Assessing Coastal Flood Risks – Modeling Sea Level Rise and Inundation Scenarios for the Northeast Coastline of Malta

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By,

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Abstract

Sea level rise poses an urgent threat to Malta's northeast coast, where urban density, economic activity, and critical infrastructure converge. This study addresses the pressing challenge of sea level rise along Malta's northeastern coastline, a region characterized by dense urban development, critical infrastructure, and significant economic activity. Given the limited availability of high-resolution, location-specific flood modeling in Malta, the research aims to support evidence-based planning and climate adaptation strategies. Despite growing recognition of coastal vulnerability, Malta lacks spatially explicit risk assessments that account for both long-term SLR and short-term hydrodynamic drivers. This research investigates the extent of inundation and infrastructure exposure under a range of climate scenarios. The study integrates Coupled Model Intercomparison Project Phase 6 (CMIP6) outputs with high-resolution Digital Elevation Models (DEMs), tidal records, and wave height data. Both magnitude-based (+0.5 m, +1.0 m, +1.5 m) and scenario-based (SSP-RCP) sea level projections were applied to generate detailed inundation maps and quantify shoreline loss. Results indicate a nonlinear increase in coastal inundation, with up to 51.5% recreational shoreline loss under high-magnitude scenarios. Under SSP5-8.5 by 2100, projected flood levels, including wave height and tide, may exceed 4.9 meters, posing severe risks to coastal roads, urban infrastructure, and essential facilities such as the Pembroke reverse osmosis plant. The findings underscore the need for integrated, anticipatory coastal adaptation frameworks in Malta. By providing location-specific flood risk assessments, this research supports informed policy development and enhances national capacity for climate resilience planning.

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List of Abbreviations

Abbreviation	Definition
CMIP6	Coupled Model Intercomparison Project Phase 6
CNRM	Centre National de Recherches Météorologiques
CNRS	National Centre for Scientific Research
DEM	Digital Elevation Model
GMSL	Global Mean Sea Level
GMSLR	Global Mean Sea Level Rise
ICZM	Integrated Coastal Zone Management
IPCC	Intergovernmental Panel on Climate Chate
RCP	Representative Concentration Pathway
RO	Reverse Osmosis
RSLR	Relative Sea Level Rise
SDGs	Sustainable Development Goals
SLR	Sea level Rise
SIS	Small Island State
SSP	Shared Socio-economic Pathway

1. Introduction

Small island nations like Malta are particularly vulnerable to the effects of climate change, with sea level rise (SLR) posing a significant and growing threat to coastal ecosystems, infrastructure, and socio-economic stability. As over 80% of the land area of Malta is coastal or coastal-influenced, the nation is acutely exposed to both chronic and acute climate-related hazards. Projected sea level increases, whether moderate or extreme, could hinder key sectors such as tourism, real estate, and transportation infrastructure at serious risk of inundation. Despite international awareness, there is limited high-resolution, location-specific vulnerability mapping for Malta, particularly in densely urbanized and economically significant areas such as the northeastern coast.

1.1 Problem Analysis Within the Context of Sustainable Development and Environmental Management

This study situates the coastal vulnerability of Malta within broader global sustainability frameworks, such as the United Nations Sustainable Development Goals (SDGs), the Paris Agreement, and the EU's Integrated Coastal Zone Management (ICZM) protocol. The increasing frequency and magnitude of flooding events challenge long-term urban planning, environmental conservation, and socioeconomic equity, making climate adaptation not just a technical priority, but a governance and justice issue. Identifying areas at risk and providing clear spatial analysis is essential for targeted resilience-building, sustainable land use, and community-level adaptation strategies.

1.2 Scope

This study uses sea level rise projections based on both temporal (2050, 2070, 2100) and magnitude-based scenarios (+0.5 m, +1.0 m, +1.5 m), combining CMIP6 model data and regional tide/wave information. It focuses specifically on the northeast coast of Malta, beginning at Pembroke and extending to Gżira, including high-density areas such as Sliema and St. Julian's, where economic activity, population density, and infrastructure converge within vulnerable coastal zones. Key outputs of this study include GIS-based inundation maps, risk quantifications for recreational beaches, and scenario-driven vulnerability assessments.

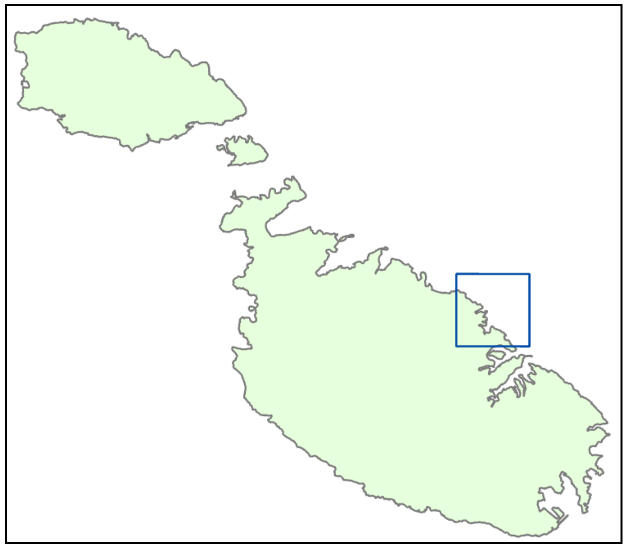

Figure 1.1: Archipelago of Malta and outlined study area.

1.3 Research Question and Aims

The purpose of this project is to develop models and visualizations that present sea level rise projections and associated inundation impacts on coastal infrastructure, as well as assess flood risk under varying climate scenarios along the northeast coast of Malta. This work is guided by the central research question: *How will the coastline of Malta change in the coming decades due to climate change, and what adaptations must be considered to ensure resilience?* The models incorporate not only long-term sea level rise projections under multiple SSP-RCP scenarios but also short-term drivers such as tidal fluctuations and extreme wave events. By integrating these physical dynamics, the analysis provides a more realistic representation of flooding risk and shoreline retreat. The results aim to inform spatial planning decisions and infrastructure adaptation priorities, particularly in vulnerable low-lying areas with high population density or economic value. Having these models available will support stakeholders in developing forward-looking mitigation strategies and responding to the broader socioeconomic implications of coastal change in Malta.

Figure 1.2: Coastline along Pembroke.

1.3 Document Structure

Section 2 provides a comprehensive literature review that establishes the foundational concepts referenced in this study. It explores key aspects of sea level rise (SLR), including physical drivers, global trends, and regional variations. The section also examines various modeling approaches used to project future sea level scenarios, with particular emphasis on their relevance to small island states such as Malta. In addition, it considers the broader socioeconomic implications of SLR, highlighting the intersection of climate change, coastal vulnerability, and sustainable development.

Section 3 details the methodology and presents the results derived from both magnitude-based and scenario-based modeling frameworks. The analysis integrates digital elevation model (DEM) data with sea level rise projections based on outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6). This dual modeling approach allows for a robust evaluation of potential inundation scenarios under varying assumptions of timing and extent of sea level rise, strengthening the study's use for adaptive coastal planning.

Section 4 synthesizes the findings and provides a set of evidence-based conclusions and recommendations. It identifies key priorities for adaptation, outlines ongoing research gaps, and underscores the importance of policy interventions tailored to local and regional climate risks. This section emphasizes the need for integrative, forward-looking planning to mitigate the long-term impacts of sea level rise on vulnerable coastal communities and infrastructure.

2. Literature Review

This section synthesizes the existing body of literature relevant to sea level rise (SLR) and its associated coastal impacts, with a specific focus on the Mediterranean region and the island state of Malta. It examines the physical drivers of SLR, the evolution of global and regional modeling approaches, and the integration of Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) within climate projection frameworks. Furthermore, it explores the current advancements in coastal inundation modeling and evaluates their applicability to small island contexts. This literature review also addresses socioeconomic vulnerabilities, infrastructure risks, and governance challenges that characterize coastal hazards in Malta. By identifying key research gaps and contextualizing the regional implications of global climate trends, this chapter establishes the basis for the modeling and analysis methods utilized in this study.

2.1 Introduction to Sea Level Rise and Coastal Inundation

Beginning in the 1980s, sea level change has been extensively monitored and modeled to advance understanding of climate dynamics [1]. The Intergovernmental Panel on Climate Change (IPCC) is a United Nations collaboration of politicians and scientists from member nations, who synthesize and communicate the global consensus on climate-related changes. According to recent IPCC assessments, global mean sea level (GMSL) is not only rising but doing so at an accelerating rate, with anthropogenic forcing identified as the dominant driver of GMSL rise since the 1970s [2]. Although climate models regarding sea level rise vary greatly, current sea level rise rates are reflecting the upper end of estimated projections [3].

Sea level rise is driven by several mechanisms operating at different spatial and temporal scales. Thermal expansion, where ocean water increases in volume as it warms, has been a dominant contributor since the early 20th century. Concurrently, melting of mountain glaciers and large-scale ice sheet mass loss from Greenland and Antarctica have added substantially to sea level rise. In particular, the Greenland Ice Sheet has experienced increasingly rapid surface melting and ice discharge, while Antarctica's contributions, especially from West Antarctica, are projected to accelerate due to marine ice sheet instability and ice shelf collapse [4,5].These processes, coupled with freshwater input from glaciers and changes in land water storage, explain both the global average and regional variability in sea level trends.

The Mediterranean Basin is increasingly recognized as a climate change hotspot where regional warming is occurring faster than the global average, by an estimated 20% [6]. Therefore, coastal inundation in Malta is a critical concern, particularly given the dependence of the nation on its low-lying coastal zones. Even under scenarios in which global CO_2 emissions reach net-zero, some sea level rise is expected due to ocean heat uptake and ice sheet dynamics [7]. A 2010 study estimates that Malta could lose approximately 12% of its land area by the end of the century, valued at 12.73 million USD [8]. This positions both natural ecosystems and urbanized coastal zones at increasing risk over the coming decades.

