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Resilient Waterfront Futures: Mapping Vulnerabilities and Designing Floating Urban Models for Flood Adaptation on the Tiber Delta

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Abstract: This paper explores the feasibility of floating urban development in Italy, given its extensive coastline and inland hydrographic network. The key drivers for floating urban development, as an adaptive approach in low-lying waterfront areas, include the increasing threats posed by rising sea levels and flooding and the shortage of land for urban expansion. However, as not all waterfront areas are suitable for floating urban development, a geographical analysis based on a thorough evaluation of multiple factors, including urban–economic parameters and climate-related variables, led to the identification of a specific area of the Lazio coast, the river Tiber Delta. A comprehensive urban mapping process provided a multifaceted geo-referenced information layer, including several climatic, urban, anthropic, and environmental parameters. Within the GIS environment, it is possible to extract and perform statistical analyses crucial for assessing the impact of flood and sea-level rise hazards, particularly regarding buildings and land cover. This process provides a robust framework for understanding the spatial dimensions of flood and sea-level rise impacts and supporting informed design-making. A research-by-design phase follows the simulation research and mapping process. Several design scenarios are developed aimed at regenerating this vulnerable area. These scenarios seek to transform its susceptibility to flooding into a resilient, adaptive, urban identity, offering climate-resilient housing solutions for a population currently residing in unauthorized, substandard housing within high flood-risk zones. This paper proposes a comprehensive analytical methodology for supporting the design process of floating urban development, given the highly determinant role of site-specificity in such a challenging and new urban development approach.

Keywords: floating development; adaptation; GIS; floating; risk; flood; sea level rise

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Academic Editor: Wei Sun

Received: 20 November 2024
Revised: 13 December 2024
Accepted: 31 December 2024
Published: 4 January 2025

Citation: Calcagni, L.; Ruggiero, A.; Battisti, A. Resilient Waterfront Futures: Mapping Vulnerabilities and Designing Floating Urban Models for Flood Adaptation on the Tiber Delta. *Land* **2025**, *14*, 87. https://doi.org/10.3390/land14010087

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1. Introduction

Coastal–riverine interface zones are complex and dynamic natural systems of transition between land and water and between terrestrial and marine ecosystems. They are generally more vulnerable to the cumulative effects, both direct and indirect, of climate change and meteorological hazards [1–3]. Additionally, they host a significant concentration of economic, cultural, and social services, assets, and activities.

Nevertheless, in Europe, about 86 million people, or 19% of the population, are estimated to live within 10 km of the coastline, and about 140,000 km^2 of coastal areas are 1 m above sea level [4–6]. In Italy, where the coast stretches for over 8300 km [7], about 70% of the population resides in coastal areas. The stretches of coastline most affected by human activities mainly concern the lower coast alone (approximately 5700 km). The United Nations Conference on Climate Change pointed out that by 2050, with current emission rates, the total urban population at risk from sea level rise (SLR) could number over 800 million people living in more than 570 cities. SLR projections for Italian coasts show an increase of between 0.94 and 1.45 m by 2100, depending on the prediction model and shared socio-economic climate change scenario. Considering both coastal and fluvial flood risk, Italy stands out as particularly vulnerable as floodplains encompass 28,885 km^2 (9.7% of the country's land area), with 13.3% of the population residing in these zones. Both figures are higher than the European average. At the same time, the rise in sea level, combined with an extensive high probability of flood risk, poses a significant challenge for several Italian cities. Assessing climate impacts on urban systems involves identifying exposed elements and classifying their related risk. According to the 6th IPCC Assessment Report's definition [8], the term risk refers to the potential for adverse effects on human or ecological systems. Risk classification is thus necessary to identify and optimize adaptation measures, prioritize preventive conservation strategies, and rehabilitate affected territories. Adaptation responses related to risk-based classification involve reducing hazard probability, exposure, and sensitivity. Currently, responses to flooding, SLR, and land subsidence include a wide range of adaptation strategies [9–13] that can be traced back to four main actions:

- Protect to reduce the likelihood of hazard;
- Accommodate by modifying buildings to reduce the impact of the hazard event;
- Retreat to reduce exposure by moving away from the source of hazard;
- Advance by creating new land by building seaward.

In 2022, the IPCC [8] highlighted floating structures for the first time as a viable accommodation strategy to address SLR and flood risks as part of a hybrid approach, combining them with protection measures. However, not all waterfront areas are suitable for floating urban development because of site-specific urban, social, cultural, infrastructural, climate, and hydrographic features. This study proposes the application of urban mapping principles to the water environment to enable the comprehension and management of complex environments by providing a multifaceted information layer. In previous studies by the authors, a geographic analysis based on a thorough evaluation of multiple factors, including urban–economic parameters and climate-related variables, led to the identification of potential areas for floating development on water within the Italian national territory [14]. This approach hinges on the assumption that floating urban development is mostly likely to take place as an extension of existing waterfront cities and settlements and that urban water bodies are an extension of the terrestrial urban surface. By overlapping soil consumption, demographic index, and urbanization degree with risk-exposed areas in terms of river flooding risk and coastal inundation risk—classified and mapped according to the Floods Directive 2007/60/EC [15]—highly vulnerable areas have been identified in terms of human lives and socio-urban–economic assets. Densely populated and urbanized cities like Milan, Turin, Rome, Modena, Forlì, Bologna, Ravenna, Bari, Catania, and Pisa also face the risk of fluvial and coastal inundation. Taking into consideration other factors like proximity to strategic transport infrastructure, environmental constraints, water quality, water level fluctuations, and microclimate conditions, prior studies have identified six vulnerable zones: Livorno (Tuscany), Tiber Delta (Lazio), Gaeta (Lazio), Po Delta (Emilia–Romagna and Veneto), Foggia (Puglia), and Catania (Sicily). This study further focuses on the Tiber Delta in the province of Fiumicino and Rome, identified as the most viable site for potential floating urban development due to its high population density, significant land use, vulnerability to SLR and flood risks, strategic infrastructure, and proximity to cultural and tourist assets without interfering with maritime navigation routes and natural restricted zones.

2. Materials and Methods

Based on the state of the art, this research proposes a compound-risk assessment analysis and relevant possible design scenarios. The analytical model was developed in a GIS environment at an urban scale. This research intends to prioritise the replicability and transferability of this approach which can be easily applied to any other site in Italy using equivalent datasets. The methodology can be traced back to three consequential steps (Figure 1):

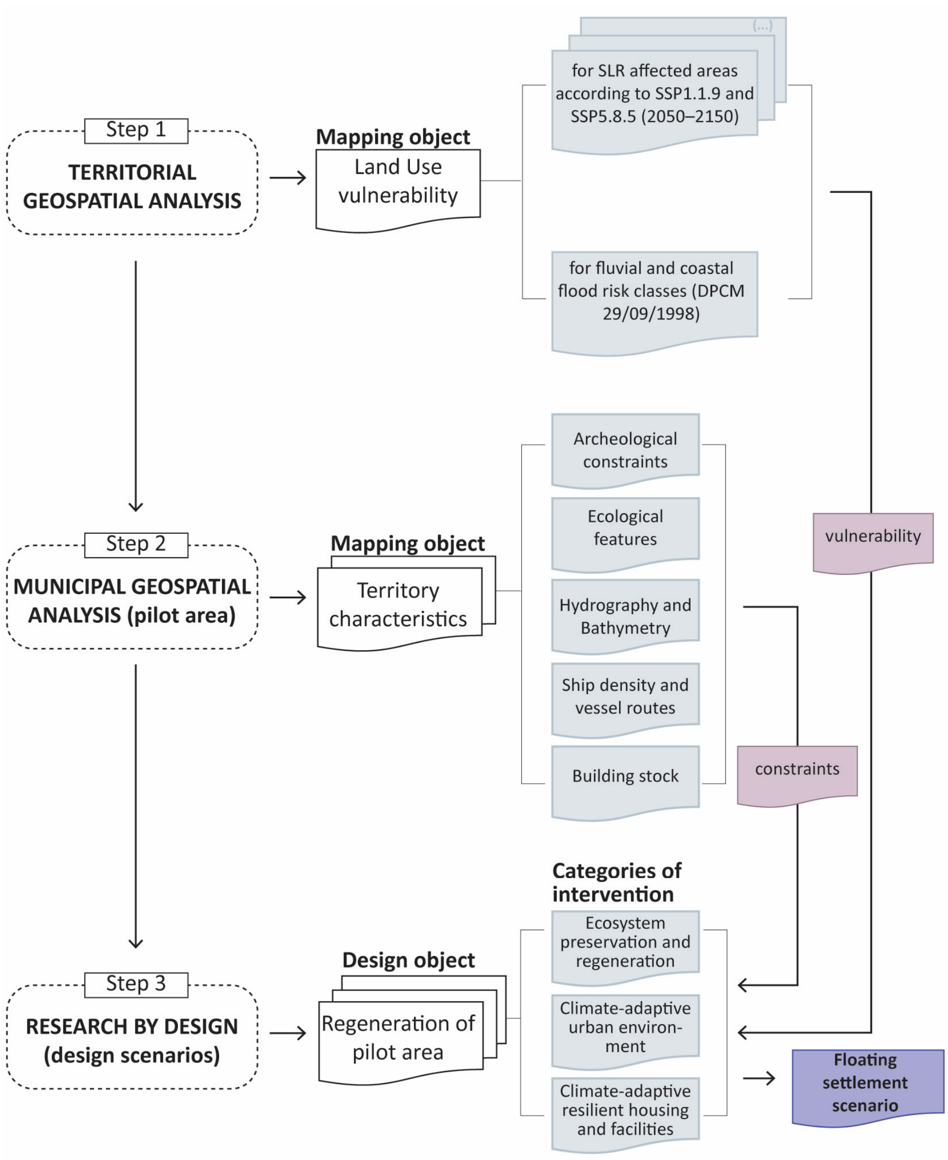

Figure 1. Breakdown summary of the methodology workflow.

