Classification Scheme for Geomorphosites' GIS Database: Application to the Proposed Geopark *Costões e Lagunas*, Rio de Janeiro, Brazil

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Abstract

The inventory of geosites is the first step for the establishment of geoconservation strategies. Especially when dealing with large and geodiverse territories, organising the inventory under a systematic database may be a difficult task. The definition of geological frameworks and a clear classification scheme for the sites are valuable tools within this context, since they standardise the insertion of sites and allow, for instance, the creation of selection filters by attributes. The objective of this work is to propose a classification scheme for geomorphosites in the territory of the proposed geopark *Costões e Lagunas* (Portuguese for Cliffs and Lagoons), in the east and north coasts of Rio de Janeiro State, Brazil. The territory embraces 16 municipalities, with a total area of about 10 thousand km^2. Due to the high geodiversity, the territory has geosites representing several typologies (e.g. tectonic, petrological, speleological, palaeoenvironmental, geomorphological, hydrogeological), which are the basis for the definition of frameworks for the inventory of geosites. Within the framework of geomorphosites, some specific issues had to be tackled because this category presents some peculiarities: the imbrication of spatial and temporal scales, and the dynamic and aesthetic dimensions. Our classification proposal is based on the acknowledgment of these peculiarities, being divided into three major keys: spatial, thematic and temporal. First, due to the imbrication of spatial scales, the geomorphosites had a spatial classification, being represented as points, lines or surfaces and considering the number of different forms and related processes, being considered single landform, group of landforms, geomorphological complex or geomorphological system. Second, the geomorphosites had a thematic classification, divided into forms (e.g. fluvial terraces, coastal dunes, coastal massifs) and processes (e.g. aeolian, fluvial, coastal, tectonic). And third, the temporal classification was included, in which the geomorphosites are classified as active, as inactive or as evolving passive geomorphosites, considering the dynamic dimension. This classification scheme showed to be appropriate for organising a GIS database considering the peculiarities of geomorphosites.

Keywords Geoconservation · Inventory · Specificities · Framework

Introduction

Geoconservation has been significantly growing in importance during the last decades and it is now recognised as a new geoscientific domain (Brocx and Semeniuk 2007;

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Henriques et al. 2011; Brilha 2017). Initiatives for the protection and promotion of geoheritage are emerging all around the planet and societies are starting to be more aware about the relevance of geodiversity in our lives (Reynard and Brilha 2018). The growing importance of geoconservation is being followed by constant improvements in methodological aspects and, within this context, the methods for inventorying and assessing geosites are highlighted.

The definition of geosites is still a topic of discussion. Brilha (2005) defined geosites as geological occurrences presenting undeniable scientific, educational, cultural, touristic or other types of values. Brilha (2016) suggested the use of the term to refer to geological sites with scientific relevance. Sites presenting other sets of values should be termed geodiversity sites. The author also stressed the importance of using different methods for inventorying and assessing geosites and geodiversity sites. However,

other authors use the term geosites not only for sites with scientific relevance, following definitions such as the one proposed by Panizza (2001), in which geosites are in situ occurrences presenting specific values (scientific, ecological, economic, cultural or aesthetic) due to human perception or exploitation.

Nonetheless, geosites have different use potentials according to the values they present. It means that the methods used for inventory and assessment must be appropriate; otherwise, the results may present problems (Lima et al. 2010). Besides presenting different sets of values, geosites also present different categories: lithological, hydrological, geomorphological, palaeontological etc. Geosites in different categories may present quite different characteristics, which can demand specific approaches.

Geomorphosite is the term used to refer to geosites of geomorphological relevance (Panizza 2001; Reynard 2009). This is a relevant category because it presents specificities when compared to other categories, such as the imbrication of spatial and temporal scales; the dynamic dimension; and the aesthetic dimension (Reynard 2009). Santos et al. (2019) tested the influence of these specificities in the assessment, concluding that methods applied to geomorphosites should consider these specificities; otherwise, the results would not be satisfactory.

Inventories of geosites are recognised as a basic tool for geoconservation strategies because they allow the identification of geosites and the recognition of their values, justifying their needs of conservation and substantiating proposals for scientific, educational and geotouristic uses. For being a fundamental tool for geoconservation, inventories need to be done through reliable methods (Brilha 2018).

Especially in large and geodiverse areas, organising a database of geosites to develop inventories is a challenge. Within the context of the Geosites Project, which had the intention of selecting world-class geosites based on frameworks, Garcia-Cortés et al. (2001) presented a list of geological frameworks to organise an international inventory of geosites. Brilha (2016), following this idea, proposed that, for large areas, the inventory must be divided into frameworks according to the different themes present in the study area. The present work is part of a bigger project, that is the inventory of geosites of the proposed geopark *Costões e Lagunas* (Portuguese for Cliffs and Lagoons), in Rio de Janeiro, Brazil. For presenting specificities that influence the assessment procedures, geomorphosites were chosen as a framework.

The first step in creating an inventory is the identification of potential geosites (according to several proposals, such as Pereira and Pereira 2010; Brilha 2016; Reynard et al. 2016; Santos et al. 2020; amongst others). In this step, a clear classification of the selected sites is essential to make the entire process more efficient. Due to the specificities

of geomorphosites, a specific classification scheme was demanded. The objective of this work was to propose a classification scheme for geomorphosites that could be applied in any geomorphological context, considering the specificities and the creation of the database in GIS environments. The scheme was applied in the territory of the proposed *Costões e Lagunas* Geopark, located in Rio de Janeiro State, Brazil.

Study Area

The area of the proposed geopark *Costões e Lagunas* embraces sixteen municipalities in the north and southeast coasts of Rio de Janeiro State, with around 10,900 km^2 (Fig. 1). It is a very geodiverse area, embracing coastal and continental landscapes, and presenting geosites of great relevance in different categories (tectonic, lithological, geomorphological, hydrological, etc.). It also presents many sites with ecological and cultural relevance (geosites or not) and hosts some of the most important touristic destinations of Rio de Janeiro State, some receiving a significant number of international tourists every year.

The geological heritage of the area registers events from the Palaeoproterozoic to the Holocene and several inventories of geosites, with different purposes, were created in the last decades, including the geomorphosite inventory presented in Santos et al. (2020), which was used in the present research. Besides Santos et al. (2020), other inventories were developed focusing on other aspects such as petrography, tectonics and cultural value. These inventories were not part of this work since they are not dealing with geomorphosites and their specificities. More than two hundred sites were already identified in the geopark territory, considering all typologies.

From a geomorphological perspective, the area is characterised by a large double-barrier lagoon system in the southern coast, where the internal barrier is of Pleistocene age and the external was developed during the Holocene (Martin et al. 1996). The coastline has an East–West orientation in this portion. After the inflection of the coastline, where it becomes South-North oriented, there is an alternance between smaller beach arcs and coastal massifs.

