Environmental and economic impacts of sea-level rise on the Basque Coast

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ENVIRONMENTAL AND ECONOMIC IMPACT OF SEA-LEVEL RISE ON THE BASQUE COAST

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A mis padres, Angel y Elisa, que siempre han creído en mi mucho más que yo misma.

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Acronyms

4AR	IPCC Fourth Assessment Report
5AR	IPCC Fifth Assessment Report
BOD	Bilbao Ordnance Datum
DTM	Digital Terrain Model
GBSLR	Geology Based Sea-Level Rise
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geographic Information Systems
IPCC	Intergovernmental Panel on Climate Change
IRSL	Feldspar Infrared Stimulated Luminescence
LiDAR	Light Detection And Ranging
LIG	Last Interglacial stage
MAHT	Maximum Astronomic High Tide
MPA	Máxima Pleamar Astronómica (see MAHT)
MIS	Marine Isotope Stage
MSL	Mean Sea Level
NMM	Nivel Medio del Mar (see MSL)
OECD	Organisation for Economic Co-operation and Development
OSL	Optically Stimulated Luminescence
PSMSL	Permanent Service for Mean Sea Level
SAR	Single-Aliquot Regenerative-dose
SRES	Special Report on Emissions Scenario
SSP	Shared Socio-economic Pathways
TAR	IPCC Third Assessment Report
UBR	Urdaibai Biosphere Reserve
UN	United Nations

Abstract

Among the projected impacts of climate change, sea-level rise poses a major threat to coastal areas. These impacts are expected to be particularly serious considering that much of the world's population is concentrated in these areas. The Basque Coast is not an exception.

This dissertation complements a geological approach, from which to analyse and design different scenarios of recent changes in sea level, together with a socioeconomic approach, which translates and monetizes the biophysical impacts on three case studies. Additionally, we analyse the role of ecosystem services provided by wetlands on damage mitigation due to sea-level rise and ecosystem-based adaptation.

Along the history of Earth, both climate and sea level experienced important variations. The geological methodology is based on the study of recent changes of sea-level through the study of microfossils (foraminifera). This way, instead of using climate modelling to project future scenarios, we use past sea-level data to estimate sea-level by 2100. This is an innovative approach, built on what already happened on Earth during a specific period of its history. The primary objective is to develop four future scenarios of sea-level rise using estimations for different recent geological periods, namely the Anthropocene (1900AD-present), Holocene1 (7000-1900AD), Holocene2 (11000-7000BP) and the last Interglacial (LIG). The age of this last scenario has been estimated using luminescence dating techniques of a coastal sedimentary sequence found in Oyambre (Cantabria). The probable depositional age of the basal beach environment of the sequence would be ca. 116 to 108 ky.

The economic approach focuses in translating the sea-level rise scenarios into economic impacts on the coastal systems potentially affected using Geographical Information Systems and flood maps. The impacts are measured considering three case studies: the Urdaibai Biosphere Reserve Estuary, the urban area along the Plentzia Estuary and the industrial area in the Muskiz Estuary (Petronor oil refinery).

Based on the loss of salt marsh area, the costs of sea-level rise on these ecosystems has been measured. By 2100, the rise of mean sea level under Scenario 3 would cause an impact of 310,000-612,000 euros (2013) in Urdaibai, depending on the discount rate used. In Plentzia, the costs would reach 288,000-756,000 euros (2013), while in Muskiz no salt marsh loss is expected.

With regard to the impacts on the urban area around the Plentzia Estuary, no damages are expected under Scenario 2. Damages would be relatively small under Scenario 1. The costs by the end of the century range between 4.000 y 680.000 euros, depending on the discount rate used. Damage costs increase significantly under Scenario 3 and the impacts could reach between 0.1 and 12.3 million euros in 2100.

The results of this project should contribute to raise awareness of regional policy makers and urgency of action to address adaptation to climate change. Furthermore, the range of economic impact estimates are expected to be useful for the policy making process.

Resumen extendido

Los cambios climáticos han ocurrido en innumerables ocasiones a lo largo de la historia de la Tierra. Concretamente el periodo Cuaternario en el que vivimos se caracteriza por un gran número de oscilaciones climáticas entre fases glaciares frías e intervalos interglaciares más templados durante sus 2,6 millones de años de duración.

Sin embargo, el fenómeno de cambio climático actual es de otra naturaleza. El último informe del Panel Intergubernamental para el Cambio Climático (IPCC) publicado en 2014 afirma que el calentamiento del planeta es inequívoco y que este fenómeno está causado por el ser humano. Algunos de los efectos de estos cambios están siendo ya observados: desde 1880 hasta 2012 CE la temperatura media de la Tierra aumentó en 0,85°C. El ascenso del nivel del mar se está acelerando y se han registrado importantes daños asociados eventos extremos, tales como huracanes o sequías. Pero además se espera que estos efectos se acentúen en el futuro. De hecho, aunque a corto plazo se adoptara un acuerdo internacional ambicioso en materia de reducción de emisiones, la propia inercia del sistema climático causará impactos a los que el ser humano deberá enfrentarse.

El País Vasco no va a quedar al margen de estos cambios. Se espera que a final del siglo XXI las temperaturas máximas puedan aumentar 1,5°C en las zonas costeras pero podrán llegar hasta 3,5°C en el resto de áreas. También se prevé un aumento de las temperaturas mínimas, que será más acusado en la región biogeográfica mediterránea. Del mismo modo, se espera que las diferencias estacionales se acentúen: en la vertiente atlántica las temperaturas invernales podrían subir entre 1,5 y 2°C pero este ascenso podría triplicarse durante el verano. Aunque la modelización de las precipitaciones es compleja, se han previsto reducciones de entre un 15 y un 20%. Pero además en un país con una topografía abrupta, donde el 60% de la población y un tercio de las actividades económicas se concentran en la costa, los cambios en el nivel del mar pueden representar una amenaza grave. La velocidad de ascenso del nivel del mar en la costa vasca desde principios del siglo XX ha sido de 2 mm año^{-1}, una velocidad casi 4 veces mayor que la registrada durante los 7000 años anteriores. Para finales de siglo, las últimas proyecciones regionales muestran ascensos del nivel del mar entre 41 y 57 cm, en función del escenario considerado.

En este contexto, las políticas de adaptación al cambio climático van a ser una pieza fundamental para reducir la vulnerabilidad de nuestra sociedad. Afortunadamente, la implementación de estas políticas tiene una fuerte componente local y regional. Esta es una característica esencial puesto que este tipo de actuaciones pueden promoverse en el marco de las competencias autonómicas y locales, sin necesidad de esperar a la adopción de grandes acuerdos internacionales.

El objetivo principal de esta tesis doctoral es, precisamente, generar información en materia de cambio climático a escala local y regional que pueda servir como input para el desarrollo de políticas de adaptación en el País Vasco.

Para alcanzar este objetivo, la Memoria de Tesis se desarrolla en dos partes bien diferenciadas. Por un lado, la construcción de escenarios de ascenso del nivel del mar basados en el registro geológico: estos escenarios serán la base para definir mapas de inundabilidad e identificar los elementos más expuestos. Por otro, la estimación de los daños económicos potenciales derivados de cada uno de los escenarios del ascenso del nivel marino en tres zonas de la costa vasca: la reserva de la Biosfera de Urdaibai, el área urbana de Plentzia y la zona industrial de Muskiz, actualmente ocupada por la refinería de Petronor (Repsol). Ambas partes se describen en detalle a continuación.

Parte I. Una aproximación al ascenso del nivel del mar desde la Geología

En este trabajo, las curvas de ascenso futuro del nivel marino se desarrollan tomando como base los cambios en el nivel del mar ocurridos en el pasado geológico reciente. Estos escenarios, aunque no son proyecciones, pueden aportar información relevante para mejorar el conocimiento sobre la magnitud o rapidez de los cambios esperados y cómo éstos pueden afectar a nuestros sistemas naturales y humanos.

Los tres primeros escenarios se han definido a partir de la velocidad de ascenso del nivel marino registrada en la costa vasca durante el Holoceno y el Antropoceno. Para ello se han utilizado los datos obtenidos en estudios previos, que desarrollaron una función de transferencia a partir del contenido de foraminíferos bentónicos presentes en los sedimentos de marismas de Urdaibai, Plentzia, Muskiz y Santoña. Está función de transferencia les permitió inferir el paleonivel del mar durante el Holoceno.

El primer escenario representa el ascenso del nivel marino durante el Antropoceno (siglo XX), medido en 2 mm año^{-1}; el segundo escenario se basa en la velocidad de aumento del nivel del mar registrada en la segunda parte del Holoceno, desde 7000 años cal BP hasta principios del siglo XX; el tercer escenario implica un ascenso drástico del nivel del mar de 10 mm año^{-1}, tal y como ocurrió durante la primera parte del Holoceno como consecuencia del final de la última glaciación. Estas velocidades de ascenso del nivel del mar se han utilizado para construir tres escenarios de ascenso desde el año 2010 hasta 2100 CE.

El cuarto escenario se ha construido a partir de los materiales de una secuencia sedimentaria costera ubicada en la playa de Oyambre (Cantabria). Esta secuencia sedimentaria había sido identificada en estudios previos como una paleoplaya colgada, varios metros por encima del nivel del mar actual, por lo que la hipótesis de partida era que representaban un paleonivel marino, probablemente correspondiente al último periodo interglacia (LIG). A escala global el nivel del mar durante el LIG se ha estimado entre 4 y 6 m por encima del nivel actual. Para determinar si efectivamente dichos materiales correspondían al LIG se llevó a cabó una toma de muestras para su datación mediante luminiscencia.

La datación por luminiscencia se basa en la cualidad de diversos minerales, como el cuarzo o el feldespato, para almacenar energía en sus estructuras cristalinas durante su enterramiento. Cuando los minerales se someten a determinados estímulos, por ejemplo el aumento de temperatura, liberan la energía almacenada en forma de luz o calor. Los minerales de cuarzo o feldespato presentes en las arenas de playa reciben energía del sol y ponen su reloj geológico a cero y cuando estos sedimentos son enterrados, comienzan a almacenar radioactividad ambiental hasta que son sometidos a un nuevo estímulo. Por tanto, cuanto más tiempo transcurre desde el enterramiento, mayor es la energía almacenada. En este estudio se han utilizado métodos de luminiscencia óptica

(OSL) para determinar la edad de los sedimentos costeros de Oyambre. Los resultados de la datación muestran que la edad probable de los materiales de la paleoplaya se encuentra entre 116 y 108 cal. ky, por lo que se corresponden con el LIG.

La base de los depósitos de la paleoplaya, que representaría el nivel mínimo del mar, está ubicada 6,901 m por encima del cero de Bilbao por lo que ésta es la referencia utilizada para construir el cuarto escenario de ascenso del nivel del mar. Aunque este nivel representa un máximo alcanzado por el mar en la costa cantábrica en el pasado y coincide con las estimaciones realizadas a escala global para los próximos siglos, no es posible determinar si se volverá a alcanzar, ni en qué fecha. Este escenario debe, por lo tanto, analizarse con precaución.

Además de los escenarios de ascenso del nivel del mar, también se ha considerado la capacidad de las marismas para acrecer en respuesta al ascenso del nivel marino. Esta resulta una cualidad extremadamente valiosa desde una perspectiva de adaptación, puesto que si la velocidad de ascenso del nivel del mar no supera un cierto umbral, las marismas del País Vasco serán capaces de adaptarse y mantener su posición relativa respecto a dicho nivel. Diversos estudios previos han medido que las marismas en estado natural acrecen a una velocidad de entre 0,5 y 3,7 mm año^{-1}, mientras que las marismas en regeneración lo hacen más rápidamente (14-18 mm año^{-1}), hasta que alcanzan el estado de equilibrio en aproximadamente una década.

Los cuatro escenarios, junto con la capacidad de acreción de las marismas, se han utilizado para construir los mapas de riesgo de inundabilidad para los estuarios de Urdaibai, Plentzia y Muskiz. Para ello se han utilizado sistemas de información geográfica (GIS). Las zonas inundadas se han definido en base a dos niveles marinos: el nivel medio del mar (NMM) y la máxima pleamar astronómica (MPA). El primero representaría una inundación permanente, mientras que el segundo se plantea como un posible análogo de un evento extremo.

Los mapas de riesgo muestran que el incremento de las superficies afectadas en los Escenarios 1 y 2 es prácticamente despreciable. Sin embargo, se observan impactos considerables en el Escenario 3. En Urdaibai los impactos derivados del ascenso del NMM se concentran principalmente en las playas, que experimentarían retrocesos importantes. Los impactos asociados al aumento del nivel de MPA afectarían no sólo a sistemas naturales sino también a sistemas socioeconómicos, especialmente a partir de 2080 CE. En Plentzia, los cambios en el NMM en el Escenario 3 afectarían fundamentalmente a zonas de marismas, pero el nivel de MPA afectaría de forma sustancial a las zonas urbanas, algunas ya desde 2030 CE. En Muskiz sólo se observan impactos en el barrio de Pobeña a partir de 2080 CE y únicamente considerando el nivel de MPA.

El Escenario 4 daría lugar a impactos críticos en todas las zonas de estudio, aunque hay que recordar que se trata de un escenario a largo plazo (en los próximos siglos). En Urdaibai la mancha de inundación alcanzaría buena parte del municipio de Gernika y en Plentzia afectaría a las partes más bajas del núcleo urbano. En Muskiz se vería afectada casi la mitad de la superficie actual de la refinería de Petronor.

Parte II. Impactos económicos asociados al ascenso del nivel del mar

De todos los aspectos relacionados con la economía de la adaptación, el presente estudio se centra en dos de ellos: las tasas de descuento y la valoración económica. Las tasas de descuento se utilizan para determinar el valor actual de un coste o beneficio en el futuro. De esta manera, tasas más bajas se traducen en un valor actual mayor de un coste o beneficio futuro, y viceversa. Por ejemplo, utilizando tasas altas, próximas a las de mercado, se obtendría un valor actual menor del coste económico de un evento extremo futuro. Esto podría tener como consecuencia el retraso en la implementación de una medida de adaptación. Sin embargo, utilizar una tasa de descuento más baja mostraría un valor actual mayor de los impactos futuros que podrían justificar la adopción de medidas a corto plazo. Por otro lado, y siguiendo con el ejemplo, tasas de descuento más bajas implicarían un esfuerzo o sacrificio mayor a la generación actual frente a las generaciones futuras que, en principio y de acuerdo con la teoría económica general, serán más ricas. Aún hoy existe un amplio debate en relación al tipo de descuento que debe aplicarse al evaluar problemas ambientales globales, pero la utilización en el Informe Stern de una tasa de descuento próxima a cero supuso un hito a favor del uso de tasas más bajas en contextos de cambio climático.

Siguiendo esta línea de razonamiento que aboga por el uso de tasas de descuento más bajas, en este estudio se utiliza el Principio de Equivalencia para estimar las tasas de descuento que deben aplicarse cuando se valoran los costes y beneficios proporcionados por las marismas de Urdaibai, Plentzia y Muskiz en el futuro.