While permanent inundation from gradual sea level rise poses long-term challenges, more immediate and frequent threats are emerging from episodic coastal flooding driven by extreme weather events. These include high-intensity rainfall, storm surges, and increasingly frequent tidal anomalies. When coupled with ongoing sea level rise, these episodic events can overwhelm coastal drainage systems, causing widespread disruptions even in areas that are not permanently submerged. In Malta's urbanized shorelines, where impermeable surfaces and limited space for runoff compound these risks, short-term flooding events can result in significant infrastructure and economic damage. Projections suggest that extreme coastal flood events, those historically considered 1-in-100 year occurrences, may become annual or decadal events by the end of the century under high emissions scenarios [9].

Populations directly dependent on ecosystem services are particularly vulnerable to SLR, especially in the absence of adaptive infrastructure [7]. Inundation not only threatens physical structures, but also public health, social stability, and economic livelihoods [10]. While the magnitude of SLR and extent of permanent inundation play a role in evaluating risks to these communities, the adaptive capacity and resilience of affected communities from these events play a greater role when determining the true severity of consequences [11]. Socioeconomic disparities, including differences in income and institutional support, play a critical role in shaping vulnerability and recovery outcomes.

Malta's geological setting further exacerbates climate risks. The islands are particularly prone to gravity driven processes such as landslides, flash flooding, and runoff, all of which are expected to intensify [12]. The IPCC anticipates more erratic weather patterns, including an increase of severity and frequency, which when coupled with SLR, will further amplify impacts on coastal communities.

2.2 RCPs and SSPs

In order to accurately predict future climate scenarios, we must first understand and anticipate not only physical processes, but also how human behavior is likely to change over time, specifically in ways that influence the rate of climate change and the severity of its impacts [13]. One of the most widely used frameworks for modeling potential climate futures is the Representative Concentration Pathways (RCPs). Developed by the IPCC, RCPs represent a range of radiative forcing trajectories, measured in watts per square meter (W/m^2), based on varying levels of greenhouse gas emissions and mitigation efforts [7]. Greenhouse gas estimates are calculated based on potential developments such as "future population growth, economic growth, energy use, uptake of renewable energy, technological change, deforestation and land use" [14]. The most commonly seen pathways are RCP2.6, RCP4.5, RCP7.0, and RCP8.5, demonstrating low, medium-low, medium-high and high emissions respectively. For instance, RCP2.6 assumes strong mitigation efforts leading to peak emissions by mid-century and a decline thereafter, potentially limiting global warming to below 2°C. RCP4.5 and RCP7.0 represent stabilization scenarios with emissions peaking later in the century but not declining as aggressively. In contrast, RCP8.5 assumes continued high emissions without significant climate policy intervention, leading to radiative forcing of 8.5 W/m^2 by 2100 and associated warming of more than 4°C [7, 15]. Recent discussions in the scientific literature have debated the framing of RCP8.5 as a "business-as-usual" scenario. Hausfather and Peters [16] argue that RCP8.5 is better interpreted as a high-end emissions pathway rather than a likely future trajectory, given recent trends in energy use and climate policy. While RCP8.5 remains useful for exploring upper-bound impacts, especially in terms of infrastructure stress testing and risk management, overreliance on this scenario could lead to exaggerated projections if used uncritically. Nonetheless, for small island nations like Malta, whose exposure to climate extremes is disproportionately high, exploring RCP8.5 still offers valuable insights for contingency planning.

It is noteworthy that there is limited divergence in temperature rise and associated impacts among RCP scenarios before 2050. However, in the latter half of the century, their differences become substantially more pronounced. High emission scenarios foresee far more severe consequences, including accelerated sea level rise, extreme weather events, and widespread ecological disruption [14]. Therefore, selecting appropriate temporal horizons is essential when interpreting outcomes for planning and policy development. For coastal and island communities like Malta, scenario-based planning using RCPs is vital. These frameworks allow policymakers, planners, and researchers to model varying degrees of sea level rise, coastal flooding, and storm surges under different emissions trajectories. This, in turn, supports evidence-based adaptation strategies, infrastructure resilience, and sustainable coastal management [6].

To incorporate broader socioeconomic considerations into climate modeling, the IPCC introduced Shared Socioeconomic Pathways (SSPs) in its Sixth Assessment Report. The SSPs outline five distinct global development trajectories, describing plausible future societal trends, including economic growth, inequality, education, and technological innovation. These narratives are designed to be paired with RCPs to generate comprehensive SSP-RCP scenarios [17]. SSP1, the "Sustainability" pathway, envisions a world that gradually transitions toward inclusive, equitable development with a strong focus on environmental protection and low-impact consumption. SSP2, or "Middle of the Road," assumes a continuation of historical patterns, resulting in uneven development progress and moderate improvements in sustainability. SSP3, "Regional Rivalry," depicts a fragmented world where nationalism and security concerns dominate, leading to weak international cooperation, slow economic growth, and worsening environmental degradation in many regions. SSP4, "Inequality," outlines a divided world in which growing disparities in wealth, education, and political power create social fragmentation and unequal environmental outcomes. Finally, SSP5, "Fossil-fueled Development," features rapid economic growth driven by fossil fuel use and technological innovation, leading to improved human capital and local pollution management but high greenhouse gas emissions and significant climate risks [18].

SSP-RCP scenarios, also referred to as SSPX-Y scenarios, combine the foundations of SSPs and RCPs to project climate models of changes in the global climate system. SSP scenarios that are used as a baseline that describe future developments including technological and equality advancements, are integrated with and equated RCP, which demonstrates the predicted level of radiative forcing. Combining SSPs with RCPs yields scenario pairings such as SSP2-4.5 (moderate development and stabilization) or SSP5-8.5 (high growth and emissions). These combinations allow researchers to explore the interactions between societal behavior and climate outcomes in a consistent framework [19]. For regions like Malta, where socioeconomic and environmental systems are tightly coupled, such integrative approaches are essential to anticipate future vulnerabilities and adaptive capacity.

SSP-RCP scenarios do more than illustrate plausible climate futures; they underscore the critical influence of human decisions on long-term outcomes. The contrast between pathways such as SSP1-2.6 and SSP5-8.5 is not solely theoretical, but it represents the tangible difference between a future where adaptation is feasible and one where impacts may exceed manageable thresholds. By assigning time-bound trajectories to sea level rise and other climate hazards, these scenarios instill a sense of strategic urgency, enabling policymakers and planners to align infrastructure investments and land-use decisions with the anticipated scale and timing of climate challenges. In this way, scenario-based modeling serves not only as a forecasting tool but also as a framework for risk-informed, forward-looking governance.

2.2 Coastal Flooding and Inundation Modeling

Recent decades have seen rapid advances in flood inundation mapping, particularly through the use of remote sensing and geospatial technologies. Munasinghe et al. [20] provide a comparative analysis of satellite-based inundation mapping methods, showing how various sensors and algorithms perform under differing conditions. Similarly, Wu, et al. [21] emphasize the importance of integrating physical processes such as wave run-up and storm surge into inundation modeling for more accurate projections. In addition to satellite and aerial imagery, LiDAR-derived digital elevation models (DEMs) have become a standard input for high-resolution coastal flood modeling, allowing for precise identification of at-risk infrastructure and low-lying zones.

Modeling approaches now increasingly differentiate between static inundation methods and dynamic hydrodynamic simulations using tools such as ADCIRC and Delft3D. These allow researchers to simulate the interactions between tides, storm surges, and wave action in response to various sea level rise and extreme weather scenarios. Platforms like Climate Central's CoastalDEM and NASA's IPCC SLR Projection Tool are widely used to visualize global SLR risks under SSP-RCP pathways. Regionally, the SAVEMEDCOASTS-2 WebGIS [22] has provided critical data on relative sea level rise scenarios along Mediterranean coasts up to the year 2100, supporting policy and spatial planning across Italy, France, and Greece.

For this study a similar approach will be applied to the northeast coast of Malta, incorporating scenario-based sea level rise projections and geospatial analysis to generate spatially explicit vulnerability maps. These outputs will serve as a foundation for evaluating adaptation needs and informing local decision-making.

2.3 Coastal Vulnerability and Regional Context

Malta is centrally located within the Mediterranean Sea and consists predominantly of sedimentary rock formations, primarily limestone. The island's stratigraphy is characterized by five main formations, including the Upper and Lower Coralline Limestone, Globigerina Limestone, and Blue Clay. These layers vary in their susceptibility to erosion and structural integrity; for instance, Globigerina Limestone is relatively soft and prone to both marine and subaerial erosion, while Blue Clay, found at mid-slopes, is unstable and facilitates landslides and mass wasting events [12]. These geologic properties contribute significantly to the island's geomorphological vulnerability.

A 2022 study investigated Malta's geomorphology and integrated their findings with marine geophysical characteristics to describe the coastal vulnerability of the island [23]**.** By combining both physical and social indicators, the research demonstrated that Malta is highly susceptible to coastal hazards including erosion, flooding, and sea level rise. These hazards are projected to intensify in both severity and frequency due to climate change, resulting in disproportionately high impacts on densely developed coastal zones. The vulnerability assessment identified several critical risk factors, including narrow coastal buffers, limited elevation, and intense anthropogenic pressure from urban development and tourism infrastructure.

The coastal margins are shaped by a combination of steep limestone cliffs, wave-cut platforms, and limited sandy beaches, with bathymetric profiles that descend rapidly in many regions. The island's tectonic setting is relatively stable, located on the African Plate near the boundary with the Eurasian Plate, yet ongoing microseismic activity and long-term crustal deformation may contribute to gradual subsidence in some areas. Although detailed subsidence rates for Malta are not well documented, satellite-based Interferometric Synthetic Aperture Radar (InSAR) methods used elsewhere in the Mediterranean (such as Venice) [24]. This method suggests that low-magnitude land subsidence can exacerbate relative sea level rise and amplify local flood risks.

Malta has approximately 80% of its surface area designated as coastal or coastal-influenced land, placing its infrastructure and population at heightened exposure to regional sea level changes and erosion processes [25]. This spatial concentration of assets in vulnerable zones elevates both the physical and economic stakes of coastal climate impacts. Together, Malta's geological composition, geomorphological features, and high coastal exposure create a complex landscape in which climate-driven processes such as sea level rise and erosion are likely to interact and compound, creating significant challenges for sustainable coastal management and infrastructure resilience.