The coastal massifs were uplifted in a tectonic event related to the opening of the Atlantic Ocean, after the breakup of Gondwana. Between the Upper Jurassic and Lower Cretaceous, rifting processes took place, generating parallel mountain ranges divided by valleys, in the format of hemigrabens (Asmus and Ferrari 1978; Zalán and Oliveira 2005). The region is also marked by the presence of two alkaline massifs generated in a magmatic event when the South American plate was affected by a hotspot (Thomaz-Filho et al. 2005).

Fig. 1 Location of the study area—proposed geopark *Costões e Lagunas* (Cliffs and Lagoons)
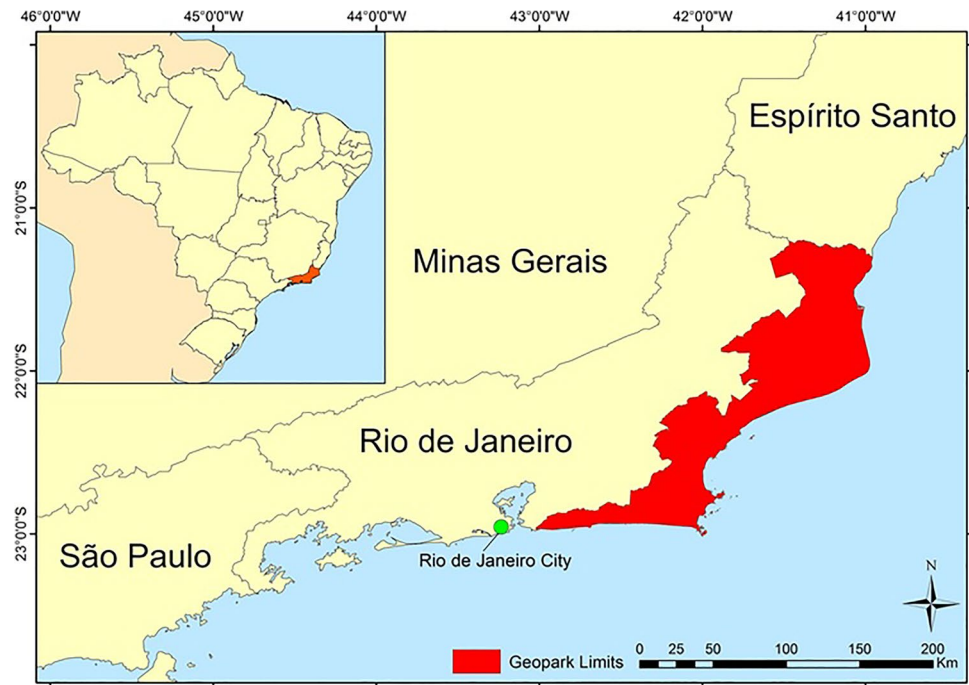
Finally, the northern portion of the coastline is characterised by large sedimentary deposits related to sea level variations during the Quaternary and by the influence of the *Paraíba do Sul* River, which was responsible for the formation of a wave-dominated delta. Rocha et al. (2019) describes that the coastal plain in this portion of the area is composed by beach ridges of different ages. These features are commonly found in areas influenced by sea level variations and sediment supply, marking palaeoshorelines. North of the delta, there is also the presence of cliffs formed by marine erosion on sedimentary rocks.

Therefore, the area is marked by a great geomorphological diversity, with coastal environments presenting different characteristics and coastal massifs 'emerging' in the coastal plains. The geomorphological history embraces tectonic events related to the opening of the Atlantic Ocean and, more recently, sea level variations that were responsible for the main characteristics of the coastal features.

Methodological Procedures

This work is part of a bigger project, that is the elaboration of the inventory of geosites of the proposed geopark *Costões e Lagunas*. In order to organise the inventory, it was divided in several frameworks. It means that the inventory will have a thematic division where different teams and coordinators will be able to develop the work focused on specific topics, making it easier and more efficient. Since geomorphosites present specificities, a decision was made to

create a framework for them. It is important to highlight that this framework could also be divided into frameworks in the future considering aspects related to the geomorphological history of the area.

The method presented in Santos et al. (2020) was chosen to create the inventory of geomorphosites. This method considers the specificities of geomorphosites and was already applied in a portion of the geopark, providing satisfactory results. However, it did not include specific guidelines on how to organise a database of geomorphosites, including not only those that were already assessed, but also potential geomorphosites that may be discovered or that were not yet target of scientific research.

To enhance the potentialities, the database was prepared in a GIS (Geographic Information System) environment. It is important because the use of GIS brings some specific questions on how to organise the spatial and non-spatial data. For instance, the vector files can be points, lines or polygons and classifying the geomorphosites according to this type of geometry requires clear guidelines; otherwise, each person would classify according to their own evaluation and no explanations for the selection would be given.

Therefore, creating a specific classification scheme to organise the geomorphosites' database was considered a necessity.

The specificities of geomorphosites (see Reynard 2009, Coratza and Hobléa 2018 and Santos et al. 2019) were considered the most relevant issues within the topic, especially the imbrication of spatial and temporal scales and the dynamic dimension. These two specificities impose a series

of questions related to the values, potential uses and degradation risks of the geomorphosites. The imbrication of spatial scale also imposes issues for the geometry guidelines in GIS environment.

Geomorphological Contexts

Following Santos et al. (2020), the selection of sites was done by defining the main geomorphological contexts of the area and choosing representative geomorphosites in each of them. However, since the main objective of this step was creating a database of geomorphosites that will be assessed in future steps, the sites were included without rigid criteria. By doing so, the database can be used for creating inventories with different objectives (geotourism, educational fieldtrips, scientific research, etc.). Therefore, the focus now was not to advance in the creation of the inventory, but to create a database following a specific classification scheme, facilitating future inventories.

Due to the geodiversity of the area, a significant number of geomorphological contexts were identified, which was important for the creation of the classification scheme because we had to deal with many different situations. The possibility of applying the same scheme to geomorphosites present in completely different contexts was used to validate the proposal.

The scheme was applied to 28 geomorphosites divided into 10 geomorphological contexts, as displayed in Table 1. The geomorphological contexts were mainly defined according to the morphogenetic processes related to the evolution of the landforms. The exceptions are the islands and mountains and summits contexts, which have the same origin of the coastal massifs (tectonic events in the Cenozoic) but have significant morphological differences.

Coastal massifs were originated by tectonic events during the Cenozoic (inactive nowadays); coastal cliffs are formed due to marine erosion on sedimentary rocks; dune fields

are the result of aeolian processes; rivers and fluvial plains are related to fluvial environments and dynamics; coastal lagoons and palaeolagoons are lagoonal environments in which the evolution is linked to sea level variations during the Quaternary; the double-barrier lagoon systems are also related to sea level variations, being composed of active (formed during the Holocene) and inactive (formed during the Pleistocene) coastal barriers; alkaline massifs are the result of magmatic intrusions during the Paleogene; beach arcs are active coastal sand deposits, presenting intense morphodynamics; and the mountains and summits are related to the Mar mountain range, which is higher than the coastal massifs and located further from the ocean.

Classification Scheme

The scheme was divided into three parts: spatial classification, thematic classification and temporal classification. Figure 2 shows how the classification scheme is organised and what is considered in each part.