En relación con la valoración económica, se utilizan dos metodologías para estimar los costes del cambio climático. En primer lugar, para la estimación de los beneficios de los servicios ecosistémicos que proveen las marismas en los tres casos de estudio, se ha utilizado una función de transferencia, basada en un meta-análisis desarrollado con datos de valoración económica de humedales de Europa y Norte América. Esta función estadística ha sido adaptada a las marismas vascas utilizando los datos de superficie de cada una, la población del entorno y el producto interior bruto regional. Los resultados muestran que las marismas aportan unos beneficios que varían entre 12.200 euros por hectárea y año en el caso de Urdaibai y 22.700 euros por ha y año en el de Plentzia. Hasta final del siglo XXI, las marismas de Urdaibai en su conjunto podrían aportar unos beneficios de 185-299 millones de euros. Más modesta es la aportación de Plentzia y Muskiz, puesto que su extensión es muy inferior a la de Urdaibai. En Plentzia los beneficios acumulados alcanzarían 14-22 millones de euros y en Muskiz entre 15 y 24 millones de euros.

Los costes del cambio climático se han calculado en función de la pérdida de marismas, en término de beneficios no prestados. El ascenso del NMM en el Escenario 3 generaría una pérdida permanente de marismas que se traduciría en una pérdida de los servicios ecosistémicos provistos. La valoración económica de esta pérdida variaría en el caso de Urdaibai entre 310.000 y 612.000 euros hasta final de siglo, apenas un 0,2%. En Plentzia las pérdidas podrían alcanzar en 2100 CE el 23% en superficie y el 3% en términos económicos, entre 288.000 y 756.000 euros. En Muskiz las marismas no se verían afectadas de forma permanente.

Estos daños económicos relativamente pequeños se deben a dos cuestiones, principalmente. En primer lugar, la capacidad de las marismas para acrecer y mantener su altura relativa respecto al nivel del mar. Una velocidad de acreción de 2 mm año^{-1} neutraliza el ascenso de los Escenarios 1 y 2 y supone una respuesta importante respecto al Escenario 3. En segundo lugar, los mayores impactos ocurren a final de siglo, por lo que debido a la aplicación de las tasas de descuento su valor actual es menor, aunque el impacto físico sea mayor.

El análisis de los daños económicos asociados a zonas urbanas se centra en el caso de estudio de Plentzia y para ello se ha utilizado una metodología habitual en la estimación de daños por inundación. Primero se han estimado las características físicas de la inundación, específicamente la extensión y profundidad de la misma, para cada escenario, aunque considerando sólo el nivel de MPA, puesto que era el único que generaba daños por inundación. Para ello se han utilizado los mapas de riesgo desarrollados anteriormente para el área urbana entorno al estuario de Plentzia. Posteriormente se ha realizado una identificación en detalle de los elementos en riesgo, clasificándolos en base a diversas categorías (tipo de vivienda, locales comerciales, garajes…). Finalmente, se lleva a cabo la valoración económica para lo cual se han utilizado las unidades de referencia de dos estudios previos realizados en el País Vasco.

Los resultados obtenidos muestran que en el Escenario 2 no se generarían daños, mientras estos serían relativamente pequeños en el Escenario 1, que en el año 2100 CE variarían entre 4.000 y 680.000 euros en función de la tasa de descuento utilizada. En el Escenario 3 los daños aumentan significativamente, pudiendo alcanzar entre 0,1 y 12,3 millones de euros en 2100 CE. En el caso de Muskiz, no se observan impactos sobre la zona industrial en ninguno de los escenarios considerados en el análisis económico (Escenarios 1-3).

1 Introduction[1]

The latest report from the Intergovernmental Panel on Climate Change is more clear than ever before when it states that the "warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen" (IPCC, 2014a: 2). According to the same report, the anthropogenic origin of many of these changes is also out of question as it declares that "human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases (GHGs, hereafter) are the highest in history. Recent climate changes have had widespread impacts on human and natural systems" (IPCC, 2014a: 2).

But unlike other global challenges, climate change shows some features that make it probably the greatest global challenge humankind has ever faced. Firstly, there is a great uncertainty regarding the impacts of climate change at the global, regional or local scales. Secondly, and even if some of the impacts are already being observed, many of the effects and the most critical ones will occur in the long term, during the second half of the 21st century and beyond. Thirdly, the responsibility and contribution of each country to this global challenge has not been and it is not being the same, so their contribution to the solution cannot be the same either. It is clear that the compromise of developed countries such as Europe, the United States, Canada or Australia cannot be the same as that of developing countries or even fast growing countries such as China, Brazil or India (Galarraga and Markandya, 2009).

To face such a challenge, a multidisciplinary approach is indispensable. The knowledge of the biophysical factors is necessary to understand the sources and effects of climate change, also to estimate their future evolution. But we should not forget that these changes will have an impact in the socio-economic systems, and neither should we omit the role of climate negotiations and policies for providing solutions at different scales. Probably, the need for a close interrelationship between natural and social sciences has never been greater (Gallastegui et al., 2009).

Following this idea, in this dissertation a multidisciplinary approach has been conducted to assess the impacts of sea-level rise in the Basque coast. In the first part of the document, a geology-based approach has been used to estimate the potential impacts of sea-level rise on natural and human systems. In the second part, the risk of coastal flooding has been valued in monetary terms in order to know the magnitude and timing of the expected impacts. This chapter introduces the problem of climate change and, more specifically, sea-level rise, both from a biophysical and a socio-economic perspective.

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[1] This chapter is partially based on the work published in Sainz de Murieta, E., Galarraga, I., Markandya, A., 2012. Klima aldaketa sozioekonomiaren ikuspegitik. EKAIA Special issue, 197–235.

1.1 Global impacts of climate change

According to the IPCC, there is undeniable evidence that the planet is warming: from 1880 to 2012 the average temperature increased in 0.85°C, and temperature is not the only indicator of a changing climate. Sea-level rise has accelerated and changes in the pattern of extreme events have also been observed since 1950. In fact, the registered temperature increase has been compared to that expected only due to natural forcings, and also to the expected effect of GHG forcing as well and the IPCC considers extremely likely (i.e. with a probability of 95-100%) that human GHG emissions have caused more than 50% of the average surface temperature increase from 1951 to 2010. In fact, the concentration of CO_2 in the atmosphere has increased 40% since the pre-industrial time (1750), and in 2011 reached 390.5 ppm (IPCC, 2013a). All these changes are already affecting many human and natural systems. Some of the main impacts currently identified have been included in Box 1.1.

Box 1.1. Observed impacts of climate change

- Almost all glaciers world-wide have continued to shrink since the IPCC Fourth Assessment Report - AR4 (IPCC, 2007a), affecting runoff and therefore water resources and availability downstream as well as sea-level rise.
- Warming has caused migration in many terrestrial species and shifts in the abundance and geographic distribution of marine species, with threats to ecosystems and food security.
- Crop yields, such as wheat and maize, have been impacted negatively especially in low latitudes. This is affecting and will affect food security and local livelihoods.
- Extreme events like flooding and heat waves have affected infrastructures and human health.
- Economic losses, especially due to extreme weather events, have multiplied globally.

Source: Sainz de Murieta et al. (2014)

Additionally to current climate change impacts, the latest IPCC Working Group II Report on impacts, adaptation and vulnerability (IPCC, 2014b) addresses future risks across sectors and countries under two emission scenarios[2]: the low emission scenario (RCP2.6), under which global temperature stays at 2°C above preindustrial levels. In the high emission scenario (RCP8.5) temperature could increase more than 4°C over that of the reference period. During the first half of the 21st century, both scenarios run close to each other with no meaningful differences between them. Actually, in the near term, up to the year 2040 approximately, non-climate stressors will be dominating. However, after this period the two emission scenarios clearly diverge and dramatic consequences, extensive impacts on natural and human systems as well as possible crossing of tipping points could occur under the most pessimistic scenario. In this sense, the larger magnitude of global warming, the more likely it will be to suffer severe and irreversible impacts (Sainz de Murieta et al., 2014).

A summary of future risks across sectors and regions grouped into five reasons for concern (RFCs) is presented in Box 1.2. First introduced in the IPCC Third Assessment Report - TAR, they represent risks that are determined by both climate-related hazards and the vulnerability and exposure of

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[2] RCPs (Representative Concentration Pathways) are a new set of future climate scenarios. The four pathways are independent and have been developed by four individual modelling groups. The numbers represent the radiative forcing levels (global energy imbalances) by the year 2100: very low (RCP2.6), medium (RCP4.5 and RCP6) and very high (RCP8.5). (Source: IIASA – RCP Database and van Vuuren et al., 2011).

social and ecological systems to climate change stressors (IPCC, 2014c). In fact, the importance of the interaction between many non-climatic stressors, such as land-use change, poverty, inequality, pollution, etc. and climate change impacts is stressed throughout the report. For instance, the damages associated with coastal flood risk in major coastal cities worldwide would multiply by seven by the year 2050 only due to population growth and socio-economic development. Anthropogenic climate change would further amplify these damages (Hallegatte et al., 2013a).

Box 1.2. Five reasons for concern: summary of risks across sectors and regions

- Unique and threatened systems are a wide range of physical, biological and human systems that are restricted to relatively narrow geographical ranges and are threatened by future changes in climate (e.g. polar human and natural systems, coral reefs, unique alpine ecosystems and species).
- Extreme weather events: there is medium confidence that risks associated with coastal and river flooding, heat waves, cyclones, droughts and other extreme events will increase with increasing global temperatures.
- Distribution impacts: impacts will not be equally distributed among regions, nations or time. Unfortunately, the most vulnerable areas and people are often the most exposed and developing countries which have contributed less to climate change will suffer most from its impact. However, this unequal distribution not only happens at the international level: the most vulnerable groups and sectors of developed countries are also at stake.
- Global aggregate impacts include risks that are aggregated globally into a single metric, such as monetary damages, lives, species or ecosystems lost. Moderate risks to the global economy and biodiversity have been estimated for a temperature increase of 1-2°C. Risks are high if temperature increases beyond 3°C (low agreement for risks on the economy and high confidence on biodiversity).
- Large-scale singular events are abrupt and drastic changes in physical, ecological, or social systems in response to smooth variations in driving forces. The precise level of climate change needed to cross critical thresholds or tipping points remains uncertain, but a temperature increase between 1°C and 4°C implies a high risk of crossing tipping points. An example of this large scale singular event is the deglaciation of the Greenland ice-sheet, which could cause up to 7 m of sea-level rise during the next centuries and millennia.

Source: Sainz de Murieta et al. (2014), based on IPCC (2014c), Box TS.5.

Sea-level rise

Of all impacts of climate change, this study focuses on the potential impacts derived from sea-level rise. Many cities and critical infrastructures are located in coastal zones and therefore a great part of the world population concentrates in these areas (Woodworth et al., 2010; Ciscar et al., 2011). Coastal development around the globe has accelerated in the last 60 years, coinciding with the Great Acceleration described by Steffen et al. (2015). At the same time, sea levels are rising and additionally an increase in the magnitude and frequency of extreme events can be expected in the future. Thus, coastal zones are already among the most vulnerable areas and face a great challenge to cope with the impacts of climate change.

Global ocean and coupled atmosphere-ocean general circulation models (AOGCMs), first developed in the 1960s, are the basis for the projections of global averaged steric[3] sea-level rise, including the IPCC assessments. The regional distribution of the change in sea level has also been assessed using these models, even though this regional distribution will also depend on geophysical processes, such as glacial isostatic adjustments[4] (Church et al., 2010b).

The IPCC AR4 included a projection of global sea-level rise by the end of the 21st century ranging between 18 and 59 cm, depending on the Special Report on Emissions Scenario (SRES) considered. This projection included contributions of models considering ocean thermal expansion[5], as well as the contribution from glaciers and ice caps and the Greenland and Antarctic Ice Sheets. The AR4 report also evaluated the risk of a rapid dynamic response of the Greenland and West Antarctic Ice Sheets, which could result in an accelerating contribution to sea-level rise of 10-20 cm by 2100. However, the report emphasises the insufficient understanding of these dynamic changes to provide the likelihood of this change.

Nevertheless, understanding changes in sea level is a difficult physical problem and large uncertainties exist even in the projection of thermal expansion (Rahmstorf, 2007). According to this author, present physics-based models have strong limitations to predict future sea-level changes based on surface warming scenarios. In fact, observed sea-level rise since 1990 is close to the upper bound of the IPCC TAR and AR4. Projections estimated in both reports are similar, particularly in the upper bound: projections corresponding to all models and scenarios in TAR predicted a range of sea-level rise of 20-70 cm by 2100, while AR4 projections from ocean thermal expansion, glaciers, ice caps and modelled ice-sheets contributions estimated a change in sea level of 18-59 cm by 2095 (Church et al., 2010b). AR4 projections also considered the rapid dynamic change of Greenland and West Antarctica ice-sheets. Quantitative projections were not available but making some assumptions, the authors estimated an increase in the upper bound of sea-level rise of 10-20 cm depending on the scenario (Meehl et al., 2007).

The recently approved IPCC Fifth Assessment Report - AR5 (2013a) analyses several approaches when projecting the changes in future sea level. The first approach refers to projections of *process-based physical models*. These calculate the contribution of each factor (thermal expansion, glaciers, Greenland and Antarctica ice sheets and land water storage) to the change in sea level. The likely[6] range of sea-level rise estimated in the recently published AR5 varies between 0.28-0.97 cm by 2100, relative to the period 1986-2005 (Church et al., 2013) (see Figure 1.1). Considering the consistency between the modelled results and the observed processes, the IPCC shows medium confidence in these projections.

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[3] The steric contribution of sea-level rise is the sum of the contributions from temperature (thermosteric) and salinity (halosteric) changes (Church et al., 2010a).

[4] Glacial isostatic adjustments are the vertical movements of the land associated with the disappearance of the great ice sheets formed during the last ice age (Woodworth et al., 2010).

[5] Thermal expansion "refers to the increase in volume (and decrease in density) that results from warming water. A warming of the ocean leads to an expansion of the ocean volume and hence an increase in sea level" (IPCC, 2013: 1463).

[6] Likely is used following the term used in AR5 and meaning a "likelihood of an outcome" of 66-100% (Church et al., 2013).

The second approach analyses *semi-empirical models (SEM)* that use the relationship between sea-level rise and other parameters of the climate system in the past to project future changes. Since 1993, sea-level rise has risen at faster rate than the average predicted by the IPCC: 3.4 mm yr^{-1} *versus* the predicted rate of 1.9 mm yr^{-1} (Rahmstorf, 2010). In fact and as mentioned before, the rise of sea level lies close to the projected upper limit (Rahmstorf et al., 2007). The SEM approach arises as an alternative to cope with some limitations that process-based projections show when comparing their results with the observed change in sea level. Several authors using this approach have predicted a much bigger sea-level rise for the 21st century than that projected by the IPCC (see Figure 1.2).