1. Territorial geospatial analysis: economic, urban, and environmental impact analysis of the pilot area in relation to flood risk range maps:
    a. Affected land use (Corine land cover) according to SSP1.1.9 (2050, 2150) and SSP5.8.5 (2050, 2150) for coastal flooding;
    b. Affected land use (Legislative Decree 180/98 [16]) for fluvial and coastal flooding in terms of risk classes.
2. Municipal geospatial analysis (pilot area): hydrography, bathymetry, microclimate, transport routes, archaeological, environmental and landscape constraints, and socio-demographic indexes.

3. Research by design: development of possible design scenarios for the pilot area following the guideline framework developed by the authors in previous studies [17,18].

The proposed methodology follows the conceptual framework of risk assessment identified by the IPCC AR5 and AR6 reports: climate risk results from the interaction between exposure, vulnerability, and hazard [8,19]. Several authors have employed GIS-based mapping methodologies to address urban challenges, demonstrating their versatility and efficacy in multi-layered contexts [20,21].

The first two steps were developed in a GIS environment (QGIS Open Source) by combining the use of several available European, national, and regional open-source databases. In step 1, two parallel operations were carried out using the datasets listed in Table 1.

Table 1. Data types and sources used for the provincial geospatial analysis (step 1).

Data Field	Dataset	Source	Geometry Type
Orography	Digital Elevation Model (DEM)	Geoportale Regione Lazio (Lazio Region Geoportal)	Raster
	Coastline	Geoportale Regione Lazio—PTPR Tavola B (Lazio Region Geoportal—Regional Territorial Landscape Plan)	Vector
Risk	SLR-affected areas SSP1-1.9 (2050–2150) and SSP5-8.5 (2050–2150)	Elaboration using data from IPCC AR6	Vector
	Hydrological landslide and flood risk classes	Geoportale Regione Lazio Carta Idro-Geotermica (Lazio Region Geoportal—Hydro-Geothermal Paper)	Vector
Land use	Corine Land Cover (2018)	Geoportale Regione Lazio -Carta di Uso del Suolo (Lazio Region Geoportal—Land Use Map)	Vector

All datasets have been reprojected in the same CSR (WGS 84/ UTM zone 32N EPSG:32632) to allow for the use of geoprocessing tools.

The first focused on identifying the extension and typology (land use) of areas affected by SLR following this process.

1. Extraction of orography contour lines (every 10 cm) from the DEM elevation data, characterised by a horizontal spatial resolution of 2 m, using the geoprocessing tool Raster Extraction Contour
2. Clipping of contour lines for the provinces of Rome and Fiumicino.
3. Selection of contour lines corresponding to the expected sea height according to the scenarios SSP1-1.9 and SSP5-8.5 for 2050, 2100, and 2150 (Figure 2).

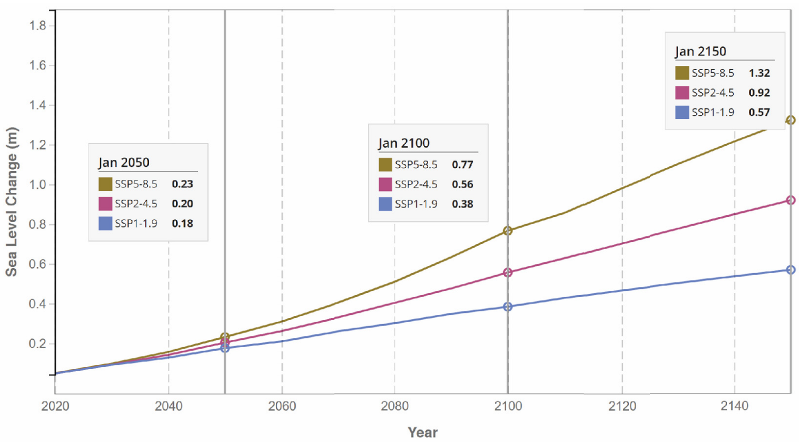

Figure 2. Sea level rise scenarios (SSP1-1.9, SSP2-4.5, and SSP5-8.5) for the years 2050, 2100, and 2150.

4. Extraction of coastline curve.
5. Creation of polygons (SLR-affected areas) using lines to polygons to identify areas between the coastline and SLR curves.
6. Land use clipping with SLR scenarios (polygons).
7. Data analysis using vector analysis—statistics by categories.

The second operation involved mapping areas designated as fluvial and coastal flood risk zones, classified into four flood risk levels R1–R4 (Table 2) according to Legislative Decree 49/2010 based on the following parameters: indicative number of potentially affected inhabitants; strategic infrastructures and structures (motorways, railways, hospitals, schools, etc.); environmental, historical, and cultural assets of significant interest present in the potentially affected area; distribution and type of economic activities in the potentially affected area; plants referred to in Annex I of Legislative Decree 59/2005 [22], which could cause accidental pollution in the event of floods and protected areas referred to in Annex 9 to Part III of Legislative Decree 152/2006; areas referred to in Annex 9 to Part III of Legislative Decree 152/2006 [23]; and other information considered helpful by the district authorities, such as areas subject to floods, with high volumes of solid transport and debris flows, or information on relevant sources of pollution.

Table 2. Flood risk level classification according to Legislative Decree 49/2010.

Risk Class	Risk Definition	Description
R 1	Moderate risk	Marginal social, economic, and environmental damage
R 2	Medium risk	Minor damage to buildings, infrastructure, and the environment which does not affect the safety of people, building usability, and economic activities
R 3	High risk	Functional damage to buildings and infrastructure, interruption of socio-economic activities, significant damage to the environment, and problems for the safety of people
R 4	Very high risk	Loss of life and injuries, serious damage to buildings, infrastructure, and the environment, and destruction of socio-economic activities

DPCM 29 Settembre 1998.

Step 2 consisted of an in-depth analysis of the area at the intersection between the Municipality of Rome and Fiumicino (the coast and Tiber Delta) in terms of existing constraints (archaeological and environmental), ecological features, hydrography characteristics, climate and microclimate conditions, infrastructure (mobility and proximity facilities), and socioeconomic and urban needs. This area was chosen as a pilot site because of the co-existence of the following criteria:

- The indicative number of potentially affected inhabitants;
- The high demographic concentration;
- City or densely populated area;
- Significant soil consumption;
- Vulnerable to SLR and coastal inundation;
- Vulnerable to flood risk: high probability hazard;
- The presence of strategic infrastructure (airport or port);
- The presence of archaeological sites;
- Flood risk classification;
- No interference with vessel routes.

The data used for this analysis are listed in Table 3.

Table 3. Data types and sources used for the territorial geospatial analysis (step 4).

Data Field	Dataset [1]	Source	Geometry Type
Vulnerability	Flood risk areas: land below annual flood level in 2050–2100 (SSP1.1.9 and SSP5.8.5)	Climate Central (https://coastal.climatecentral.org/ accessed on 20th November 2024)	Vector
	Flood classification risk	Geoportale Regione Lazio, Mappe del rischio (Lazio Region Geoportal—Risk maps)	Vector
Urban–Anthropic	Built environment (building stock)	Geoportale Regione Lazio (Lazio Region Geoportal)	Vector
	Mobility on land (main and secondary roads, bridges)	Geoportale Regione Lazio (Lazio Region Geoportal)	Vector
	Mobility on water (main vessel routes)	Vesselfinder *	Vector
Environmental	Bathymetry map (seabed topography)	Isprambiente viewer—Coastenergy Webgis *	Raster
Constraints	Archeological areas	Geoportale Lazio—Aree Archeologiche (Lazio Region Geoportal—Archeological areas)	Vector
	Natura 2000 areas	Geoportale Lazio—PTPR -Rete natura 2000 (Lazio Region Geoportal—Natura 2000 areas)	Vector

[1] All datasets have been reprojected in the same CSR (WGS 84/ UTM zone 32N EPSG:32632) to allow for the use of geoprocessing tools. All sources marked with * do not provide open-access data for GIS systems. Therefore, the data were re-elaborated by the authors.

