

## Article

# Coastal Vulnerability Assessment along the North-Eastern Sector of Gozo Island (Malta, Mediterranean Sea)

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**Abstract:** The coastal landscape of the Maltese Islands is the result of long-term evolution, influenced by tectonics, geomorphological processes, and sea level oscillations. Due to their geological setting, the islands are particularly prone to marine-related and gravity-induced processes, exacerbated by climate change. This study aligns different concepts into a relatively concise and expedient methodology for overall coastal vulnerability assessment, taking the NE sector of Gozo Island as a test case. Geomorphological investigation, integrated with analysis of marine geophysical data, enabled characterization of coastal dynamics, identifying this stretch of coast as being potentially hazardous. The study area features a high economic value derived from tourist and mining activities and natural protected areas, that altogether not only make coastal vulnerability a major concern but also the task of assessing it complex. Before introducing the methodology proposed for overall vulnerability assessment, an in-depth revision of the vulnerability concept is provided. The evaluation was carried out by using a set of key indicators related to local land use, anthropic and natural assets, economic activities, and social issues. Results show that the most critical areas are located east of Marsalforn including Ramla Bay, an important tourist attraction hosting the largest sandy beach in Gozo. The method combines physical exposure and social vulnerability into an overall index. It proves to be cost effective in data management and processing and is suitable for the identification and assessment of overall vulnerability of coastal areas to consequences of climate- and marine-related processes, such as coastal erosion, landslides and sea level rise.

**Keywords:** coastal morphodynamics; climate change; vulnerability index; Gozo; Malta

## 1. Introduction

Coastal zones are host to very dynamic and complex environmental systems, subject to the direct and indirect influence of a number of factors that have contributed to their evolution over time. The present-day landscape of coastal areas is the combined result of interactions between natural agents that include physical factors inherent in the system and external climatic and marine forces [1,2]. Human activity also plays an important role in shaping coastal dynamics, often exerting additional

pressures that may dominate over natural processes [3]. During the past decades, the rate of human occupation along littoral areas has risen significantly [4] and currently, in Europe, about 86 million people are estimated to live within 10 km from the coastline [5]. Furthermore, approximately one-third of the Mediterranean population is concentrated along its coastal regions and around 120 million inhabitants are concentrated in coastal hydrological basins located in the southern region of the Mediterranean Sea [6]. Coastal areas are the transitional zone between the aquatic and the terrestrial ecosystems and they have an environmental intrinsic value on account of their high level of biological diversity, which supports the provision of several ecosystem services essential for human well-being [7,8]. In view of these considerations, the sustainable conservation of coastal areas is a worldwide issue and coastal vulnerability evaluation and risk assessment are of paramount importance for integrated coastal management [9].

Coastal hazards, including marine-related and gravity-induced processes such as landslides, coastal erosion, storm water runoff and coastal flooding, have different impacts on coastal values, due to differing local geomorphological and anthropogenic settings. The impact of these processes is expected to increase with climate change. The assessment reports of the Intergovernmental Panel on Climate Change [10–13] emphatically forecast increase in both the frequency and the severity of extreme weather/climate events, combined with sea level rise, which altogether will undoubtedly impact coastal areas more adversely.

The Sendai Framework for Disaster Risk Reduction 2015–2030 [14], whose implementation is overseen by the United Nations Office for Disaster Risk Reduction (UNDRR), has recognized risk assessment as an important preliminary action on the basis of its relevance internationally. This points towards the prioritisation of the role of “understanding disaster risk” and “enhancing disaster preparedness” and promotes the use of “foresight” and “scenarios” for improving the level of preparedness for existing, emerging and new types of risk. At the same time, the identification of suitable climate adaptation strategies, which also account for future scenarios, is essential for increasing the resilience of coastal areas and ensuring the long-term conservation of coastal natural services and anthropic activities [15].

At the European level, risk assessment and mapping have been included in a number of legislative instruments, such as the Floods Directive [16], which requires member states to provide maps and indications for risk management, prescribing specific requirements for climate change impact evaluation.

As highlighted in the Special Report on “managing the risks of extreme events and disasters to advance climate change adaptation” published by the Intergovernmental Panel on Climate Change (IPCC) [17], vulnerability has been a pivotal concept for disaster risk reduction since the 1970s. Initial studies in this field, carried out by Baird et al. [18], O’Keefe et al. [19], Lewis [20], and Hewitt [21], introduced the concept of disaster risk as the combination of the probability of occurrence of a hazardous event with its negative consequences. Over time, the concept of vulnerability has been interpreted in different ways [22–25] reflecting how the approaches and conceptual models for its assessment differ among the scientific research communities [23,25].

This paper proposes and applies a methodological approach that integrates physical exposure and social vulnerability into an “overall vulnerability index”, to identify areas that can be negatively affected by climate- and marine-related processes, such as coastal erosion, landslides and sea level rise.

## 2. Conceptual Framework

Given the spectrum of possible conceptual interpretations of “vulnerability” and other related terms such as “exposure”, it is deemed essential that, as of primacy, and prior to proposing the methodology adopted in this research for the overall assessment, the range of most-commonly used concepts of vulnerability and exposure coined in the contexts of both climate change and disaster risk management are first introduced here, before clarifying which concept and definition are adopted by this study. The disaster risk community identifies the notion of vulnerability as one of the

elements required for risk assessment [26]. In this scientific context, “risk” is defined by exposure to a hazard, which is a potentially damaging physical event or phenomenon, and vulnerability, which denotes the relationship between the severity of the hazard and the degree of damage caused to the exposed element [27]. Specifically, according to the United Nations International Strategy for Disaster Reduction [26], vulnerability is defined in a qualitative way as “the characteristics and circumstances of a community, system or asset that makes it susceptible to the damaging effects of a hazard”. In the same document, exposure is also defined qualitatively as “people, property, systems, or other elements present in hazard zones that are thereby subject to potential losses”.

In earlier definitions, vulnerability was considered as the degree of loss of an element at risk after the occurrence of a natural process [28]. On one hand, the above-mentioned and more recent (but not the latest) definitions consider the notion of vulnerability as denoting a pre-existing condition related to the characteristics of the elements at risk and gives less emphasis to the process [29]. On the other hand, in the Climate Change Adaptation (CCA) context, more focus is placed on the concept of vulnerability defined as a function of exposure, sensitivity and adaptive capacity [10,30]. Therefore, in the risk context, the definition of vulnerability is quite similar to that describing the sensitivity of the system’s components in the climate approach [10], while in the climate change community it is defined in a similar way to the concept of risk used in the Disaster Risk Reduction (DRR) context [31].

Only in more recent years have the United Nations Institutions (UNDRR, IPCC) had a key role in converging on a common and shared definition of the vulnerability concept in CCA and DRR fields. In fact, the IPCC integrates the different conceptualizations of vulnerability and provides its upgraded and clearer definition in the glossary of the Fifth Assessment Report (AR-5, [11]), in which vulnerability expresses “the propensity or predisposition to be adversely affected. Such predisposition constitutes an internal characteristic of the affected elements (or societies) and includes the concepts to cope with, resist, and recover and the lack of capacity to cope and adapt to the adverse effects of a physical event”. Indeed, in this latter AR, the definition of risk (as a whole) is expressed as being the result of the interaction between vulnerability, exposure and hazard, whereby the distinction between the contribution of vulnerability and exposure to risk has been made clearer, which is a view also shared with the DRR community. This paper adopts a method of combining “physical exposure” information and “social vulnerability” data, which is in line with this evolution and convergence of concepts of vulnerability and exposure, across the above discourses.

In parallel to the vulnerability concept development, several actions taken in the last couple of decades have also focused on the development of methods and tools for supporting decision-makers in the reduction of coastal hazards’ impacts. Particularly noteworthy is the index-based approach, which was introduced by Gornitz at the beginning of the 1990s [32,33]. This is mainly based on indirect analysis supported by photointerpretation and topographic maps and is still the most commonly used method for coastal vulnerability assessment at regional levels [34–40].

At the European level, a number of transnational research projects have been funded with the aim of improving scientific knowledge and increasing the awareness of decision-makers on coastal vulnerability, the potential damages of marine processes and the effectiveness of coastal adaptation strategies (such as EUROSION, MICORE, RISC-KIT, ANYWHERE, OPERANDUM). In particular, the main outputs of the RISC-KIT Project are represented by a set of tools that allow identification of the most vulnerable areas (hot-spots) by means of a coastal index [41,42] and then selection of suitable measures for increasing coastal adaptation and therefore favouring risk reduction [43].