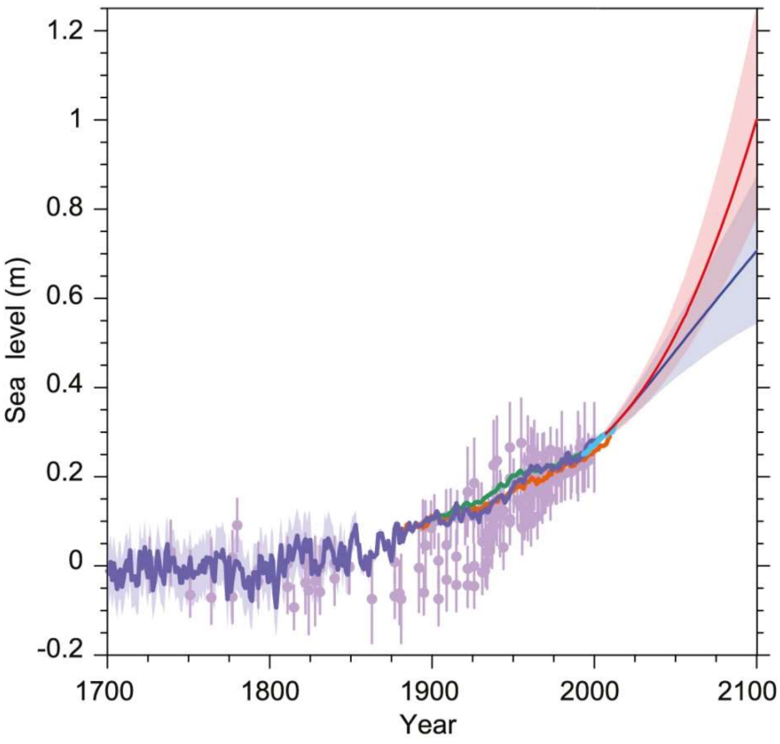

Figure 1.1. Compilation of palaeo sea-level data, tide-gauge data, altimeter data, and central estimates and likely ranges for projections of global mean sea-level rise for RCP2.6 (blue) and RCP8.5 (red) scenarios, all relative to pre-industrial values. Source: Church et al. (2013), Figure 13.27.

At present, however, the IPCC understands that there is low confidence in the results of the SEM approach for two main reasons: firstly, because these methods imply that future sea-level rise will happen following the same relationship with physical drivers as it has done so far and this should not necessarily be so; and secondly, because it seems to be low scientific consensus about the reliability of this methodology (Church et al., 2013).

The third approach is based on palaeo-records of sea level during previous interglacial periods. However, the forcing factors for current climate change and those occurred in the past may have been different and the effects may therefore be different as well, so the IPCC shows low confidence in these results. Yet, palaeoclimate information has gained importance in AR4 and AR5 which contain a specific chapter dedicated to the Palaeoclimate Archives (Chapter 5), which could suggest a contradiction with this conclusion included in the chapter devoted to changes in sea levels (Chapter 13). Additionally, in depth knowledge of past processes may provide valuable information on other aspects such as process interactions or the rates of change (Oldfield, 2005).

The fourth and last approach is focused on ice-sheet dynamical change and its potential contribution to sea-level rise. Although scenarios obtained by several authors seem physically possible, the results differ greatly and the likelihood cannot be quantified.

Due to all the above mentioned circumstances, and concerning global sea-level rise, Church et al. (2013) show a higher confidence in process-based projections rather than the rest of the approaches. However, which approach shows better or more exact results remains to be seen.

Additionally to sea-level rise, the IPPC AR5 concludes that it is very likely that sea-level extremes will happen more frequently.

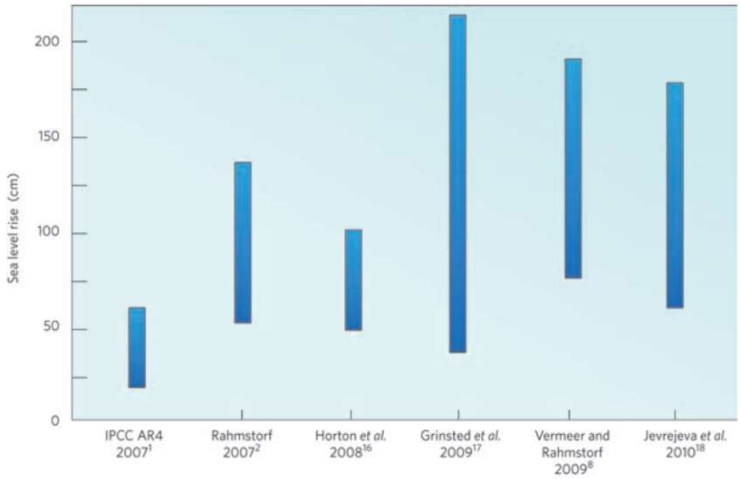

Figure 1.2. Estimates for 21st century sea-level rise from semi-empirical models compared to the IPCC AR4 (from Rahmstorf, 2010).

1.2 A geological approach to climate change

The climate system, as defined by the IPCC (2013b: 1451) is a “highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and anthropogenic forcings”. In fact, the Quaternary Period in which we are living now, is characterised by frequent changes in Earth’s climate and one of the many consequences resulting from these climate changes were the associated changes in global sea levels.

Being this so, it may seem reasonable to look at these past interglacial stages as potential analogues for future anthropogenic climate change. However, many Earth system components, such as orbital parameters, radiative forcings, landmass topography or ocean circulation, were different and straightforward analogies between past and future climate changes should be avoided (Oldfield, 2005).

Nevertheless, past analogues can play a key role for improving the knowledge on natural *versus* anthropogenic climate variability as climate change will result from the interrelation between natural processes and human activities. It is therefore not only useful, but necessary to look at the past in order to fully comprehend how the undisturbed Earth system has worked before humans (Loutre and Berger, 2003; Oldfield, 2005). We share the opinion that a geological approach of this kind can provide useful information to understand future changes in climate and, more specifically, changes in sea levels. This information may prove to be relevant to cope with or adapt to future impacts as well.

This work focuses on the analysis of sea level during the last interglacial period (LIG), as well as the rate of sea-level rise during the Holocene and Anthropocene epochs.

An introduction to the Anthropocene

The Quaternary, the youngest Period in the history of Earth, is characterised "by the development of widespread glaciations in temperate northern regions, and by associated physical and biotic readjustments" (Gibbard and Head, 2009: 125). First proposed by G. Arduino in 1759, its boundaries were last ratified by the International Union of Geological Sciences (IUGS) in June 2009, lowering the base of the Quaternary System/Period to 2.58 Ma. The base of the Pleistocene Series/Epoch and Gelasian Stage/Age were also lowered making the three boundaries coterminous (Gibbard et al., 2010).

The most recent epoch of the history of Earth is known as the Holocene, which means "entirely recent" (Walker et al., 2009) or "recent whole" (Crutzen, 2006). Its base is established at 11,700 calendar yr b2k (before 2000) based on the NGRIP2 ice core in Greenland which shows an exceptional resolution for the Pleistocene-Holocene boundary (Walker et al., 2009). Despite its short extent, during the Holocene human activities have had an increasing impact on the Earth system, first pointed out as early as the 19th century by Marsh (1864) and Stoppani (1873). The huge influence of humans is now several times greater than ever before. This situation led to Crutzen and Stoermer (2000) to propose a new geological epoch called the "Anthropocene", starting in the late 18th century at the same time as the invention of the steam engine in 1784.

The term Anthropocene was defined to "capture the quantitative shift in the relationship between humans and the global environment" (Steffen et al., 2011) and even if it has been informally used since it was first coined, the official definition of this potential new epoch is currently under discussion by the Anthropocene Working Group of the International Commission of Stratigraphy.

One of most argued issues refers to the starting date for the Anthropocene. Authors such as Ruddiman (2003) supports that the onset should be defined during the Neolithic (8000-5000 years ago) when, according to the author, CO_2 and CH_4 concentrations in the atmosphere increased beyond natural variability coinciding with the beginning of the agriculture in Eurasia.

Crutzen and Steffen (2003) explain that several phases could be identified within the Anthropocene, representing an exponentially increasing degree of change: the first, the one identified by Ruddiman, would represent a small degree of change; the second, from the beginning of the Industrial Revolution (end of the 18th century) up to 1950; and the last stage, from 1950 onwards, the so-called "Great Acceleration", when the rate of change has reached unprecedented levels. In fact, this turning point can be clearly identified for several socio-economic and biophysical indicators, whose evolution from 1750 to 2010. Most of the indicators experience a simultaneous exponential increase around the year 1950, which would support the idea that the beginning of the Anthropocene should be defined in the mid-20th century. Zalasiewicz et al. (2015) share this opinion as this is the moment in time with the most pronounced and globally synchronous signal.

Another issue under discussion is related to the stratigraphic characteristics of the Anthropocene. All previous geological divisions have been defined in geological terms based on "tangible evidence obtained from the rock record" (Zalasiewicz et al., 2011: 1038) while we are actually *living* in the Anthropocene. Still, the current environmental change can also be identified in stratigraphic terms and it seems there is sufficient evidence "for a formal chronostratigraphic definition of the

Anthropocene Epoch" (Zalasiewicz et al., 2011: 1049). In fact, the authors describe several examples of how human activities have shaped the characteristics of the geological record that have been summarised in Table 1.1.

Table 1.1. Stratigraphic evidence as summarised by Zalasiewicz et al. (2011)

Evidences		Some examples
Lithostratigraphy	Modifications of natural sedimentary environments	• River channelling • Building of dams • Coastal reclamation • Erosion by deforestation
	New sedimentary environments and structures	• Cities • Artificial deposits
Chemostratigraphy	Increase in the amount of chemicals due to different human activities, together with its indirect effects, such as temperature rise or biodiversity loss	• CO_2 in the atmosphere • Reactive nitrogen • Particulate reactive iron • Lead • Petroleum products and sub-products
Sequence stratigraphy		• Changes in sea level
Biostratigraphy	The ongoing biological change	• Records of biodiversity change, such as latitudinal migration of species or extinctions • Invasive species

From a lithostratigraphic perspective, human action has reshaped natural sedimentary environments, such as river channels or estuaries and even created new sedimentary environments, like urban areas or artificial deposits. The amount and nature of chemicals in the sediments have also changed as a result of different human activities, as agriculture that increases the amount of N in the soils, industrial processes that produce heavy metals, etc. Changes in sea levels have been registered in coastal sediments and shifts in distributions of species might also be identified in a near future.

If we look at scientific production, the term Anthropocene is being increasingly used in the literature. In November 2015, the Thomsom and Reuters Web of Knowledge database contained 772 publications which included the word Anthropocene as a topic. The search on Google Books also reflects the great scientific interest for this new geological time.

For all these reasons and even if the Anthropocene it is not formally approved as a geological unit, we will use this term to refer to the time period between 1950[7] and the present day.

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[7] The concept of the "Great Acceleration" occurring after 1950 is currently the idea accepted by a majority of members within the Anthropocene Working Group and so this is the starting date considered in this dissertation.

1.3 An economic approach to climate change

In order to cope with climate change, there are two types of actions that can be implemented as it is possible to act limiting the hazards. In the context of climate change this means reducing or avoiding GHG emissions, which is known as *mitigation*. But it is also possible to lower the vulnerability and/or the exposure. In fact, even if mitigation policies were extensively implemented and successful, some impacts will happen anyway due to the inertia of the climate system (Parry et al., 1998). It is therefore crucial to address policies and measures in order to adapt to these impacts and lessen their effects. This is known as *adaptation*. The overall risk of climate change will depend to a great extent on the mitigation and adaptation options to be adopted in the near future (IPCC, 2014c). Even if mitigation has been the major target of climate change policymaking for a long time, adaptation has become now the centre of attention in climate change research and policymaking. This is due both to responses to recent extreme climatic events (specially those hitting developed countries such as huracan Katrina in 2006 or Sandy in 2012), and the realisation that if the mitigation efforts continue to be modest then significant anthropogenic climate change can be expected for the 21st century (IPCC, 2014c).

Economics has much to say in this complex context. In the presence of limited resources, long time horizons, uncertainty and risk, economics can provide key tools and methodologies to identify the most cost-effective policies and measures and to guide the prioritisation process.

From an economic perspective, climate change is considered a negative externality, that happens when “the cost of an activity falls on people other than those who pursue the activity” (Frank and Bernanke, 2007a: 348). Referring to climate change, it is considered a negative externality because it is caused GHGs emitted by one party which cause a loss or damage also to third parties not (necessarily) involved in the activity. Also, those who contribute to climate change do not pay for the effects their activities are generating and the ones suffering the consequences of global warming receive no benefits from being impacted (Stern, 2007; Galarraga and Markandya, 2009). This results in the “overuse of a common property resource” (Harris and Roach, 2007: 3), that is, an overuse of global climate as a public good[8] that leads to a market failure.

The economic theory shows that markets work efficiently when a very restrictive set of conditions are met. According to Gallastegui et al. (2009) and in relation to climate change, three are the conditions to be met: the existence of markets for all the goods or services, the absence of public goods as described above and the absence of external effects of technological nature. Obviously, there is no market for the global climate, thus it can be considered as a global public good and technological external effects are behind the causes of climate change. Thus in economic terms climate change can be considered a market failure. In fact, Stern described climate change as the greatest market failure of all times (Stern, 2007).

It is beyond the scope of this dissertation to carry out a full analysis of the economics of climate change but rather the focus will be on the economics of impacts and adaptation. Impacts and

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[8] In economics, a public good or service is considered as such if it “is, at least to some degree, both non-rival and non-excludable” (Frank and Bernanke, 2007a: 448). Non-excludability means that it is “difficult, or costly, to exclude nonpayers from consuming” the good, while a non-rival good is that “whose marginal consumption by one person does not diminish its availability for others” (Frank and Bernanke, 2007a: 448). Global climate meets both conditions.

adaptation are closely related, as the estimation of impacts both in physical and monetary terms is a key input to the design and evaluation of adaptation policies and measures. Moreover, the benefit of adaptation policies is usually measured in terms of the impacts avoided through the implementation of adaptation, and the methodologies used in both cases are the same (Galarraga et al., 2011c).

1.4 Regional setting: the Basque coast

1.4.1 Geomorphological and geological characteristics

The Basque Country[9] is located in the northeastern coast of Spain. From a geological perspective, the Cantabrian coast follows an E-W orientation and is formed by steep cliffs of Mesozoic-Cenozoic sedimentary rocks. The abrupt relief is due to the tectonic activity occurred during most of the Cenozoic and is only sporadically interrupted by short and narrow estuaries (Cearreta et al., 2002; García-Artola, 2013). Sandbars, beaches and dune deposits separate the estuaries from the open sea and salt marshes are limited to the inner part of these (Leorri and Cearreta, 2004).

This study is focused on three estuaries located in the easternmost part of the Cantabrian coast, namely, the Urdaibai, Plentzia and Muskiz estuaries (Figure 1.3). The Urdaibai Estuary is the largest and best preserved tidal area of the Basque coast (Cearreta et al., 2013). The tidal part of the Oka River is the central axis of the Urdaibai Biosphere Reserve (UBR). It occupies 765 ha and it is 12.5 km long and 1 km wide, representing, approximately, 70% of its original surface (Rivas and Cendrero, 1992; Borja et al., 2004). Human action is responsible for all the area lost so far (more than 300 ha), even though the anthropogenic influence in the Oka Estuary has been smaller than that experienced in other Basque estuaries. Salt marshes cover almost half of the estuarine area. These ecosystems have experienced a gradual regeneration process since the forsaking of agricultural activity during the 1950s and 1960s (Borja et al., 2004; Cearreta et al., 2013). The agricultural crisis and related farm abandonment had other side-effects, unfortunately not as positive from an environmental perspective as the recovery of salt marsh ecosystems: the landscape of Urdaibai changed dramatically due to the expansion of fast turn-over forest monocultures of *Pinus radiata* and *Eucalyptus* sp. during the last decades (Rodríguez-Loinaz et al., 2011).

