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The Climate-Proof Planning towards the Ecological Transition: Isola Sacra—Fiumicino (Italy) between Flood Risk and Urban Development Prospectives

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Abstract: The increasing concentration of people and economic activities in urban areas intensifies the pressure on the urban environment and hastens environmental degradation processes. Therefore, addressing the impact of climate change on cities is an urgent matter that demands the immediate attention of policymakers, researchers, and the general public, not only for its environmental but also socioeconomic ramifications. Within this framework, the research focuses on the effects of climate change on coastal cities and aims to define guidelines for the innovation of urban planning tools from a climate-proof perspective. Specifically, the study analyses the effects of two phenomena related to climate change: heavy rainfall, river overflow, and sea-level rise, to establish a replicable approach for updating the documents that constitute the cognitive framework of the Local Urban Plan through the preparation of a multi-risk map (that considers different time horizons) and consequently the prescriptive apparatus of the Plan through the definition of a toolkit of site-specific design actions oriented towards urban adaptation. The proposed methodology is tested on the case study of Isola Sacra, Fiumicino (Italy), and is intended to apply to other territorial contexts. The aim of this study, in accordance with the principles of the Disaster Risk Reduction (DRR) framework, is to furnish theoretical-methodological and operational guidelines to translate risk knowledge, despite its limitations due to variables and uncertainties in measurements, into effective urban adaptation measures.

Keywords: climate-proof planning; coastal multi-risk; local urban plan

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1. Introduction

1.1. The Socioeconomic Impact of Climate Change on Cities

The World Urbanization Prospects report [1] indicates that currently, 55% of the world's population resides in urban areas, and this percentage is expected to increase to 68% by 2050 due to increased migration flows. This trend makes urban settlements increasingly vulnerable to the impacts of climate change. The growing concentration of people and economic activities in cities intensifies the pressure on the urban environment, hastening environmental degradation processes [2,3]. The United Nations' 2030 Agenda for Sustainable Development [4] acknowledges that climate change impacts are transboundary and necessitate a coordinated global response. Addressing this issue requires integrated approaches to risk management, sustainable planning and design of urban settlements, prudent management of natural resources, and civil society awareness of the effects of climate change on cities and territories [5,6]. Recent global warming trends [7] have resulted in an increase in the frequency and intensity of heatwaves, droughts, and extreme precipitation events. These events, in turn, have contributed to a rise in the number of floods due to land use change and the consequent loss of drainage capacity of surfaces in urbanised areas [8,9]. Therefore, addressing the impacts of climate change on cities is an urgent matter that demands the immediate attention of policymakers, researchers, and the general public, also considering its socioeconomic impacts.

In relation to this, the AR6 Report of IPCC (2021) integrates future climate scenarios with the inclusion of socioeconomic indicators, introducing for the first time the concept of Shared Socioeconomic Pathways (SSP) to better understand how climate change and related policies influence society and the economy. Indeed, AR6 combines SSP and RCP (trajectories of greenhouse gas concentrations that describe different climate futures) in a scenario matrix architecture that provides a more comprehensive view of the future, considering the interrelationships between environmental and socioeconomic components. As a result, five "possible climate futures" emerge, ranging from "very low emissions" SSP1-1.9, "low" SSP1-2.6, and "intermediate" SSP2-4.5, to "high" SSP3-7.0 and "very high" SSP5-8.5 [7,10].

The most recent trends in terms of socioeconomic impacts caused by climate change are reflected in the data. According to the Global Report on Internal Displacement [11], by the end of 2021, 59.1 million people would have been displaced globally, of which 53.2 million were displaced due to conflict and violence and 5.9 million due to climate change-related disasters. Although the number of people displaced by climate change may seem smaller than that caused by conflict and political instability, the International Organisation for Migration (IOM) forecasts that the number of climate crisis migrants alone could reach one billion by 2050 [12]. Furthermore, the EU New Pact on Migration and Asylum [13] emphasises that the effects of climate change in developing countries will exacerbate the migratory phenomenon towards Europe by encouraging the migration of populations at risk to urban centres [14,15].

Indeed, Iyakaremye et al. [16] examine the projected effects of climate change on Africa by comparing temperature extremes recorded between 1991 and 2010 with those anticipated between 2041 and 2060. They demonstrate that the intensity of high-temperature extremes will increase by 0.25 to 1.8 °C (SSP2-4.5) and 0.6 to 4 °C (SSP5-8.5). These trends suggest that by the middle of the 21st century, the continental population's exposure will increase by about 25–28% compared to the reference period, with the largest increase in exposure expected in West Africa, followed by East Africa.

Ullah et al. [17] also note that South Asia has the potential for widespread changes to the Wet Bulb Globe Temperature (WBGT) of 6.5 °C, which could exceed the theoretical limits of human tolerance by the mid-21st century. This scenario is projected for the short-, medium-, and long-term temporal scenarios of Shared Socioeconomic Pathways (SSP) SSP2-4.5 and SSP5-8.5.

1.2. Submerged Landscapes: A Focus on Coastal Cities

Based on what has been expressed so far, this study focuses on the effects of climate change on coastal cities.

The European Environment Agency's report, Marine messages II. Navigating the course towards clean, healthy and productive seas through implementation of an ecosystem-based approach [18], highlighted how coastal multi-risk is expected to increase in Europe due to the combined effect of climate change, population growth, migration, and urban development. This fact is also confirmed by the World City Report 2022 [19] and, in the Italian context, by the documents Report sulle condizioni di pericolosità da alluvione in Italia e indicatori di rischio associati [20] and the 2021 Dossier I migranti ambientali. L'altra faccia della crisi climatica [21]. The first shows that the threat is particularly serious for the delta areas of the Po, Adige, Arno, and Tiber; the latter highlights that floods caused by river overflow are also associated with the sea-level rise phenomenon, a circumstance that will compromise the lives of large and small coastal urban areas, in which storms will be increasingly frequent and cause serious damage, forcing the population to migrate to safer places.

The Italian Geographical Society's Conference of 30 January 2023 on "Submerged Landscapes" highlighted the urgency of Italy's coastal environments due to erosion processes by 2050 and sea-level rise by 2100 as a consequence of climate change, expressing the need to devote the 2023 Annual Report, soon to be published, to the topic.

The urgency of addressing the issue of coastal multi-risk from the disciplinary point of view of urban planning also emerges from reflecting on calamitous events that have impacted some of the world's major cities in recent years. These events have made it evident that there is a close relationship between spatial planning and the impacts of climate change, as recognised by experts and the general public [22,23]. Examples include Hurricane Sandy, which devastated much of Manhattan's southeast coast in 2012, and, in the Italian context, the storm that hit Venice in November 2019, as well as the disasters that affected the Marche region and the island of Ischia in 2022.

This research is part of the broad thematic framework of coastal multi-risk, which is the complex interaction of different factors caused by climate change. These factors include sea-level rise, coastal erosion, river overflow, high tide phenomena caused by heavy rainfall, storm events, land subsidence, and the displacement of coastal residents.

The interaction of these, which threatens coastal environments and economies, derives from the overlap of transient extreme events, and their understanding would require a comprehensive risk assessment across a range of spatial and temporal scales that demand complex and differentiated approaches [24]. In particular, Vousdoukas et al. (2017) [25] note the lack of comprehensive projections of extreme sea levels that consistently include sea level, tides, waves, and storm surges.

Due to the uncertainties surrounding the determination of the impacts caused by the confluence of various factors, this study focuses on the static analysis of two phenomena related to climate change in coastal cities: heavy rainfall, river overflow, and sea-level rise.

Therefore, the gap in the research and the contribution of this study lie in the fact that the two phenomena (heavy rainfall, river overflow, and sea level rise) were considered individually and then superimposed on each other without considering all the variables that their concomitance can generate.

