSDs to a specific group (see Section 4 for description). (**1-A**) spatial distribution of siliciclastic beach sediments; (**2-A**) spatial distribution of mixed beach sediments; (**3-A**) spatial distribution of carbonate beach sediments; (**1-B**) spatial distribution of siliciclastic SSD sediments; (**2-B**) spatial distribution of mixed SSD sediments; (**3-B**) spatial distribution of carbonate SSD sediments.

The beaches characterised by carbonate sediments (60–100%) are mainly located in cells B, E, and F (Figures 2 and 5, Panel 3-A) in the Sinis Peninsula and a few in cell D. The sediments of the beaches with carbonate composition fall into all the 4 groups (G1, G2, G3, and G4, Figure 5, Panel 3-A). The SSDs deposits of carbonate sediments fall predominantly in group G2 (Figure 5, Panel 3-B). One square grid (Figure 5, Panel 3-B) contains 4 stations belonging mainly to group G2. Sub-cells 10 has an equivalent sediment in marine deposits, while sub-cells 3 and 9 have no sediment reservoir at sea.

Beach sediments and SSDs were also characterised by colour. Table 2 shows the colours of each littoral cell and sub-cell (corresponding to the beaches) together with the colour of SSDs partitioned in groups identified by the DA.

The sediments of the beaches are characterised by light colours (light grey, light yellowish, pale brown, white, pink, etc., Table 2). Regarding the sediments of SSDs, two sediment groups (G1 and G4) are characterised by reddish/yellow colours, while the remaining two groups (G2 and G3) are characterised by light colours (light grey, light brown, and very pale brown; Table 2).

The results of the grain size and compositional compatibility analysis are summarised in Table 4.

Table 4. Summary of the availability of compatible sediments from strategic deposits for each beach taking in account the grain size, the composition, and the colour properties.

Cell	Sub-Cell	Grain Size /Composition	Colour
A	1	No	No
B	2	Yes	No
	3	No	No
C	4	Yes	No
	5	Yes	No
D	6	Yes	No
	7	Yes	No
	8	Yes	No
E	9	No	No
F	10	Yes	Yes
G	11	Yes	Yes
	12	No	No

Out of 12 beaches analysed, 8 beaches have a deposit of marine sediments of similar grain size and composition, while 4 beaches have none. However, the beach sediments of cells B, C, and D are characterised by very light colours with shades from white to pink (Table 4), while marine sediments have yellow/reddish or brownish colours. Therefore, it is possible to state that, taking into consideration also the colour, only two beaches (sub-cell 10 and 11) have compatible sediments in the SDDs (Table 4).

5. Discussion

The adaptation strategy against coastal erosion and coastal flooding can be summarised in four main approaches as listed by Linham and Nicholls [59] and modified by Masselink and Russel [16]: hard protection, soft protection, accommodate and retreat. To better understand which approach might be useful to increase (decrease) the resilience (vulnerability) of a beach and dune system in relation to the climate change effects and to coastal erosion in general the knowledge of the SSDs in terms of availability and compatibility of sediment would be achieved. In a recent study Pranzini et al. [60] investigated a large tract of Italian coastline and propose actions at local and regional scale to counteract effect of coastal erosion considering colour compatibility and sediment budget. This approach allows to explore, and in some case promote, the utilisation of the soft protection approaches to counteract coastal erosion and the effect of climate change along sandy shoreline.

In this framework, the availability of compatible strategic sediment reservoirs is crucial for the planning of soft protection approaches, in particular beach nourishment and dune reconstruction, but also for the sediment management along coastal areas [61]. The analysis of sediment similarity is primarily based on grain size characteristics [62] which is the most important physical variable for the design of a nourishment intervention. General recommendation for borrow sand is: "a nourishment should use fill material with composite media grain diameter equal to that of one of the native beach materials" [62]. This approach could be not suitable in case of polymodal grain size distribution, as occurred along the studied area [23,33]. Different methods can be adopted to determine the similarity of sediment grain size data based on the comparison of statistical moments, specific percentiles, indexes based on the whole grain size spectra [61]. Pranzini et al. [61] introduce the Stability index based on grain size characteristics of native and borrowed sand. The ratio is to ensure a good stability to the borrowed sand, this sand should be coarser than the native sand. The new approach proposed in this study, based on multivariate statistics, has the advantage to consider the whole grain size spectra enabling to compare sediments with a particle size distribution that diverges from the normal Gaussian distribution (i.e., multimodal distribution), originating from the mixture of different populations. The multivariate analysis was able to highlight a good grain size compatibility between the sediments of the beaches and those of the SSDs. Whereas the method proposed by Pranzini [61] has the advantage to provide an indication on the extent of the nourishment project, the approach followed in the present study is mainly focused on the similarity between native sediment and sediment available along the continental shelf that can be used to counteract coastal erosion. This is realised analysing the whole grain size spectra, for both: native and potential borrow sediment.

The mineralogical composition and the colour of the grains determine the aesthetic appearance of the sediments. Beach colour is a primary component of the coastal landscape [63,64] and is determined both by mineral type and/or rock fragments present (e.g., [65,66]) and/or by organic fragment occurrence (e.g., [67,68]) which are frequently mixed in different proportions (e.g., [69,70]).

