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Agustín Sánchez-Arcilla Jr., Vicente Gracia and Agustín Sánchez-Arcilla *

Laboratori d'Enginyeria Marítima, LIM/UPC, Universitat Politècnica de Catalunya, BarcelonaTech (UPC), Jordi Girona, 1, Campus Nord UPC, 08034-Barcelona, Spain; agustin.sanchez-arcilla@upc.edu; vicente.gracia@upc.edu

* Correspondence: agustin.arcilla@upc.edu

Abstract: Coastal zones experience increasing climatic and human pressures, which lead to growing risks and tipping points (TPs) under future scenarios and natural resource scarcity. To avoid crossing TPs with irreversible coastal losses, this paper proposes the development of adaptation pathways based on advanced coastal oceanography and engineering knowledge that enables an objective assessment of evolving coastal risks. These pathways feature sequential interventions, combining conventional engineering works with nature-based solutions (NbS), steered by simulations and observations as a function of available coastal resources (space and sediment) and risks for infrastructure and socioeconomic assets. Such an adaptation has been developed for urban and peri-urban Mediterranean beaches, considering conventional coastal engineering together with NbS. Both types of interventions are assessed in terms of key physical variables, which serve to evaluate performance and estimate TPs. This analysis supports the new coastal protection and management plan promoted by the local government and the coastal adaptation plan of the central government. The approach and results illustrate the potential of adaptation pathways for beach sustainability, enhancing the compatibility between short/long-term coastal protection objectives under present/future climate and management scenarios. The adaptation pathways development underpins an increasing stakeholder cooperation to achieve shared decisions for coastal sustainability.

Keywords: coast; climate; adaptation; risk; tipping-points; Mediterranean; engineering; nature-based-solutions

1. Introduction

Coastal zones and in particular those of the Mediterranean, present a notable bio/geo-diversity and experience high socio-economic pressures, which make them particularly vulnerable to climatic changes. Such a diversity hampers the proposal of unified solutions for coastal vulnerability assessments and adaptation plans [1,2], while the Mediterranean climate variability and geodiversity increase the uncertainties to characterise metocean extremes [3], delineate coastal segments [4] and analyse impacts for risk reduction [5,6].

Coastal adaptation [7] offers a flexible and holistic [8] approach to risk reduction in terms of key parameters, mainstreaming natural resilience into coastal management plans. These plans should, in our case, explicitly consider Mediterranean weather variability [9,10] under future scenarios [10], together with the multiple infrastructures affecting coastal dynamics and supported by GIS and statistical tools depending on site-specific criteria [11,12]. Adaptation plans should be tailored to the features of the analysed coastal archetype [13], considering its socioeconomic and biophysical

features, as well as the limitations imposed by the availability of resources such as freshwater or sediment [14], commonly affecting Mediterranean coastal archetypes.

Urgent coastal adaptation is required for deltas [15], small islands [16] and cities [17], where urban coasts present high vulnerability under present and future climates [5,18–20]. Urban and peri-urban beaches are the coastal archetype selected in this paper to develop a set of adaptation pathways under climate change, in support of the transformative change promoted by the local government of Catalonia (new Coastal Protection and Management Plan, CPM plan in short). These pathways have been delineated for two coastal profiles, representative of high- and mid-levels of rigidization, aiming to reduce risks on low-lying coasts and illustrating how environmental research can support new coastal policies and lead to actionable adaptation plans.

Adaptation pathways can support decision making [21] under transient climate and management scenarios, eschewing tipping points (TPs) that would make beach recovery unlikely [22] and therefore contributing to a more transparent governance for coastal risk reduction [23]. The adaptation pathway framework combines different scales [24] and stakeholders [8] to propose sequenced interventions that look for a transformative socio-economic consensus in heavily anthropized areas [20,25]. Such consensus and the convergence of stakeholder criteria are based on an explicit assessment of synergies and tradeoffs for the proposed coastal interventions, including estimations of costs, impacts and carbon footprint.

A sequential adaptation with a multirisk assessment [26] enables a flexible set of interventions to enhance coastal resilience, avoid TPs and, in the approach here proposed, demonstrating the shared benefits of nature-based solutions (NbS) or living shorelines. The developed dynamic adaptation plans [27] consider climate and management evolution, proposing a set of actionable interventions and estimating their contribution to risk reduction in terms of key and robust physical parameters, simpler to project than ecologic or socioeconomic ones.

Because NbS take a longer time to develop and deliver ecosystem services, adaptation pathways should include a monitoring and maintenance plan, supported by an early warning system (EWS) based on numerical models [28] or metamodels [29] that underpins proactive decisions. Risk is measured by the distance to TPs, which also determines the urgency to implement the proposed interventions within an adaptation plan that considers uncertainties and proposes limit dates for interventions, as a function of co-decided objectives, on risk reduction [30] according to stakeholder criteria.

The coastal stretch selected for adaptation presents fine and coarse sand beaches with rigid coastal infrastructure and impulsive storms, which condition adaptation capacity and criteria to rank actionable interventions [31,32]. The resulting adaptation pathways are steering adaptive management decisions, according to co-designed objectives that avoid tipping points and mainstream environmental values into coastal policies [33,34]. Adaptation is set out as a function of the efficiency of implemented measures and the rate of change observed or projected in climate and management, incorporating the best available technical-scientific tools and recent experiences in coastal protection to facilitate a convergence of stakeholders' political and socio-economic criteria.

Such convergence is leading to a transformation of governance mechanisms, illustrated by the participatory process in the new CPM plan, that considers, from a holistic perspective, key social-ecological interactions, aiming to increase the acceptability of the proposed coastal interventions by showing explicitly the achieved risk levels [36]. Such risk assessments require, because of the underlying uncertainties, ethic-based approaches that aggregate different values and socio-economic criteria, sweeping the full range of actionable interventions for a wider social engagement [6,37].

Based on a combination of observations and modelling, this paper develops and applies the adaptation pathway model for two vulnerable coastal stretches in the Catalan (Spanish Mediterranean) coast, considering the common legal and administrative constraints and their differential social-ecological traits. Both stretches are typical of urban and peri-urban beaches in the Mediterranean, covering the case of coarse and fine sand sediments and two contrasting levels of anthropic pressure. The coarse sand beach, located north of Barcelona, features high first line buildings and private industries, with limited accommodation space and is located at the

downstream end of a littoral cell. The fine sand beach is within a deltaic system, south of the Barcelona harbour (according to the average direction of net longshore transport under present climate) but with some available accommodation space. Both coastal stretches are currently experiencing strong erosion and have been analysed for the same future climate scenarios and horizons. The paper presents the developed adaptation pathways, analysing the differences between fully rigidized and partially flexible coasts, represented, respectively, by the coarse and fine sand beaches. The paper ends with a review of the main barriers and enablers to a coastal adaptation that enhances resilience ([6]), suggesting criteria to implement the proposed adaptation pathways by all involved stakeholders.

2. Materials and Methods

The materials considered in this paper are the initial characteristics of the selected coastal archetype [20], the projected evolution rates, the downscaled climate scenarios and, finally, the portfolio of proposed interventions. The main output of the proposed methodology is the set of adaptation pathways [38], the derived risk estimators and the proposal for a more equitable distribution of scarce resources such as sand or coastal accommodation space.