In the final step, the design team, led by Prof. Alessandra Battisti, coordinated by Livia Calcagni, and supervised by Adriano Ruggiero, developed various climate-adaptive future design scenarios for the pilot area. As described in Table 4, several meta-design strategies were identified to address the different climate-related and anthropic effects on the pilot area at different scales of intervention. The meta-design strategies can be traced back to a general urban regeneration approach. The transition from conventional models toward resilience scenarios requires a strong inter-scalar relationship. From this perspective, urban regeneration is not only conceived as the requalification of existing buildings, micro-recovery interventions, urban acupuncture, and measured building replacement but also as new resilient, sustainable construction capable of restoring living dignity to those who live in degraded and inadequate housing contexts. For this reason, given that the site is a distressed urban area, as shown by the socioeconomic and urban analyses, it lends itself particularly well to implementing regeneration processes in its broadest sense. The regeneration process involves three main design categories of intervention (CI):

- (A) Ecosystem preservation and regeneration
- (B) Climate-adaptive urban environment
- (C) Climate-adaptive resilient housing and facilities.

Table 4. Design strategies aimed at addressing climate change (CC) and anthropic effects: category of intervention (CI) and scale.

Exposure	Impact	Scale of Intervention	Design Strategy	CI
SLR (inundation)	Loss of biodiversity	Landscape/Urban/District	Ecosystem restoration, coastal buffer zones, and green and blue infrastructure (GBI)	A B
	Loss of built fabric	Landscape/Urban/District/Building	Resilient construction and flood adaptive buildings	C
	Population displacement	Urban/District	New resilient housing and facilities in proximity areas	C
	Accelerated coastal erosion	Landscape/Urban	Artificial eco-based reefs Residents relocation	A C

Table 4. *Cont.*

Exposure	Impact	Scale of Intervention	Design Strategy	CI
Flood risk	Loss of biodiversity	Landscape/Urban/District	Ecosystem restoration, river buffer zones, and GBI	A B
	Loss of built fabric	Landscape/Urban/District/Building	Resilient construction and flood adaptive buildings	C
	Urban run-off	Urban/District	Improved drainage systems, elevation of structures, and GBI	B C
	Interruption of essential services (transportation/healthcare)	District/Building	Resilient services and facilities (buildings)	C
Urbanization	Soil consumption and sealing	Urban/District	Permeable pavements and sustainable densification	B A
	Heat island effect	Urban/District	GBI	B
	Air quality degradation	Urban/District	GBI, passive energy systems, and sustainable urban mobility networks	B A

The table provides a comprehensive overview of the scale of intervention and design strategies to address the impacts of climate change (CC) and anthropic activities [24]. Sea-level rise- and flood risk-related effects are tackled through interventions at various scales that emphasize ecosystem restoration, the establishment of coastal and river buffer zones, green and blue infrastructure, improvements in drainage systems, flood-adaptive buildings, artificial eco-based reefs, and the relocation of residents in proximity areas to avoid displacement.

To mitigate urbanization challenges, targeted interventions at urban and district levels include the permeabilization of roads and public spaces, sustainable densification, urban greening, GBI, the integration of passive energy systems and renewable energy systems, and enhanced urban mobility networks.

As several strategies within the third category (C) involve the introduction of resilient and flood-adaptive constructions to host either housing or facilities, the design action linked to this strategy consists of the design of a floating settlement meant to host the population living on the flood-prone areas (identified in step 2). The floating settlement is conceived as a response to the new rising and dynamic climate and urban needs, exploring the potential of a floating settlement as the extension of the existing urban area. The removal of dwellings in flood-prone areas implies the relocation of current residents. A settlement on the water provides new homes near the places where the local community has lived for the last thirty-forty years without uprooting and relocating them to distant areas. The district is intended to accommodate approximately 25–40 individuals and provides, in addition to residential units, at least one neighbouring facility. For this purpose, a particular foundation system is used as a floating base for the floating settlement. It is composed of hexagonal concrete modules with a surface area of 210 m^2 (Figure 3), designed by SEAform, a spin-off of the Politecnico di Torino, within the Marine Offshore Renewable Energy Lab [25]. Different design scenarios are explored and developed using the framework developed by the authors [17,18].

The study presented in this article was conducted to test and validate a research methodology that can be easily replicated in other areas and with similar datasets. The analysis of sea level rise scenarios (step 1) was carried out using a GIS model based on a Digital Elevation Model (DEM). While the methodology remains consistent, the accuracy and sensitivity of the entire GIS model depend on the precision of the initial DEM data. In this case, the DEM was created using aerial imagery that produces thematic orthophotos through the overlap of various frames. Unfortunately, for this coastal analysis, the data provided by national and regional databases have limited resolution because the DEM is derived from satellite imagery. The DEM is the result of interpolation, auto-correlation, and ortho-correction processes, which produce a discretized elevation model. Such discretized products are not designed for analyses at this high level of precision. The DEM used in this study has a vertical accuracy of ±1 m, with contour lines extracted at 10 cm intervals, which is not meant for detailed hydrogeological analyses.

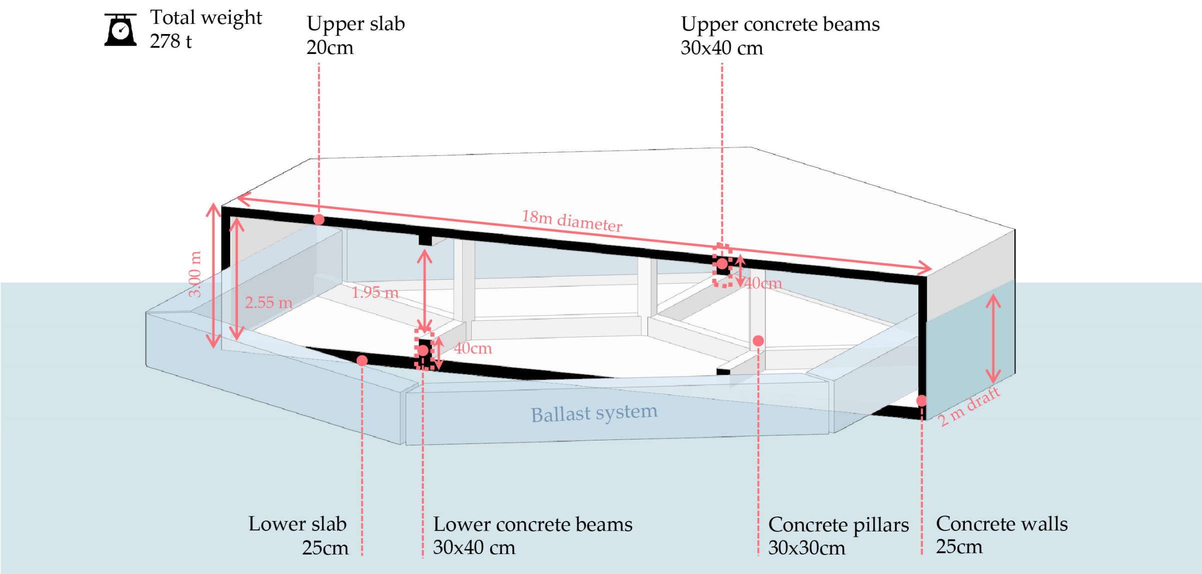

Figure 3. Foundation module developed by SEAform MOREnergy Lab© at Politecnico di Torino.

If the same methodology were applied using LiDAR data with a resolution of 20 cm, the creation of contour lines at 10 cm intervals would have a negligible margin of error, significantly improving the sensitivity and reliability of the analysis.

3. Results

3.1. Impact Analysis at the Provincial Scale: Potential Economic and Social Damage in the Built Environment Due to SLR Risk

The maps in Figures below illustrate the projected extension of SLR on land use and hydrogeological risk classifications along the coastal region of the provinces of Fiumicino and Rome, emphasizing potential economic and social damage to the built environment. SLR projections are presented in Figures 4 and 5 for the years 2050, 2100, and 2150 under climate scenarios SSP1-1.9 (low-emissions or best-case scenario), SSP2-4.5 (intermediate scenario), and SSP5-8.5 (high-emissions or worst-case scenario). Based on IPCC's latest assessment, in the best-case scenario, global warming is limited, and SLR is expected to be moderate, with projections of approximately 0.18 m by 2050, rising to 0.57 m by 2150. The worst-case scenario, SSP5-8.5, anticipates higher emissions and less climate action, leading to more significant warming and accelerated SLR.