The evolution and emergence of concepts of vulnerability and exposure as being different features is warranted in certain situations, to provide a better understanding of “why” and “how” societal assets and values may be under threat or at risk under different scenarios of exposure. This can provide guidance to planners and policy makers in identifying suitable adaptation measures and actions, but it also makes risk assessment far more complex.

Some factors that contribute to the vulnerability of society can be expressed in terms of the dependence of societal wellbeing on certain exposed physical assets or other values that are at risk.

Examples of this are infrastructure and utilities, which underpin societal wellbeing to different degrees, depending on their nature. This component of vulnerability is distinct from vulnerability associated with the inherent characteristics of society. A community relying on physical elements for its wellbeing can be deemed as being vulnerable to the extent (or level) of its dependence on those specific physical elements located in a hazard-prone area. This creates different levels of “physical exposure”, in direct relation to their level of importance and to the degree to which societal wellbeing is dependent on and would be affected by losses to them. Thus, “physical vulnerability” is considered as one part of “overall vulnerability”, while “social vulnerability” (attributed to inherent societal factors) is considered as another component of “overall vulnerability”.

In this context, the research presented here aims to evaluate the overall vulnerability, and to refine the analysis and understanding of two distinct components, physical vulnerability (representing exposure from dependence on physical elements) and social vulnerability to a given set of external climate- and marine-related processes. Mirroring physical exposure as physical vulnerability and combining it with social vulnerability into an overall vulnerability index, an expedient and cost-effective method for the identification (and assessment) of the overall vulnerability of coastal areas at risk is provided.

The selected coastal study area, located along the NE sector of the Island of Gozo (Maltese archipelago), is one for which considerable applicative research has already been undertaken in order to showcase the high geological and geomorphological significance of its coastal landscapes [44]. Although the area is known to be particularly susceptible to several coastal hazards (erosion, storm surges, floods, sea level rise, landslides), it still lacks a detailed and refined appraisal of its natural and anthropic coastal elements, based on an analysis of assets and values that could potentially be at risk. Approaching the assessment of vulnerability of this coastal area from the perspective of the two components of social vulnerability and physical vulnerability provides a sharper analytical insight into overall vulnerability. Furthermore, the analytical methods and tools used in this study provide a methodological template for overall vulnerability assessment in the form of an Overall Vulnerability Index (OVI) that can be computed and used, with relative ease at different scales.

The scientific literature review carried out as part of this study reveals a gap in the area of assessment of vulnerability. Studies carried out to date have focused on the overall evaluation of hazard and susceptibility along the Maltese coastal sectors [45], rather than on the methodological assessment of vulnerability per se. Integrated approaches have been applied along the NW coast of Malta for landslide hazard assessment [46–49]. Landslide susceptibility assessment assisted by Persistent Scatterers Interferometry (PSI) was carried along the same stretch of the NW coast of Malta [49,50]. Based on the assumption that the identification and analytical mapping of the exposed elements represents a key step for the evaluation of the coastal risk, this study tries to bridge this gap by proposing a relatively simple yet reliable, cost-effective and easily replicable procedure for the assessment of coastal vulnerability. Nonetheless, while not being overly complex, the proposed approach provides an analytical discernment of different components of overall vulnerability that, when mapped geographically, provide sufficient guidance as to which areas are most vulnerable and on what account.

Following on from the methodological approaches proposed in previous studies [42,51–54], this study formulates and applies a research method for overall vulnerability assessment, which is based on the following steps: (i) identification of the main exposed elements (natural and anthropic) located in the investigated area; (ii) definition of their relative exposure level, in economic and ecological terms; (iii) assessment of the social vulnerability of the population living in the investigated area; (iv) calculation of the overall vulnerability by means of a combined index. As highlighted in [55] the use of an index as an evaluation tool requires the definition, weighting and aggregation of a number of indicators, which are defined as variables that are “an operational representation of a characteristic or quality of a system” [56,57].



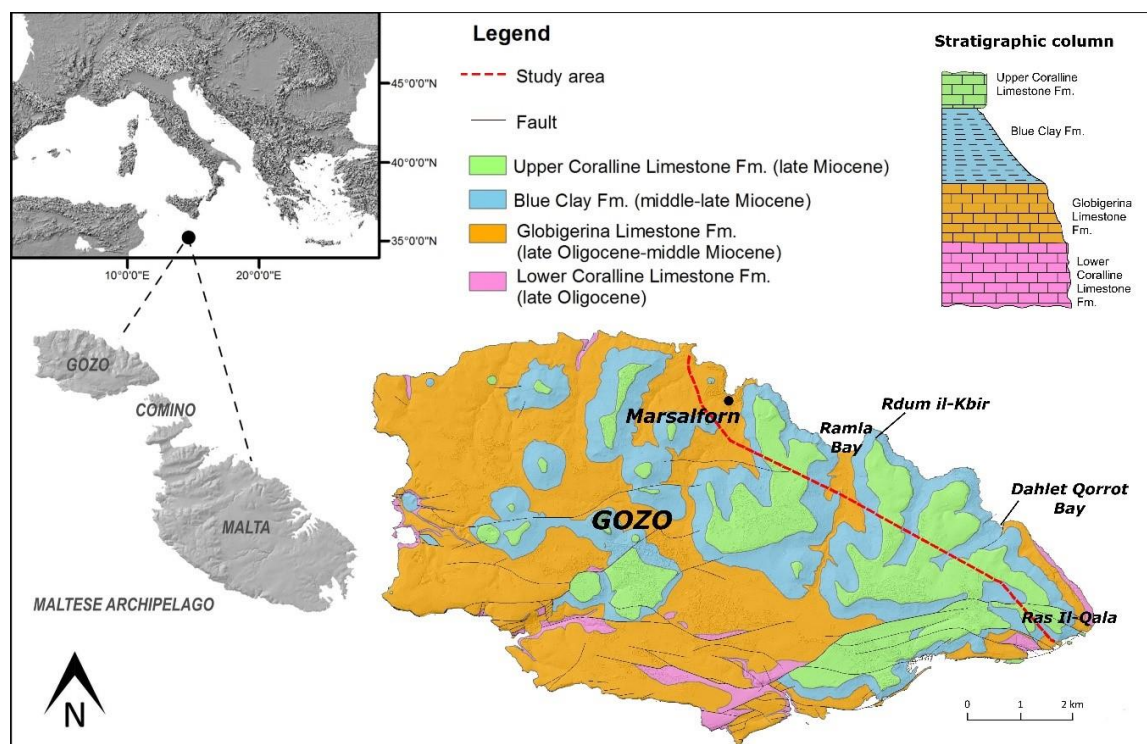
In detail, the method applied here foresees a set of indicators for the evaluation of the exposure level of local land uses (considering both the presence of economic activities as well as natural protected areas) and anthropic assets (such as transport networks and main utilities). Furthermore, the social context that characterizes the investigated area is also taken into account, in order to include social vulnerability in terms of population capacity to respond to and cope with a hazardous event in the overall evaluation of vulnerability. The combination of physical and social vulnerability provides the overall index, which expresses the level of overall vulnerability.

The use of distinct physical and social vulnerability indicators, and the definition of an Overall Vulnerability Index (OVI), has the main advantage of summarizing complex issues making them more easily interpretable, facilitating decision making and communication among stakeholders [58]. Meanwhile, the distinction between the two components at analysis stage provides a more in-depth understanding of specific anthropic elements that contribute to different risk levels.

### 3. Study Area

#### 3.1. Geological and Geomorphological Setting

The Maltese archipelago is located in the central Mediterranean Sea and comprises the main islands of Malta, Gozo and Comino (Figure 1). The coastal landscape (Figure 2) is the result of long-term evolution under the influence of tectonic activity, geomorphological processes and sea level oscillations. Due to their geological and geomorphological setting, these islands are particularly prone to different marine-related and gravity-induced processes such as landslides, coastal erosion, storm water runoff and sea level rise, enhanced by ongoing climate change. Multidisciplinary research and integrated investigations have been carried out to better understand the evolution of the geomorphological processes within the archipelago in the wider dynamic scenario of ongoing climate change as a way towards the reduction of risks associated with these processes [47,59–61].