The Urdaibai Biosphere Reserve, declared as such by Unesco in 1984, was the first protected site of the Basque Autonomous Community and it encompasses a total area of around 22,000 ha. The limits were established as those of the watershed of the Oka River and within these boundaries there are 22 municipalities, although 10 of them are only partially part of the Biosphere Reserve.

The Plentzia Estuary forms the tidal part of the Butroe River. Within the Basque estuaries, it represents a medium size estuary, with a length of 8 km, an average width of 20 m and a total surface of 115 ha. This mesotidal estuary has a mean tidal range of 2.5 m, varying between +1.2 m and +3.7 m (Cearreta et al., 2002; Borja et al., 2004; García-Artola et al., 2011b). According to Rivas and

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[9] In this dissertation the term *Basque Country* refers to the Basque Autonomous Community and not to the bigger cultural area that includes within its limits the Foral Community of Navarre and the Northern Basque area located in Aquitaine.

Cendrero (1992), approximately 63% of its original Holocene surface has been lost due to anthropogenic occupation.

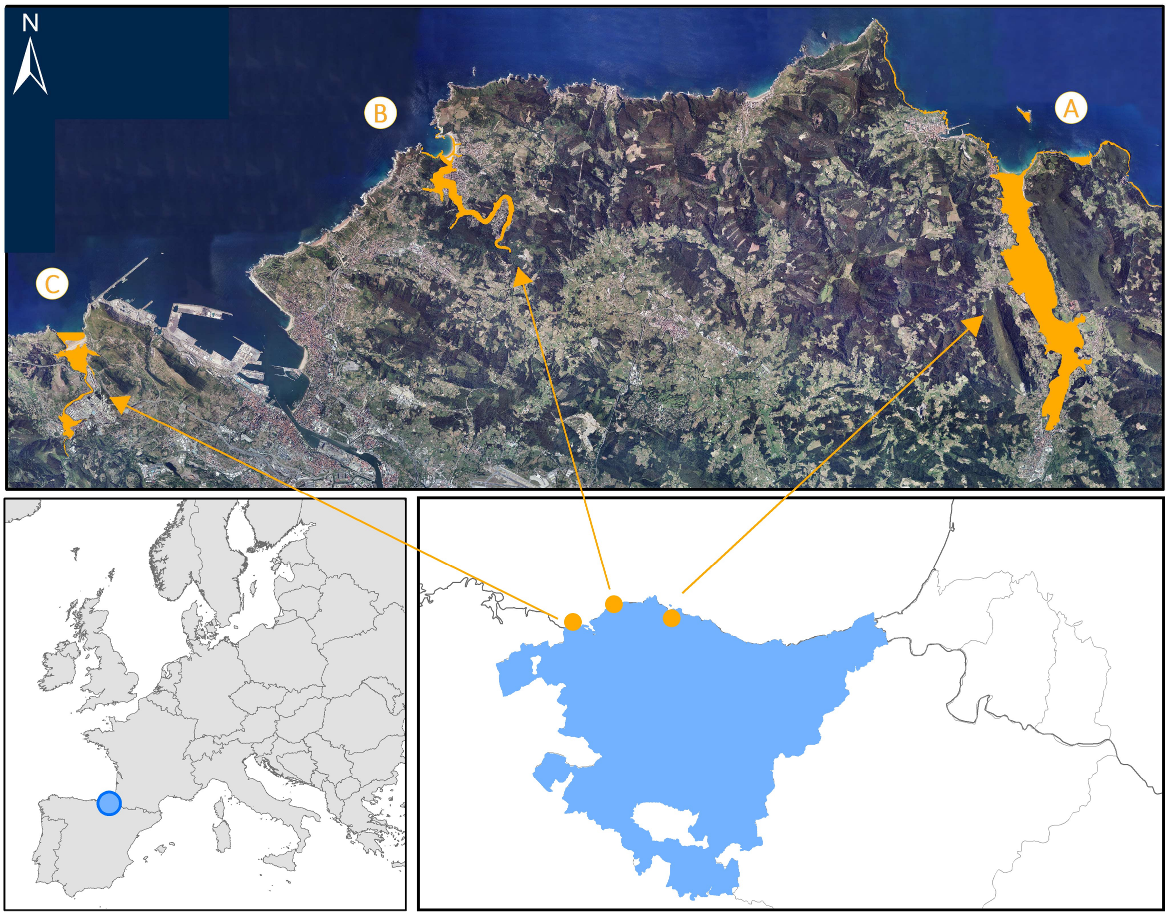

Figure 1.3. Geographical location of the estuaries under assessment: Urdaibai (A), Plentzia (B) and Muskiz (C).

The Muskiz Estuary, that originally occupied 204 Ha, represents the tidal part of the Barbadun River (Cearreta et al., 2008). It is one of the shortest estuaries in the Basque Country, with a total length of 5.6 km and an average width of 5-10 m (Borja et al., 2004). This mesotidal estuary has semidiurnal tides ranging from 4.96 m during spring tides to less than 1.7 m during neaps (Cearreta et al., 2008). Only 19% of the original surface of the estuary is preserved today and 90% of the lost land is due to the human action (Rivas and Cendrero, 1992), and more specifically to the establishment in 1968 of one of the largest oil refinery in the Iberian Peninsula (Petronor, Repsol Group).

1.4.2 Historical evolution

Coastal areas worldwide have been and still are subject to great human pressure (Woodworth et al., 2010) and the Basque Coast is no exception. Most of the pressures during the 17th century were linked to agriculture development. In this context, a marsh reclamation process was carried out for agricultural and disease-eradication purposes; this practice extended until the second half of the 19th century (Cearreta et al., 2002). It has been calculated that more than 50% of the original salt marshes in the eastern Cantabrian region has been lost (Basque Government, 2004) and according to Rivas and Cendrero (1992) marsh reclamation can be considered, by far, the main factor in geomorphological evolution of the Basque coast during the last two centuries.

Fortunately, there have been important steps forward during the last decade. In 2004 the Basque Government approved the Sectorial Spatial Plan for Wetland Protection, which has been a major milestone for the conservation of wetland ecosystems in the Basque Country. Also, some restoration projects have been carried out by regional and local governments[10].

In relation to industrial development, the Basque Country can be described as an old industrial region, i.e. one of the leading regions during the early industrialisation process in the European economy. The region has a strong industrial past, mainly based on the steel and ship-building manufacture, linked to the iron-rich ore resources exploited around Bilbao since the 19th century (González-Eguino et al., 2012). In this period, the estuary of Bilbao, once the greatest estuary of the Cantabrian coast, became the centre of the industrial revolution in the region (Leorri and Cearreta, 2004).

During the 1970s, the crisis hit the industrial sector that once had been the driver of socio-economic growth, especially affecting the iron and steel manufacture. As a result, unemployment rate in the Bilbao Metropolitan Area grew from 2.6% in 1975 to 26% in 1986 (Rodríguez, 2012). A decade later unemployment rate was still 26%, but this changed during the late 1990s and in 2005 it was as low as 6.6% in Bilbao (5.7% in the region), mainly due to the impulse of the regional government in favour of a technology-based industrial policy (Gómez Uranga and Etxebarria, 2000)[11]. Despite the restructuration that followed the crisis and led to the development of new technology-intensive activities and the service sector, the share of the industry in terms of gross domestic product (GDP) is still high (35.5% in 2005) compared to Spain (18.4%) or the EU-27 average (19.7%) (González-Eguino et al., 2012).

1.4.3 Climate change in the Basque Country

Basque contribution to climate change

From the baseline year of the Kioto Protocol (1990) until 2013, CO_2 emissions in the Basque Country have decreased by 10%. In the overall evolution of emissions three phases can be identified (Figure 1.4): a first phase where economic growth and emissions run parallel, approximately from 1990 to 2003. A second phase when decoupleing seems to start and emissions stabilise despite GDP growth. The Basque Plan to Combat Climate Change approved in 2008 anticipated a 14% increase in emissions by 2012 (Basque Government, 2008). However, the third phase shows a reduction of emissions from 2008 onwards, coinciding with the global economic crisis (Basque Government, 2015a).

The figure also shows a significant reduction of the emission intensity, i.e. the ratio of GHG emissions respect to GDP that decreased in 42% during the 1990-2013 period. This lower emission intensity is

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[10] See, for example, the restoration project on the Oka River by the Department of Environment of the Basque Government.

[11] In 1990 the Basque Government defined the first Plan for Technological Strategy, which was followed by the Plan for Industrial Technology (1993-1996) and afterwards by the Plan for Science and Technology that has been updated since then every four years.

due to the combined effect of emission reduction (-10%) and economic growth (+67%). This lower emission intensity therefore represents the decoupling of emissions and economic growth in the Basque Country.

According to the official inventory of emissions, the sectors that contribute most to GHG emissions are the energy sector (35%), the transport sector (28%) and the industrial sector (22%). The residential sector contributes with 7%, but it has increased its emissions in 24% since 1990 (Ihobe, 2015).

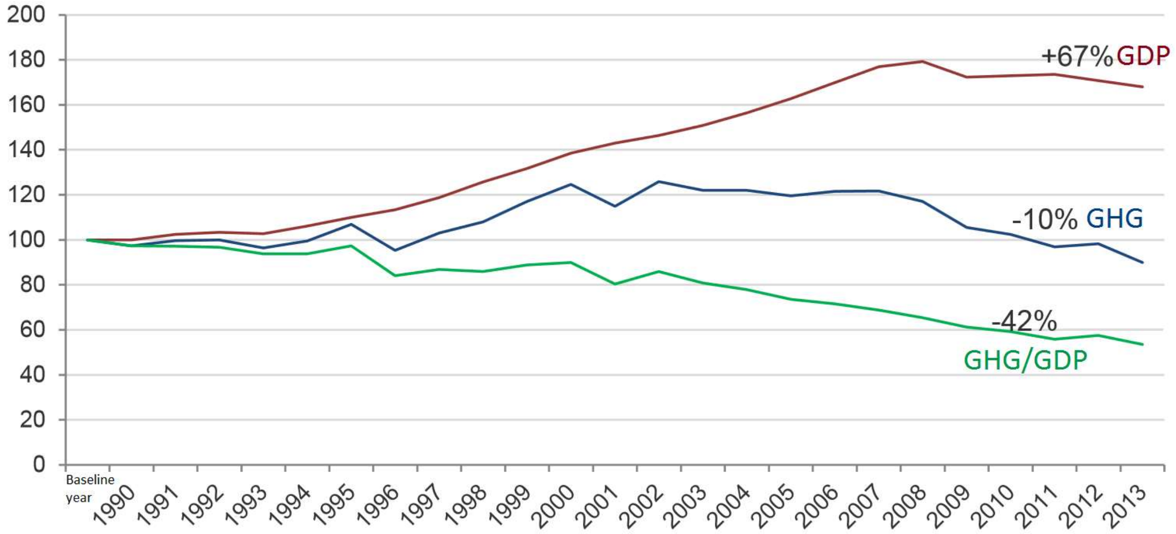

Figure 1.4. GHG emission evolution in the Basque Autonomous Community for the period 1990-2013 (blue line). The red line represents the growth of the gross domestic product (GDP) and the green line is the evolution of the index GHG/GDP.

The impacts of climate change in the Basque Country

In the Basque coastal zone, maximum temperatures are expected to increase 1.5°C, while the rest of the region will suffer a greater increase, up to 3.5°C. The rise of minimum temperature can also be expected, 1-1.5°C in the coastal zone and 2-2.5°C in the Atlantic biogeographic region. In areas with Mediterranean conditions minimum temperatures could rise 2.5-3°C. Seasonal differences will likely occur. For example, in the Atlantic zone temperatures could rise 1.5-2°C during the winter but up to 4.5-5.5°C in the summer. Projecting precipitation is very complex, but the estimates for the region show a reduction trend, as much as 15-20% (Basque Government, 2008).

Among all climate change impacts expected in the Basque Country, sea-level rise could represent a major threat, as a great part of the Basque population lives in low-lying coastal areas and many industrial assets are also concentrated in this narrow zone (Cearreta et al., 2004). Based on geological evidences, the rate of sea-level rise in the Basque coast during the 20th century has been measured in 2 mm yr^{-1}. This result agrees with that provided by the instrumental record: the Bilbao tide gauge has registered a 2.08 ± 0.3 mm yr^{-1} rise from 1943 until 2004 (Chust et al., 2009). Satellite records provide a rate of 2.7 mm yr^{-1} for the period 1993-2005 (García-Artola, 2013), while the combination of both sets of data has been calculated in 3.09 ± 0.3 mm yr^{-1} for the period 1993-2002 (Marcos et al., 2007a).

Regarding future projections, Chust et al. (2010) estimated that sea level for the year 2100 would rise 28.5-48.7 cm, using several AOGCMs for IPCC scenarios A1B and A2. These results were obtained considering regional thermal expansion and global ice-melting. Regarding extreme events at the regional scale, Marcos et al. (2012b) estimated that future storm surge[12] events in the Basque coast could increase as much as 62 cm above present maximum astronomic high tide (MAHT) level, which is already 243 cm above Bilbao's present mean sea level (MSL, hereafter).

All these changes will have an economic impact on the Basque society, although there is still little information on these potential costs. For example, Galarraga et al. (2011c) estimated that the annual average costs of flooding in the town of Amurrio (Araba), could increase in 15% due to the effect of climate change, from 56,097 euros to 64,451 euros (2005). Note that this estimate is given in terms of annual losses, but translated into the effects of an extreme event the cost could reach 20 million euros (2005). The same authors estimated the impacts of sea-level rise on differente coastal habitats at the end of the 21st century. Their results show losses of 87-231 million euros with a discount rate of 2% and 201-550 million euros with a discount rate of 1%. These estimates are quite high considering that they analysed the impacts on natural areas and left aside the impacts on socio-economic systems. Another example assessed the risk of river flooding in Bilbao and the results revealed that climate change could increase the damage costs by 56% (Basque Government, 2007).

These studies are a key reference for the work carried out in this dissertation, in relation to the assessment of the economic impacts of sea-level rise.

1.4.4 The role of regional governments in the fight against climate change

In order to implement climate change policies it is essential a global compromise and coordination, but regional[13] governments can also play a key role. According to the United Nations (UN), for the first time in history there are many regions involved in the development of climate policies, both at the national and international level (UNDP-UNEP-EMG-ISDR, 2008). Often, regions are responsible for designing climate policies and implementing international agreements. Many regions in Europe, for example, are in charge of sectorial policies such as energy, transport, research or education, as it is the case of the Basque Country. In fact, many states could not guarantee their compromises without involving the regions in the process. The proximity of the regions to the citizens can also be seen as an opportunity for promoting public participation and awareness, and even a more successful implementation could be achieved due to this proximity. Obviously, not only there are advantages, some difficulties can also be identified, related to the region-state coordination and in order to coordinate the policies of the different regions (Galarraga et al., 2011a).