Projections reach 0.23 m by 2050, 0.77 m by 2100, and up to 1.32 m by 2150. In both scenarios, the total area affected by SLR by 2050 is approximately 4800 km^2. However, by 2150, this area increases significantly to 15,048 km^2 under SSP1-1.9 and to 19,103 km^2 under SSP5-8.5.

The pie charts in Figure 6 show the percentage distribution of land use within the projected SLR-affected areas, shown in Figure 6. In both the SSP1-1.9 and SSP5-8.5 scenarios for 2050, artificial surfaces constitute a substantial portion of the affected area (69%), highlighting the potential impact on urbanized residential and industrial zones. Agricultural areas represent 17% of the affected land in each scenario, while forest and semi-natural areas comprise around 8%, with wetlands accounting for approximately 5% of the land use distribution. Notably, in SSP1-1.9, the SLR scenario for 2150 shows a gradual increase in the proportion of forested areas (38%) and agricultural areas (27%) and a decrease in artificial surfaces (33%). This new ratio highlights that the most urbanized and populated areas are closest to risk sources, such as coasts and rivers, while agricultural and natural zones are located in more sheltered locations.

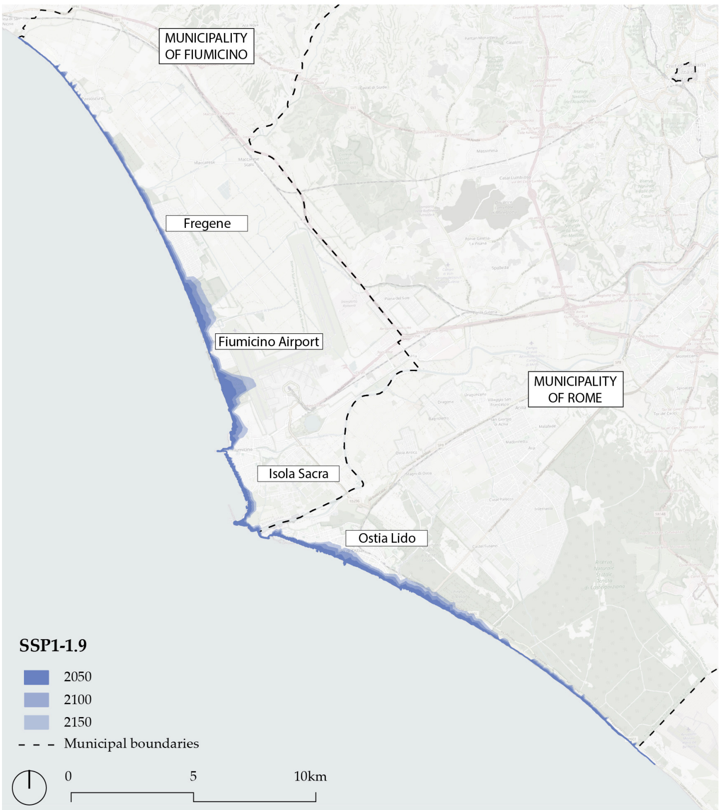

Figure 4. Sea level rise scenario SSP1-1.9 for the years 2050, 2100, and 2150.

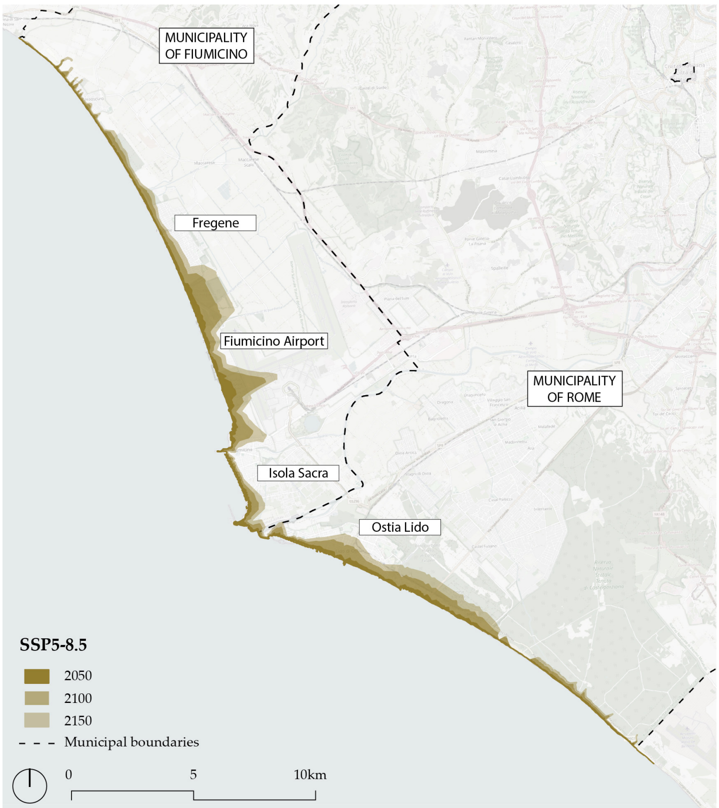

Figure 5. Sea level rise scenario SSP5-8.5 for the years 2050, 2100, and 2150.

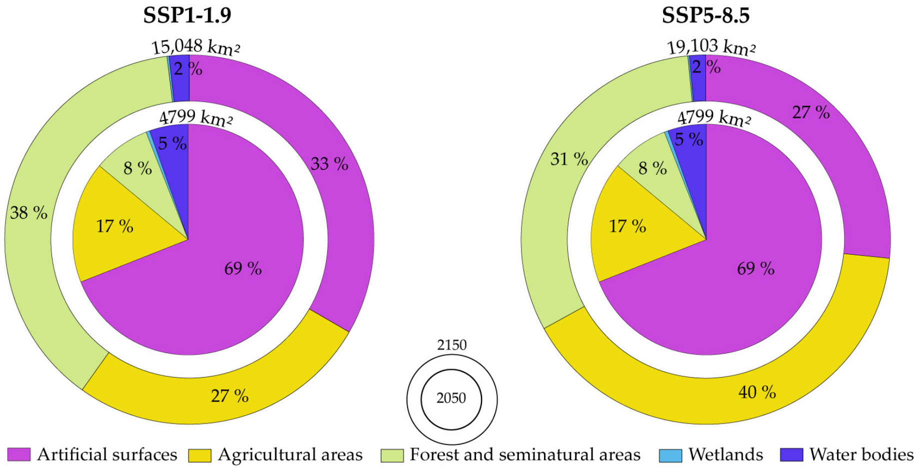

Figure 6. Land use cover percentage of SLR-affected areas according to SSP1-1.9 and SSP5-8.5 for 2050 and 2150.

By 2150, however, these figures indicate that not only will residents and cities face direct risks but biodiversity and food production will also be threatened, leading to severe indirect consequences for human life in surrounding areas. The same applies for SSP5-8.5 in 2150 (Figure 7): artificial surfaces retain a similar impact proportion, though the total affected area is substantially larger, suggesting greater urban exposure to future SLR in the worst-case scenario.

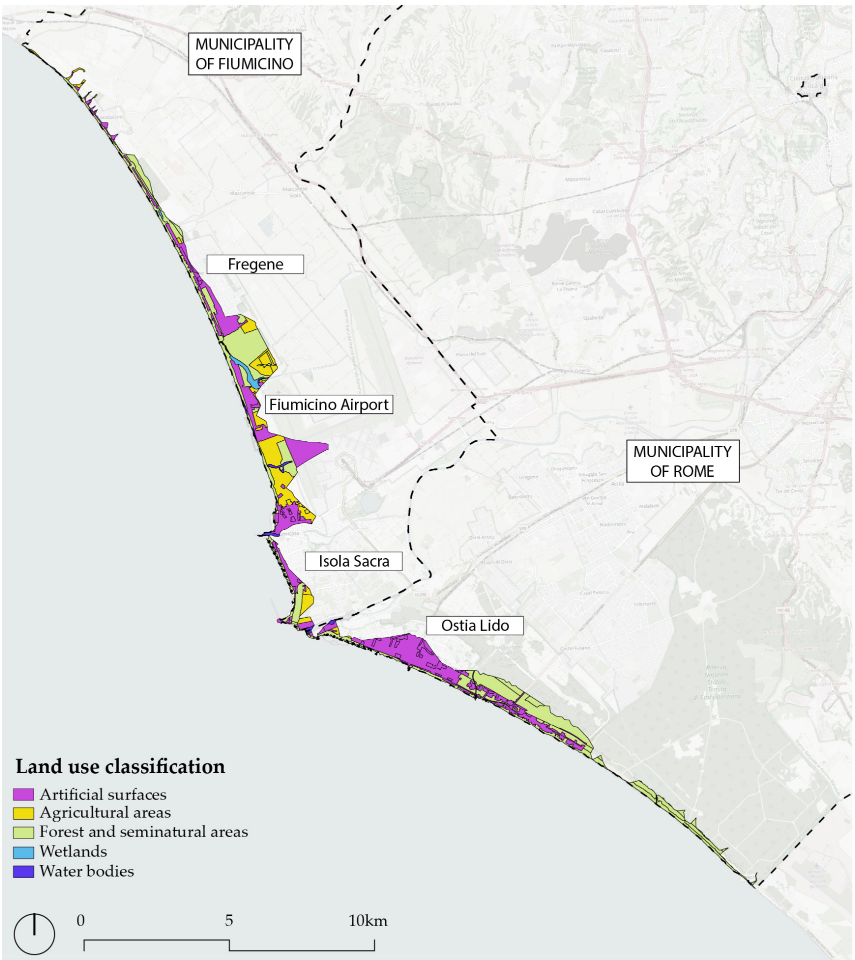

Figure 7. Land use classification for SLR-affected areas according to SSP5-8.5 (2150).