As a development of the research, it would be interesting to collaborate with experts in the fields to determine these variables. In this way, it would be possible to conduct a more comprehensive analysis, leading to a more effective site-specific adaptation action toolkit.

It should be noted that the research's intention, for this research's progress, is not multi-risk assessment but instead to evaluate the physical hazard and exposure of the studied city to these two phenomena, which generally depend on its peculiar geological, environmental, and socio-economic characteristics and the nature of the exposed elements.

In this sense, the objective of the study is to define guidelines for the innovation of urban planning tools, considering current knowledge on the impact of coastal flooding on the urban environment. This objective translates into two expected outcomes:

- Defining a methodology to correlate flood-prone areas with the components of the urban structure;
- Defining a framework for a toolkit of site-specific adaptation actions exportable to different territorial contexts.

1.3. State of the Art: The "Regulatory Dimension" of Territorial Government Tools

This article is contextualised within the research project "Pianificazione climate-proof e strategie di rigenerazione per l'adattamento al fenomeno del sea-level rise. Sperimentazione e innovazione del Piano urbanistico locale nei territori a rischio del Lazio", financed by Sapienza—University of Rome (Principal Investigator Prof. Carmen Mariano), which aims to define urban regeneration strategies to adapt coastal cities to the effect of heavy rainfall, river overflow, and sea-level rise, with a time horizon up to 2100.

Consistent with the authors' research path on what they define as the "regulatory dimension" of the updating of territorial government tools from a climate-proof perspective [26,27], the results returned in this article propose some theoretical-methodological and operational references for the innovation of the Local Urban Plan from two closely connected points of view, the first (Step 1), preparatory to the second (Step 2):

Step 1: Implementation of the territory's cognitive framework through the preparation of a "multi-risk" map—with a time horizon of 2100—concerning the consistency of floods caused by the simultaneous presence of heavy rainfall and river overflow (transient and non-linear phenomena) and sea-level rise (stable and progressive phenomena);

Step 2: Definition of a toolkit of site-specific adaptation actions embedded in broader urban resilience strategies of "defence," "adaptation," and "relocation" [28].

The proposed approach's innovation lies in the fact that current documents that make up the Territorial Knowledge Framework of the Fiumicino Urban Plan in particular and the ones of most national urban plans in general do not provide information about flood-prone areas due to the two analysed phenomena. Indeed, in Italy, the risk related to heavy rainfall and river overflow is included in a sectoral tool, Piano di Gestione del Rischio Alluvioni—PGRA, introduced by the European Directive 2007/60/EC (so-called 'Floods Directive') [29], which does not relate flood-prone areas to urban components since the scale of analysis is territorial.

Moreover, there is no urban or sectoral document providing information on the extent of the areas at risk of flooding due to sea-level rise. As a result, the lack of an integrated document that establishes the correlation between flood-prone areas and urban components (at the local level) makes the identification of priority intervention areas and the consequent formulation of site-specific adaptation strategies difficult.

For these reasons, the experiment proposed aims to urge public opinion, experts in the field, and policymakers to take charge of updating urban planning tools from a climate-proof perspective and to pursue long-term and resilient urban development in territories at risk through the definition of a toolkit of site-specific adaptation actions [30–32].

In Italy, there are currently a limited number of Local Urban Plans that effectively consider the potential impacts of climate change on their respective territories and, consequently, provide precise guidelines for the implementation of prescriptive documents. The Plan for Territorial Government (PGT) in Milan represents a virtuous example, as it incorporates a "climate change impact reduction index" within its prescriptive document as a parameter to be considered for urban development actions [33].

On the contrary, in most cases, guidelines have been drawn up for the definition of plans for adaptation to climate change, which often do not align with the prescriptions of the local government tools in force.

This is why the authors are convinced that the integration of risk analysis at the local level and the consequent definition of site-specific adaptation measures should go directly into the Local Plan, to guarantee their real implementation.

This purpose is also supported by the fact that in the traditional Disaster Risk Reduction (DRR) framework, risk increases whenever our (often limited) knowledge of the hazard is not translated into effective mitigation, adaptation, or significant exposure reduction, especially when low-frequency yet high-impact events are considered [34].

2. Materials

2.1. Case Study

The proposed experimentation was conducted in the Municipality of Fiumicino, which was identified by Antonioli et al. (2017) [35] as one of the thirty-three Italian areas most at risk of flooding due to SLR by 2100. However, as mentioned in the previous paragraph, no urban or sectoral document provides information on the consistency of the areas at risk of flooding caused by this phenomenon. The Municipality of Fiumicino is also subject to floods caused by heavy rainfall, which contributes in turn to the Tiber's overflow. Unlike the risk of flooding from SLR, the risk related to heavy rainfall and river overflow is included in a sectoral tool: the Piano di Gestione del Rischio Alluvioni dell'Appennino Centrale (Flood Risk Management Plan of the Central Apennines) [36,37]. This Plan proposes risk maps for three different temporal probability scenarios, including the low, medium, and high probability of flood events with return periods (RP) of 300 years, 100–150 years, and 30 years, respectively. The article focuses on the area known as "Isola Sacra," which has a specific geo-morphological conformation resulting from anthropic modifications dating back to the Claudian period at the beginning of the 1st century A.D. [38]. The analysis specifically targets Area A—Passo della Sentinella (Figure 1), characterised by the presence of a spontaneous settlement built since the 1960s, where many people currently reside despite the area's high risk of flooding, which causes significant damage every year. Additionally, the Fiumicino Local Urban Plan [39] suggests the demolition of the existing building in this area and its relocation to geomorphologically safer areas to facilitate environmental reclamation operations (Figure 2).

Regarding the three macro-strategies of urban resilience to climate change, which were previously conceptualised by the authors in their joint research activity as "defence," "adaptation," and "relocation" [28], the Fiumicino Municipality's Administration is currently only undertaking actions related to the "defence" strategy. This is being done through the construction of massive embankments to protect the most vulnerable areas. However, it should be noted that these interventions completely disregard any communication, even visual, between the urbanised areas and the natural element (the river), which has a negative impact on the place's identity (Figure 3).

An example of this approach Is the construction of the "embankment road". This barrier only protects the northernmost settlement of Isola Sacra, isolating Target Area A—Passo della Sentinella, which is the closest area to the mouth of the Tiber River (Figure 4) and separating it from the rest of the fabric. At the same time, the "embankment road" will have negative effects on the target area because, in the event of a flood, it will not allow the water to flow out, leading to a "pool effect" in the area.

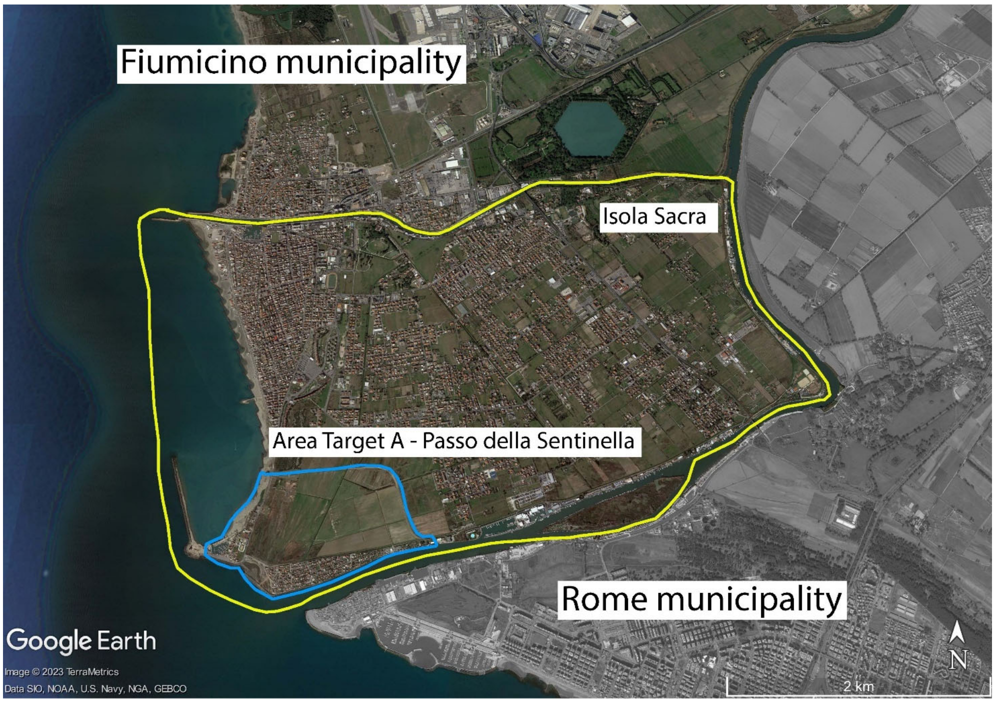


Figure 1. Contextualisation of the area called "Isola Sacra" (yellow perimeter) within the Municipality of Fiumicino and of Target Area A—Passo della Sentinella (light blue perimeter) within Isola Sacra. Source: Google Heart Pro, elaboration by the authors (2023).