Spatial Classification

The spatial classification is the most complex part. In this step, the geomorphosites are classified according to the geometry and the complexity of the forms and processes. Concerning the geometry, it can be points, lines or polygons (surfaces). It does not refer exactly to the forms, but more to how the geomorphological phenomena are expressed in the landscape. For instance, a river could be classified as a line if the intention is to show the format of meanders but could also be classified as a surface if the intention is to show the dynamics of the flood plain.

Considering the complexity of geomorphosites, they can be classified as single landform, group of landforms, geomorphological complex or geomorphological systems. A single landform is when the geomorphosites are representing only one specific landform; a group of landforms is when two or more examples of the same type of landform are present; a geomorphological complex occurs when there are different landforms related to the same process; and a geomorphological system is when the geomorphosite presents several processes and landforms. Figure 3 summarises the spatial classification scheme, being based on Perret (2014) (viewpoints were not included in the present work).

Thematic Classification

The thematic classification is simpler when compared to the spatial classification. The objective is classifying the forms and processes represented in the geomorphosite. It is directly influenced by the spatial complexity since a site can be a single landform or a geomorphological complex or system.

Table 1 Geomorphological contexts and number of sites in each of them

Geomorphological context	N° of sites
Coastal massifs	3
Coastal cliffs	2
Dune fields	4
Rivers and fluvial plains	2
Coastal lagoons and palaeolagoons	3
Double barrier-lagoon system	3
Alkaline massifs	2
Islands	1
Beach arcs	5
Mountains and summits	3

Fig. 2 Classification scheme for geomorphosites
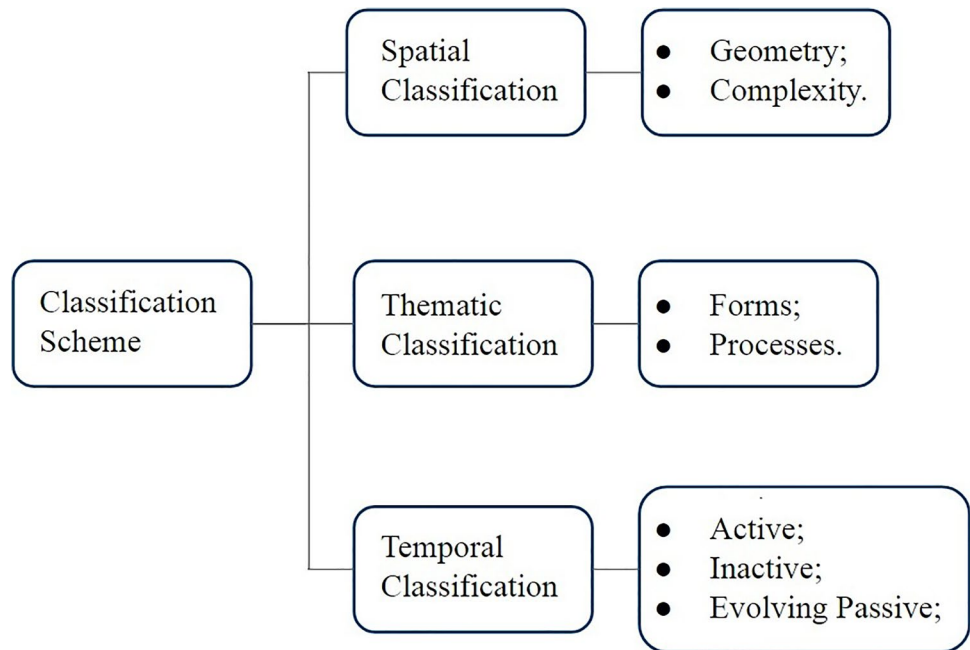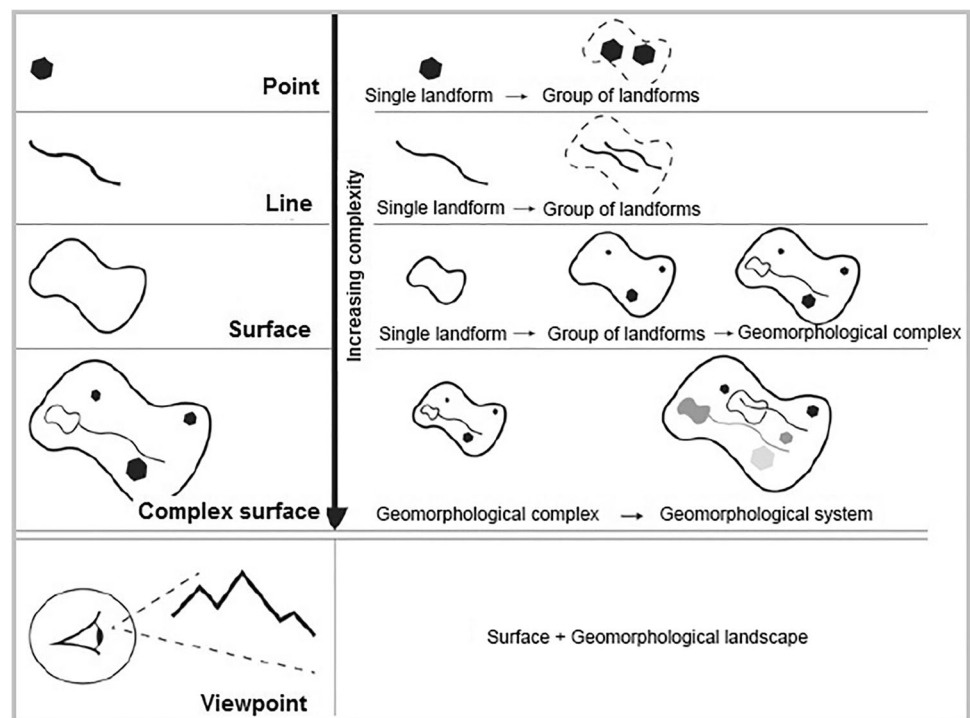

Fig. 3 Scheme for the spatial classification of geomorphosites (translated from Perret 2014)

More landforms and processes create a more complex thematic classification. The thematic classification of geomorphological complexes will be done with the definition of one main process and a list of landforms related to it. The most complex cases are the geomorphological systems, where several processes and landforms are present. Each process and landform must be included in the thematic classification to provide complete information about the geomorphosite.

Temporal Classification

The temporal classification is related to the dynamic dimension of geomorphosites, classifying them as active, inactive or evolving passive geomorphosites.

Active geomorphosites are those presenting the active processes that generated their landforms. Inactive geomorphosites are those that no longer present the processes that

generated the landforms, being inherited landforms related to past tectonic/climatic/geomorphological conditions. It is important to highlight that inactive geomorphosites may present other active processes since there is no static landform. What matters is the fact that the geomorphosite presents inherited landforms and the processes that have originated them are no longer active.

Evolving passive geomorphosites is a classification proposed by Pelfini and Bollati (2014), being applied to geomorphosites that would be classified as inactive but are being rapidly modified by ongoing processes. Therefore, the use of this classification is strongly based on a temporal analysis of how the active processes are modifying the inherited landforms.

