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Título: COASTAL ADAPTATION PATHWAYS FOR A CHANGING CLIMATE. EBRO DELTA CASE

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Abstract

The Ebro delta is the most important delta of the Iberian Peninsula, constituting one of the natural areas with great environmental, social and economic value, but which nowadays is in serious danger largely due to climate change.

Apart from the region owns fragility, there are a series of actions and threats that are increasing this weakness which are mainly the anthropic actions. The construction of reservoirs in the upper part retains the majority of sediments, which should be transported naturally to the mouth of the river. Due to this retention, the vertical growth of the region is halting, losing its natural resistance to erosive processes and the impact of waves, as well as being more vulnerable to the sea level rise (SLR).

Besides this, problems such as subsidence (due to the compaction of sediments), saline intrusion in fertile lands, contamination of river water, biological degradation and eutrophication affect the environmental quality and future resilience of the area.

This project will analyze with the help of mathematical and software (ArcGIS) models what is the current defensive capacity of the delta against storms (beach erosion and wave runup) with a long return period, as was the case of Gloria, in addition to a rise in sea level. By doing this, we will be able to obtain the hot-spots of the deltaic region.

This analysis will be carried out for different socio-economic (SSP) and climatic (RCP) scenarios throughout the years, from 2021 to 2100. In this way, we will be able to observe how different emission levels (RCP 2.6 and RCP 8.5) affect the resistance and natural defensive capacity of the coastal fringe, as well as propose different solutions and pathways for each of the future scenarios.

To try to combat and eliminate these threats, different interventions are presented, from hard and soft engineering works to natural strategies in order to protect or adapt the delta by the end of the 21st century. In addition, the actions that are being carried out in other deltas of the world are analyzed, such as the delta of the Rhine, the Mississippi and Po among others.

Once the different interventions and strategies have been assessed, a framework of adaptation pathways will be proposed. This consists of a series of possible pathways (which are different solutions) that guarantee the survival of the delta. There will be cases in which an intervention presents a tipping point, which specifies the condition under which an action will fail (usually this condition will be time due to SLR). In this case, the path will deviate in one or more possible alternatives.

Keywords: delta, climate change, management strategies, sea level rise, erosive processes, SSP and RCP scenarios, hazard map, adaptation pathway.

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1. Introduction

With a surface area of about 325 km^2, the Ebro delta constitutes the second biggest delta in the western Mediterranean in its final length. The Ebro delta is approximately triangular in shape, with a smooth and flat shoreline created by fine sand and a drainage system characterized by a single major canal (Ebro River). It's said to be conditioned by the movement of the waves, according to sedimentology (wave dominant). It is one of the most important natural ecosystems along the Catalan coast.

In the context of global environmental issues, the delta offers a unique challenge for the society. It's a very susceptible place that is constantly changing due to a variety of variables that determine their dynamics and geomorphology (Sánchez-Arcilla 1994).

The Ebro Delta is currently at risk of erosion, as well as a reduction of its emerged surface, owing to natural phenomena such as climate change (SLR) and a decrease in the contribution of sediments and water from the Ebro River as a result of the construction of dams in the upper part of the river.

To these processes are added other natural ones such as subsidence (due to sediment compaction), waves impact action, as well as other anthropic actions that are polluting the final stretch of the river.

Figure 1. Photography of the Ebro delta region.

2. Area of study

Our area of study is situated on the Iberian Peninsula's east coast, in the province of Tarragona, at south of Catalonia. It is located in the Montsiá and Baix Ebre regions. Deltebre, L'Aldea, Sant Jaume d'Énveja, Camarles, Amposta, L'Ampolla, and Sant Carles de la Ràpita are among the municipalities that make up the Delta del Ebro region.

It's a Holocene delta with a surface size of around 325 km^2 and a submerged area of 1845 km^2. It features a 52-kilometer-long coastline that is mostly made up of sandy beaches. Its continental shelf extends around 50 kilometers into the sea, with steep slopes up to 100 meters deep.

The existence of two side arrows, El Fangar (to the northwest) and La Banya (to the southwest), partially closes two bays: Fangar and Alfacs. Jiménez, J.A. (1996) estimates that the two arrows cover an area of 82 km^2. The Barra del Trabucador, which is roughly 6 km long and 250 m wide, connects the Punta del Banya to the rest of the Delta. The bar has a narrow width and can break during severe storms, making Punta de la Banya an isolate island. Buda Island is located between the Ebro's central lobe and mouth.

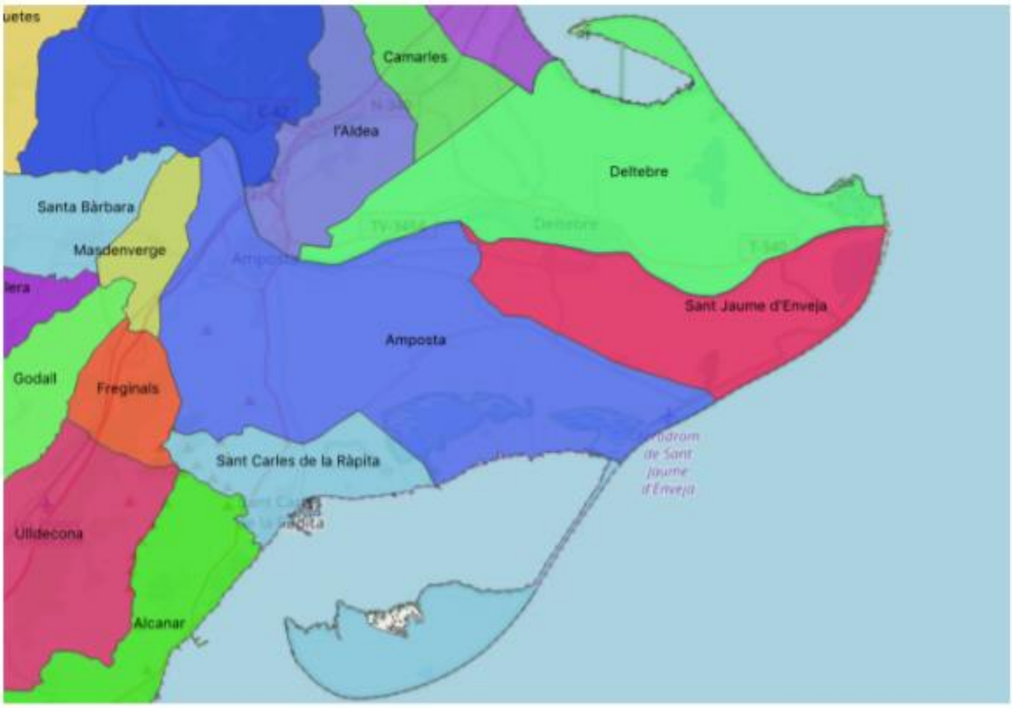


Figure 2. Municipalities in the south of the province of Tarragona.

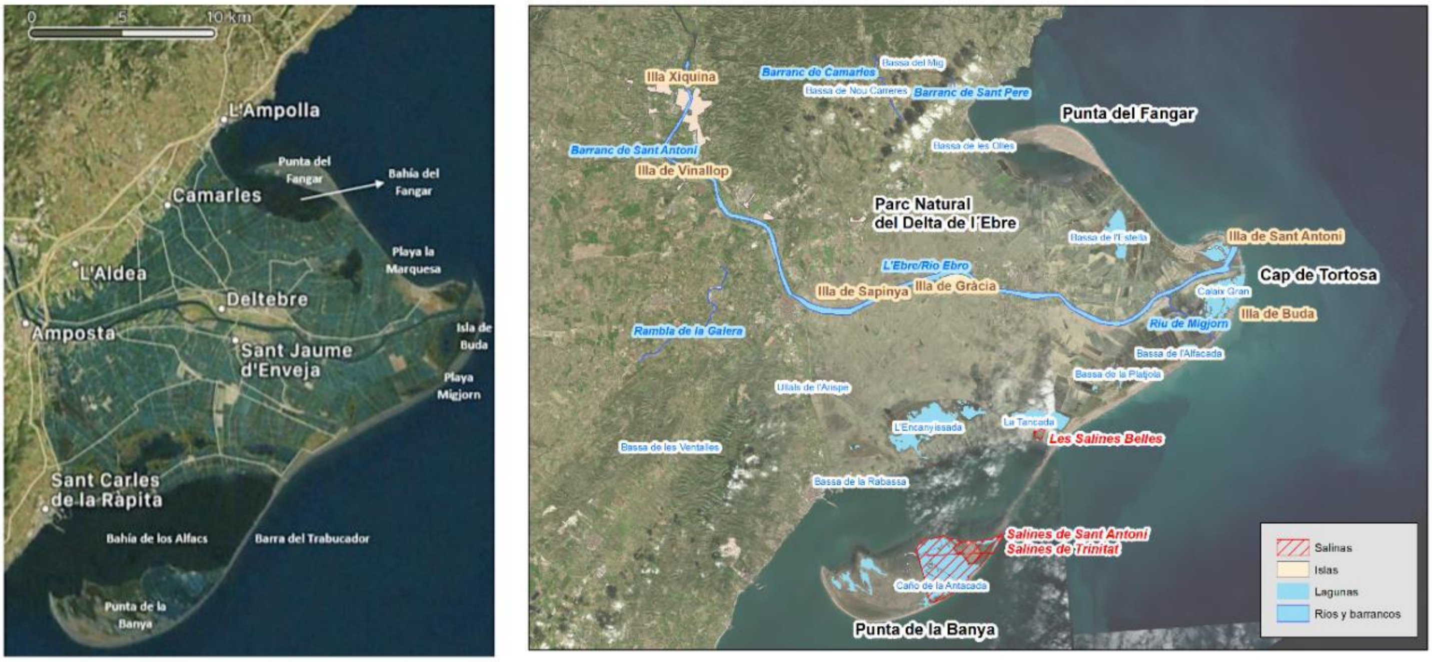


Figure 3. Satellite image of the Delta de l'Ebre Natural Park pointing out the most emblematic areas

2.1. Geomorphology and sedimentology

The Ebro Delta's shape is the consequence of a dynamic equilibrium between the river's sedimentary contributions and its mobilization by both fluvial and marine processes. The floods of the deltaic plain, which result in the deposit of layers of sediment and their vertical accretion, are fundamentally the fluvial dynamics that affect the morphology of the Delta; this fact is not socially acceptable at the present time, and it causes significant economic losses.

The Ebro Delta is mostly made up of quaternary deposits and elements from the Pleistocene and Holocene periods. There are three basic physiographic units that may be recognized:

1. The delta plain
2. The deltaic front - Coastal and transitional environments
3. The prodelta - Marine environments

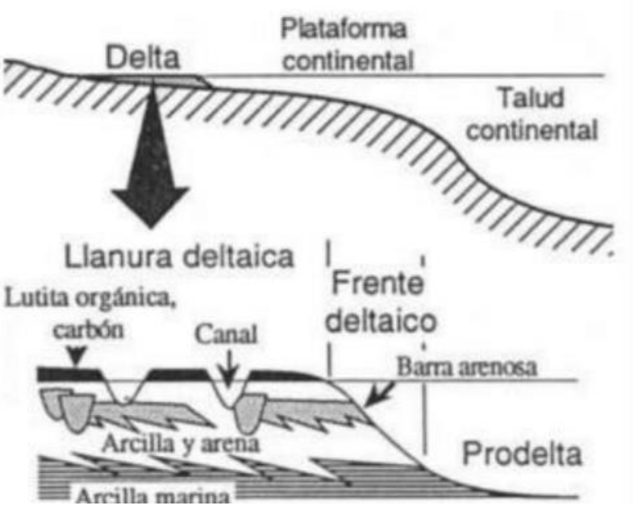


Figure 4. Physiographic units of the Delta del Ebro

2.1.1. The delta plain

Fluvial, lacustrine, and marshy environments make up the deltaic plain, which covers the majority of the land surface.

2.1.1.1. Fluvial environment

River channels and levees, are used to represent them. The materials that make up the levees are mostly sand and silt, and they are organized on both banks of the river. The grain size and proportion of intermittent sand levels reveal a general decrease towards the river's mouth.

2.1.1.2. Lacustrine environment

A change of estuary causes a process of filling the former riverbed (abandoned river channels) and the formation of a lake environment. Lacustrine and marshy ecosystems are found in locations that are frequently or permanently flooded. Coastal lagoons and marshes are common places where they might be found.

The presence of black organic sediments of the sapropel type, near the lake's bottom characterizes the ecosystem. This ecosystem, which is prevalent on Buda Island, encompasses large swaths of the delta plain.

2.1.1.3. Marshy environment

The establishment of marshy habitats, in which helophytic or halophytic vegetation occupies nearly all of the open water space, is the ultimate phase of lake environments. Significant thicknesses of plant organic matter can build in watery or saline conditions, leading to peat formations over time.

Due to clogging, the marshes represent a more evolved stage in the evolution of marsh habitats. In general, the shift between lake and marsh ecosystems is gradual. The Ebro Delta has the most marshes, ranging from fresh to brackish water.

2.1.2. Coastal and transitional environments

It includes places influenced by rivers, but where sediment is mobilized by marine forces. The deltaic front, which is formed by crescent-shaped sand bars and is associated with deltaic progradation, is a good example of a transition environment.

Sediments from two independent sources generate the beaches, littoral bars, and arrows of the Ebro Delta:

1. river sediments delivered later by coastal currents
2. sediments derived from erosion of abandoned delta lobes.

Coastal bars are submerged or emergent landforms that run parallel to the shoreline and are up to 6 meters deep. They join with the prodelta sediments at a depth of around 10 m as they approach the sea.

The conditions of the waves determine the evolution of the submerged bar system. An arrow is formed by the grouping of numerous bars and their subsequent emergence.

2.1.3. Marine environment

The massive coastal arrows that surround the delta define the bay habitat. The sediments in this environment can be classified into three categories based on their texture:

1. Holomarine sands, which are found on the shallow water platform
2. Localized uniform suspension deposits at the bay’s bottom
3. Pelagic deposits (from a textural point) which are only found in the deepest parts of the bay de los Alfacs, where the weak swell of the bay does not affect the bottom.

The biological activity is high, resulting in bioturbation of the major sedimentary formations.

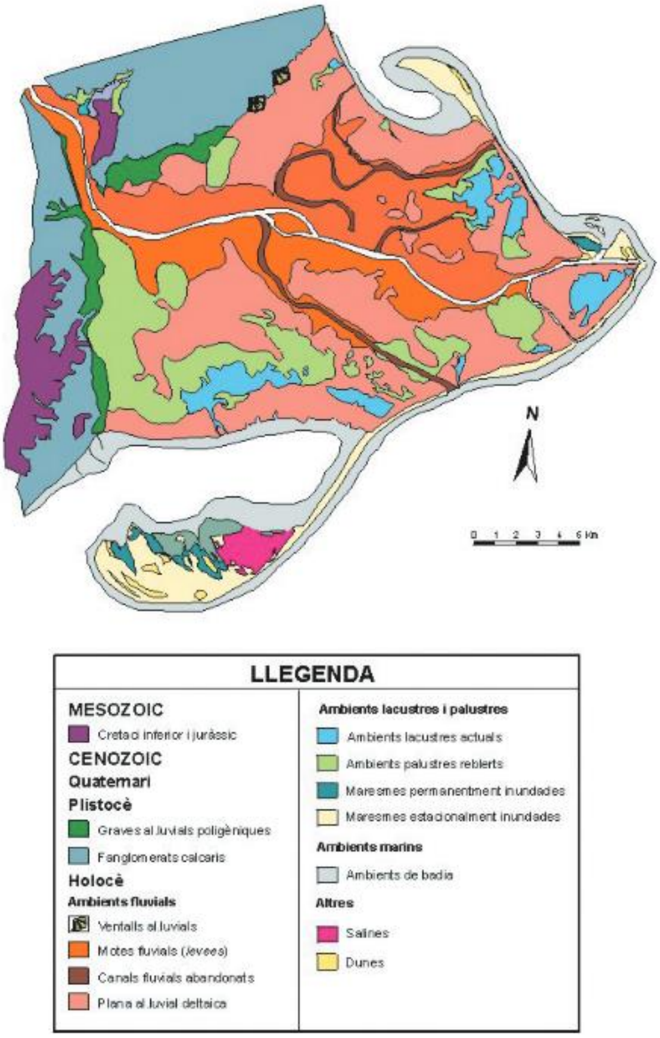


Figure 5. Geological map of the sedimentary environments of the Ebro delta and neighboring areas. According to Maldonado (1977)

2.2. Basin and river regime characteristics

The Ebro River is 928 kilometers long. It is born at an altitude of 880 meters in the Cantabrian Mountain range, more precisely in Fontibre, near Reinosa. The Nela, Zadorra, Ega, Aragón, Arba, Gállego, Cinca, and Segre are its more important tributaries in the north. Oca, Najerilla, Alhama, Jalón, Huerva, Aguas Vivas, Guadalope, and Matarraa are located on the southern slope.

The flow is erratic in terms of monthly and annual oscillations, giving it a distinct Mediterranean character. Nearly 60% (7,700 hm^3) of the basin's runoff is regulated by more than 180 reservoirs. The dammed water is utilized for hydroelectric production (60,000 hm^3 per year), irrigation (6,310 hm^3 per year), nuclear power plant cooling (3,354 hm^3 per year), and population supply (313 hm3 per year) (Hydrographic Confederation of the Ebro, 2020).

In Catalonia, the Ebro is the river with the biggest flow. The evolution of the flow annual average has decreased significantly in the last 100 years. According to Ibáñez et al. (1996), the causes of the decrease in average flows in the lower section of the river Ebro are:

1. An increase in water demand in the basin, primarily for agricultural purposes, which would account for 74% of the reduction
2. Evaporation of the water stored in the basin, which would account for 22% of the reduction
3. The remaining 4% would be attributed to the consequences of climate change and potential changes in land usage.

Figure 6. The Ebro basin

2.3. Biodiversity

2.3.1. Flora

The soils in the delta have a unique salinity gradient that oscillates between salty soils and fertile land ideal for agriculture. The plant diversity it produces enables for the establishment of large communities typical of humid zones, which are in a remarkable condition of conservation.

The salt evaporation pond are the most significant communities as seawater penetrates the water table and accumulates salts on the surface when it evaporates. The plant communities *Arthrocnemetum 7ruticose*, *Schoeno-Plantaginetum crassifoliae*, *Salicornietum emerici*, and *Crucianelletum maritimae* make up the halophilic vegetation of salty soils.

The helophytic community that surrounds the lagoons is made up of reed beds, which may be vast in some circumstances, such as on Buda Island. Its significance is exceptional because it holds wind-borne sediments and inhibits erosion, and it is an essential resource for waterfowl.

Psammophilic plant communities develop in the more stable dunes, suited to the soil's mobility, high permeability, and high solar reflection index.

2.3.2. Fauna

Hundreds of species, the most of which are birds, rely on the Ebro delta wetland for their survival. The Ebro delta supports 360 of Europe's 600 bird species. 95 are nesters and many others hibernate, rest and feed during migrations. Some reptiles, fish, and invertebrates, like the noble pen shell (*Pinna nobilis*), stand out for their distinctiveness. In the case of the noble pen shell, it's in current state of decline.

The protozoan parasite *Haplosporidium pinnae* was the major cause of this mollusk's extinction. In the beginning of 2016, there was a first epidemic, which wiped off 99 percent of the population. Common noble pen shell populations are now considered nearly extinct along the Spanish coast, with just solitary individuals remaining. The only populations that have been preserved are those in the Ebro delta.

2.4. Socio-economic aspects

The Ebro Delta is home to about 60.000 people, with 15,000 living in the interior towns (Deltebre and Sant Jaume d'Enveja) and the remainder in the towns along the river's edge (Sant Carles de la Rápita, Amposta, L'Aldea, Camarles, and l'Ampolla).

	Gender	Total Population (2020)	%
Sant Jaume d'Enveja (Montsià)	Male	1781	2.88
	Female	1746	2.83
l'Ampolla (Baix Ebre)	Male	1683	2.72
	Female	1594	2.58
Deltebre (Baix Ebre)	Male	5849	9.47
	Female	5729	9.27
Sant Carles de la Ràpita (Montsià)	Male	7316	11.84
	Female	7637	12.36
Amposta (Montsià)	Male	10675	17.28
	Female	10440	16.90
l'Aldea (Baix Ebre)	Male	2197	3.56
	Female	1950	3.16
Camarles (Baix Ebre)	Male	1617	2.62
	Female	1577	2.55
	Total	61791	100.00

Table 1. Population data of the municipalities of Delta de l'Ebre (Institut d'Estadística de Catalunya)

Crops and urban areas cover 80 percent of the Delta's overall area, with rice accounting for 65 percent of the Delta's total area (21,000 hectares). The other 20% is made up of natural environments, which include 10% of beaches and sandy regions and another 10% of lagoons and marshes. Before colonization, the Delta's marshes were the most widespread, but they now only cover 5% of its entire area.

2.4.1. Economic activities

2.4.1.1. Primary sector

Agriculture, as previously said, is one of the Delta's major contemporary economic pillars, with rice clearly dominating (more than 20,000 hectares, or nearly all of Catalonia's rice output). The orchard and fruit trees take up a tiny amount of space. Agricultural cooperatives, particularly rice chambers, are quite significant. The volume of rice grown in the Delta accounts for about 98 percent of Catalonia's total production.

The value of rice fields to the ecosystem is largely owing to the bird populations that they support. Finally, it's worth noting that rice fields are part of an ecosystem that connects fluvial, lacustrine, and marine habitats.

Aside from agriculture, fishing is an important industry; in fact, Catalonia's Ebro Delta fishery captures 10% of the entire volume of the autonomous community. Catches have declined in recent years, according to data given by the Generalitat of Catalonia. This appears to be a result of pollution and overexploitation of marine resources, primarily.

The aquaculture industry as a whole is also a significant source of revenue for the local economy. More than 75% of Catalan firms engaged to this industry are located in the deltaic area.

2.4.1.2. Secondary sector

The delta's industry is undeveloped, and it is nearly usually based on agriculture. The production of salt from the Banya Peninsula was another traditionally important business in this region. 35,000 tons of unprocessed salt were produced annually in 1995, but connection issues with the main body of the Delta caused by the Trabucador Bar forced their departure.

The ones that are still standing are Las Salinas de la Trinidad, which harvest around 25,000 tons of salt each year and export it to parts of northern Europe**.**

2.4.1.3. Tertiary sector

Finally, tourism is the activity that has grown the greatest in recent years. A huge number of people visit the natural park. The growth of tourism activities in the delta environment has been severely hampered by a lack of appropriate tourist infrastructure and the territory's relative inaccessibility.

However, the Delta as a whole contains a number of characteristics that can help to favor and encourage tourism focused on interpretive activities and natural exploration.

3. Review of existing deltaic management strategies

It's widely known that the majority of deltas are on an inevitable route to an unsustainable condition. Multiple threats, including relative sea level rise and human actions, are putting deltaic regions at risk, making them increasingly vulnerable to storms, floods, salinity intrusion, and other hazards, which are expected to increase as the climate patterns changes. In this point we are going to investigate and review the current technical, ecological and social systems being applied around the world to ensure the prosperity to their delta regions.

As said before, one of the main concerns regarding the survival of the deltas is the response and adaptability against SLR (sea level-rise). According to sea level scenarios, ocean will continue to rise, eventually reaching 1.84–5.48 m by 2500.

Even though the majority of the deltas may have withstood significant rates of SLR in the past, the current management problem is to determine how altered deltas will fare in the future. Due to dam building, river sediment transport and deposition have declined, and this fluvial sediment shortage has become a global phenomenon. In the case of the Mississippi delta, river sediment flux by 50% in the Mississippi Delta, as the construction of artificial levees has prevented the majority of river sediment from reaching the delta plain. In the case of the Ebro Delta, the decrease of this flux has an order of about 99%.

Therefore, it is vitally important to try to recover and maintain natural processes as well as to try to reduce the actual trend of reinforcing coastal protection (to maintain human activities and infrastructures). In the case human initiatives continue to isolate marine and fluvial mechanics from the deltaic region, sediment supply is constantly reduced or the delta can't move landward since there isn't enough area the disappearance of these weak regions will be practically guaranteed.

So, as said before, it's important to try to recover these processes but taking into account the properties of each delta in particular. Increasing system resilience by adjusting land usage (and economic activities) to eco-geomorphic changes and adopting ecological engineering to regulate natural dynamics.

Adaptation solutions for expected SLR have mainly focused on physical protective measures, with little emphasis paid to restoration and retreat strategies. Nowadays, the notion of "rising grounds" (aggradation or vertical accretion) rather than "rising dikes" is considered one of the best alternate methods, although a mix of the two may also be required and used in many situations.

3.1. Netherlands management strategies in deltaic regions

The Netherlands (with a total area of roughly 34.000 km^2) is placed in the deltaic region composed by rivers Rhine and Meuse. This country has a long history of creation, innovation and modifying natural water systems to meet the needs of the population such as housing, agriculture, and shipping. Following the famous floods of 1993 and 1995, the Dutch government devised new measures to deal with the rising water levels in both rivers previously named.

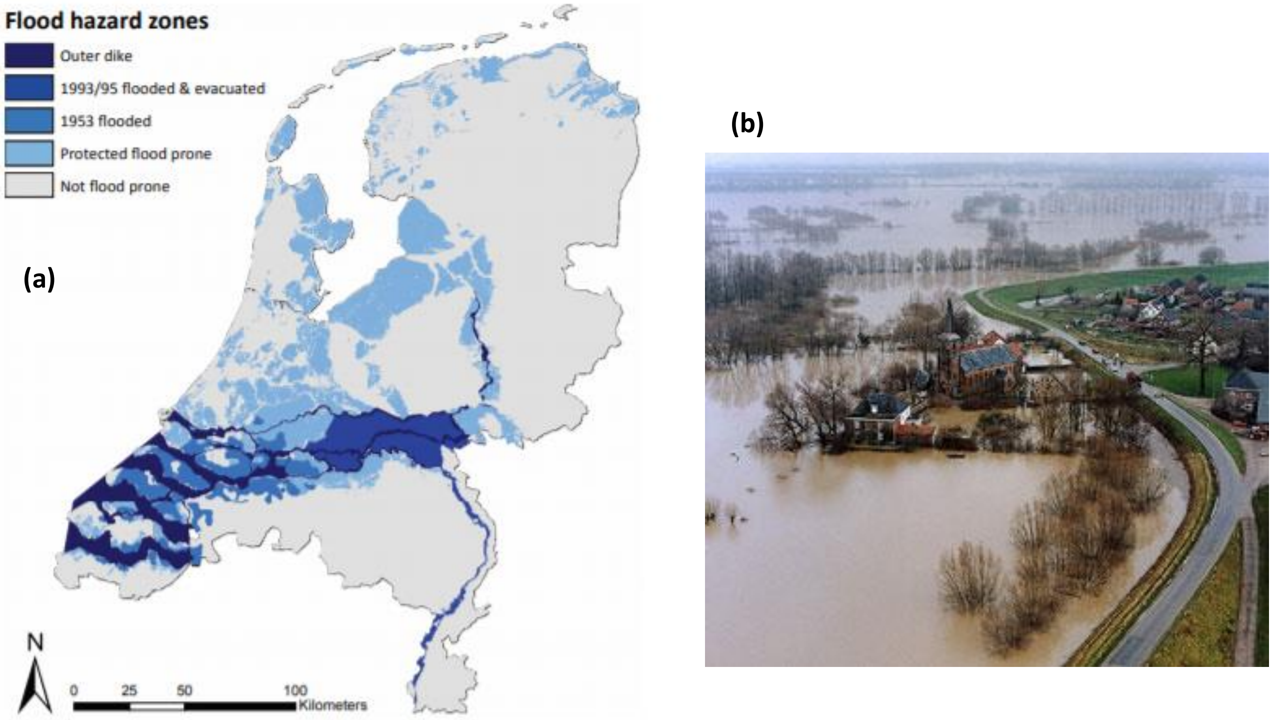


Figure 7. a) Flood hazard zones map. b) 1995 Flooding in Netherlands (Photo source: Rijkswaterstaat)

They noticed that in the past, flood protection and control via dikes and increasing river flow capacity were the main goals. As a result, the amount of space provided for rivers was reduced.

What's more, water and sediment flow patterns have been altered to the point that high or low precipitation rates are now mirrored in high or low river discharges. Rapid run-off of precipitation and consequent high discharge peaks in rivers are caused by the large-scale draining of agricultural land and the expansion of metropolitan areas, which are composed nearly entirely by impermeable materials.

Even though agriculture has been benefited, the hydromorphological resilience of river basins has been weakened by large-scale wetlands reclamation and stream control.

Once the problems were analyzed, the Advisory Committee on Water Management, in 2001, came up with an action plan for the Netherlands' future water management. Some of the most important points are the following:

3.1.1. Three-step-strategy:

Which consists in a method to reduce previously presented problems, based on the following concepts:

3.1.1.1. Anticipating rather than reacting.

3.1.1.2. Not entrusting water management issues to others.

3.1.1.3. In addition to taking technical solutions, additional area should be allocated to rivers.

3.1.2. Spatial Planning: The objective is to preserve the river's discharge capacity by applying legislation that prohibits non-river-related human activity in floodplains and modifying municipal zoning systems.

3.1.3. Other goals: Where rivers are given greater room, this space must be used to fulfill other goals that are consistent with water storage wherever possible.

So, as point number two explains, flood risk management also requires dealing with spatial planning. Nowadays, land usage in certain polders that are now flood-protected should be limited in order to avoid future costs of moving dikes farther inland.

The obvious implementation approach will have to begin by enlarging to give the river greater horizontal room, or building bypasses. Only then may solutions in the vertical dimension, such as deepening the river or lowering floodplains be considered. However, the final solution should be always to raise the dikes height.

Regarding point number three, the additional area allocated to rivers should be used to achieve other goals, such as upgrading the water system, and recovering water-related ecosystems. Because water storage sites are frequently used for agricultural production, increasing the physical and chemical water quality is a critical condition to avoid new problems of soil pollution, biological degradation, and public health concerns.

So, regarding this need to enhance the water quality, we can relate to point 3.1.1.2, in which rules and instruments governing maximum water levels, maximum discharges… are being developed in order to prevent problems from being passed from one basin or administrative body to another.

Remark the idea of "blue nodes" that has been established. Water is moved from one basin to another – in an administrative sense –at these points along a river.

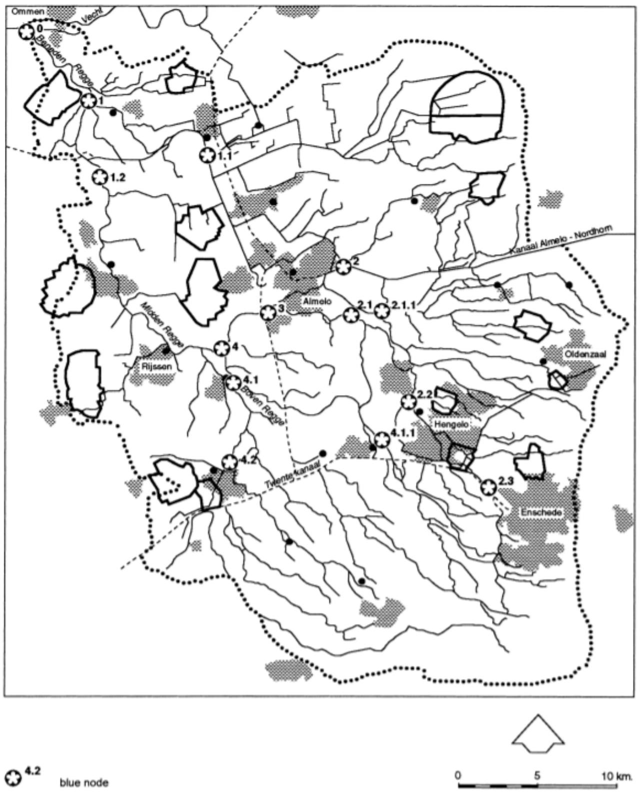


Figure 8. Blue nodes in the basin of the river Regge

Although it has been previously observed how the Dutch government is trying to reduce the cost of the construction and maintenance of large defense systems by applying innovative methods, it still continues to be one of the leaders in coastal protection the usage of hard engineering infrastructures. The Dutch society has always responded by strengthening and constructing flood defenses.