2.1. Coastal Archetype and Profiles

The archetype selected corresponds to Mediterranean urban (anthropized) beaches, which experience erosion under present conditions and therefore require an adaptation plan to reduce future risks, combining adaptation with a reduction of the carbon footprint associated to coastal protection, so as to align coastal adaptation with climate mitigation. The first coastal profile within this archetype represents beaches without backbeach accommodation space and strong urban development, with high pressures of co-existing and often incompatible uses. It is illustrated by the Badalona beach, located north of Barcelona (NE Mediterranean Spanish coast), featuring coarse sand and a high berm up to 3.5 m (Figure 1). The small available beach width places this coastal stretch close to its maximum tourist carrying capacity in the summer, while the coarse sand ($D_{50} = 0.96$ mm) reduces actual sediment transport. This coastal profile is at the down drift end of a physiographic unit, with multiple harbours, groynes and longitudinal revetments. Because of this there have been no recent artificial nourishments to maintain a beach width of about 15 m., which is the beach emerged area with the highest occupation density [24]. Longshore transport is responsible for the mid-long term morphodynamic response while cross-shore transport dominates beach response under storms, leading to a baseline erosion between 0.5 and 1.0 m/year.
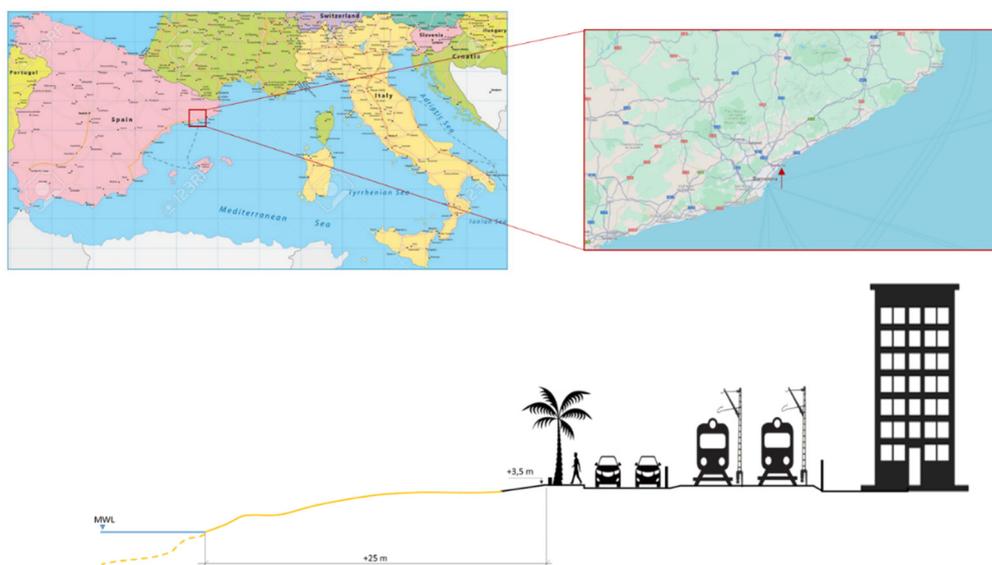

Figure 1. Representative profile for Mediterranean urban beaches without accommodation space, illustrating (based on the Badalona beach, location displayed in the upper panel) a heavily rigidized coastal fringe with coarse sand and a high berm level.

The second coastal profile within this archetype represents a deltaic Mediterranean beach, subject to moderate subsidence and with fine sand (D_{50} = 0.30 mm), featuring a lower berm of about 1.5 m. The beach profile presents several sub horizontal berms, resulting from wave storm action and there is enough accommodation space at the backbeach (Figure 2), associated with a lower urbanisation pressure. The available beach width is however too narrow to reduce erosion and flooding risks to acceptable levels under present wave storms, which has required artificial nourishment and periodic revamping of the backbeach promenade. This coastal transect is located within a littoral cell directly exposed to wave action, without breakwater/groyne barriers that would lead to complex nearshore circulation patterns. As for the previous case, longshore transport is the main dominant factor for the mid-long term morphodynamic response, while cross-shore transport dominates cross-shore storm impacts, leading to baseline erosion rates from 1.0 to 1.5 m/year.
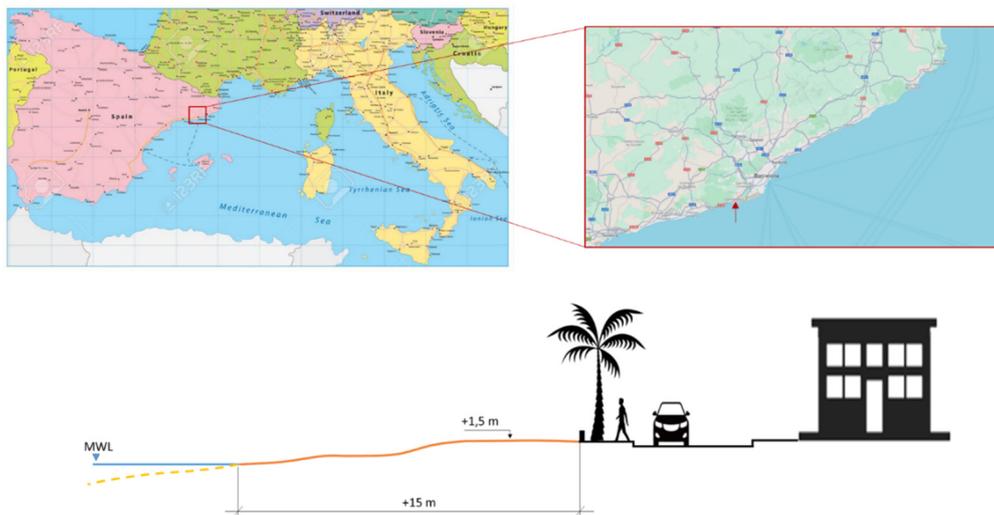

Figure 2. Representative profile for Mediterranean urban beaches with some accommodation space, illustrating (based on the Gavá beach, location displayed in the upper panel) a moderately rigidized coastal fringe with fine sand and a low berm level.

The profiles analysed enable an adaptation comparison for: a) rigidized urban beaches (Badalona case) with no accommodation space and coarse sand; b) peri-urban beaches with partially regulated dynamics (Gava case), accommodation space and fine sand. The dominant socio-economic typologies for the considered beaches go from predominantly working class and residential population, associated with socio-economic inequalities (urban beach) to a more affluent population combined with tourism, with smaller socio-economic inequalities (the peri-urban beach). In both cases the governance is fragmented, combining municipal, local and central Government stakeholders, as is typical of many Mediterranean beaches. However, in both cases there is a good organisation and solidarity, although the social commitment and sense of place is considered to be higher for the urban beach. The urban beach (northern profile) can be considered an illustration for cases without accommodation space and permanent maintenance needs, while the peri-urban beach (southern profile) represents a sediment starved coastal stretch, offering some natural resilience and affected by deltaic subsidence.

2.2. Coastal Adaptation Pathways

Adaptation pathways [6,8,39] offer a structured approach to develop and implement coastal protection measures as a function of evolving risk. The pathways here developed combine: a) risk reduction by means of NbS or hybrid interventions (NbS + conventional coastal engineering solutions); b) no-regret sequences of interventions (compatibility between short to long-term coastal protection); c) Maintenance plans based on monitoring to assess the distance to tipping points (for

proactive decisions); d) Regular presentation of results for socioeconomic engagement (shared compromise).

The proposed adaptation, steered by monitoring and maintenance, is based on proactive decisions linked to an EWS in support of new regional environmental and territorial policies, illustrated here by the new CPM plan (*Pla de Protecció i Ordenació del Litoral a Catalunya)* of the local government (Generalitat de Catalunya). The selected adaptation pathways favour: a) Preventive actions that reduce costs and impacts and that apply the precautionary principle; b) consensus decisions that minimise total costs (environmental, social and political) and socio-economic acceptability; c) evidence-based demonstrations from a set of pilot interventions, in particular NbS, that enable fine-tuning the engineering required by NbS.