Figure 2. View of the spontaneous settlement of Passo della Sentinella, located right at the mouth of the Tiber River. Detail of the "trabocchi", a specific type of stilt house constructed to fish without venturing to sea, with the aim of taking advantage of the rocky morphology of certain fishing areas on the most prominent point. The nets are thrown into the sea thanks to a monumental system of wooden arms.

Figure 3. View of the river from an internal area of Isola Sacra. The numerous imposing embankments that protect the settlement and the agricultural areas from floods deny, at the same time, the relationship (even visual) with the river. As a result, the only visible elements of the river landscape are the masts of boats, while the visual connection with the river itself is completely obstructed. Source: Marsia Marino (2021).

Figure 4. An aerial view of the embankment road reveals that the spontaneous settlement of Passo della Sentinella is not protected by the embankment. Protection is only provided for the built-up area to the north of the embankment. Source: Google Heart Pro.

This intervention highlights how the definition of "defence," "adaptation," and "relocation" actions should be planned while considering the complexity of the urban context. This operation requires coordination managed within the urban planning tool at the local level. Hence, the latter should provide a clear cognitive framework concerning risk phenomena and prescriptions in line with the future scenarios profiled.

For the experimentation, the following materials were used, some of which are described in the following paragraphs:

- DEM with 10-m resolution [40];
- Shapefile of the PRG (General Regulatory Plan) of the Municipality of Fiumicino [39];
- Projections of mean sea-level rise in the Mediterranean Sea to 2100 [41];
- RP 30-year and RP 100-year PGRAAC Risk Maps [42].

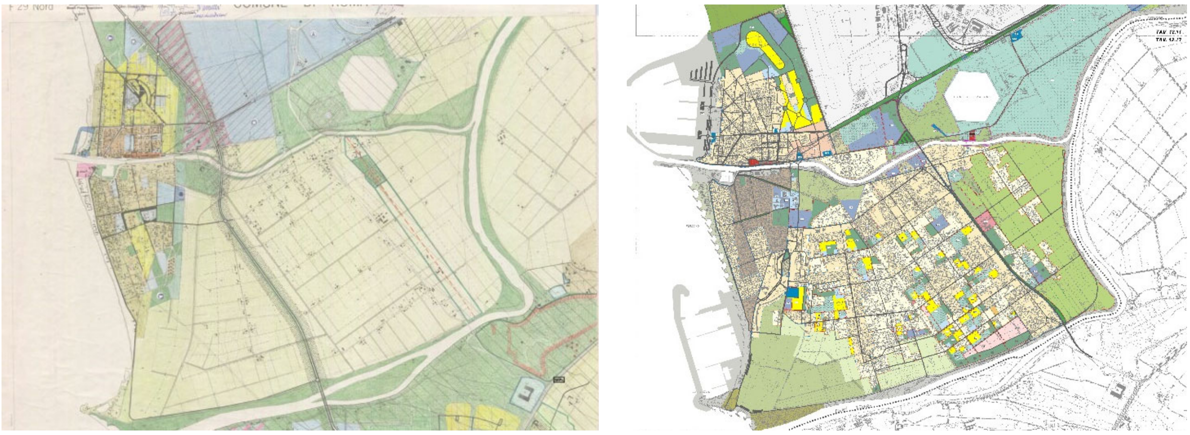
2.2. PRG of the Municipality of Fiumicino

Fiumicino became an autonomous municipality in 1992, prior to which it was included in the municipal territory of Rome, and its administrative boundaries were part of the 1962 General Regulatory Plan (PRG) of the Municipality of Rome. The first General Regulatory Plan of the Municipality of Fiumicino was not implemented until 2006, which meant that from 1992 to 2006, Fiumicino lacked clear indications for urban planning. This peculiarity, along with the illegal construction that affected the entire Italian territory in the 1970s, contributed to the proliferation of spontaneous and unauthorised settlements, which were often in contrast with the provisions of Rome's 1962 PRG. These irregularities were acknowledged and rectified by the 2006 Fiumicino Plan.

One example of this was the spontaneous settlement of "Passo della Sentinella". The Rome Plan of 1962 designated this area as a "public park" (Figure 5a) because of its extreme vulnerability to flooding caused by its position at the mouth of the Tiber River. However, the current PRG of Fiumicino (2006) classifies it as Zone B, or "completion: consolidated residential building"—Sub-zone B1b, or "building maintenance for environmental reclamation and restoration" (Figure 5b).

Table 1. Technical Implementation Regulations (NTA) for the Homogeneous sub-zones of the Fiumicino PRG (2006) included in Target Area A—Passo della Sentinella.

Homogeneous Territorial Zones	Homogeneous Sub-Zone	Art. of the NTA	Specifications
B	Sub-zone B1c	Art. 54.3 Maintenance, completion, and redevelopment of existing fabric: building maintenance zone for rehabilitation and environmental remediation	[...] The nucleus known as Passo della Sentinella will be subjected to implementation planning aimed at the environmental redevelopment of the site. This target may be pursued through reclamation works, as well as after the demolition of the existing building stock and relocation of the same in external areas [...].
E	Sub-zone E1	Art. 60.1 Agricultural activities in suburban areas: agricultural areas in the settled territory	[...] Lands with hydrogeological vulnerability [...].
F	Sub-zone F2c	Art. 63.4 Public green: Territorial Equipped Park	[...] Only public facilities that are essential for enjoying the park itself or for the recovery and redevelopment of the entire river channel are envisioned.
	Sub-zone F2e	Art. 63.4 Public green areas may include concessionary facilities for coastal use as well as open-air facilities for tourism and leisure activities	[...] The adaptation of sanitary facilities is permitted up to a 10% increase of the existing covered surface area, as well as the demolition and reconstruction of existing buildings, with indications of their use for bathing services, refreshments, storage, and outdoor equipment [...]
	Sub-zone F2g	Art. 63.8 Public green: Embankment Protection Area	[...] The reconversion of existing shipyards and buildings for use along the Tiber is allowed if landscape and environmental principles and values are respected [...]



(**a**) (**b**)

Figure 5. (**a**) An extract from the 1962 PRG (General Regulatory Plan) of Rome, showing a detailed map of Isola Sacra. Here, Passo della Sentinella is designated as a "public park". (**b**) An extract from the 2006 PRG of Fiumicino, showing a detailed map of Isola Sacra. Here, Passo della Sentinella is designated as "Sub-zone B1b". This means that in the transition from the 1962 Rome PRG to the 2006 Fiumicino one, the area of Passo della Sentinella turns into a built-up area, despite the prescriptions of the previous Plan (details on the Homogeneous Territorial Zones falling within the target area are in Table 1).