Returning to SLR, this country was one of the first to analyze the effects of high-end scenarios on the coast. A good example of defense against this SLR scenario is the storm surge barrier *Maeslantkering* located at Rotterdam Harbor, which automatically closes when the water level is 3 meters above MSL.

Maeslantkering consists in a movable storm surge barrier which provides a flexible flood protection for lowlands surrounding harbor regions. Two hollow hemispherical steel structures swung from the banks into the river and sank on the riverbed. Both gates are parked in river bank docks while the retaining walls are not in use.

Regarding the closure of the barrier, it actually occurs every ten years, which is cost-effective; but, with the projected water level in 2100, the closure criterion is predicted to be five to fifty times more frequent.

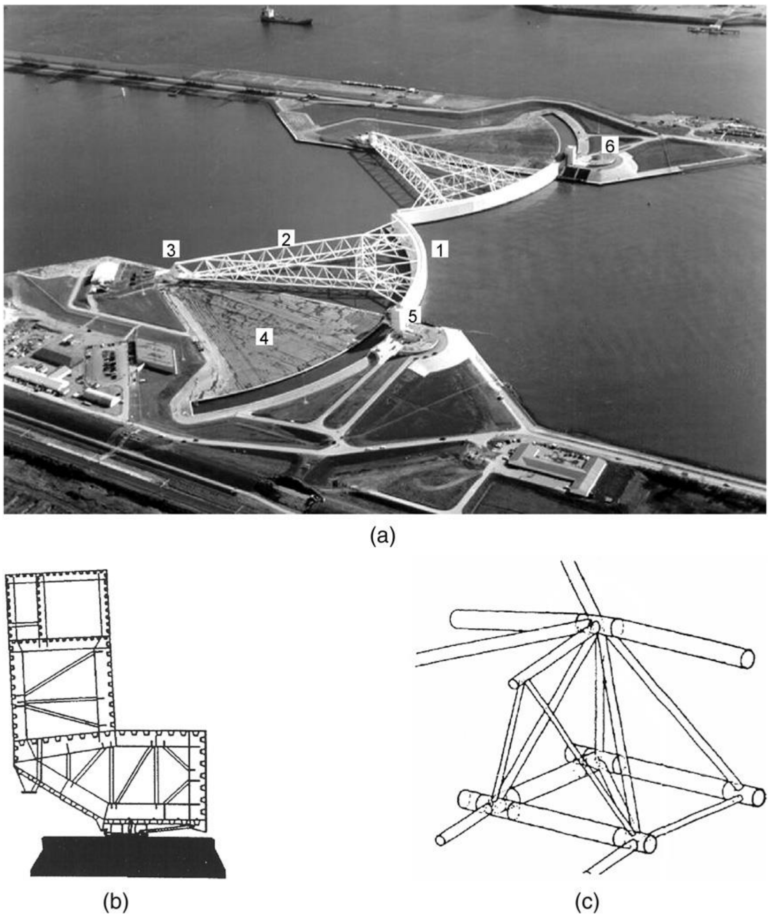


Figure 9. Principal parts of the Maeslant storm surge barrier, (a) general overview: (1) retaining wall, (2) triangular space trusses, (3) ball-joint, (4) parking dock, (5) control engines, (6) control center; (b) detail of the retaining wall; (c) detail of the steel trusses.

3.2. Italy management strategies in deltaic regions. Po delta case, and Mose barrier in Venice

A wide system of shallow lagoons, wetlands, and reclaimed areas characterizes the Po River delta. This Italian Delta, like many other deltaic regions, has mostly subsided as a result of natural and anthropogenic processes, having a considerable impact on its geomorphological evolution and significant socioeconomic repercussions.

In the case of the Po delta, groundwater pumping is one of the most significant cause of major sinking in the deltaic region. What's more, the sediment fluvial flows decreased dramatically throughout the twentieth century, from 12.8 Mt/year between 1918 and 1943 to 4.7 Mt/year between 1986 and 1991, owing mostly to the construction of dams and dykes. Carminati and Di Donato (1999) calculated that the Po Delta's long-term subsidence rate is 2.5 mm/year.

In 1960, the Italian Minister of Public Works suspended the production of gas-bearing water in the area most affected by land subsidence, and sinking was nearly reversed after 5 years.

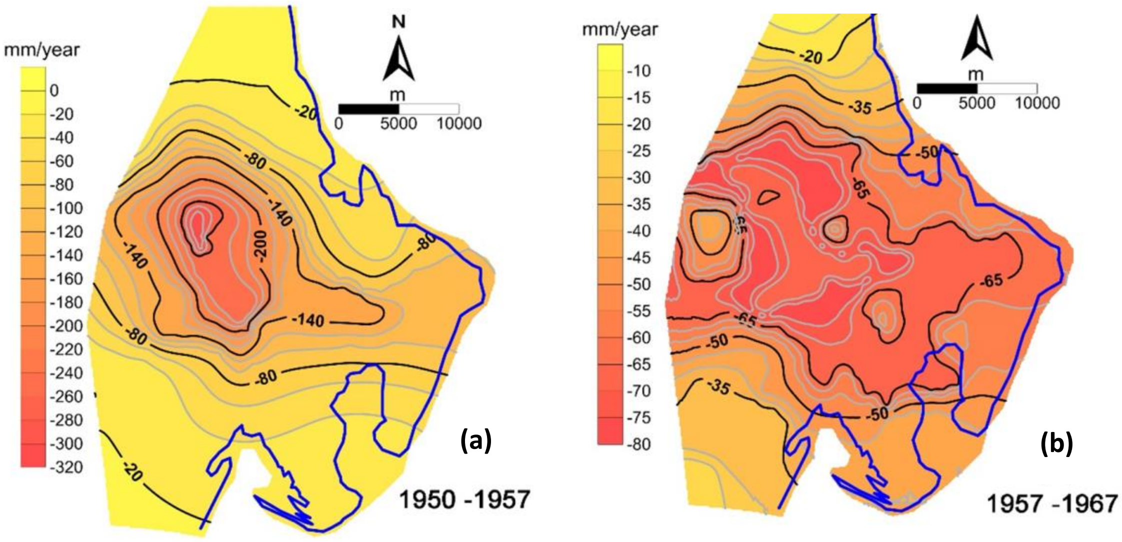


Figure 10. Land subsidence rate (mm/year) over the periods of 1950-1957 (a) and 1957-1967 (b)

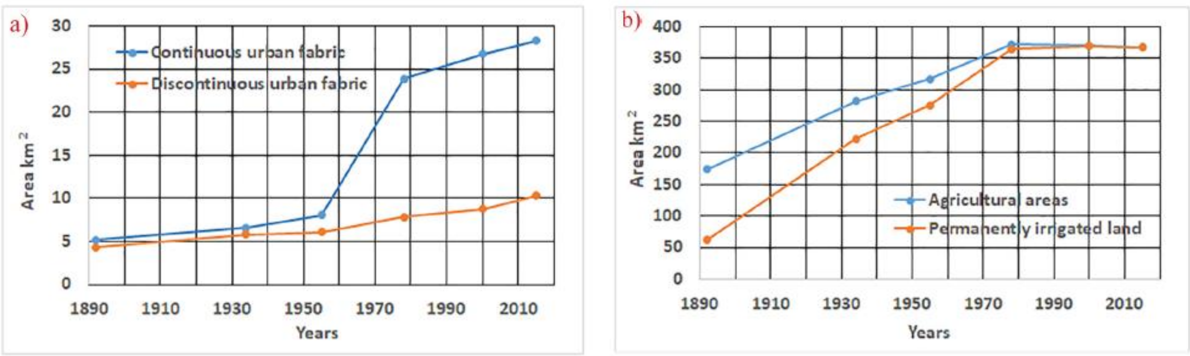


Figure 11. Variations from 1890 to 2010 of (a) the urban region at the delta and of (b) the agricultural area

As well as other deltaic regions, the most significant land-use changes in the Po Delta produced the highest subsidence rates. The decrease of land elevation relative to mean sea level induced by gas-bearing removal from relatively-deep aquifers had a profound impact on land cover.

Another process related to land subsidence, reclamations, and climate change is saltwater intrusion in the nearby farmlands, which leads to contamination of soils and shallow aquifers.

So, once they had analyzed the evolution and the primary problems of this system it was easier for the Italian government to initiate a management strategy in order to protect this fragile coastal area.

One of the ideas they came up to was the installation of moveable barriers along the last section of the watercourses, as well as the selection of salt-tolerant crops.

Aside from the anthropogenic prosses affecting the system, the area is still being affected by land subsidence caused by natural consolidation of compressible Holocene sediments. This means that the restoration of river sediment flow to the delta appears to be the only solution against this problem.

In 2013, IPCC (Intergovernmental Panel on Climate Change) proposed the three following management strategies (similar to the ones presented by the Dutch committee in 2001):

3.2.1. Defend: consists on the most conservative solution, composed by the application of hard and/or soft techniques used to maintain current conditions. Its goal is to protect the delta's current setting. The main problem with this alternative it's the expensive maintenance cost, which will be increasing in the nearby future.

3.2.2. Adapt: this second alternative involves continuing to use the delta area without trying to avoid flooding. This strategy will demand the conversion agriculture to fish farming or using salt-tolerant crops.

3.2.3. Managed retreat: this third solution is quite interesting, as it allows wetlands to migrate inland and respond to rising sea levels. With this option, the delta's current configuration will be unsustainable. In the specific case of the Po's delta, the loss of emerged land will be around 65%.

Notice that all three approaches have socioeconomic consequences that are difficult to assess. Maybe the best solution could be picked by applying a cost-benefit analysis of the situation for each alternative, and choose the best contender, but it would be a complex labor.

As we have previously analyzed *Maeslantkering* surge barrier, it could be interesting to evaluate the Mose barrier, located at Venice. The Mose barrier is composed by a series of smaller mobile gates, which are placed at three different inlets: Lido, Malamocco and Chioggia.

These mobile gates consist of a housing box connected to a metal box-like structure by two hinges. The floodgates are full of water when they are not in use, and they are entirely hidden by housing box. Compressed air is injected into the sluices, which empties it from the water, only in the case of a particularly high tide that might cause a flooding event. As the water leaves, the gates rise up to impede the passage of the incoming tide in the lagoon.

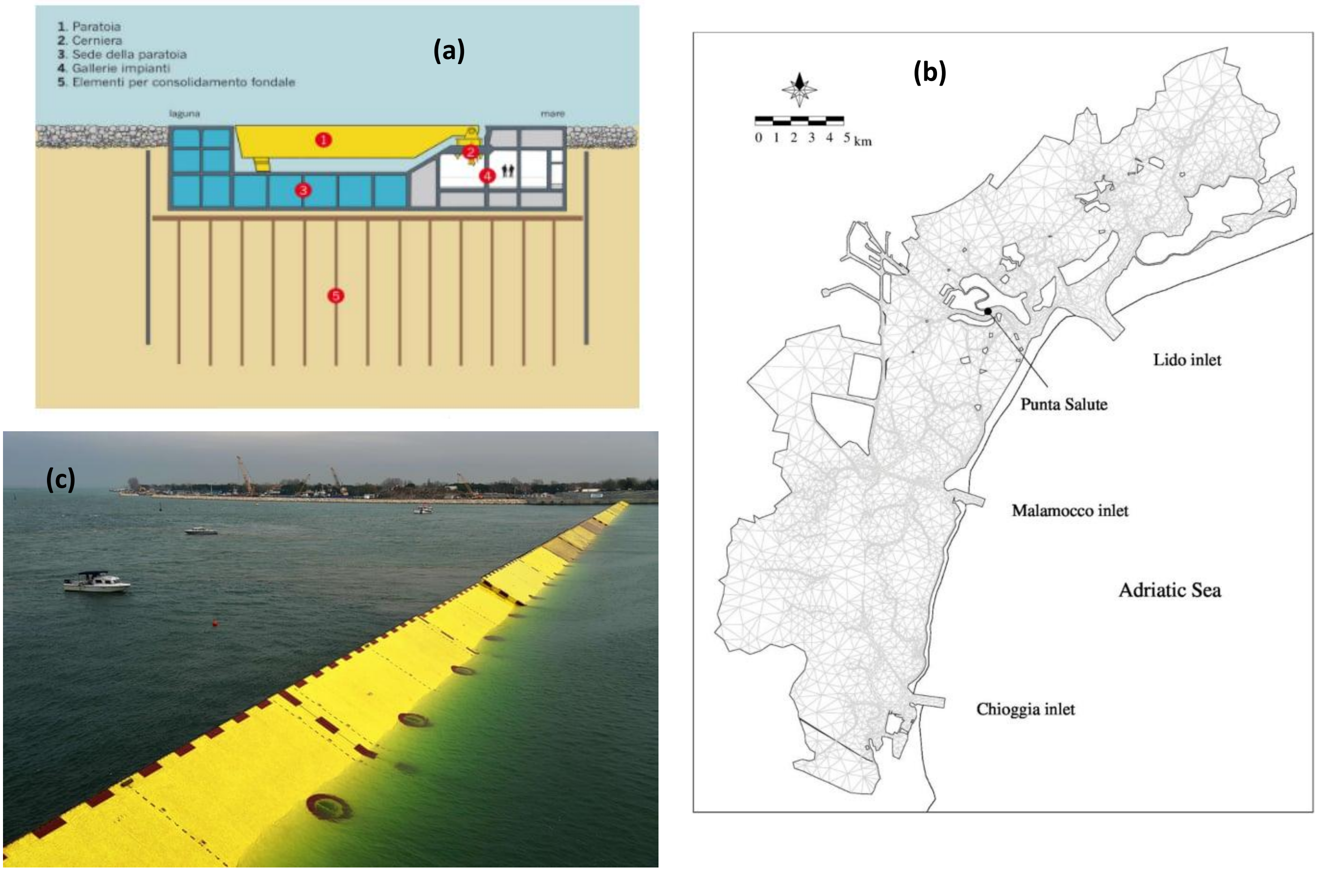


Figure 12. a) Mose cross-section and construction elements b) Venice Lagoon map, with the three inlets indicated and the city center (Punta Salute) c) Mose floodgates during the opening operation

The actual average number of closures is of 5 to 12 each year, considering no SLR, with a closing time of the port inlets of 4~5 hours for each closure. Recent hydrodynamic models have been used to recreate the performance of Venice's mobile barriers under sea level rise scenarios. For an SLR of 50 cm, the number of closures increases from the current scenario to 300–430 closures each year.

The results of these investigations show that even with a high number of closures, the movable barriers will be able to defend the city from modest sea level rises. However, the cost is too high when considering a frequency of one barrier closure for each day.

3.3. Louisiana management strategies in deltaic regions.

In the case of the Mississippi river, the suspended sediment load has decreased by more than half since 1950, from 400 MT to 145 MT, according on recent measurements (2008–2010). Dams, levees, meander cutoffs, revetments, and other artificial structures, as well as better soil conservation for croplands, have all contributed to this reduction.

Since the big flood of 1927, the US Army Corps of Engineers (USACE) has made the majority of the river's alterations. It was determined that a robust public work infrastructure in the lower Mississippi Valley was required to provide the necessary flood risk control.

One of this project's goals was to limit Mississippi river flow to a limited portion of the natural floodplain in order to safeguard farmlands and towns from flooding. Another, less evident goal was to avoid sediment from filling the low-water navigation channel. However, both objectives were contrary. Reducing channel's width always raises flood stage and velocity for a given discharge, which would have resulted in greater sediment movement and deposition.

Since the 2005 hurricane season, the state of Louisiana and the United States government have collaborated on an extensive rehabilitation initiative. A Comprehensive Master Plan was published by the Louisiana Coastal Protection and Restoration Authority (CPRA). A 50$ billion investment to build and maintain land, reduce flood risk in communities and provide habitats that support ecosystems. 25$ billion for to delta restoration and the remaining $25 billion used to raise traditional levees and elevation or floodproof structures (risk reduction)

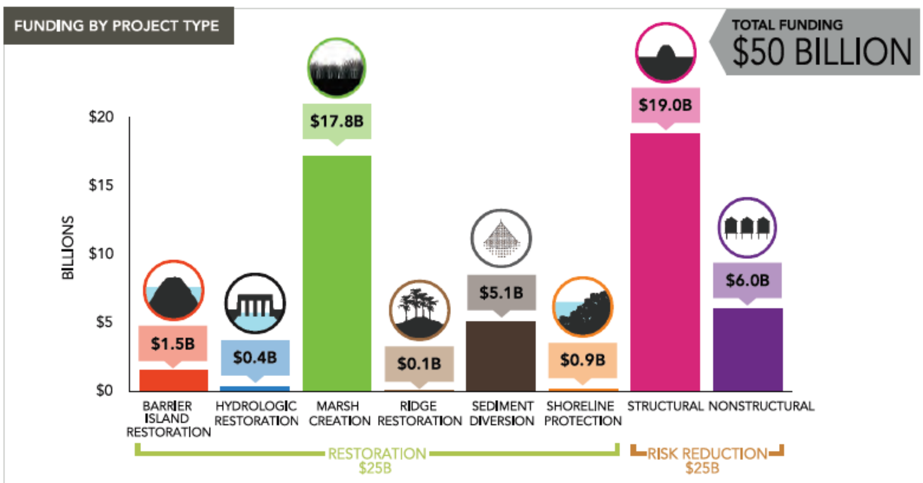


Figure 13. Graphic scheme of the budget used for Louisiana Coastal Protection Master Plan 2017

In our project, we will briefly focus on three different project types:

3.3.1. Sediment diversion: Consists on a large-scale coastal restoration project that will include the construction of a network of gates into the Mississippi River levee system to enable river water, sediment, and nutrients to flow into deteriorating wetlands, helping to sustain and restore land.

Diversions are increasingly recognized as a method of providing sediment and nutrients to increase wetland capacity in order to combat SLR. What's more, sediment diversion is projected to generate land at a cost of 85 percent less than other approaches (dredging or pipeline)

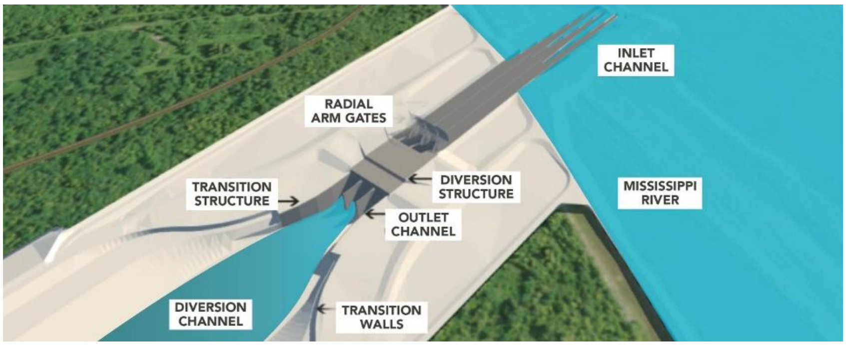


Figure 14. Sediment diversion system structure scheme

3.3.2. Marsh and wetland creation: dredged or extracted sediments have long been used to create wetlands. In the past, this process was used to preserve navigation channels at the mouths of the rivers (Mississippi and Atchafalaya). However, nowadays marshes that have been flooded or fragmented are being rebuilt through dredging.

One of the main advantages of this procedure from the previous one is that land may be generated relatively fast wherever it is needed, especially as a flood protection buffer or to restore skeleton features of the coastal landscape such as natural levee ridges.

3.3.3. Barrier island restoration: meant to preserve and restore the distinctive features of Louisiana's barrier island systems. The Master Plan involves restoration of barrier beaches and islands because of the importance of these sandy features, in terms of physical processes like waves and tides resistance and in terms of the life cycles of many species.

Engineered structures such as breakwaters and jetties appear to be ineffective in stabilizing eroding deltaic barriers. Sand-trapping fences and vegetative plants, on the other hand, have been effective in maintaining sand dunes on barrier islands.

So, one of the main conclusions would be that raising the city dikes in conjunction with the restoration of adjacent wetlands to produce a large elevation gain to buffer the effects of storms would be the most suitable solution.

Therefore, once we have analyzed the most innovative mechanisms and strategies that are being implemented in Europe and the United States to try to guarantee the survival of the deltas, we will summarize them in the following table:

Deltaic management strategy		**Region/s being applied currently or planned to project**
1	Restoring the river sediment flux through by-pass techniques in the reservoirs	China regions (Martín Vide, 2005), Ebro delta, Nile delta
2	Spatial Planning (prohibition of non-river-related human activity in floodplains)	Rhine delta (Netherlands)
3	Hard or soft engineering solutions (dikes, levees, revetments…)	Ebro delta, Rhine delta, Mississippi delta, Po delta
4	*Maeslantkering* or Mose gate solution	Rhine delta (Rotterdam harbor), Venice lagoons
5	Adaptation, by continuing to use the delta area without trying to avoid flooding (fish farming or using salt-tolerant crops)	Po delta
6	Managed retreat, by allowing wetlands to migrate inland	Po delta
7	Sediment diversion	Mississippi delta
8	Marsh and wetland creation by dredging operations	Mississippi delta
9	Non-structural solution (elevation of residential properties)	Mississippi delta
10	Natural solution (erosion resistant flora)	Ebro delta (currently under investigation)
11	Polderization	Rhine delta
12	No intervention strategy	Ebro delta

Table 2. Existing deltaic management strategies

4. Review of existing river basin management strategies

Water management infrastructure and techniques have significantly altered river basins around the world. Focusing in Mediterranean climate zones, there are a lot of parallels in the patterns of ecological changes that have occurred as a result of the massive construction of dams and water control infrastructure.

The lowering of winter peak flows and the rise of summer baseflows have altered natural flow regimes. Sediment transport variations, water quality deterioration, and reductions in freshwater biodiversity are all frequent patterns of disturbance.

Progress toward integrated and sustainable water management models is expected to occur in the near future, owing to a rising knowledge of climate change's consequences and public demands for more efficient water usage and better environmental quality.

Unlike humid regions, where year-round rainfall irrigates crops and replenishes reservoirs, med-regions have extremely variable precipitation patterns, a longer dry season, and a shortage of natural lakes, making rivers a main supply of water. The seasonality of precipitation patterns has acted as a key motivator for dam construction to control the timing and volume of water delivery. Even more, many med-river basins have considerable topographic relief, making them attractive places for water storage and hydropower production.

Water resource development has been crucial in enabling improved agricultural productivity, economic development, and population expansion in med-regions. Water projects, on the other hand, have come at a significant environmental cost. Fundamental hydrological processes are affected by impoundments, dam operations, and other water infrastructure.

New water management techniques have been developed to increase river protection and create a better balance between freshwater resource consumption and ecosystem maintenance in response to the loss of biodiversity and important ecosystem services. It is becoming increasingly clear that plans should be based on the idea of sustainable water use, which consists in water management that benefits the economy, the ecology, and water consumers' equality.

However, before applying any new management strategy, it's important to know the geography, water-use patterns and previous management plans that have been applied to the river basin. In our case, the Ebro River flows 930 kilometers from west to southeast into the Mediterranean Sea (Ebro Delta), approximately 160 kilometers south of Barcelona. Agriculture is the major land use in the Ebro River basin, containing about 8,000 kilometers of irrigated land (10% of basin area)

The Ebro River basin has had a significant impact on human settlement patterns in the Iberian Peninsula, as well as being crucial to political and economic development in the entire country. Water from the Ebro River is used for irrigation, residential water supply, industry, and transportation. Irrigation accounts for over 90% of water usage in the basin, which is regulated by a complex network of dams and irrigation systems. On the Ebro River, there are 289 dams. Even more, the basin has 340 hydroelectric plants with permits to utilize about 12,000 m^3/s.

Another example of a river basin, also with a Mediterranean climate, to be able to establish comparisons would be the Sacramento River basin, located in California.

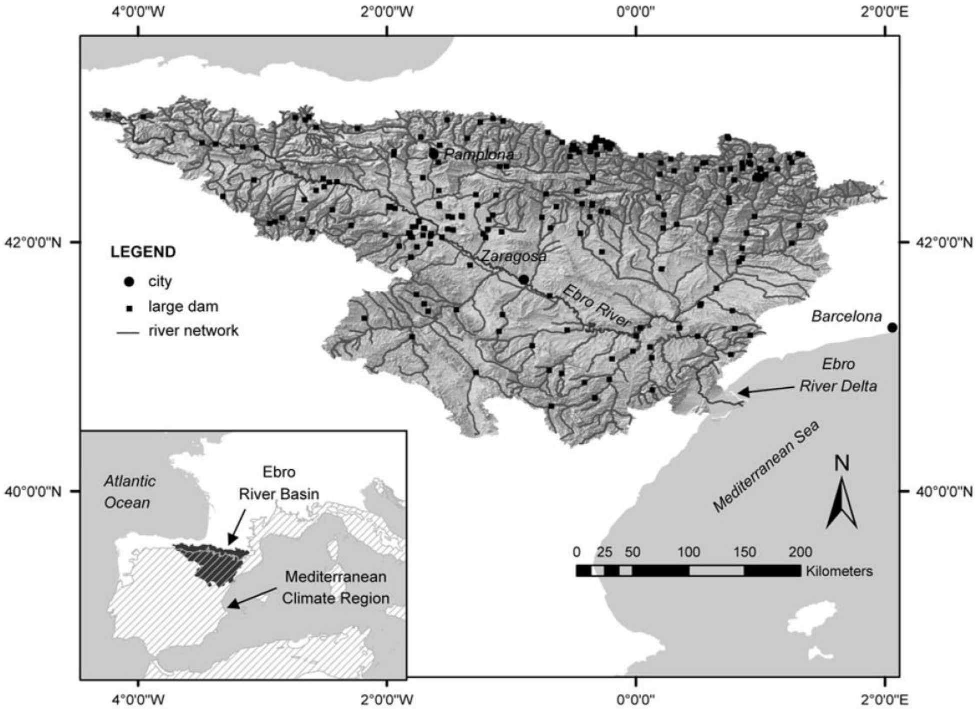


Figure 15. Ebro River basin

	Ebro	Sacramento
Basin size (km^2)	85,5	70,56
River mainstream length (km)	930	640
Urban	853 (1%)	1.287 (1,8%)
Irrigated agriculture	8.534 (10%)	8.680 (12,3%)
Dryland agriculture	29.081 (34%)	1.611 (2,3%)
Forest and shrub	28.000 (32,7%)	51.000 (73,5%)
Mean annual precipitation (mm)	650	930
Number of dams in basin	289	406
Agricultural gross	6,3	10,3
Agricultural net	4,4	7,4
Domestic net	0,2	0,7

Table 3. Geographic characteristics, water availability and demands comparisons between Ebro and Sacramento

Now, regarding the past water management strategies in Spain, specifically in Ebro River basin, in the nineteenth century the idea was primarily concerned with agricultural and municipal water supplies. The first joint attempt to build centralized water projects to facilitate agricultural land development occurred towards the end of the nineteenth century. However, because to the Spanish Civil War in 1936, these ambitious attempts were eventually failed.

Despite the fact that the Hydraulic Era concept has been in existence since the turn of the century, substantial water infrastructure construction in Spain was postponed until Franco's dictatorship. Diversification and expansion of water needs, as well as increased dangers of regional water shortages, accompanied changes in social and economic structure. During the Franco period, over 400 dams were built in Spain, and a shift to more intensive farming practices resulted in a significant rise in the use of fertilizers and pesticides. Pollution was dumped into rivers and polluted groundwater supplies as a result of industrial activities fueled by hydropower.

These changing environmental, political, and economic pressures exposed flaws in Spanish water policy, prompting substantial revisions under the Spanish Water Act of 1985 and the start of Spain's Integration Era of water management. The Water Framework Directive is the most important piece of EU law that has influenced water management in Spain. By combining aquatic ecological safeguards, transparency and social involvement, and economic cost recovery at the center of its management strategy, the WFD directly opposes Hydraulic Era ideals. It provides long-term environmental objectives as well as a set of benchmarks to aid progress toward sustainability in water resource planning and management. However, even the WFD's implementation has not resulted in a total rejection of Hydraulic Era ideas.

The case of the Sacramento River follows a similar evolution except for its origins, with the Gold Rush of the mid-nineteenth century. Dam construction on major tributaries to the Sacramento River soon followed, which provided water to gold mining operations.

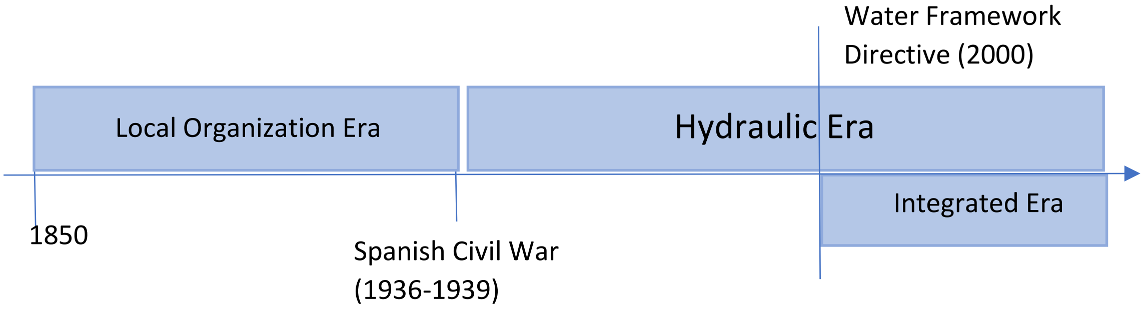


Figure 16. Time line of water resources management in Spain

Once we have analyzed the geographical characteristics, and the evolution of water management, we will focus on the different effects that these strategies have had on the hydrological behavior, geomorphic processes and on the water quality of the river basin. These effects can be obviously extrapolated to other med-regions basins.

4.1. Water management effects on hydrologic regimes, and ecological responses

Natural flow regimes have been significantly affected across the world as a result of the construction of major dams and conveyance water project basins. Large dam building has had the overall impact of reducing the amplitude and frequency of high flow episodes in the winter and spring, while increasing summer and autumn base flow. Furthermore, the flood magnitude has been considerably decreased, especially during moderate floods.

Also, urban settlements appear to be a major cause of flow regime change in other med-rivers, according to research. Small tributaries and streams are frequently diverted from upstream sources to model water demands, reducing flows downstream and hastening stream drying in the summer. Domestic irrigation runoff, on the other hand, may account for a considerable percentage of the stream flow downstream of urban areas.

Now, freshwater ecosystem deterioration and loss of aquatic variety have been linked to these constructed dams and implementation of flow control. Hydrologic changes have led in changes in the structure and function of river ecosystems, which have been observed in all of the study basins. Dams have been recognized as the most major factor influencing freshwater fish population reductions in California and Spain. Large dams on the Ebro River have also limited the spread of eels, lampreys, and sturgeon in comparison to their historical range.