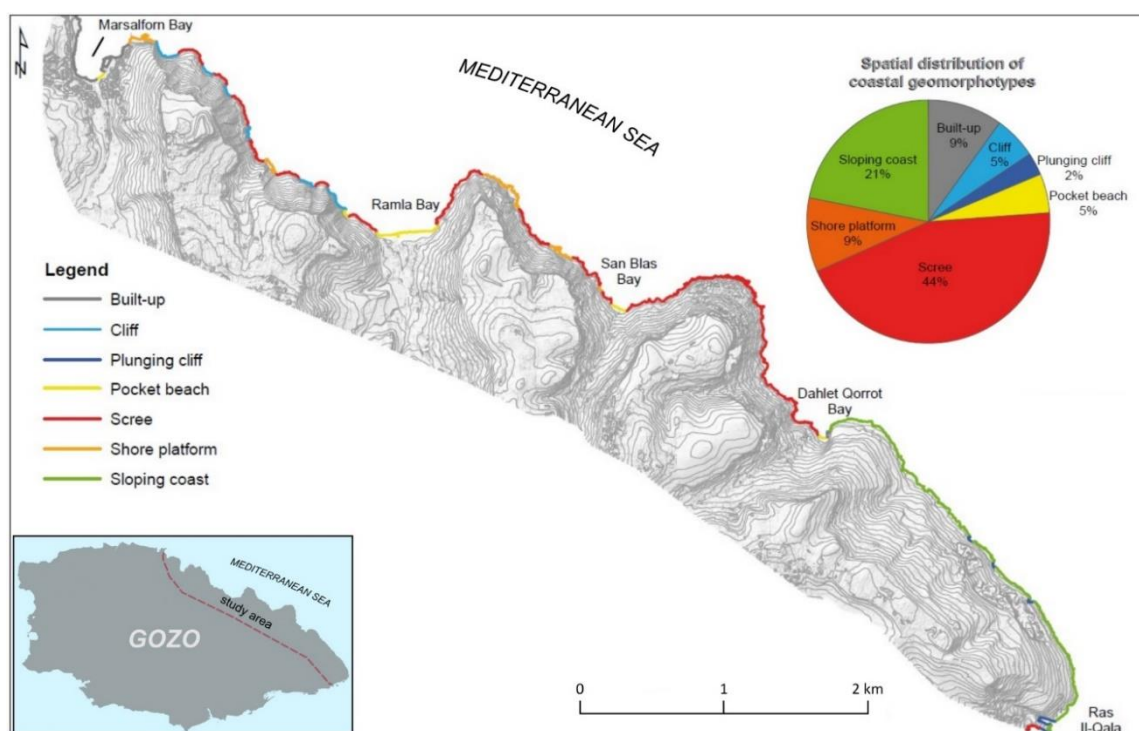
**Figure 1.** Geological setting of the Maltese archipelago (cf. [62]) and location of the study area, bounded by the NE coastline of Gozo and the red dashed line parallel to it on the inland side (after [44], modified).



**Figure 2.** Main geomorphic features of the study area: (a) block slides (west of Daħlet Qorrot Bay); (b) rock fall at the bottom of a limestone plateau and earth flow/slide affecting the underlying clayey terrain (between San Blas Bay and Daħlet Qorrot Bay); (c) plunging cliff between Daħlet Qorrot Bay and Ras il-Qala; (d) sloping coast between Daħlet Qorrot Bay and Ras il-Qala; (e) shore platform east of Marsalforn Bay; (f) Ramla Bay pocket beach; (g) cliff shaped in Blue Clay east of Marsalforn Bay; (h) built-up coast of Marsalforn Bay. After [44], modified.

Previous studies of the Island of Gozo have focused on general aspects of coastal features [60,63–66]. Only a few papers deal with the specific geomorphological aspects of the island [67–69], some of them referring to its rich geoheritage [70–73]. A detailed geomorphological map of the investigated stretch of coast (NE Gozo), based on geomorphological and geological field surveys integrated with the analysis of marine geophysical data, has been published recently [44]. The geomorphological map is accompanied by two other maps that show land use and the distribution of coastal geomorphotypes (Figure 3). Such documents constituted the basis for carrying out the vulnerability analysis presented below.





**Figure 3.** Distribution of coastal morphotypes in the study area (after [44], modified).

From a geomorphological perspective, the investigated coastal stretch is characterized by limestone plateaus bounded by steep structural scarps which are progressively reshaped by gravitational and/or degradation processes. Clayey slopes, located at the foot of the limestone plateau, accommodate terraced fields of actively used or abandoned agricultural land. Numerous blocks of rock are strewn over the clayey terrain (a unique landscape known as *rdum* in Maltese) that slopes more gently away from the plateau edge.

The investigated coastline is characterized by the alternation of inlets and promontories. The accumulation of sand and mixed grainsize deposits results in the formation of pocket beaches where this corresponds with bays and coves. The large sandy beach of Ramla il-Ħamra Bay ('red sandy beach') is a particularly noteworthy example. It is also partly bounded by dunes on the landward side and is protected as a Special Area of Conservation (SAC) within the Natura 2000 network. The main inhabited centre of the investigated stretch of coast is Marsalforn, with its homonym bay, the latter being intensely urbanised and anthropized, comprising a predominantly built-up coastline.

The landscape of the investigated stretch of coast, and in general of the entire Maltese archipelago, is largely controlled by the different erodibility of the exposed lithostratigraphic units constituted by marine limestones and marls of the late Oligocene-Miocene [74,75]. The outcropping geological formations comprise (from the oldest to the youngest): Lower Coralline Limestone Formation (late Oligocene, Chattian), Globigerina Limestone Formation (late Oligocene—middle Miocene, late Chattian—Langhian), Blue Clay Formation (middle-late Miocene, Serravallian—Tortonian) and Upper Coralline Limestone Formation (late Miocene, Tortonian—early Messinian).

The Lower Coralline Limestone Formation consists of pale grey, hard, shallow marine biomicrites and biosparites [76], and outcrops in a restricted coastal stretch forming subvertical cliffs. Few Lower Coralline plunging cliffs (*sensu* [77]) are found in the investigated stretch of coast. They host roof notches with an asymmetric shape, recognized by Furlani et al. [78]. Lower Coralline Limestone is more commonly found in sloping coast formations, as typified in the stretch between Dahlet Qorrot Bay and Ras il-Qala.

The Lower Coralline Limestone Formation underlies the Globigerina Limestone Formation, the latter being younger and more erodible with respect to the former. The Globigerina Limestone

Formation consists of flattened areas along the coast, and includes yellowish, fine-grained, planktonic foraminiferal limestones. This formation features prominently as shore platforms along the investigated stretch of coast, where it outcrops above sea level and where the overlying softer blue clay layer has been eroded away, with examples at the Rdum il-Kbir promontory and on the eastern side of Marsalforn Bay. The Blue Clay Formation, overlying the Globigerina Limestone Formation, consists of grey, soft marls, clays and silty sands, forming gentle slopes. Sea cliffs shaped in Blue Clay can be also found within the study area. Finally, the youngest unit outcropping in the study area is the Upper Coralline Limestone Formation. This layer forms the plateaus at the top and is frequently weathered into steep cliffs and well-developed karst topography. It is also the source of the blocks of rock strewn onto the clayey slopes that slope away from the plateau edge more gently. A schematic stratigraphic column is shown in Figure 1.

The NE coast of Gozo is particularly prone to gravity-induced processes such as rock spreads, block slides, rock falls and earth flows/slides. This is mainly due to the tectonic and geological features of the area which is characterized by a dense network of joints and fractures [79] and by the superposition of terrains with different geomechanical behaviour (cf. [80]). In fact, the brittle limestone plateaus overlying clayey terrains enhance the fracturing of the plateaus and the development of lateral spreading locally evolving into block sliding [44,46,81–85].

Moreover, clayey slopes are more prone to shallow earth flows and earth slides [86], while limestone cliffs are affected by rock falls, which has caused scarp retrogression over time.

Geomorphological investigations, relevant to the submerged area along the investigated stretch of coast [44], have revealed that block slides and earth flow/slide runout continue locally below the sea level, reaching ca. −20 m of depth. This is also in agreement with evidence from other submerged areas along the Maltese Islands [44,87]. Evidence from landslide dating in the NW coast of Malta infer that these deposits were emplaced in a subaerial environment during sea level lowstands and subsequently became submerged during the post-glacial marine transgression [61].