Based on stakeholder requirements and dominant hydro-morphodynamic processes, five alternative pathways have been developed, which represent technical flexibility, economic suitability and social acceptability for the studied archetype. The first pathway (Figure 3) consists in artificial nourishment supplemented by conventional structures (seawalls and groynes) to reduce short-term risks, albeit with large impacts and costs. It represents maintaining the present coastal protection approach and is denoted as pathway A, which based on the recent past experience, has a limited life cycle (t_A, estimated in the following sections) linked to an increasing sand scarcity and environmental impacts. It presents growing costs and mixed social acceptance, with those more exposed favouring rigid short-term interventions, while those with a longer-term view lean towards more sustainable (lower costs, impacts and carbon footprint) interventions.
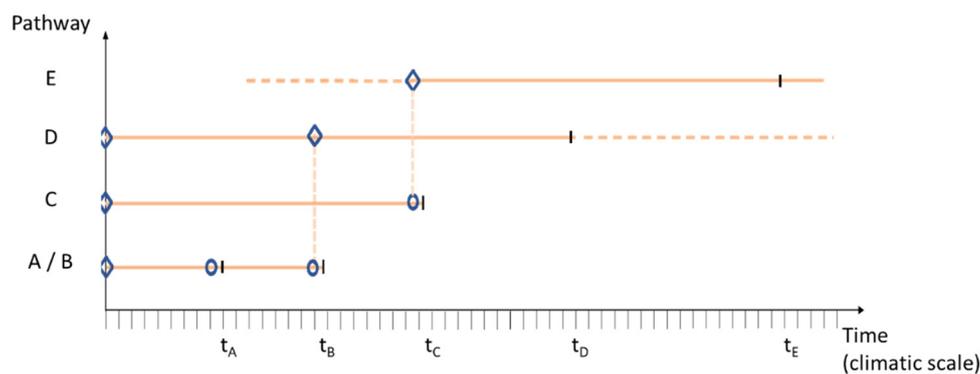

Figure 3. Schematic representation of a set of possible adaptation pathways for the coastal profiles (schematized in Figures 1 and 2) characterising the Mediterranean coastal archetype analysed in this work.

Pathway B complements pathway A and consists of artificial sand nourishment with combined NbS and rigid structures (hybrid interventions), representing the expected evolution of pathway A, due to the increasing inefficiency of rigid engineering solutions under decreasing sand and sea level rise (SLR). Because of that, pathway B has a longer life cycle t_B ($t_B > t_A$). Pathways A and B correspond to an increasingly rigidized coastline, with growing risks and maintenance costs under SLR and changes in wave storminess due to the lack of natural resilience for a rigidised coast [40]. The expected increase in the carbon footprint for progressively larger rigid defences and increasing frequency of shore nourishments, make it necessary to introduce pathways with a longer life, such as C or D (Figure 3).

Pathway C corresponds to a totally rigidized coast, with increasing costs and environmental impacts, as well as a progressively more unacceptable carbon footprint, which should be considered technically and socio-economically from the beginning of this pathway. Such a pathway is possible for the analysed coastal profiles, although the projected acceleration in SLR and more frequent extreme wave storms will increase risks and costs and therefore the rigidized coastline performance is expected to slump after time t_C. Moreover, pathway C would hinder the transition towards a decarbonised coastal protection, based on either NbS (pathway D) or management realignment

(pathway E). The hurdles for a transition from pathway C towards pathways D or E are linked to the investments required by pathway C, which include high social, economic and are environmental costs. The political and image costs associated with the deconstruction of rigid interventions can make such a transition unacceptable.

Pathway D, involving NbS with some remaining rigid structures for areas without any accommodation space, will feature, according to the performed assessments, increasing risk reductions under climate change, with a carbon footprint and costs significantly smaller than for traditional coastal protection. Because of that, pathway D is projected to last longer than C, considering that it also enables a better distribution of interventions and investments, as is typically the case for NbS [40], which lead to an optimization of costs, impacts and carbon footprint.

Pathway E corresponds to managed realignment, considered from the beginning although this trajectory presents higher difficulties for a wide socio-economic acceptance until time t_c. At that moment in time, present coastal interventions, linked to rigid infrastructure or continued nourishment, will have shown their increasing limitations under accelerated SLR and wave storminess. Because of socio-economic acceptability, present governance will more naturally support a late start of pathway E, which can be continued without a clear deadline, since this deadline will be linked to available accommodation space and land planning.

The adaptation pathway map (Figure 4) shows tipping points (TPs) associated to limits in accommodation space, available sand/freshwater volumes or to some irreversible coastal state. The actual times to reach TPs have been estimated using SLR as the basic "pressure" variable, subsequently "translated" into actual times depending on the two co-selected scenarios, SSP2-4.5 and SSP5-8.5 [41], corresponding to an average and pessimistic projection of climate change evolution.
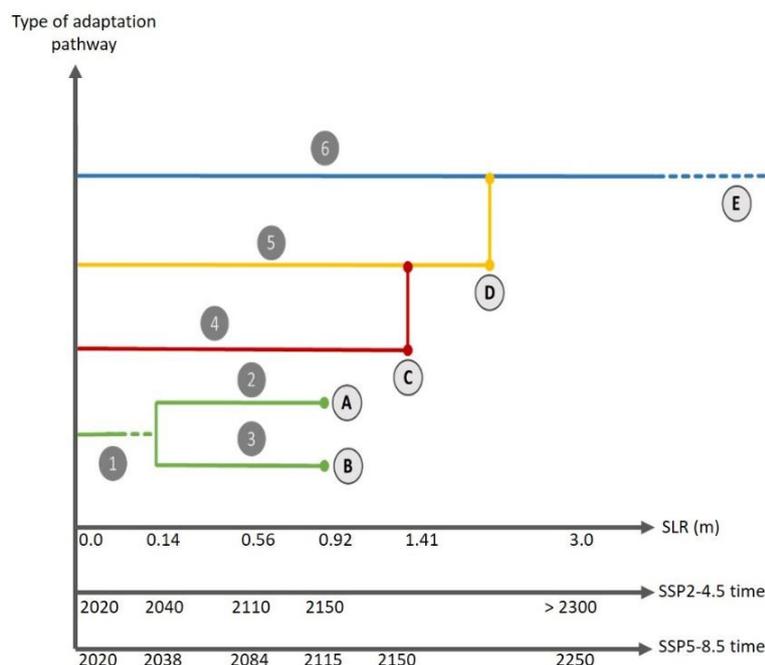

Figure 4. Illustration of actionable adaptation pathways for the studied Mediterranean coastal profiles, including both conventional coastal engineering and NbS interventions. The horizontal axis indicates SLR as a basic (independent) variable, then translated into two different time-lines, depending on the selected climate change scenario. Tipping points are reached earlier for the pessimistic scenario (SSP5-8.5) than for the medium level scenario (SSP2-4.5). Pathways 1 and 2 represent small/mid-scale reactive interventions; pathway 3 stands for large-scale rigidization and pathways 5 and 6 are associated with mid/large scale restoration (5) with adaptive maintenance (6).

2.3. Climate and Management Scenarios

The proposed adaptation pathways combine the following key climate and management variables: a) metocean drivers (waves, surges, mean sea level…); b) geomorphological constraints (sediment volume, diameter, beach width…); c) artificial existing or planned barriers (ports, promenades, groynes…); d) present and planned beach uses (protection, tourism, ecosystem services…); e) maintenance and monitoring plans, including the application of an EWS. The selected future scenarios combine physical drivers with socio-economic and policy scenarios [42], considering historical effects which condition risk memory and social adaptation capacities [22]. Management scenarios are projected to evolve from rigid coastal protection, usually preferred for short term plans, towards more flexible NbS interventions [6,43]. Managed retreat policies will be difficult to implement until the projected tumble of conventional coastal engineering solutions becomes apparent, which will condition future policies and adaptation governance.

Projected coastal morphodynamics, mainly driven by mean sea level (MSL) rise and changes in wave storminess, present large uncertainties due to the errors associated with future sediment transport calculations [44]. Physical projections like those for SLR, based on IPCC AR6 [43] regionally downscaled values, are combined with socio-economic projections (SSP scenarios), where the stakeholder preferred set of future conditions has been SSP2-4.5 and SSP5-8.5. The former (SSP2-4.5) corresponds to an average scenario for physical conditions and a continuation of shared socio-economic pathways (SSP2), where social, economic and technological trends do not significantly depart from present patterns [48]. This set of futures, associated with an average increase of population in the second half of this century and where technological challenges to reduce vulnerability persist, represent "middle of the road" trajectories. SSP5-8.5 (pessimistic future) corresponds to an enhanced global warming and accelerated SLR, where SSP5 represents a future scenario of innovation and participatory societies with technological progress for sustainable development. Here social and economic development is projected to be combined with the exploitation of fossil fuels and an enhanced consumption of resources and energy, underpinning a rapid increase of worldwide economy and population, which reaches a peak and then decreases, assuming that local environmental problems are successfully managed.