4.2. Water management effects on geomorphic processes, and ecological responses

Sediment transport and other geomorphic processes have also been adversely influenced by water management. As a result of dam building, flood-control infrastructure, bank protection, and gravel mining, sediment loads have steadily decreased during the twentieth century.

Dams obstruct sediment transport by collecting bedload material and causing suspended load deposition in low-velocity reservoir waters. The river, on the other hand, preserves some of its sediment transport capacity by entraining material from the riverbed and lateral deposits, resulting in river channel incision.

During high flow events, channel incision and coarsening of bed sediments is a common result of reduced sediment inputs to reaches below dams. This phenomenon is known as the "hungry water effect."

By limiting lateral erosion, extensive bank protection by levees and revetment structures has also reduced sediment supplies to the river channel. The mining of aggregate from the river channel amplifies the impact of reduced sediment load caused by dams. Agricultural activities and flood-control measures have significantly changed floodplains in basins. Floodplain conversion for agricultural purposes usually results in river channel stability behind embankments, restricting natural channel movement and floodplain flooding times. Increases in summer base flows, on the other hand, have aided the growth of riparian vegetation in the river channel, further stabilizing it and decreasing active channel wandering.

Dams have disrupted sediment movement in the Ebro River, which has had significant ecological consequences, notably in the delta. The Ebro River Delta is one of Spain's most significant biological regions for migratory shorebirds, and it supports a varied assemblage of fishes, macroinvertebrates, and other animals.

4.3. Water management effects on water quality, and ecological responses

Water quality in the study basins is affected by a wide range of water management operations. Changes in flow regimes caused by dams and water diversions have a significant impact on downstream temperatures and river diluting capacity. Agricultural irrigation runoff, as well as wastewater and runoff from urban areas, are major sources of pollution in rivers. Finally, industrial operations that use rivers to generate energy and commerce are big polluters and degrade water quality.

The lower Ebro's salinity has grown as a result of water management. The reduction in floods and stability of dry season flows has resulted in the incursion of a long-lasting marine salt wedge into the lower Ebro River, stretching up to 25 kilometers.

Heavy metals and organic compounds from mining, industry, and urban sources are abundant in the upper reaches of the river. The buildup of nutrients and salts, largely from agricultural sources, has an impact on the river's middle course.

So, the main concerns about water quality include temperature fluctuations, nutrients, industrial pollutants, and heavy metals. The conservation of this species depends on the regulation of downstream temperatures. Other ecological characteristics, such as increases in particulate organic matter and zooplankton biomass, have been observed to change as a result of release management, which may have an impact on the aquatic food web.

As a conclusion, strong and effective water governance systems are required; yet, existing management frameworks, guiding principles, and institutional competencies may be insufficient to meet these problems.

4.4. Integrated management of river basins

As we have been able to read previously, the vast majority of basins have hydrological, geomorphic, and ecological problems… We have been able to observe how in 2000, in Spain, an integrated management began to be applied.

This concept's (Integrated management) use reflects an increasing understanding of river basins' complexity as hydrological, ecological, economic, political, and social systems. It's dealing with a similar set of problems: the necessity for land and water management to deal with a wide range of interconnected concerns and stakeholders.

The rise of integrated river and watershed management reflects both the rising human strain on rivers and the growing technological understanding of how rivers and catchments operate. So, the main drivers for integrated management are the following:

4.4.1. Population and pressures

There is minimal need for management when human populations or demands are modest in comparison to the water or water-based resource. However, when demand rises, either as a result of population growth or as a result of increased harvesting or usage per capita, rivalry and disputes emerge. The requirement to control a certain element of the resource is frequently the primary management reason for a river. It may be a need to manage fishery, navigation…

Consider the situation where agricultural water demands cannot be satisfied without the building of infrastructure such as weirs and dams, which may obstruct navigation and fish migration. As the population and demand expand, there is a greater need for cross-sector management.

4.4.2. Increased technical understanding

The study of the ecohydrological processes that occur inside rivers and their catchments has grown rapidly. Improved river gauging techniques are being developed. River flow modelling at large scales has also played a significant role. Geomorphology of rivers has progressed at a quick pace as well.

Environmental flows in streams have lately received increased attention, with approaches for analyzing and designing acceptable flow regimes becoming increasingly complex.

4.4.3. Management pressures

Resolving actual or potential disputes about water use and water sharing have also been a driver for developing river use agreements between jurisdictions.

What's more, any of the earliest agreements for many rivers arose from a need for environmental management, particularly for those rivers that had little control until recently.

Agreements to minimize pollution, fisheries management, and cooperative use and preservation of waterways are all examples of environmentally based management solutions.

4.5. "Room for the River" Dutch Integrated program

At this point, the integrated program discussed above in section number three will be explored further.

Traditional flood risk management techniques, which focus on 'defending against the water,' are universally acknowledged as insufficient. Traditional flood defense methods (e.g., building or strengthening dikes) are coupled with measures that emphasize the 'accommodation of the water' in integrated flood risk management (e.g., dike relocation)

Rijkswaterstaat, provinces, municipalities, and regional water authorities (i.e., water boards) collaborated on 34 projects along the Rhine and its branches, the Waal, Ijssel, and Nederrijn, as part of the Room for the River initiative. The initiative had a dual goal: each project was supposed to improve the spatial quality of the riverine environment while also increasing the ability of the rivers to deal with high water levels.

During the implementation of the project, the Cluster Spatial Quality provided guidance. An independent 'Quality Team' aided and advised this Cluster.

The 34 initiatives that made up Room for the River were coined measures. The types and scales of the measurements differed. Three sorts of measurements were identified in general:

- 1: Conventional flood risk management methods, such as reinforcing dikes
- 2: Measures inside the banks, such as floodplain excavations
- 3: Measures beyond the banks

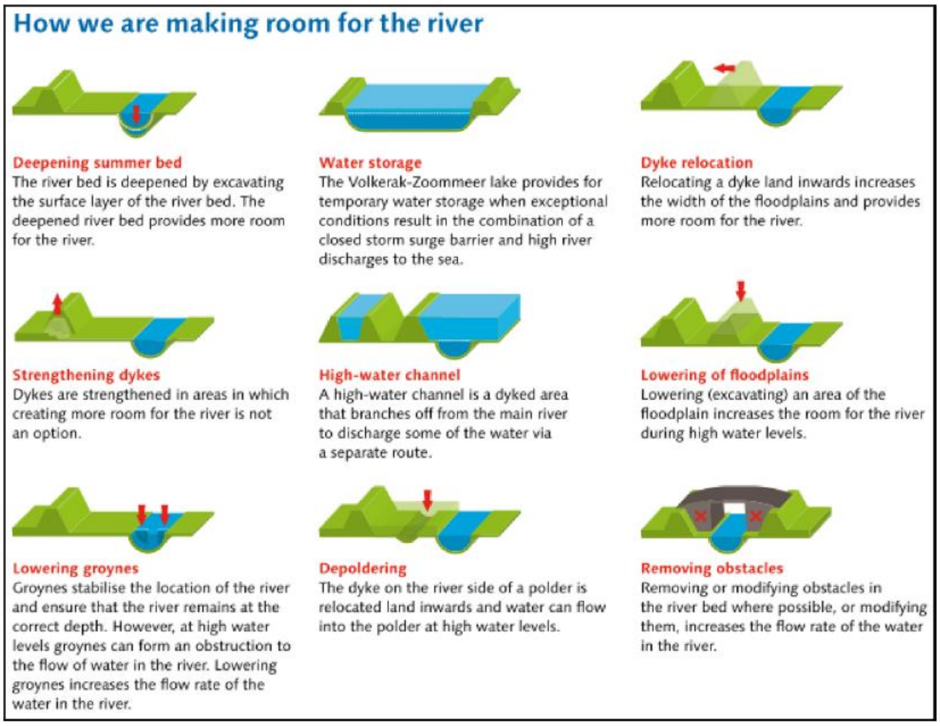


Figure 17. Different types of measures taken in the Room for Rivers program

River basin management strategy		Brief explanation
1	Deepening river bed	The river bed is deepened by excavating the surface layer of the river bed
2	Water storage	Consists on a lake that provides temporary storage when exceptional conditions are occur.
3	Dyke relocation	Relocating a dyke land inward increases the width of the floodplains
4	Strengthening dykes	Dykes are strengthened where more room for river is not an option
5	High-water channel	Dyked area that branches off from the main river to discharge water via a separate route
6	Lowering of floodplains	Lowering an area of the floodplain increases the room for the river
7	Lowering groins	At high water levels groins can form an obstruction to the flow of water in the river
8	Depoldering	Dyke on the river side of a polder is relocated land inwards so water can flow into the polder at high water levels
9	Removing obstacles	Removing or modifying obstacles in the river bed where possible

Table 4. River basin management strategies presented by the ``Room for river´´ Dutch program

5. RCP, SSP and SPA scenarios

Researchers from various modelling groups around the world were in the need to create new scenarios in the late 2000s to better anticipate the potential impacts of climate change, as well as to see how the world may evolve for the rest of the twenty-first century.

That's why, The Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC-AR5) established a worldwide scenario framework consisting of RCP (Representative Concentration Pathways), SSP (Shared Socioeconomic Pathways), and SPA (Shared Climate Policy Assumptions) scenarios, in order to solve this problem.

Nowadays, these three scenarios are being used as the main inputs for the most recent climate models, as well as to investigate how societal decisions will impact greenhouse gas emissions and how the Paris Agreement's climate targets (avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C) can be met.

5.1. SSP scenarios

A first group was assigned with predicting how socioeconomic aspects will evolve over the next century. Population, economic growth, education, urbanization, and the rate of technological progress are all factors to consider. These "Shared Socioeconomic Pathways" (O'Neill et al., 2014) look at five alternative scenarios for how the world may evolve, in the absence of climate change or climate policies.

The five different narratives are the following:

SSP	**Challenges**	**Illustrative starting points for narratives**
SSP 1	Low for mitigation and adaptation	The world is slowly but steadily moving toward a more sustainable course, with a focus on more equitable growth that respects environmental boundaries. The global commons' management is gradually improving. The focus on economic growth is shifting to a broader focus on human well-being. Inequality has decreased.
SSP 2	Moderate	The world is moving down a path where social, economic, and technical developments do not deviate much from historical experience. Global and national organizations seek to achieve sustainable development goals, but progress is gradual.

SSP 3	High for mitigation and adaptation	Consists on a return of the nationalism. Over time, policies have shifted to become more focused on national and regional security concerns. Inequalities persist or worsen over time as a result of material-intensive consumption. Environmental deterioration is exacerbated by a low international priority for resolving environmental problems.
SSP 4	High for adaptation, low for mitigation	A mixed world, with relatively rapid technological development in low carbon energy sources in key emitting regions, leading to relatively large mitigative capacity in places where it mattered most to global emissions. However, in other regions development proceeds slowly, inequality remains high, and economies are relatively isolated, leaving these regions highly vulnerable to climate change with limited adaptive capacity.
SSP 5	High for mitigation, low for adaptation	In the absence of climate policies, energy demand is high and most of this demand is met with carbon-based fuels. Investments in alternative energy technologies are low, and there are few readily available options for mitigation. Nonetheless, economic development is relatively rapid and itself is driven by high investments in human capital. Improved human capital also produces a more equitable distribution of resources, stronger institutions, and slower population growth, leading to a less vulnerable world better able to adapt to climate impacts.

Table 5. SSP’s scenarios

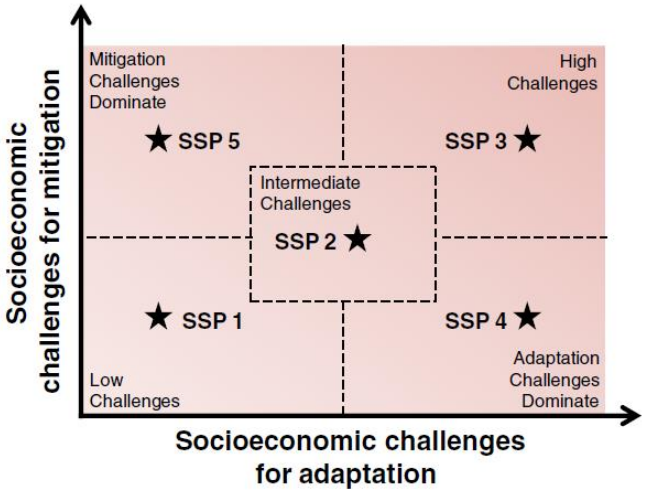


Figure 18. Graphical representation of the mitigation and adaptation challenges for each SSP scenario

The figure above represents in a graphical way the different mitigation and adaptation challenges for each scenario. Due to its rapid technological progress, relative global income equality, and concentration on environmental sustainability, SSP1 faces few problems in terms of mitigation and adaptation.

On the other hand, SSP4 has comparable low mitigation problems owing to rapid technological progress, but high adaptation challenges due to persisting inequality and poverty in many regions of the world.

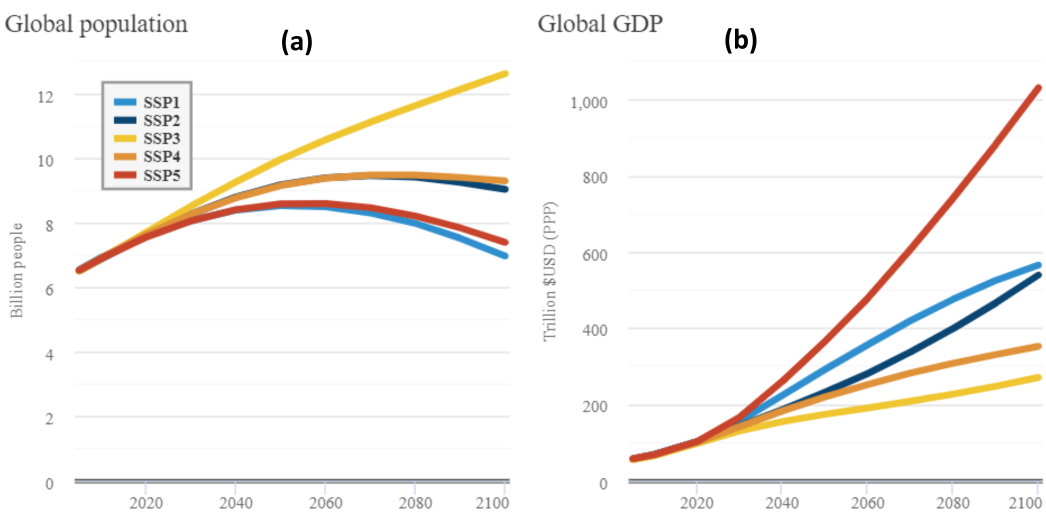


Figure 19. a) Global population evolution between 2005-2100 for each SSP scenario. b) Global GDP (Gross Domestic Product) evolution between 2005-2100 for each SSP scenario.

5.2. RCP scenarios

Regarding the "Representative Concentration Pathways" (van Vuuren et al., 2011) were created by a second group of researchers consisting of a series of global climate scenarios that account for greenhouse gas and other air pollution emissions, as well as changes in land use. They include trajectories for "radiative forcing" of the global climate system, a measure of the effect on the energy balance of the system of changes in the composition of atmosphere, such as due to emissions of greenhouse gases.

Radiative forcing is generally represented as a change in net energy flow into the climate system per unit of area compared to pre-industrial periods. Each of the four RCPs has a distinct force at the end of the twenty-first century and is called after the amount of forcing in the year 2100:

RCP	Description
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m2 (~1370 ppm CO2 eq) by 2100.
RCP 6	Stabilization without overshoot pathway to 6 W/m2 (~850 ppm CO2 eq) at stabilization after 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m2 (~650 ppm CO2 eq) at stabilization after 2100
RCP 2.6	Peak in radiative forcing at ~3 W/m2 (~490 ppm CO2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m2 by 2100).

Table 6. RCP's scenarios

5.3. SPA scenarios

The SPAs (Shared Climate Policy Assumptions) are the global scenario framework's last component (third dimension). They capture key policy attributes such as the goals, instruments and obstacles of mitigation and adaptation measures (Kriegler et al., 2014) They serve an important role in connecting RCPs and SSPs, as well as providing a platform for developing common assumptions in order to analyze the effects of certain adaptation and/or mitigation policy options.

What's more, the SPA narrative should contain information on the various timelines of regions and countries' involvement in emissions mitigation regimes, as well as whether mitigation stringency is global or regionally differentiated. It could also contain information about the nature of climate policies, such as the differences between policies to mitigate fossil fuel and land-use change emissions, and focusing mitigation more on upstream technology solutions for energy supply.

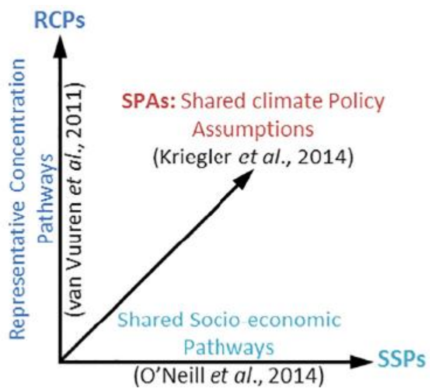


Figure 20. Three dimensions of the global SSP-RCP-SPA scenario framework of the IPCC AR5

5.4. Combining SSP, RCP and SPA scenarios

As said before, these Shared Socioeconomic Pathways look at alternative scenarios for how the world may evolve, in the absence of climate change or climate policies. However, researchers also sought to see how various levels of climate mitigation and adaptation might fit into each SSP's predicted future. The graph below depicts emissions over time for all SSP baselines (grey lines) and various SSP-RCP combinations, with radiative forcing restricted to 6.0, 4.5, 3.4, 2.6, and 1.9 watts per meter squared in 2100. (Colored lines).

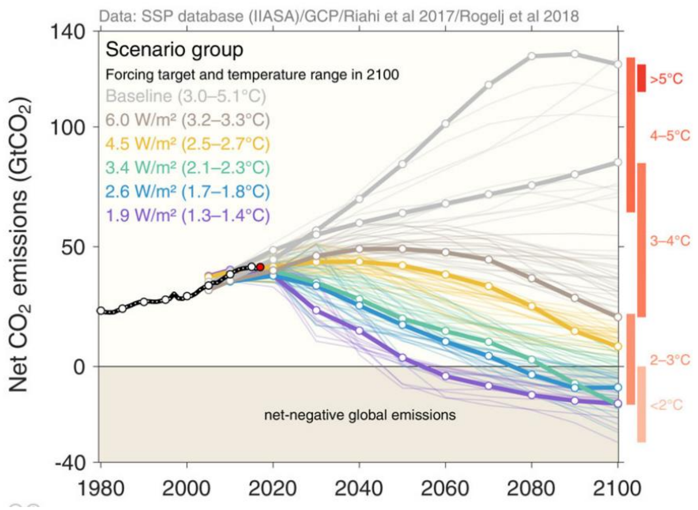


Figure 21. Net CO_2 global emissions for all SSP baselines (grey) and mitigation targets (colored)

Furthermore, whereas all combinations of RCPs and SSPs are theoretically conceivable, only a few are realistic. Only SSP5 (associated with the greatest economic growth) could be entirely compatible with RCP8.5 and lead to RCP8.5-compliant emission levels, whereas RCP2.6 emission levels would be impossible to achieve in an SSP3 society.

The researchers used six different integrated assessment models (IAMs) to convert the SSPs' socioeconomic circumstances into predictions of future energy usage and greenhouse gas emissions. These IAMs consists on various computer models that analyze a large amount of data in order to provide information that may be utilized to aid decision-making (in climate change research)

Each box in the following graphic represents the number of models that were able to successfully meet the RCP target:

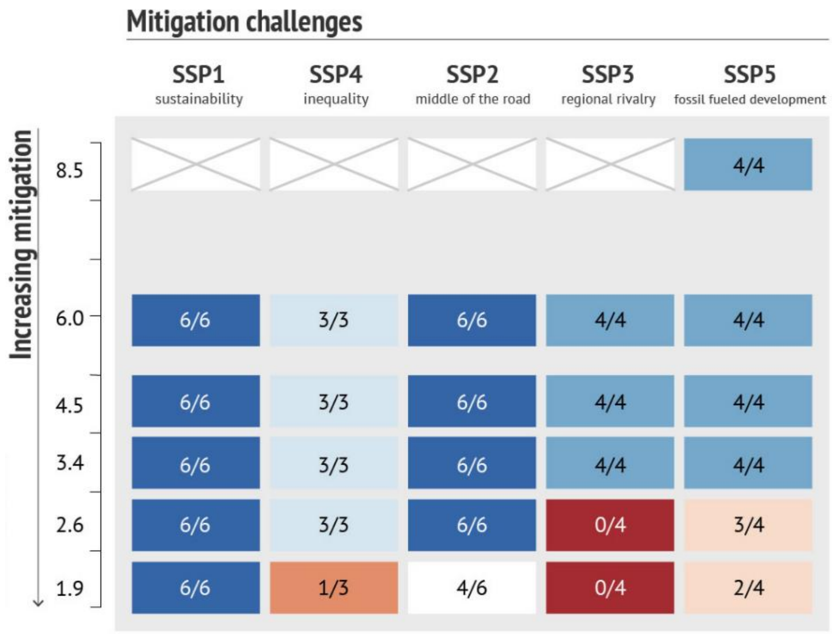


Figure 22. Combination of SSP and RCP model runs.

Models used shared policy assumptions (SPA) regarding short-to-medium-term constraints to international cooperation and the potential pace of emission reductions to determine if the underlying socioeconomic variables in an SSP allow for the degree of mitigation required to reach RCP targets.

The capacity of scenarios to have substantial near-term reduction of greenhouse gas emissions is influenced by the variations across SSPs. While SSP1 and SSP4 allow for immediate global action to reduce emissions beyond those previously agreed to in the Paris Agreement, in the case of SSP5, emissions climb too much and decline too slowly to comply the Paris objectives.

Finally, one last consideration that is being taken into account in the present regarding modelling is the use of the high-emission high-warming RCP8.5 as their "business as usual" baseline – a worst-case scenario.

However, because only SSP5 may achieve the same level of emissions as RCP8.5, it may not be the ideal choice for further study as the sole baseline scenario.

On the other hand, SSP2, where social, economic, and technical tendencies do not deviate significantly from historical patterns, is perhaps the most representative of contemporary situations. The under-development RCP7.0 will correspond to the greenhouse gas values in the SSP2 baseline.

5.5 Practical application of the SSP, RCP and SPA scenarios in three different deltaic regions

This previous framework presented has been applied within the DECCMA (Deltas, vulnerability and Climate Change: Migration and Adaptation) project with the purpose of exploring migration and adaptation in three deltas across West Africa and South Asia: (i) the Volta delta (Ghana), (ii) the Mahanadi delta (India), and (iii) the Ganges-Brahmaputra-Meghna (GBM) delta (Bangladesh/India).

Climate change is, on one level, a global phenomenon that is the consequence of large-scale global processes linked to collective greenhouse gas emissions and the earth system's response to them. These processes, on the other hand, occur inside and have an influence on a variety of social and economic processes, such as markets.

DECCMA's project major goals are to:

- Analyze the efficacy of adaptation alternatives in deltas
- Examine migration as a means of adaptation in deltaic habitats under changing climates
- Provide policy support for long-term adaptation in deltaic areas.

This report will only focus on an in-depth look at the structure and approach presented by DECCMA, as the analysis of its results may be too complex.

Within and across the three deltas, the study includes assessments and comparisons of the implications of future climatic, environmental, and socio-economic changes in terms of:

- Short to medium-term (i.e., up to 2050) socio-economic impacts (e.g., on migration, well-being, and livelihoods)
- Long-term (i.e., up to 2100) biophysical changes (e.g., in river flows and nutrient
- Models of the consequences of sea-level rise over a very long-time horizon (beyond 2100) (e.g., area at risk of flooding)

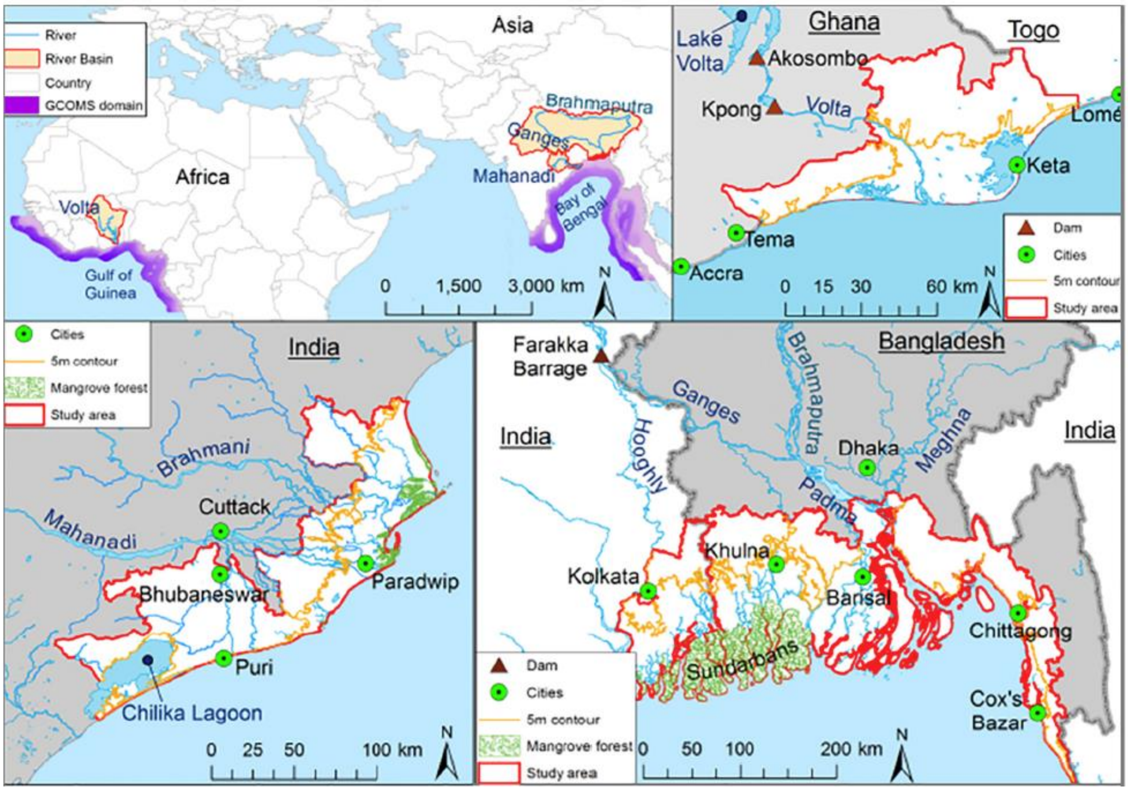


Figure 23. Location and main characteristics of the studied deltaic regions.

5.5.1. Global scenarios:

Greenhouse gas emissions (and therefore climate change) and socio-economic variables affecting the global economy are the most important elements at the global level.

In their analysis, they emphasize on the global RCP8.5 scenario in order to consider the strongest climatic signal in the late 21st century, as well as the highest atmospheric greenhouse gas concentrations. This maximizes the sampling of future climate change uncertainty and provides a demanding (but as said before, not adequate for modelling) scenario environment against which to evaluate the robustness of human and natural systems, as well as climate change adaption strategies.

DECCMA developed three SSP-based scenario narratives going up to 2050 that are compatible with the RCP8.5 climate scenario: Medium (SSP2), Medium– (SSP3), and Medium+ (SSP5).

The long-term biophysical assessment, which is more experimental in character and does not contain stakeholder-driven scenarios, focuses on a post-2050 analysis based on a mix of RCP8.5 and SSP5.

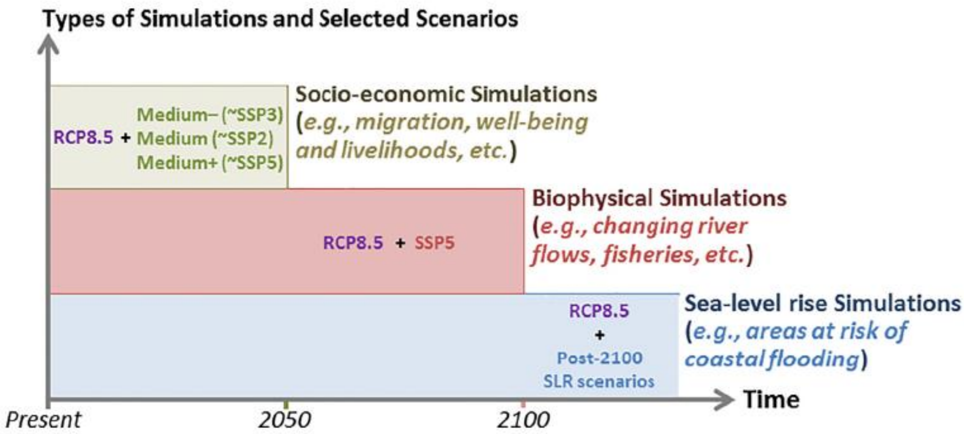


Figure 24. DECCMA SSP and RCP scenarios over the three respective time horizons

5.5.2. Delta scenarios:

There are endogenous and external environmental and socioeconomic change factors at the delta scale. Climate, environmental, and socioeconomic change factors that operate at higher/coarser geographical scales (e.g., national, regional, global) are exogenous drivers, as mentioned before. They determine the delta scale scenarios and adaptation policy narratives and trajectories' boundary conditions.

Local human-induced subsidence (e.g., owing to groundwater extraction), local political economy, and socioeconomic/ecological circumstances are examples of endogenous causes, whereas global climate change/sea-level rise, markets, and food prices are examples of mostly external forces. Regarding the four adaptation policy trajectories (SPAs) that are defined in the study:

SPA	Definition
Minimum intervention (MI)	Seeks to save expenses while safeguarding residents from the effects of climate change.
Economic capacity expansion (ECE)	Focuses on promoting economic growth and using the additional financial capacity that comes with it to safeguard the economy from climate-related damage.
System efficiency enhancement (SEE)	Focuses on encouraging the most effective management and exploitation of the present system, looking at methods to distribute labor, balance livelihood options, and best utilize ecological services to improve in the context of climate change.

System restructuring (SR)	In response to significant challenges to the delta's present socio-ecological system, embraces pre-emptive fundamental change to the delta system's social and physical functioning.

Table 7. SPAs defined in the study

The following figure explains the general conceptual framework, scenario matrix design, and method used to generate the different adaptation policy choices investigated.

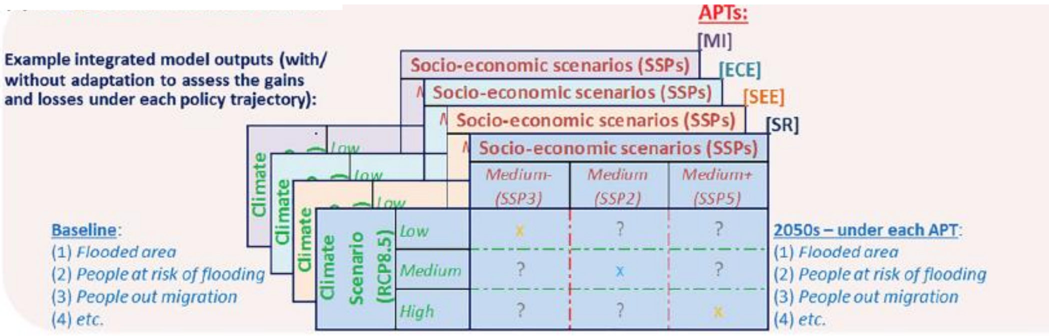


Figure 25. The overall scenario matrix architecture investigated in DECCMA.