Regarding risk classification (Figure 8), the area is exposed to R4 risk near the river Tiber embankment, especially along the Tiber Delta area. It is exposed mainly to R2 risk at less than 300 m distance from the embankment of the Tiber and its tributaries and along the coast, especially in Isola Sacra (Tiber Delta), in Maccarese (Arrone River), and Ponte Galeria. The assets exposed to R4 risk fall within the flood zone characterized by the greatest danger, with event return period (Tr) 50, and are characterized by very high sensitivity. Assets exposed to R2 risk can have a very high or high sensitivity in relation to their intended use but are included within the flood zone between Tr 200 and Tr 500 or in indirect flood areas due to flood with Tr 200 or marginal to the same and northernmost tributary.

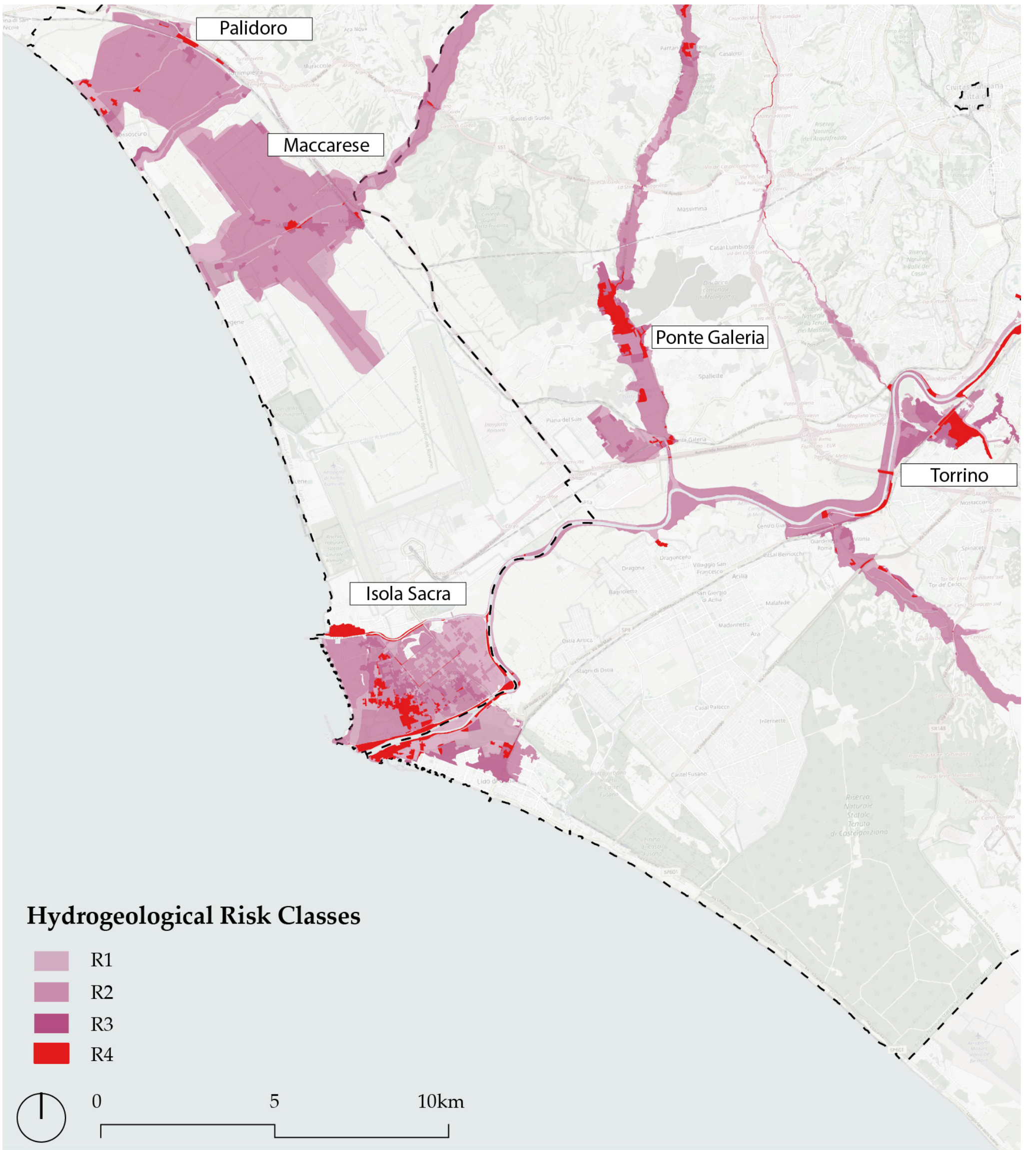

Figure 8. Hydrogeological fluvial and coastal inundation risk map (Geoportale Regione Lazio).

3.2. Pilot Area Analysis: River Tiber Delta, Lazio Region

The Tiber Delta, or Isola Sacra, located at the confluence of the Metropolitan City of Rome (Ostia) and the Municipality of Fiumicino, along the stretch of coast analyzed in the previous paragraph, serves as the pilot area for in-depth analysis and design scenarios (Figure 9).

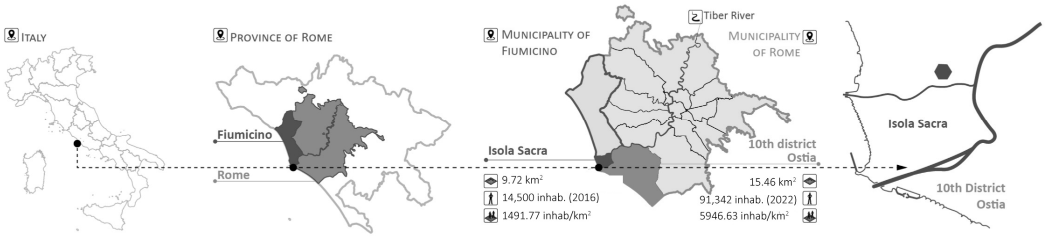

Figure 9. Territorial framework of the pilot area of Isola Sacra.

The coast represents both the territory's natural boundary and the settlement fabric's morphological edge between Ostia's embankment and that of Isola Sacra. It is a low-lying coastal region of strategic importance for Rome's metropolitan area, though it faces significant vulnerabilities due to spontaneous and unplanned urbanization, coastal erosion, and flood risk. Although urban expansion in Isola Sacra surged in the 1970s, recent construction pressures persist due to its proximity to Fiumicino Airport and related activities. Soil consumption along the entire Lazio coast is extremely alarming; the figures below (Figure 10) clearly show the transformations the Isola Sacra and Port of Ostia underwent between 1944 and 2023. As a result, the region's urban fabric is marked by irregular residential, artisanal, and industrial structures, which lack a unitary design.

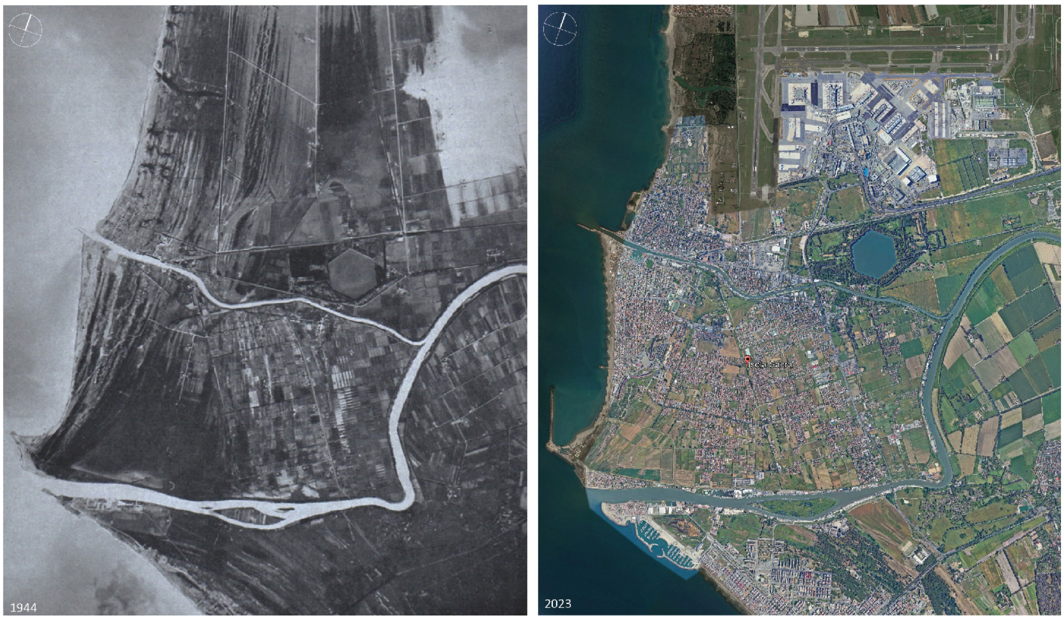

Figure 10. Soil consumption around the Tiber Delta from 1944 (RAF—Royal Air Force—satellite image) to 2023 (Satellite image from Google Earth: Data SIO, NOAA, U.S. Navy, NGA, GEBCO Image © 2023 TerraMetrics).