2.4 Socio-Economic and Infrastructure Impacts

As a Small Island State (SIS) and EU member, Malta's economic model is especially dependent on climate-sensitive sectors such as tourism, real estate, and maritime services [26]. Tourism contributes approximately 30% of Malta's GDP and is heavily reliant on coastal infrastructure such as hotels, restaurants, marinas and associated services [27]. Consequently, sea level rise and coastal inundation present a significant threat to the nation's economic stability. Despite a growing awareness among stakeholders regarding the potential consequences of climate change, there remains a notable reluctance to consider relocation or other long-term adaptive strategies. This hesitancy is largely due to the high economic value and strategic importance of waterfront properties [28]. This perception-reality gap (where stakeholders recognize risk but delay action) poses barriers to effective long-term resilience and planning. Spiteri and Gauci also highlight a persistent lack of localized risk communication and preparedness among Malta's coastal business communities. As a result, tourism-centric areas are disproportionately vulnerable to infrastructure damage and economic losses in the face of increasing coastal hazards.

In addition to the vulnerability of built infrastructure, projected shoreline retreat poses a critical threat to Malta's tourism sector. Malta's beaches are a central attraction for international visitors, and shoreline erosion or inundation is expected to directly affect both tourist numbers and associated revenue. It was found that countries that rely on a "sun-and-beach" tourism model are more likely to experience a Gross Domestic Product (GDP) decline and economic vulnerability [29]. This study includes an estimation of projected shoreline loss under varying sea level rise scenarios, which serves as a key input for evaluating Malta's economic fragility.

However, conventional coastal restoration methods are unlikely to be effective across much of Malta's coastline due to its distinctive geology. Beach nourishment, typically involving the offshore dredging and deposition of sand to artificially widen shorelines, is the most widely adopted response to beach loss globally [30]. Yet, the majority of Malta's coastline consists of coralline limestone outcrops, limiting the feasibility of sediment-based interventions. This geological constraint complicates the implementation of standard adaptation practices and necessitates more tailored, site-specific solutions.

Within the study area, only two small artificially maintained beaches, St. Julian's Bay and Balluta Bay, resemble sand-like shorelines. Both sites are backfilled with imported sand or pebbles to emulate sandy beaches and are situated directly at sea level, bounded by urban infrastructure and roadways, leaving little to no space for lateral expansion. Balluta Bay, approximately 50 meters in length, is subject to annual sand replenishment as part of a managed adaptation strategy. However, as sea levels rise and intertidal zones narrow, the cost and effectiveness of these replenishment efforts are expected to diminish. Over time, the reduction in viable shoreline space may reveal such interventions as economically unsustainable and physically impractical.

Figure 2.1: Balluta Bay.

The Maltese Islands are served by four Reverse Osmosis (RO) desalination plants, situated in Pembroke, Ċirkewwa, Għar Lapsi, and Ħondoq (Gozo). These facilities collectively produce an average of approximately 62,425 cubic meters of potable water per day, contributing around 64% of the national water supply. The remaining amount is sourced primarily from groundwater abstraction to meet the country's overall water demand [31]. As seen in Malta, it is important for RO plants to be located on or near the coastline as the plants require large and continuous volumes of seawater as input. Being near the coast minimizes the need for long-distance intake pipelines, reducing energy costs, infrastructure complexity, and environmental impact. Furthermore, RO plants produce brine (a concentrated saltwater byproduct) that must be safely discharged. Coastal locations allow direct return of this brine to the sea [32].

Figure 2.2: Pembroke reverse osmosis plant and discharge pipe.

Information regarding Malta's RO plants and their locations are particularly relevant to this specific research endeavor, as the Pembroke RO plant is located within the designated study area and may be directly impacted by future sea level rise and coastal inundation scenarios. In addition to the facility itself, the plant's critical infrastructure, particularly intake and brine discharge pipelines, are positioned at or below current sea level. If these components were to become submerged or physically damaged due to elevated sea levels, storm surges, or erosion, the plant's operational capacity could be severely compromised [33]. Such disruptions would not only pose a threat to national water security, given the plant's substantial contribution to Malta's potable water supply, but could also lead to environmental consequences, particularly if brine discharge systems fail or become misaligned, affecting nearby marine ecosystems. Therefore, assessing potential inundation risks to coastal infrastructure such as the Pembroke RO facility is essential in national climate adaptation and water resource planning.

In addition to the risks faced by surface infrastructure such as RO plants, Malta's groundwater reserves are also increasingly vulnerable to salinization due to sea level rise. A significant portion of the nation's water supply, particularly for agricultural and domestic use, originates from the Mean Sea Level Aquifer (MSLA) and the Perched Aquifers distributed across the islands, where a layer of freshwater, sustained by rainfall, floats on top of seawater due to differences in density. As sea levels rise, the gradient between seawater and freshwater in coastal aquifers becomes altered, allowing saltwater to migrate inland and upward into freshwater zones [34]. This phenomenon, known as saltwater intrusion, results in the contamination of previously potable groundwater with elevated salinity levels, rendering it unsuitable for consumption or irrigation without costly treatment. In Malta, this process is further exacerbated by long-standing over-extraction, which reduces freshwater pressure and allows saline water to encroach more rapidly into aquifers.

The implications of this are particularly severe in a context like Malta, where groundwater abstraction remains a key component of the national water budget, as there are no above-ground fresh water supplies and alternative water sources are limited. Prolonged exposure to saline conditions can permanently alter aquifer chemistry and reduce recharge capacity, leading to long-term loss of groundwater viability. As such, SLR-driven saltwater intrusion threatens to compound Malta's existing water stress, further increasing reliance on RO desalination and thereby amplifying the critical importance of safeguarding both surface and subsurface water infrastructure. Effective adaptation will require integrated water resource management, including restrictions on abstraction, improved aquifer recharge monitoring, non-conventional water sources and long-term land use planning.

2.5 Policy, Governance, and Adaptation Gaps

Despite Malta's growing exposure to climate-related coastal hazards, the country's governance architecture for adaptation remains insufficiently coordinated and largely reactive. While various strategies and infrastructure projects signal progress, they often operate in isolation, without the cohesive institutional frameworks necessary for long-term resilience. This section examines the disjointed nature of Malta's adaptation efforts, highlighting critical policy, planning, and governance gaps that undermine the country's capacity to manage accelerating coastal risks.

Malta's climate adaptation governance remains fragmented and underdeveloped, despite the ratification of the Integrated Coastal Zone Management (ICZM) Protocol in 2019. Although this commitment formally endorses a holistic approach to coastal governance, its implementation has been limited. A 2022 policy review by the Malta Environment and Resources Authority (ERA) acknowledged that while ICZM principles are present in national strategies, they have yet to translate into enforceable policies due to weak inter-agency coordination and the absence of binding adaptation mandates [35]

Among the most notable infrastructural initiatives in recent years is the National Flood Relief Project (NFRP), launched in 2019 with European Union funding. This large-scale effort aimed to address severe stormwater challenges through the construction of subsurface tunnels, retention basins, bridges, and culverts, primarily in urban flood-prone catchments. These interventions substantially increased Malta's capacity to manage pluvial flooding by channeling and storing excess runoff during extreme rainfall events, thereby mitigating impacts on property, transport systems, and public health [36].

The NFRP represents a significant advancement in Malta's climate adaptation infrastructure, offering a scalable approach to urban flood control that can respond to projected increases in precipitation intensity under climate change scenarios. However, while the project represents a significant step forward in stormwater adaptation, it primarily addresses short-term, episodic flooding driven by extreme rainfall events, rather than long-term chronic hazards such as sea level rise and coastal inundation. As such, it exemplifies a reactive, event-driven model of climate resilience, focusing on storm response rather than anticipatory coastal planning. The lack of integration with coastal zone management, land use policy, and sea level rise projections limits the NFRP's utility in safeguarding against permanent inundation or saline intrusion, which require spatial retreat, zoning regulation, and dynamic coastal modeling. A comprehensive resilience strategy must therefore build upon such stormwater infrastructure while concurrently advancing proactive, long-term adaptation measures for Malta's exposed coastlines.

The Coastal-COVER strategy (2021–2023) sought to close data gaps by conducting national-scale coastal vulnerability assessments. However, its lack of site-specific flood risk maps and legally binding outputs has restricted its applicability in operational and spatial planning [37]. As Kelman [38] highlights, small island states often experience vertical governance mismatches, where national adaptation plans fail to translate into local action due to under-resourced municipal bodies and limited decentralization. In Malta, this is exacerbated by the significant influence of private developers on coastal land use, often through project-specific exemptions that contravene long-term risk assessments.

The Malta Planning Authority (MPA), which oversees development permitting and spatial planning, continues to approve coastal projects that may be incompatible with future sea level rise projections, especially in vulnerable low-lying zones like Marsaskala, Sliema, and Bugibba. The influence of private developers in shaping the coastal urban fabric, often through piecemeal rezoning and project-specific exceptions, further complicates resilience efforts. Pace et. al [39] argues that Malta's planning system suffers from choosing short-term economic objectives while overriding long-term environmental safeguards.

Malta's Strategic Plan for Environment and Development (SPED) serves as the main spatial planning document and outlines a high-level vision for sustainable development [40]. However, it lacks detailed coastal vulnerability metrics or enforceable adaptation zoning. Existing local plans, many of which date back over a decade, do not incorporate recent climate risk data or reflect new sea level rise projections. Furthermore, these plans focus primarily on land development permissions and provide minimal guidance on long-term coastal resilience.

Updating these documents to integrate flood modeling, hazard zones, and retreat strategies is essential for effective adaptation. Additionally, Malta's National Climate Change Adaptation Strategy, while identifying coastal zones as priority areas, does not mandate cross-sectoral integration with tourism, infrastructure, or emergency response agencies. The strategy remains predominantly aspirational, with limited accountability mechanisms or budgetary allocations for coastal resilience. To transition from a reactive to an anticipatory governance approach, it is essential that Malta update its legal and planning frameworks to embed climate risk considerations. Without these reforms, Malta's coastal management will remain vulnerable to climate-induced shocks, including sea level rise accelerates in the Mediterranean basin.