Results

The classification scheme was applied to 28 geomorphosites located in different geomorphological contexts, as displayed in Table 2. The diversity of processes and landforms allowed assessing the efficiency of the classification scheme in different situations, which is quite important considering that the scheme was built to be applied in any type of geomorphosite.

Spatial Classification

The spatial classification reflects both the dimensions and complexity of the geomorphosites. It is also fundamental for creating GIS vector files, which require the definition as point, line or polygon, bringing some relevant issues. For instance, one of the geomorphosites present in the inventory of the *Costões e Lagunas* Geopark is the *São João* Hill, which is an alkaline massif located within a coastal plain, being quite remarkable in the landscape. This geomorphosite could be classified as a point—single landform, since it is a punctual occurrence of a hill in a coastal plain, that is a large and flat area. However, due to its dimensions and format, it is easy to delimitate the area and classify it as a surface—single landform geomorphosite (Fig. 4).

The point classification is used when the geomorphosites' dimensions create difficulties in the delimitation of the landform. One example is the geomorphosite Cliffs and Palaeocliffs of *Rasa* Beach, which consists of one active cliff and several punctual occurrences of palaeocliffs that are related to higher sea levels in the past. Cliffs would normally be classified as lines because of their regular format. However, in this particular case, the cliffs were mostly eroded and only a few outcrops of the sedimentary rocks can be seen, making it impossible to draw lines and represent it on a map. Therefore, this geomorphosite was classified as points—group of landforms, since there are several occurrences of the same type of landform (Fig. 5).

To exemplify the line classification, we have the *Conchas* Beach Arc geomorphosite that is a beautiful example of how wave diffraction may be responsible for shaping the coastline. In this geomorphosite, the phenomenon generates a rounded beach arc because of a narrow passage for the waves that come from the open ocean. This geomorphosite was classified as a line because the highlighted feature is the rounded format of the beach (Fig. 6).

Another interesting example of geomorphosite in which the line classification was used is the *Pai Vitório* Point. This site consists of an aligned hill associated with a fault. A belt of cataclasites and tectonic breccia is responsible for a process of differential erosion that generated the peculiar landform. Figure 7 shows the line representation of the geomorphosite and two photos that allow the observation of the aligned ridge. It is interesting to note that the fault continues along the ocean, and it is possible to see the fault scarp in the island. Again, the line classification was used because the most important geomorphological feature is a ridge aligned with the fault.

Besides the geometry, the classification proposal includes the complexity within the spatial classification of the geomorphosites, which is essential because the imbrication of scales is a common thing when we are dealing with geomorphological sites. It is especially important for the use of GIS database and also for the cartographic representation of sites classified as geomorphological complex or geomorphological systems. Figure 8 brings an example of a geomorphological system, where different landforms generated by different processes are connected in the same geomorphosite. The aerial photograph of the site allows the observation of the main features of the site that is composed by marine, lagoonal and aeolian features in a coastal environment.

Summarising, the spatial classification consists of classifying the geomorphosites according to the geometry (points, lines or surfaces) and according to the complexity, considering the number of landforms and processes being represented in the site. This step is important for considering the imbrication of spatial scales, highlighted as an important specificity of geomorphosites, and also important for using GIS and for the cartographic representation of the sites, as displayed in the examples that were presented.

Thematic Classification

The thematic classification consists of classifying the forms and geomorphological processes present in the geomorphosite. Therefore, more spatially complex geomorphosites will present more complex classifications since several forms and processes may be present.

The *Lagoa Doce* Cliffs geomorphosite (Fig. 9) is composed of a single landform (cliffs), generated by one process

Table 2 Geomorphosites classified according to the proposed scheme

Geomorphosite	Spatial classification		Thematic classification	Processes	Temporal classification
	Geometry	Complexity	Forms		
Ponta Negra Promontory	Surface	Single landform	Rocky promontory	Tectonic uplift (inactive); denudational processes	Active/inactive
Brejo do Espinho	Surface	Geomorphological system	Double-barrier-lagoon system; fore-dunes; parabolic dunes	Lagoonal; coastal; aeolian	Active/inactive
Cabo Frio Island	Surface	Geomorphological system	Alkaline massif (island); beach arc; climbing dunes; *sambaquis*	Magmatic intrusion (inactive); aeolian; coastal; anthropic (inactive)	Active/inactive
Dama Branca Dune Field	Surface	Geomorphological complex	Foredunes; barchans; barchanoids; parabolic dunes; parabolic megaform dune; nebkhas	Aeolian	Active
Cliffs and Palaeocliffs of Rasa Beach	Points	Group of landforms	Cliffs; inactive cliffs	Coastal	Active/inactive
Ferradura Beach Arc	Line	Single landform	Beach arc	Coastal; wave diffraction	Active
Saquarema Promontory	Surface	Single landform	Rocky promontory; cave	Tectonic uplift (inactive); denudational processes; chemical weathering	Evolving passive
Jacarepiá Lagoon	Surface	Geomorphological system	Double barrier-lagoon system; intralagoonal spits; foredunes	Coastal; lagoonal; aeolian	Inactive
Foredunes and Secondary Dunes of Massambaba	Surface	Geomorphological system	Foredunes; parabolic dunes; coastal barrier; lagoon	Aeolian; overwash	Evolving passive
São João Hill	Surface	Single landform	Alkaline massif	Magmatic intrusion (inactive); denudational processes	Active/inactive
Tartaruga Beach	Line	Single landform	Beach arc	Coastal	Active
Conchas Beach Arc	Line	Single landform	Beach arc	Coastal; wave diffraction	Active
Pai Vitório Point	Line	Single landform	Aligned ridge	Tectonic processes (inactive); differential erosion	Evolving passive
Aldeia Velha River	Line	Geomorphological complex	Stream channel; floodplain; fluvial terraces	Fluvial	Active
Vermelha Lagoon	Surface	Geomorphological system	Double barrier-lagoon system; *salinas*	Coastal; anthropic	Active/inactive
Papagaios Island	Surface	Single landform	Coastal island	Tectonic uplift (inactive); coastal	Evolving passive
José Gonçalves Marine Terrace	Surface	Geomorphological complex	Marine terrace; beach arc	Coastal	Active/inactive
Araruama Lagoon Spits	Surface	Group of landforms	Lagoonal spits	Lagoonal	Active
Tucuns Dune Field	Surface	Geomorphological complex	Coastal dunes	Aeolian; anthropic	Active
Lagoa Doce Cliffs	Line	Single landform	Coastal cliffs	Coastal	Active
Pedra Lisa Inselberg	Surface	Single landform	Inselberg	Tectonic uplift (inactive); differential erosion	Active/inactive
Palaeolagoon of Reserva Tauá	Surface	Single landform	Lagoonal plain (i.e. plain composed of palaeolagoonal deposits)	Lagoonal	Inactive
Sapiatiba Hills	Surface	Single landform	Coastal massif	Tectonic uplift (inactive); denudational processes	Active/inactive

Table 2 (continued)

Geomorphosite	Spatial classification		Thematic classification		Temporal classification
	Geometry	Complexity	Forms	Processes	
Peró Dune Field	Surface	Geomorphological complex	Foredunes; parabolic dunes; barchanoids; nebkhas; climbing dunes; deflation zone	Aeolian	Active
Fumaça Waterfall	Point	Single landform	Knickpoint	Fluvial	Active
Peito de Pombo Summit	Point	Single landform	Rocky summit	Differential erosion	Active
Brava Beach	Line	Single landform	Beach arc	Coastal	Active
Salgada Lagoon	Surface	Single landform	Coastal lagoon	Coastal; lagoonal	Inactive

(marine erosion). Therefore, it is an example of geomorphosite with a quite simple thematic classification.