### 3.2. Social, Economic and Tourist Setting

Studies that include geoheritage assessment and geosite inventory highlight that the Maltese archipelago is considered as an attractive geotourist destination due to the strong interaction between natural and cultural aspects (cf. [71,88]). Data from the World Travel and Tourism Council (WTTC) for the year 2017, retrieved from Selmi et al. [88], show that 27.1% of Malta's GDP and 28.3% of total Maltese employment (corresponding to 55,000 jobs), were accounted for by activities directly related to and induced by travel and tourism [89,90]. Taking the type of tourism into consideration, data referring to 2017 show that the majority of tourists (almost 85%) visited Malta for holidays, while a very low percentage visited the country for business and other purposes (8% and 7%, respectively). More recent data show that the number of tourists is constantly increasing (standing at 2.6 million in 2018). The WTTC forecast that the travel and tourism contribution to national GDP will rise to 34.6% by 2027.

The tourism on the Island of Gozo is highly dependent on tourism activity of the main island, Malta [91], given that all of Gozo's tourist traffic necessarily passes through mainland Malta. Tourism is a significant source of income and employment and it is one of the primary contributors to the Gozo economy. Gozo's tourism also relies heavily on domestic tourists (with 400,000 domestic tourists or visitors per year coming from Malta) and on one-day trips of international tourists [92]. In 2018, almost 100,000 guests including resident and non-resident spent an average of three to four nights in one of the accommodation facilities of Gozo [93].

The Gozo Island attracts many tourists, especially during the summer period, for its environmental, cultural and geological heritage. Moreover, senior and middle-aged foreign residents more commonly chose the Island of Gozo as a place for their retirement, mainly for its relative peacefulness and quiet, combined with its array of scenic features (Gozo is colloquially known as “the place where time stood still”).



The coastal sector investigated by this study includes four administrative districts: Żebbuġ (7.6 km<sup>2</sup>), Xagħra (7.6 km<sup>2</sup>), Nadur (7.2 km<sup>2</sup>) and Qala (5.9 km<sup>2</sup>), which are characterized by extensive urban development. The study area is host to two renowned tourist destinations, Marsalforn Bay and Ramla Bay, both of high importance to Gozo tourism. Marsalforn Bay is one of the main inhabited centres located on the Gozo coast. The availability of a significant number of accommodation facilities, shops, restaurants and several diving centres contribute to a dense tourist population and to lucrative businesses in Marsalforn, especially in summer.

Total guests in the Gozo and Comino region increased by 12.6% to 97,781 in 2017, while total nights spent went up by 11.1% to 347,943 when compared to the previous year [94]. Within a continuous upward trend in the last five years or so, the Gozo and Comino region recorded a strong growth in terms of inbound tourist arrivals in 2017 [94]. It is worth noting that among the top five localities where inbound tourists to Gozo stayed longest [94], two are within the study area, with important tourist destinations such as Marsalforn and Ramla Bay.

Ramla Bay is the largest sandy beach in Gozo. It is characterized by golden-reddish sand, which lends it its name in Maltese (Ramla il-Ħamra) and makes this beach peculiar and unique to the Maltese Islands. The area around the beach is also of archaeological and historical interest, hosting Roman remains lying beneath the sand, a submerged seawall, fugass and battery defensive structures constructed by the Knights of St. John of Jerusalem in the mid-18th century, and the famous Calypso Cave looking over the western side of the beach.

Furthermore, the study area as a whole includes areas of high natural and ecological importance, hosting two wide natural protected zones, *Għajn Barrani* (located west of Marsalforn, including Ramla Bay) and *Il-Qortin tal-Magun u l-Qortin il-Kbir* (located close to Dahlet Qorrot Bay), both included in the Natura 2000 network as SAC. Finally, it should be noted that the high economic value of the study area is also derived from specific land uses in certain areas, such as quarrying, which occupy a surface of 0.13 km<sup>2</sup>.

#### 4. Materials and Methods

The method proposed and applied in this research for the assessment of coastal vulnerability is in line with the most recent index-based approaches generally used for this kind of analysis. In detail, the method relies on the outcomes of other research in the field [41,95] and is based on a new approach for the evaluation of indicators referring to: (i) the potentially exposed categories of assets (defined as “physical indicators”); and (ii) a number of parameters related to the social context (defined as “social indicators”).

The indicators are interpreted here as operational representations (cf. [56,57]) of the physical and social characteristics of the area. Each physical indicator comprises different categories of assets, to which a score representing an increasing level of exposure was attributed. In order to tailor the approach to the local settings of the study area, the exposure level assigned to each category of assets was defined based on expert judgment. It is a widely shared opinion that the scoring and aggregation of indicators into indices may have a large impact on the resulting rankings and, consequently, on decision-making [55].

The spatial overlay of the physical indicators provides an estimate of the physical vulnerability level, which ranges from very low to very high vulnerability. Meanwhile, the various social indicators refer to vulnerability of the socio-economic aspects. These are also classified into five levels ranging from very low to very high, to provide a measure of the social vulnerability level for the investigated area. The overlay of the two sets of aggregated physical and social indicators enables an overall zonation that shows grades of the combined physical-socioeconomic vulnerability, defined as “overall vulnerability”, thus identifying which are the most vulnerable stretches of the investigated coastal area.

Specifically, the method applied here comprises the following four main steps:

1. Definition of the landward limit of the coastal area to be investigated;
2. Classification of physical and social indicators into levels;
3. Data overlay and computation of an Overall Vulnerability Index;
4. Overall coastal vulnerability zonation and representation on a map.

The analyses are supported by GIS tools, which allow identification of the exposed coastal assets (i.e., natural and semi-natural environments, buildings, infrastructure, and agriculture), their combination with social data, and the calculation and mapping out of the overall vulnerability levels.

#### *4.1. Definition of the Landward Limit of the Coastal Area to be Investigated*

The area investigated was delimited according to the definition of a RICE area (Radius of Influence of Coastal Erosion and Flooding) proposed in the framework of the EUROSION project [95] for the identification of the coastal areas potentially impacted by marine-related process. The limit was set at a maximum distance of 500 m inland, or reaching a maximum of 5 m a.s.l. from the coastline. Furthermore, a buffer area of 100 m inland from the edge of the scarps formed in the Upper Coralline Limestone—which are extensively affected by landslide processes—was also added to the area defined in the above manner, in order to specifically account for landslide hazard. Information about landslide distribution provided by the geomorphological map of the study area (cf. [44]) was used specifically for this purpose, so as to identify the areas prone to slope instability.

The resulting landward limit was simplified and shown as a dashed red line in Figure 3, in order to provide a more linear indication of the investigated coastal sector.

#### *4.2. Classification of Physical and Social Indicators*

This step comprises the identification of data required for the evaluation and classification into five different levels, from very low to very high, for each of the two sets of indicators (physical and social indicators).

The evaluation of the anthropic and natural assets potentially exposed to coastal hazards is based on the elaboration of the following indicators: land use, transport network, and utilities. A GIS layer has to be created for each indicator in order to identify polygons representing the spatial unit to which the related exposure level is assigned, indicating its specific numerical value, ranging from 1 (very low exposure) to 5 (very high exposure). These layers are first converted to a raster format (5 × 5 m) and then overlaid to estimate the physical vulnerability level, by considering the maximum exposure value assigned to each cell.

At the detailed level, the land use information was collected from the land use map available in Prampolini et al. [44], in which land use categories were classified as: (i) natural and semi-natural areas, (ii) agricultural areas, and (iii) artificial surfaces. This land use map was supplemented with additional detailed information in order to include strategic elements, such as civil protection posts, police stations, emergency posts, fire corps posts, port authorities' posts, hospitals, and schools. The identification of these elements was supported by photointerpretation of the most accurate maps available for the study area and verified in the field during the investigation.

An exposure level (ranging from 1, very low exposure, to 5, very high exposure) was assigned to each land use category based on expert judgement. The highest exposure level was attributed to the areas occupied by settlements, constructions, and human activities while the lowest level was assigned to abandoned agricultural zones. Details concerning the land use indicator and the exposure levels related to each category are shown in Table 1.

**Table 1.** Physical indicators and expert-based exposure level (ranging from value 1 to value 5) assigned to each category of assets.