2.6 Knowledge Gaps and Research Needs

While the general risks to Malta's coasts are well-documented, significant data gaps persist, particularly in relation to high-resolution inundation mapping and community-level vulnerability assessments. Several regional and EU-funded initiatives contribute to understanding and managing sea level rise in the Mediterranean.

IWAVEnet [41] focuses on wave modeling in the central Mediterranean Sea and provides high-resolution data on wave dynamics, useful for integrating storm surge and wave run-up into coastal risk models. It supports early warning systems and adaptation planning in Malta and neighboring countries. MedSeaRise [42] produces regional projections of sea level change using downscaled CMIP6 data and historical tide gauge records. The platform emphasizes scenario planning, coastal land loss, and socioeconomic impact assessments. It is particularly relevant for evaluating temporal and spatial sea level variability at the national scale. SAVEMEDCOASTS-2 [22] is a webGIS platform that offers spatially explicit sea level rise projections combined with storm surge overlays up to the year 2100. The tool is critical for decision-makers and urban planners, allowing for user-defined area queries to examine relative sea level rise, exposure layers, and vulnerability indicators across Mediterranean coastal zones.

Projects such as IWAVEnet, MedSeaRise , and SAVEMEDCOASTS-2 provide critical regional overviews and tide-state modeling platforms. However, they often lack spatial detail at the neighborhood or parcel scale. This limitation reduces their utility for precise urban planning and policy formulation.

A common shortcoming that many existing studies face is the tendency to generalize national or regional risks rather than quantifying localized consequences. This can include but is not limited to which buildings, infrastructure, or neighborhoods would be directly affected, and by how much [43]. Risk assessments that detail specific locations and quantified impacts are far more influential in shaping policy and driving climate adaptation measures [44]. A location-specific resolution is especially critical for urbanized coastal zones in Malta, where competing land uses, dense development, and economic dependence on tourism intersect.

Despite a growing body of research on coastal vulnerability in Gozo, the smaller of Malta's two main islands, relatively little work has been dedicated to systematically quantifying climate risks on the main island, particularly in its northeast region. The northeast coast, including St. Julian's and Sliema, represents a core area of concern. These neighborhoods are not only the epicenter of Malta's hotel and resort industry, but also attract a significant proportion of the island's 3.56 million annual tourists [27]. Many hotels, restaurants, and businesses are located within just a few meters of the existing shoreline, placing them at direct risk of coastal inundation under even moderate sea level rise scenarios. Moreover, coastal roads, pedestrian promenades, and infrastructure that support these economic activities are also exposed to these risks [45]. By assessing detailed, spatially explicit sea level rise models, this project will contribute to bridging the gap between global climate scenarios and actionable, local scale risk assessments.

Ultimately, this study contributes to climate resilience efforts by enabling evidence-based and location-specific decision-making, critical actions for small island nations like Malta, where economic livelihoods and coastal habitability are tightly intertwined.

2.7 Modeling Frameworks and Scenario Applications for Sea Level Rise

This study employs both temporal and magnitude-based projection frameworks to evaluate future SLR impacts on Malta's northeast coastal region. The temporal SLR projections model 50, 70, and 100 years from the year 2000 (2050, 2070, and 2100 respectively). These intervals correspond to near-, mid-, and long-term planning periods, aligning with international adaptation targets. Complementing this approach, the orders of magnitude simulate sea level increases of +0.5 meters, +1.0 meters, and +1.5 meters, regardless of timing.

Although the impacts of sea level rise are expected to be negative, research indicates that, with the implementation of effective mitigation and adaptation strategies, the overall outcomes, such as impacts on national gross domestic product (GDP), can be minimized [47]. This underscores the critical importance of developing robust, evidence based mitigation and adaptation plans. Many adaptation policies and initiatives are strategically aligned with international targets and deadlines, including the 2030 climate goals, the United Nations Sustainable Development Goals (SDGs), and commitments under the Paris Agreement. These frameworks serve as guiding benchmarks for coordinated climate resilience and sustainable development efforts. Projections on a timeline can inform long-term infrastructure plans and resilience frameworks. Time-based projections support adaptive management, allowing planners to update decisions as more data become available over time [47]. Figures using timelines are also critical when communicating with decision-makers and the public. Discussing what 2050 may look like resonates more than under one meter SLR, and better portrays the urgency related to the associated risks.

One of the limitations of using time-relevant predictions is that uncertainty increases as the target year moves further into the future. Projections farther down the timeline carry larger uncertainties due to unknown variables such as actual emissions, threshold points and socioeconomic factors. Focusing too heavily on specific years may also give a false sense of precision. These models are only a prediction, and will not be accurate compared to reality. It is essential to convey to decision makers and planners that these scenarios should be interpreted with caution, acknowledging their inherent uncertainties.

Magnitude-based projections also have different attributes to offer and work well coincided with temporal scale models. Scenarios based on the measurement of SLR allows planners to focus directly on physical impacts such as ecosystem loss, inundation, and infrastructure vulnerability. Magnitude based SLR allows flexible "what if" analysis. Planners can model a one meter rise regardless of when it happens, supporting decision making under uncertainty. These projections will also aid in defining tipping points that may occur only after a specific amount of sea rise and account for uncertain timing. In contexts where an estimation is more certain than the other, for instance if it is sure that sea level will rise by one meter but the year is unknown, these predictions will be practical.

On the other hand, magnitude-based modeling has its challenges. For example, a single magnitude doesn't always show the rate of change, which is a crucial factor when planning for adaptation windows or infrastructure or evacuation planning. Local governments often need to know what should be expected in the next 10 to 30 years for budgeting and resilience planning; magnitude-only projections lack this temporal guidance.

To simulate sea level rise and tidal variation, this study utilizes model outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6), a globally coordinated climate modeling initiative led by the World Climate Research Program (WCRP) Working Group on Coupled Modelling (WGCM). CMIP6 provides a standardized framework in which climate modeling institutions from around the world run simulations of the Earth's climate systems by using comparable scenarios and inputs. These simulations allow for standardized results that aid in the improvements of said models and validations of the results [48]. This harmonization improves model comparability, accuracy, and usability for climate impact assessments [49]. Four climate models were employed in this study, each containing one or more SSP-RCP frameworks.

2.8 CMIP6 Model Frameworks Supporting Mediterranean Sea Level Rise Analysis

This section describes the four CMIP6 climate models utilized in the study, detailing their structural characteristics, regional relevance, and contributions to sea level rise projections in the central Mediterranean region. Each model contributes unique strengths in representing ocean-atmosphere processes, hydrological cycles, and regional variability. They also support a range of SSP-RCP combinations and offer unique capabilities that inform the scenario-based projections applied in Section 3.

2.8.1 Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research Model (AWI-CM)

The Alfred Wegener Institute Climate Model (AWI-CM), developed by the Helmholtz Centre for Polar and Marine Research, plays an important role in sea level rise and climate impact assessments, particularly in the context of high latitude feedbacks and European regional climate dynamics. This model, which supports a wide range of SSP-RCP combinations, projects global warming trajectories that align closely with the ensemble mean of CMIP6 climate models. However, it offers notable distinctions in polar feedback mechanisms, particularly through its projection of more rapid Arctic sea ice decline than many earlier models [50]. This accelerated ice loss is critical for understanding global sea level contributions from polar regions and associated feedbacks in atmospheric circulation.

Importantly, the AWI-CM model projects that ocean currents, including the Gulf Stream, remain relatively stable under future climate scenarios. This suggests that Europe and the North Atlantic may experience less relative warming compared to other mid latitude regions, due to the persistence of oceanic heat transport. Such stability in thermohaline circulation is relevant for Mediterranean and North African climate modeling, as it influences regional precipitation patterns, heat distribution, and coastal impacts. In the context of Malta and the broader Mediterranean Basin, the AWI-CM model contributes valuable insight into region-specific sea level dynamics, atmospheric-ocean coupling, and potential shifts in climate patterns under multiple emissions pathways.

2.8.2 Centre National de Recherches Météorologiques Model (CNRM-CM6-1)

The CNRM-CM6-1, developed by the Centre National de Recherches Météorologiques (CNRM) in collaboration with the National Centre for Scientific Research (CNRS) is part of the CMIP6 ensemble and supports a full range of SSP-RCP scenario pairings. This model emphasizes improvements in land-atmosphere interactions and ocean heat uptake, incorporating advanced parameters of cloud microphysics and convection processes [51]. It performs particularly well in simulating hydrological cycles and surface temperature gradients, which are essential for understanding Mediterranean basin precipitation trends and coastal stressors. Given Malta's exposure to compounded climate risks such as drought, runoff, and precipitation variability, the CNRM-CM6-1 model provides regionally relevant projections for integrated climate and water resource modeling [52] . Its high resolution and strong performance in simulating Mediterranean climate dynamics make it particularly useful for assessing localized impacts of sea level rise and heat extremes.

2.8.3 National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory Model (GFDL-CM4)

The GFDL-CM4, developed by the Geophysical Fluid Dynamics Laboratory under National Oceanic and Atmospheric Administration (NOAA), represents one of the most physically comprehensive models in the CMIP6 framework. Used under high-emissions scenarios such as SSP5-8.5, the model emphasizes coupled ocean-atmosphere interactions and includes a representation of radiative transfer, cloud dynamics, and ocean biogeochemistry. It is particularly noted for its high skill in modeling global ocean circulation and vertical heat distribution, which is vital for estimating steric sea level rise and for isolating regional variations [53]. While the model tends to predict a stronger warming signal globally, it also captures complex dynamics such as the weakening of Atlantic Meridional Overturning Circulation (AMOC) under high emissions, which has significant implications for regional sea level patterns in Europe and the Mediterranean [54]. For Malta, this model helps estimate both large scale oceanic mass redistribution and thermal expansion that influence relative sea level trends.