In the Basque Country the first measures to combat climate change were included in the Basque Environmental Strategy for Sustainable Development (2002-2020). Already in that document climate

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[12] Storm surges are defined as the temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). The storm surge is defined as being the excess above the level expected from the tidal variation alone at that time and place (IPCC, 2013: 1463).

[13] The word regional is used in this work to refer to the sub-state level.

change appeared as one of the five main challenges of the Basque environmental policy. The Strategy developed through more specific four-year programmes. The first Environmental Framework Programme (EFP 2002-2006) included several measures, but the second Environmental Framework Programme (EFP 2006-2010) represented a major step-forward as the government committed to the design of the first Basque Plan to Combat Climate Change (Basque Government, 2008). This plan was approved in 2008 and it comprised a specific reduction target and 120 measures from several sectors to respond to the main objective. The plan focused on mitigation policies, and very little was considered regarding adaptation measures. After a few years of impasse, the Basque Government has recently approved a long term Basque Climate Change Strategy 2050 (Basque Government, 2015a). This new strategy has two main objectives: the first is to reduce GHG emissions in at least 40% by 2030 and 80% by 2050 (referred to 2005). Related to this mitigation target, the strategy stablishes that the share of the renewable energy in 2050 should be at least 40% of final consumption. The second objective is to guarantee the resilience of natural and human systems of the Basque Country.

In relation to adaptation, there has been another relevant initiative assessing the impacts of and adaptation to climate change in the Basque Country. For three years, 2007 to 2009, the project K-Egokitzen[14], funded by the Basque Government, brought together the main technology centres and several research groups from the University of the Basque Country (UPV/EHU) that analysed the impacts and adaptation options in the main sectors or areas such as hydrological resources, urban systems, coastal zones, terrestrial, marine and river ecosystems and agriculture (Basque Government, 2011).

1.5 Aim and objectives

Sea-level rise poses a major threat to coastal areas around the globe, and the Basque Country is no exception. In fact, during the definition process of the Basque Climate Change Strategy 2050, coastal zones were identified as one of the main priorities, based on their vulnerability and strategic relevance (Basque Government, 2015b).

> The **aim of this dissertation** is to contribute to generate climate-change-related information at the local and regional scales, in order to contribute as an input in the design and implementation of climate-change-adaptation policies in the Basque Country.

This general goal is developed through two specific objectives. The first objective is the development of sea-level rise scenarios based on the recent geological record. We have argued previously in this chapter that even if this scenarios are not future predictions, they can provide useful information to understand the magnitude and speed of change, as well as the interrelation between natural and anthropogenic processes. In this process, the analysis carried out in the coastal sequence of Oyambre is especially interesting for two main reasons: first, the uniqueness of this outcrop in the Cantabrian

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[14] K-egokitzen “Cambio Climático: Impactos y Adaptación” (http://www.neiker.net/k-egokitzen/inicio.html)

coast (a palaeobeach environment located several metres above current levels); second, the methodology used to determine the age of those materials, i.e. optically stimulated luminescence (OSL) dating techniques. Another interesting issue relates to the response of salt marshes to changes in sea level. Previous studies have shown that salt marsh ecosystems have the capacity to adapt to certain sea-level rise and this adaptation process has been quantified in several Basque marshes. These data has been taken into account when building flood risk scenarios. Most of the adaptation initiatives so far tend to focus on hard (infrastructural) and technical options (Sainz de Murieta et al., 2014) but in this work we stress the value of salt marshes as a cost-effective ecosystem-based adaptation option.

The second objective is to estimate the economic costs generated by sea-level rise in three sites of the Basque coast: Urdaibai, Plentzia and Muskiz estuaries. A non-market valuation approach is followed to estimate first the benefits provided by salt marshes in all three case studies. The impacts due to climate change are then calculated in terms of the loss of benefits provided by those salt marshes. A market based approach is used to value the costs of sea-level rise in an urban area (Plentzia) and an industrial area (Muskiz).

The information related to the quantification of economic impacts could be relevant for the planning of public adaptation policies as they represent the monetary costs that could be avoided by implementing adaptation policies and measures. Generally, the costs derived from climate change exceed by far the costs of adaptation (Galarraga et al., 2011c).

1.6 Structure of the dissertation

In order to respond to the research objectives aforementioned, this dissertation is organised in two parts:

Part I deals with the geological approach to the impacts of sea-level rise in the Basque coast and includes Chapters 2 and 3. Chapter 2 describes the methodology of the geological approach. First, changes in sea-level occurred during the last interglacial period (LIG), the early and late Holocene and the Anthropocene epochs are analysed. The next section details the methodology used to estimate the sea level during the LIG in the Cantabrian coast based on the sedimentary record of the Oyambre outcrop (Cantabria). These data, together with the rate of sea-level change during Holocene and Anthropocene, are used to define four geology-based sea-level rise (GBSLR) scenarios for the future. Finally, the methodology to develop coastal flood-risk maps based on the GBSLR scenarios is explained.

Chapter 3 presents the results of the geological approach. First, the outcome of the analysis of the coastal sequence of Oyambre is explained. The second part of this chapter presents and describes the flood-risk maps built for the three case studies located in the Basque coast: Urdaibai, Plentzia and Muskiz. These maps allow the identification of the affected salt marsh areas and the estimation of the magnitude of the impacts on different urban assets.

Part II of this dissertation develops the economic approach to the impacts of sea-level rise and comprises Chapters 4 and 5. In Chapter 4 a review of the economics of adaptation is presented, focusing first on the main methodological challenges. The next section explains the key sectorial characteristics, and also addresses other dimensions of adaptation.

Chapter 5 assesses two of the different methodological challenges described in the previous chapter: discounting and economic valuation. In relation to the first issue, an alternative approach to discounting is applied to the case studies, i.e. the Equivalency Principle, applicable when the long term value of natural land is involved. Secondly, an economic valuation of the ecosystem services provided by salt marshes in the case studies is carried out using a meta-analytic transfer function. The impact of sea-level rise on salt marsh areas is estimated in terms of the benefits not provided by the loss of salt marsh zones. Next, the economic impacts on urban areas are estimated for the case study of Plentzia and the chapter ends with an analysis of the situation in the industrialised Muskiz Estuary.

Finally, Chapter 6 reviews the main conclusions of both the geological and the economic approaches. It also explains the main limitations of this work and presents ideas for further research.

PART I.

A geological approach to the impacts of climate change

2 Methodology of the geological approach

In this chapter the methodology to define future scenarios of sea-level rise is presented, based on palaeodata obtained from the late Quaternary geological record. These GBSLR scenarios are then used to build flood risk maps of the three case-study areas during the 21st century.

The chapter is structured as follows: section 2.1 analyses the changes in sea level during the Last Interglacial stage and the Holocene. The methods used to define future scenarios of sea-level rise are detailed in section 2.2 and section 2.3 presents the methodology for building flood-risk maps for the Basque coast. Finally, section 2.4 highlights some concluding remarks.

2.1 Past changes in sea level

The Quaternary Period is characterised by frequent changes in global climate, during which oscillations between warm interglacials and cold ice ages have occurred. However, direct, accurate and high resolution evidences are only available as far in time as the LIG, around 126 ky ago (Lambeck et al., 2002). Going further back in time has only been possible recently thanks to the use of climate proxies, such as oxygen isotope signals measured from the tests of calcareous marine foraminifera. This method is used to calculate the $\delta^{18}O$ ratio, i.e. a ratio of two oxygen isotopes, $^{18}O/^{16}O$, which is used as an indicator of global ice volume[15]. Isotope ^{18}O is two neutrons heavier than ^{16}O, so is the lighter oxygen isotope the one mainly evaporated from the sea. As a result, during glacial periods, when a great part of the evaporated water containing O is trapped on the continents forming the ice caps and the water cycle is altered, the oceans are enriched in the heavier isotope and the $\delta^{18}O$ ratio is found to be larger (Lambeck et al., 2002). On the contrary, during interglacial periods, the evaporated water containing ^{16}O returns to the Earth surface by precipitation and then to the sea as part of the water cycle, and the relative content of ^{18}O decreases in the oceans.The evolution of the $\delta^{18}O$ ratio during the last 800 ky is shown in Figure 2.1 (green line).

In the figure, it can be observed how low peaks in the $\delta^{18}O$ ratio, representing warmer interglacial stages (in yellow), have a correspondence with higher global sea levels, represented by the blue line. During interglacial stages, the sea level curve gets close to zero (today's reference), while during some glacial stages sea levels dropped to around 100 m, or even more, below current level.

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[15] The isotope ratio is estimated as follows: $\delta^{18}O=\{(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{standard} -1\}$, expressed as parts per thousand (Lambeck et al., 2002).

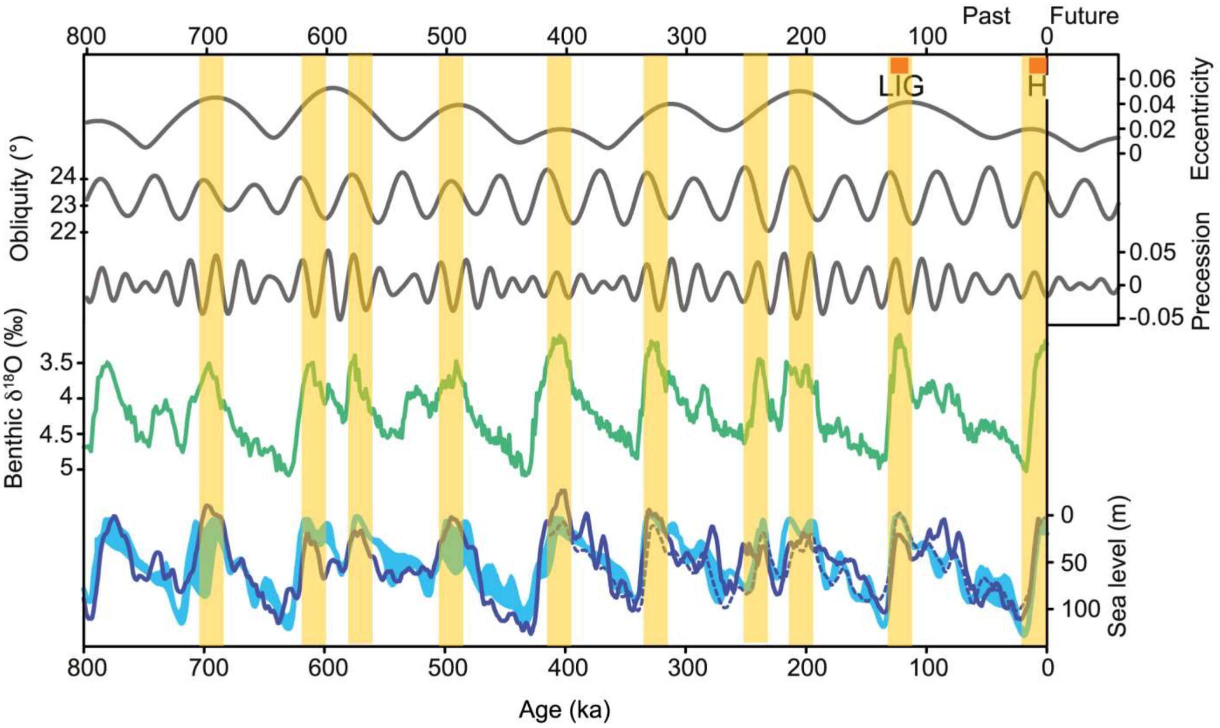

Figure 2.1. Orbital parameters and proxy records over the past 800 ky. Black lines represent the changes in orbital parameters: eccentricity, obliquity and precession. The green line shows the δ18O ratio and the blue line indicates changes in sea levels in a scale from 0 to 100 m below current level. Yellow vertical areas represent warmer interglacial stages. Source: adapted from IPCC (2013), Figure 5.3.

In this section we will analyse the changes in sea level in two past intervals, namely the LIG, which occurred about 126 ky ago, and the Holocene, which is the epoch that started 11,700 years ago and in which we are formally living in.

2.1.1 Sea level during the LIG

The LIG or Marine Isotope Stage (MIS) 5e[16] is "the most recent geological interval during which conditions were similar to the present interglacial" (Tzedakis, 2003: 763). Global mean temperatures during this stage were at least 2°C warmer than present (Rohling et al., 2008), sea level was, most probably, more than 5 m above current level (Cuffey and Marshall, 2000; Hearty et al., 2007; IPCC, 2007a) and sea-level-rise rates could have reached 1.6 m per century (Rohling et al., 2008). As mean global temperatures during this stage are close to the predicted by some SRES scenarios by the end of this century, this interval has received special and increasing attention, particularly regarding sea-level rise. As an example, the IPCC included a mention in the TAR in 2001. However, the 4AR and the 5AR include a full chapter on Palaeoclimate Archives in which different characteristics such as duration, temperature GHG concentrations and sea level of previous interglacials, including the LIG, are analysed.

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[16] Isotope studies from the bottom sediments of the oceans has allowed a definition of a scale based on alternating warm and cold periods on Earth's climate. The intervals "differentiated in isotope sequences are termed Marine Isotope Stages (abbreviated as MIS)". The stages are numbered starting at the present day interglacial (MIS1) and going backwards in time. In this way, glacial intervals are represented by even numbers while interglacials are expressed with odd numbers. Additionally, Stages might be divided into smaller sub-stages that are illustrated with lower case letters. For example, MIS 5 is divided into warm substages 5a, 5c and 5e, and cold substages 5b and 5d (INQUA-SACCOM, 2015).

Nevertheless, it is important to underline that CO_2 concentration during the LIG was similar to preindustrial levels (Archer and Rahmstorf, 2009) and warming had a strong orbital forcing component (Berger and Loutre, 2003; Archer and Rahmstorf, 2009). Nowadays, the configuration of the Earth's orbit around the sun is closest to the MIS11 interglacial (Figure 2.3), rather than the MIS5e. Loutre and Berger (2003) suggest that when the change in the amplitude of insolation is small, such as in the MIS11 and the MIS1, high CO_2 concentrations over a long time period can hamper the growth of ice sheets (Loutre and Berger, 2003). Therefore GHGconcentrations may play a very important role in shaping the future climate (Berger and Loutre, 2003; Loutre and Berger, 2003; Mcmanus et al., 2013). Nevertheless, van Kolfschoten et al. (2003) argue that the LIG might still be considered a primary analogue of present conditions, specially for two reasons: first, the availability of higher resolution data than in older interglacials, including fossils, a wide variety of sediments, well preserved sedimentary sequences, etc.; second, there are several dating techniques that can be applied to these Eemian materials, such as OSL, U-series or amino-acid geochronology. Anyhow, the analogy between the present and past interglacials should always be used carefully, and not as a straightforward correspondence.