6. Risks associated with the delta, analysis of coastal fringe hot spots and hazard map

As we commented in previous points, multiple factors, including relative sea level rise and human activity, are placing deltaic regions at danger, making them more vulnerable to natural disasters, such as storms, floods, etc.

A categorization based on the dominating processes is a classic technique of evaluating the condition of a delta. To do it, we will rely on following figure, presented by Galloway:

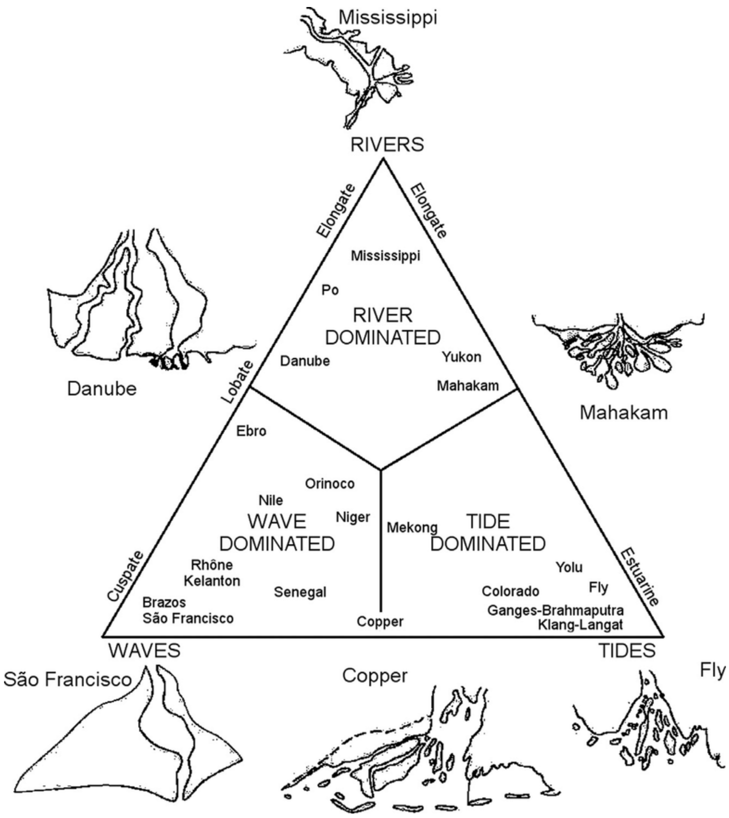


Figure 26. Delta classification by Galloway (1975)

The Ebro Delta was once thought to represent a transitional zone between river and marine dynamics. Because the Delta is located inside the Mediterranean Sea, the tides have always played a minor role in its development.

Fluvial impact, on the other hand, has been significantly diminished, therefore we'd locate it in a wave-dominated categorization. In the future, it is possible tide processes may have a significant impact on the Delta, due to RSLR.

To introduce this point, we will briefly comment on the main threats to which the delta is subject to:

6.1. Risks associated with the delta

6.1.1. Marine erosion

As we commented before, the decline in sediment contributions has resulted in a dynamic in which the action of the waves has become a decisive element in the shape and evolution of the Delta.

Nowadays, it is mostly influenced by the swell, which carries sediments from the shoreline and therefore defines the existence of erosive and accumulation zones, modifying the delta's structure.

The Delta's erosive processes can be categorized based on the time scale at which they occur (Sánchez-Arcilla et al., 1997):

6.1.1.1 Episodic events

Episodic occurrences, such as large storms, are linked with phenomena having a long return time. The coast's reaction to these occurrences is almost instantaneous.

6.1.1.2 Medium-term events

Longitudinal transport produced by the swell is the most common reason. It has a period of several years

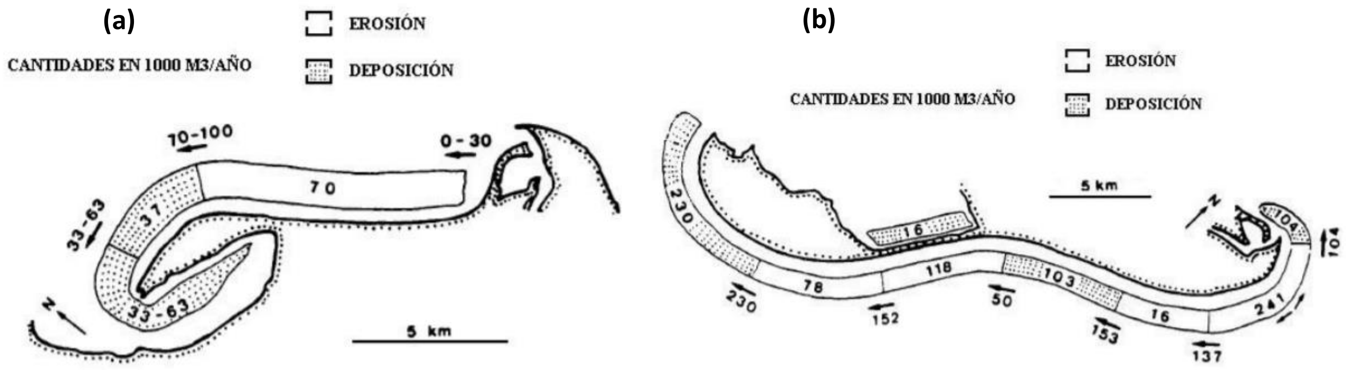


Figure 27. a) Sedimentary balance and longitudinal transport scheme in the medium term in the North hemidelta (Sánchez-Arcilla et al, 1997). B) Sedimentary balance and longitudinal transport scheme in the medium term in the hemidelta Sur (Sánchez-Arcilla et al, 1997).

6.1.1.3 Long-term changes

Represents the development of the Delta in every dimension, as well as the fluctuation in total sediment balance. The time scale is decades, and the agents that produce these changes include river sediment inputs, variations in relative sea level, and other factors.

6.1.2. Changes in sediment contributions

The volume of sediment reaching the Ebro Delta has decreased dramatically over the previous century, accounting for less than 1% of the solid flow before the building of major reservoirs in the basin.

The majority of the dams are in the upper stages of the bigger tributaries, where erosion is most severe, but those in the lower parts of the river, in the Delta, play a critical role. The retention of river sediments is crucial. The percentage of the drainage basin that is not impacted by dams is around 2.75 percent (Varela et al., 1986).

The existence of reservoirs has the greatest impact on sand-size particles. These are generally part of the background load, which consists of particles crawling down the river's bottom.

The following table shows the decrease in solid contributions from the Ebro River over the years:

Year	Author	$x10^6$ (t/year)	$x10^6$ (m^3/year)
1880	Gorría	25	10
1936	Carreras and Candi	17	6,8
1976-78	PIDU	2	0,8
1990	Nelson	6,2	2,48
1990	Jiménez et at.	0,107-0,263	0,043-0,105

Table 8. Decrease in solid contributions from the Ebro River over the years

Despite the current low levels of production, the source of sediment is a concern not only in terms of the volume of material it provides to the sea and the Delta's beaches, but also in terms of the distribution of that contribution. It presently results in an unbalanced distribution of sediments outside of the Delta, since almost all, if not all, of the sediments are dispersed in the northern hemidelta:

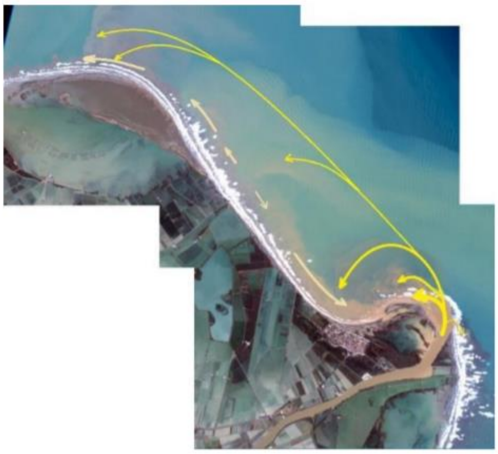


Figure 28. Sediment movements observed in the satellite image of February 23, 2020 (Source: ICGC)

6.1.3. Flood events

As previously stated in marine erosion (episodic events) section, episodic occurrences are those that have immediate consequences on the Delta's configuration and are typically triggered by large storms, where the effects of the waves and the meteorological tide combine to produce floods.

The Ebro Delta contains regions that are particularly vulnerable to storms that bring economic, social, and environmental damage. The fracture of the Trabucador bar is the most famous episodic occurrence connected to storms. Because to its low height (1.5m), the bar can be quickly swept away by the wave in rough circumstances.

On the 22nd of January this year, in relation to the storm Gloria, a recent occurrence that illustrates the relevance of floods in the morphology and evolution of the Ebro Delta took place. With waves of more than eight meters, the water advanced three kilometers inland, flooding 3,000 hectares, or about half of the Delta's surface area.

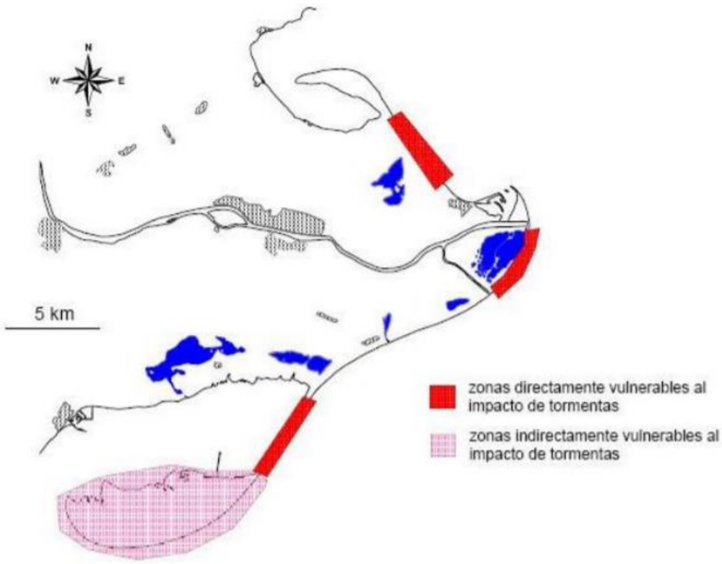


Figure 29. Areas most vulnerable to episodic storm events (Valdemoro, 2005).

6.1.4. Anthropogenic pressure

The Ebro delta is subjected to substantial anthropogenic pressure, which has a direct impact on its geomorphological and environmental structure. The irrigation canals of the Ebro and its tributaries, which can also help to reduce sediment flow from the river, are an issue connected with human activity in the delta's ecosystem. Heavy metals have been found in the prodelta sediments, which has been linked to pollution from the industrial sector.

6.1.5. Climate change

The following are examples of climate change pressures and their potential consequences on the coastal physical environment: a rise in sea level can result in flooding of emerging delta regions, coastal erosion, increased salt intrusion, and the loss of coastal wetlands.

Swell variations can cause major changes in coastal erosion processes, beach morphologies, and the operation and durability of marine defensive structures. The erosion of the shoreline associated with the rise in mean sea level is the most closely connected to climate change in the Delta.

6.2. Analysis of coastal fringe hot spots and hazard map

There is a higher need for action, which necessitates prioritizing in the measures to be taken and resources to be given for coastal risk mitigation. Because of the scarcity of resources, a transparent and comprehensive risk assessment procedure, including multiple levels of governance, is required.

A number of tools and approaches have been developed to assist decision-making processes, with the goal of better integrating various threats and impacts, increasing stakeholder involvement, and expanding the use of those tools through open-source methodologies and increased ease of use (Zanuttigh et al., 2014; Torresan et al., 2016a; Vafeidis et al., 2008).

Nowadays, the recently developed RISC-KIT project (Resilience Increasing Strategies for Coasts Toolkit) offers the Coastal Risk Assessment Framework (CRAF), a comprehensive and systematic methodology that involves a first assessment of impact and risk at the regional scale in order to identify so-called hotspots, which are defined as specific locations with the highest risk (on a scale of 1–10 km).

The first stage is analyzing storm-related risks in terms of flooding and erosion hazards associated with a certain likelihood of occurrence and their possible consequences along the shore, in order to identify sectors with higher risks than the surrounding areas.

This is accomplished by calculating a risk index, CI, along the coast, which is made up of two indicators: a hazard, i_h, and an exposure, i_{exp}.

$$CI_{hazard} = (i_h \cdot i_{exp})^{\frac{1}{2}} \qquad (1)$$

In our case, we divided our study area (Delta Ebro) into 13 sectors along the shore, which are the 13 different beaches at the delta: Punta de la Banya, Platja Trabucador, Platja Eucaliptus, Platja de la Platjola, Platja Serrallo, Platja del Migjorn, Platja del Buda, Platja Sant Antoni, Embarcador Riu Ebre, Platja Riumar, Bassa Arena, Platja Marquesa, Platja del Fangar.

In our case, we will obtain all the necessary data to identify the hot-spots from the *Llibre verd de l'Estat of the coastal area of Catalonia, 2010*. Now, each sector has been defined in terms of a representative beach profile. However, there are some sectors (or beaches), whose beach profile representation are not included in *Llibre Verd*. Is the case of Punta de la Banya, Platja de la Platjola and Platja Sant Antoni. Therefore, due to the lack of relevant data, we conducted a number of hotspots analyzes in 10 of the 13 sectors.

The magnitude of the flooding hazard was assessed by estimating the water level extreme climate along the coast and the extension of the area to be flooded. Storm surges in the area are relatively small (maximum recorded values up to 0.5 m) and thus, wave-induced runup, Ru, becomes the main contributor to water levels during storms (Mendoza and Jiménez, 2008). This parameter Ru is already given by *Llibre Verd* with a return period of $T_r = 10\ and\ 100\ years$:

Sectors	Wave climate – Hs with Tr=100 years (m)	Wave induced runup (Ru) with Tr=10 years (m)	Wave induced runup (Ru) with Tr=100 years (m)	Beach slope m
Platja Trabucador	7,39	2,36	3,44	0,06
Platja Eucaliptus	7,39	2,36	3,44	0,07
Platja Serrallo	7,39	2,12	2,73	0,06
Platja del Migjorn	7,39	1,27	1,63	0,06
Platja del Buda	7,39	1,27	1,63	0,06
Embarcador Riu Ebre	7,39	1,73	2,21	0,04
Platja Riumar	7,39	1,41	2,06	0,07
Bassa Arena	7,39	3,42	4,39	0,12
Platja Marquesa	7,39	1,15	1,48	0,05
Platja del Fangar	7,39	1,15	1,48	0,05

Table 9. Wave significant height and wave run up for each sector and a Tr of 10 and 100 years

Now, for the calculation of our hotspots, we will consider a return period of $T_r = 50\ years$. So, considering that the relationship between the wave runup and the probability of exceedance is linear, and interpolating we will obtain the following results:

$$y = y_1 + \frac{(y_2 - y_1)}{(x_2 - x_1)}(x - x_1) \qquad (2)$$

Sectors	Wave climate – Hs with Tr=100 years (m)	Wave induced runup (Ru) with Tr=50 years (m)	Beach slope m
Platja Trabucador	7,39	2.84	0,06
Platja Eucaliptus	7,39	2.84	0,07
Platja Serrallo	7,39	2.39	0,06
Platja del Migjorn	7,39	1.43	0,06
Platja del Buda	7,39	1.43	0,06
Embarcador Riu Ebre	7,39	1.94	0,04
Platja Riumar	7,39	1.70	0,07
Bassa Arena	7,39	3.85	0,12
Platja Marquesa	7,39	1.30	0,05
Platja del Fangar	7,39	1.30	0,05

Table 10. Wave run up for each sector and a Tr of 50 years

However, all of these previous values were calculated and obtained in 2010. 11 years have passed since then, and that's why, by using the data provided by *Puertos del Estado*, we will compute again the significant wave height for a return period of 100 years.

To obtain this value, first we will select the closest buoy to our region. In this case is the Tarragona`s buoy:

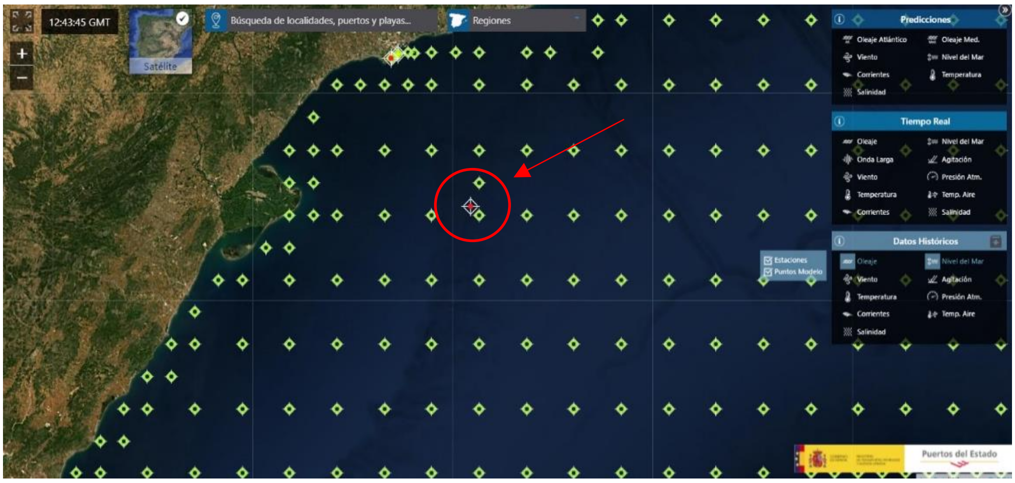


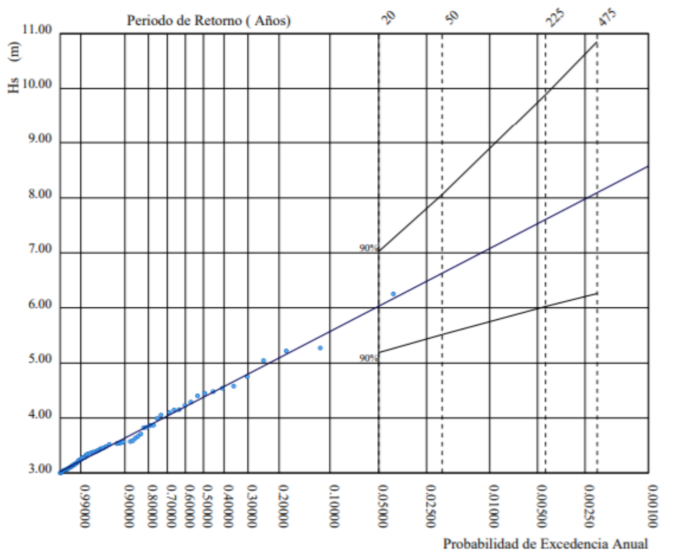
Figure 30. Tarragona's buoy – Puertos del Estado webpage

Once we have selected the corresponding buoy, we download the extreme wave climate data. An extreme wave regime is precisely a statistical model that describes the probability with which a storm of a certain height can occur. We obtain the following information, from a period between 2004-2017:

3. Resultados Escalares.

REGIMEN EXTREMAL ESCALAR DE OLEAJE

LUGAR :	Tarragona		
PARÁMETRO :	Altura Significante	SERIE ANALIZADA :	Ago. 2004 - Nov. 2017
PROFUNDIDAD :	688.0		



P. de Retorno (Años)	20.00	50.00	225.00	475.00
Estima Central de Hs (m)	6.03	6.63	7.61	8.09
Banda Sup. 90% Hs	7.02	8.06	9.89	10.86
Valor Esperado de Tp (s)	10.05	10.58	11.42	11.81
Prob. de Exc. en 20 Años	0.64	0.33	0.09	0.04
Prob. de Exc. en 50 Años	0.92	0.64	0.20	0.10

Figure 31. Extreme wave climate – Significant wave height

Therefore, as can be seen in the image above, we have a linear regression that relates the significant wave height and the exceedance probability. As stated previously, the return period we considered in this project is of 50 years. So, the corresponding significant wave height will be $\boldsymbol{H_s = 6,63\ meters}$.

Now, regarding the peak period, the data provided the following equation that relates these both parameters:

$$T_p = 3{,}74 \cdot H_s^{0{,}55} \qquad (3)$$

So, applying the equation 3 from above, we will obtain a peak period of $\boldsymbol{T_p = 10,58\ sec}$. Now that we have computed both parameters, significant wave height and peak period, we will be able to obtain the wave runup value.

Wave run-up is the sum of wave set-up and swash uprush and must be added to the water level reached as a result of tides and wind set-up. In our case, for waves collapsing on the beach, we will apply a first order-of-magnitude estimate which is given by the empirical formula of Hunt (1959):

$$R \sim \eta_u + H_s \cdot \xi \qquad (4)$$

Where η_u is the wave set-up, and can be approximated to:

$$\eta_u \sim 0{,}2 \cdot H_s \qquad (5)$$

And H_s is the significant wave height, and ξ is the surf similarity parameter:

$$\xi = \frac{tan\beta}{\sqrt{H_s/L}} = T \cdot tan\beta \cdot \sqrt{\frac{g}{2 \cdot \pi \cdot H_s}} \qquad (6)$$

Where:

- $L = \frac{g \cdot T^2}{2 \cdot \pi}$, is the offshore wave length
- $tan\beta = m$ is the beach slope
- T is the wave peak period

So, applying the equations above, we will obtain the wave runup produced by a wave height with a return period of 50 years:

$$R \approx 0{,}2 \cdot 6{,}63 + 6{,}63 \cdot 10{,}58 \cdot m \cdot \sqrt{\frac{9{,}81}{2 \cdot \pi \cdot 6{,}63}}$$

Now, applying the equation above we will obtain the following results:

Sectors	Wave induced runup (Ru) (m) – Llibre Verd	Wave induced runup (Ru) (m) – Puertos del Estado + Hunt
Platja Trabucador	2.84	3.37
Platja Eucaliptus	2.84	3.71
Platja Serrallo	2.39	3.37
Platja del Migjorn	1.43	3.37
Platja del Buda	1.43	3.37
Embarcador Riu Ebre	1.94	2.69
Platja Riumar	1.70	3.71
Bassa Arena	3.85	5.41
Platja Marquesa	1.30	3.03
Platja del Fangar	1.30	3.03

Table 11. Wave run up with a Tr of 50 years from Llibre Verd and Puertos del Estado

Now, in order to have a single wave runup value, we will consider the second result obtained (*Puertos del Estado* and Hunt expression) as twice as significant as the *Llibre Verd* value, due to being computed with recent data:

$$Ru_f = \frac{1}{3} \cdot Ru_1 + \frac{2}{3} \cdot Ru_2 \quad (7)$$

We obtain the following results:

Sectors	Wave induced runup (Ru) (m)
Platja Trabucador	3.19
Platja Eucaliptus	3.42
Platja Serrallo	3.04
Platja del Migjorn	2.72
Platja del Buda	2.72
Embarcador Riu Ebre	2.44
Platja Riumar	3.04
Bassa Arena	4.89
Platja Marquesa	2.45
Platja del Fangar	2.45

Table 12. Final wave run up value with a Tr of 50 years

The extension of the area to be potentially flooded along the coast will be determined and calculated using both the beach profile topography, provided by *Llibre Verd*, and an ArcGIS model.

Estimating the equivalent shoreline retreat during the storm's effect in each sector along the coast, was used to determine the severity of storm-induced erosion danger. This was accomplished by the use of the Vellinga model (1986).

It's one of the most well-known approaches is the erosion profile, which uses an empirical study of large-scale laboratory experiments and data fields to forecast the form of the "erosion profile" after a storm passes. Due to lack of significant data, we will not be using more complex models which take into account other parameters as storm duration. The profile of erosion will be determined by the following equation:

$$\Delta x = 250 \cdot \left(\frac{H_s}{7{,}6}\right)^{1{,}28} \cdot \left(\frac{0{,}0268}{w}\right)^{0{,}56} \qquad (8)$$

Where, H_s is the significant wave height, Δx storm erosion cross-shore reach and w the speed of sediment fall. Now, regarding the value of w, we will apply the Owens equation:

$$w = k\sqrt{d \cdot (\rho_s - 1)} \qquad (9)$$

Where:

- w: falling/sedimentation speed, in m/s
- d: particle diameter, in m
- ρ_s: specific weight, in g/cm^3
- k: constant that varies according to the shape and nature of the grains, in our case with a value of 9,35

From *Llibre Verd* we are able to obtain all the necessary data:

Sectors	Particle diameter d (mm)	Specific weight (g/cm^3) (fine wet sand)	Falling speed (m/s)
Platja Trabucador	0,225	1,8	0.125
Platja Eucaliptus	0,226	1,8	0.126
Platja Serrallo	0,229	1,8	0.127
Platja del Migjorn	0,225	1,8	0.125
Platja del Buda	0,200	1,8	0.118

Embarcador Riu Ebre	0,183	1,8	0.113
Platja Riumar	0,190	1,8	0.115
Bassa Arena	0,208	1,8	0.121
Platja Marquesa	0,203	1,8	0.119
Platja del Fangar	0,203	1,8	0.119

Table 13. Granulometric information

Later, the extension of the area to be potentially eroded along the coast will be determined and calculated using the beach profile topography.

The next stage is to calculate the value of related hazard indicators, i_h, based on the probability distributions of storm-induced risks along the shore. This is accomplished by picking the danger magnitude linked with the analysis' target probability and ranging them from 0 to 5 on the scale shown in the following table:

i_h		Hazard	
		Erosion	Flooding
		Beach width after erosion (m)	Flooding extension (m)
5		Beach fully eroded	> beach width + 60 m
4		$W<\Delta X_{10}$	< beach width + 60 m
3		$\Delta X_{10} < W < 2\Delta X_{10}$	< beach width + 40m
2		$2\Delta X_{10} < W < 3\Delta X_{10}$	< beach width + 20m
1		$3\Delta X_{10} < W < 4\Delta X_{10}$	< 100% beach width
0		$4\Delta X_{10} < W < 5\Delta X_{10}$	< 50% beach width

Table 14. Hazard scales for erosion and flooding along the Ebro Delta coast as a function of the remaining beach width (W) after storm impact and extension of the flooding respectively $<\Delta X_{10}$ corresponds to the storm reach associated to a return period of 10 years.

However, we will leave the computation of the hazard indicators for later, as it requires the use of complex software as ArcGIS and other calculations.

Following the approach given in Viavattene et al., 2018, exposed values sensitive to the impacts of storm-induced hazards were defined in order to estimate the "consequences" component of the risk. To accomplish so, an exposure indicator (i_{exp}) was developed that took into account five categories of receptors: land use (i_{exp-LU}), population (i_{exp-SV}), transportation systems (i_{exp-TS}), key infrastructures (i_{exp-UT}), and business settings (i_{exp-BS}). It is provided by the following equation:

$$i_{exp} = \left(i_{exp-LU} \cdot i_{exp-SV} \cdot i_{exp-TS} \cdot i_{exp-UT} \cdot i_{exp-BS}\right)^{\frac{1}{5}} \qquad (10)$$

However, as the expression below is quite complex and it requires a large amount of data that we do not have, we will simplify the formula as follows:

$$i_{exp} = \left(i_{exp-LU} \cdot i_{exp-TS} \cdot i_{exp-BS-UT}\right)^{\frac{1}{3}} \qquad (11)$$

So, i_{exp-LU} assesses the relevance of the many types of land uses that may be impacted, i_{exp-TS} identify whether or not a transportation network exists and how important it is and the last self-made index $i_{exp-BS-UT}$ which takes into account the presence and importance of business as well as the utility of the sector/beach itself.

Exposure indicators	**Consequences**				
	1 **Inexistent or very low**	**2** **Low**	**3** **Moderate**	**4** **High**	**5** **Very high**
i_{exp-LU}	Barren Riparian buffer/wetland Grassland	Forest Urban green	Beach and dune Cropland	Campsite Industrial	Urban
i_{exp-TS}	No significant	Local road	National road	Coastal railway	National road + coastal railway
$i_{exp-BS-UT}$	No significant	Mainly local and small	Moderate of local/ regional importance	High dense/multiple utilities and business of local/regional importance	High dense/multiple utilities and business of national/international importance

Table 15. Each component of the exposure indicator is assigned a value using a scale.

Now, in order to quantify each indicator for each sector, we will use the Google Maps application. In this way, it's quite easy to identify each element for every sector. The exposure limit is computed on a 100-meter area landwards of the beach.

But before continuing, we must present graphically the area of study, divided in the 10 different sectors to be analyzed:

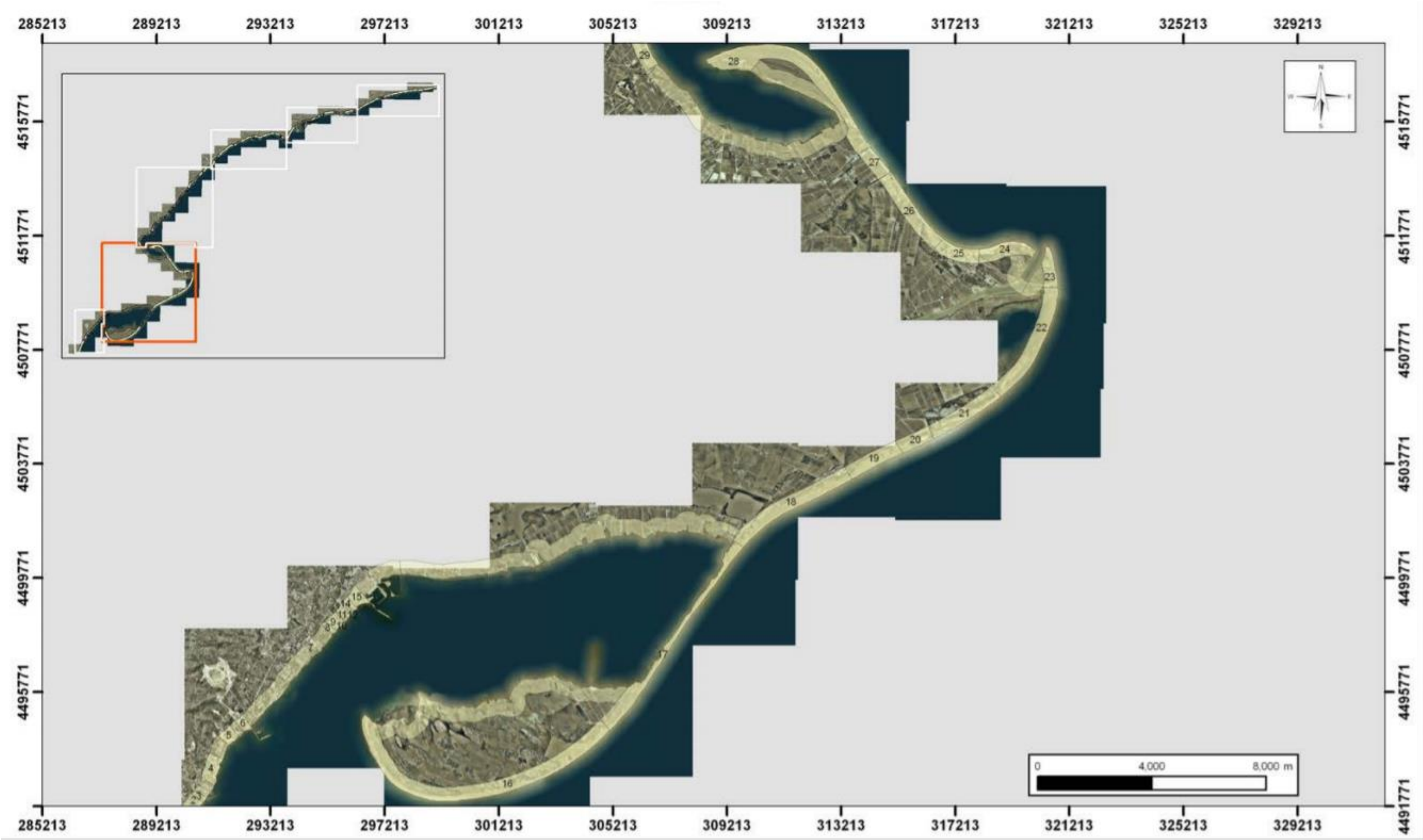


Figure 32. Delta del Ebro divided in 13 sectors/beaches

Figure 33. Each numbered sector of the Ebro Delta

For the calculation and decision of the exposure index for each sector in the region, the time factor will not be taken into account. Therefore, the value awarded will remain constant throughout the analysis. In this way, the SSP and RCP scenarios will not be taken into account in this part of the work, as they will only be considered in the calculation of the hazard index.