2.8.4 Met Office Hadley Centre Model (HadGEM3-GC31-LL)

The HadGEM3-GC31-LL model, developed by the UK Met Office Hadley Centre, is a flagship global climate model. It includes advanced representations of aerosol-cloud interactions, land-surface feedbacks, and ocean eddies, contributing to improved modeling of regional climate extremes and variability. This model is well known for simulating North Atlantic storm tracks and European climate variability, both of which are relevant for assessing storm surge and wind driven coastal flooding in the central Mediterranean [55]. HadGEM3's high spatial resolution also enables better capture of Mediterranean microclimates and nearshore interactions that affect SLR impacts on small islands. For Malta, the Hadley model offers high quality outputs related to atmospheric dynamics, seasonal variability, and extreme event frequency, all of which are critical components of coastal vulnerability assessments.

The primary variable analyzed from these models was *zos,* representing sea surface height anomalies relative to the geoid [56]. The geoid is a model of Earth's mean sea level used as a reference surface for measuring elevations, accounting for variations in gravitational potential

3. Methodology

This chapter outlines the analytical framework and modeling procedures used to assess sea level rise (SLR) and coastal flood risk along Malta's northeastern coastline. It includes magnitude-based and scenario-based modeling strategies, as well as the integration of wave height and tidal variation into future sea level rise projections. The methods described here were used to generate spatial flood extents and infrastructure exposure scenarios, which are presented in the subsequent chapter.

3.1 Magnitude-Based Modeling

To simulate static sea level rise, Digital Elevation Model (DEM) data with a one-meter spatial resolution was processed using ArcGIS Pro. Using the Raster Calculator and conditional extraction tools, threshold filters representing incremental sea level increases of +0.5 meters, +1.0 meters, and +1.5 meters were applied. These elevation thresholds allowed the generation of inundation extents, representing permanent sea level rise scenarios under static conditions.

To evaluate shoreline vulnerability, publicly accessible beach areas were delineated using a combination of field survey observations and digitized satellite imagery. These beach polygons were clipped to intersect with each modeled inundation layer using ArcGIS overlay analysis. Subsequently, the "Calculate Geometry" tool was employed to derive the remaining recreational beach area within each sea level threshold. The magnitude-based inundation maps are provided in Section 4.

3.2 Scenario-Based Modeling (SSP-RCP Framework)

To project long-term sea level rise under different climate futures, a scenario-based approach was adopted using data from the Coupled Model Intercomparison Project Phase 6 (CMIP6). Local sea surface height anomaly data (*zos*) were extracted from four of the CMIP6 model outputs using Panoply, a NetCDF viewer developed by NASA's Goddard Institute for Space Studies [57]. The extracted *zos* datasets were organized according to their associated SSP scenarios (SSP1-2.6, SSP2-4.5, SSP3-70 and SSP5-8.5).

To establish a historical baseline, the average sea surface height for each model was calculated over the period 1 January 1850 to 16 December 1999. This baseline was then used to normalize sea level values from 16 January 2000 through 16 December 2100, enabling the creation of continuous, scenario based projections.

For each time step from 2000 to 2100, the mean *zos* value across models was computed within each SSP scenario. To approximate total relative sea level rise (RSLR) in Malta, the *zos* outputs, representing local sea surface height anomalies relative to the geoid, were added to global mean sea level rise (GMSLR) projections derived from the IPCC Sixth Assessment Report. This integration accounts for both regional dynamic sea level effects and global ocean volume changes. The factors accounted for in these projections, as seen in Figure 3.1, include thermal expansion, land water storage and the melting rates of glaciers, greenland and Antarctica [59].

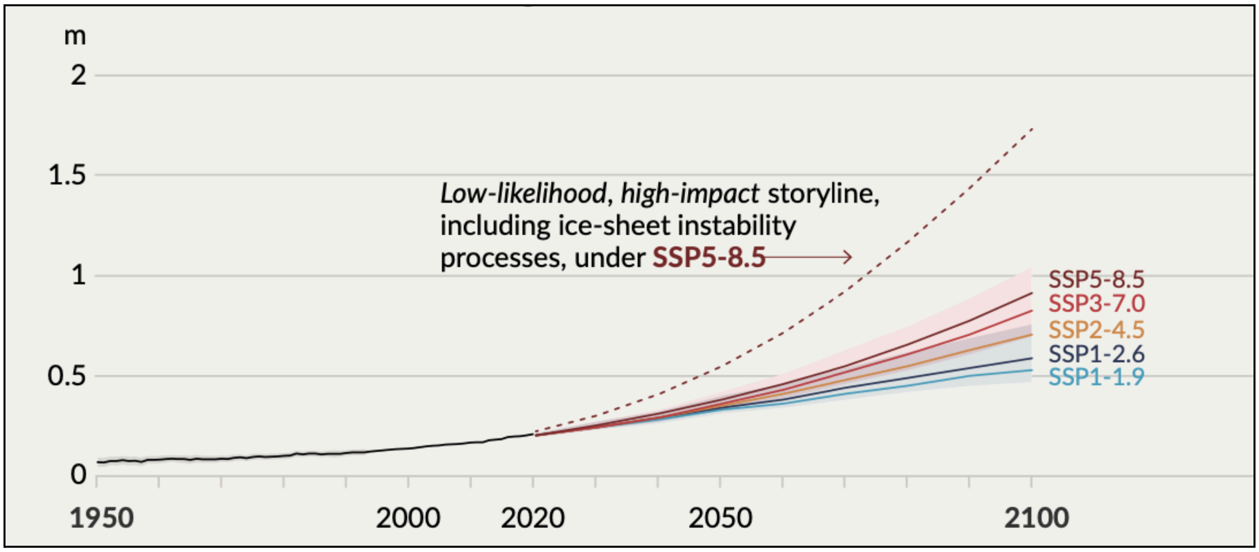

Figure 3.1: Global mean sea level change relative to 1900. Adapted from: IPCC [58]

3.3 Integration of Wave Height and Tidal Variation

To better simulate episodic coastal flooding and account for dynamic marine processes, wave height and tidal data were incorporated into the static SLR scenarios.

Average (0.96 m) and maximum (4.5 m) wave heights were obtained from the MedSeaRise project, which models wave conditions specific to the central Mediterranean. These wave heights were superimposed onto the RSLR projections from Section 3.2 to create compound flood heights, representing both daily and extreme conditions.

To complement the sea level rise projections, tidal modeling was conducted using the TPXO10v2 global tide model, developed by the Oregon State University Tidal Inversion Group. This model provides high-resolution tidal constituents and is widely used for coastal and oceanographic applications. Tide data for Portomaso, a city located in the study area, was retrieved covering observed data from 2020 and extending to a predictive outlook for 2030 (Table 3.1).

Table 3.1: Summary of tidal data retrieved from Portomaso sea station.

Minimum	-0.14 meters
Maximum	0.15 meters
Mean	0.00 meters
Standard Deviation	0.06 meters
95th Percentile	0.09 meters
99th Percentile	0.12 meters

3.4 Infrastructure Exposure Analysis

To assess vulnerability of coastal infrastructure, the modeled flood extents were used to spatially intersect with vector datasets of buildings and roads. These included OpenStreetMap-derived infrastructure layers clipped to the defined study area. Six scenarios were chosen to represent average and extreme scenarios for 2050 and 2070.

Infrastructure types were further categorized (e.g., road type, land use function) to allow qualitative interpretation of risk to utilities, transportation networks, and tourism infrastructure. These exposure results are presented and discussed in detail in Section 4.

4. Findings and Discussion

This chapter presents the results derived from the modeling techniques described in Chapter 3 and explores their implications for infrastructure, policy, and long-term climate resilience. The findings reveal escalating coastal risk for Malta's northeastern shoreline, with implications for urban planning, economic stability, and national adaptation strategies.

4.1 Loss Under Magnitude-Based Projections

The application of +0.5 m, +1.0 m, and +1.5 m SLR scenarios revealed coastal inundation and recreational shoreline loss. Inundation in the study area is represented by Figure 4.1. The percentage of beach area projected to be lost under each SLR scenario was subsequently calculated using the Calculate Geometry tool. It was found that under +0.5 m SLR there would be approximately 9.27% beach area loss in the study area and with +1.0 m SLR and +1.5 m SLR, beach area loss would be 27.96% and 51.55% respectively (Figure 4.2). This shows a nonlinear increase in vulnerability, with a significant escalation of loss between the moderate and high-end projections. This level of shoreline loss effectively eliminates public beach access in key tourism zones like Balluta Bay, threatening the economic foundation of Malta's beach-based tourism industry. Such a decline would likely displace both seasonal employment and strain public infrastructure designed to accommodate coastal visitors.