The shape file of Fiumicino's PRG [39], which divides the Plan into Homogeneous Territorial Zones, was used for experimentation. Homogeneous Territorial Zones are the areas into which a municipal territory is divided in Italy as part of the zoning carried out in local urban planning instruments. These zones are grouped by affinity, and each has different prescriptions according to the peculiarities of the area.

Homogeneous Territorial Zones were formally introduced by Law no. 765 of 6 August 1967 and further regulated by Ministerial Decree no. 1444 of 2 April 1968. These zones include:

- Zone A: historic centre, historic buildings;
- Zone B: completion zone, consolidated residential building;
- Zone C: expansion housing;
- Zone D: zone for productive settlements;
- Zone E: agricultural area;
- Zone F: zone for collective facilities and equipment.

Each zone is further divided into different sub-zones, and different prescriptions are given for each of them.

2.3. PGRAAC Risk Maps

The shape files, which were prepared by the Central Apennine District Basin Authority in the Piano di Gestione del Rischio Alluvioni dell'Appennino Centrale (Flood Risk Management Plan of the Central Apennines) [36,37], were used to verify the consistency of the areas at risk of flooding with RP between 30 and 100 years. The risk maps depict the risk of flooding under three distinct probability scenarios:

(a) Low probability or extreme event scenarios;
(b) Average probability of flooding;
(c) High probability of flooding.

With regards to this, Italian Legislative Decree 49/2010, which implements the national Floods Directive, establishes that high probability scenarios or frequent floods correspond to return periods between 20 and 50 years (for scenario c = Rp $\leq$ 30 years), whereas medium probability scenarios or infrequent floods correspond to return periods between 100 and 200 years (for scenario b = Rp $\leq$ 150 years). Therefore, low-probability or extreme-event scenarios are those corresponding to return periods exceeding 200 years (for scenario a = Rp $\leq$ 300 years).

It must be specified that the uncertainties in the predictions of flood risk with respect to return periods can be multiple and depend on the data sources used and the analysis methodologies employed. For example, some of the main sources of uncertainty could include the reliability of input data (such as topography, rainfall, vegetation, etc.), mathematical modelling of hydrological processes, selection of modelling parameters, limited spatial resolution of input data, uncertainty in climate change predictions, and limitations of the computer tools used. Being aware of such uncertainties, the experimentation is based on the maps published in the PGRAAC document [36,37], which currently represents the most updated document at the national level on the subject.

Based on the scenarios outlined by the PGRAAC, the target area is entirely impacted by high-probability flooding phenomena with frequent flooding (RP 30). In Figure 6, the yellow colour represents the high risk (frequent floods), orange represents the medium risk (infrequent floods), and brown represents the low risk (rare floods).

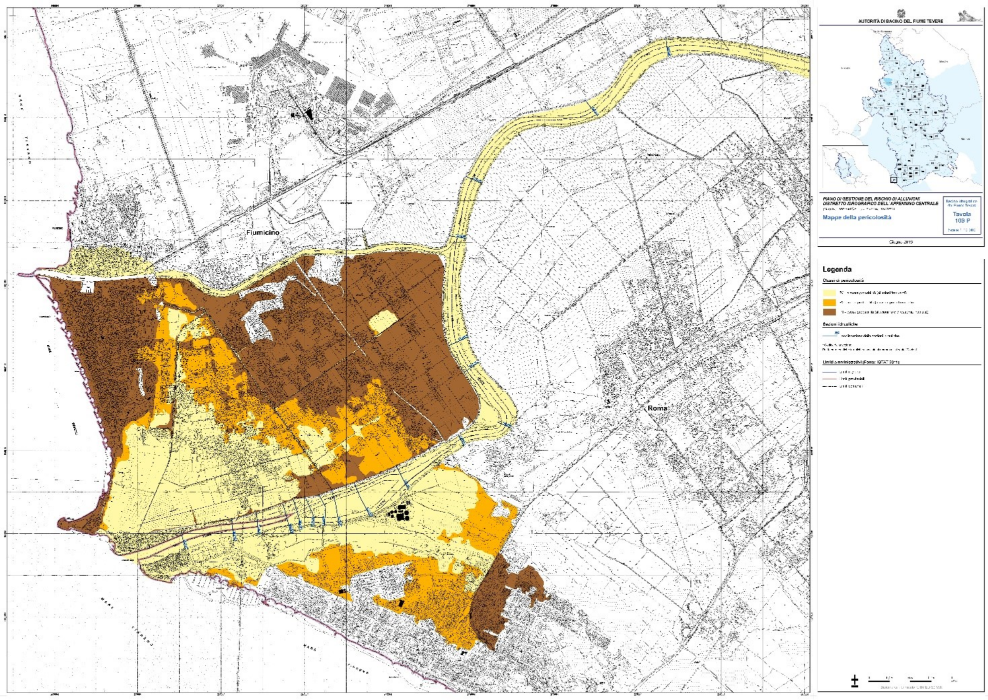


Figure 6. Flood risk map developed by the Central Apennine District Basin Authority. Detail of Isola Sacra, Fiumicino (Lazio, Italy). The Target Area A—Passo della Sentinella is entirely impacted by high-probability flooding phenomena with frequent flooding (RP 30). The yellow colour represents the high risk (frequent floods), orange represents the medium risk (infrequent floods), and brown represents the low risk (rare floods). Source: PGRAAC (2018).

2.4. SLR Projections to 2100

Even for the SLR projection, the authors are aware that these are subject to inherent uncertainty, which has led researchers to adopt a variety of alternative estimates in their impact assessments. Thiéblemont et al. (2019) [24] analysed the effects of a median estimate of about 80 cm and two different high-end scenarios resulting from two alternative extreme estimates of the sea-level equivalent of melting glaciers and other individual contributions. Antonioli et al. (2017) [35] reviewed possible alternative ranges for the projected high-end SLR at 2100, using the 530–970 mm interval reported in the IPCC AR5 and Rahmstorf's semi-empirical estimate of about 1400 mm.

Recently, improved projections from the next generation of global models have been published by the Assessment Report 6 Working Group 1 [43]. However, the spatial resolution of current global models is still not sufficient to provide realistic estimates of local sea-level rise in areas such as the Mediterranean, where crucial processes are far from being explicitly resolved and hardly allow reliable parameterization. [44].

Specifically, the projection data of the average Mediterranean Sea-level rise up to 2100 considered in this paper (63 cm) is based on a simulation of the RCP 8.5 high emission scenario ("business as usual"), following the Representative Concentration Pathways indicated in the AR5 [45]. As a future research development, it may be useful to update these datasets using Shared Socioeconomic Pathways (SSP) [46] as a reference point.

We have decided to consider the worst-case scenario for our experimentation to analyse the maximum impact that this phenomenon could cause on the components of the urban structure by 2100, also with the aim of raising public awareness and alerting policymakers to the possible loss of the coastal urban landscape, suggesting the need for prompt action in updating planning tools from a climate-proof perspective.

It is important to note that the authors do not delve into the details of how the projection data are defined, which is the responsibility of climate modelling. Instead, these projections represent a reference for understanding how they can be related to the forecasts of the Local Urban Plan. This is done in order to update both the territory's cognitive framework concerning future risk scenarios (as far as the indicative apparatus is concerned) and the prescriptive apparatus by proposing site-specific adaptation actions compatible with the risk scenario as integrations of the Technical Implementation Regulations (in Italian: Norme Tecniche di Attuazione—NTA).

It is worth noting that the use of such data has a purely demonstrative purpose and would change little for this research, even if fluctuations in sea-level rise in the order of a few centimetres were recorded. This is because, as specified in the introduction, the purpose of the experimentation is not the assessment of multi-risk but the definition of guidelines for the innovation of the urban planning tool, considering current knowledge on the impact of coastal flooding on the urban settlement.