The LIG is often known as Eemian and, at the same time, the term Eemian and MIS 5e have been often used interchangeably (Oldfield, 2005). However, the limits of either the marine or the terrestrial stages are not fully coincident (Tzedakis, 2003), as shown in Figure 2.2. The Eemian, identified by pollen analysis in a vegetational sequence, started well within MIS5e at approximately 126 ky, and finished at around 110 ky, already in MIS5d. The beginning of this stage is characterised by a coincident drop of steppic vegetation and increase of Eurosiberian and Mediterranean forests; a concurrent increase of steppic vegetation and a drop in Eurosiberian trees marked the end of this terrestrial stage, as seen in Figure 2.2 (Shackleton et al., 2003). As this dissertation deals with sea-level rise, it is considered more appropriate to use the terms LIG or MIS5e, rather than Eemian.

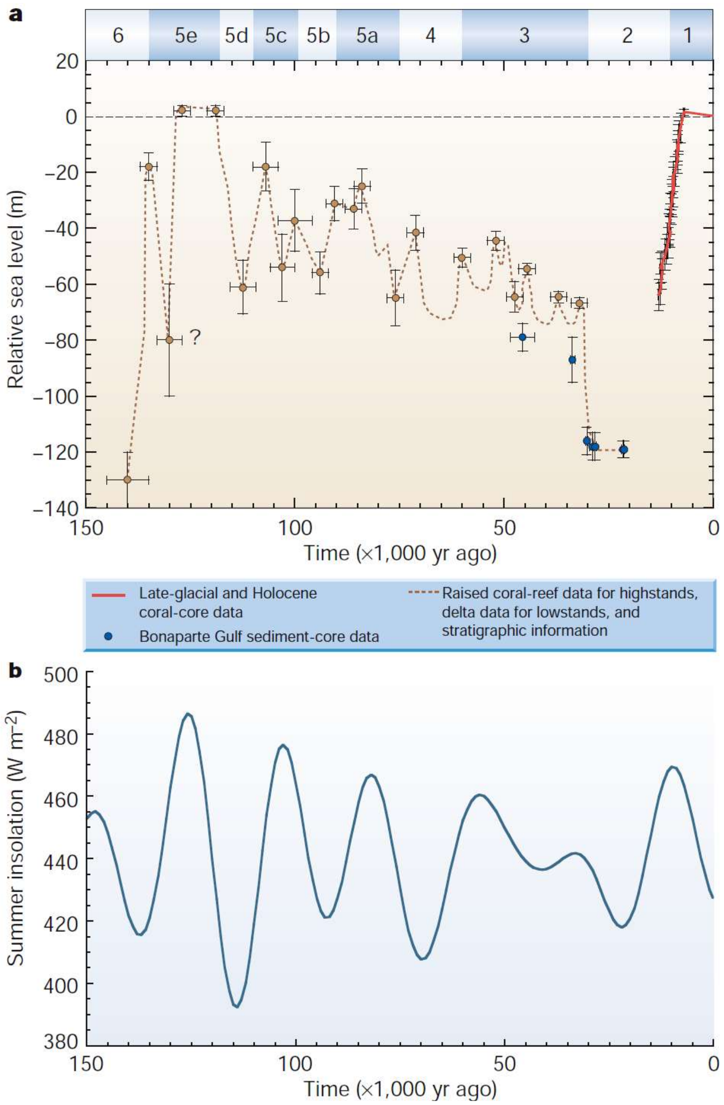

Figure 2.3. Relative sea level and insolation for the last climatic cycle (Lambeck et al., 2002).

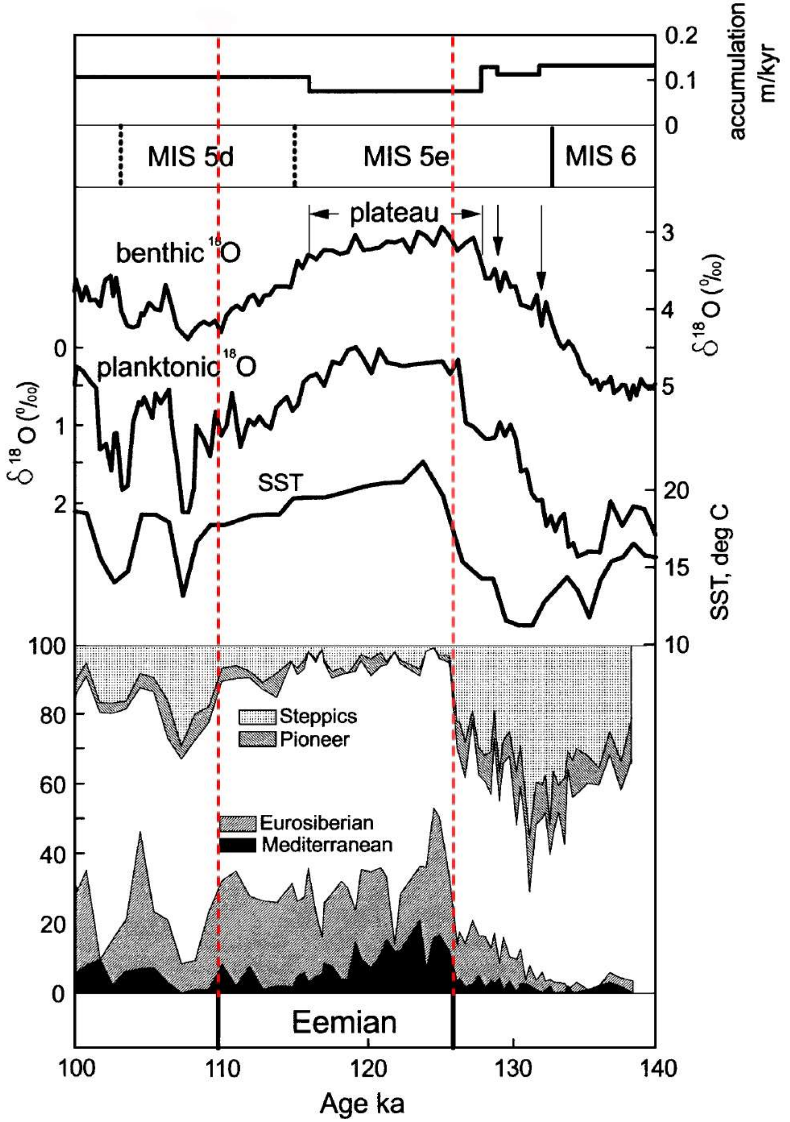

Figure 2.2. Marine and continental records of the last interglacial, from Shackleton et al. (2003). At the top, sedimentation rates implied by age controls marked; below, benthic δ18O record; planktonic δ18O record; sea-surface temperature and last, major groups of pollen taxa.

2.1.2 Changes in sea level during the Holocene

Changes in sea level have been registered by tide gauges during the last century, although there are records going back to the 18th and 19th centuries. The Brest tide gauge in France has collected data for more than 200 years, since 1807 (Leorri et al., 2008b) and the longest continous record in Europe, provided by the Permanent Service for Mean Sea Level (PSMSL) in Stockholm, goes back to 1774. However, these historical data have several limitations. The first is related to the quality of the record as it is not always complete. The reading should also be used carefully as it often represents high water levels and inferring MSL might not be forthright (Mitchum et al., 2010). The second refers to the limited time scope of the measures, as very little data go back to the 18th and even the 19th centuries. Finally, the third limitation relates to the fact that tide-gauge records are only available for a few specific locations around the globe.

The analysis of past changes in sea level beyond the 19th century, therefore, requires the use of techniques based on other types of sea-level indicators. As summarised in Table 2.1, there are four main types of proxies that can be used to deduce past changes in sea level: morphological, biological, sedimentological and archaeological. Each type provides information at different scales. For example, emerged marine terraces or erosional notches are morphological features that indicate a palaeosea level, as presented in Figure 2.4. These elements can serve to identify sea levels occurred from thousands to millions of years ago, with a resolution of metres to decimetres.

Table 2.1. Summary of main palaeosea-level indicators.

Sea-level indicators	Examples	Time span	Accuracy
Morphological	Erosional terraces - Depositional shorelines Erosional notches	Thousands of years	Metres (m)
Biological	Organisms which can indicate evidence of sub-, mid- and supralittoral positions, such as. corals, molluscs or salt marsh microfossils	Thousands of years to interannual variation	From centimetres in the case of corals to millimetres in the case of salt marsh microfossils
Sedimentary	Beach rocks, palaeo-beaches Mangrove sediments Cave deposits (submerged caves and speleothemes)	Thousands of years to decades	Centimetres (cm)
Archaeological	Terrestrial structures or artefacts (such as settlements or dwellings) Coastal structures (such as ports or fish tanks)	Thousands of years	Centimetres (cm)

Source: Lambeck et al. (2010)

Among the different types of biological and geological palaeosea-level indicators, the use of salt marsh microfossils as proxy records has shown to be very valuable as a complement of tide-gauge records. This is due to the fact that these records can go further back in time than the longest tide-gauge observations and could be studied in geographical areas where instrumental records are not available. Also, they can provide high resolution reconstructions of past sea levels with an accuracy of milimetres (Mitchum et al., 2010).

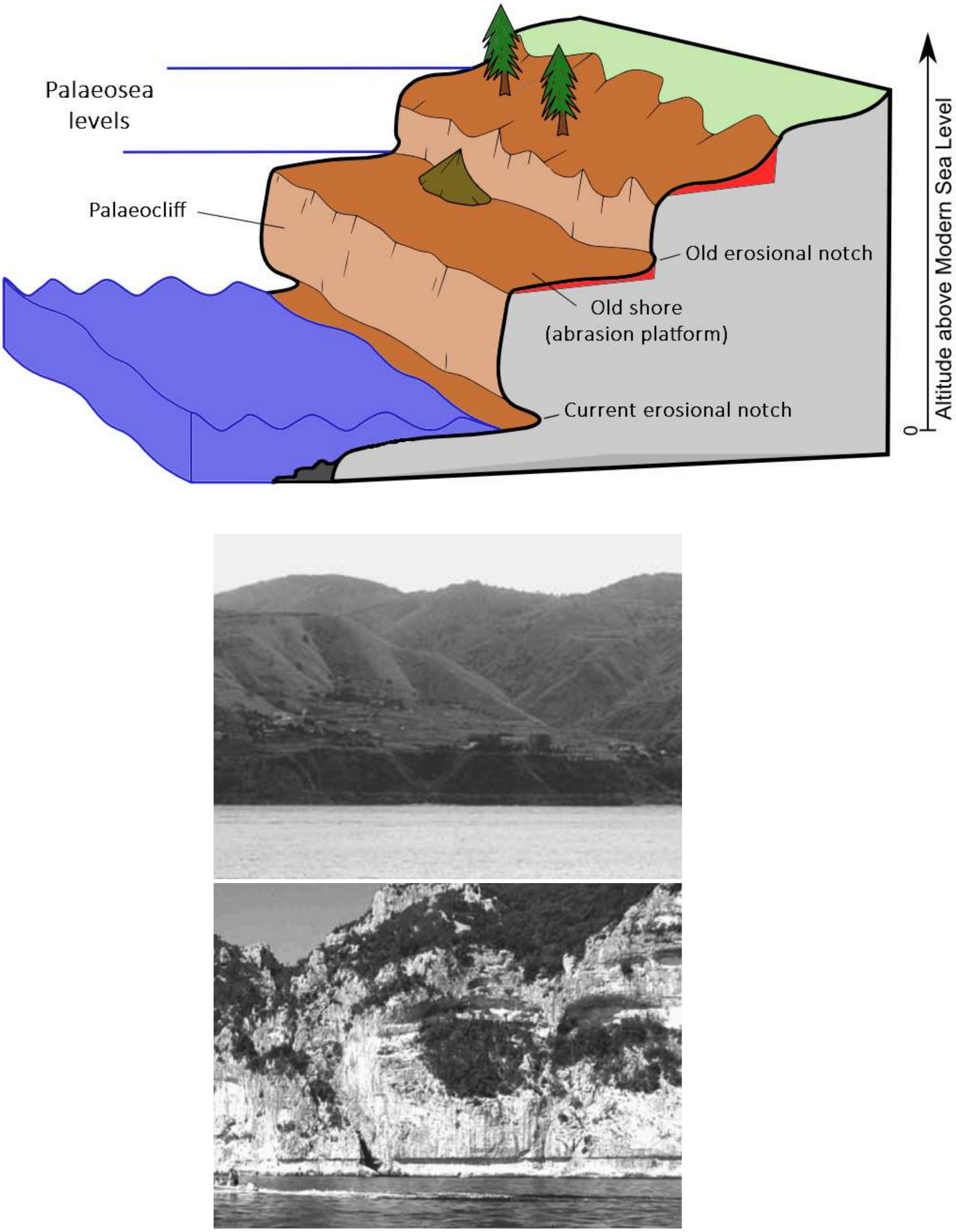

Figure 2.4. The upper figure shows a schematic representation of some morphological indicators that can be used to identify past sea levels. The figures below show examples of an old abrasion terrace in Calabria (left) and an erosion notch in Sardinia.

Sources: upper figure adapted from Marine Terrace Diagram (c) Shekk12, CC BY-NC-SA 3.0. Wikipedia. Images below taken from Ferranti (2006).

Salt marsh foraminifera follow a vertical zonation depending on their relative position to the tidal frame (Figure 2.5). The current relationship between characteristic foraminiferal assemblages and sea level can be quantified and applied, through statistical transfer functions, to the sedimentary record in order to build past sea level (Horton and Edwards, 2006). High-resolution sea-level reconstruction has been significantly improved in recent years as a result of the development of foraminifera-based transfer functions all over the world (García-Artola et al., 2009; Lambeck et al., 2010). In fact, salt marsh foraminifera, considered the most accurate biological indicators for sea level, are broadly used to estimate Holocene sea level (Scott and Medioli, 1978; Gehrels, 1994; Horton and Edwards, 2006; Leorri et al., 2010).