The "average" scenario, SSP2-4.5, approximately corresponds to the upper level of emissions defined for the 2030 Nationally Determined Contributions, with global warming from 2.7°C to 3.4°C by 2100, in spite of the net 0 objectives for 2050 adopted by many countries. SSP2-4.5 supposes preparing our coastal systems for a global temperature increase of 2.7°C by 2100 and a regional SLR below 1.0 m (Figure 5) without considering subsidence [43].
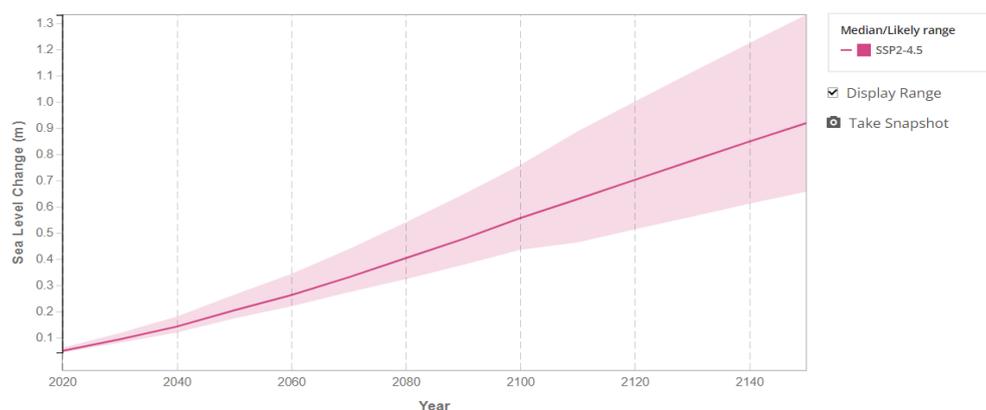

Figure 5. Sea level rise projections for climate change scenario SSP2-4.5 and the Western Mediterranean region, where the analysed coastal archetype (located in the coast of the Barcelona province) is situated. The shadowed area, representing the likely variation range and estimated uncertainty, is based on IPCC AR6 (https://sealevel.nasa.gov/).

Scenario SSP5-8.5 corresponds to no additional climate policies and a global and extensive use of fossil fuels during this century, with high emissions and an unfavourable climatic evolution (IPCC-

AR6). This scenario is similar to the previous RCP 8.5, although with increased emissions of CO_2 (about 20%) and SLR rates (Figure 6). Demographic increase is low with a peak of global population by 2050 and a reduction to present levels by 2100. The high economic and technological development will enable a new set of technological solutions for coastal protection.

These projections, combining biophysical and socio-economic variables, are used to prepare adaptation pathways under climate change [45], supported by a combination of observations and simulations at different scales [46–48].
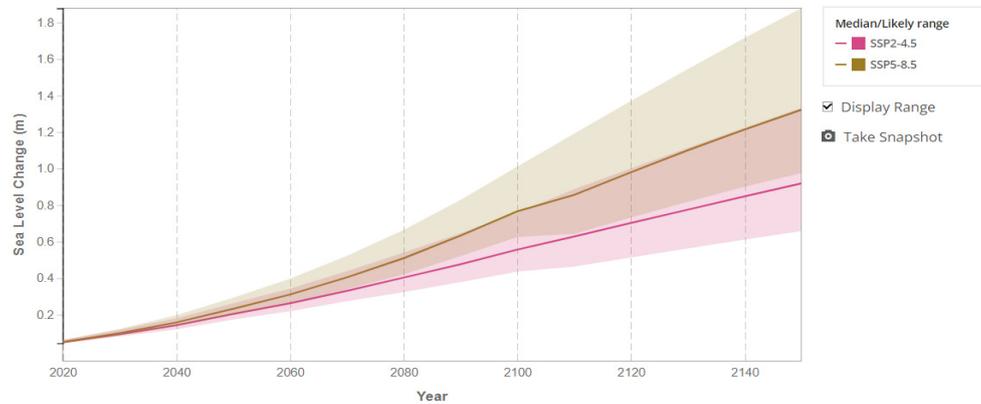

Figure 6. Sea level rise projections for climate change scenario SSP5-8.5 and the Western Mediterranean region where the analysed coastal archetype (located in the coast of the Barcelona province) is situated. The shadowed area, representing the likely range of variation and estimated uncertainty, is based on IPCC AR6 (https://sealevel.nasa.gov/).

Future wave storm features have been inferred from data [49,50] coming from the network termed XIOM (Xarxa d'Instrumentació i Observació Marítima de la Generalitat de Catalunya), now discontinued, and from the Puertos del Estado network that combines buoys and forecasts [48]. The selected significant wave height levels are shown in Table 1, where all storms come from NE, which is the dominant direction for energetic wave storms in this part of the Western Mediterranean. In this table, XIOM represents the locally measured data, PDE represents the data from Puertos del Estado and PIMA represents the projections recommended by the Ministry for Ecological Transition, where the interval limits and the central estimate have been derived for the co-selected medium and pessimistic scenarios (SSP2-4.5 and SSP5-8.5). The values correspond to medium-term (2026-2045) and long-term horizons (2081-2100), considering six climatic models and 20-year windows to be comparable with other climatic assessments performed in Spain.

Table 1. Selected significant wave heights for metocean storms with return periods of 50 and 100 years for the studied coastal archetype in front of the Barcelona province (Spanish Mediterranean coast). The values correspond to three different data sources. Based on their associated hazard levels, these values characterise the storms selected in this study to develop adaptation pathways. Wave parameters have been derived from the available data (see text) and, when there is enough information, the range of variation for this data is presented within brackets ([]).

Hs(m)	XIOM Llobregat 41.2758 N, 2.1352E 45m Depth 1984-2012	PdE Boia Barcelona II 41.320N, 2.200E 68m Depth 2004-2020	PIMA Punto Port Olímpic 41.333N, 2.4167E
T=50 years	5.13	5.76	4.8 [3.92 – 6.06]
T= 100 years	5.41	6.11	5.22 [4.16 – 6.56]

The discussion of future climate and management scenarios, involving researchers and stakeholders, is leading to convergent criteria to sequence coastal interventions and achieve a socioeconomic transformation. Such a transformation considers how future coastal systems will be different from present ones, with different levels of commitment and a governance that incorporates new national/EU legislation (e.g., the new EU restoration law).

2.4. Portfolio of Actionable Interventions

Considering the criteria of relevant stakeholders, the two more widely accepted pathways for the studied coastal archetype, valid until 2100 and probably beyond, are: a) traditional coastal protection based on improved coastal engineering solutions that combine sand nourishment with hybrid (conventional plus NbS) interventions; b) innovative coastal adaptation that promote NbS from the beginning. The NbS here proposed combine dunes and wetlands for the emerged beach (including the narrow intertidal area under the microtidal Mediterranean conditions) and seagrass meadows for the submerged beach. Dunes reduce risks for first line (closest to the sea) infrastructures, while wetlands are designed to increase coastal resilience and facilitate self-adaptation under accelerating SLR, particularly for the deltaic profile where subsidence increases the rate of relative SLR. Seagrass meadows reduce incoming wave energy and trap sediment from upstream coastal sectors, bounding erosion and flooding risks. The set of proposed adaptation pathways frame the actionable interventions for risk reduction in this Mediterranean coastal archetype.