Physical Indicators (Value)	Very Low/Null Exposure (1)	Low Exposure (2)	Medium Exposure (3)	High Exposure (4)	Very High Exposure (5)
Land Use	Abandoned agricultural area. Bare rock	Agricultural area; Green urban areas; Natural and vegetated area, Terraced agricultural field; Land principally occupied by agriculture with significant areas of natural vegetation	Residential area; Dump; Quarry; Cemetery	Beaches; Dunes; Sand	Historical and archaeological site; Natural protected area (SCI); Strategic elements; Entertainment (commerce, finance, business, recreational, leisure, and sport)
Transport	Absence of transport network or highly degraded transport network	Footway; Path; Track; Steps	Tertiary road; Living street; Residential; Services	Secondary road	Primary road
Utilities	Absence of utilities	Mainly local and small utilities	Street lighting	11kV overhead line	Substations; Feeder pillar

The transport network information was retrieved from Open Street Map downloaded from [96] as a shapefile. In this case, the roads were classified as follows: primary road, secondary road, tertiary road, inhabited street, residential, services, footway, path, track, and steps; the greater exposure level was attributed to roads of national or international importance. For each polyline element, a buffer distance was built (up to 20 m of total width for the primary road) in order to take into account a proper area of pertinence. Details concerning the exposure levels defined for the transport indicator are shown in Table 1.

The electricity network was taken into account for the utilities. The spatial distribution of these elements is available on Malta Inspire Geoportal [97]. In this case, a buffer zone up to 10 m width (10 m for substations, feeder pillars, and overhead lines, and 5 m for street lighting) was considered for each element. Details concerning the exposure levels associated with each electricity element are indicated in Table 1.

The social indicators allow characterization of the districts located in the investigated coastal area by evaluating, directly and indirectly, the social characteristics of the population living in the zone and therefore prone to be affected by coastal hazards. Generally, the social vulnerability information is obtained from census data. In this study, social data was downloaded from the Inspire Geoportal [97] and integrated with information available in the special report recently published by the Malta National Statistics Office (NSO) [98]. The social indicators are gauged from the economic budget allocated by the Government for supporting the population. The social vulnerability analysis carried out here is based on the assumption that higher allocation of social schemes corresponds to higher vulnerability of the population living in the investigated districts.

Specifically, the following indicators were taken into account: health care, disability, old age, children, and unemployment. These aspects represent some of the higher-risk groups of society, which social services and budget allocations aim to protect. The NSO provides a classification of these indicators in five classes that were here converted in a numerical value ranging from 1 to 5. The available data is provided by the NSO at district level and thus a numerical value was assigned to each district as a whole. The social vulnerability was then calculated as geometric mean of the values attributed to each indicator and then classified into five levels (from 1, for very low vulnerability, to 5, for very high vulnerability) by means of an equal interval classification method. A detailed description of the social indicators used in this study is reported in Appendix A.

The physical and social indicators identified are weighted equally, as in most of the indicator-based studies [99], meaning that each individual indicator has the same influence on the final calculation of the overall vulnerability.

#### 4.3. Data Overlay and Computation of an Overall Vulnerability Index

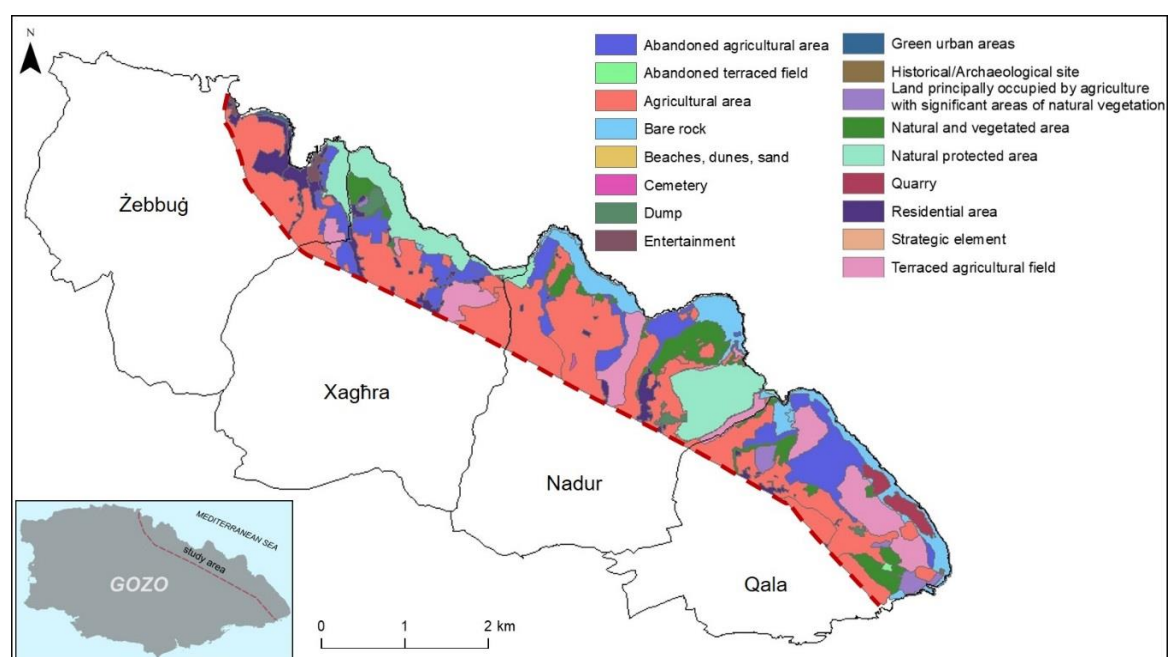
Once all the required data related to the physical and social vulnerability are collected and expressed in five levels, they are overlaid by means of a specific GIS tool. The overall vulnerability calculation is therefore the result of the aggregation of the physical vulnerability and social vulnerability data, the combination of which provides the definition of the Overall Vulnerability Index (OVI) as follows:

$$\text{Overall Vulnerability Index} = (\text{Physical vulnerability} \times \text{Social vulnerability})^{0.5} \quad (1)$$

Finally, the Overall Vulnerability Index is classified into five levels of increasing vulnerability (from very low to very high vulnerability) by means of the equal interval classification method.

## 5. Results

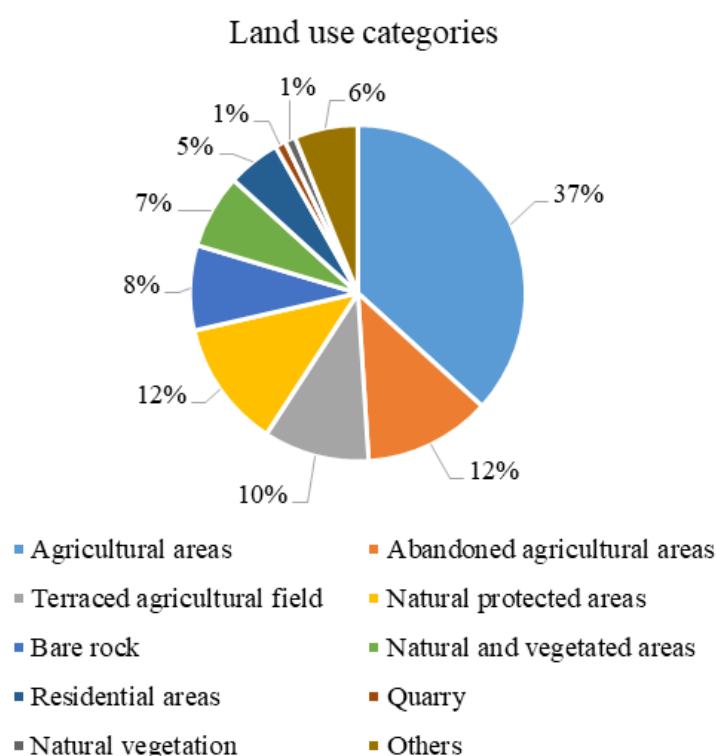
The results of this study are represented by: (i) GIS-based maps that show the spatial distribution of the natural and anthropic exposed elements and their classification in terms of physical vulnerability; (ii) social vulnerability level estimated for each investigated coastal district; (iii) overall vulnerability map of the NE part of the Gozo Island; (iv) areal extent and relative percentage of each vulnerability level. The land use classification (Figure 4) enables the evaluation of the surface occupied by different categories of natural and anthropic elements (cf. Table 1 in Section 4.2).



**Figure 4.** Detailed land use map. The red dashed line identifies the inland boundary of the study area. The districts' boundaries are also indicated.