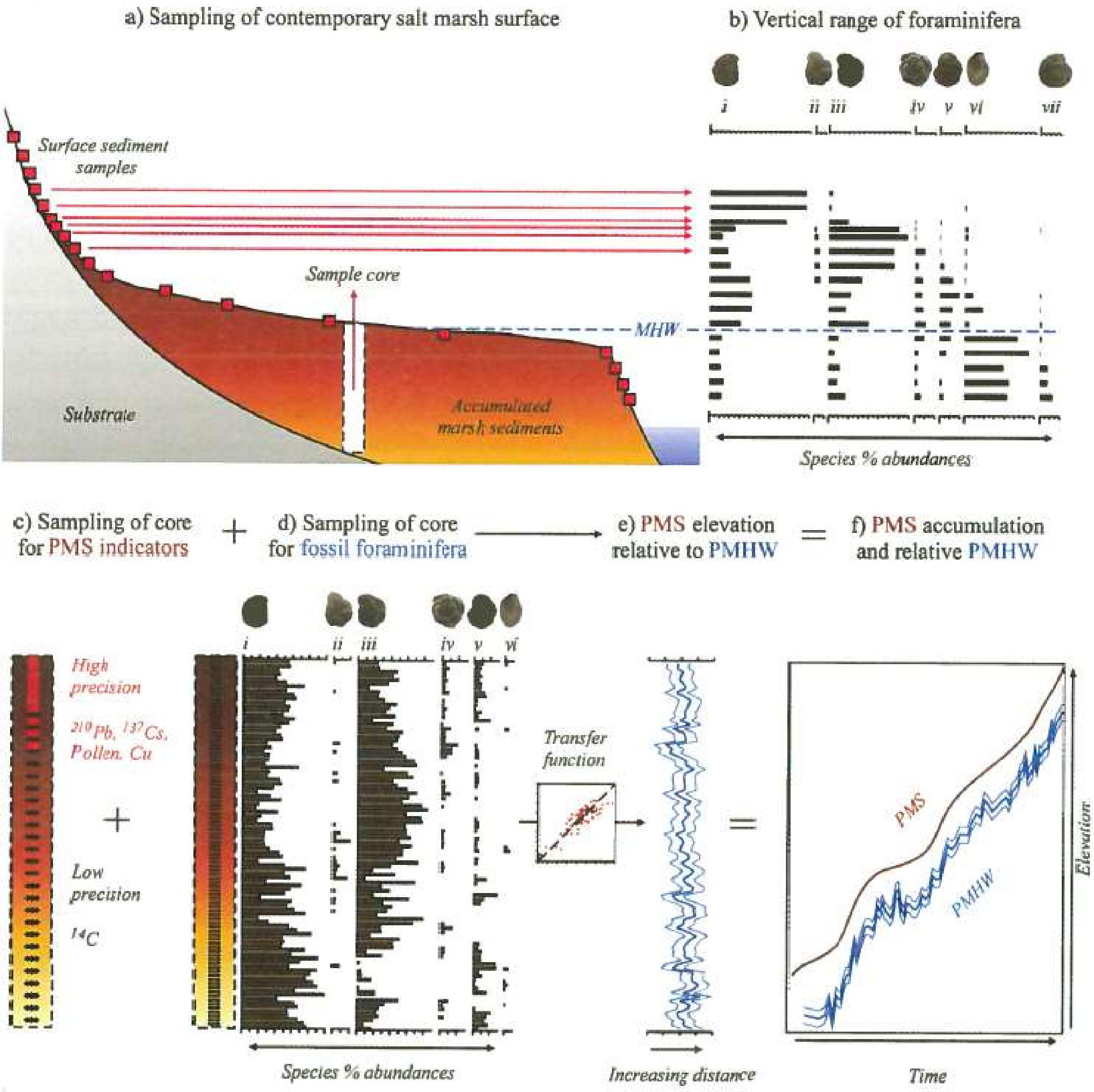

Figure 2.5. Schematic illustration of the steps for reconstructing sea-level changes using salt marsh foraminifera. In the figure MHW stands for "mean high water"; PMS for "palaeo-marsh surface" and PMHW for "palaeo-mean high water".
Source: Lambeck et al. (2010)

Long et al. (2014) analysed several sea-level reconstructions from salt marshes in the eastern and western coasts of the North Atlantic and found substantial differences among them, particularly in relation to the pattern and timing of modern sea-level rise. One of the best dated and most precise sea-level rise reconstructions, from a salt marsh in North Carolina (USA), shows that sea-level rise accelerated during the late 19th century. However, European tide-gauge data shows a later acceleration, well into the 20th century. They performed a sea-level rise reconstruction from Newtown marsh (Isle of Wright, UK) that agrees with those carried out in the Plentzia Estuary (Basque Country; Leorri et al., 2008b) and the Morbihan Golfe (Atlantic France; Rossi et al., 2011). Differences with results obtained from the eastern coast of the USA are important, but this was expected due to regional variability and also the "complex and linked atmospheric and oceanographic circulation" in the North Atlantic (Long et al., 2014: 120). Thus, the study stresses the importance of different regional scale reconstructions, as no single location has proven to be representative of global changes in sea level.

Leorri et al. (2010) found that foraminiferal assemblages of four different salt marshes from SW Europe (France, Spain and Portugal) show a strong vertical zonation and, in all cases, *Jadammina macrescens* and *Trochammina inflata* are the dominant foraminiferal species in high marshes. Low marshes, however, show a greater species variability among salt marshes due to the influence of different environmental parameters, such as salinity. Two important conclusions are drawn from this study. First, the elevation range considered when building the transfer function is a key element for optimal results. Second, due to the differences found in the various study areas transfer functions should be defined at the regional scale, and even at the local scale, in order to obtain the most accurate sea-level reconstructions.

In line with this idea of defining transfer functions at the local scale, there are several recent studies in the Basque coast which contribute to the reconstruction of past sea levels by using salt marsh foraminifera as proxies. Leorri et al. (2008a) developed a foraminifera-based transfer function for the Bay of Biscay from a total dataset of 46 samples obtained in four Basque marshes. The transfer function showed a strong performance ($R^2 = 0.87$) and a precision of ±0.12 m, comparable to other functions applied in the northern Atlantic Ocean.

This transfer function was improved by Leorri et al. (2008b) based on 59 samples from the same four Basque marshes. The precision (between 0.11 and 0.19 m) and performance (R^2 between 0.74 and 0.81) obtained were also comparable to that of other transfer functions. The authors applied the transfer function to estimate recent changes in regional sea level. In order to do so, a 50 cm length core was extracted in the Ostrada marsh (Plentzia) and calibrated using the transfer function. The time framework for the core was calculated measuring the sediment-accumulation rates through the analysis of short-lived radionuclides ^{137}Cs and ^{210}Pb concentrations in the sediments. The results showed a general sea-level rise rate of 2.0 ± 0.3 mm yr^{-1} from 1884 to 1994. Even if the reconstruction revealed large temporal errors, the general trend was in very good agreement with data from the Brest and Santander tide gauges, which are close to the study area.

However, estimations obtained from a single core could represent local rather than regional changes in sea level, but regional evolution should have been recorded in different salt marshes of the Basque coast. Under this hypothesis, Leorri and Cearreta (2009a) applied the foraminifera-based transfer function previously developed by Leorri et al. (2008b) to a 50 cm long core extracted in the Muskiz marsh. The results showed that, for the period from 1936 to 2003, sea level has risen at a general trend of 2.4±0.4 mm yr^{-1}, in general agreement with the results from the Ostrada core. García-Artola et al. (2009) obtained consistent results applying the transfer function to a sediment core from the Kanala marsh (Urdaibai Estuary).

Following the same methodology in the analysis of a sediment core from the Murueta marsh, Sainz de Murieta (2011) obtained a relative sea-level rise rate of 2 mm yr^{-1} for the 20th century. All four results are in agreement with regional tide-gauge data; so it is possible to conclude that the estimated sea-level rise trend represents a regional signal. This means that we can asseverate that sea-level rise has occurred in the Bay of Biscay at a pace of 2 mm yr^{-1} along the 20th century and the processes behind this change in sea level are beyond specific local conditions.

Using the transfer function developed by Leorri et al. (2008b), Leorri and Cearreta (2009b) estimated sea-level changes during the Holocene in two Basque estuaries, Bilbao and Urdaibai. The results show the changes in relative sea level from 8500 cal yr BP to 200 cal yr BP. Within the main rising trend, two phases are identified: the first, before 7000 cal yr BP, which ranges from 9 to 12 mm yr^{-1}; the second, since 6700 cal yr BP until the 19th century, shows an average rise of 0.7 mm yr^{-1} (Figure 2.6a).

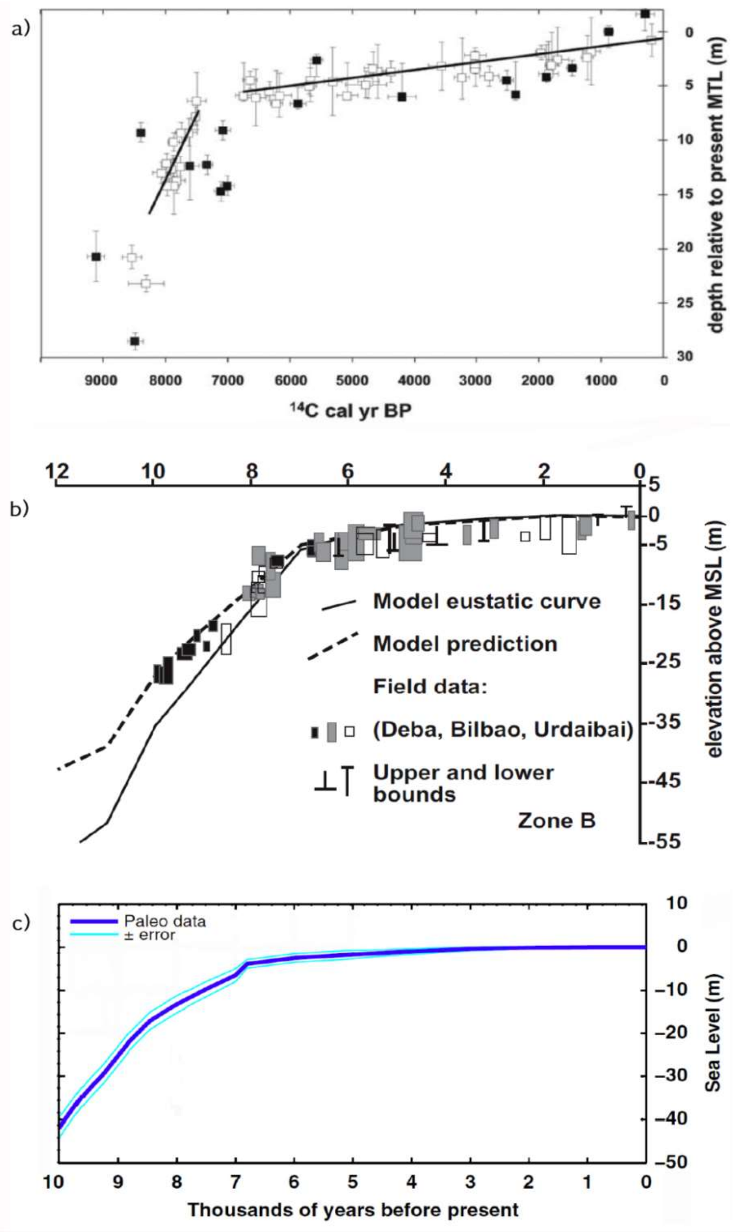

Figure 2.6. Sea-level changes during the Holocene. a) Results from Leorri and Cearreta (2009b) based on sediment cores from the estuaries of Bilbao and Urdaibai. b) Results from Leorri et al. (2012) for the Basque coastal zone. c) Estimates of sea-level change during the last 10,000 years BP (Church et al., 2008).

Leorri et al. (2012) analysed several cores from the estuaries of Bilbao, Urdaibai and Deba and the Holocene sea-level curve obtained is consistent with previous results: a first rapid phase during which sea level rose from -27 m (below mean sea level, bmsl) at 10,000 cal yr BP to -5 m (bmsl) at 7000 cal yr BP; and a second phase where sea level was almost steady, rising slowly at 0.7-0.3 mm yr^{-1} from 7000 cal yr BP to 200 cal yr BP (Figure 2.6b). The authors then compared the results with similar data measured in the North Atlantic and found a regional north-south trend with higher sea-level rise rates in the northern areas (French-Iberian Atlantic coast).

The curve of sea-level rise obtained for the Basque coast during the Holocene is also consistent with the global trend of changes in sea level for this epoch. The transfer function developed for the Basque coast is, therefore, representative of the changes occurred at the regional and even global scales, as shown in Figure 2.6c.

2.2 Building future scenarios of sea-level rise from the geological record

The IPCC's future projections of sea-level rise rely mostly on process-based-modelling approaches that according to some authors, such as Rahmstorf et al. (2007), have led to underestimation of the rate of sea-level rise. In fact, these projections have been reviewed in the IPCC 5AR and are now significantly higher compared to those from previous reports. Also, we have explained in the introductory chapter that sea levels have changed in the past due to the concurrence of many different factors, from orbital changes to geophysical processes that can play an important role at the regional scale. So there is no single or ideal approach to such a complex problem, but each approach can contribute to improve the existing information and future projections.

In this section we explain how data obtained from the recent geological record in the Cantabrian coast can be used to build future scenarios of sea-level rise. The data correspond to two different stages of the Late Quaternary: the LIG (MIS5e), occurred during the upper Pleistocene, and the Holocene (MIS1). The aim of this exercise is not to create accurate projections of changes in sea level, but to provide useful information about the type of impacts that could occur depending on the magnitude and rate of change.

2.2.1 SLR scenario based on the LIG geological record

Due to global warming, there is an increasing interest in studying the past as key to understand the future, not only from a climate perspective, but also considering changes in sea-level positions. Beach deposits located above current sea level represent an emerged coastline. This higher position might be either a result of tectonic movements, eustatic changes or a combination of both of them (Bird, 2008). Marine terraces and emerged beaches along the Cantabrian coast have been studied to analyse sea levels in the past, but the LIG has never been accurately dated in this area (Alonso and Pagés, 2007).

At the Oyambre beach (Cantabria, north of Spain) (Figure 2.7), a 15 m-thick coastal sequence made of coarse, sandy (and muddy) sediments located above an erosive surface at about +4.5 m above present mean sea level (reference Bilbao ordnance datum) was identified. This surface separates Oligocene marls from a probable LIG/MIS5e deposit (Figure 2.8). In this sub-section we detail the methodology followed to determine the age of the Oyambre sequence and verify if it represents a MIS5e sea level highstand.

Figure 2.7. Location of the Oyambre outcrop (province of Cantabria, Spain).

Description of the Oyambre outcrop

The sedimentary succession comprises materials containing bioclasts and foraminiferal assemblages indicative of a beach environment, namely, represented by a basal boulder gravel (1.5 m thick) and fine sands (2 m thick); followed upwards by transitional sediments recorded by muds (<1 m thick) and medium to fine sands (the upper 10 m of the succession) (Figure 2.9).

Figure 2.8. The Oyambre outcrop: Oligocene marls are separated from the Quaternary sequence by an erosional surface (dashed yellow line) representing a former sea-level highstand.

Garzón et al. (1996) described the outcrop as a “beach sequence consisting of basal gravels, clays and aeolian sands”. They performed an aminoacid racemization analysis of two types of molluscs from the basal unit which showed discrepant ages of 71,570±13,400 and 21,140±9,400 yr BP but they recognise that “outcrop data and general sea stages arrangement allows them to support a pre-glacial age for this beach level”. On the other side, Cearreta (unpublished data) carried out in 2010 an AMS radiocarbon dating of a shell sample (Beta-287876) from the same basal unit that produced a result of >43,500 yr BP beyond the resolution of this dating method. Furthermore, the lack of neotectonic activity on this coastal area suggests that this Oyambre deposit could represent an upper Pleistocene sea-level highstand.

Figure 2.9. Schematic representation of the Quaternary Oyambre sequence (Cantabria).

Luminescence dating

Many minerals, quartz and feldspars among them, are able to store energy within their crystal structures. The energy a mineral releases in the form of light when subjected to different stimuli, such as heat or light, is called luminescence (Duller, 2004).