The thematic classification of geomorphological complexes will be done with the definition of one main process and a list of landforms related to it. The example shown in Fig. 10 highlights three landforms within a fluvial environment. In this case, one type of process (fluvial) is responsible for the setting of different landforms. The thematic classification of this geomorphosite must include the process and all landforms.

The most complex cases are the geomorphological systems, where several processes and landforms are present. Each process and landform must be included in the thematic classification to provide complete information about the geomorphosite. *Vermelha* Lagoon is an example of geomorphological system where natural and anthropic activities generate a quite complex geomorphological setting. Figure 11 presents a simplified geomorphological map of the geomorphosite, composed by landforms associated to marine, aeolian, lagoonal and anthropic processes.

The *Salinas* are anthropic landforms created to produce salt through natural evaporation tanks. This is a historical activity in the region that was developed due to the favourable geomorphological and climatic conditions. Besides them, the geomorphosite presents several other landforms, such as coastal barriers (active and inactive), dunes and lagoons, representing diversity of processes.

Therefore, the thematic classification consists of classifying the landforms and processes. The idea of this step is providing basic geomorphological information about the geomorphosites. The spatial complexity of the geomorphosites will determine the degree of complexity of the thematic classification.

Temporal Classification

The temporal classification was designed to account for the dynamic dimension of geomorphosites that may present active or inactive features. Figure 12 shows examples of active and inactive geomorphosites, illustrating each situation.

Evolving passive geomorphosites are those in which current processes are modifying inherited geomorphological features, being interesting for representing sites with palaeogeographical value that are quickly being modified. An example of evolving passive geomorphosite is the Foredunes and Secondary Dunes of *Massambaba* (Fig. 13), in which aeolian and marine processes are constantly modifying dune fields that were formed during the Pleistocene. The flat area shown in the photo is a portion of the dune fields modified by overwash processes that take place during storm events.

Some geomorphosites consist of landforms generated by tectonic events that are no longer active, such as the coastal massifs or islands. However, their current shapes were originated by denudational processes that are still active but happen too slowly
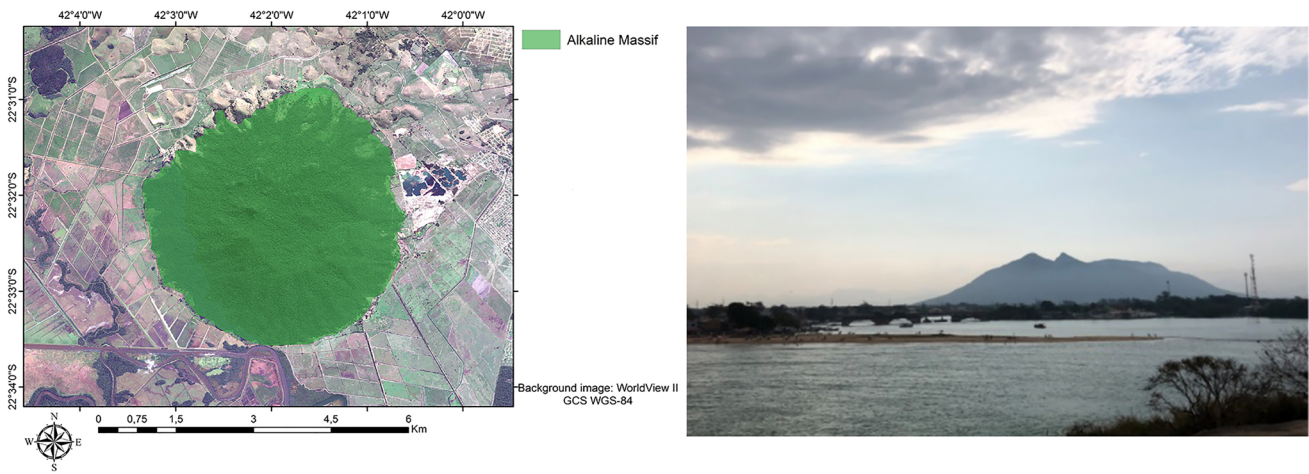
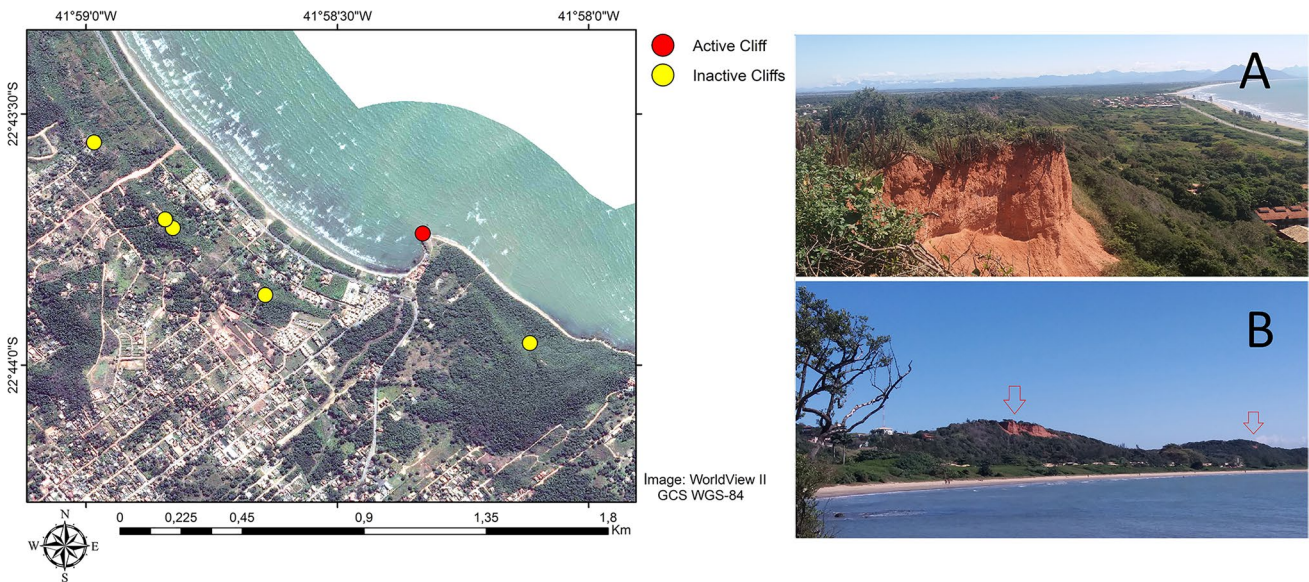**Fig. 4** Surface representation of *São João* Hill geomorphosite

Fig. 5 Palaeocliffs at *Rasa* Beach. **A** The top of one of the palaeocliffs. **B** The red arrows mark the location of two of the palaeocliffs in the area. Photos: Daniel Santos

to be considered an evolving passive geomorphosite. Figure 14 shows an example. *Peito de Pombo* Summit presents a peculiar shape that is related to active erosional processes. However, these processes are happening for a long time and the modification of the shape is not perceivable in a human time scale. Therefore, it was classified as presenting both inactive and active processes. This situation happens in other geomorphosites (see Table 2).