The colour may influence the selection of holiday sites by summer guests; indeed, tourists' preferences are for white and golden sand [71], with a progressive dislike of the beach as sand becomes darker in colour [63]. The perception of beachgoers is relevant on the success of a nourishment project. The example of nourishment from the Sardina Island highlight, as it was very criticised by local public for the colour and for the grain size of the borrowed sand [36]. Indeed, the colour of sediment beach is very important for the beachgoers in the choice of the beach [47].

Along our study area 12 beaches enclosed in 7 littoral cells were characterised in terms of grain size, composition and colour of sediment and the comparison of sediment characteristics among beaches and SSDs deposits was highlighted in Table 4. The table shows that compatibility of sediments in terms of grain size and composition occurred for most of the studied beaches (8 out of 12). When the colour data were added to the analyses only few beaches (2 out of 12) showed chromatic compatibility with the SSDs. Therefore, the use of sediments from the SSDs for beach nourishment would entail a drastic change in the appearance of the beaches with the replacement of light-coloured sediments (white and pink) with reddish and yellowish one.

The source to sink process of SSDs and beach sediments are quite different, thus producing marked differences in sediment grain size, composition, and therefore in chromatic appearance. The sediments deposited along the beaches bordering the Sinis Peninsula and the Gulf of Oristano derive from three sources: (i) the riverine input, (ii) reworking of relict sediments of the inner shelf and (iii) biogenic carbonate production associated to coastal ecosystems.

Two main rivers feed sediments to some of the studied beaches. The small Pischinappiu River, flowing in Is Arenas beach (cell A) (Figure 2) drains a basin composed by volcanics, and Tertiary marls and limestones. The Tirso River flowing in the Gulf of Oristano (cell G) (Figure 2), drains a large catchment basin including the Palaeozoic crystalline basement (granite and metamorphic), volcanics and sedimentary rocks.

The bioclastic sediments feed the beaches of cells A-F (Figure 2) and derive from the production of carbonate shells associated with seagrass meadows [33,72,73]. These sediments are mixed, in various proportions, with the terrigenous siliciclastic sediments of transgressive origin that derive from the reworking of relict sediments deposited on the continental shelf [23,74]. The presence of rocky outcrops along the beaches and in the sea area determines the compartmentalisation of the coastal area in several sedimentary cells similarly to what happens in other coastal areas with complex geomorphology [24]. Consequently, the composition of beach sediments varies from one beach to another.

The sediments of the SSDs along the continental shelf are composed of two distinct deposits: (i) sediments of alluvial origin, re-worked during the transgressive phase related to the last sea-level rise, which derive from the catchment area of the Tirso River [28,32,34]; and (ii) a veneer of mixed and bioclastic sediments deriving from the erosion and transport of biogenic sediments produced in the carbonate factories distributed along the shelf (seagrass meadows and coralligenous assemblages [75,76]). The SSDs are present on the form of depositional terraces, which formed during the last rise in sea level [31]. The shelf is typically starved [77] and high-stand deposits are confined in proximity of the Tirso River mouth and the beach wedges [22,28].

To counteract the effect of climate change and of coastal erosion along shores the coastal management plans should include the potential strategy that can be adopted to minimize these effects. These strategies would also include the compatibility analysis of beaches and SSDs sediments. Indeed, as our study highlights, not even the SSDs can provide adequate compatible sediment in terms of grain size, composition, and colour. Consequently, the beaches may not have sufficient strategic sediment reservoirs to cope the climate change effects adopting soft protection approach (sensu [16]). Indeed, in the case of beaches in which compatible sediments are not available, or in which the use of available sediments would drastically change the landscape aspect of the beach it will be necessary explore approach oriented to favour the adaptation and retreat options of coastal infrastructures [15,16] over protection interventions by nourishment in the coastal management plans.

6. Conclusions

To counteract the effect of climate change and coastal erosion, the characterisation of beach sediments and the characterisation of the strategic sediment reservoirs (SSDs) is crucial to plan and promote an adaptation strategy.

A sediments compatibility study was performed (i.e., grain size, composition, and colour) among 12 beaches partially geologically constrained, and the strategic sediment deposits (SSDs) highlights the importance this assessment to address management strategies aimed at decreasing the vulnerability of sandy shores towards coastal erosion and sea level rise.

The results of the present study highlight:

1. A novel approach was presented to compare beach and SSDs sediments. The adopted method was based on multivariate statistics and applied to whole grain size spectra to assess the compatibility between the SSDs and the sediments of adjacent beaches. This methodology can be applied to sediments with a multimodal distribution, originating from the mixture of different populations. This new approach might be applied to other beaches mainly conditioned by geological control.
2. The compatibility of sediments in terms of grain size and composition occurred for most of the studied beaches, 8 out of 12. Additionally, considering the sediment colour, only 2 out of 12 beaches showed chromatic compatibility with the SSDs.
3. The source to sink process of SSDs and beach sediments are quite different, thus producing marked differences in sediment grain size and composition therefore, in

chromatic appearance. This is due to the compartmentalization of sediments cells resulting in a high variability of beach sediment grain size and composition.

4. Adaptation and retreat options of coastal infrastructures over protection interventions would be necessary to counteract coastal erosion when compatible sediments are not fully available.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14233971/s1: Table S1: Sedimentological dataset.

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