Sectors	**Exposure indicators**			
	i_{exp-LU}	i_{exp-TS}	$i_{exp-BS-UT}$	i_{exp}
Platja Trabucador	3 (beach zone)	1 (unpaved road)	5 (only access to Punta de la Banya sector)	2,46
Platja Eucaliptus	5 (urbanization, camping and apartments)	2 (local road TV-3451)	3 (Moderate importance)	3,10
Platja Serrallo	3 (beach zone + cropland)	1 (no significant roads)	2 (Low importance)	1,81
Platja del Migjorn	3 (beach zone + natural park)	1 (no significant roads)	4 (Mouth of the Migjorn river)	2,29
Platja del Buda	3 (beach zone + natural park)	1 (no significant roads)	5 (only protection of Malecó de la Crevera lake)	2,46
Embarcador Riu Ebre	3 (beach zone)	1 (no significant roads)	5 (Mouth of the Ebro River)	2,46
Platja Riumar	5 (urbanization, camping and apartments)	1 (no significant roads)	4 (High importance)	2,71
Bassa Arena	3 (beach zone + natural park+ cropland)	1 (no significant roads)	2 (Low importance)	1,81
Platja Marquesa	3 (beach zone + cropland)	2 (local road TV-3451)	2 (Low importance)	2,29
Platja del Fangar	3 (beach zone + natural park)	1 (no significant roads)	2 (Low importance)	1,81

Table 16. Exposure index for each sector

Now, in the following page the map of the Delta del Ebro region divided in each sector with the previously computed exposure index:

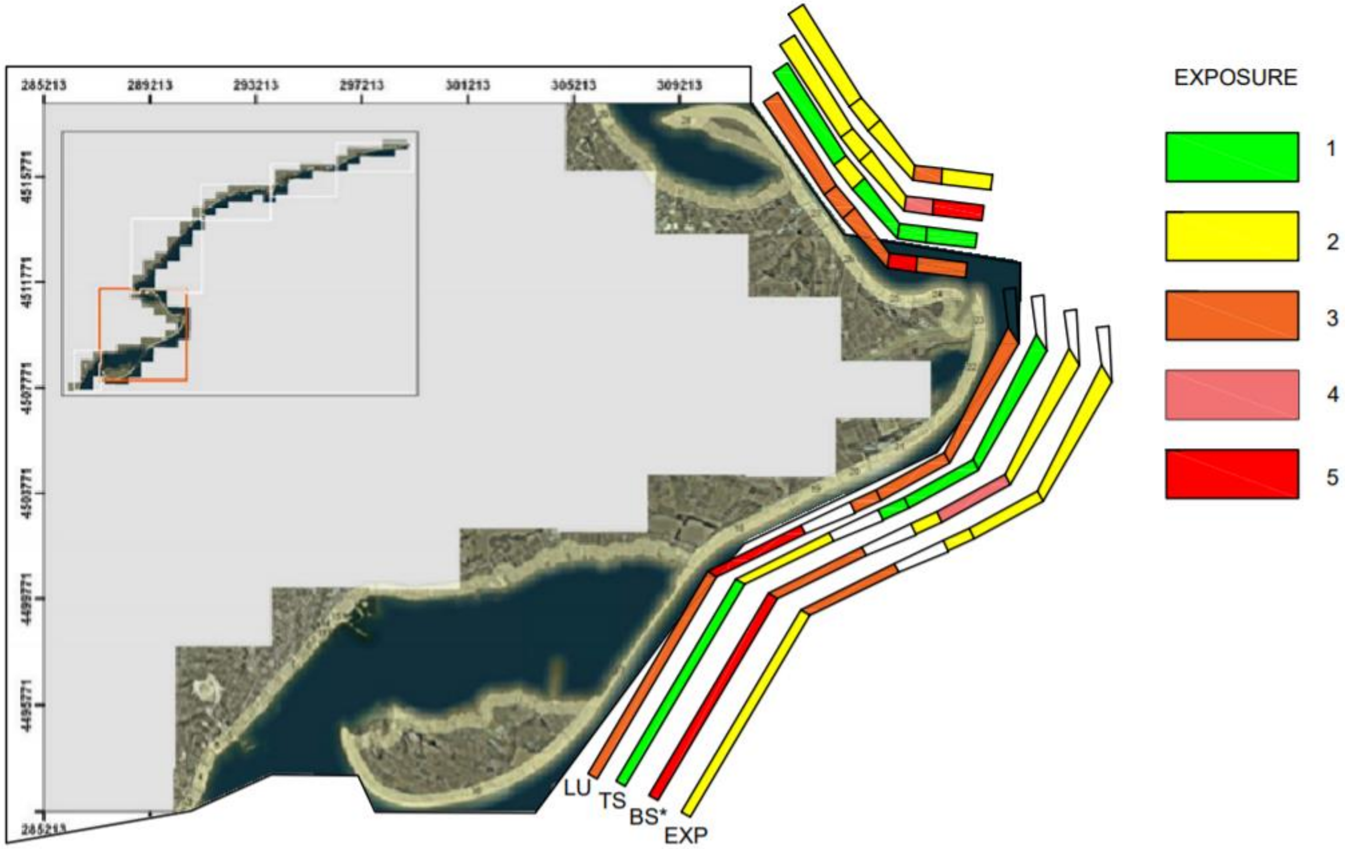


Figure 34. Exposure indicator and contributing components along the Ebro Delta

Once we have calculated the exposure indices for the different sectors into which the delta has been divided, the next step is to calculate the flooding and erosion indices.

6.2.1 Flooding index and RSLR computation

As said previously, we have considered both the data from *Llibre Verd* and *Puertos del Estado* and Hunt equation to calculate the runup value for hazards with a return period of 50 years.

Once we have done it (see Table 12), we must determine the flooding extension caused by the hazard. Therefore, it depends on the area that the event reaches, it will be classified from 1 to 5, going from less intensity to greater.

In order to quantify this flooded area in a simplified way, we will use the ArcGIS software and the DEM (digital elevation models) data provided by the National Cartographic and Geological Institute. In addition to the runup calculation, it will be calculated with the same ArcGIS model how the sea level rise (for each scenario considered) will affect the deltaic region.

In this case, and unlike before, we will take into account the different future SSP and RCP scenarios. As seen in previous points, different RCP scenarios lead to different environmental outcomes. In our case, we will focus on the impact on sea level.

In the event that humanity takes a course similar to that set out in the SSP3 or SSP5 scenario, the RCP 8.5 concentration pathway will be followed. In this way, the sea level in the year 2100 will be significantly increased. On the other hand, if the humanity takes a course similar to that set out in the SSP1, the RCP 2.6 concentration pathway will be followed, which will result in a much smaller increase than in RCP 8.5. The following figure represents the future sea level for each representative concentration pathway:

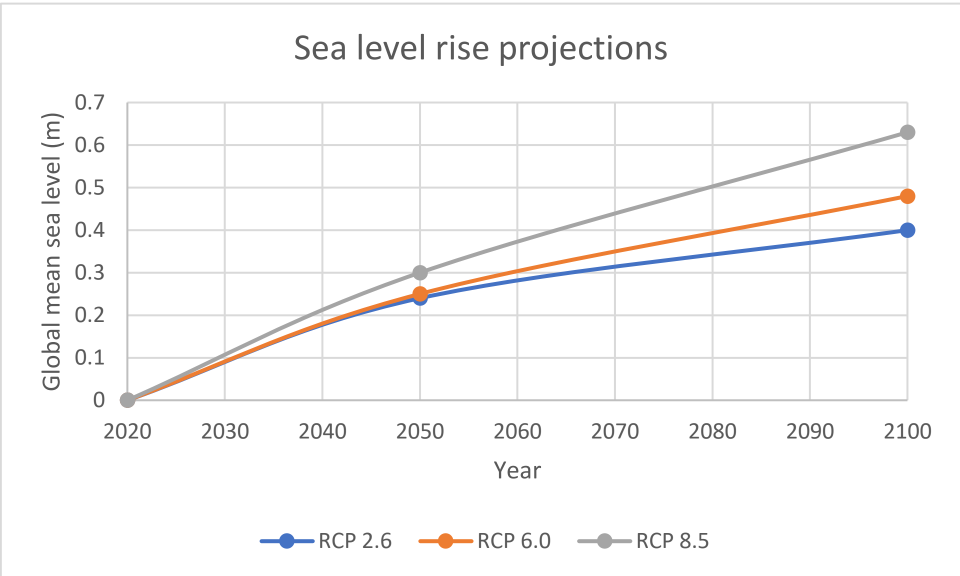


Figure 35. Sea level rise projections for each scenario

So, for our project we will calculate the relative sea level rise for different scenarios and in different years: 2021, 2035, 2050, 2075 and 2100. Now, regarding the socioeconomic scenarios, we will consider the following:

- The first case in which humanity follows the guidelines established by the SSP5 scenario, achieving an emission level of RCP 8.5
- The second case in which humanity follows the guidelines established by the SSP2 scenario (historical evolution), achieving an emission level of RCP 6.0.
- the third case in which humanity follows the guidelines established by the SSP1 scenario (historical evolution), achieving an emission level of RCP 2.6

Once the work system has been established, we will use the DEM data and the ArcGIS model to achieve the desired results. As the computation of 10 different models for each sector would be quite complex and time consuming, we are going to simplify it by encompassing the entire Ebro Delta region. In this project we will explain briefly the procedure to obtain the flooded area:

- First the download in DEM (digital elevation model) format of the entire sector in question. Notice that we selected the maximum resolution of 2x2 in order to obtain more detailed results:

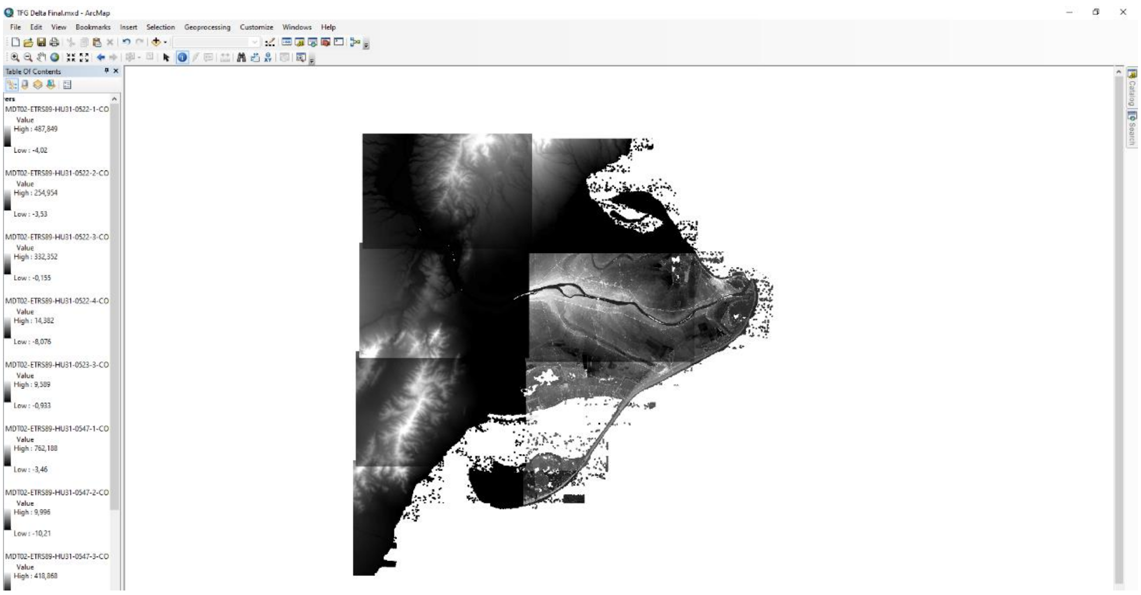


Figure 36. DEM data of Ebro Delta

The second step consists of obtaining the orthophotos of the study region, also provided by the National Geological Institute. These new images will be used only for aesthetic reasons, as in the raster maps the different areas cannot be differentiated.

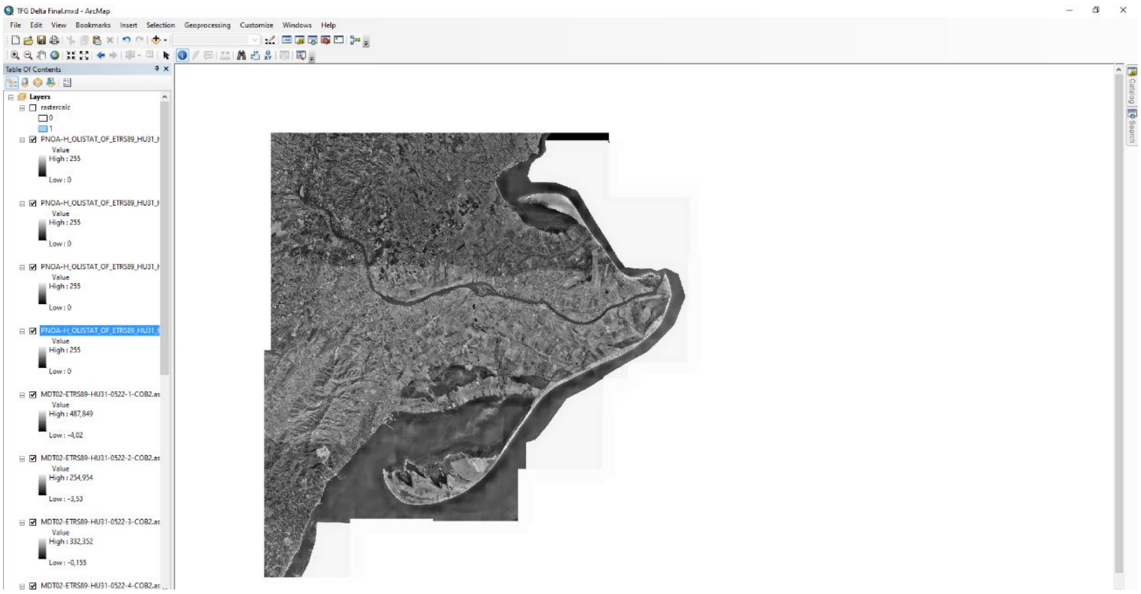


Figure 37. Orthophotos of the Ebro Delta

The third step will consist in the creation of a new raster map that will separate the flooded area (represented with number 1 value) and the area that will remain emerged (represented with number 0 value). To do it, it will require Spatial Analyst Tool -> Map Algebra -> Raster Calculator. Here, we must select the limit height that will divide the two zones, thus representing the rise in sea level. Refining the details and properties, we will obtain the following map:

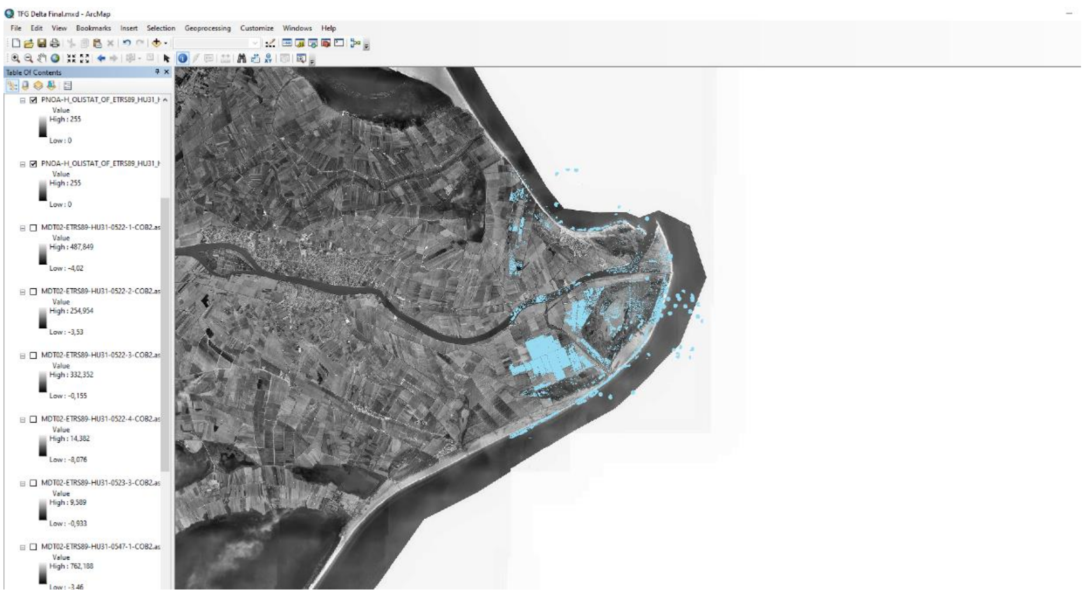


Figure 38. Flooded area due to an SLR of 0,16 meters

Notice that this procedure must be done with all the 9 raster maps that compose our deltaic region.

Finally, the last step would be to eliminate isolated flooded areas that are not directly connected to the coastline hydrologically. We will say that's an anomaly, and in order to get rid of that we will convert the raster that we have reclassified into a polygon vector file, which will then let us edit more easily.

Below, the maps made with the ArcGIS model for each scenario and each year of study:

RCP 8.5

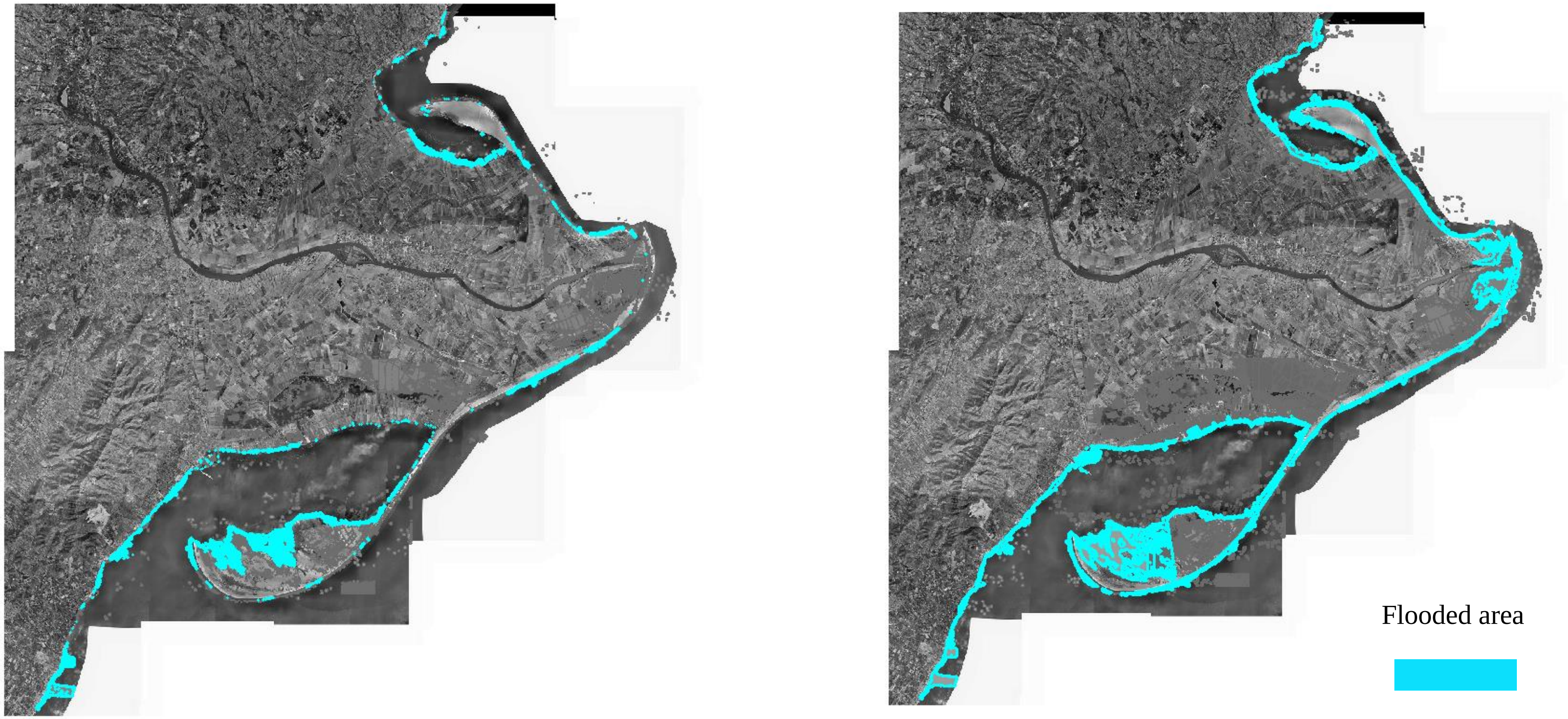


Figure 39. a) Coastal flooding, Ebro Delta region, RCP 8.5 scenario, year 2035 – RSLR of 0,16 m. b) Coastal flooding, Ebro Delta region, RCP 8.5 scenario, year 2050 – RSLR of 0,30 m

RCP 8.5

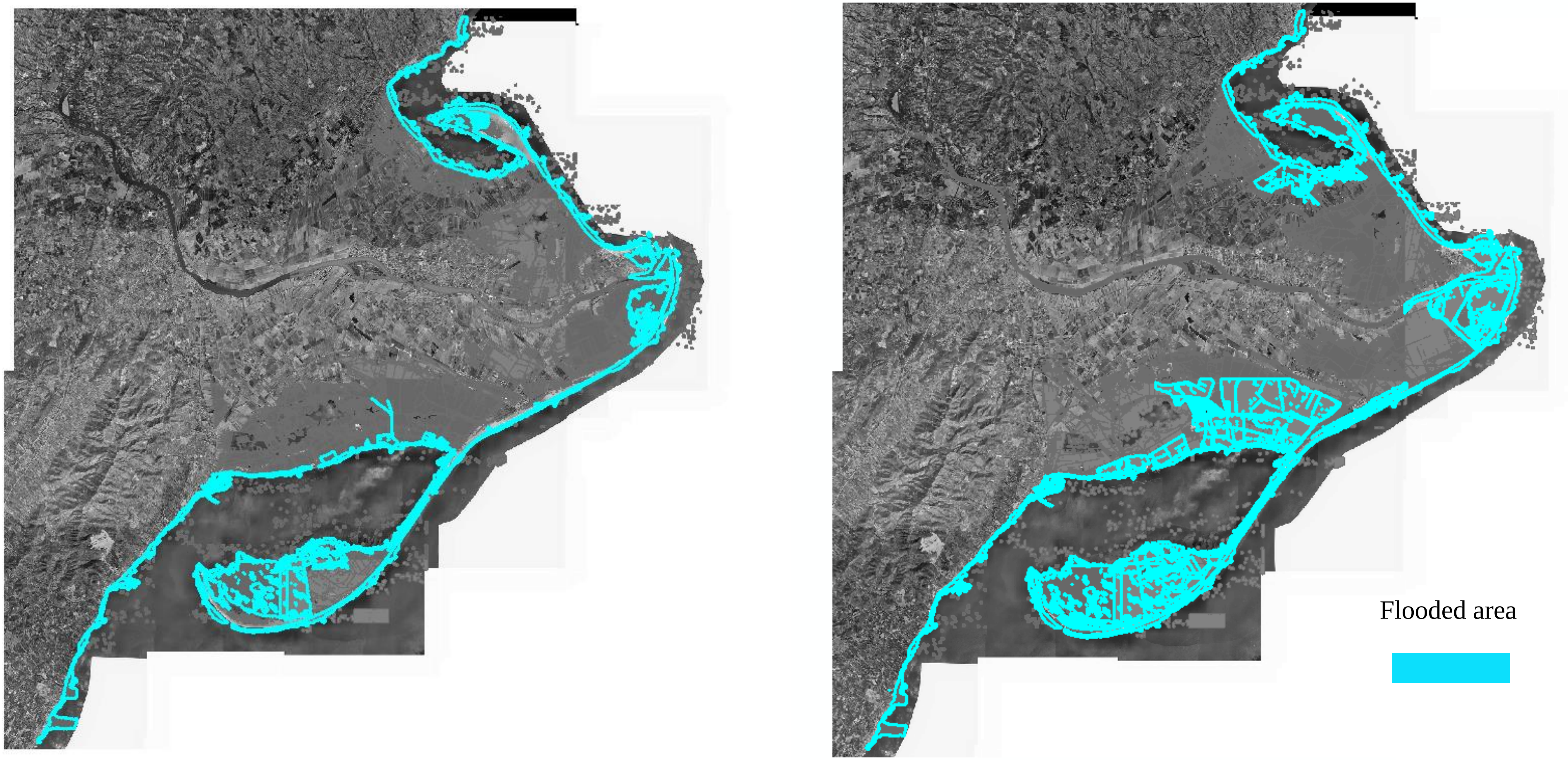


Figure 40. a) Coastal flooding, Ebro Delta region, RCP 8.5 scenario, year 2075 – RSLR of 0,47 m. b) Coastal flooding, Ebro Delta region, RCP 8.5 scenario, year 2100 – RSLR of 0,63 m

RCP 6.0

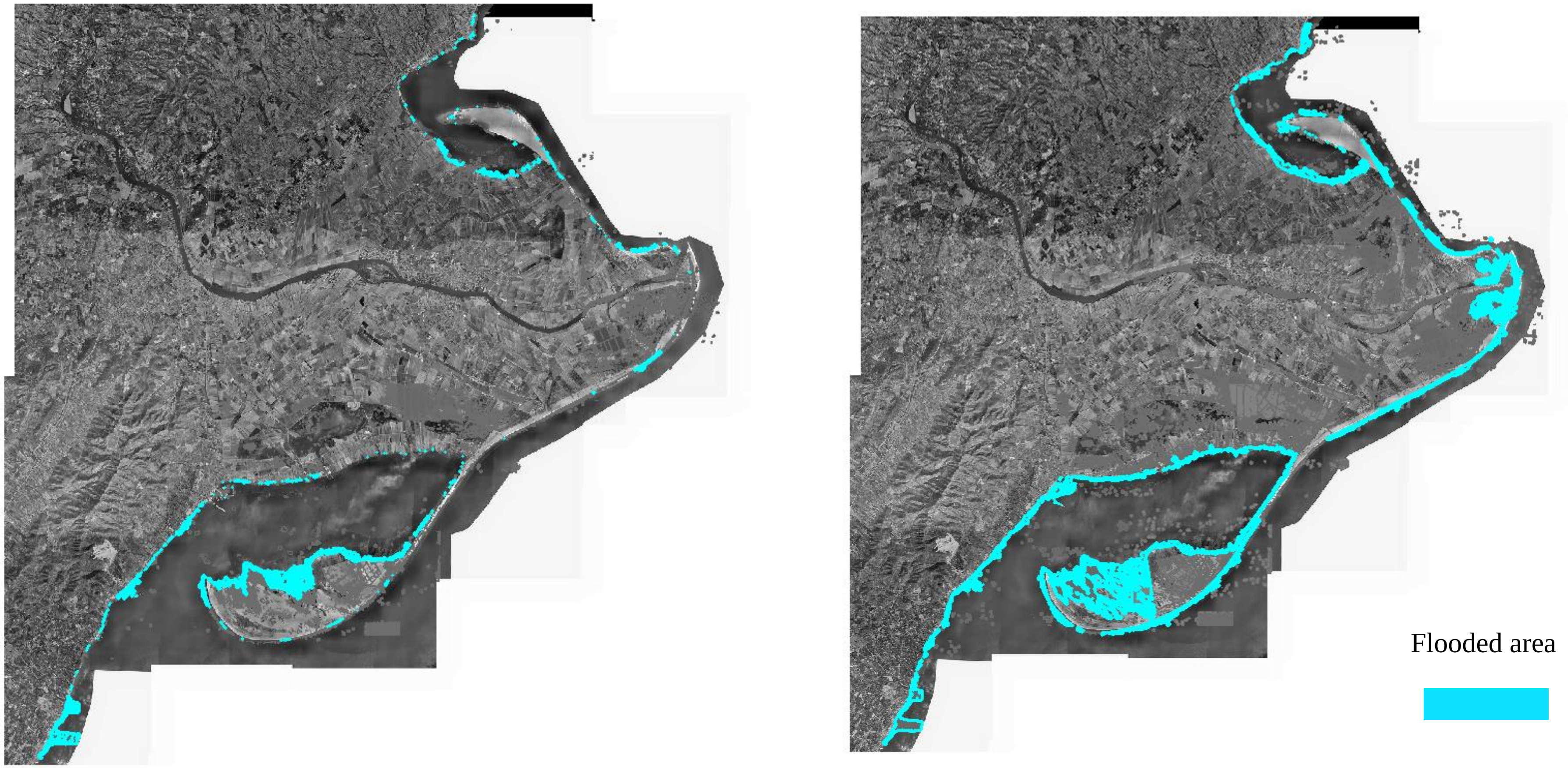


Figure 41. a) Coastal flooding, Ebro Delta region, RCP 6.0 scenario, year 2035 – RSLR of 0,13 m. b) Coastal flooding, Ebro Delta region, RCP 6.0 scenario, year 2050 – RSLR of 0,25 m