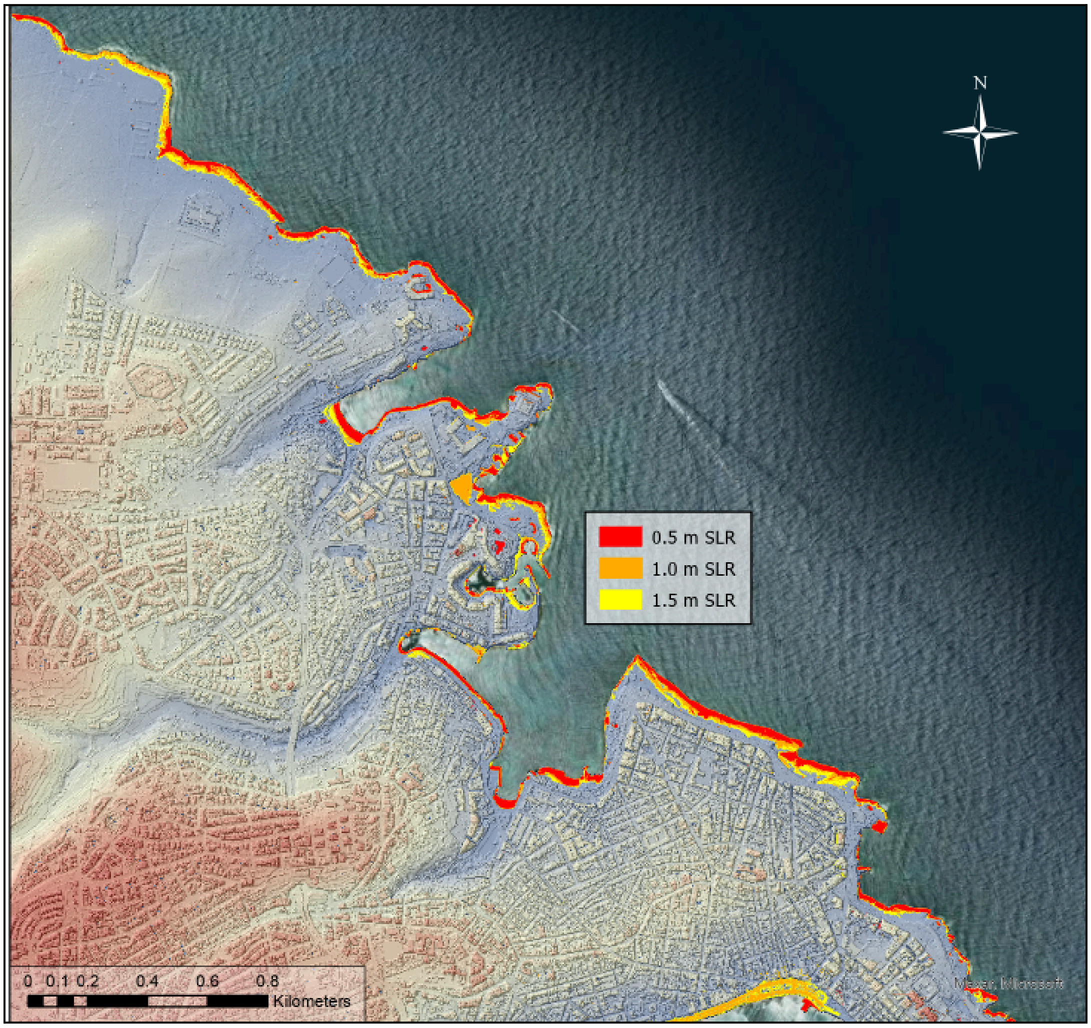

Figure 4.1: Visualization of +0.5 m, +1.0 m and +1.5 m of sea level rise on the northeast coast of Malta.

Figure 4.2: Loss of accessible recreational shoreline under magnitude-based SLR scenarios (+0.5 m, +1.0 m, +1.5 m), along Sliema coast.

4.2 Scenario-Based RSLRR Projections (SSP-RCP)

In the CMIP6 outputs analyzed, *zos* values that represent sea level height about the geoid for Malta are consistently negative, indicating that regional sea level rise is projected to remain below the global mean. This does not imply an absence of sea level rise, but rather reflects the redistribution of ocean mass and steric changes due to regional dynamics and gravitational effects [7]. To normalize these values, they were added to the IPCC's projections for GMSLR, discussed in section 3. In the following figures and corresponding appendix tables, *minimum* values represent the lowest projections from the most conservative model, *maximum* values reflect the highest projections from the most extreme scenario, and *mean RSLR* denotes the average relative sea level rise across all models.

Table 4.1: Projected relative sea level rise means and maximums in meters for Malta under SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 in incremental years. Data combines global GMSL with regional *zos* adjustments.

	2050 max	2050 mean	2050 min	2070 max	2070 mean	2070 min	2100 max	2100 mean	2100 min
1-2.6	0.26	0.22	0.19	0.38	0.32	0.28	0.47	0.44	0.4
2-4.5	0.22	0.21	0.21	0.41	0.38	0.34	0.58	0.55	0.52
3-7.0	0.29	0.22	0.18	0.44	0.38	0.32	0.72	0.68	0.64
5-8.5	0.3	0.26	0.22	0.5	0.44	0.39	0.81	0.77	0.69

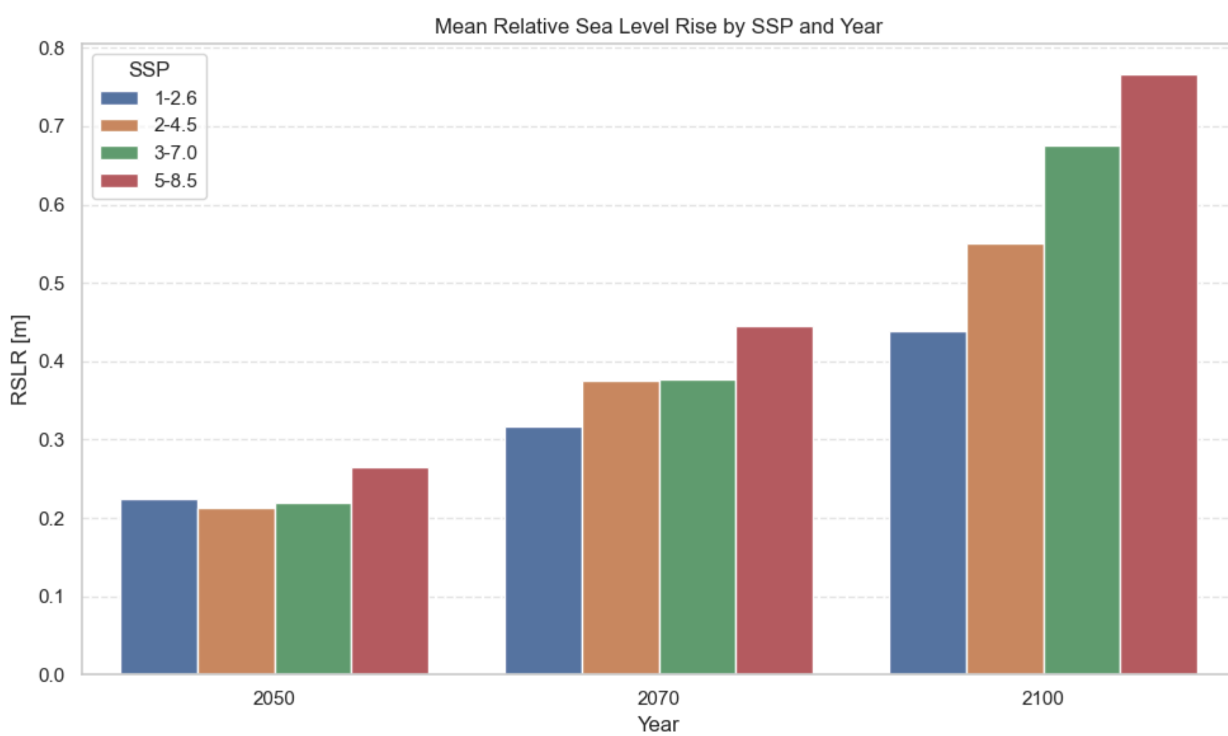

Figure 4.3: Mean RSLR divided by year and SSP.

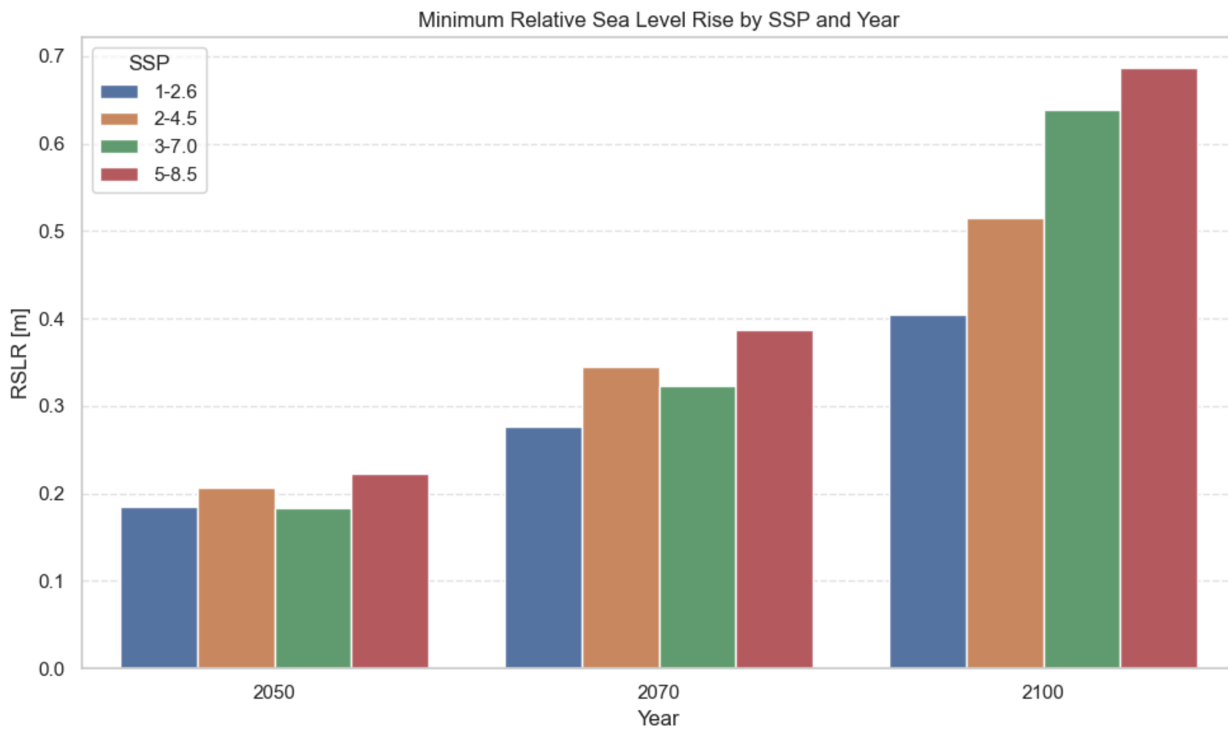

Figure 4.4: Minimum RSLR divided by year and SSP.