Discussions

Despite the years of development and the great number of published methods, the process of inventorying geosites still raises issues that need to be discussed (see Mucivuna et al. 2019). This work was inserted within the context of inventorying geosites in the territory of a proposed geopark that presents a significant geodiversity, embracing geosites in many different categories. Because of this, the first issue that needs to be raised is the importance of frameworks when dealing with large and geodiverse areas.

By defining geomorphosites as a framework, specific questions were brought, questions that do not appear in other frameworks. For instance, the geopark collaborators are also working with the inventory of geosites representing records of sea level variations. The classification scheme proposed for the geomorphosites cannot be used in this framework because many important information would not be addressed (type of record, altitude in relation
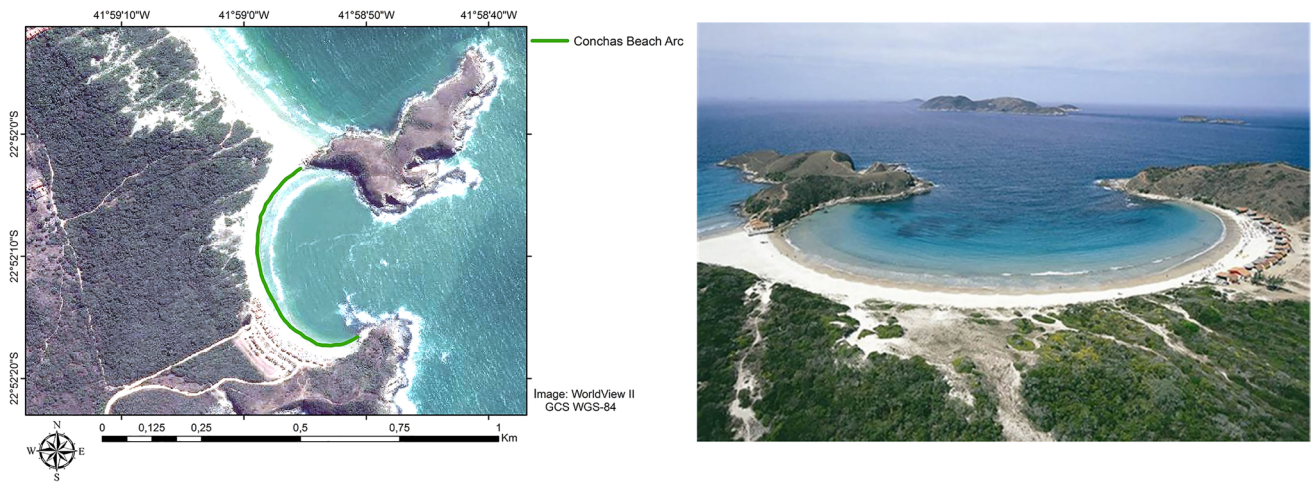
Fig. 6 Line representation of the *Conchas* Beach Arc geomorphosite. Photo: Hotel Paradiso Corporate
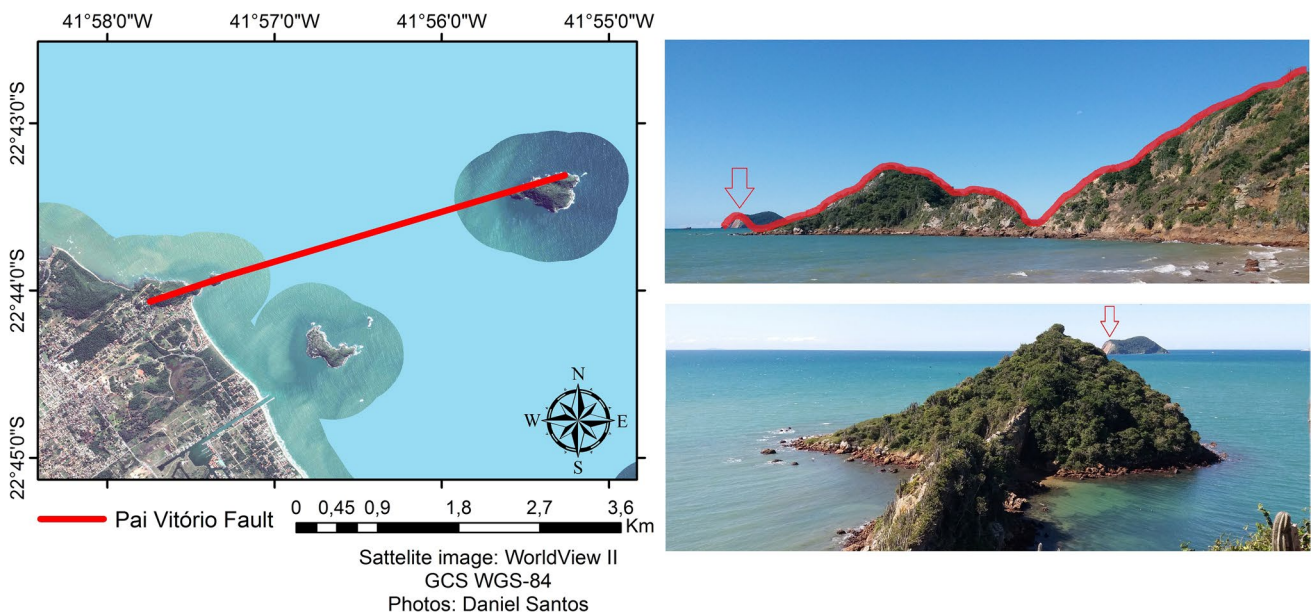

Fig. 7 Aligned ridge at the *Pai Vitório* Point geomorphosite. The red arrows show the fault scarp located in the island. Photos: Daniel Santos

to current sea level, absolute dating, etc.). So, the definition of frameworks is a very important step for the inventory and it may bring specific questions depending on the frameworks chosen and the most relevant information about each of them.

Considering geomorphosites, this is even more relevant because of the specificities of this category of geosites. The literature already highlighted the importance of the specificities and during the creation of the GIS database in the present work, it was clear that a classification considering these peculiarities was necessary. Therefore, the proposal

was mostly based on the need of a scheme that could be applied to geomorphosites in any geomorphological context.