The portfolio of protection interventions includes: a) repeated artificial nourishments; b) construction of progressively higher/wider seawalls; c) NbS for the emerged/submerged beach; d) managed realignment. These interventions have been tuned according to local experience (social and technical memory) and projected climates, with a minimum beach width of 20 metres to ensure the protection and touristic functions. These state-of-the-art interventions [51] consider local constraints and history as manifested by stakeholders and are prioritised according to effectiveness based on local experience and numerical simulations [50]. Their sequencing along adaptation pathways requires monitoring and a maintenance programme, where the proposed interventions will be adapted to maintain risk reduction in spite of the uncertainties in future climatic and management conditions. The criteria to select interventions favour: a) interventions that do not lead to irreversible impacts; b) short term decisions that do not mortgage medium to long term targets; c) interventions that enable the change between adaptation pathways when getting near TPs. The final selection and ranking are based on a multicriteria assessment that combines local expertise, stakeholder preferences and scientific-technological knowledge, always complying with local, national and European legislation. The resulting sequence of interventions includes a plan to keep track of biophysical and socioeconomic impacts as well as carbon footprint. Such a plan incorporates criteria stemming from the risk perception and tolerance by the receiving coastal communities, considering the deep uncertainty in future scenarios particularly socioeconomic ones. To facilitate consensus only three horizons (2030, 2050 and 2100) have been considered, associated with short-, medium- and long-term protection aims and considering the different times required by rigid structures and NbS to achieve risk reduction, where NbS feature a slower performance, since coastal ecosystems take a longer time to deliver their ecosystem services, although they are projected to become more competitive than conventional protection under accelerated SLR.

2.5. Aggregated Risk Estimators

For sequencing and ranking purposes, the set of coastal interventions is assessed in terms of risk, estimated as the product of hazard times the damage (vulnerability), first calculated in hydro-morphodynamics terms. This means that the main hazard probabilities considered in this assessment stem from flooding and erosion, where the key driver variables are SLR, wave storminess and surges. The key response variables are beach width, berm height and available sand volume. The expected risk value is estimated from Equation (1), where 'A' indicates the average economic value of the climatic-induced damages, therefore a measure of vulnerability. For the sake of comparisons, the A

reference value for sandy beaches is taken as 1 while the corresponding one for areas with infrastructures is taken as 100, where the two orders of magnitude difference is based on local values for beach surface and first-line infrastructure.

$$E(R) = \frac{A}{X_0 - X_{SLR} - X_{storm} - X_{base}} \qquad (1)$$

The difference of X values in the denominator (X representing the cross-shore beach coordinate) indicates the remaining beach width at any time horizon with respect to an initial value of X_0. This difference is denoted by X_{marge} in Equation (2), which represents a compact form of Equation (1) for stakeholder discussion. The X variable can also denote berm height and beach volume, depending on the risk assessment performed and is projected to evolve according to the key driver variables selected. For the case of beach width, X will decrease with time until it reaches a minimum beach width of 20 metres (climatic alarm level) and 15 m for the TP. These thresholds are based on available experience [1] and stakeholder criteria to ensure the beach can provide successful protection and touristic functions.

$$E(R) = \frac{A}{X_{marge}} \qquad (2)$$

X_{base} in the risk equation (1) denotes the baseline erosion derived from the Green Book of the Catalan coast [52], applying an asymptotic trend since the calculated shore retreats in the Green Book correspond to the 1995-2005 decade and therefore cannot be indefinitely extrapolated. This asymptotic trend is based on an exponential decrease of erosion rates with time, indicating a trend towards coastal dynamic equilibrium. Given the uncertainty of these projections beyond 2030, the same erosion rates but adjusted to dominant sediment sizes, have been applied for the two studied profiles, to facilitate comparisons between profile evolution as a function of time horizon and interventions.

X_{SLR} corresponds to the erosion due to relative SLR, evaluated with a Bruun rule adapted to the littoral Catalan [53] and that can be written as in Equation (3), where SLR is the rate of relative sea level rise, L is the dissipation width for incoming waves until the depth of closure (DoC). B indicates the berm height, derived from field measurements and L has been obtained from a combination of field data and calibrated beach equilibrium profile formulations.

$$X_{SLR} = SLR \cdot \frac{L}{(DoC + B)} \qquad (3)$$

X_{storm} represents beach erosion due to a sequence of storms characteristic of a typical (average) stormy period in this part of the Mediterranean, corresponding in this work to return periods of 50 years and 100 years. This range of return periods allows assessing the sensitivity of TPs to different climatic scenarios. Considering available wave time-series (up to 30 years length), the risk assessment has been performed with: a) 50-year return period wave storms, projected to happen at horizons 2080 and 2150; b) 100-year return period wave storms, projected to happen at horizons 2030 and 2100.

All adaptation pathways have been delineated from "present" conditions (year 2022 representing the 2017 to 2022 period) and until 2150, as a common final horizon for the comparison that includes some future after 2100. In all pathways the sequence of projected impulsive wave storms has been the same. The sequence of projected storms to estimate risks, in agreement with stakeholders, features: a) energetic wave year (with 100-year storm) at the beginning of the assessment period (fixed at 2030); b) medium wave year (with 50-year storm) with increased SLR for the 2080 horizon; c) new energetic year (with 100-year storm) with high MSL for the 2100 horizon; d) new medium year (with 50-year storm) and including the cumulative effects of SLR and background erosion.

The sequence of proposed interventions for risk reduction, following the criteria of key stakeholders, has taken into account: a) projected evolution of physical climatic variables (SLR, wave storms and surges); b) availability of sedimentary material (quality and quantity); c) evolution of coastal population density (as a measure of coastal rigidization); d) past interventions (as a measure

of socioeconomic criteria and funding commitment). Risk estimators parameterise the role of NbS for: a) submerged beach (restored seagrass meadows); b) intertidal beach (reconstructed wetlands); c) emerged beach (staggered embryo-dunes). The NbS parameterization for wave storm erosion is between 0.4 and 0.6 (modulated by sediment size and availability), while for background erosion, based on past experience, simulations and consensus, it has been estimated between 0.6 and 0.7. The proposed NbS will have a more limited effect under extreme wave events and because of that, a 0.0 factor has been applied for future energetic storms.

Artificial nourishment has been sequenced as a function of the remaining beach width, aiming for a minimum width of 20 m and a tipping point for 15 m, as a limit to urgently start a new sand nourishment operation. The co-selected horizons (2030, 2050 and 2100) for the comparison are to be reviewed depending on future SLR, storms and performance of the executed interventions. The proposed artificial nourishment can be assimilated to small scale "sand engines" [54,55], regularly maintained to ensure durability because of the limited sand volumes available in the studied coastal archetype.

3. Results for Urban and Peri-Urban Beach Adaptation

The analysis for urban beaches, less prone to adaptation due to the lack of accommodation space, starts with a projection of future shorelines considering the proposed sequence of storms supplemented by background and SLR erosion (scenario-dependent). For SSP2-4.5, the urban beach "disappears", i.e., it reaches the minimum acceptable width by 2075, while for the pessimistic scenario SSP5-8.5, this happens some decades before. This means that the present beach configuration, with a minimum acceptable beach width of 20 metres and an initial beach width oscillating around 50 metres, will "last" until 2070, when hinterland urban areas will start to experience strong impacts, not easily acceptable with present socioeconomic criteria. Tables 2 and 3 show the sequencing of interventions proposed for each adaptation pathway, as a function of remaining beach width and for the two selected scenarios. Critical interventions within pathway A have to start under the two scenarios by 2080, although the transition to pathway B should happen, based on technical and economic criteria, at around 2100 for the pessimistic scenario SSP5-8.5 and at around 2110 for the more optimistic scenario SSP2-4.5. At these horizons, corresponding to the transition from pathway A to pathway B, a possible "change of station" to pathway C or pathway E, representing respectively NbS or managed realignment, is also considered.