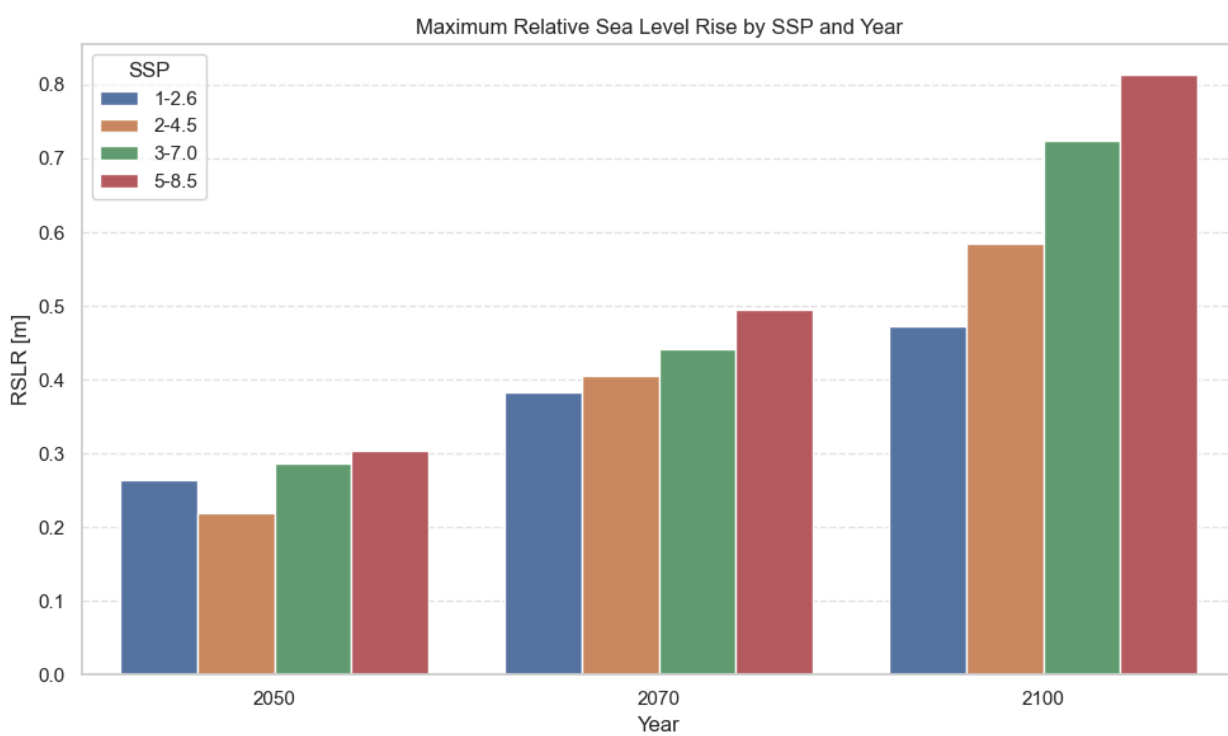

Figure 4.5: Maximum RSLR divided by year and SSP.

Figure 4.6 (below) illustrates projected worst-case coastal flooding scenarios for Malta by the year 2070. The year 2070 was chosen as a target year for inundation mapping to strike a balance between near and long-term projections. Unlike 2050, which may underestimate long-term impacts, or 2100, which carries greater model uncertainty and is often considered too distant for actionable planning, 2070 provides a strategic horizon that aligns with infrastructure lifespans and risk management timelines, especially in the context of coastal planning and adaptation in Malta. Under Shared Socioeconomic Pathway (SSP) 5-8.5, using the mean projected relative sea level rise (RSLR) and mean wave height, inundation levels may reach approximately 1.406 meters. When combining the maximum modeled sea level rise with the maximum projected wave height, potential inundation could reach up to 4.996 meters along the Maltese coastline. These scenarios indicate not only the encroachment of shorelines but also substantial flooding of coastal roads and infrastructure. The scenario incorporating mean RSLR and wave height is estimated to submerge approximately 47.36% of the identified recreational shoreline areas, while the most extreme scenario has the potential to inundate the entirety of coastal beaches in the study area. Although these outcomes represent high-end projections and may be considered unlikely, assessing such extremes is critical for understanding risk boundaries and informing long-term coastal adaptation strategies. Appendices A, B and C provide the full list of SLR projections for all of the researched SSP-RCP scenarios and target years.

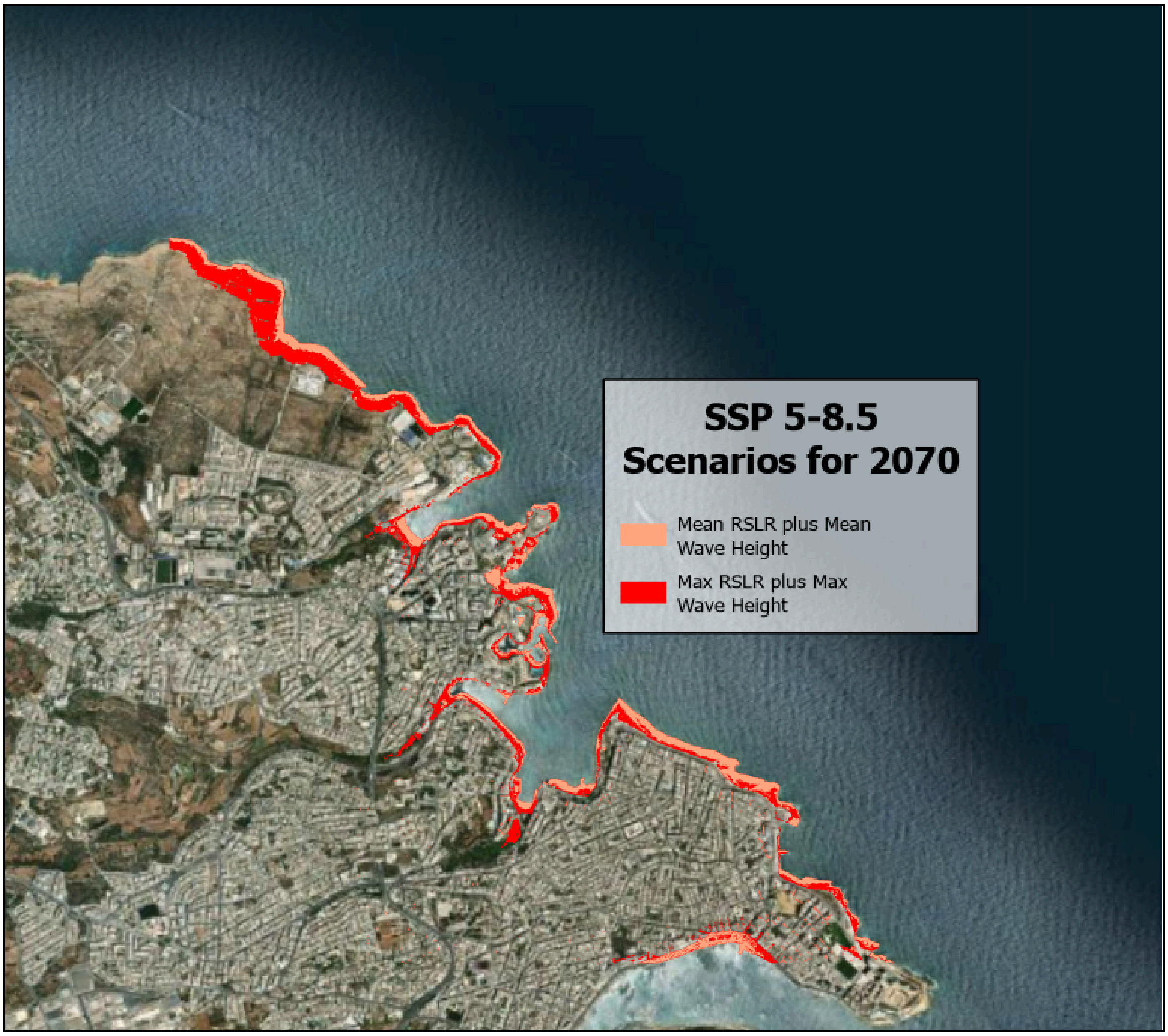

Figure 4.6: Visualization of mean and maximum scenarios for SSP 5-8.5 by 2070.

4.3 Role of Tidal Variation

The statistical analysis of tide data aids in creating a starting point for understanding local sea level behaviors. As seen in Table 3.1, the minimum and maximum values recorded between 2020 and 2030 at the Portomaso sea station reflect a narrow tidal range, from -0.14 meters to 0.15 meters, consistent with the Mediterranean's classification as a microtidal region. The mean represents the average sea level across the time series, while the standard deviation of 0.06 meters indicates relatively low variability in tidal levels. This metric is critical for assessing the frequency and magnitude of events in an otherwise microtidal environment, as even minor deviations from the mean could signal significant events in such a stable system. The 95th and 99th percentile values, 0.09 meters and 0.12 meters, respectively, highlight the thresholds for extreme high tide events, suggesting that tides exceeding 0.12 meters are highly uncommon.

While tides alone do not pose a major risk for coastal flooding in Malta, the consistently low amplitude means that even modest SLR due to climate change could cause today's extreme events to become more regular. Consequently, this baseline understanding is crucial for interpreting how projected sea level increases may interact with local tidal dynamics and exacerbate inundation risks over the coming decade.

Figure 4.7: Tidal scenarios for SSP 3-7.0 in 2070, including mean RSLR and mean wave height.

To streamline the analysis and avoid over-representing the scenario space, the map in Figure 4.7 includes tidal factors that focus on SSP 3–7.0 for the inundation mapping component, along with mean wave height and mean RSLR. SSP3–7.0 represents a middle-to-high emissions trajectory characterized by limited international cooperation and persistent regional challenges to sustainable development. While more extreme (SSP5–8.5) and more optimistic (SSP1–2.6) scenarios were reviewed in the broader model analysis, SSP3–7.0 was selected for spatial visualization as it provides a representative, policy-relevant projection that balances likelihood with impact. This approach ensures clarity without compromising comprehensiveness or decision making relevance.

The results seen in Figure 4.7 reveal only marginal differences: maximum tidal elevation resulted in a shoreline inundation reach of 1.49 meters, while the 95th percentile produced 1.43 meters. Even under the conditions using the mean tide, zero meters, there are minimal differences regarding its impact to RSLR. Resulting inundation maps appeared nearly identical, indicating that tidal variation within this range has minimal effect on the spatial extent of flooding under the selected scenario. While the visual output differences were limited, the inclusion of tidal variation ensures a comprehensive approach and provides a basis for evaluating worst-case versus high-probability tidal conditions.