The prevailing fabric is spontaneous, characterized by a preponderance of residential unauthorized constructions (Figure 10). The area took a while to develop, also because of the irregular and unplanned road infrastructure.

Especially along the riverfront, which strongly suffers from flood risks, several built-up fringe and edge areas are left incomplete and poorly defined despite being classified as public green spaces and local services in Rome's 2008 Master Plan [26]. Yet, urban amenities remain scarce, and private piers monopolize access to the river and sea, limiting public accessibility. Despite the area's limited infrastructure, it includes key facilities such as Leonardo da Vinci Airport and the tourist port of Rome, situated on the Ostia coast. However, it lacks public transportation, rail, or cycling networks, with most roads remaining unpaved.

Significant archaeological and architectural artefacts underscore the area's historical and cultural identity (Figure 11). Archaeological sites and parks spread along the coast and at the mouth of the Tiber, bearing witness to its century-old history and cultural identity. The natural landscape is still visible and characterized by plenty of undeveloped land, mostly uncultivated.

Figure 11. Photos of the unauthorized informal fabric of Isola Sacra: (**a**,**b**) coastal stretch houses on stilts; (**c**) unpaved road and informal house; (**d**) houses on stilts in the port area; (**e**) unauthorized informal houses (**f**) flooded unpaved road; and (**g**) unpaved inner road and informal fabric.

All things considered, both sides of the river in this stretch can be defined as distressed urban areas: areas that suffer social, economic, cultural, and ecological deprivations within the city and are characterized by serious conditions of underdevelopment compared to the city itself and to the national average [27].

Located on the last stretch of the Tiber where the river meets the sea, Isola Sacra is subject to the combined effects of coastal and riverine influences. Approximately 220 km of Lazio's 290 km coast are low-lying, sandy shores that have suffered significant erosion, especially in Ostia, where the situation worsened from 2016 to 2018 when seawater intrusion through the drainage channels degraded local ecosystems. Erosion control efforts included submerged barriers near Ostia. However, recent pollution, mainly from the Ostia wastewater treatment plant, continues to impact the Tiber's main channel, exacerbated by industrial, urban, and agricultural discharge. This ecological decline underscores the potential of floating habitats as nature-based solutions that offer water purification and enhance biodiversity, mitigating some ecological impacts of the area's urban sprawl and water pollution.

Portions of the area fall within the Natural State Reserve (Figure 12), a protected zone supporting diverse ecosystems and significant plant formations in line with EU Habitat Directive 92/43/EEC. Key ecosystems include the delta wetlands, semi-natural ditches, and coastal plains, which serve hydrogeological, biological, and ecological functions, such as nutrient trapping and flood regulation. The Regional Landscape Plan (PTPR) emphasizes these coastal habitats' value, framing them as critical for biodiversity conservation and ecosystem resilience. Adjacent to Passo della Sentinella, a large segment is designated as a Special Conservation Area (SCA) under the EU's Natura 2000 network. Conservation measures focus on maintaining or restoring natural habitats and species under European directives, and regional Management Plans allow for projects targeting ecological conservation, heritage preservation, and infrastructure improvements aligned with sustainable architecture and environmental quality standards.

The PTPR's Management Plan stipulates strict intervention rules to safeguard the ecological, cultural, and landscape assets of Isola Sacra. Prohibited activities include new construction in hydrographic buffer zones; however, public service facilities or minimal-impact infrastructure (like pedestrian routes) are allowed. In coastal areas, only sustainable developments that minimize land and energy resource consumption are authorized, with specific constraints for improving public access, safety, and local resilience against climate risks.

This environmental and regulatory profile highlights Isola Sacra's challenges, where flood risks, coastal erosion, and limited access to natural resources converge in a complex context of urban sprawl, historical heritage, and ecological value.

Ultimately, important data to be considered for the design of floating settlements concern the seabed orography and typology. The bathymetry contour lines (Figure 12) show how the seabed depth increases as one moves away from the coast, reaching a depth of −35 m at a distance of 5 km. The depth of the seabed inside the river mouth and in the area adjacent to the sea reaches a maximum depth of 8 m at the farthest point from the coast. The average depth inside the river varies between 4 to 5 m, reaching 3 m in the area closest to the river banks.

All things considered, the project area for the development of design scenarios consists of the river embankment and the water plot of 2000 m^2 located at the mouth of the Tiber River.

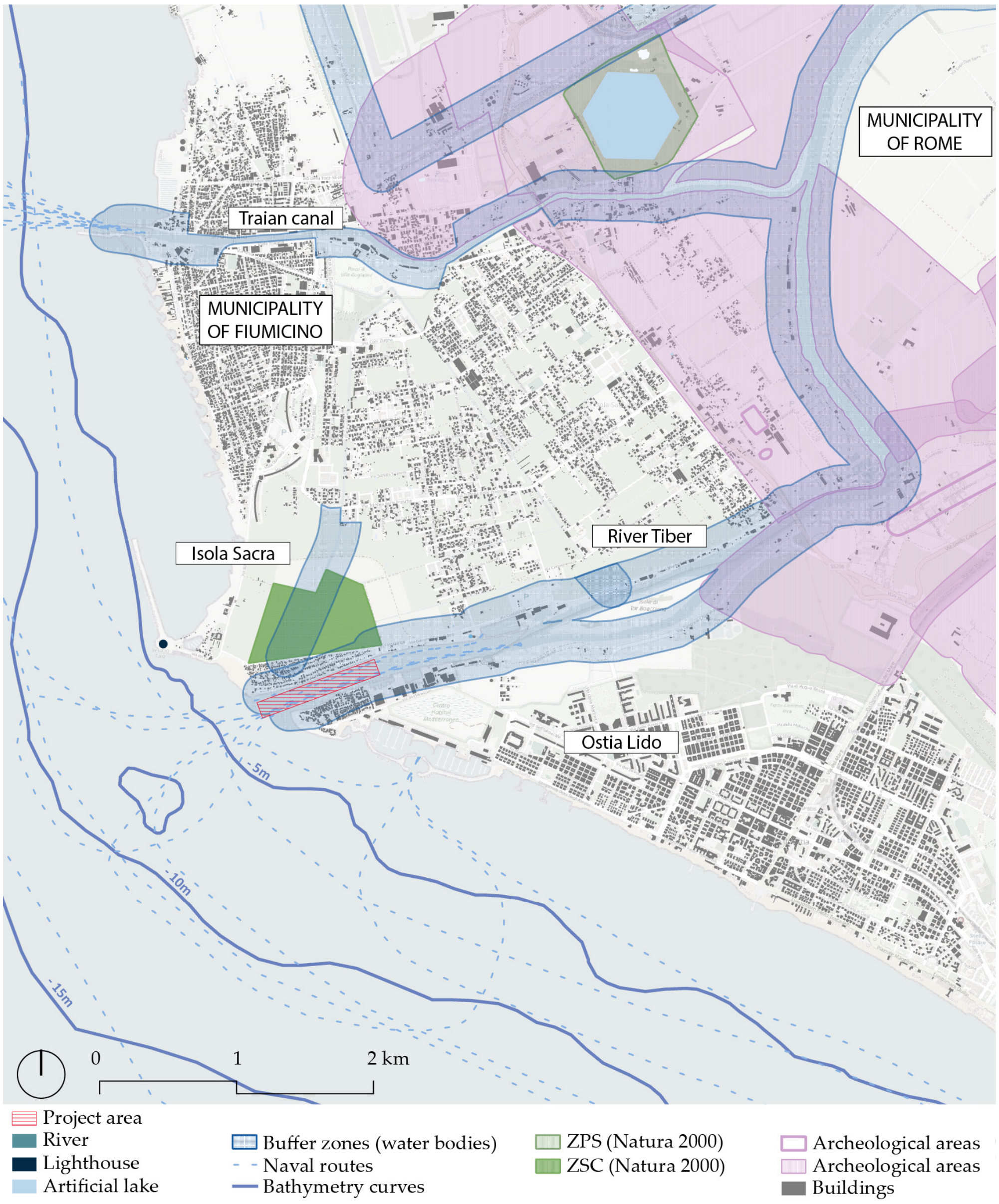

Figure 12. Pilot area analysis: hydrography, naval routes, bathymetry, natural protected areas, and archaeological areas.