Table 2. Estimated coastal evolution (erosion/accretion) rates for the moderately rigidised coastal profile (Figure 2) and medium climate change scenario SSP2-4.5. The left side column indicates the time-line for coastal evolution under climate change and with the proposed interventions. The rest of columns indicate (from left to right): For pathways A+B: 1) the initial value of the additional beach width generated by maintenance interventions (artificial nourishment); 2) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions; 3) the hinterland width affected by shoreline retreat, considering the effect of the interventions under climate change. For pathway C: 4) the beach advance/retreat associated with coastal rigidization; 5) the remaining beach width for a rigidized coast (progressive rigidization). For pathway D: 6) the beach width remaining after the combined effect of background erosion, sea level rise retreat and cumulative storm erosion (see text for a more detailed explanation); 7) the initial value of the additional beach width generated by maintenance interventions; 8) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions. The boxes marked in grey (left column) indicate the occurrence of an energetic storm, according to the sequence described in the text. The boxes marked in ochre indicate the times tA, tB, tC, tD, (see Figure 3), which represent tipping points associated to the different pathways considered.

A+B	C	D

Year	Accumulated advance by interventions (m)	X remaining with interventions (m)	Hinterland width affcted with interventions (m)	Advance by interventions (m)	X remaining with interventions (m)	X remaining by SLR + Storm + background erosion (m)	Accumulated advance by interventions (m)	X remaining with interventions (m)
2010	0.0	25.0						0.0	25.0
2020	0.0	22.0	0.0				23.0	0.0	23.0
2030	0.0	13.0	-7.0	0.0	13.0	14.0	15.0	29.0
2040	0.0	11.0	-9.0	0.0	11.0	13.0	15.0	28.0
2050	0.0	9.0	-11.0	0.0	9.0	12.0	15.0	27.0
2060	0.0	7.0		0.0	7.0	11.0	15.0	26.0
2070	0.0	5.0		0.0	5.0	10.0	15.0	25.0
2080	15.0	13.0		0.0	-2.0	4.0	15.0	19.0
2090	15.0	11.0		0.0	-4.0	3.0	30.0	33.0
2100	15.0	2.0		0.0	-13.0	-6.0	30.0	24.0
2110	30.0	15.0		0.0	-15.0	-7.0	30.0	23.0
2120	30.0	14.0		0.0	-16.0	-8.0	30.0	22.0
2130	30.0	12.0		0.0	-18.0	-9.0	30.0	21.0
2140	30.0	10.0		0.0	-20.0	-9.0	45.0	36.0
2150	30.0	4.0		0.0	-26.0	-15.0	45.0	30.0

Table 3. Estimated coastal evolution (erosion/accretion) rates for the moderately rigidised coastal profile (Figure 2) and pessimistic climate change scenario SSP5-8.5. The left side column indicates the time-line for coastal evolution under climate change and with the proposed interventions. The rest of columns indicate (from left to right): For pathways A+B: 1) the initial value of the additional beach width generated by maintenance interventions (artificial nourishment); 2) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions; 3) the hinterland width affected by shoreline retreat, considering the effect of the interventions under climate change. For pathway C: 4) the beach advance/retreat associated with coastal rigidization; 5) the remaining beach width for a rigidized coast (progressive rigidization). For pathway D: 6) the beach width remaining after the combined effect of background erosion, sea level rise retreat and cumulative storm erosion (see text for a more detailed explanation); 7) the initial value of the additional beach width generated by maintenance interventions; 8) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions. The boxes marked in grey (left column) indicate the occurrence of an energetic storm, according to the sequence described in the text. The boxes marked in ochre indicate the times tA, tB, tC, tD, (see Figure 3), which represent tipping points associated to the different pathways considered.

| Year | A+B | | | C | | D | | |
	Accumulated advance by interventions (m)	X remaining with interventions (m)	Hinterland width affcted with interventions (m)	Advance by interventions (m)	X remaining with interventions (m)	X remaining by SLR + Storm + background erosion (m)	Accumulated advance by interventions (m)	X remaining with interventions (m)
2010	0.0	25.0					0.0	25.0
2020	0.0	23.0	0.0			24.0	0.0	24.0
2030	0.0	14.0	-6.0			14.0	15.0	29.0
2040	0.0	13.0	-7.0			13.0	15.0	28.0
2050	0.0	11.0	-9.0			12.0	15.0	27.0
2060	0.0	10.0				11.0	15.0	26.0
2070	15.0	9.0		0.0	4.0	9.0	15.0	24.0
2080	15.0	17.0		0.0	-3.0	3.0	30.0	33.0
2090	15.0	15.0		0.0	0.0	2.0	30.0	32.0
2100	30.0	19.0		0.0	0.0	-8.0	30.0	22.0
2110	30.0	18.0		0.0	0.0	-9.0	30.0	21.0
2120	30.0	16.0				-10.0	30.0	20.0

2130	30.0	14.0		-11.0	30.0	19.0
2140	30.0	12.0		-12.0	45.0	33.0
2150	30.0	5.0		-18.0	45.0	27.0

Pathway C, following stakeholder criteria, is suggested to start by 2070 and projected to last until 2120 for the pessimistic SSP5-8.5 scenario, where the seawall would have to be higher than 1.5 metres to maintain its functionality. Since this height is considered the acceptable limit by stakeholders, due to barrier intrusiveness and maintenance costs, a TP has been defined for that barrier level. Pathway E, for the urban coastal profile, consists of seagrass meadows because the lack of back beach space for accommodation or realignment makes it compulsory to act on the submerged beach. Restored seagrass meadows would suppose a continuation of the submerged seagrass corridor that existed along this coastal stretch, still observable in some upstream (NE) sectors. Emerged beach NbS can only be deployed locally, for sub-sectors that provide enough width to construct embryo-dunes to enhance natural beach resilience under waves and storm surges [6].

The proposed sequence of interventions, with change stations and TPs, is schematized in Figures 7 and 8, corresponding to scenarios SSP2-4.5 and SSP5-8.5, respectively. Blue diamonds indicate [56] the start of an adaptation pathway, while circles correspond to change stations. The black vertical limits indicate the functional end of an adaptation pathway.
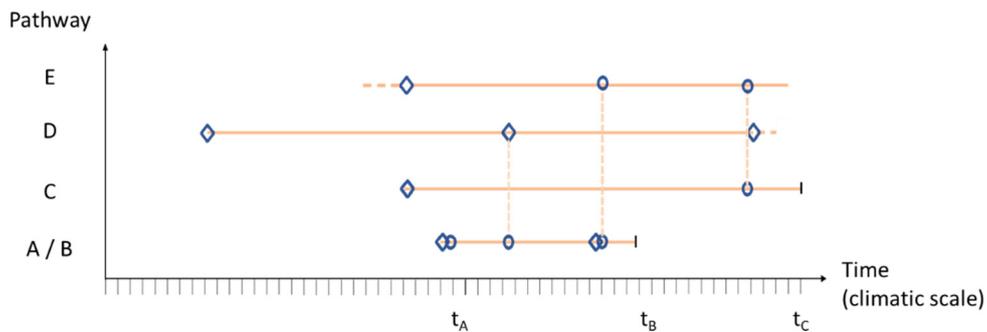

Figure 7. Adaptation pathways for the analysed urban coastal profile (Badalona case) and SSP2-4.5. Diamonds indicate the beginning of an adaptation pathway, following the pathways defined in Figure 3 and associated text. Circles indicate change of pathway "stations" and the vertical black lines the functional end of the pathway, following scientific and socioeconomic criteria.
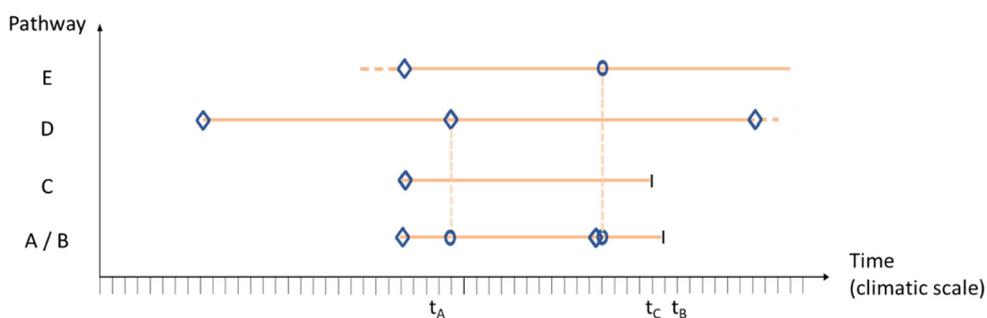

Figure 8. Adaptation pathways for the analysed urban coastal profile (Badalona case) and SSP5-8.5. Diamonds indicate the beginning of an adaptation pathway, following the pathways defined in Figure 3 and associated text. Circles indicate change of pathway "stations" and the vertical black lines the functional end of the pathway, following scientific and socioeconomic criteria.