4.4 Infrastructure Vulnerability and Socioeconomic Risks

In addition to the earlier shoreline loss estimations, this study identifies buildings and road infrastructure that are projected to be directly affected by relative sea level rise (RSLR), excluding impacts from storm surges or other extreme weather events. These spatial analyses were conducted using ArcGIS. The resulting exposure data (Table 4.2) provides a foundational basis for future cost assessments and supports evidence-based decision-making for infrastructure planning and climate adaptation strategies.

Table 4.2: Infrastructure Impacts under selected SLR scenarios.

Scenario	SSP-RCP	End Year	RSLR	Tide & Wave Height	Calculated SLR (m)	Impacted Infrastructure
1	1-2.6	2050	Mean	Mean	1.19	Smaller coastal roads, pathways and piers; Entire waterfronts of Balluta Bay and St. Julians Bay; Shoreline-adjacent restaurants
2	1-2.6	2100	Maximum	Maximum	4.97	Major Roads along the coasts and flooding of offshoot streets; Coastal parking lots; entire waterfronts of Balluta Bay and St. Julians Bay; Shoreline-adjacent restaurants; Reverse osmosis plant discharge and intake

						Pipe
3	3-7.0	2050	Mean	Mean	1.18	Smaller coastal roads, pathways and piers; entire waterfronts of Balluta Bay and St. Julians Bay; shoreline-adjacent restaurants
4	3-7.0	2100	Maximum	Maximum	5.22	Major Roads along the coasts and flooding of offshoot streets; Coastal parking lots; entire waterfronts of Balluta Bay and St. Julians Bay; Shoreline-adjacent restaurants; Reverse osmosis plant discharge and intake Pipe
5	5-8.5	2050	Mean	Mean	1.23	Smaller coastal roads, pathways and piers; entire waterfronts of Balluta Bay and St. Julians Bay; shoreline-adjacent restaurants
6	5-8.5	2100	Maximum	Maximum	5.31	Major Roads along the coasts and flooding of offshoot streets; Coastal parking lots; entire waterfronts of Balluta Bay and St. Julians Bay; Shoreline-adjacent restaurants; Reverse osmosis plant discharge and intake Pipe

The infrastructure exposure summarized in Table 4.2 demonstrates that even under moderate sea level rise (SLR) scenarios, vital assets, including coastal roads, piers, and businesses in areas like Balluta Bay and St. Julian's Bay are at considerable risk of flooding. By 2100, scenarios combining the highest projected sea level rise with extreme wave heights suggest potential inundation of major roadways, coastal parking areas, and critical facilities such as the reverse osmosis plant. Accounting for wave height is essential, as it captures dynamic water level variations from wave run-up and storm surges that can coincide with high tides, significantly intensifying flood impacts beyond static SLR estimates. Integrating both mean and maximum wave data into these scenarios yields a more realistic picture of risk, reflecting the combined influence of gradual and episodic coastal hazards.

These projected impacts also have important socioeconomic implications. Damage to transport links and essential services can disrupt economic activity, slow emergency response, and reduce property values in vulnerable coastal zones. Impacts to tourism infrastructure, including restaurants, promenades, and beach access, could further threaten revenue and employment in sectors closely tied to the shoreline. Disruption of the RO plant's intake and discharge systems would pose serious water security risks, while loss of transport and tourism infrastructure would destabilize economic activity. Accurately assessing these risks is crucial for supporting cost-benefit analyses and guiding adaptation priorities.

Overall, the integrated modeling highlights the complex nature of coastal vulnerability in Malta's northeast, showing how sea level rise, wave dynamics, and infrastructure exposure intersect. This comprehensive assessment offers a practical foundation for targeted adaptation planning, helping decision-makers prioritize the most effective resilience strategies.

4. Conclusions, Limitations and Recommendations

This study set out to reveal the growing vulnerability of Malta's northeastern coastline to sea level rise (SLR), with projected impacts that extend far beyond gradual inundation. It specifically aimed to quantify potential shoreline loss, identify critical infrastructure at risk, and evaluate governance and policy gaps in climate adaptation. The findings offer new insights into both the physical exposure and institutional readiness of Malta's coast, addressing the original research questions posed in Section one.

4.1 Key Conclusions

The analysis reveals a growing vulnerability of Malta's northeastern coastline to sea level rise, particularly in densely developed areas like Sliema and St. Julian's. Even under moderate SLR scenarios, substantial portions of recreational zones and public beach areas are projected to be inundated. The economic implications are significant due to Malta's reliance on coastal tourism, real estate, and infrastructure concentrated in low-lying zones.

Importantly, the study highlights that static sea level projections alone are insufficient for understanding real-world coastal risks. When wave run-up, storm surges, and tidal variations are overlaid onto regional sea surface height anomalies, the extent and severity of inundation increase dramatically. This highlights the need for comprehensive modeling frameworks that account for both chronic and episodic flooding events, particularly in urbanized and economically vital coastal zones.

Current governance frameworks in Malta remain fragmented, with national climate strategies failing to fully empower local councils or translate into enforceable coastal adaptation plans. Institutional barriers, coupled with high economic stakes in waterfront property, have delayed long-term resilience actions despite increasing awareness of climate threats. Gaps in high-resolution vulnerability mapping continue to hinder precise planning and investment.

4.2 Limitations

Although this assessment offered valuable insights, several important limitations should be acknowledged. The analysis was constrained by the resolution and availability of data; higher-resolution RCP models and digital elevation models (DEMs), along with detailed storm surge probability maps and coastal bathymetric data, would have allowed for more precise vulnerability assessments tailored to Malta's context as a small island state. Computational and time constraints also shaped the approach, leading to reliance on static inundation mapping rather than dynamic hydrodynamic modeling, which in turn limited the ability to visualize scenario outcomes through interactive maps or animations. Furthermore, the study's geographic focus was restricted to a selected portion of northeastern Malta, reducing the generalizability of the findings to other coastal zones with different geomorphological or socioeconomic characteristics. Finally, the assessment did not fully address the impacts of extreme storm events beyond sea-level rise and wave run-up proxies, and was unable to incorporate a detailed analysis of socio-demographic vulnerability, mainly due to time constraints.

4.3 Future Work Recommendations

Building on these findings, several pathways for future research and practice are recommended:

- **Expansion of geographic scope**: The methodology applied here should be extended to assess SLR vulnerability across the entirety of Malta, including the smaller islands of Gozo and Comino. As mentioned in the earlier sections, global projections of SLR do not encapsulate the full extent of impacts on SIS, specifically in the Mediterranean Basin.

- **Integration of groundwater modeling**: Saltwater intrusion into coastal aquifers due to SLR is an understudied but critical threat to Malta's freshwater security. Future work should incorporate groundwater and salinization models to simulate aquifer contamination under various SLR and climate change scenarios. This will aid in proactive land-use planning, desalination strategies, and sustainable water resource management.

- **Use of dynamic hydrodynamic models**: Future assessments should leverage advanced modeling tools to simulate storm surge, wave interaction, and compound flooding events in real time. These models can better inform coastal infrastructure planning and emergency response systems.

- **Development of hyperlocal projections**: Location-specific, high-resolution datasets on erosion, biodiversity loss, infrastructure exposure, and demographic vulnerability would significantly improve planning and prioritization. This is especially crucial for small island states like Malta, where small spatial changes can have disproportionate impacts.

- **Institutional reforms and participatory planning**: Research should also explore how institutional structures can be reformed to better align national and municipal adaptation efforts. Engaging local communities in co-developing adaptation strategies will be vital for long-term resilience and social buy-in.

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6. Appendices

Appendix A: Full list of projections considering RSLR and wave height scenarios for the year 2050, in meters.

SSP-RCP Scenario → **Factors ↓**	**1-2.6**	**2-4.5**	**3-7.0**	**5-8.5**
Raw RSLR (mean)	0.22	0.21	0.22	0.26
Raw RSLR (min)	0.19	0.21	0.18	0.22
Raw RSLR (max)	0.26	0.22	0.29	0.30
RSLR (mean) + mean wave height	1.19	1.17	1.18	1.23
RSLR (min) + mean wave height	1.15	1.17	1.15	1.18
RSLR (max) + mean wave height	1.23	1.18	1.25	1.27
RSLR (mean) + max wave height	4.72	4.71	4.72	4.76
RSLR (min) + max wave height	4.69	4.71	4.68	4.72
RSLR (max) + max wave height	4.76	4.72	4.79	4.80

Appendix B: Full list of projections considering RSLR and wave height scenarios for the year 2070, in meters.

SSP-RCP Scenario → **Factors ↓**	**1-2.6**	**2-4.5**	**3-7.0**	**5-8.5**
Raw RSLR (mean)	0.32	0.38	0.38	0.44
Raw RSLR (min)	0.28	0.34	0.32	0.39
Raw RSLR (max)	0.38	0.41	0.44	0.50
RSLR (mean) + mean wave height	1.23	1.34	1.34	1.41
RSLR (min) + mean wave height	1.24	1.31	1.28	1.35
RSLR (max) + mean wave height	1.34	1.37	1.40	1.46
RSLR (mean) + max wave height	4.82	4.88	4.88	4.94
RSLR (min) + max wave height	4.78	4.85	4.82	4.89
RSLR (max) + max wave height	4.88	4.91	4.94	4.99

Appendix C: Full list of projections considering RSLR and wave height scenarios for the year 2100, in meters.

SSP-RCP Scenario → **Factors ↓**	**1-2.6**	**2-4.5**	**3-7.0**	**5-8.5**
Raw RSLR (mean)	0.44	0.55	0.67	0.77
Raw RSLR (min)	0.40	0.52	0.64	0.69
Raw RSLR (max)	0.47	0.59	0.69	0.81
RSLR (mean) + mean wave height	1.40	1.51	1.64	1.73
RSLR (min) + mean wave height	1.37	1.48	1.60	1.65
RSLR (max) + mean wave height	1.43	1.55	1.69	1.77
RSLR (mean) + max wave height	4.94	5.05	5.17	5.27
RSLR (min) + max wave height	4.90	5.02	5.14	5.19
RSLR (max) + max wave height	4.97	5.09	5.22	5.31