RCP 6.0

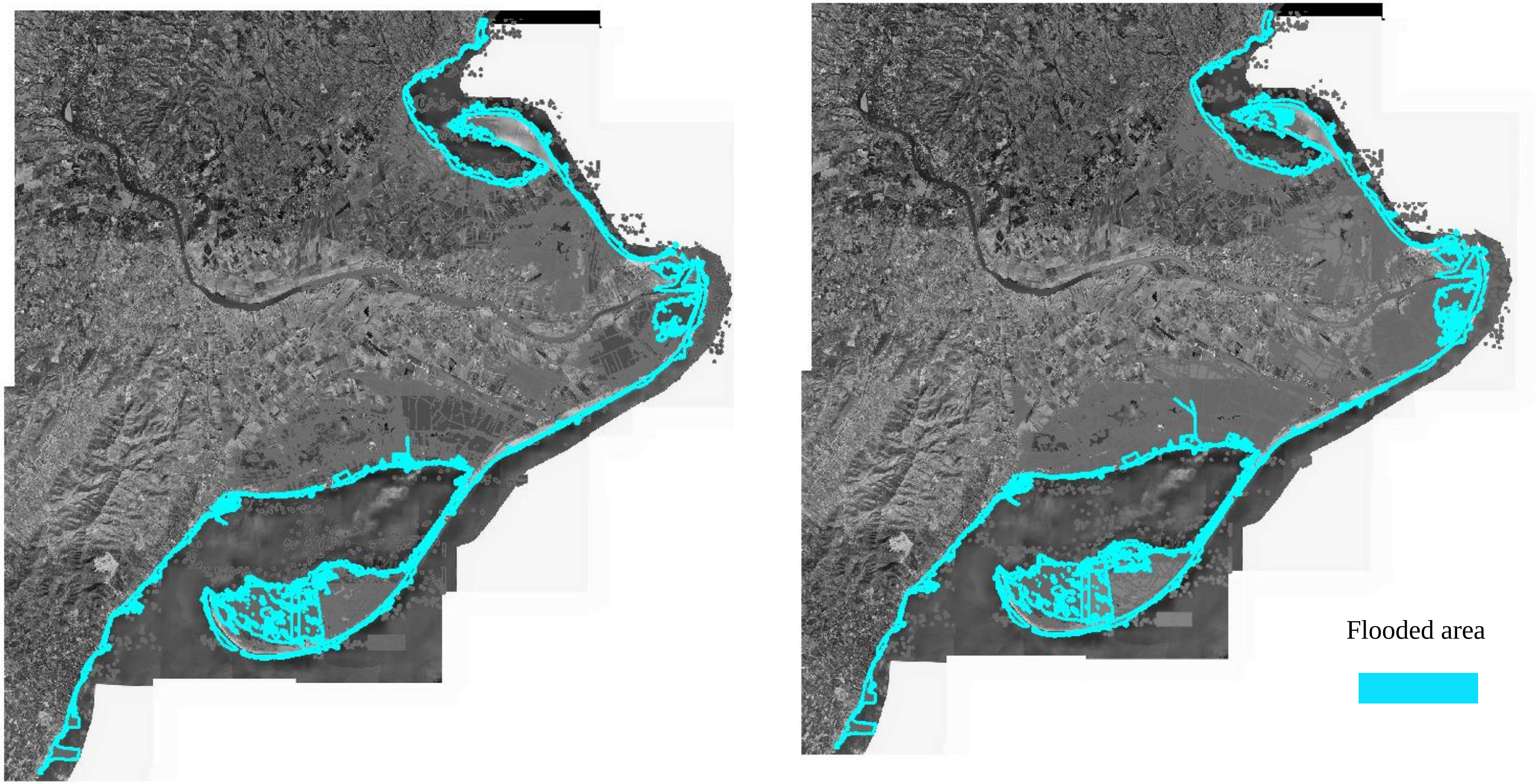


Figure 42. a) Coastal flooding, Ebro Delta region, RCP 6.0 scenario, year 2075 – RSLR of 0,38 m. b) Coastal flooding, Ebro Delta region, RCP 6.0 scenario, year 2100 – RSLR of 0,48 m

RCP 2.6

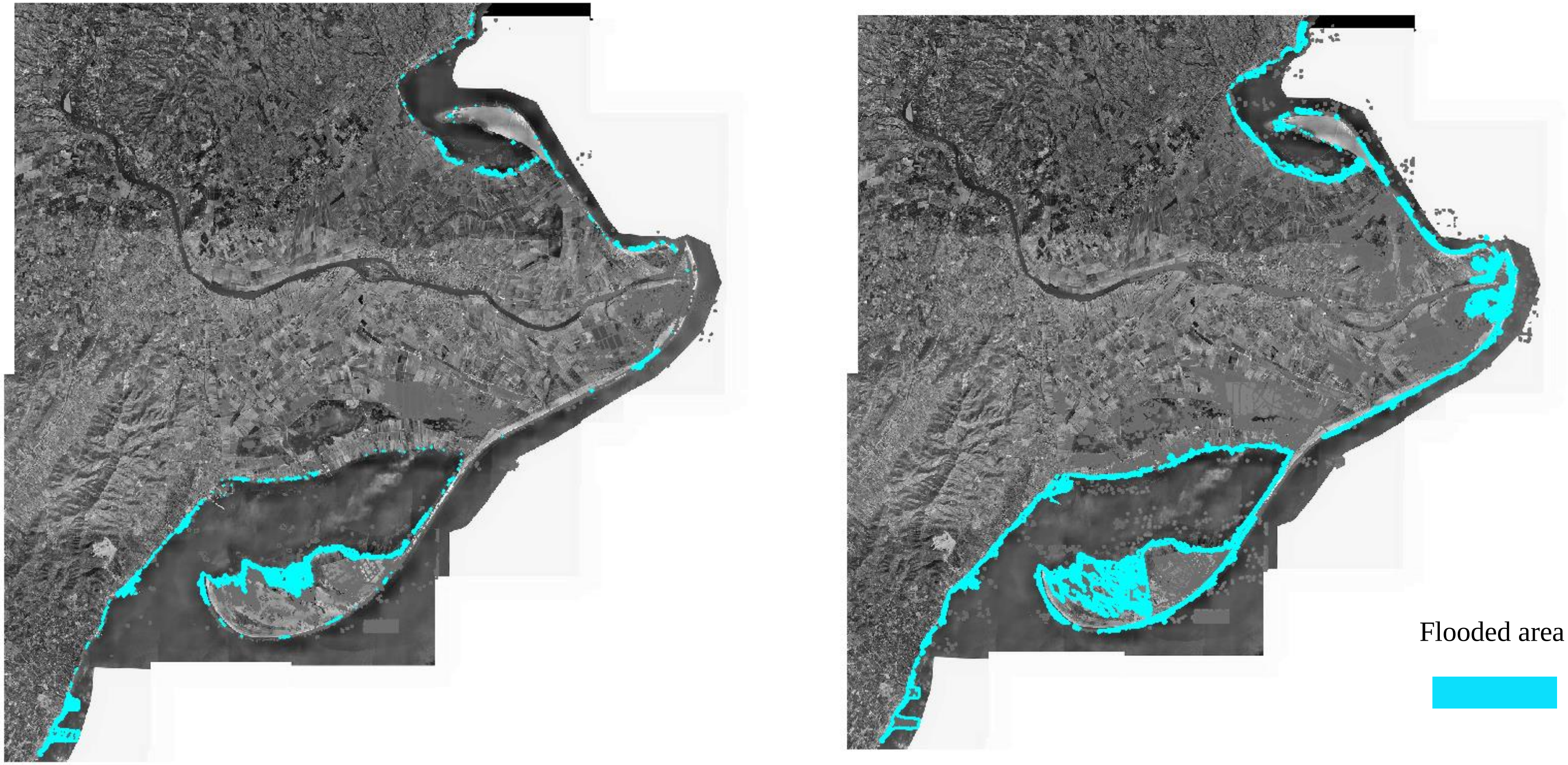


Figure 43. a) Coastal flooding, Ebro Delta region, RCP 2.6 scenario, year 2035 – RSLR of 0,125 m. b) Coastal flooding, Ebro Delta region, RCP 2.6 scenario, year 2050 – RSLR of 0,24 m

RCP 2.6

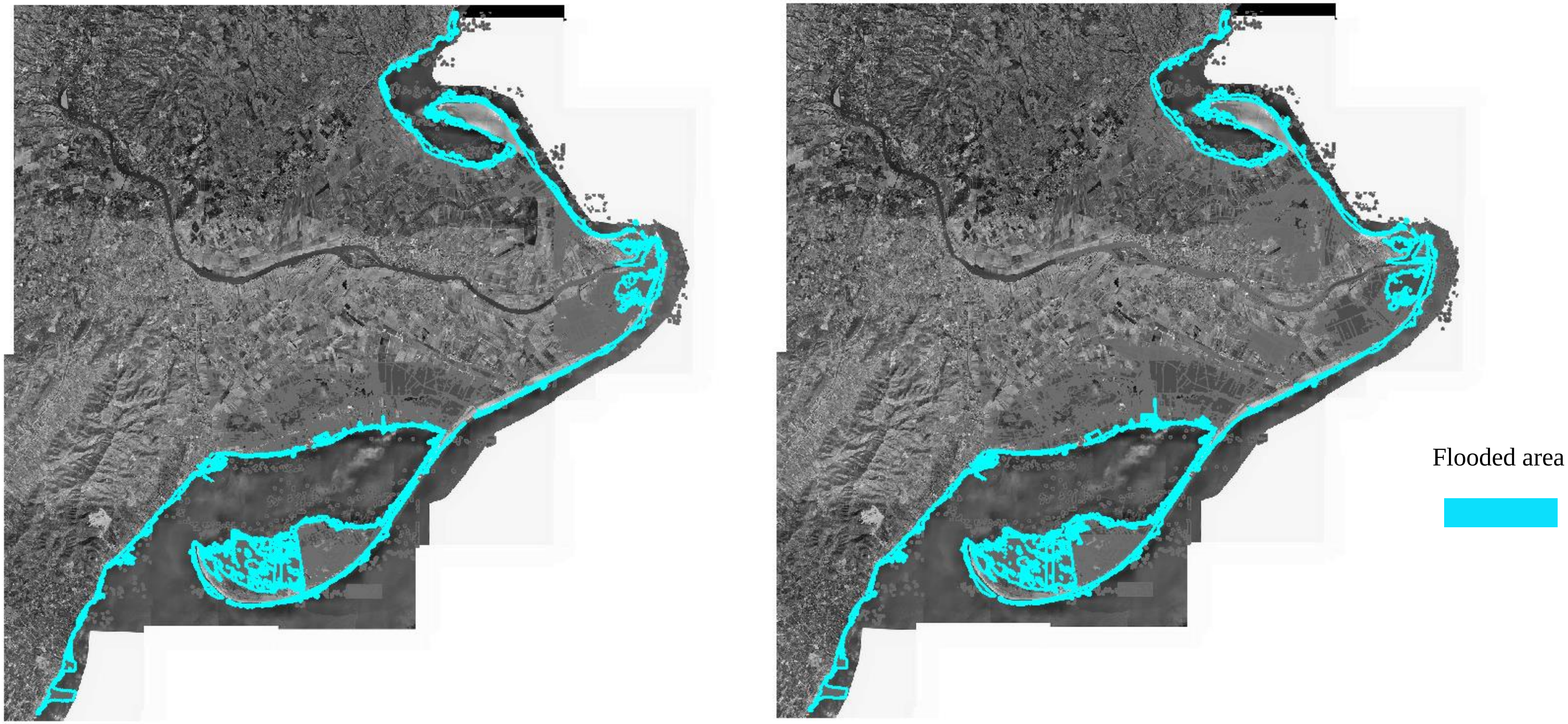


Figure 44. a) Coastal flooding, Ebro Delta region, RCP 6.0 scenario, year 2075 – RSLR of 0,32 m. b) Coastal flooding, Ebro Delta region, RCP 6.0 scenario, year 2100 – RSLR of 0,40 m

As can be seen in the previous images, most of the delta's coastal fringe is very vulnerable to rising sea levels. This fragility is more accentuated at the end of the century (year 2100) and in unfavorable climatic scenarios (RCP 8.5). The areas that would be most affected would be Badia dels Alfacs and the interior of Punta de la Banya, the urbanization of Poble Nou, the Illa de Buda and the urbanization of Riumar.

Once we have finished modeling the impact of sea level rise in our study area, we will continue with the effect of the runup produced by the waves during a hazard with a return period of 50 years. As we have seen previously, for each sector/beach we had different runups, but for the computation of the hazard map we will need a single value. The best option could be to consider the length of each sector in order to obtain a more detailed result, but in this case the average of the ten values will be chosen:

Sectors	Wave induced runup (Ru) (m)	Mean wave induced runup (Ru) (m)
Platja Trabucador	3.19	3,03
Platja Eucaliptus	3.42	
Platja Serrallo	3.04	
Platja del Migjorn	2.72	
Platja del Buda	2.72	
Embarcador Riu Ebre	2.44	
Platja Riumar	3.04	
Bassa Arena	4.89	
Platja Marquesa	2.45	
Platja del Fangar	2.45	

Table 17. Mean wave induced runup for the entire Ebro Delta

We obtain the following results:

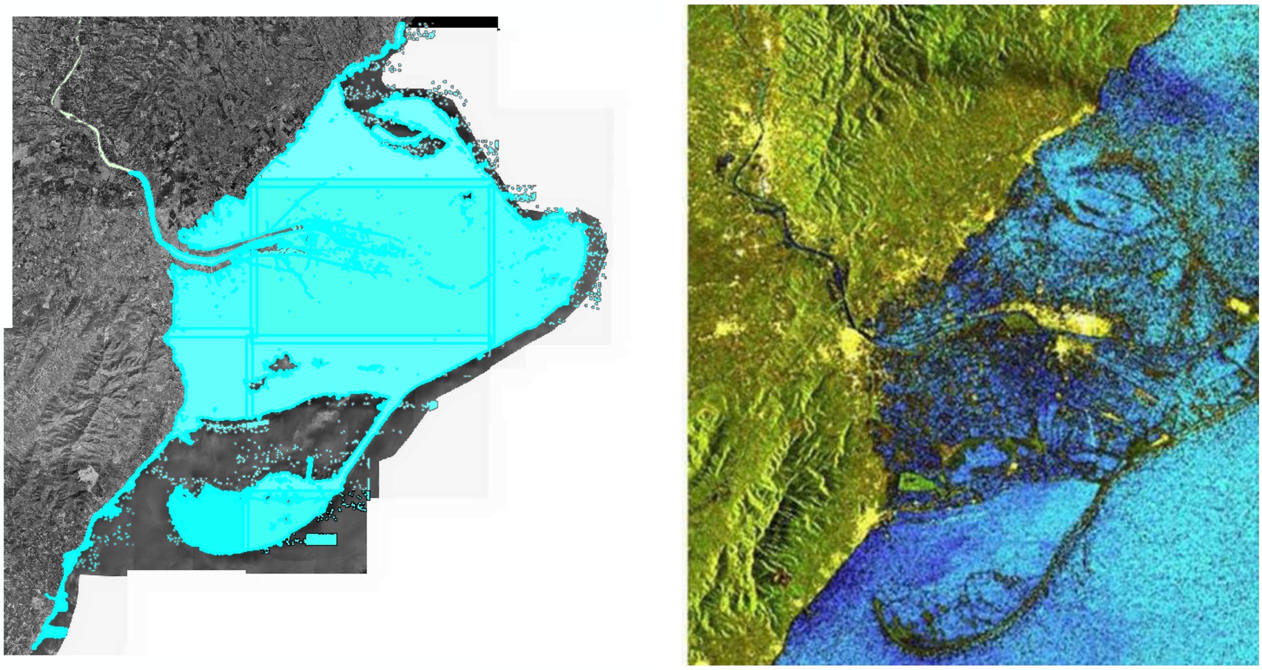


Figure 45. a) Flooding produced by a hazard-wave runup action with a return period of 50 years b) Flooding produced by the Gloria hazard in early 2020 with a return period of 50-300 years

Therefore, as can be seen in the result and comparing side by side with a storm of similar intensity, the results of both cases are practically the same, the complete (or almost complete) flooding of the deltaic region of the Ebro Delta.

In the calculated model, practically no small area remains emerged, whereas in the real case, certain areas could be observed above the water level, such as parts of Platja del Trabucador, Punta de la Banya and certain central parts of the region. This may be due to the difficulty of modeling the runup effect of the incident waves in our area.

Therefore, we can conclude by stating that the prediction of our model, despite being very close to reality, tends to overestimate the damage caused / sectors flooded. Furthermore, if we return to the table 14, we can see how all sectors of the region would rate their flood index with a maximum value of 5. This is due to two reasons:

1- The entire deltaic region of the Ebro Delta is located a few meters above sea level (the causes of this problem have been explained above), which makes it a very vulnerable area to a rise in the sea level and to the effect of the waves during a hazard.

2- The classification chosen to differentiate the values of the flood index is based on a previous analysis of the coast of the province of Barcelona (J.A. Jiménez et al., 2018), which includes the Tordera Delta. Therefore, in a wider and more varied region, a certain variety of values may be observed, unlike in our case.

Sectors	Hazard indicators
	$i_{flooding}$
Platja Trabucador	5
Platja Eucaliptus	5
Platja Serrallo	5
Platja del Migjorn	5
Platja del Buda	5
Embarcador Riu Ebre	5
Platja Riumar	5
Bassa Arena	5
Platja Marquesa	5
Platja del Fangar	5

Table 18. Flooding indicator for each sector

6.2.1. Erosion index computation

Once the flood indicator and the impact of the rising sea level have been calculated for each sector, the last step will consist of calculating the erosion index. For this, two tools will be used, the profiles of the different beaches and the Vellinga formula previously raised.

In this case, the significant wave height considered will have a return period of 10 years to be able to classify each sector. Notice that this information is provided by *Llibre Verd*. As previously the sediment fall rate *w* has been determined, we will have all the necessary data to calculate the erosion in each area:

Sectors	H_{s10} (m)	Falling speed *w* (m/s)	Beach width (m)	Remaining beach width W (m)	ΔX_{10} (m)	$i_{erosion}$
Platja Trabucador (south)	5.57	0.125	28.5	0	70.91	5
Platja Eucaliptus	5.57	0.126	307	236.41	70.59	1
Platja Serrallo	5.57	0.127	60	0	70.28	5
Platja del Migjorn	5.57	0.125	44	0	70.91	5
Platja del Buda	5.57	0.118	58	0	73.23	5

Embarcador Riu Ebre	5.57	0.113	93.5	18.47	75.03	4
Platja Riumar	5.57	0.115	87.5	13.21	74.29	4
Bassa Arena	5.57	0.121	22.7	0	72.21	5
Platja Marquesa	5.57	0.119	122	49.11	72.89	4
Platja del Fangar	5.57	0.119	52	0	72.89	5

Table 19. indicator for each sector

Below, the different representative profiles of each sector:

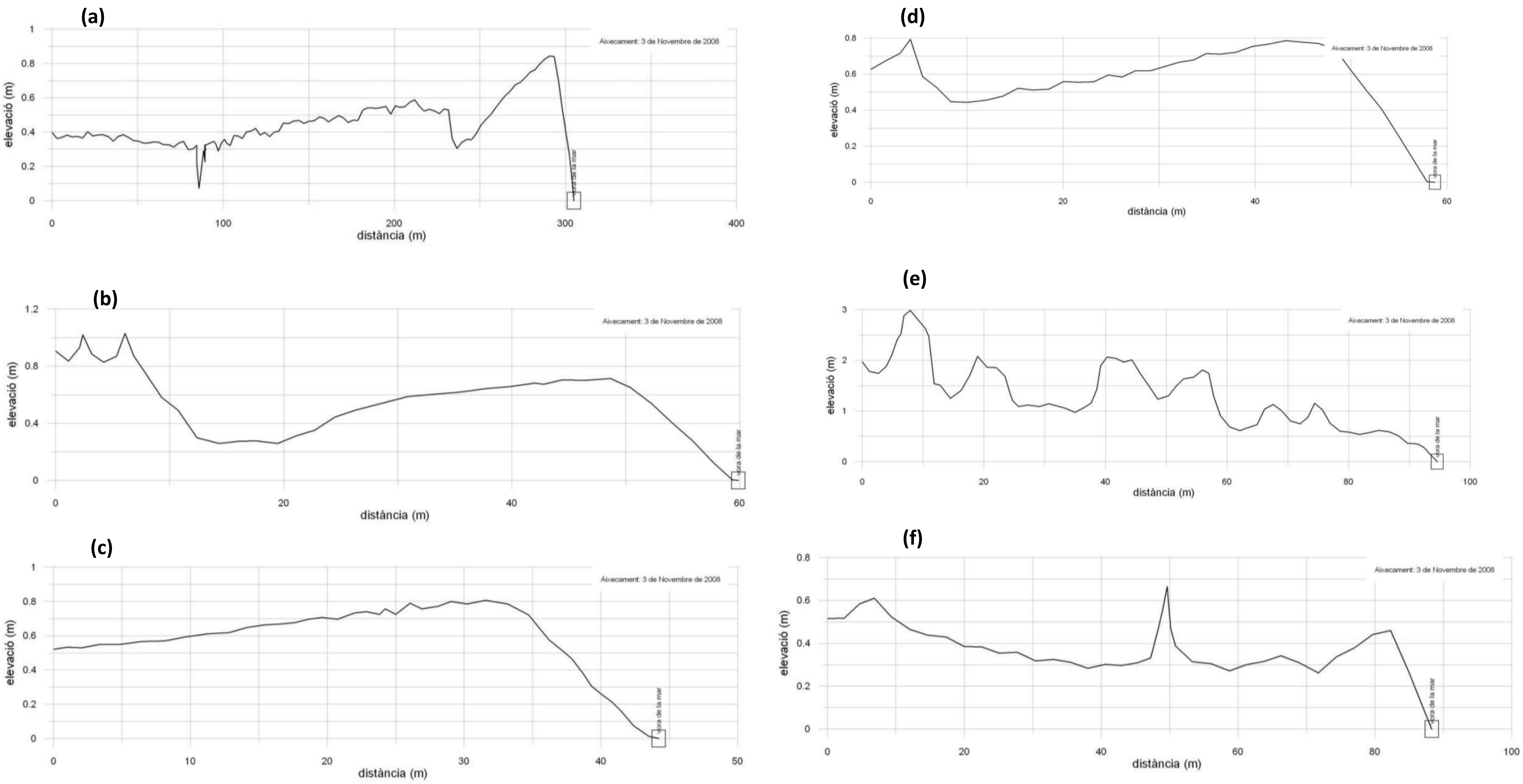


Figure 46. a) Platja Eucaliptus. B) Platja Serrallo. C) Platja del Migjorn. D) Platja del Buda. E) Embarcador del riu Ebre. F) Platja Riumar

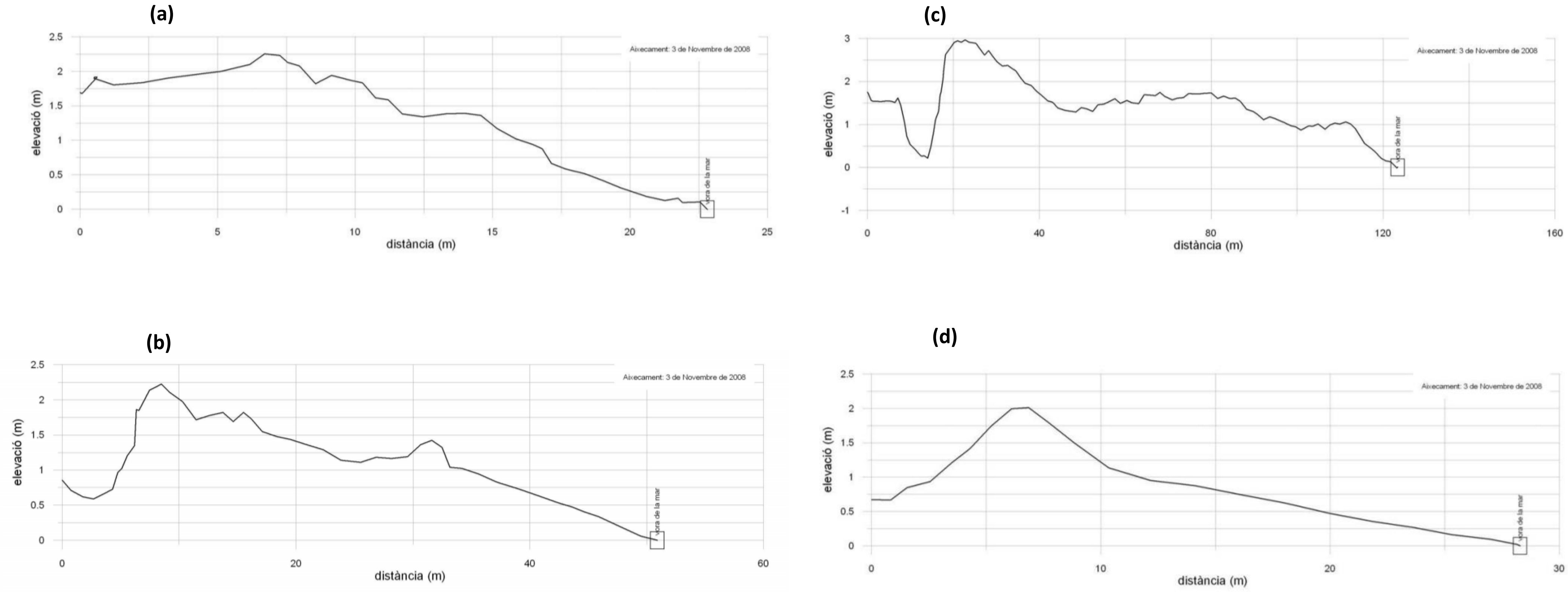


Figure 47. a) Bassa Arena. B) Platja del Fangar. C) Platja Marquesa. D) Platja del Trabucador (south).

Now, considering the hazard index as the following expression:

$$i_h = (i_{flooding} \cdot i_{erosion})^{\frac{1}{2}} \tag{12}$$

And taking into account the expression number 1, presented before, we will be able to compute the risk index CI along the coast of our deltaic region:

Sectors	i_{exp}	$i_{flooding}$	$i_{erosion}$	i_h	CI
Platja Trabucador (south)	2,46	5	5	5.00	3.51
Platja Eucaliptus	3,10	5	1	2.24	2.63
Platja Serrallo	1,81	5	5	5.00	3.01
Platja del Migjorn	2,29	5	5	5.00	3.38
Platja del Buda	2,46	5	5	5.00	3.51
Embarcador Riu Ebre	2,46	5	4	4.47	3.32
Platja Riumar	2,71	5	4	4.47	3.48
Bassa Arena	1,81	5	5	5.00	3.01
Platja Marquesa	2,29	5	4	4.47	3.20
Platja del Fangar	1,81	5	5	5.00	3.01

Table 20. Risk index CI for each sector of the coastal region

As we can see, it has been shown that all sectors in our region have obtained risk index values greater than 2, very close to a 3 value. A first conclusion would be that it is shown that the Ebro Delta region is at a medium-high level of threat in the face of events such as hazard, floods, erosion and sea level rise.

Furthermore, with circumstances such as climate change, these threats will not only increase their impact and strength, but also the frequency between these events. It is accentuated above all the coastline of the region, which is the first line of defense.

Notice that the **Barra del Trabucador** and **Platja de Buda** has obtained the highest danger index value, not only for its great environmental importance working as a union with the Punta de la Banya area and the only protection of the internal lake respectively, but also for its weakness shown against the runup of the waves. During great storms, which both in the models and in reality (Temporal Gloria) cause its total flooding. Furthermore, due to its relatively small width, erosion processes are very damaging. In addition to being the connecting element with the Punta de la Banya area, it separates the

Mediterranean Sea from the Alfacs bay, preserving and protecting not only the bay itself but also many native species of flora and fauna that inhabit it. The same affirmation can be done for the Platja del Buda.

Finally, the rise in sea level directly affects this sector, leaving it practically or totally flooded in the year 2100 in all the scenarios considered (see images above). We can robustly conclude that the Barra del Trabucador and Platja Buda are possibly the weakest areas in the Ebro Delta region, obtaining in this way the first and most important hot spot.

The second sector that we will analyze will be the **Riumar beach**. In our analysis, it has obtained the second highest dangerousness index value. This case is not as delicate as the previous one, but it does present a series of characteristics and problems that must be considered in detail.

As before, it is a very exposed and stunted area in the face of storms with a high return period. The runup of the waves devastatingly affect the entire area. Regarding the defense against erosion, although it has obtained a value of 4 (due to a greater width) it is still a very high value, indicating that it is also very weak against these events. Regarding the rise in sea level, this area is severely affected in the RCP 8.5 scenario at the end of the 21st century. Finally, regarding the high exposure index, it is one of the conditions to obtain the second highest value. It is a sector that has a great urban density, as well as a high level of commerce for the area. All these factors make it the second hot spot to consider in our area.

The last sector that we will consider as a hot spot will be the **Migjorn beach**, which has obtained the third highest risk index value. In this case, the level of exposure is not the highest, but its weakness in the face of possible floods, erosion effects and the impact of sea level rise in some scenarios at the end of the century make it an area to consider.

Figure 48. Hot-spots and zones vulnerable to SLR map

7. Selection of feasible coastal interventions

For many years, action plans have been proposed for the Delta del Ebro in response to a variety of issues. Fortunately, it has realized that the problem is global, and that it should be handled globally. The balance between natural resources and human exploitation has not been simple, therefore the Generalitat of Catalonia authorized the construction of the Ebro Delta Natural Park in 1983, providing this region particular protection and prohibiting any reckless action that is not in accordance with the plan. It is located in the Montsià (right hemidelta) and Baix Ebre areas (left hemidelta).

When it comes to performing in the Delta, there are a variety of possibilities. The first, more engineering, seeks to keep the existing condition by investing in hard works. Another, more ecological perspective chooses to direct the Delta's normal growth to a balanced and sustainable point while causing little harm to the Delta's existing usage.

The last and most questioned option would be the withdrawal towards the inland of all the urban, commercial and agricultural zones located at the coastal fringe. Thus, losing a great amount of fertile and useful area, but also protecting and guaranteeing the survival of the community of the deltaic region.

7.1. Flushing, controlled dragging and other similar methods

As commented before, in the 1960s, huge dams were erected, and rice farmers had to pay a special fee (siltation tax) to be allowed to open irrigation channels after harvest so that sediments could be introduced to the paddy field during periods of high river flow.

Long-term accretion rates of more than 0.5 cm have been recorded in rice fields between 1860 and 1960, prior to dam building. Nowadays, a vertical accretion of 1 cm $year^{-1}$ might be accomplished by recovering about 20% of the original load (5–6 million T $year^{-1}$) and delivering roughly 20% of this load to the delta plain. If the whole pre-dam sediment load is retrieved and utilized, annual accretion rates might reach 10 cm $year^{-1}$.

Farmers nowadays continue to raise the height of their rice fields using non-deltaic sediments, occasionally trucking imported soil. Higher elevation, according to traditional wisdom, equals lesser salinity and increased rice yield (Ibañez et al., 2014).

As a result, we'll need to give a considerable amount of sediment to the river. The accumulated sediments in the Riba-Roja and Mequinenza reservoirs can be used as a solution.

In regard to the absence of sediment deposits that allow the delta plain to accrete vertically, the most efficient technique for extracting sediments from reservoirs and incorporating them into the river is controlled flushing or controlled dragging, followed by pumped pipe. The goal of this approach is to use the power of water to remove sediment from reservoirs and drain it into background drains.

To do so, we must empty the reservoir so that the water flowing through it accelerates and creates a path through the sediments. Through the bottom drains, water and eroded particles are channeled downstream of the dam.

Other options for recovering and transporting these required sediments include the use of barges in reservoirs, as well as rail or road transportation. The problem is that economically they are less efficient than those previously mentioned.

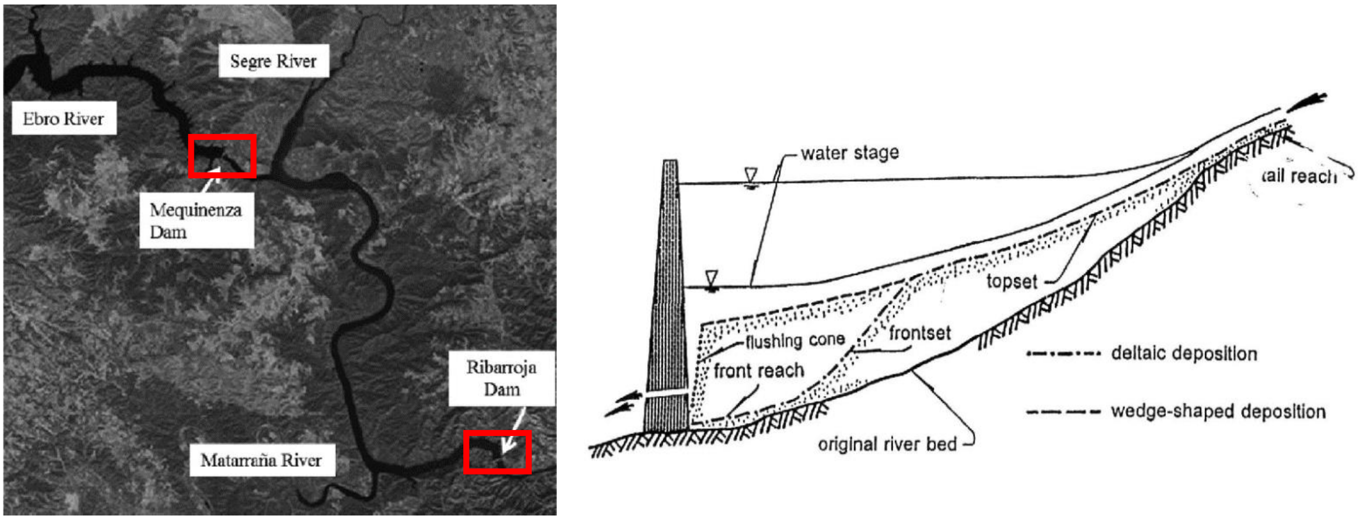


Figure 49. a) Riba-Roja and Mequinenza reservoirs location. b) Flushing sediment through reservoirs scheme

7.2. Regular execution of maintenance floods

Here, we will need a program that will allow us to reduce the impact of dams on the downstream river ecosystem's operation. One approach would be to do maintenance floods on a regular basis. These controlled river floods allow for the distribution and categorization of sediments as well as the orderly growth of vegetation, the removal of invasive species and excessive populations of particular species.