3. Methodology

3.1. Step 1: Integration of the Territory's Cognitive Framework Concerning the Risk of Flooding Due to Heavy Rainfall, River Overflow, and Sea-Level Rise Phenomena

First, it was necessary to develop a SLR (Sea Level Rise) risk map with a time horizon of 2100, using the methodology previously elaborated by the authors [27,47]. To accomplish this, contour lines were extracted from the DEM (Digital Elevation Model) with a resolution of 10 m [40] using the Q-GIS 3.10.2 software. The contour line at an elevation of 63 cm [34] was isolated, which represents the projection of the coastline at 2100. The shape file of the Fiumicino PRG (2006) was then edited to highlight the Homogeneous sub-zones included in Target Area A—Passo della Sentinella (Figure 7). The specifications of these sub-zones are described in Table 1.

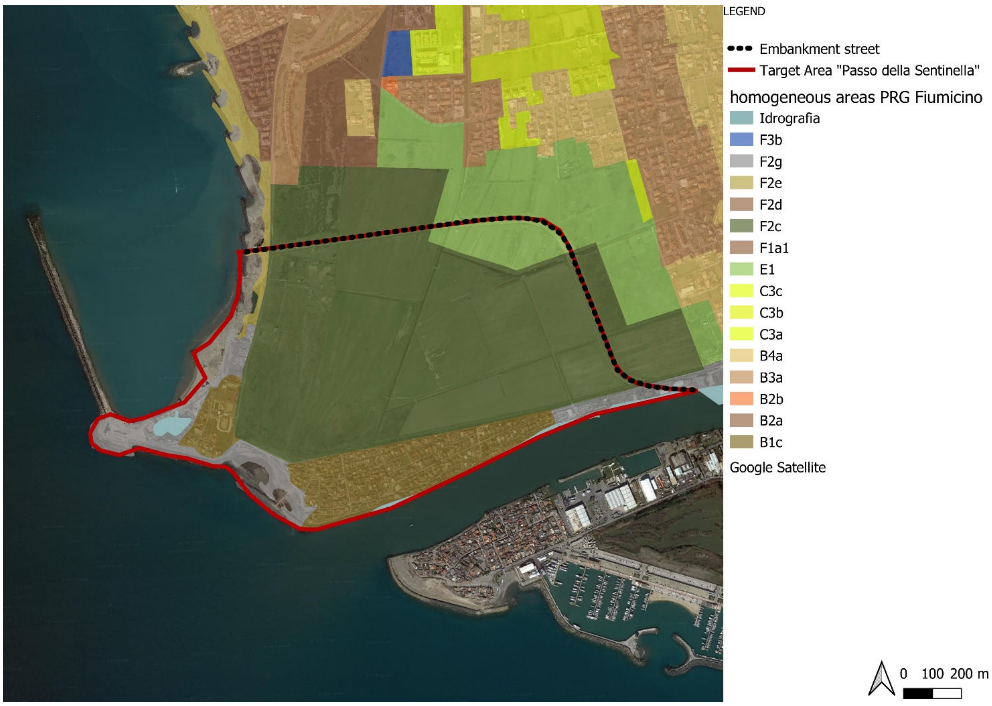


Figure 7. Highlights of the Homogeneous sub-zones of the PRG of the Municipality of Fiumicino (2006). The target area (indicated with the red perimeter) is divided into Homogeneous sub-areas B1, E1, F2c, F2e, F2g (the characteristics of which are described in Table 1). Software: Q-GIS 3.10.2. Authors' elaboration (2023).

Next, the previously obtained projection of the coastline to 2100 was superimposed, and the percentages of Homogeneous zones potentially affected by flooding by 2100 due to sea-level rise were determined using a quantity-qualitative reading, as described in the section on Step 1 results (Section 5.1) (Figure 8).

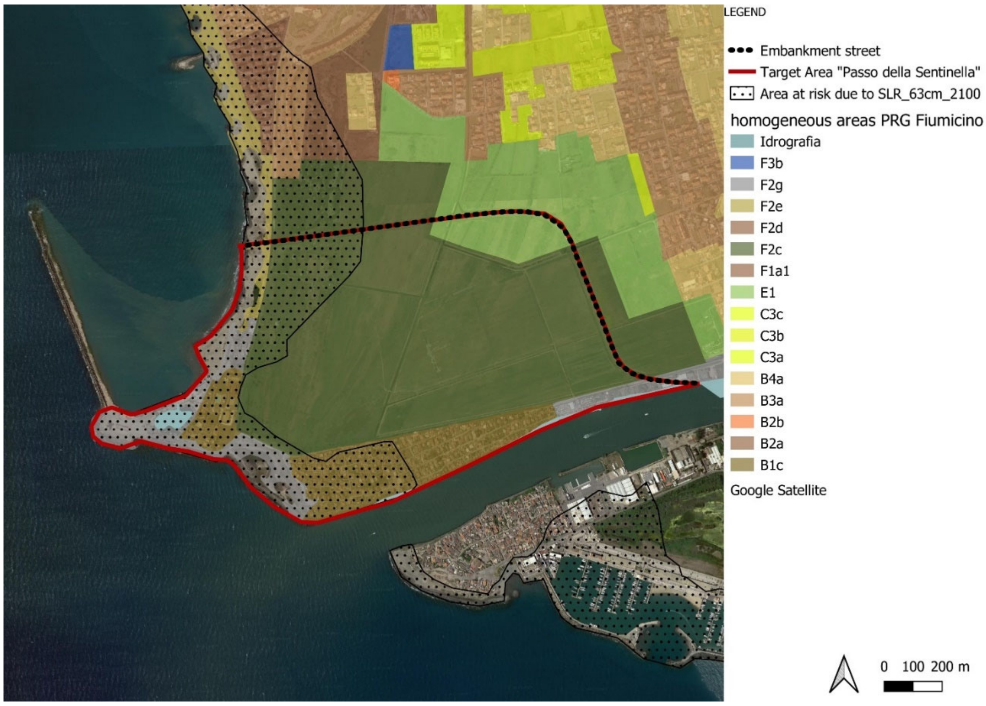


Figure 8. The projection of the coastline in 2100 was obtained by extracting the contour line at an altitude of 63 cm (the sea-level rise data used for the exercise). Then this line was superimposed on the Homogeneous Sub-zones of the PRG of the Municipality of Fiumicino (see Figure 7). The area indicated with small black dots indicates the one at risk of flooding due to the SLR at 2100 (the difference between the current coastline and that of 2100). This operation is useful to verify the relationship between the flood risk and the provisions of the current Local Urban Plan. Software: Q-GIS 3.10.2. Authors' elaboration (2023).

After defining the flood risk in 2100 caused by a sea-level rise of 63 cm, the risk relative to floods caused by heavy rainfall and river overflow phenomena was defined. The shape files of the PGRAAC risk maps [36,37] with 30-year RP (Return Period) and 100-year RP, which are coincident for the Target Area A—Passo della Sentinella (Figure 9), were superimposed on the Fiumicino PRG (2006) [39]. Similarly to what was done for the SLR phenomenon, the percentages of Homogeneous zones involved and affected by flooding with 30-year and 100-year RP were determined using a quantity-qualitative reading, as described in the paragraph on the Step 1 results (Section 5.1).

Finally, by superimposing the consistency of the SLR risk areas and the area at risk of flooding due to heavy rainfall and river overflow with RP 30 and 100 years, it can be seen that the entire Target Area A—Passo della Sentinella is affected by flooding with a time horizon of 2100 (Figure 10).