In detail, 3.6 km<sup>2</sup> are occupied by agricultural areas, 1.2 km<sup>2</sup> by abandoned agricultural areas, 1 km<sup>2</sup> by terraced agricultural field, 1.2 km<sup>2</sup> by natural protected areas, 0.8 km<sup>2</sup> by bare rock, 0.7 km<sup>2</sup> by natural and vegetated areas, and, 0.5 km<sup>2</sup> by residential areas. Finally, quarrying and land occupied mainly by agriculture with significant areas of natural vegetation occupy 0.1 km<sup>2</sup>. The remaining surface area (corresponding to 602,268.2 m<sup>2</sup>) is occupied by the following categories: strategic elements (including a Police station), historical/archaeological sites (The Tower of Ta Sopus, west of Dahlet Qorrot Bay, and Saint Anthony's Battery at Ras il-Qala), green urban areas, beaches, dunes, sand, abandoned terraced fields, entertainment zones, and a cemetery. These values are indicated as percentages in Figure 5.

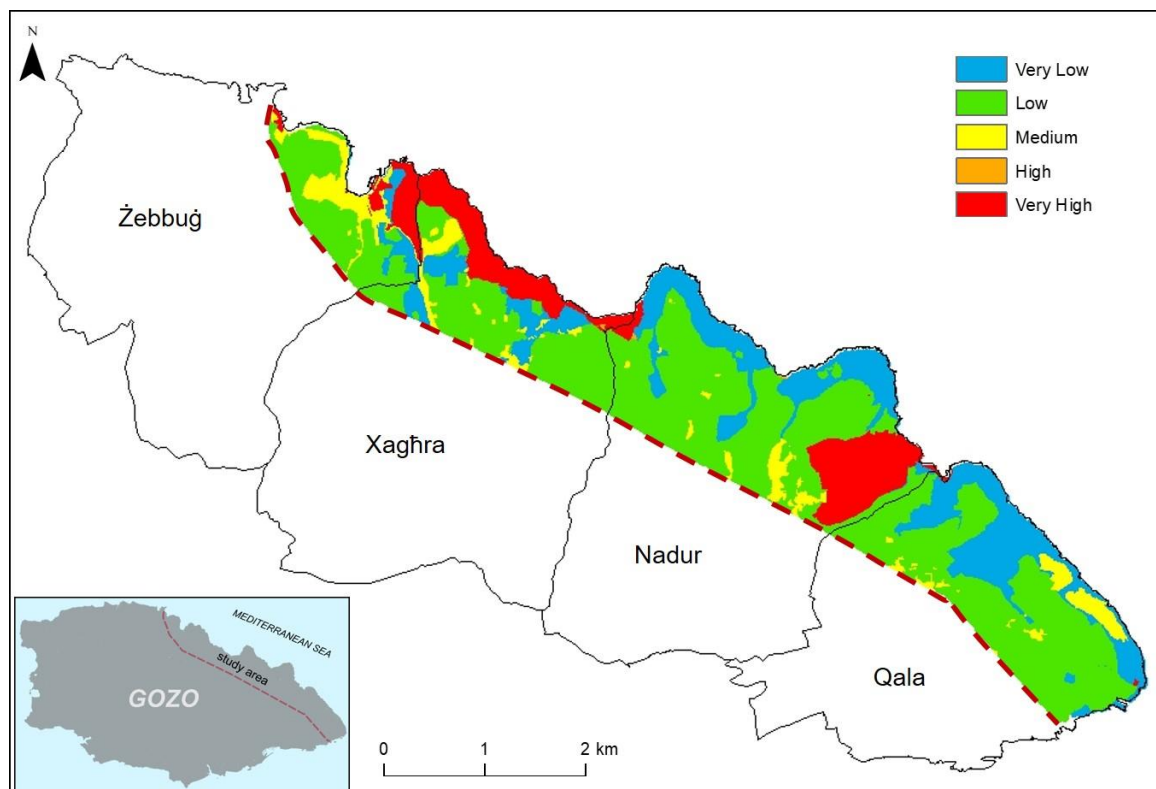


**Figure 5.** Percentage of the area occupied by each land use category according to the classification shown in Figure 4.

The interpretation and spatial representation of the overlaid physical indicators (cf. Section 4.2) (cf. Table 1) is representative of the different levels of physical vulnerability, given that the physical exposure levels are correlated directly to the level of value of the assets at risk.

This enables the zonation and calculation of what are, in effect, the extent of the areas with different levels of physical vulnerability, expressed in square kilometres and in percentages of the total surface investigated. The spatial interpretation of physical vulnerability is mapped in Figure 6 while the corresponding numerical values are reported in Table 2.

The numerical values assigned to each of the social vulnerability indicators for the investigated coastal districts are summarised in Table 3.



**Figure 6.** Physical vulnerability map resulting from data overlay of the physical indicators (land use, transport and utilities). The red dashed line identifies the inland boundary of the study area.

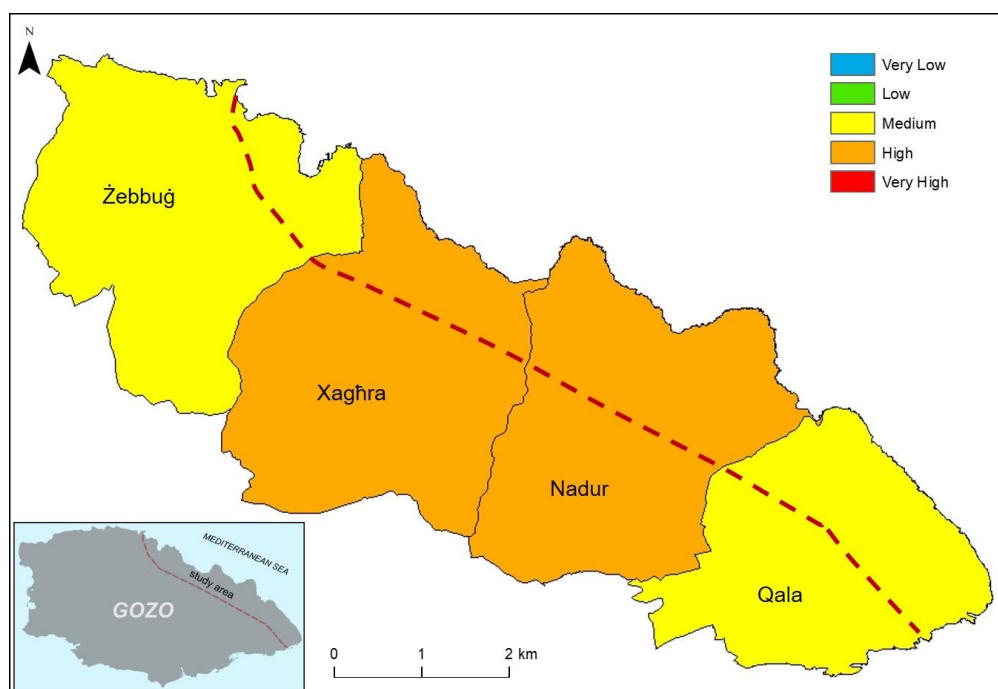
**Table 2.** Areal distribution of each physical vulnerability level resulting from the overlay and aggregation of the physical indicators (land use, transport network and utilities).

Physical Vulnerability	Surface (km <sup>2</sup> )	Surface (%)
Very low	2.0	21.7
Low	5.4	57.8
Medium	0.7	7.4
High	0.005	0.1
Very high	1.2	13.0

**Table 3.** Social indicators evaluated for the four coastal districts of the study area. The method for attributing the numerical value assigned to each indicator is indicated in the methodological paragraph (cf. Section 4.3).