The classification proposal was divided into three parts to take into account all of the most relevant issues related to the specificities of geomorphosites, especially the imbrication of spatial and temporal scales and the dynamic dimension. The aesthetic dimension, despite being a very important aspect, was not relevant at this point of the work. As demonstrated in previous works (e.g. Goudie 2002; Pralong 2005; Coratza et al. 2016; Santos et al. 2019), the aesthetic dimension is particularly important, amongst other things, in raising
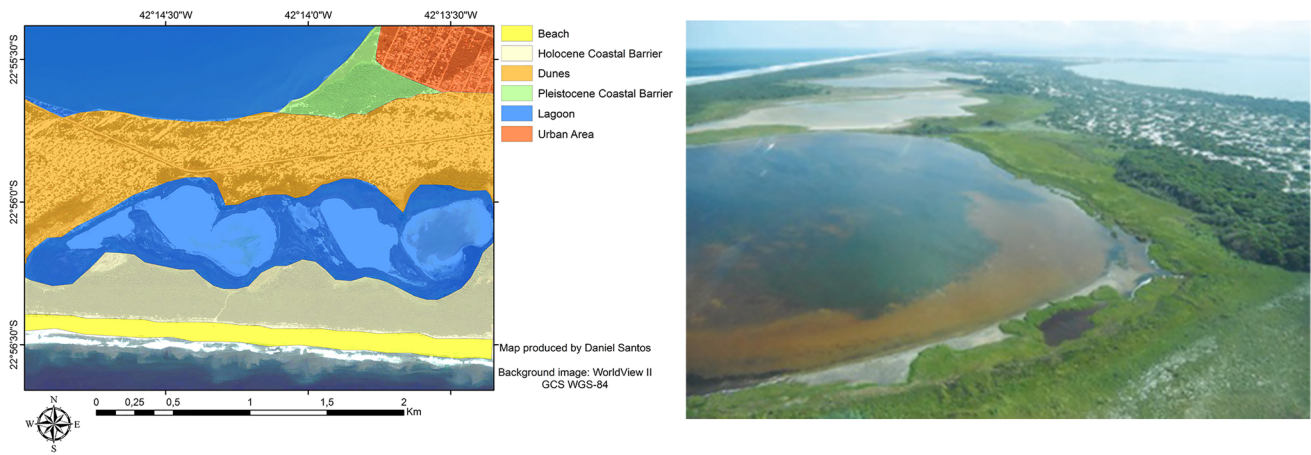
Fig. 8 *Brejo do Espinho* geomorphosite as an example of geomorphological system. Photo: Kátia Mansur

Fig. 9 *Lagoa Doce* Cliffs geomorphosite. Photos: Kátia Mansur

awareness to the wide public about geomorphology and its importance for society. However, since the present work is focused on a very initial step, it was not yet a relevant aspect.

Creating the database in a GIS environment brought the spatial scale as a first issue because the geomorphosites, as vector files, needed to be classified as points, lines or polygons (surface). Geomorphological phenomena may be expressed in the landscape in different ways, so the definition of the geometry is not obvious, depending more on what is being represented than on a clear delimitation of the landforms. It means that registering geomorphosites in a GIS environment will not necessarily be equal as in a geomorphological map. Creating cartographic representations of geomorphosites is not the same as mapping the geomorphology of an area, demanding different approaches.

So, for the classification scheme proposed, the geometry of the geomorphosites is not only defined by the shape of the landforms, but on what geomorphological phenomena are being represented. In addition, the scale is also a relevant aspect because, depending on the dimensions of the geomorphosite, the point classification may be needed due to the impossibility of delimiting lines or surfaces.

The spatial classification also includes the complexity of the geomorphosites, which is related to the imbrication of spatial scales. Geomorphosites may present single landforms related to a single process or several landforms related to different processes. Sometimes, the scientific, educational and geotouristic use potentials are due to this complexity. For instance, geomorphosites representing geomorphological systems usually have high educational values for allowing the observation of integrated landforms and processes. The management of the site is also usually more challenging in complex geomorphosites because, amongst other issues, the assessment of degradation risks becomes more challenging when several processes and landforms need to be considered.
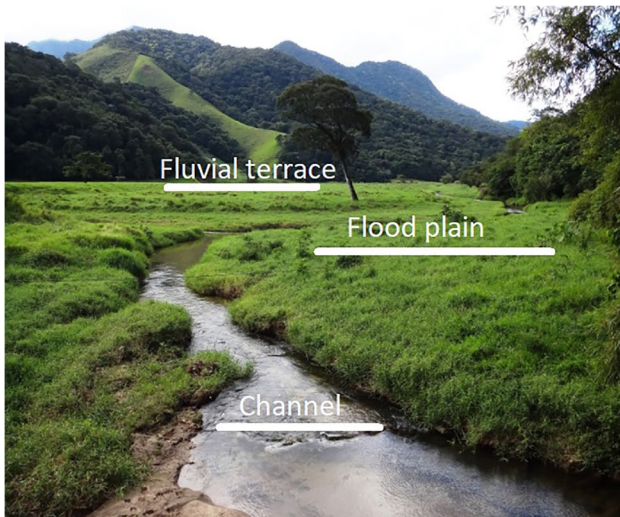
Fig. 10 *Aldeia Velha* River geomorphosite representing different landforms associated to a single process. Photo: geoparquecostoese-lagunas.com (modified)

The thematic classification consists of classifying the landforms and processes, providing information about the geomorphological and morphogenetic contexts represented in the geomorphosite. It is essential because the database is not yet focused on specific objectives, so any researcher or professional could make use of it with different aims. Because of that, the possibility of creating effective selection filters is mandatory to enhance the potential use of the database. The thematic classification allows a quick identification of particular themes within the entire geomorphological diversity of the area. The creation of geotouristic routes or educational fieldwork plans are significantly facilitated with

a clear thematic classification since this type of activity is usually focused on specific themes.

The dynamic dimension was addressed in the temporal classification. The possibility of observing and measuring active processes enhances the scientific and educational potential uses. In other cases, the dynamic dimension is linked with the aesthetic dimension, enhancing the geotouristic potential use. Similarly to the imbrication of spatial scales, the active processes also impose challenges for the management of the geomorphosite because, for instance, protecting a landform without considering the related process may not be enough for the conservation of the site.

It is the case of one of the geomorphosites included in the database: the *Dama Branca* Dune Field. This site consists of a large coastal dune field that is now located inside a protected area. However, there is an intense process of urbanisation that is slowly modifying the aeolian processes that feed the dunes (Fig. 15). Therefore, protecting the landforms without considering the related geomorphological process was not enough to guarantee the conservation of this important geomorphosite (the biggest dune field in Southeast Brazil).