3.3. Development of Design Scenarios

Concerning the first two categories of intervention (A and B) described in the Section 2, design actions include creating a dune park along the shore to provide natural protection against erosion and storm surges, acting as a buffer between the water and inland areas. This intervention also fosters coastal ecosystems that support autochthonous flora and fauna and, thus, biodiversity. Establishing ecological corridors enables the movement and interaction of species. Blue barriers, such as planted reed beds and marshlands, protect against flooding while serving as habitats for aquatic species. Salt-resistant and low-maintenance vegetation is introduced to stabilize soil, aid erosion control, and create retention basins and rain gardens. Phytoremediation for rainwater treatment prevents pollutants from reaching the natural ecosystem. Rainwater is treated naturally in rain gardens and gradually reintroduced into the ground or waterways. Another intervention to reduce erosion involves placing biodegradable nets filled with collected shells along the dune parks. The nets encourage the build-up of sand and support the development of marine habitats. Regarding the on-land built area, integrating green and blue infrastructure, such as green roofs, rain gardens, and water squares, further enhances local microclimates by providing natural cooling and moisture regulation. Introducing pedestrian and cycle paths is meant to encourage sustainable transport modes, reducing car emissions and air pollution.

The third intervention category focuses on a floating settlement conceived as a basic prototype that is expandable and repeatable according to the new rising climate or urban needs. The design implies carefully considering the relevant on-land area and creating meaningful tangible and intangible relations and connections between land and water. The precise location of the water plot along the embankment slightly varies according to the scenario based on the evaluation of the preliminary analysis (e.g., water access roads, presence or absence of existing or planned services on land, microclimate, social demand, and other relevant specific needs). All three scenarios (Figure 13) are designed following an approach that combines ecological preservation, climate resilience, and sustainable climate-adaptive urbanism to create a settlement that is both environmentally integrated and responsive to local needs.

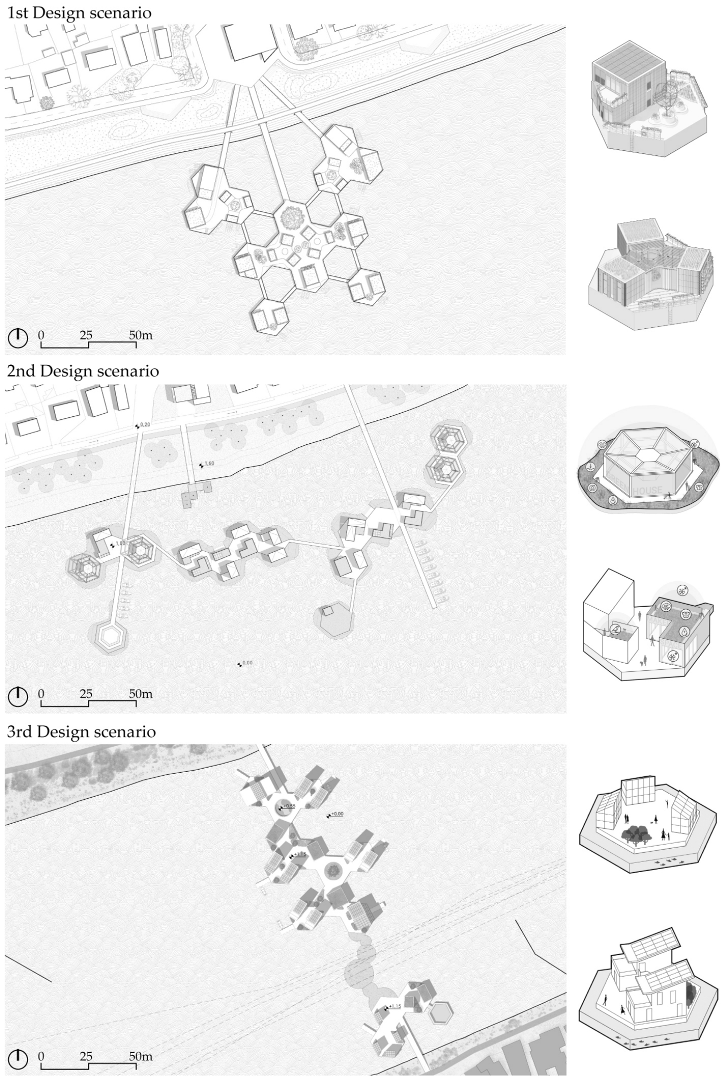

Figure 13. Design scenarios for a pilot area developed by the design and research team led by Prof. Alessandra Battisti, coordinated by Livia Calcagni, and supervised by Adriano Ruggiero: 1st Design Scenario by Federico Bambini, Alessia Baglieri, Francesca Chiarini, and Anita Conti Da Cunha; 2nd Design Scenario by Cherry Aala, Mattia Morgia, Rosa Bianco, and Giusy Solis; 3rd Design Scenario by Flavia Leone, Anna Mezzalana, and Daniele Scalia.

Scenario 1: Branching Compact Development

- (A) Large-scale preservation of natural ecosystems by defining marine protected areas and wildlife refuges.
- (B) Coastal dune systems designed to reduce erosion and enhance biodiversity.
- (C) Resettlement of local inhabitants on floating houses and the integration of basic services and facilities to support specific local needs, including healthcare services, spaces for material treatment and recycling, food production areas, and co-working spaces.

Scenario 2: Linear Coastal Development

- (A) Forestation initiatives along existing irrigation canals to increase biodiversity and improve microclimatic conditions at a large scale.
- (B) The creation of buffer zones to mitigate erosion and preserve biodiversity along the shore and a dune barrier along the riverbank to mitigate flooding.
- (C) A floating settlement for young couples and families to promote socio-demographic diversity and a dynamic social environment; the promotion of self-sufficiency in terms of food, waste, and energy management for resilient living.

Scenario 3: Perpendicular Shoreline Development (bridge settlement)

- (A) Implementation of blue barriers to protect and restore marine ecosystems.
- (B) Renewable energy production from marine sources for sustainable development.
- (C) Reconnection of riverbanks with infrastructure that serves as a landmark, fostering local identity and economy through algae cultivation and its diverse applications.

All projects are characterized by the use of passive and active systems and a certain degree of modularity, which ensures flexibility and allows for future expansion and integration of additional infrastructure.

4. Discussion

4.1. Impact Analysis at the Provincial Scale

This study has emphasized the critical role of preliminary territorial and risk analyses in identifying viable zones for floating urban developments, particularly in areas like the Tiber Delta, which face compounded risks from SLR, coastal erosion, and fluvial flooding. By overlaying SLR projection extensions with land use and combining the results with hydrogeological risk classification (R1–R4), we identified areas where high flood risk converges with dense urbanization, underscoring the need for localized ecological coastal protection measures and climate-adaptive urban models.

We recognize the critical role of the accuracy of GIS models based on DEMs in defining areas at hydrological risk. The DEM used for this analysis was derived from satellite imagery and is subject to limitations, including a vertical accuracy of ± 1 m and contour line extraction every 10 cm. These inherent discretization errors may introduce uncertainties in identifying areas at risk, especially for long-term scenarios. Potential errors in elevation data could alter the delineation of SLR-prone areas and, consequently, the exact extension of the affected land use. It is important to note that the errors in input data could propagate through the model and affect the interpretation of the SLR scenarios. Future studies will involve a comparative analysis using higher-resolution LiDAR data to refine the outcomes and reduce uncertainties. Such data will allow for the generation of contour lines every 10 cm with negligible error, thereby significantly improving the precision of the risk assessments.

However, when comparing the SLR-affected areas with hydrogeological risk classifications (R1 to R4), the overlap provides insight into regions with compounded risks. Areas classified as R4, the highest hydrogeological risk level, are primarily situated along river valleys and low-lying coastal zones, which are generally also highly susceptible to SLR impacts. In contrast, lower-risk areas (R1 and R2) tend to be further inland and less affected by the projected SLR zones. This overlay highlights regions where both SLR and hydrogeological vulnerabilities intersect, necessitating priority interventions and robust coastal protection measures. The comparison illustrates a clear alignment between the areas of greatest economic vulnerability in urban zones (high artificial surface percentage) and high-risk classifications, underscoring the need for targeted adaptation strategies to mitigate both hydrogeological and SLR-induced risks in critical areas. Urban zones with significant economic and social infrastructure are particularly vulnerable, as climate change threatens not only ecological balance but also economic stability and public safety. Over time, sea-level rise increasingly impacts biodiversity and food production as, by 2150, it will reach further inland, affecting agricultural land and untouched natural areas.