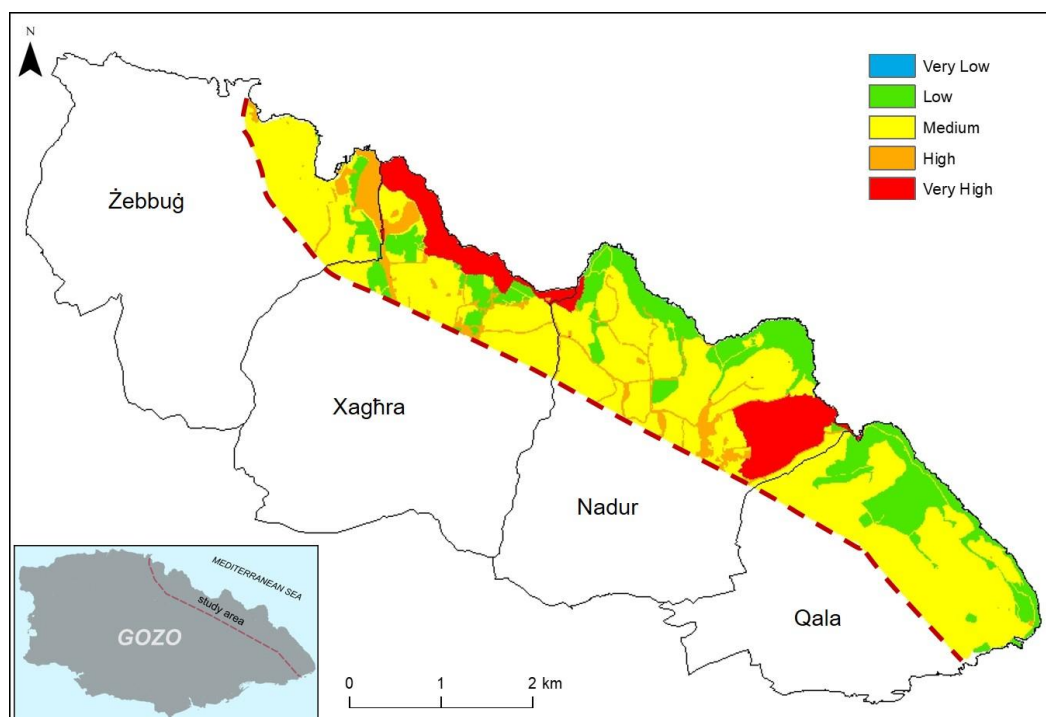
Social Indicators	Żebbuġ District	Xagħra District	Nadur District	Qala District
Health care indicator	3	2	3	3
Disability indicator	3	5	4	5
Old age indicator	2	3	3	3
Family/Children indicator	3	3	3	3
Unemployment indicator	5	2	2	2
Population (number of inhabitants, 2016)	2043	4029	4001	1885

The aggregation of the social vulnerability indicators (cf. Table 3) enables the evaluation of the social vulnerability level for each of the investigated districts (Figure 7). Specifically, two districts (Nadur and Xagħra) are characterized by medium vulnerability and two (Qala and Żebbuġ) by high vulnerability.



**Figure 7.** Social vulnerability map of the four administrative districts located in NE Gozo. The red dashed line indicates the inland boundary of the study area.

Finally, the overlay of the physical vulnerability levels with the social vulnerability levels enables a computation (and mapping) of the Overall Vulnerability Index for different polygons in the study area (cf. Section 4.3). It provides the basis for evaluating the variation in the overall vulnerability levels across the investigated coastal sector and enables this to be represented spatially (Figure 8).



**Figure 8.** Overall vulnerability map resulting from the spatial aggregation of the physical vulnerability levels and the social vulnerability levels over the area. The red dashed line indicates the inland boundary of the study area.

In sum, 1.9 km<sup>2</sup> are occupied by areas showing a low overall vulnerability level, 5.6 km<sup>2</sup> are occupied by areas showing a medium overall vulnerability level, 0.7 km<sup>2</sup> are occupied by areas with a high overall vulnerability level and, finally, areas characterized by a very high overall vulnerability level cover 1 km<sup>2</sup> (Table 4).

**Table 4.** Areal distribution of overall vulnerability levels that are the result of the combination and overlay of spatial distributions of the physical and social vulnerability factors.

Overall Vulnerability	Surface (km <sup>2</sup> )	Surface (%)
Very low	-	-
Low	1.9	20.4
Medium	5.6	61.3
High	0.7	7.3
Very high	1	11

## 6. Discussion

The proposed index-based method allows zoning of the investigated coastal stretch into different levels of vulnerability to climate- and marine-related processes. Results show that the study area is divided in four zones only (from low to very high vulnerability), since there are no areas with a very low level of vulnerability.

The coastal sectors located east of Marsalforn Bay, which include Ramla Bay and the area on the western side of Daħlet Qorrot Bay, show the highest overall vulnerability level. This is due to the combination of very high physical vulnerability levels pertaining to the presence of two Natura 2000 sites (cf. Section 3.1 and Section 5) and high social vulnerability levels for the Xagħra and Nadur districts. The high social vulnerability of Xagħra and Nadur is explained by the fact that each of the latter districts accounts for more than 4000 inhabitants, which is twice the number of inhabitants of the two other districts considered, Żebbuġ and Qala, for which a medium social vulnerability is assigned.

The coastal sector surrounding Marsalforn Bay is mainly characterized by a medium level of overall vulnerability as a result of the combination of a medium physical vulnerability level, explainable by the presence of residential areas, and, a medium social vulnerability level obtained for the Żebbuġ district. Furthermore, the innermost sector of the study area shows a prevailing medium overall vulnerability level, resulting from the combination of a low to very low physical exposure level, owing to the presence of cultivated and abandoned agricultural fields respectively, and a high social vulnerability level resulting for the districts of Xagħra and Nadur, as discussed above. The eastern part of the investigated sector, with bare outcrops of rock, hosts areas characterized by a low overall vulnerability.

The index-based method here proposed can be considered a suitable approach for the identification of coastal areas that are most vulnerable to consequences of different climate- and marine-related processes. Since the method adopted here combines vulnerability and exposure, the results represent an overall vulnerability assessment. It relies on the evaluation of the two main components that are used to define the overall vulnerability: physical and the social vulnerability, thus accounting for both the physical assets potentially exposed to climate and marine processes and the social aspects of the local population. This approach is in line with the convergence of different terms by the IPCC in its Fifth Assessment Report (AR-5, [11]).

The application of the proposed OVI method has allowed identification of a number of operational advantages. First of all, as the analysis is based on a sequence of steps, the method is relatively simple and easy to apply. It has been found to be cost-effective on account of the possibility of managing and processing the acquired data in a GIS environment with relative ease. Furthermore, it does not require intense field work, since it relies on indirect analysis, supported by existing geological-geomorphological information that is either readily available in the literature or easily collected. It can therefore be applied to wider coastal stretches, as in the case of other index-based approaches [40,100–103]. It should be underlined that the applied method can take advantage of data



sets and information concerning the natural and anthropic assets which are generally freely accessible and downloadable, e.g., from national geoportals available in most of the countries (at least across Europe), and from open databases, such as OpenStreetMap. Therefore, the method may have a wide range of applicability at different scales. Large scale analyses are based on detailed information about exposed/vulnerable elements and population (such as the land use and vulnerability maps proposed in this study). Meanwhile, small scale vulnerability maps concern wide areas, taking into account only the most prominent and spatially persistent exposed/vulnerable elements and regional data about the exposed/vulnerable population (as in the case of EUROSION Project), which accounted for all the European countries and provided a comprehensive European-level data repository at scale 1:100,000 [95].

The OVI method provides a sound approach suitable for the identification (and assessment) of vulnerable areas and sectors, even as an expedient and cost-effective scoping stage to identify which area may be analysed more specifically and at greater expense. It provides a useful tool for an overall time-efficient and cost-effective approach to focus limited research resources onto where they are needed most.

The presented research is a pilot-study and a first-ever combined overall vulnerability assessment carried out for any area in the Maltese archipelago, and it promises to provide new contributions at different levels and in different ways. At the localised level, the proposed method, and the results obtained from it, are promising as they reveal the potential applicability of this method for other (and potentially wider) coastal areas of the Maltese archipelago. Moreover, even at the local level, the overall vulnerability assessment could be easily updated by using any newly available or more detailed data regarding the social vulnerability of the investigated districts, as and when this becomes available. The relatively simple combined approach makes it more possible to keep the OVI up to date, even at the localised level. By way of example, it is relevant that during 2016, Malta's social protection outlay rose by €70.3 million in comparison to 2015 and that Old Age and Sickness/Health Care witnessed the biggest increases in social outlay [98]. The NSO [94] published statistical data on the basis of six different regions, from which localities can be studied specifically as socio-economic parameters change. This means that the social vulnerability level of the investigated district could be expected to rise in the next decades, influencing the overall vulnerability assessment. At the national level, the method could be applied to provide a first-round assessment of overall coastal vulnerability, to identify the most vulnerable stretches of coastal areas and values, and then to follow this up with a more detailed qualitative and quantitative analysis and comparison of risk assessments for specific areas and sectors, for different hazard types.