The peri-urban beach profile, featuring comparatively finer sand and, thus, milder slopes, shows, according to the performed projections, an enhanced loss of emerged beach, which tends to "disappear" (i.e., fall below the acceptability threshold of 20 m with a TP at 15 m) by the 2030 horizon. From this horizon onwards, the back beach would progressively experience more severe storm

impacts affecting the present public domain boundary, located about 80 m landwards from the average shoreline. This means that the present beach configuration will last for about 50 years and, after that, hinterland assets will be negatively impacted by waves and surges. Pathway A starts with an artificial nourishment to gain 15 m beach width by 2030. This intervention provides a transition to pathway B, with a new nourishment 20 years later. The combined gains will not last beyond 2050, based on a projection of erosion rates under SLR, meaning that pathway A+B has a TP by the middle of this century. As a consequence, conventional nourishment will not comply with risk reduction, cost and carbon footprint criteria beyond the 2050 horizon. A similar behaviour, although delayed in time, characterises pathway C, where the seawall is projected to remain functional until the 2070 horizon, where a SLR of 0.5 m above present values will limit the seawall functionality according to stakeholder criteria.

Pathway D, based on NbS, combines dunes for the emerged beach and wetlands for the intertidal beach, with sand dikes as barriers to reduce sediment transport and wetlands (minimum width of about 100 m) providing additional buffer areas for the selected 50- and 100-year storms. Pathway D requires a first nourishment by 2030 to generate a beach width larger than 15 m, to provide enough space for the proposed NbS. This artificial beach nourishment is associated with the calculated minimum beach width, which means that monitoring and maintenance will be required during the first years after restoration, until the NbS is developed enough to provide self-resilience under SLR and wave/surge storms. The space requirements imply a second small-scale nourishment 20 years later, and then another one by 2100. These nourishment interventions involve limited volumes of sand, so as to maintain healthy ecosystems in the intertidal and submerged beach. Beyond 2100 it is difficult to project how these interventions will behave and because of that the pathway (Figure 9) is represented by a dashed line.
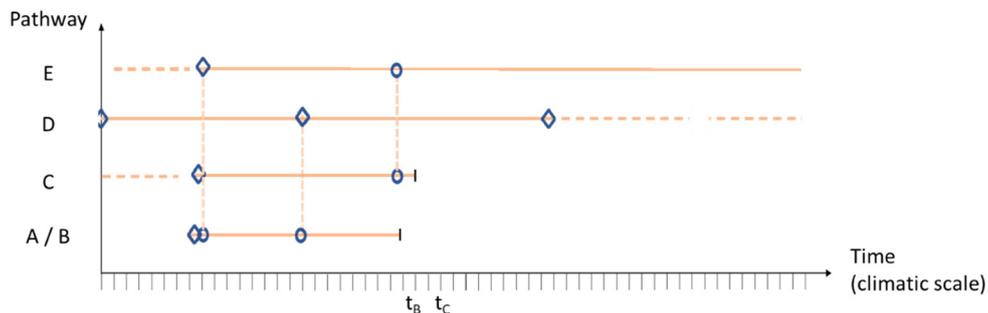

Figure 9. Adaptation pathways for the analysed peri-urban coastal profile (Gavá case) and both considered scenarios, since the differences in projected behaviour are small and within the uncertainty associated with the performed calculations. As in previous figures, diamonds indicate the beginning of an adaptation pathway, following the pathways defined in Figure 3 and associated text. Circles indicate change of pathway "stations" and the vertical black lines the functional end of the pathway, following scientific and socioeconomic criteria.

Pathway E, corresponding to managed realignment, is also indicated in the figure without a deadline, since for peri-urban profiles there is usually enough accommodation space to enable a backward spreading of land activities and infrastructures to enhance resilience. That is indeed the case for the studied profile, which thanks to that available space can use natural beach dynamics for partial self-protection, developing dissipative profiles and landward migration as required by SLR. The proposed interventions and associated projection of beach width for scenarios SSP2-4.5 and SSP5-8.5 appear, respectively, in Tables 4 and 5.

Table 4. Estimated coastal evolution (erosion/accretion) rates for the heavily rigidised coastal profile (Figure 1) and climate change scenario SSP5-4.5. The left side column indicates the time-line for coastal evolution under climate change and with the proposed interventions. The rest of columns indicate (from left to right): For pathways A+B: 1) the initial value of the additional beach width generated by

maintenance interventions (artificial nourishment); 2) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions; 3) the hinterland width affected by shoreline retreat, considering the effect of the interventions under climate change. For pathway C: 4) the beach advance/retreat associated with coastal rigidization; 5) the remaining beach width for a rigidized coast (progressive rigidization). For pathway D: 6) the beach width remaining after the combined effect of background erosion, sea level rise retreat and cumulative storm erosion (see text for a more detailed explanation); 7) the initial value of the additional beach width generated by maintenance interventions; 8) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions. The boxes marked in grey (left column) indicate the occurrence of a storm, according to the sequence described in the text. The boxes marked in ochre indicate the times tA, tB, tC, tD, (see Figure 3), which represent tipping points associated to the different pathways considered.

Year	Accumulated advance by interventions (m)	X remaining with interventions (m)	Hinterland width affected with interventions (m)	Advance by interventions (m)	X remaining with interventions (m)	X remaining by SLR + Storm + background erosion (m)	Accumulated advance by interventions (m)	X remaining with interventions (m)
2010	0.0	15.0					0.0	15.0
2020	0.0	10.0	0.0			12.0	0.0	12.0
2030	15.0	14.0	-6.0	0.0	-1.0	2.0	15.0	17.0
2040	15.0	11.0	-9.0	0.0	-4.0	1.0	15.0	16.0
2050	30.0	22.0	2.0	0.0	-8.0	-1.0	30.0	29.0
2060				0.0	-12.0	-3.0	30.0	27.0
2070				0.0	0.0	-5.0	30.0	25.0
2080				0.0	0.0	-13.0	30.0	17.0
2090				0.0	0.0	-15.0	30.0	15.0
2100				0.0	0.0	-25.0	45.0	20.0
2110				0.0	0.0	-26.0	45.0	19.0
2120				0.0	0.0	-28.0	45.0	17.0
2130				0.0	0.0	-30.0	45.0	15.0
2140				0.0	0.0	-32.0	45.0	13.0
2150				0.0	0.0	-39.0	45.0	6.0

Table 5. Estimated coastal evolution (erosion/accretion) rates for the heavily rigidised coastal profile (Figure 1) and climate change scenario SSP5-8.5. The left side column indicates the time-line for coastal evolution under climate change and with the proposed interventions. The rest of columns indicate (from left to right): For pathways A+B: 1) the initial value of the additional beach width generated by maintenance interventions (artificial nourishment); 2) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions; 3) the hinterland width affected by shoreline retreat, considering the effect of the interventions under climate change. For pathway C: 4) the beach advance/retreat associated with coastal rigidization; 5) the remaining beach width for a rigidized coast (progressive rigidization). For pathway D: 6) the beach width remaining after the combined effect of background erosion, sea level rise retreat and cumulative storm erosion (see text for a more detailed explanation); 7) the initial value of the additional beach width generated by maintenance interventions; 8) the temporal evolution of the remaining beach width after the interventions, subject to projected wave, surge and sea-level rise conditions. The boxes marked in grey (left column) indicate the occurrence of a storm, according to the sequence described in the text. The boxes marked in ochre indicate the times tA, tB, tC, tD, (see Figure 3), which represent tipping points associated to the different pathways considered.