For what concerns land use cover, the rationale behind the decision to use the most recent land use datasets (2018) rather than a predictive land use model relevant for the SLR scenarios analysed consists of the fact that the study area is subject to strict landscape and environmental protection regulations, which prohibit building construction or significant alterations to land use. These constraints aim to preserve the balance between urbanized and natural areas, which together constitute the largest portion of the territory today. Given these legal conditions, we assume that the distribution between artificial urbanized areas and natural areas will remain relatively stable at least for the scenarios projected to 2050. This assumption was supported by the cross-checking of the land use predictive model for 2050, which shows hardly any variations compared to today's condition. While long-term projections (2150) might theoretically consider potential deviations due to external factors such as climate change or socio-economic shifts, we intentionally focused on the most immediate and regulated time horizon to provide a robust analysis. Incorporating predictive models for land use, while valuable for exploratory scenarios, would introduce additional uncertainty and assumptions that are not aligned with the current legal constraints governing the area.

Overall, the GIS-based methodology to identify suitable sites for floating development, underlines the importance of geospatial analysis in assessing environmental and urban vulnerabilities. Setting aside the model accuracy, this methodology can be replicated in other regions with similar datasets, demonstrating potential for widespread adaptation in areas facing similar climate risks and urban dynamics. In fact, the Tiber Delta, characterized by unauthorized developments and limited infrastructure, exemplifies the challenges of coastal flood adaptation in urbanized areas.

4.2. Pilot Area Analysis

Location influences several aspects of the design of floating buildings and settlements, including structural integrity, maintenance, utility, self-sufficiency, motion comfort, and environmental adaptability. Therefore, understanding the local context's unique characteristics and physical, ecological, and social dynamics is essential for creating sustainable and resilient floating structures embedded in the natural and anthropic environment. From this perspective, an accurate pilot area analysis is crucial for handling the site specificity and dynamic nature of the context, enabling a data-driven design process that still leads to valid diverse design proposals.

While the proposal of floating settlements as a flood-adaptation solution in informal or distressed areas may initially appear costlier than traditional land-based solutions, the broader perspective reveals significant advantages. First of all, the economic evaluation of floating settlements extends beyond mere construction costs and includes lifespan and resource and infrastructure costs. Several studies [28–30] agree that floating settlements provide a cost-effective and durable solution that adapts to changing climatic conditions over time, avoiding obsolescence tied to specific scenarios. Moreover, unlike land reclamation, which involves resource-intensive processes like dredging and massive sand consumption [31], floating structures minimize the environmental impact while maintaining adaptability to evolving risks. The IPCC AR6 Report highlights that effective adaptation responses—such as retreat, accommodation, protection, and advance—are most successful when combined or sequenced. However, each measure has site-specific physical, time-related, and social limits. For instance, ecosystem-based protection solutions such as wetlands provide environmental co-benefits and reduce costs for flood defence but lose effectiveness at high rates of SLR beyond 0.5–1 cm/year. Other protection measures like seawalls, while effective in the short term, can lead to maladaptive outcomes, resulting in lock-ins and an increase climate-risk exposure unless they are integrated into a long-term adaptive plan. Retreat strategies often entail relocating vulnerable populations and abandoning existing urban assets and communities, which can have significant social and economic costs. All things considered, the IPCC AR6 Report (Chapters 13.2.2 and 13.6.2) has identified accommodation strategies, including elevated or floating buildings, as effective climate-proof solutions, recognizing that they should be implemented as part of a hybrid urban approach [32,33]. Floating architecture, in particular, offers a long-term solution that adapts to climate projections without being constrained by fixed timeframes like seawalls or other protective measures.

Failing to address flooding risk in a timely manner can lead to severe economic, social, and environmental consequences. Delayed action exacerbates damage to infrastructure, disrupts communities, and increases recovery costs. Proactive, preventative measures—such as integrating adaptive strategies like nature-based solutions, climate-proof floating or amphibious buildings, and robust flood management systems—significantly reduce risks and long-term expenses. Early preventive intervention transforms the challenge of flooding into an opportunity for innovation in climate adaptation.

4.3. Design Scenarios

The design scenarios for floating settlements offer innovative urban solutions that address land-water connectivity, coastal management, flexibility and scalability potential, and relocation capability. The findings indicate that future adaptive measures should prioritize high-risk zones, where urban density, infrastructure, and population are highly exposed to flood hazards. Although still experimental, floating settlement prototypes offer a transformative urban approach that responds to environmental threats and provides dynamic urban models and sustainable housing solutions. Designed for expansion and adaptability to address both current and future challenges, the prototype projects we developed can accommodate shifts in climate and urban needs, offering a resilient alternative for communities currently inhabiting substandard and flood-prone areas in Isola Sacra.

Despite the evident potential of floating settlements, significant regulatory, social, and technical issues remain to be addressed. Their implementation requires compliance with undefined and non-specific regulations, while integration with existing infrastructure requires careful planning. Concerning regulatory challenges, it is important to underline that the Municipality of Rome must grant a building permit for a floating structure on the Tiber, or any other water body, as the structure is anchored to the riverbank and constitutes new construction. Additionally, a state concession is needed from the State Property Office to access public river lands. Only after obtaining both approvals can construction begin. Although the same framework and guidelines are followed for the development of each scenario, a remarkable morphological variety of floating structures and layout aggregations distinguishes the different scenarios.

Another challenge encountered in the design process is to avoid the tendency to replicate terrestrial urban-planning approaches without fully addressing the specific and unique needs and dynamics of floating settlements, highlighting the challenges in transitioning from terrestrial to aquatic urbanism. The margin, or the water–land boundary, must be adequately designed to integrate floating settlements with the surrounding terrestrial environment. Designers must blur boundaries between land and water and address issues like height differences and fluctuating water levels to improve connectivity between floating and land structures. The potential of water in floating design goes far beyond energy harvesting, opening opportunities for biodiversity, plastic recovery, biophilic design, and aesthetic value. Adapting greenery and natural infrastructure for the water environment can also contribute to microclimatic regulation and psychological well-being.

In addition to design and regulatory challenges, the success of such settlements depends on the acceptance of local communities, who may resist moving toward unconventional housing models.

Overall, the design scenarios highlight the need for a mind shift in tackling the challenges posed by floating settlement design. Architects and urban planners must move beyond replicating terrestrial design approaches and embrace the unique opportunities and constraints of the aquatic environment. This requires a deep understanding of water-based communities' physical, ecological, and social dynamics. The morphological variety, margin integration, integrated design thinking, resource utilization, and management of complex systems are critical considerations for successful, sustainable, resilient floating settlements.

In conclusion, this analytical and design approach based on a comprehensive framework for floating urban development, tested on the Tiber Delta, offers a replicable model that could be adapted to similar vulnerable coastal zones in the Italian and European contexts, thereby enhancing urban resilience and ensuring sustainable development amidst changing climate conditions. Future research should aim to refine these prototypes by incorporating larger and more accurate datasets and developing robust social and economic frameworks that meet the communities' needs while addressing ecological constraints.

Author Contributions: Conceptualization, A.B. and L.C.; methodology, A.B. and L.C.; software, L.C. and A.R.; validation, A.B., L.C., and A.R.; formal analysis, L.C. and A.R.; investigation, L.C. and A.R.; resources, L.C. and A.R.; data curation, L.C. and A.R.; writing—original draft preparation, L.C. and A.R.; writing—review and editing, A.B., L.C., and A.R.; visualization, L.C. and A.R.; supervision, A.B.; project administration, A.B.; funding acquisition, A.B. and L.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received external funding from EU European Union Found within the Italian national research project PNRR Spoke 7 PE 5 (grant number CUP B53C22003780006)—FONDAZIONE CHANGE Protection and conservation of Cultural Heritage against climate changes, natural and anthropic risks. This research received external funding also from Sapienza University of Rome (Protocol no. AR1221816C296FC) within the Call "Research Initiation Projects—Type 1 year 2022" as part of the research entitled "Inhabiting water as a new resilient urban frontier through innovative smart and green floating settlement systems. Elaboration of meta-design guidelines".

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The authors wish to acknowledge the SEAform MOREnergy Lab at the Politecnico of Turin for their significant collaboration in the final part of the research: the development of the design scenarios. The lab's provision of technical materials concerning their patented foundation model was integral to the work of the junior architects involved in the design phase presented in the research, allowing for the integration of the module as a foundational component in the design process. This collaboration substantially contributed to the scientific rigor and practical application of the design scenarios.

Conflicts of Interest: The authors declare no conflicts of interest.

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