Running parallel to other research at the European level, further studies could include the spatial susceptibility analysis, including each of the coastal hazardous processes already identified here as affecting the investigated stretch of coast (e.g., erosion, sea level rise, landslides). As already done for other coastal zones in Europe [39,40,54], the investigated area should be classified into zones with different susceptibility, accounting for their proneness to be potentially affected by the specific impacts from extreme events and related processes pertaining to the particular hazard types (e.g., erosion, sea level rise, landslides). The susceptibility to different climate- and marine-related hazards could then be coupled with the vulnerability data derived by this study to perform a complete risk analysis (as done for example in [25,53]).

In this context, it is worth noting that the Maltese archipelago is situated centrally in the Mediterranean Sea, which has been classified as one of the regions most sensitive to climate change and, therefore, it is considered as a hot-spot area [104]. Climate change projections for the Mediterranean region [105] show that the area is experiencing an increasing temperature with consequent change in spatial and temporal distribution of weather/climate extremes [106]. More intense events, with alternating and more severe drought and precipitation, are expected to trigger and exacerbate erosive and mass movement processes [11,13], affecting the spatial distribution of the susceptibility to these types of events and hazards.

A direct consequence of global temperature increase is the rise in sea level, the direct impacts of which on coastal systems become manifest with larger rates of erosion, increase in flooding events, wetland loss, and saltwater intrusion [107]. Studies regarding the reconstruction of sea level changes in the Mediterranean Sea during the last 2000 years have shown that, in tectonically stable Mediterranean areas, the sea rose about 1.1 m [108,109] while for the last two decades the estimated rise was of about 3 cm/decade [110]. However, differential vertical land movements, including uplift and subsidence, characterize the Mediterranean coasts and, for this reason, the trends of sea level rise in the Mediterranean Sea have a large spatial variability [111]. Taking into account the role of terrestrial ice melt, steric effects and glacial isostatic adjustment, the future total Mediterranean averaged sea level rise has been estimated to be between 9.8 and 25.6 cm by 2040–2050, depending on the Representative Concentration Pathways scenario [112]. Sea level projections, obtained by coupling modelled eustatic trends with local ground movements, are in general used for supporting the assessment of the future coastal risk to sea level rise, which is aimed at reducing its impacts on natural coastal environments and human economic activities [3].

Based on the assumption that the investigated coastal area could potentially be affected by all the above mentioned climate-related hazards, further research activities should focus on risk analysis and mapping, as already done with reference to hazards related to sea level rise in several parts of Europe [113,114] and worldwide ([115–119] and reference therein). In this context, the results obtained in this study can prepare the ground for a comprehensive risk assessment, combining the identification of the exposed assets and the evaluation of vulnerability levels with a quantitative assessment of the hazardous processes affecting the area.

Finally, it is worth noting that the study is in line with the methodological approach proposed by the European Environment Agency (EEA) for the identification and implementation of climate change adaptation strategies (European Climate Adaptation Platform Climate-ADAPT). Specifically, in the EEA approach, six steps of analysis are indicated: (i) preparing the ground for adaptation; (ii) assessing risk and vulnerability; (iii) identifying adaptation options; (iv) assessing adaptation options; (v) implementation; (vi) monitoring and evaluation. The vulnerability analysis shown here represents a useful tool for addressing Step 1 and Step 2, while further activities should be planned with the aim of developing and tailoring the most suitable adaptation actions for the protection of the natural ecosystem and the maintenance of the anthropic activities.

## 7. Conclusions

This research represents a first attempt at the evaluation of coastal overall vulnerability in the Island of Gozo (Maltese archipelago) to the main climate- and marine-related processes, such as coastal erosion, landslides and sea level rise, to which the island is particularly prone. The analysis method developed and tested in this study is based on a conceptual interpretation of overall vulnerability, defined as the combination of two distinct components, namely, physical vulnerability and social vulnerability.

The study departs from a discussion of different notions of risk, including commonly used notions of exposure and vulnerability, which are defined qualitatively in the most authoritative sources (cf. Section 2). Given the identified, often conflicting understanding of the concept of vulnerability by various sectors of researchers and policy makers, it was determined that an in-depth consideration of the vulnerability concept was required prior to determining the vulnerability assessment methodology.

The study proposes a method for the assimilation, analysis and computation of overall vulnerability, and for its graphical spatial representation. The method manages to converge different qualitative notions of physical exposure and social vulnerability, and also makes it possible to derive a spatial quantitative distribution of the Overall Vulnerability Index. The latter can be represented in a map showing different coastal vulnerability levels that are easily readable spatially, making it simple to communicate comprehensibly to decision makers.

The Overall Vulnerability Index is calculated by means of an index-based method that is proposed along the lines of approaches developed in the framework of previous research projects and adapted specifically for the context of the study area and to the available information.

The study area was identified as possessing features of high economic value derived from tourist and mining activities and natural protected areas, altogether making coastal vulnerability a major concern. The final results of the analysis reveal that most of the investigated area (61.3%) is characterized by a medium level of overall vulnerability. A very high overall vulnerability level (11%) was obtained for the areas located east of Marsalforn Bay and close to Daħlet Qorrot Bay, including Ramla Bay, mainly owing to the presence of two sites protected as Special Areas of Conservation within the Natura 2000 network (Għajn Barrani and Il-Qortin tal-Magun u l-Qortin il-Kbir sites). A high vulnerability (7.3%) resulted for the main roads, while 20.4% of the total surface is characterized by low vulnerability areas mainly corresponding to abandoned agricultural fields and bare rocks outcrops.

The type of analysis presented here can be easily replicated for other coastal regions because the data sets required for the proposed method are almost always freely available or relatively easy to compile. Furthermore, the wider application of this method to the entire coastal area of the Gozo Island as well as to the coastal zones of the Maltese Islands has the potential to contribute to an overall risk characterization for the entire Maltese archipelago and it provides a useful tool for the identification of the most exposed and vulnerable zones (hotspot areas) that require action for their protection as a matter of priority. Starting from readily available data, which can be processed and mapped in a GIS environment with relative ease, the method proposed and tested here can provide policy makers, as well as coastal management agencies, with a graphical representation of easily comprehensible and useful data to support decision-making processes at both operational (short-term) and strategic (medium-long-term) level, enabling them to devise adaptation and structural protection measures in a more specific and effective manner.

Moreover, the method is cost-effective and time-efficient on account of ease of data processing, and it can also be a precursor for more detailed qualitative and quantitative analysis of risk (from different hazard types) at different scales for the areas or sectors considered to be at greater risk.

Finally, beyond the site-specific results, the method represents an important contribution toward more comprehensive risk assessment, also in terms of its potential transferability and replicability to different hazard types, including the local effects of climate change from extreme weather/climate events and sea level rise that need to be taken into consideration in a timely and effective manner.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

The evaluation of the social vulnerability for the coastal districts located in the investigated area was based on the calculation of a synthetic index that takes into account a number of indicators that represent social protection schemes that provide, where possible, protection against a single risk or need. For a comprehensive description of the social protection gross expenditure, readers can refer to the social protection report for the period 2012–2016, published in 2019 and directly

downloadable at: [https://nso.gov.mt/en/publicatons/Publications\\_by\\_Unit/Documents/A2\\_Public\\_Finance/Social%20Protection%202016.pdf](https://nso.gov.mt/en/publicatons/Publications_by_Unit/Documents/A2_Public_Finance/Social%20Protection%202016.pdf)

The social indicators taken into account in this study are:

- The Health Care function, which consists of all those benefits paid to persons during temporary periods of unemployment due to sickness or injury, and health care provided in the framework of social protection;
- The Disability function, which mainly covers cash benefits paid to persons who are below the retirement age and unable to work because of a mental or physical disability;
- The Old Age function, which covers all interventions against the risks linked to retirement and ageing. These include pensions given to a person once they retire from the labour market, lodging in specialized retirement homes and any services provided to persons unable to independently care for themselves.
- The Family/Children function, which includes cash benefits provided to households with children, various childcare services available to families and other social services provided with the specific intention to assist families with children.
- The Unemployment function, which represents benefits paid to either compensate an individual for the loss of his/her gainful employment or to cover the income of persons who retire from employment prior to the statutory age.

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