The temporal classification also highlights the relevance of inherited landforms. These features represent past tectonic and climatic conditions, being important for the understanding of the history of the Earth, justifying their scientific and educational values. Finally, introducing the concept of evolving passive geomorphosites, proposed by Pelfini and Bollati (2014), showed to be interesting for identifying specific cases where active processes nowadays are quickly modifying inherited landforms. It is relevant both for the use potentials and for the management of
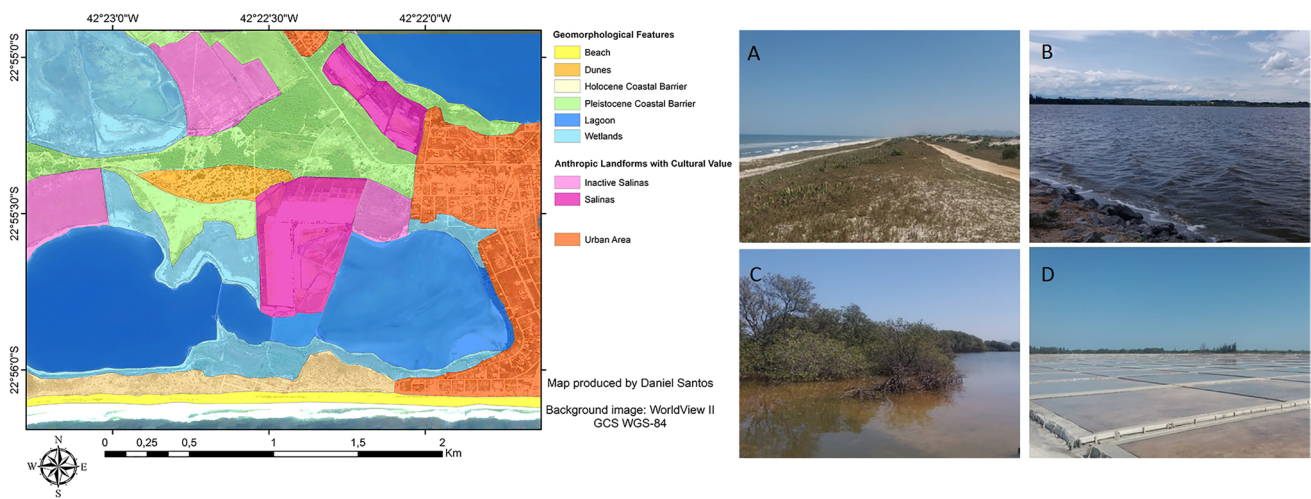

Fig. 11 Simplified geomorphological map and geomorphological features in *Vermelha* Lagoon geomorphosite. **A** Active coastal barrier developed during the Holocene. **B** Internal lagoon 'behind' the inactive coastal barrier, developed during the Pleistocene. **C** External lagoon 'behind' the Holocene coastal barrier. **D** *Salinas*. Photos: Daniel Santos

Fig. 12 **A** *Dama Branca* Dune Field, an active geomorphosite presenting aeolian features. **B** *Jacarepiá* Lagoon, an inactive geomorphosite showing the place where a lagoon was located during higher sea level periods in the Holocene

Fig. 13 Foredunes and Secondary Dunes of *Massambaba*: an example of evolving passive geomorphosite. Photo: Débora Francelino

Fig. 14 *Peito de Pombo* Summit, an example of geomorphosite that is currently being modified by ongoing processes, but too slowly to be considered an evolving passive geomorphosite

the site since the dynamics may require measures for the conservation and for the safety of visitors.

Therefore, the proposed classification scheme of geomorphosites was based on two main aspects: the application in GIS environments and the specificities of geomorphosites. The study area presents a significant geomorphological diversity, which allowed using the classification scheme in quite different geomorphological contexts. It was important for the development and validation of the proposal. The database created is now ready to be used (although new geomorphosites are constantly being included as new studies are developed) by different users that can apply selection filters to find geomorphosites with the desired characteristics. It is an important starting point for creating new inventories, proposing geotouristic routes, organising educational activities, supporting geoconservation initiatives, etc.

Selection filters may be used, for instance, to organise fieldtrips with students. The area of the geopark is constantly visited by professors from different universities and disciplines, such as coastal geomorphology, Quaternary geology and geoconservation. The database allows quick identification of sites with specific topics to be approached. Professors may easily find sites presenting current marine erosion processes, geomorphological complexes related to different morphogenetic processes, geomorphosites being quickly modified by natural processes, etc. The same principle is applied for other users, such as geotourism professionals, basic education teachers, stakeholders or even common visitors interested in the subject.
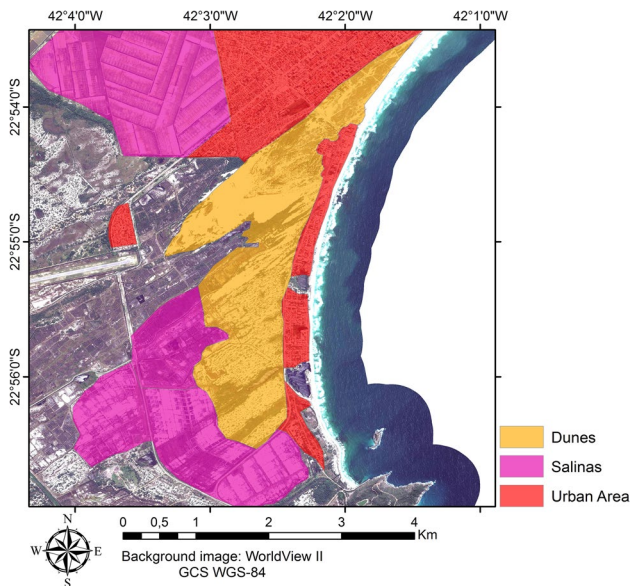
Fig. 15 Scheme showing the urbanisation and other anthropic modifications around *Dama Branca* Dune Field, affecting its sediment supply

The proposed scheme provides a basis for more advanced studies in geoconservation since researchers can use it as a starting point for creating specific inventories with different frameworks. Geomorphology is still a broad topic to be used as framework, so it could be divided into more specific topics and give rise to new inventories (e.g. inventory of aeolian geomorphosites; inventory of coastal massifs; inventory of sites with palaeogeographical value). Therefore, providing a database of geomorphosites without restricting it to more specific frameworks is interesting for making it possible to be used by a wider range of geoscientists in the future.

Conclusion

Significant methodological advances marked the last decades of development of geoconservation. The methods proposed so far brought different issues to the discussion, representing improvements that are strengthening geoconservation initiatives all around the world. The intention of this work was contributing to this process, focusing on the initial steps of creating inventories.

The creation of a solid database of geosites is an essential starting point for several initiatives and activities. Considering the context of a geopark proposal in a large and geodiverse area, with more than 200 sites identified, an organised and easily handled database brings efficiency and can be used for different purposes. Using GIS environment to create the database brings even more potentialities and ease and, in order to use this tool, issues concerning the spatial characteristics of

geomorphosites had to be considered, especially because of the imbrication of spatial scales.

The classification scheme proposed was developed considering the specificities of geomorphosites and the issues related to it. Using the same procedures for geosites in different categories may hide relevant information, so, after the definition of frameworks, it is essential to determine what is the most relevant information and create a classification scheme adapted to it. The present proposal was applied to geomorphosites in different contexts and with quite different characteristics, showing that it can be more widely used in other works and not only for the geopark *Costões e Lagunas*.

Therefore, we conclude that classification schemes can be valuable tools to provide initial basis for geoconservation strategies and initiatives. In this case, the focus was geomorphosites, but it is highlighted that other categories may also require specific classification schemes. It does not mean that the entire process of inventorying and assessing must be specific for each category. This initial database is only a support for activities that come after and does not influence on the definition of the inventory and assessment method.

Declarations

Competing Interests The authors declare no competing interests.

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