7.3. (Hard) Engineering works

The most important engineering project completed to date is the artificial dune that was built in 1992 to repair the Barra del Trabucador after it was broken during the incident in October 1990.

An artificial dune of 1 km emergency length, 1.5 m high, 12 m wide at crest, and 24 m width at base was built to prevent future bar breaking, which mostly impacted the salt flats on the Banya peninsula. In January 1991, the first half of the performance was staged.

The project was finished in 1992, with the prior dune being extended along the whole length of the bar. To avoid breaking when over-lifting happens, the dune is situated in the interior section of the bar, near to the bay. Dune vegetation was used for fixation, including *Elymus Factus*, *Amophila Arenaria*, and *Othantus Martima*, among others.

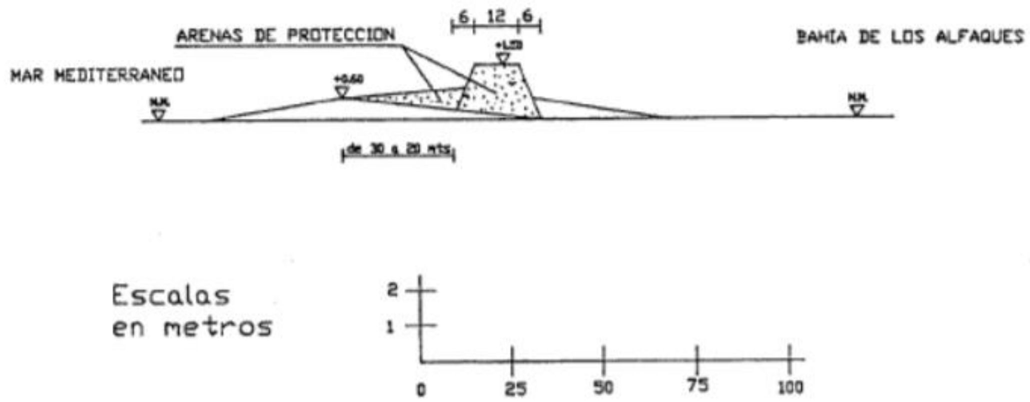


Figure 50. Project profile of the dune built in the Barra del Trabucador.

The retreat and reform of the coast is a phenomenon that, together with the increase in sea level, endangers the coastline of the delta, as well as economically, socially and environmentally important areas.

Hard engineering works are one of the potential maintenance management techniques of the present distribution of the region. Breakwaters, protection of erosive regions, protection walls, perpendicular breakwaters, and exempt levees are just a few of the projects that might be undertaken.

Regrading erosion medium term problems, in order to change the sediment transport gradient, the waves would have to be altered with hard engineering solutions such as detached breakwaters (it would spread throughout the coastline, because its installation in specific regions would have an impact on surrounding sectors). Another option would be the use longitudinal protection walls in the region that needs to be protected. We'd let a section of sand drift away until the shore arrived to our defense.

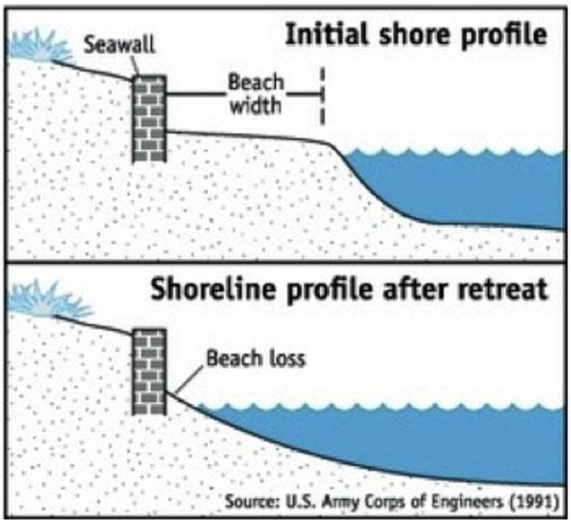


Figure 51. Seawall protection and beach loss process example

7.4. Submersible inflatable docks (analogous to the Mose barrier)

From the City Council of Deltebre, there has been a study on aspects such as the regression and protection of the beaches of Deltebre. A proposal, after two years of work, which consists of smart dikes, submersible and inflatable using seawater.

These dikes, depending on the conditions of the waves, remain inflated or deflated. On the one hand, in situations of strong storms, all dikes swell generating a protective barrier that breaks the storm surge before reaching the coast.

On the other hand, in non-temporary situations, the corresponding dikes are inflated to facilitate or avoid, depending on the needs, the transport of sediments along the coast. With the aim, the latter, of achieving a more homogeneous beach width along the coast, as well as avoiding the accumulation of sand at the mouth of the Fangar´s bay (Ebreactiu 2019).

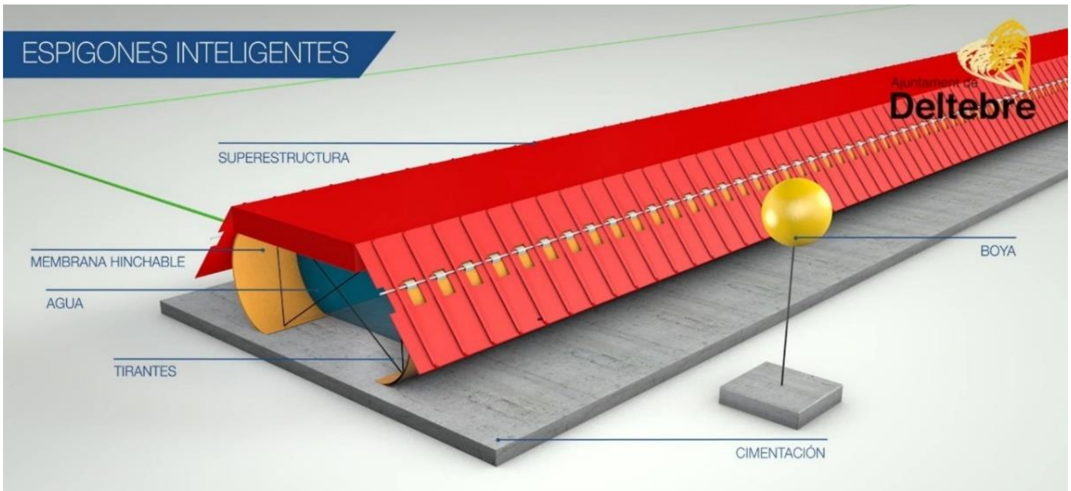


Figure 52. Smart dams, proposed by the Deltebre city council

7.5. Polderization

Another interesting engineering intervention consists in the "polderization," which entails the construction of dikes along the Delta's coast (inspired by Dutch polders) (including inland lagoons). These dikes would separate it from the sea and, in conjunction with an extensive pumping and drainage system, would prevent flooding of the lands that now make up the city, despite the fact that they were below sea level. Because the relative rise in sea level is not combated, the difference in elevation (and pumping power) grows forever, the pumping includes a significant and rising economic expenditure over time.

7.6. Coastal protection strip and sediment extraction and deposition

This approach entails delimiting the public domain and establishing a free coastal protection strip that allows for natural coast evolution; this band would be created by the current area of and a strip of width required for free beach evolution to be acquired as public land. This action would be considered for the entire coastal strip of the delta. In this way, their capacity to respond to the impact of storms would increase.

Apart from its creation by the absorption of the interior zone, forward growth could also be considered through the contribution of sediments. In addition, it would be necessary to increase the height of the posterior dunes. The dune would serve as a sediment reserve for the beach during the storm.

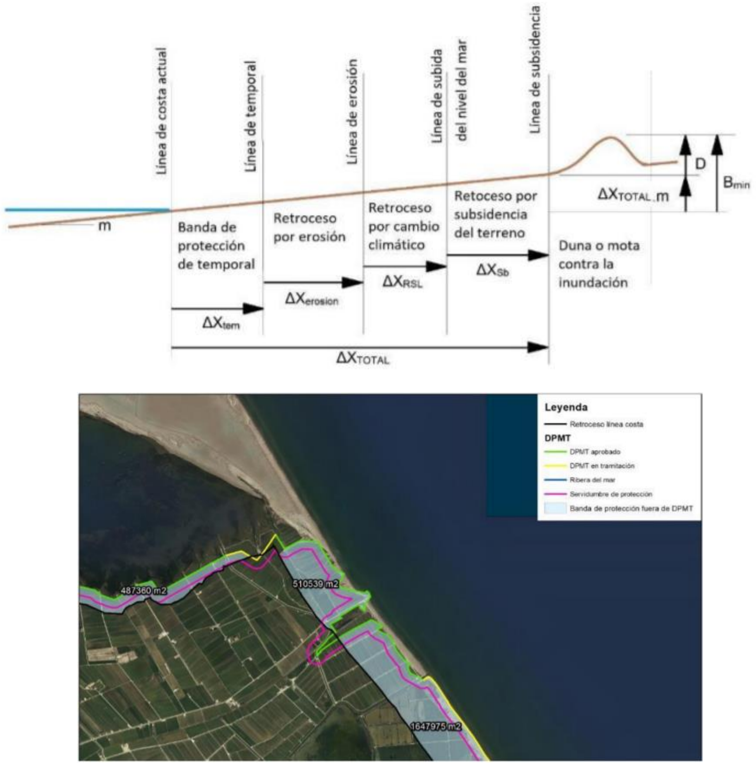


Figure 53. a) Scheme of the typical profile of the beaches of the Ebro deltaic plain. b) Protection band proposed by *Plan para la Protección del Delta del Ebro 2020* in the Bassa d'Arena and Platja de la Marquesa areas

According to the *Plan para la Protección del Delta del Ebro*, the total area that would have to pass into the public domain taking into account all areas of the Delta would be of: 8,320,547 m^2.

Now, in order to minimize the impacts of erosion mid-term difficulties it would be done by the contribution of sedimentary material, with a volume of sand equal to that which is lost. It has no environmental impact and does not change the form of the shore, but it is plainly unsustainable: a significant cost that must be repeated from time to time.

The extraction areas would be the Banya peninsula, the Platja de l'Eucaliptus and the Fangar peninsula:

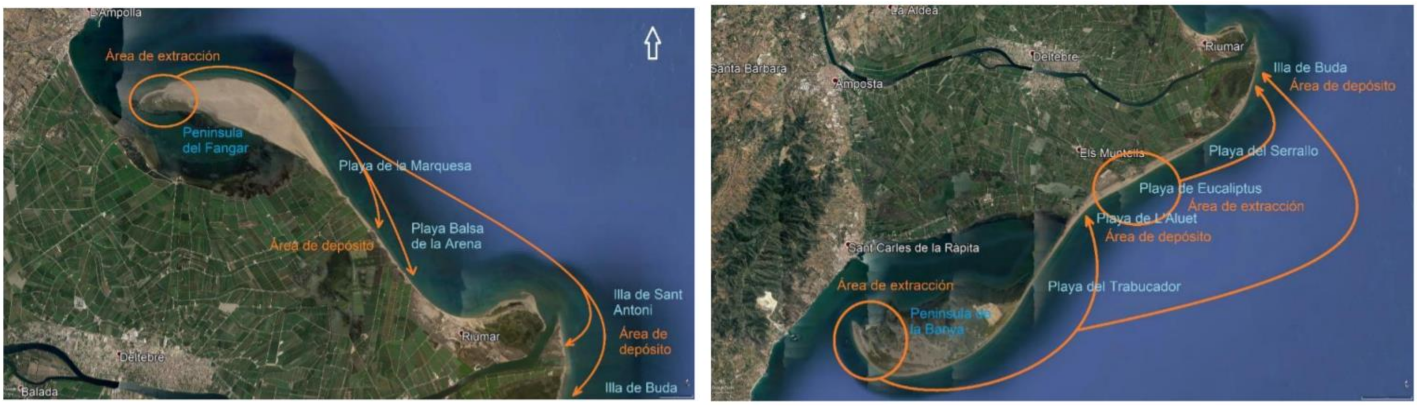


Figure 54. Extraction and deposition 79ruti proposed by *Plan para la Protección del Delta del Ebro 2020*

7.7. Natural intervention – *Salicornia fruticosa* (erosion protection)

Due to the attraction of beneficial insects, the introduction of native vegetation into the strips of land that separate the rice fields can become a helpful weapon in the fight against pests. The presence of these kind of plants also aids in the **slowing of erosion** along these edges. In 2020 year, IRTA researchers started a groundbreaking study to establish the measure's usefulness in the fields and then transmit it to the farmers themselves.

The cords, in the landscape of the deltaic rice fields, are usually treated with phytosanitary products to eliminate the vegetation, often identified like weeds. In some cases, even their occasional presence is interpreted as a sign of negligence on the part of the farmer.

This project can definitely radically transform this perception. The presence of plants rooted in the margins also helps to improve the strength of the cords and slow down their erosion, either by the onslaught of water or by the action of well-known invaders such as the American red crab, which often digs endless galleries. One of the most used native plants in this project and which is giving good results is *Salicornia fruticose*.

Figure 55. *Salicornia fruticosa*, at Ebro Delta.

7.8. No intervention strategy

No intervention is an entirely different approach. The shoreline has a tendency to “guard itself,” taking on a shape that absorbs more energy and reduces erosion. As a result, the Delta will reach a new equilibrium between sediment imports and erosion. If the volume of eroded material, compaction, and subsidence are not offset by sediment inputs, a regressive tendency will persist, perhaps leading to the delta’s death.

There are a number of issues that this solution must address. The most crucial difference is the value of the land acquired against the land lost: whereas the first will almost certainly be dune fields and beaches, the latter will be rice fields, urbanizations, and places of great ecological importance.

7.9. Salt tolerant crops

Low-lying coastal regions are progressively being flooded with seawater as sea levels rise, eventually polluting the land. Although rainfall can disperse these salts, climate change is increasing the frequency and intensity of extreme weather events such as droughts and heat waves.

Salt pollution, which causes limited and inconsistent plant development, is estimated to damage 20% of the world’s farmed land. As their lands get inundated, farmers all over the world (Po delta, Bangladesh area, etc.) are increasingly switching to fish farming and salt tolerant crops.

Grain sorghum, sudangrass, sweet sorghum, and sorghum/sudangrass hybrids are all salt-tolerant sorghum species. Many millets are salt resistant, with Japanese millet being an excellent choice for salty soils. Salt tolerance is quite high in small grains.

7.10. Managed retreat strategy

This solution has been already explained before, which allows wetlands to migrate inland and respond to rising sea levels. Like in Po’s delta, with this option, the delta’s current configuration will be unsustainable.

8. Framework of adaptation pathways. Tipping points

First of all, in this project, the entire study region (Ebro Delta) has been analyzed: its geomorphology, its fluvial characteristics, its biodiversity that inhabits it as well as both economic and social aspects, to present and understand the area that we want to study.

In the same way, all the major problems it presents (marine erosion, changes in the sedimentary contribution, the rise in sea level due to climate change …) the delta have been examined to understand what factors are causing these problems, in which circumstance we are currently, and how these threats will evolve and affect over the years (with a perspective set to the year 2100).

To complement these known threats, an extensive and complex analysis of the coastline has been carried out, obtaining as a result that the entire coastal zone of the region is at a considerable level of danger (especially in the face of flooding and erosion events), highlighting the hottest sectors (hot spots) of Barra del Trabucador, Platja Riumar, and Platja del Migjorn. To accompany these results, different maps have been made (Hazard maps) with raster models to see how this rise in sea level would affect each sector of the region.

The third point that has been made has been the analysis and selection of the different coastal interventions that could be applied in the delta to try to solve the different problems that it presents and, in this way, guarantee the survival of the region, as well as its economy, society and environmental value it represents.

For the selection of these proposals, it has been analyzed the different strategies that are being developed or implemented in other deltaic regions, and that could be compatible with our area. As the range of deltaic regions in the world is very large (Mississippi, Amazon, Ganges, Rhine, Nile …) we have tried to select those interventions that are being applied in deltas similar to ours, both at the climatic level, as well as at the social and economic level of the country where it is located.

The issue with these suggested interventions and investments is that they have considerable and, in many cases, long-term repercussions. In order to evaluate alternatives and make decisions in the face of a truly unpredictable future, we will need more than standard prediction or scenario-based decision approaches.

As a result, we'll use the Dynamic Adaptive Policy Pathways (DAPP) technique, which seeks to assist in the design of an adaptive plan capable of dealing with significant uncertainties. It is based on a method developed by Deltares and TU Delft. An adaptive plan identifies measures that need be performed right now to prepare for the near future, as well as measures that should be taken immediately to keep choices open for future adaptation.

Regarding the Adaptation Tipping Points (ATP), they are a key concept in DAPP. An adaptation tipping point specifies the conditions under which the status quo or a policy action will fail. An adaptation tipping point is reached when the magnitude of external change is such that a policy no longer can meet its objectives, and new actions are needed to achieve the objectives. The timing of an adaptation tipping point (the sell-by year of actions) is scenario dependent (Deltares 2019).

Following that, we present and evaluate the Dynamic Adaptive Policy Pathways method for the Ebro Delta region. The next stage will be to evaluate the effectiveness of each individual activity based on our findings and expert knowledge (previous interventions on the region). What's more, we must determine the sell-by date for each intervention, which will be different according to the scenario considered. For example, a solution like the implementation of *Salicornia fruticose* or a no intervention strategy could be feasible to guarantee the survival of the delta until the year 2050 in the case in which the emission level is of RCP 2.6.

On the other hand, in the case that the emission level is of RCP 8.5, it would be possible that these interventions were only feasible until the year 2030 due to higher sea level rise.

Below, the table with all the interventions and strategies previously proposed. Each of the interventions is classified with the cost involved, the benefits it provides and the sell-by date. It should be noted that the assessment of the characteristics of each intervention (cost, benefit, and sell-by date) has been carried out taking into account historical data, previous similar interventions, results of the analyzes carried out… Even so, they are not carried out by experts in the matter so their assessment could present some flaws and be slightly different according to each person.

Intervention	**Benefit**			**Cost**	**Sell-by date (years)**
	Safety	**Natural repercussion**	**Social acceptance**		
Flushing and controlled dragging	++	+++	+++	++	2050-2075
Maintenance floods	0	+++	++	+	Complementary strategy (2100)
(Hard) engineering works	+++	--	--	+++	>2100
Submersible inflatable docks	++	+	+	+++	2050-2100
Polderization	+++	---	---	+++	>2100
Coastal protection strip and sediment extraction and deposition	+++	++	-	+++	2075-2100

Natural intervention: *Salicornia fruticose* (erosion protection)	+	+++	++	+	2040
No intervention strategy	0/-	-	-	0	2030
Salt tolerant crops	0	+++	+	+	Complementary strategy (2100)
Managed retreat strategy	+++	-	---	+++	>2100

Table 21. Actions and assessment of their relative performance in terms of benefits, cost and sell-by date

--- large negative impact, -- moderate negative impact, - negative impact, 0 no or minor impact, + positive impact, ++ moderate positive impact, +++ large positive impact.

Next, the reasons for the valuation for each strategy will be briefly explained, taking into account the benefits, the costs and the sell-by date. It is important to bear in mind that, as mentioned above, the individual assessment of each intervention can be highly complex due to the different factors on which it depends (especially the sector of implementation can greatly affect the performance) and the lack of public data.

Furthermore, it should be noted that possibly no intervention (except for the polderization strategy and the managed retreat of the population and plantations) could successfully combat hazards with long return periods (as is the case of the Gloria storm). Therefore, in the safety section of the benefits, issues such as sea level rise due to climate change, erosive processes and the normal runup of waves are being taken into account mainly.

Having said that, we continue with the explanation of each assignment:

8.1. Flushing and controlled dragging:

8.1.1. Safety:

It has been previously commented that only by recovering 20% of the original sedimentary load (before the construction of the dams) a vertical growth of the delta of 1cm per year could be achieved. Considering that our study has a vision towards the year 2100, this could suppose that by the end of the century the territory has grown by 80 cm. Only with this growth, the SLR could be perfectly combatted at the worst emission level of RCP 8.5, which is 0.63 cm.

Even so, I have not evaluated it with the highest score (+++) because it has not been demonstrated that the growth of 1cm per year is homogeneous throughout the area, especially in the coastal fringe. Furthermore, erosion and wave problems would continue to exist.

8.1.2. Natural repercussion:

In this section, I have evaluated this strategy with the highest score because it would contribute the recovering of the original dynamics and morphological characteristics of the river basin and the delta in general. From now on, in the case of contributing to a recovery of the original behavior of the river, it will be scored with the highest score.

8.1.3. Social acceptance:

Both the community and the majority of the politicians that govern this region agree that the only possible implementation should be one that does not affect the natural behavior of the river and the area. It is based on a non-negotiable condition, the preservation of the current coastline of the Delta, its morphology, and not giving up the first coastal strip.

This is why it has been considered that this solution would be highly regarded by society. Furthermore, the actions to transport sediments from the swamps, downstream, are also considered essential to achieve the elevation of the Delta, has commented Xavier Pallarès, delegate of the Generalitat (La Vanguardia, 2020).

8.1.4. Cost:

This section is surely the most difficult to assess in all interventions. This is due to the large scale of the project, the different factors to take into account in each specific area of the delta, the complexity of execution in each case …

Even so, an attempt will be made to provide accurate data in each of the strategies to try to classify each intervention as best as possible. In this case, we will base on data provided by Martín Vide et al., 2004, which presented the following table:

	Mequinenza	Riba-roja	Flix
Barges	5,5	2,3	0,90
Road		29,2	
Railway		-	
Pipe without pumping	3,6	1,4	0,57
Pipe with pumping	4,9	1,0	0,38
Flushing	-	0,54	-

Table 22. Sediment transport costs in €/m^3. Regardless of the artificial extraction (Martín Vide, 2004)

Now, at the price of 0.54€/m^3 for the transport, the cost of sediment extraction should be added, which is around 10€/m^3. Therefore, the total cost of the intervention would be about 10.54€/m^3. Now, if we remember the annual amount of sediment needed to recover 20%, it would be about 5-6 tons.

Considering that the sediments retained by the dams are mainly clays and sands, the average density of the sediment would be:

$$\frac{2{,}1t/m^3\ (sand) + 2{,}837t/m^3\ (clay)}{2} = 2{,}46t/m^3$$

So:

$$0{,}54\frac{€}{m^3}\cdot\frac{1\ m^3}{2{,}46\ t} = 0{,}22€/t$$

That means that each year, this intervention would present a cost of 1,1 – 1,32 million of euros. And, in a future of 80 years, this will represent a total amount of **88-105,5 millions of euros**.

8.1.5. Sell-by date:

Regarding its implementation time until its failure (tipping point), as it has been considered that although its defense could be very useful, it is not a strategy that can guarantee the integrity of the area at the end of the century and at emission levels. Very tall. Therefore, that range of 50 years, depending on the scenario in which we find ourselves.

8.2. Maintenance floods:

8.2.1. Safety:

In this intervention, the level of security would decrease because this measure is more focused on the river restoration of the Ebro River. Therefore, with respect to the level of security that this strategy would grant, it would be null. It can be considered as a complementary work, with the aim of minimizing the impact of the dams.

8.2.2. Natural repercussion:

As we commented before, in the case of contributing to a recovery of the original behavior of the river, it will be scored with the highest score.

8.2.3. Social acceptance:

In this case the quantification is more complex. It is true that it recovers natural aspects of the behavior of the river, and that there are a large number of farmers who agree with the process due to the large washing load it provides (large amount of sediment). Even so, the event of a flood always has a bad image, whether it is controlled or not, and that's why the maximum score is not given.

8.2.4. Cost:

Its economic quantification is also difficult, since it cannot be equaled that of unforeseen floods. As they are controlled and measured, the impact they will have will be much less, but it can affect certain areas if it is not done properly. That is why it does not receive a null score.

8.2.5. Sell-by date:

It would only function as a complementary work.

8.3. (Hard) engineering works:

8.3.1. Safety:

Regarding the safety aspect offered by this intervention, it has been classified with the maximum level of +++. This is due to the fact that it is capable of defending the coastal strip with great efficiency, both for the SLR, as well as for erosive or wave impact events (detached breakwaters, seawalls, coastal rock revetment…).

Even more, the use and construction of these kind of structures is widely known, so their application would not pose any unknown risk.

8.3.2. Natural repercussion:

Its natural impact would obviously be negative, limiting or eliminating natural processes such as the longitudinal transport of sediments, affecting the shape of the beaches, and in the extreme case producing their elimination.

Even so, it has not been cataloged with the worst score, since there are strategies with an impact even worse than this.

8.3.3. Social acceptance:

As mentioned before, the great majority of the urban, agricultural and political community agrees with the use of natural and soft interventions that do not break the morphological cycle of the river and the delta. This strategy is therefore against these principles.

Even so, there are small sectors that would see in a positive way the installation of hard works such as dams, in order to defend the area. That is why it has not received the worst score. Also comment that the intervention worsens the coastal landscape context of the delta.

8.3.4. Cost:

For The Netherlands, Jonkman et al., 2013 estimate costs at $19.3–27.2 million/km per meter of dike raised, and for Vietnam at $0.9–1.6 million/km per meter of dike raised. These case-study results are in the same range as those determined by a large study by Prahl et al., 2012 who estimate the cost of raising sea dikes in European cities at $21.8–31.2 million/km per meter of dike raised.

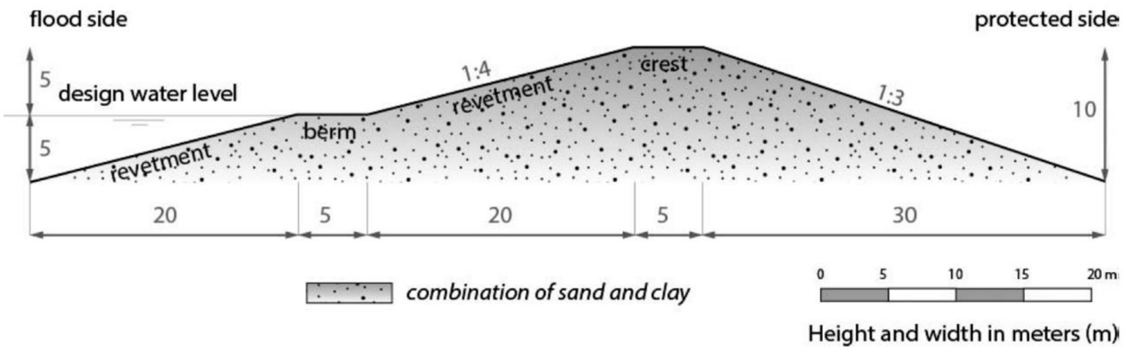


Figure 56. Marine dike scheme

Now, considering that its construction should be carried out along almost the entire delta coast (52km long coastline), for instance the 50% (26 km). What's more, regarding the construction height, an average height of 6 meters could be considered (5 meters deep from the sea + 1 meter above the MSL). That would give us a total cost of:

$$26{,}5\ million\frac{\$}{km\cdot m}\cdot 26\ km\cdot\ 6\ m = 4.134{,}0\ million\ \$ \sim 3.513{,}9\ million\ €$$

As can be seen, the budget for the realization of this work is absurd, so it would have to be applied in certain areas (the weakest zones, like the hotspots), in addition to negatively affecting neighboring beach areas. That's why it receives the highest score for cost.

8.3.5. Sell-by date:

As mentioned in the security point, it is a measure that excellently protects the coastal area of the region, not only against minor erosion and impact events, but also in more intense events it would be capable of considerably reducing the energy of the incoming waves.

8.4. Submersible inflatable docks:

8.4.1. Safety:

Regarding the safety aspect offered by this intervention, it has been classified with a moderate level of ++. This is due to the fact that it is capable of defending the coastal strip with great efficiency, both for the SLR, as well as for erosive or wave impact events. However, in the case of the distant future (2100) and scenarios with high levels of pollution (thus increasing the mean sea level), it is possible that this solution may not be fully prepared. Its height is not as considerable as in the case of fixed dikes. For example, in the case of Mose barrier at Venice, it's designed to cope with a 60 cm rise in sea level.

8.4.2. Natural repercussion:

This assessment can be a bit complex. The structure can influence natural coastal processes only when it is fully swollen. The rest of the time it will not impede the longitudinal transport of sediments, but even more, it will help to distribute their distribution. That is why it has been scored with +.

8.4.3. Social acceptance:

In this case the qualification given was +. This is because it is among the hard-engineered solutions and the more natural solutions, somehow satisfying both sides. Even so, because it is not a 100% natural solution and that it can influence the landscape of the area, it has not received a higher rating.

8.4.4. Cost:

Its economic quantification is also difficult. At the moment the pilot test has cost about 6 million euros (lengths or heights of the structure are not detailed). Even so, being a solution similar to the previous one, and which would require regular maintenance, it has been rated with the highest score.

8.4.5. Sell-by date:

The explanation would be similar to that of intervention number 1.

8.5. Polderization:

8.5.1. Safety:

Regarding the safety aspect offered by this intervention, it has been classified with the maximum level of +++. This is due to the fact that it is capable of defending the coastal strip with great efficiency, both for the SLR, as well as for erosive or wave impact events (detached breakwaters, seawalls, coastal rock revetment…).

Even more, the use and construction of these kind of structures is widely known, so their application would not pose any unknown risk. In this case, the level of protection provided could be even higher than intervention number 3.

8.5.2. Natural repercussion:

The natural repercussion would be the worst possible. This is due the construction of dikes which would separate the ground area from the sea and, in conjunction with an extensive pumping and drainage system, would prevent flooding of the lands that now make up the city.

It would completely break all the morphological processes of the delta and the river, thereby eliminating many areas of great environmental value, as well as a large amount of native fauna and flora of the region.

8.5.3. Social acceptance:

Due to the environmental, social and economic impact (especially tourism) so negative that it would cause, its acceptance would be null by the population of the area. In addition, the unique landscape would be destroyed.

8.5.4. Cost:

The cost of this strategy would be equal to or surely greater than that of point 3. Therefore, its realization would be almost impossible due to the high budget required.

8.5.5. Sell-by date:

A point in favor of this strategy would be that it would guarantee the survival of the delta until the end of the century. Even so, the energy problem of maintaining the water pumps could appear, which could make it unsustainable not only in the distant future but also in this same century.