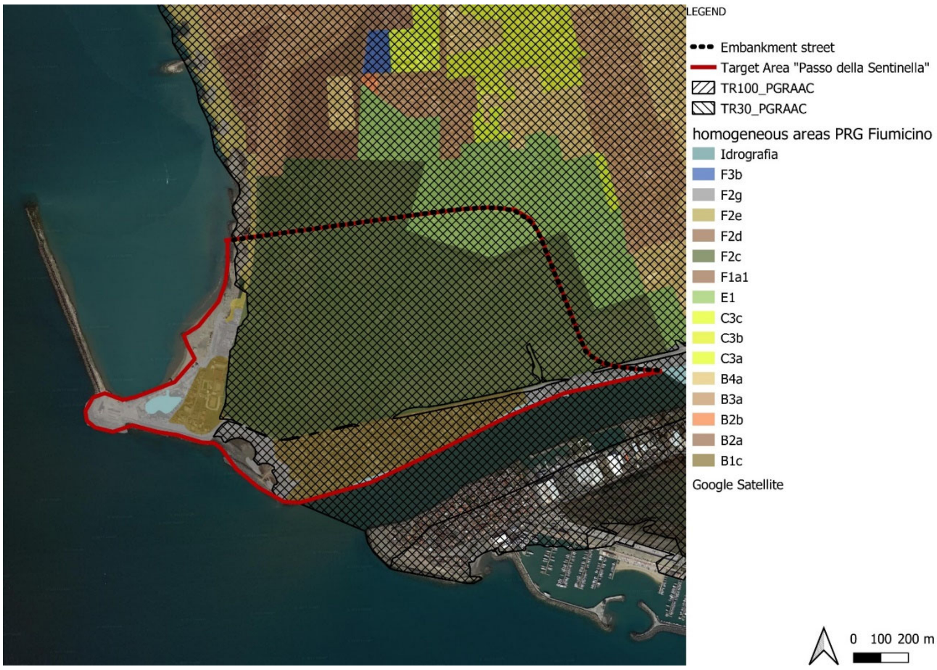


Figure 9. The hatch in the figure shows the flood risk area with RP at 30 and 100 years calculated from the PGRAAC (due to heavy rainfall and river overflow). These areas were also superimposed on the Homogeneous Sub-zones of the PRG of the Municipality of Fiumicino to see the relationship between the flood risk and the provisions of the current Local Urban Plan (the area at risk RP 30 years and the one at risk RP 100 years are coincident for the Target Area A—Passo della Sentinella). Software: Q-GIS 3.10.2. Authors' elaboration (2023).

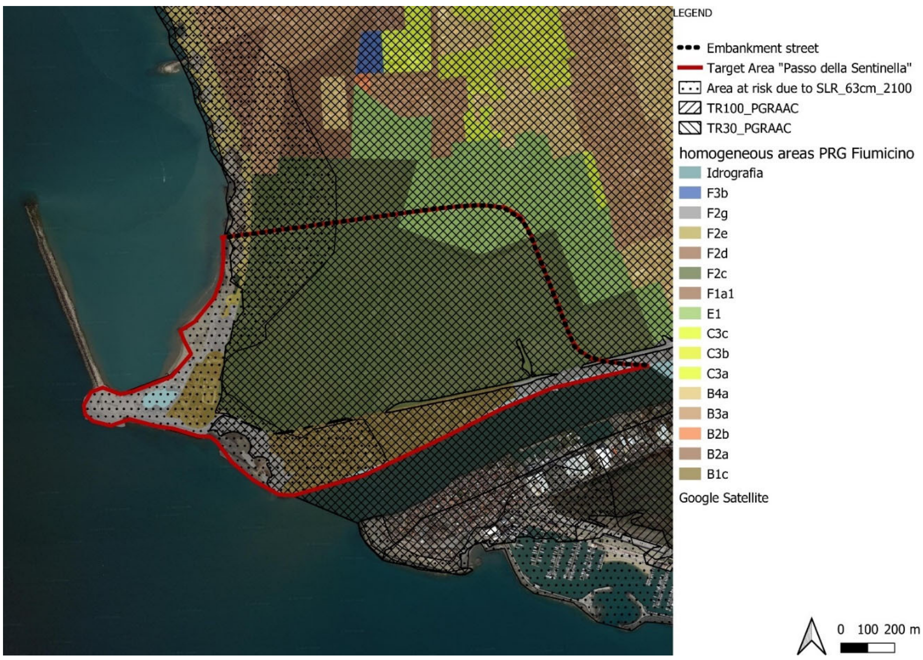


Figure 10. The areas at risk of flooding due to SLR by 2100 and the ones due to heavy rainfall and river overflow with RP 30 and 100 years have both been superimposed on the Homogeneous Sub-zones of the PRG of the Municipality of Fiumicino. This operation is useful to graphically demonstrate how Target Area A—Passo della Sentinella is subjected to multiple risks that encompass 100% of its extension. Software: Q-GIS 3.10.2. Authors' elaboration (2023).

3.2. Step 2: Definition of the Site-Specific Action Toolkit for the Risk of Flooding Caused by Heavy Rainfall, River Overflow, and Sea-Level Rise Phenomena

The authors have been working for several years on the definition of macro-strategies and design actions for climate adaptation, first defining the three macro-strategies of urban resilience, named "defence," "adaptation," and "relocation" [28], then a toolkit of site-specific design actions that relate the design actions [48–52] with the systemic components that make up the urban structure [53–63]. For this work, the methodology conceptualised by the authors has been augmented and updated and includes the explanation of:

- A "state of affairs", which considers the current Local Plan forecasts for the Homogeneous sub-zones included in the target area;
- A "state of forecast to 2100", with a 100-year time horizon, which validates or supplements the forecasts currently in force for those areas, to provide indications for the future updating of the Plan in the light of the risk highlighted by the multi-risk maps of the area obtained in "Step 1".
- In the "state of affairs," the following are made explicit:
- The Homogeneous sub-zones within the target area;
- The challenges affecting the reference sub-zones to which the adaptation action must respond (in this case, heavy rainfall, river overflow, and sea-level rise);
- The forecasts (currently in force) indicated in the NTAs of the Plan for each Homogeneous sub-zone;
- The physical-territorial system most affected by the risk phenomenon and therefore the one that will receive the greatest benefits from adaptation action is the Ecological-environmental System, the Settlement System, and the Infrastructure and Services System;
- In the "state of forecast to 2100", the following are made explicit:
- Some targets (i.e., the adaptation goals to be achieved in light of the flood risk);
- Specific adaptation actions (each of which will refer to a reference macro-strategy: "defence," "adaptation," or "relocation") to be sought (during the project phase) in best practises with similar characteristics to the area under study.

The methodology for constructing the toolkit is designed to be exportable and replicable in different contexts and includes the possibility of being integrated according to circumstances.

The results of the application of the toolkit to Target Area A—Passo della Sentinella are presented in the Step 2 results section (Section 5.2).

4. Discussion

Adaptation to climate change is a critical issue in contemporary society, and many researchers have investigated various aspects of adaptation, including strategies, measures, policies, and planning. For example, Rosenzweig et al. (2018) discussed several adaptation options, such as green and grey infrastructure, ecosystem-based adaptation, and social and institutional measures [64]. Similarly, Balica et al. (2019) proposed a framework for adaptation to climate change that encompasses vulnerability assessment, adaptation options, implementation, and monitoring [65]. Recent studies have highlighted the importance of addressing the social and economic dimensions of adaptation as well. For instance, Dulal et al. (2009) emphasised the need to incorporate social equity considerations into adaptation planning and implementation [66], while Kettle et al. (2014) stressed the importance of local knowledge and participation in developing and implementing adaptation strategies in urban areas [67]. Moreover, recent research by Sturiale et al. (2019) investigated the role of green infrastructure in urban adaptation to climate change, demonstrating the potential of green spaces for reducing urban heat island effects and enhancing resilience to extreme weather events [68]. These studies offer valuable insights and approaches for addressing the complex challenges of climate change adaptation.

An et al. (2022) present a novel approach that utilises the Remote Sensing Ecological Index (RSEI) to examine the environment of the Three Gorges Ecologic Economic (Eco-

Economic) Corridor. They aim to identify the human interaction factors that affect its ecological environment quality, including per capita GDP and agriculture, forestry, animal husbandry, and fishing [69,70].