Year	Accumulated advance by interventions (m)	X remaining with interventions (m)	Hinterland width affected with interventions (m)	Advance by interventions (m)	X remaining with interventions (m)	X remaining by SLR + Storm + background erosion (m)	Accumulated advance by interventions (m)	X remaining with interventions (m)
2010	0.0	15.0					0.0	15.0
2020	0.0	10.0	0.0			13.0	0.0	13.0
2030	15.0	15.0	-5.0	0.0	0.0	3.0	15.0	18.0
2040	15.0	12.0	-8.0	0.0	-3.0	2.0	15.0	17.0
2050	30.0	24.0	4.0	0.0	-6.0	0.0	30.0	30.0
2060				0.0	-10.0	-1.0	30.0	29.0
2070				0.0	0.0	-4.0	30.0	26.0
2080				0.0	0.0	-11.0	30.0	19.0
2090				0.0	0.0	-14.0	30.0	16.0
2100				0.0	0.0	-25.0	45.0	20.0
2110				0.0	0.0	-27.0	45.0	18.0
2120				0.0	0.0	-29.0	45.0	16.0
2130				0.0	0.0	-32.0	45.0	13.0
2140				0.0	0.0	-34.0	45.0	11.0
2150				0.0	0.0	-42.0	45.0	3.0

4. Discussion

These projections assume that present sediment transport formulations and morphodynamic evolution trends, duly modulated for SLR and asymptotically adjusted towards an equilibrium configuration, can be applied. The proposed pathways also assume that Bruun's rule for profile evolution under SLR remains valid, although such an approach tends to overestimate erosion rates due to the underlying assumption of an equilibrium profile in a longshore uniform coast. These projections should, thus, be periodically reassessed with a systematic observation program, which should also serve to determine the efficiency of NbS and to update the fronting bathymetry, so that the pathway development is always based on the most updated characterization of the beach active profile and associated offshore area.

The developed coastal adaptation pathways are based on local expertise, climate projections, hydro-morphodynamic simulations and stakeholder criteria on governance, funding and policies. Such a combination [21] of techniques, finance and governance underpin a transition towards a proactive coastal adaptation that mainstreams NbS into coastal protection, aligning adaptation with climate mitigation efforts. Numerical simulations are proposed to steer a maintenance program supported by an EWS to avoid reaching TPs, where EWS [28,57] will support a proactive maintenance of the coast, optimising interventions before storm impacts. The EWS, working at short time scales (order of 1 week), should be supplemented by a climatic warning system [6], which projects coastal evolution under future scenarios and provides climatic alarms whenever the risk level becomes unacceptable, which would justify a change of pathways [58].

The proposed climatic alarms (Figure 10) are associated to hazard or risk levels, depending on whether the damage valuation is included (risks) or not (hazards), both expressed in terms of co-designed robust indicators, such as for instance SLR, remaining beach width, available sand volume or cumulative damages.
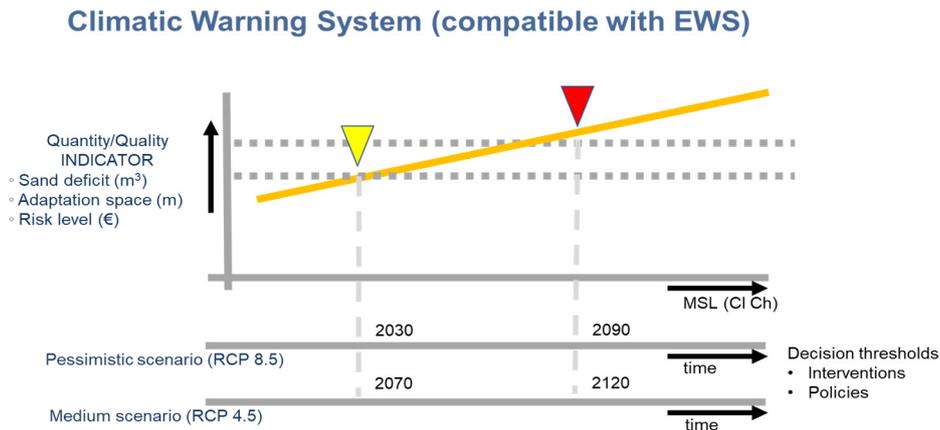
Climatic Warning System (compatible with EWS)

Figure 10. Representation of alarm thresholds for a climatic warning system, compatible with an EWS and based on co-designed limits for key variables, whose evolution with time (decadal scales) characterise the quality of the analysed coastal archetype or the quantity of available adaptation resources. The dependent key variables in this diagram are sand deficit, adaptation space or risk level, so that the thresholds correspond to co-defined levels for these variables. The independent variable for establishing the climatic alarm system can be any robust variable characterising climatic pressures, taken here to be mean sea level (MSL), then associated to time in the same x-axis, depending on the selected physical scenario. The pessimistic scenario corresponds to SSP5-8.5 while the medium scenario corresponds to SSP5-4.5, as explained in the text. Decisions on interventions or policies are associated to these thresholds and are referred to these time axes.

The analysed coastal archetype is managed by several departments of two different governments (central and regional), being conditioned by a wide range of applicable plans and legislation, from Municipal to European Union level. The introduction of coastal maintenance contracts, as promoted within some EU projects linked to the Green Deal [6], will underpin the co-design of new interventions and the maintenance of the already implemented ones, benefiting from experimental pilot projects. The development of adaptation pathways is a dynamic and multicriteria process, where the combination of predictions and projections, with explicit metrics to assess risk levels, will favour the convergence of criteria aligned with the new EU restoration law. The ensuing consensus, associated with a progressive build-up of social and governance cohesion for a shared coastal adaptation, will avoid the present overdominance of short term and reactive interventions, which seldom consider their carbon footprint or internalise all their costs. Changing the scale of analysis, introducing the medium to long term view, and changing the level of engagement for coastal maintenance, should lead to an enhanced accountability and socioeconomic co-responsibility, both required to maintain risk levels under the projected climate scenarios.

5. Conclusions

Adaptation pathways for urban and peri-urban beach profiles, representative of climatic vulnerability hotspots such as are Mediterranean coastal cities, can help steering new coastal policies, such as the new CPM plan (*Pla de Protecció i Ordenació del Litoral a Catalunya*). This plan, developed by the Catalan Government (Generalitat de Catalunya), can benefit from the delineated adaptation trajectories. Pathways A, B and C aim to increase the level of coastal protection, with a focus on short-term risk reduction, while pathways D and E propose a transition to a new coastal paradigm. This new paradigm addresses a multi-scale coastal zone planning, redefines coastal boundaries, incorporates coastal dynamics for natural resilience and requires an integrated management of coastal scarce resources (such as freshwater and sand volumes). The proposed approach to coastal adaptation combines a new level of coastal multi-disciplinary observations within early and climatic warning systems, to steer coastal maintenance and prompt the implementation of pilot tests to mainstream NbS into coastal protection.

Such an approach, based on adaptation pathways, is fully aligned with the PIMA Adapta Costas program of the Spanish Ministry for Ecological Transition and with the new EU Nature restoration law, proposing sequenced coastal interventions, promoting NbS, as well as defining change stations and TPs for natural resilience. Such an alignment will pave the way for a wider uptake of NbS, based on monitored and progressively refined pilot tests, enabling a robust characterization of delivered ecosystem services, including biodiversity gains. These monitoring plans, associated with consensus metrics for risk reduction that combine hydro-, morpho-, and ecologic parameters, will support proactive interventions and avoid crossing tipping points.

The proposed approach to coastal adaptation, although developed for an urban coastal archetype in the Mediterranean, is considered to be applicable to most coastal vulnerability hotspots, particularly those experiencing accelerating climatic and anthropogenic pressures. The combination of simulations (to predict and project shore evolution) and monitoring (to assess the performance of conventional engineering works versus NbS) make the approach generic and exportable to other coastal systems, particularly vulnerability hotspots that will require, under climate change, an additional adaptation over present coastal protection efforts, often associated to a large impact and carbon footprint.

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