8.6. Coastal protection strip and sediment extraction and deposition:

8.6.1. Safety:

Regarding the safety aspect offered by this intervention, it has been classified with the maximum level of +++. This is due to the fact that it is capable of defending the coastal strip with great efficiency, both for the SLR, as well as for erosive or wave impact events (detached breakwaters, seawalls, coastal rock revetment…).

8.6.2. Natural repercussion:

Regarding the natural impact, this has received the second highest score. Although the morphology and behavior of the river would not be directly affected, for its execution certain areas of the Ebro natural park could be lost or required, that is why it does not obtain the maximum score.

8.6.3. Social acceptance:

The problem is that for its execution it would require a large amount of land, in which there are cultivated fields (rice fields), possible parts of the natural park and urban areas. This is the main reason for this rating.

8.6.4. Cost:

For its execution, a large quantity of sand extracted and distributed would be required for the creation of the beaches and dunes, as well as a large quantity of expropriations by the Administration.

8.6.5. Sell-by date:

The explanation would be similar to that of intervention number 1.

8.7. Natural intervention:

8.7.1. Safety:

In this intervention, the level of security would decrease down to +, because the level of erosion protection would be lower than in previous methods, so as SLR and erosion processes increases it will begin to fail in the case that is the only solution being applied, in addition to being focused on solving environmental and biological problems (vegetation, fauna …). that's why it receives only a +.

8.7.2. Natural repercussion:

As we commented before, in the case of contributing to a recovery of the original behavior of the river, it will be scored with the highest score.

8.7.3. Social acceptance:

In this case, its considered social acceptance would be the second maximum. This is because it is a natural solution, to the liking of the community. Even so, due to its appearance it may not be to the liking of some people (especially tourists), because its presence could break the landscape of the beach, making it seem like a more wild and natural territory.

8.7.4. Cost:

Regarding its cost of execution, no representative data has been found on the subject. Even so, it can be easily assumed that its cost will obviously be less than the implantation of the flushing but it is different than zero, that is why it receives a +.

8.7.5. Sell-by date:

It could be considered as a good secondary or complementary work to a larger one, for example the creation of the coastal protection strip with the implementation of this type of plants (Salicornia) to reinforce the dunes. The problem is that by itself, its life expectancy could decrease a lot.

8.8. No intervention strategy:

8.8.1. Safety:

in this case the security could vary depending on the different scenarios and futures considered. As mentioned above, it would be possible for the delta itself to reach an equilibrium state by itself, so it would value the intervention with a 0.

On the other hand, it is also very possible that, despite reaching an equilibrium point, factors such as the SLR or erosive processes greatly affect the delta, obtaining a negative evaluation for the first time.

8.8.2. Natural repercussion:

Regarding the natural impact, this has been considered slightly negative because the intervention does not try to solve any current morphological problem (for example, sediment retention in dams)

8.8.3. Social acceptance:

In this case, the assessment has also been negative because it would be very possible that the society of the area would look down on the non-intervention by the different Councils to try to solve the current problems.

8.8.4. Cost:

The cost of non-intervention would be 0.

8.8.5. Sell-by date:

As discussed in the security section, this type of intervention would have a very short efficient duration due to the large number of threats that the region presents.

8.9. Salt tolerant crops:

8.9.1. Safety:

This type of intervention would not produce any type of security, since they are more focused as secondary or complementary works.

8.9.2. Natural repercussion:

The natural repercussion of this intervention would be positive, since original plantations resistant to seawater would be recovered (unlike the rice fields which were installed in a more artificial way).

8.9.3. Social acceptance:

Regarding social acceptance, this would obviously be positive since it would be addressing the problem of saline intrusion into the soil in an intelligent way. Even so, it has not received a higher score since current rice farmers could have a negative view, considering that they could end their type of crops and affecting in this way to their economy.

8.9.4. Cost:

The cost explanation would be similar as point 7.

8.9.5. Sell-by date:

It would only function as a complementary work.

8.10. Managed retreat strategy:

8.10.1. Safety:

The level of security that this intervention would provide would surely be the highest of all the possibilities analyzed. The problem is that a large amount of land that has great economic, social and environmental value would be given up.

8.10.2. Natural repercussion:

The explanation would be similar as point 8.

8.10.3. Social acceptance:

Its acceptance would be very negative, even exceeding the level of polderization. This is due to the fact that, as has been commented, a large amount of land that has great economic, social and environmental value would be given up, affecting in this way to a large amount of people who live at this region.

8.10.4. Cost:

The cost associated with this intervention would be that of the compensation to all the families affected by the strategy (such as urbanizations, saline companies, agricultural fields, tourist areas, areas with great environmental value …)

8.10.5. Sell-by date:

This intervention is surely the one that can be extended and used the most in the future (both near, medium or distant).

Once the reason behind each assessment for each intervention has been explained, we will continue with the following table which summarizes the global final assessment of each intervention, this assessment being from 0 to 6, making it more intuitive:

Intervention	**Benefit**			**Cost**	**Sell-by date**	**Final value**
	Safety	**Natural repercussion**	**Social acceptance**			
Flushing and controlled dragging	5	6	6	1	4	4,4
Maintenance floods	3	6	5	2	-	-
(Hard) engineering works	6	1	1	0	6	2,8
Submersible inflatable docks	5	4	4	0	4,5	3,5
Polderization	6	0	0	0	6	2,4
Coastal protection strip and sediment extraction and deposition	6	5	2	0	5,5	3,7
Natural intervention: *Salicornia fruticose* (erosion protection)	4	6	5	2	1,5	3,7
No intervention strategy	3/2	2	2	3	0,5	2,1/1,9
Salt tolerant crops	3	6	4	2	-	-
Managed retreat strategy	6	2	0	0	6	2,8

Table 23. Actions and assessment of their relative performance in terms of benefits, cost and sell-by date (ranging from 0 to 6)

The equation used to obtain this value is the following:

$$FV = \frac{n_{saf} + n_{nat} + n_{soc} + n_{cost} + n_{year}}{5} \quad (13)$$

Therefore, as can be seen in the equation above, each characteristic has been evaluated with the same percentage. It is possible that the percentage of the natural impact could have been considered more important than the rest of the characteristics, since for the community of the deltaic region it is a very important aspect. Even so, due to its great complexity and objectivity, an equitable distribution has been chosen.

Regarding the evaluation of the sell-by date, it has been classified as follows:

Sell-by date (years)	Value
2020-2030	0
2030-2040	1
2040-2050	2
2050-2060	3
2060-2070	4
2070-2080	5
2080-2100	6

Table 24. Evaluation of the sell-by date characteristic

As can be seen in the table obtained above, the strategy that has obtained a higher score is that of flushing and controlled dragging, followed by the coastal protection strip, natural intervention and the submersible dock.

It should be noted that precisely this flushing solution is one of the most considered by the community and the administration for many years. In addition, many expert authors in the matter comment that it would be viable even for high-end scenarios. Even so, in our project we have considered that in no RCP scenario this intervention by itself would be viable until the year 2100. Therefore, once it has reached its tipping point, it should be branched out and lead to other interventions.

Next, the designed **Dynamic Adaptive Policy Pathways** will be presented, which has been designed based on all the data, factors, analysis and results previously carried out. For its realization, the Pathway Generator program offered by Deltares and the University of Delft has been used.

8.11. Dynamic Adaptive Policy Pathways – Ebro Delta (Global scenario)

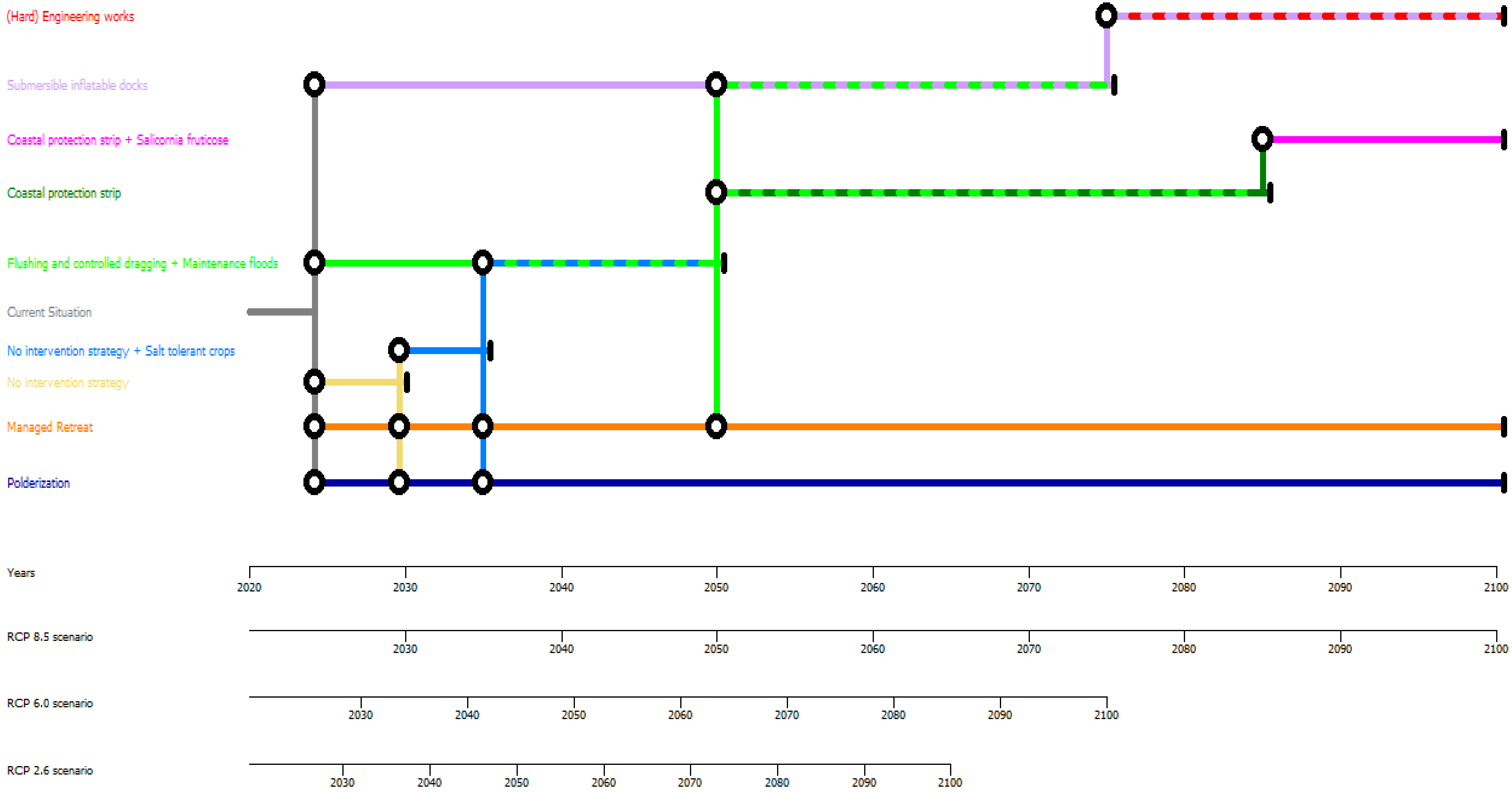


Figure 57. Adaptation pathways map for the Ebro delta area

8.12. Dynamic Adaptive Policy Pathways – Preferred pathway (Global scenario)

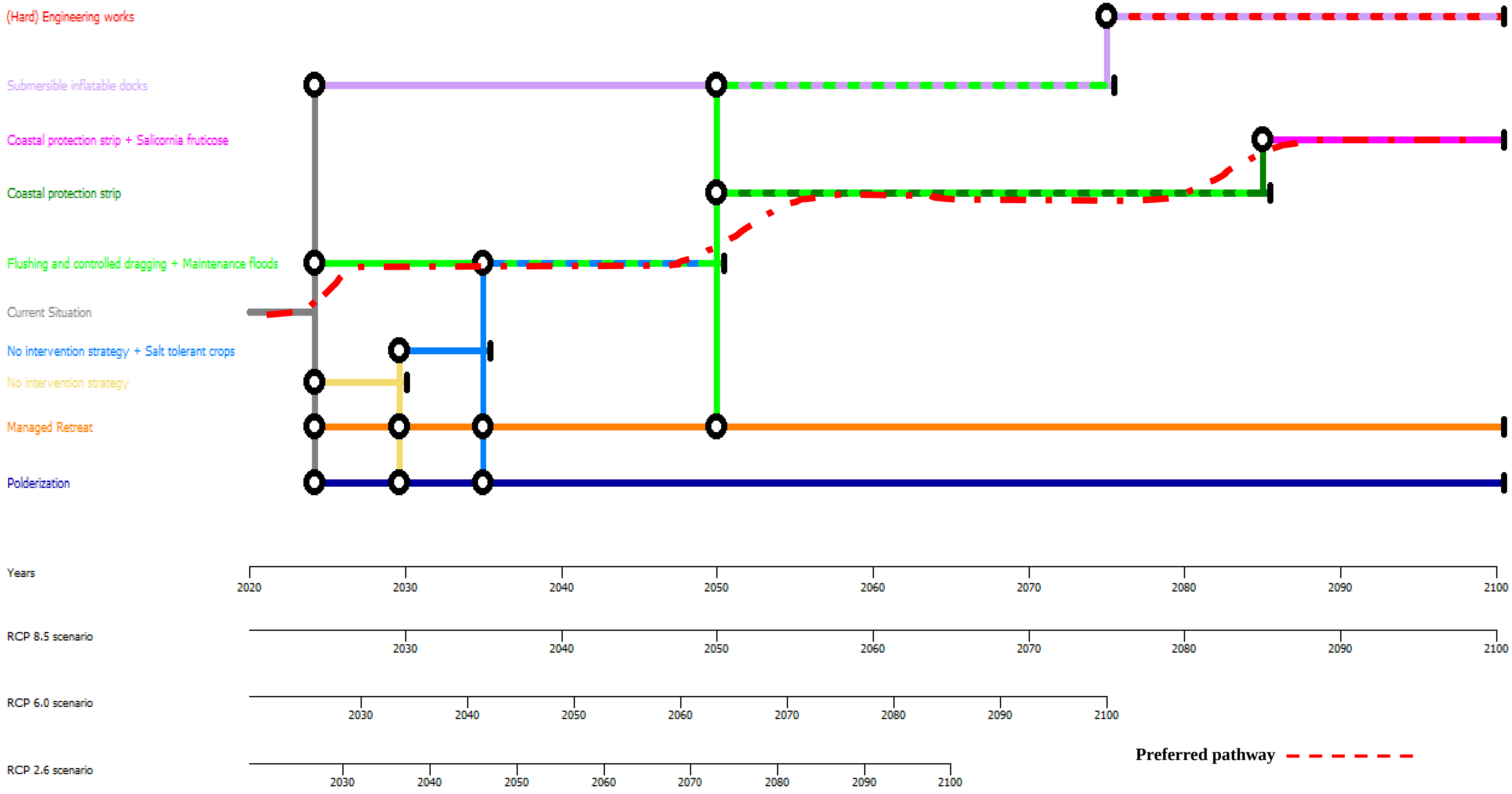


Figure 58. Adaptation pathways map for the Ebro delta area – Preferred pathway marked with red striped line

8.13. Dynamic Adaptive Policy Pathways – Preferred pathway (Barra Trabucador and Illa de Buda)

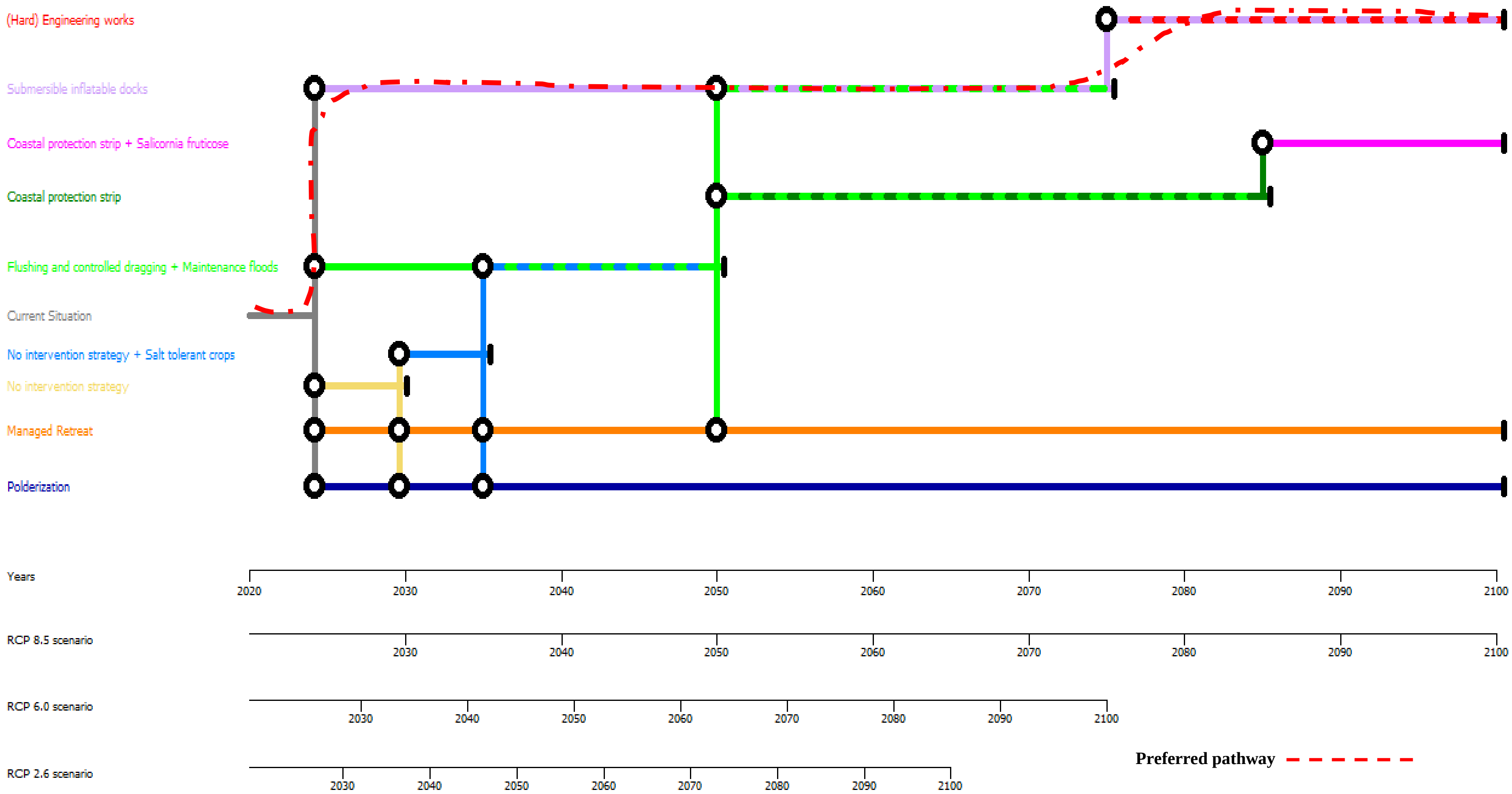


Figure 59. Adaptation pathways map for the Ebro delta area – Preferred pathway for Barra del Trabucador and Illa de Buda area

8.14. Dynamic Adaptive Policy Pathways – Preferred pathway (Interior coast of Badia dels Alfacs)

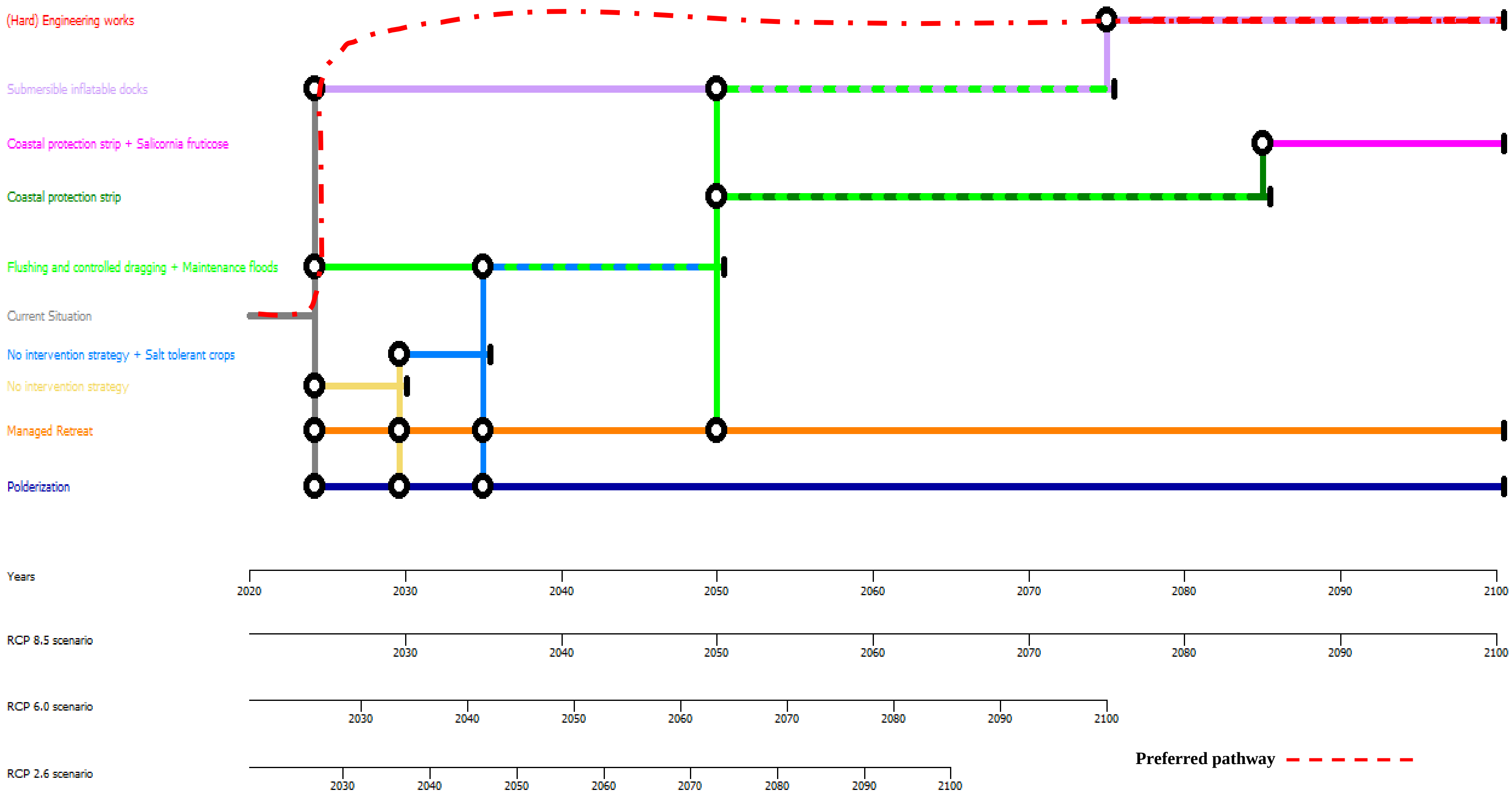


Figure 60. Adaptation pathways map for the Ebro delta area – Preferred pathway for Barra del Trabucador and Illa de Buda area

Once the different Dynamic Adaptive Policy Pathways have been proposed, the reason for choosing the preferred route in each sector will be explained.

8.15. Preferred pathways explanation:

8.15.1. Preferred pathway (Global scenario):

As can be seen in figure 58, the pathway that has been chosen as the preferred one is the following:

1. Flushing and controlled dragging + Maintenance floods
2. Coastal protection strip
3. Coastal protection strip + Salicornia fruticose

Previously it has been shown that the flushing intervention is the best valued strategy (according to our criteria and analysis). Furthermore, as it is a natural intervention, it would be highly regarded by the community in the area, in addition to being able to guarantee the survival of the Ebro delta for a few more decades in the worst-case scenario (RCP 8.5). Even so, because it has not yet been implemented in the delta so its efficiency is not based on field work, it has been considered that by itself it could not guarantee the survival of the region until the end of the 21st century.

The selected intervention number 2 (Coastal protection strip) would be combined with the previously selected strategy. The fact of re-naturalizing some beaches and sectors of the coastal fringe would increase their resistance not only to the SLR, but also to the effect of transverse erosion and the impacts of waves during storms. These beaches, in addition to incorporating a width greater than the natural one, would be accompanied by sand dunes thus protecting the interior.

It has been considered that with the application of these two interventions the survival of the delta could be guaranteed in the RCP 2.6 and RCP 6.0 scenarios. Even so, for the RCP 8.5 scenario, it has been considered that it would also require the application of Salicornia in order to guarantee the defense of the most exposed or weak areas. In this way, erosive processes during storms would be diminished.

It should be noted that the application of this natural intervention could also be incorporated in the other two scenarios during the creation of these new coastal strips. Therefore, it should not be considered a unique application of the RCP 8.5. As mentioned above, it is a strategy that could work very well in the case of being complementary.

8.15.2. Preferred pathway (Barra del Trabucador and Illa de Buda):

As can be seen in figure 59, the pathway that has been chosen as the preferred one is the following:

1. Submersible inflatable docks
2. (Hard) Engineering works

In the Barra del Trabucador and Illa de Buda sectors, a preferred adaptation route has been chosen that is different from the previous one. This is basically due to the fact that the width of both beaches is very small, in addition to not being connected in their inner part to the mainland. Therefore, the intervention of the coastal protection strip would be ruled out.

Therefore, the strategy of the inflatable submersible dock has been chosen, which could function and protect both sectors in an excellent way. In addition, it has the advantage of not being a fixed structure, so it would be hidden most of the time. As discussed above, it could also help redirect sediment.

In the RCP 2.6 and RCP 6.0 scenarios, this intervention, even though its high cost, would be sufficient to protect both sectors until the end of the century. However, in RCP 8.5 scenario it has been considered that it would stop working properly, so it would require a combination with engineering works, such as the construction of an artificial dune, the same as in 1992, which could be reinforced with Salicornia. Another option would be to re-naturalize both sectors, increasing their long-term resistance, but decreasing their tourist attractiveness.

8.15.3. Preferred pathway (Interior coast of Badia dels Alfacs):

As can be seen in figure 60, the pathway that has been chosen as the preferred one is the following:

1. (Hard) Engineering works

As has been observed during point 4, the interior area of the Badia del Alfacs would be very exposed due to the SLR. This event would occur in all three scenarios, leaving a large part of Punta de la Banya flooded, thus endangering the Salinas de la Trinitat, and its own survival. That's why in this sector it can be created a coastal guard path projected between Sant Carles de la Ràpita and El Trabucador. This path could be reinforced with natural methods, or even implement a bike lane at the top. The problem it would suppose is that it could negatively affect the morphology and the environmental value of this particular sector.

9. Conclusions

Once all the necessary information has been collected, analyzed the different aspects of the study area, projected several models on possible futures and proposed several interventions and pathways, it is time to end this project with the compilation of all the conclusions drawn during this work.

Regarding the review of the management strategies for river basin and deltaic regions, we can highlight that:

- Each deltaic region, as well as each river basin, has different characteristics (river dominated, wave dominated, tide dominated), aspects, threats, societies, cultures and economies, so it may be impossible to consider a single valid strategy for any area.
- The economic aspect of the country or region where the delta or river is located originate a division in terms of strategies that can be considered. Deltas such as the Mississippi, Rhine, Po and Ebro are fortunately in countries with sufficient technical and economic resources to try to save them. On the other hand, in deltas such as Ganges, Niger or Mekong they tend to resort to social interventions due to their lack of budget and technology. It is for this reason that the interventions proposed by these regions have not been so thoroughly studied in the project.
- Even with similar technology and resources, there are strategies that could be successful in certain countries and unsustainable in others. A great example is that of the availability of sand (from the sea) that the Rhine delta presents in contrast to the Ebro delta. Therefore, in the Netherlands the creation of dikes and sand dunes could be considered in a simple and inexpensive way, which here would require prior studies and analysis.
- Thanks to the rapid evolution of marine technology, today it is possible to propose and design coastal structures that defend deltas, without having to resort to fixed structures of hard engineering work. The Mose gate and the Ebro submersible dock are two clear examples.

Let us now turn to the conclusions drawn from the analysis of the SSP and RCP scenarios:

- It is clear that the threat posed by climate change puts the survival of many areas and regions that were not previously at risk. These threats, including the anthropic action in the deltas, multiply these dangers, casting doubt on their future continuity. That is why the modeling of future socio-economic and climatic scenarios can help us to combat and prevent these problems.
- The creation of these models can be successfully incorporated in delta regions. They allow us to analyze where the origin of each problem/threat is, in addition to considering the application of different interventions or strategies in parallel.

One problem that it can present is its high degree of complexity, since we are talking about a model with 4 dimensions: SSP scenarios, RCP scenarios, SPA scenarios and time itself.

- In this project, a case of application of this type of models has been summarized (Volta, Mahanadi and Ganges). Although it does not go into detail, its incorporation in the study has the objective of offering an example as well as its computation in a deltaic region.

The next point from which we will explain its conclusions is that of the delta risks, analysis of the coastal fringe and hazard map:

- In the first instance, it can be affirmed that the Ebro delta is mainly dominated by marine processes, and with events such as climate change and the SLR these marine processes are greatly accentuated. As previously mentioned, factors such as the low altitude of its emerged area with respect to the MSL and anthropic actions such as the creation of dams and reservoirs also increase these marine events.
- Marine erosion, the effect of waves, the lack of sediments, factors such as climate change and the use of this area for economic purposes are the main responsible for the current weakness that the region presents.
- During the creation of the hazard map, using the ArcGIS software, it has been obtained that the impact of the SLR on the coastal strip of the delta is very considerable, especially at the end of the century and in unfavorable climatic scenarios. It is so much the impact that areas such as Punta de la Banya, Barra del Trabucador or urban areas such as Poble Nou or Riumar could be partially or totally flooded.
- It can be firmly stated that the defensive capacity of the delta against storms with very high return periods (50-100 years) is nil. Not only in the results of the ArcGIS model it is demonstrated, but also after seeing the damage caused by the storm Gloria.
- The little amplitude and lack of re-naturalization make the delta beaches vulnerable to marine erosion processes. 6 of the 10 selected beaches would be totally eroded in the face of a storm with a return period of 10 years.
- After analyzing all the sectors that make up the coastline, it has been obtained that the most important hot-spots (and therefore the most vulnerable) are Barra del Trabucador, Riumar beach and Migjorn beach.

Regarding the selection of alternatives and possible interventions, as well as the creation of the Dynamic Adaptive Policy Pathways, we can conclude the following:

- The selection of alternatives to guarantee the survival of the delta has tried to be as broad as possible: from hard and soft engineering solutions, through more natural strategies to alternatives such as retreating to the inland. Many other interventions (such as elevating the buildings as in the Mississippi Delta) have been considered, but after analysis and deliberation they have been ruled out.
- Regarding the classification and scoring of each intervention, it has been based on historical data, technical information on the strategy (such as the price of execution or construction), news and opinions published on the internet about past actions. Even so, it can be firmly concluded that doing an analysis of this caliber can be very complex and for greater effectiveness it should be carried out with a group of experts in the field. The time each strategy could last has also been based on the same basis.
- Regarding the adaptation pathway, it can be said that it is a very useful tool when making certain decisions. Each branch has to be thought of in a logical sense, so it requires a certain understanding of the situation that is being analyzed. Attempts have been made to avoid paths that started with natural actions and led to hard engineering actions.
- Finally, the preferred pathways have been based both on the results obtained during the project and on the current criteria of the administration of the area. In any case, it has been avoided to choose favorite pathways based on more extreme alternatives such as polderization or managed withdrawal.

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