What distinguishes this study is its final purpose, which is to highlight the logical path that should guide administrations in defining site-specific actions, namely the close link between the components constituting the "state of affairs" and those constituting the "state of forecast to 2100."

The study's first objective was to evaluate flood risk in Target Area A—Passo della Sentinella due to sea-level rise, heavy rainfall, and river overflow. This objective translated into a quanti-qualitative analysis of the risk maps presented in sub-paragraph 3.1, from which the authors derived a list of the sub-zones most at risk of flooding in 2100 and with return periods of 30 and 100 years. These are presented in Tables 2 and 3.

Table 2. Quanti-qualitative reading of areas affected by future flooding due to sea-level rise. Projection: 63 cm by 2100.

Homogeneous Territorial Zones	Homogeneous Sub-Zone	Area of the Sub-Zone within the Target Area	Area at Risk Falling within the Sub-Zone (%)
B	Sub-zone B1c	186.29484 m^2	111.421442 m^2 (59.81%)
E	Sub-zone E1	57.865863 m^2	0%
F	Sub-zone F2c	781.719024 m^2	115.745177 m^2 (14.81%)
	Sub-zone F2e	9.239793 m^2	100%
	Sub-zone F2g	106.194836 m^2	86.90514 m^2 (81.84%)

Table 3. Quanti-qualitative reading of areas affected by flooding due to heavy rainfall and river overflow with 30-year RP and 100-year RP.

Homogeneous Territorial Zones	Homogeneous Sub-Zone	Area of the Sub-Zone within the Target Area	Area at Risk Falling within the Sub-Zone (%)
B	Sub-zone B1c	186.29484	142.710330 m^2 (76.69%)
E	Sub-zone E1	57.865863 m^2	100%
F	Sub-zone F2c	781.719024 m^2	766.205248 m^2 (98.02%)
	Sub-zone F2e	9.239793 m^2	5.122698 m^2 (55.44%)
	Sub-zone F2g	106.194836 m^2	38.362938 m^2 (36.12%)

After the quantitative-qualitative analysis, the study's second objective was to define a toolkit of site-specific adaptation actions, presented in Table 4.

Table 4. Toolkit of site-specific actions applied to *Target Area A—Passo della Sentinella*.

State of Affairs			State of Forecast to 2100					
Homogeneous Sub-Zone (PRG, 2006)	**Challenges**	**NTA Forecasts (PRG, 2006)**	**Territorial System**	**Target**	**Site-Specific Actions**	**Macro-Strategies**		
						a	**b**	**c**
B1c Art. 54.3: Maintenance, completion and redevelopment of the existing fabric	1. Heavy rainfall and river overflow; 2. Sea-level rise	Planned relocation of existing buildings to external areas may involve the demolition of the existing building stock.	Settlement System	Relocation of the inhabitants of Passo della Sentinella for reclamation works in the area	Identification of completion areas within the municipality in which to relocate part of the inhabitants			●
					Strengthening and integration of defence embankments near the mouth of the Tiber River	●		
					Creation of a raised platform at the level of the embankment on which to allocate new buildings (to relocate part of the current population)	●	●	
		Environmental rehabilitation is planned	Ecological-environmental System	Land reclamation and renaturation of the area	Creation of wetlands		●	
					Creation of areas for eco-friendly recreational activities also related to water		●	
E1 Art. 60.1: Agricultural activities in suburban areas	1. Heavy rainfall and river overflow	Hydrogeological vulnerability constraints are respected	Ecological-environmental System	Redevelopment into a Territorial Equipped Park	Creation of wetlands		●	●
					Creation of areas for eco-friendly recreational activities		●	●
F2c Art. 63.4: Public green: Territorial Equipped Park	1. Heavy rainfall and river overflow; 2. Sea-level rise	Only public facilities that are indispensable to the enjoyment of the park itself and/or destinations aimed at the recovery and redevelopment of the entire river channel are envisaged	Ecological-environmental System	Reconversion of areas into a Territorial Equipped Park. (The area is currently occupied by agricultural fields, contrary to the Plan's provisions)	Creation of wetlands		●	●
					Creation of areas for eco-friendly recreational activities		●	●
					Construction of playgrounds		●	●
					Creation of areas equipped for sport		●	●
F2e Art. 63.4: Public green areas may include con-cessionary facilities for coastal use	1. Heavy rainfall and river overflow; 2. Sea-level rise	Areas equipped for tourism and recreational activities are also planned	Infrastructure and Services System	Deanthropisation and	Relocation of present activities			●
			Ecological-environmental System	Renaturalisation of the area	Restoration of the dune cordon		●	
F2g Art. 63.8: Public green: Embankment Protection Area	1. Heavy rainfall and river overflow; 2. Sea-level rise	Planned reconversion of existing shipyards and constructions along the Tiber must follow landscape and environmental principles and values	Infrastructure and Services System	Embankment protection actions	Maintenance and possible integration of embankments	●		
			Ecological-environmental System	Renaturalisation of the area	Relocation of present activities			●

The letters refer to the 3 macro-strategies of "defence" (a), "adaptation" (b), and "relocation" (c).

5. Results

5.1. Step 1: Quanti-Qualitative Reading of Sub-Zones at Risk of Flooding Due to Heavy Rainfall, River Overflow, and Sea-Level Rise

Thanks to the methodology presented in Step 1 (Section 3.1), it was possible to perform a quanti-qualitative reading of the flood risk at 2100 caused by a predicted sea-level rise of 63 cm. The table below shows the percentage of the area at risk of flooding with respect to the area of the reference sub-zone included in Target Area A—Passo della Sentinella (Table 2).

It follows that the sub-zone B1c, which pertains to the "Maintenance, Completion, and Redevelopment of Existing Buildings", would be affected by flooding due to SLR at 2100 for approximately 59.81% of its area. The sub-zone F2c, designated as a "Public Green: Equipped Territorial Park" (currently occupied by agricultural fields, in violation of current regulations), would be affected for about 14.81% of its area. The sub-zone F2e, classified as "Public Green: Concessionary Facilities for the Enjoyment of the Coast," would be entirely affected within the target area. The sub-zone F2g, designated as a "Public Green: Embankment Protection Area," would be affected for approximately 81.84% of its area. However, the area of sub-zone E1, which pertains to "Agricultural Activities in the Extra-Urban Territory" and is included in the target area, would not be compromised due to flooding at SLR to 2100 (see Table 2).

Similarly, it was possible to perform a quanti-qualitative reading of the expected floods due to heavy rainfall and river overflow with RP 30 years and RP 100 years. As previously stated, these two phenomena coincide in the target area. The table below shows the percentage of sub-zones at risk of flooding included in Target Area A—Passo della Sentinella (Table 3).

As a result, sub-zone B1c, which pertains to the "Maintenance, Completion, and Redevelopment of Existing Tissue," would be affected by flooding with RP 30 years and RP 100 years for approximately 76.69% of its area. Sub-zone E1, which pertains to "Agricultural Activities in the Extra-Urban Territory" and is included in the target area, would be entirely affected. The sub-zone F2c, designated as a "Public Green: Equipped Territorial Park" (and currently occupied by agricultural fields, in violation of the Plan's regulations), would be affected for approximately 98.02% of its area. The sub-zone F2e, classified as "Public Green: Facilities under Concession for the Enjoyment of the Coast," would be affected for about 55.44% of its area. Finally, sub-zone F2g, designated as a "Public Green: Embankment Protection Area," would be affected by approximately 36.12% of its area (see Table 3).

5.2. Step 2: Application of the Toolkit to Target Area A—Passo Della Sentinella

After completing the quanti-qualitative reading of Tables 2 and 3, it was possible to conduct specific evaluations on the current prescriptions of the Fiumicino Local Plan (NTA), which is currently in force (refer to Table 1). These evaluations will provide useful indications to the Local Administration for updating the Plan in accordance with the risk scenarios outlined in Step 1.

As outlined in the Step 2 methodology (Section 3.2), the toolkit (Table 4) includes:

- A "state of affairs" that illustrates the current NTA prescriptions for the relevant sub-zones within the target area, the risk scenario they face (determined in Step 1 with Tables 2 and 3), and the territorial system in which the urban components most affected by flooding occur (Ecological-environmental System, Settlement System, Infrastructure, and Services System);
- A "state of forecast to 2100", which outlines the goals for adapting the area through site-specific actions (which fall under one of the three macro-strategies of "defence", "adaptation", and "relocation", indicated in Table 4 as "a," "b," and "c," respectively).

Regarding the "state of affairs" of sub-zone B1c, which encompasses the maintenance, completion, and redevelopment of existing buildings, we can observe that it is affected by both SLR-induced flooding with a time horizon of 2100 and flooding with RP 30 years and RP 100 years caused by heavy rainfall and river overflow phenomena. The most affected territorial systems are the Settlement and the Ecological-environmental Systems. The "state forecast to 2100" proposes the following targets:

1. The relocation of Passo della Sentinella's inhabitants for reclamation works (a target already stated in the current Plan's provisions);
2. Land reclamation and renaturation of the area. In turn, the two targets are divided into the following site-specific actions:
    - 1.1 Identification of completion areas within the municipal territory to which part of the inhabitants will be relocated (an action also explicitly stated in the current Plan's forecasts);
    - 1.2 Strengthening and integration of defence embankments near the mouth of the Tiber River;
    - 1.3 Creation of a raised platform at the embankment level to construct buildings, including residential buildings, in which part of the current population will be relocated;
    - 2.1 Creation of wetlands;
    - 2.2 Creation of areas for eco-friendly recreational activities related to water.

Thus, the adaptation of sub-zone B1c will require an integrated approach that involves "defence," "adaptation," and "relocation" strategies.

About the "state of affairs" of sub-zone E1, which is currently designated for agricultural activities in suburban areas, it appears that it is only affected by floods with RP 30 and RP 100 years caused by heavy rainfall and river overflow, with the most affected System being the Ecological-environmental.

In this regard, the "state forecast to 2100" proposes the following target:

1. Reconversion into a Territorial Equipped Park, which aligns with the intended use of contiguous "F2c" zones as per the current NTAs. It is considered plausible that even though the portions of the E1 sub-zone falling within Target Area A—Passo della Sentinella seem not to be affected by flooding from SLR, this will still be affected in some way as they are excluded from the protection of the embankment road. To achieve this target, the following site-specific actions have been proposed:
    - 1.1 Creation of wetlands;
    - 1.2 Creation of areas for eco-friendly recreational activities.

Therefore, the adaptation of sub-zone E1 will have to be done with an integrated approach involving "adaptation" and "relocation" strategies (as far as previously planned agricultural activities are concerned).

About the "state of affairs" of sub-zone F2c, which is "Public green: equipped territorial park", it can be seen that this area is affected by floods caused by both SLR with a time horizon of 2100 and floods due to heavy rainfall and river overflow with RP 30 years and RP 100 years, and that the most affected System is the Ecological-environmental.

In this regard, the "state forecast to 2100" proposes the following target:

1. Conversion of the area into a Territorial Equipped Park. The target is divided into the following site-specific actions:
    - 1.1 Creation of wetlands;
    - 1.2 Creation of areas for eco-friendly recreational activities.

It follows that the adaptation of sub-zone F2c will have to proceed with an integrated approach that includes "adaptation" and "relocation" strategies (in regards to the agricultural activities currently in use, which are contrary to the Plan regulations).

About the "state of affairs" of sub-zone F2e "Public green: concessionary facilities for the use of the coast", is it possible to see how it is affected by both the flooding caused by the SLR with a time horizon of 2100 and floods due to heavy rainfall and river overflow with RP 30 and 100 years. The Infrastructure and Services and the Ecological-environmental Systems are the most affected.

The "state forecast to 2100" proposes the following targets:

1. Deanthropisation;
2. Renaturalisation of the area. These two targets are further divided into the following site-specific actions:
    1.1 Relocation of present activities;
    2.1 Restoration of the dune cordon.

Therefore, the adaptation of sub-zone F2e will have to proceed with an integrated approach involving "adaptation" and "relocation" strategies.

About the "state of affairs" of sub-zone F2g "Public green: Embankment protection area" it can be seen that this area is affected both by floods caused by the SLR with a time horizon of 2100 and by floods due to heavy rainfall and river overflows with RP 30 and 100 years, and how the Systems most affected are the Infrastructure and Services and the Ecological-environmental.

In this regard, the "state forecast to 2100" proposes the following targets:

1. Actions to protect embankments (a target that is also made explicit in the current provisions of the Plan);
2. Renaturalisation of the area. In turn, the two targets are articulated in the following site-specific actions:
    1.1 Maintenance and possible integration of embankments;
    2.1 Relocation of present activities

It follows that for the adaptation of the F2g sub-zone, it is necessary to proceed with an integrated approach involving "defence" and "relocation" strategies.

6. Conclusions

The innovation of the research lies in two main aspects:

- Linking flood-prone areas with the components of the urban structure by defining risk maps (Step 1);
- Creating a toolkit of site-specific actions that relates the "state of affairs" (which takes into account factors such as Homogeneous sub-zones, Challenges, NTA forecasts, and the Territorial System) and the "state of forecast to 2100" (which takes into account factors such as Target, Site-specific actions, and macro-strategies) (Step 2).

The methodology thus defined can be exported to other territorial contexts and can provide theoretical, methodological, and operational references for updating the Local Urban Plan from a climate-proof perspective, both in its descriptive components (see methodology of Step 1) and in its prescriptive components with the definition of site-specific adaptation actions (see methodology of Step 2).

Furthermore, the structured toolkit (Table 4) could also help public administrations compare the current prescriptions of the Local Urban Plan with the risk scenarios up to 2100 to understand how prepared the city is, in terms of territorial governance tools, to address the impacts of climate change. Indeed, as it is possible to see from Table 4, the toolkit for Target Area A—Passo della Sentinella reveals that, in some cases, the "state forecast to 2100" validates the prescriptions of the NTAs of the Local Plan, while in other cases, it highlights the need to modify/supplement them.

For the target area analysed in the paper, the cases in which the targets and site-specific actions of the "state forecast to 2100" validate the current NTAs are:

- Sub-zone B1c, concerning the relocation of the inhabitants of Passo della Sentinella to identified completion areas within the municipal territory;
- Sub-zone F2g, concerning embankment protection actions.

For the remaining sub-zones within the target area, amendments/integrations of the NTA are necessary.

The article aims to demonstrate the importance of constantly updating the territory's cognitive framework to identify the areas at risk of flooding over different time horizons. Furthermore, it stresses the need to pursue a resilient development of the territory based on an integrated approach of "defence," "adaptation," and "relocation" through the cascading definition of targets and site-specific actions [71].

The authors are aware of the shortcomings of the research.

First, the uncertainty in estimating sea-level rise could result in flood scenarios different from those projected in this study. Additionally, there is uncertainty in the measurements adopted to determine flood risk maps due to significant variations in different emission scenarios. Furthermore, both sea-level rise-induced flooding and heavy rainfall and river overflow-induced flooding can vary based on multiple factors such as coastal erosion, high tide phenomena, storm events, land subsidence, and so on.

As future developments of the research progress, it would be interesting to collaborate with experts in the fields to determine the variable results determined by the combination of various factors related to climate change. In this way, it would be possible to conduct a more comprehensive analysis, leading to a more effective site-specific adaptation action toolkit.

It is also in the interest of the authors to apply the proposed methodology to other areas of the Lazio coast subject to the same risk phenomena and implement the proposed actions following a detailed analysis of international case studies that present the same challenges and propose nature-based approaches.

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