When a quartz grain is exposed to sun light, the energy stored is released; thus, its “clock” is set to zero. Immediately after burial, the luminescence signal will start to accumulate within the crystal structure of the quartz grain due to ionising radiation from the sediment and a contribution from cosmic rays. If other environmental parameters remain stable, luminescence will increase with time from the date in which it was buried (Figure 2.10). The longer the burial time of a sediment (thus, the longer the exposure to ionising radiation), the greater the energy it will store and therefore, the stronger the luminescence signal it will emit when stimulated. This characteristic is extremely useful for dating Quaternary sediments, as it makes possible to determine the age at which the sediment was last exposed to heat or light (Oldfield, 2005).

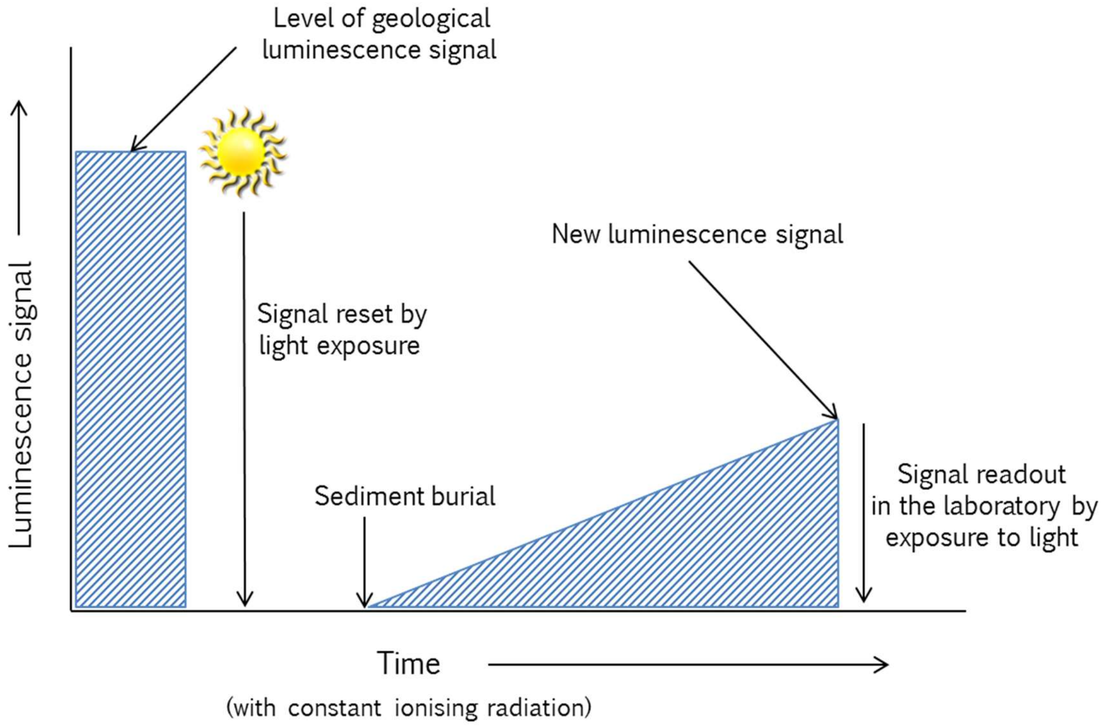

Figure 2.10. Changes in luminescence signals with time. Source: Bradley (1999).

There are four processes that can reset the energy within the crystal (the "clock") to zero: crystallization, extreme pressure, heating the mineral or exposing it to light. When dating Quaternary materials, the first process is rarely relevant and it remains controversial whether applying extreme pressure is effective or not. Heating and exposing a mineral to light are, therefore, the processes mostly involved (Duller, 2004). Luminescence dating procedures based on heating the materials are known as Thermoluminescence (TL) methods, while those subjecting the mineral to light are known as OSL techniques (Oldfield, 2005). TL methods have been broadly used since Wintle and Huntley (1979) first applied them to deep-sea sediments, but OSL processes are currently preferred for dating materials (Bradley, 1999; Duller, 2004).

Luminescence dating techniques play a key role to establish absolute dates in Quaternary sediments or materials. This is due to the fact that nowadays there is no other technique that can be generally used with such a wide age range. For instance, Quartz OSL dating has a limit ranging from 100 ky to 200 ky, whereas radiocarbon dating is limited to the last 45 ky and it requires organic matter *in situ* (Buylaert et al., 2012). Feldspar-rich samples can also be used to date older sediments. Buylaert et al. (2012) measured sediments as old as 600 ky using a new pRIR protocol based on feldspar signals that opens new possibilities for Middle Pleistocene geological archives.

With regard to Qtz OSL dating it is important to note that the luminescence signal saturates at equivalent doses of ca. 120-200 Gy. As the final burial age is the ratio between the equivalent dose (Gy) and the dose rate (Gy·yr^{-1}), the upper limit of the estimated burial age will depend on the dose rate. For example, some aeolian or beach sands have dose rates of 1.4 Gy, therefore burial ages can be estimated up to 140 ky. In the case of fluvial sediments, however, Qtz OSL dating provides burial ages up to 30-130 ky, as these sediments have higher dose rates (1.4-4.2 Gy) (Cunha, 2013).

Quartz OSL method was used to date the samples from the Oyambre outcrop.

a. Sampling for luminescence dating

Samples were collected hammering opaque steel tubes (70 x 300 mm) into the sediment (Figure 2.11), once the outcrop was previously cleaned by excavating 0.5 m from the original surface. Starting from the top of the basal boulder gravel deposit, 36 samples were collected up to the current cliff topmost. Two modern sediment samples were also collected, one at the Oyambre beach and the other from aeolian sands of the active dune for calibration. Altogether, 38 tubes were sampled at the study site (see Table 2.2 for precise geographic position of the samples). In order to obtain a quick estimation of water content, water saturation content and dose rate, a sub-sample (an additional bag of sediment) was collected immediately adjacent to each sampling tube (Figure 2.12).

Figure 2.11. Metallic tubes were introduced into the sediment using a hammer.

The sampling strategy was to collect material from the base and top of each identified level (Cunha et al., 2008), depending on its thickness (Figure 2.13). Each tube was carefully covered with paper and black plastic to avoid exposure to daylight during the transportation.

Figure 2.12. Sample 11: steel tube inserted into the sediment and sub-sample bag.

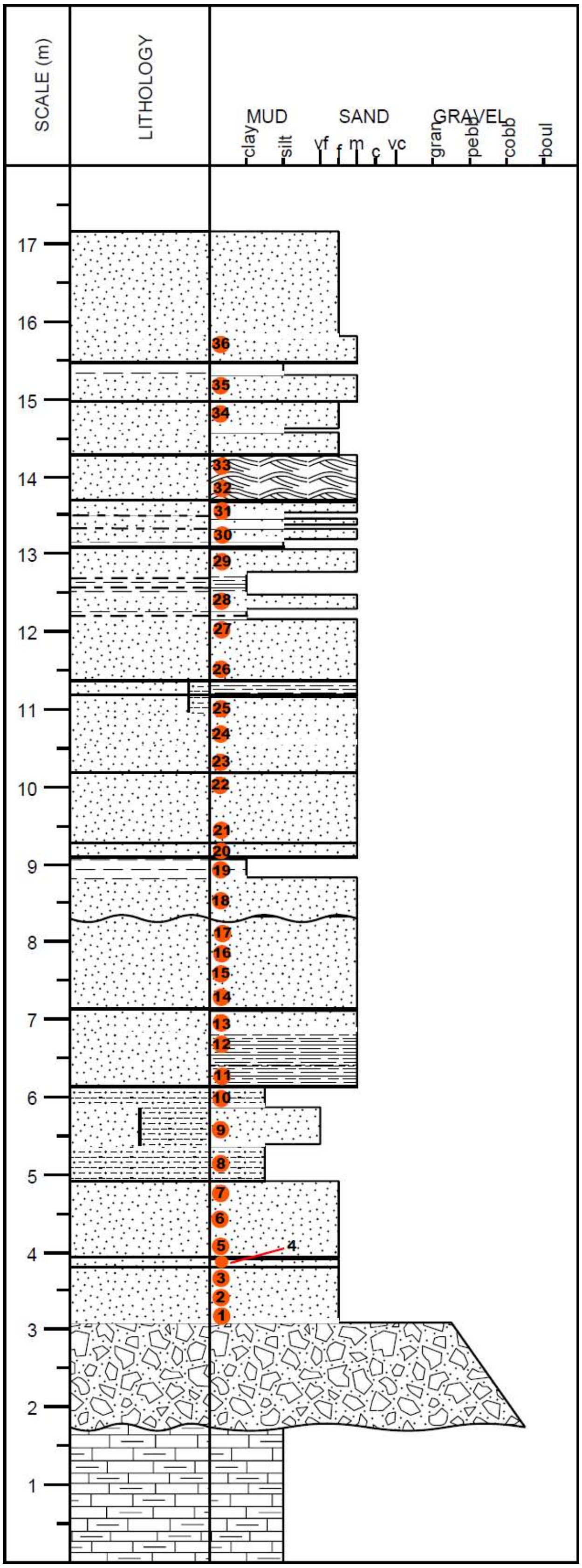

Figure 2.13. Schematic sedimentary log of the Oyambre outcrop and sampling scheme followed.

b. Geographical location and topographic elevation measurements

Precise location and elevation of sedimentary levels, tubes and surface samples were determined in the field by Mendi Topografia (Bilbao) using a Global Positioning System-Real Time Kinematic (GPS-RTK) and a total station, with a horizontal precision of ±2 cm and a vertical accuracy of ±3.5 cm (Figure 2.14). Coordinates X, Y and Z of the samples are referred to the ED50 geographical system in planimetry and the Bilbao ordnance datum (BOD).

Figure 2.14. Measuring topographic elevation of the samples in the Oyambre outcrop.

The precise geographic and topographic position of the tube samples are shown in Table 2.2.

Table 2.2. Geographic location of tube samples taken at the Oyambre outcrop. Topographic positions are shown in metres above Bilbao ordnance datum.

CODE	X COORDINATE	Y COORDINATE	Z COORDINATE
Sample 36	391588.730	4806038.159	20.900
Sample 35	391588.984	4806038.045	20.269
Sample 34	391589.140	4806037.989	19.903
Sample 33	391589.418	4806037.712	19.361
Sample 32	391590.229	4806037.123	19.069
Sample 31	391590.506	4806037.367	18.645
Sample 30	391591.638	4806037.166	18.421
Sample 29	391591.693	4806037.254	18.091
Sample 28	391591.798	4806037.371	17.744
Sample 27	391592.066	4806037.278	17.448
Sample 26	391592.562	4806036.958	16.887
Sample 25	391592.998	4806036.867	16.440
Sample 24	391593.248	4806036.944	16.157
Sample 23	391593.472	4806036.954	15.732
Sample 22	391594.126	4806037.197	15.296
Sample 21	391594.401	4806037.352	14.969
Sample 20	391594.638	4806037.486	14.594
Sample 19	391595.230	4806037.767	14.385
Sample 18	391595.334	4806037.842	14.095
Sample 17	391595.594	4806037.942	13.623
Sample 16	391595.761	4806038.017	13.254
Sample 15	391595.942	4806038.090	12.921
Sample 14	391596.854	4806038.835	12.592
Sample 13	391597.019	4806038.953	12.360
Sample 12	391597.197	4806039.051	11.951
Sample 11	391597.794	4806039.706	11.842
Sample 10	391598.621	4806039.894	11.395
Sample 9	391599.221	4806040.049	10.879
Sample 8	391600.387	4806040.106	10.481
Sample 7	391600.457	4806039.975	10.300
Sample 6	391600.911	4806040.167	9.854
Sample 5	391601.670	4806039.937	9.437
Sample 4	391601.790	4806040.039	9.286
Sample 3	391601.841	4806040.107	9.111
Sample 2	391601.934	4806040.187	8.860
Sample 1	391602.168	4806040.285	8.716
Oyambre Dune	392477.461	4805120.260	4.250
Oyambre Beach	391639.380	4806041.884	3.176

c. Preparation of the samples

The sample preparation was carried out in the Sedimentology laboratory of the Department of Earth Sciences at the University of Coimbra (Portugal), under subdued red light to prevent resetting the luminescence signal. In order to separate the 180-250 μm grain fraction sediment, samples were wet sieved and then treated with HCl (10%) and H_2O_2 (10%) to remove carbonates and organic matter respectively.

The K-feldspar rich fraction was obtained by flotation using a sodium polytungstate solution (ρ = 2.58 g cm^{-3}). Quartz grains were extracted by treating another fraction with HF (40%). The K-feldspar portion was etched with diluted HF (10%, 40 min) that also removes the outer alpha-irradiated layer. After etching, any remaining fluorides were removed from both fractions using HCl (10%) (Cunha et al., 2008; Cunha, 2013; Carvalhido et al., 2014).

d. Determination of equivalent doses and resulting ages

Ages were obtained at the Nordic Laboratory for Luminescence Dating (University of Aarhus, Denmark). Two parameters are needed to estimate the age of a sample by using luminescence techniques: the equivalent dose (ED or D_e) and the dose rate. The dose of radiation that the mineral grains have absorbed is known as “equivalent dose” and is measured in “greys” (1 Gy = 1 J kg^{-1}) and the amount of radiation to which a sample is exposed each year is the dose rate (Duller, 2004). Once the two parameters are calculated, the age of a sample can be estimated following

$$Age\ (ky) = \frac{Equivalent\ dose\ (Gy)}{Dose\ rate\ (Gy \cdot yr^{-1})}$$

Environmental dose rates were quantified from the radionuclide concentrations of the sediment, measured by high-resolution gamma spectrometry (Murray et al., 1987). Equivalent doses (D_e) were obtained on Risø TL/OSL DA- 20 readers. Quartz 8 mm aliquots were mounted on stainless steel discs and K-feldspar 2 mm aliquots mounted on stainless steel cups (Carvalhido et al., 2014).

A standard single-aliquot regenerative-dose (SAR) protocol was used to estimate the quartz dose, using blue light stimulation at 125°C for 40 s with a 240°C preheat for 10 s, a 200°C cut heat and a high temperature (280°C) blue-light stimulated clean-out step (Wintle and Murray, 2000; Murray and Wintle, 2003). The OSL signal was detected through a U-340 filter. All samples have a strong fast component. The net OSL signal was calculated from the initial 0.0–0.8 s of stimulation and an early background between 0.8 and 1.6 s.

The K-feldspar D_e values were measured using a post-IR IRSL[17] SAR protocol using a blue filter combination (Thomsen et al., 2008; Buylaert et al., 2012). After a pre-heat of 320°C for 60 s the aliquots were first IR bleached at 50°C for 200 s and subsequently stimulated again with IR-light at 290°C for 200 s. Buylaert et al. (2012) showed that the post-IR IRSL signal measured at 290°C gives accurate results without the need to correct for signal instability. For all estimations, the initial 2 s of the luminescence decay curve less a background derived from the last 50 s was used.

Grain-size analysis

A total of 38 sediment samples were collected (Table 2.2), 36 from the coastal outcrop and 2 modern sediment samples (beach and aeolian dune sands).

The grain size of each sediment sample was determined by laser diffraction analysis of the <2 mm fraction, using a Coulter LS 230 laser granulometer (calculations from 0.4 µm to 2000 µm; the accuracy of the grain size analysis is up to 5%. The volume statistics (Mean, Median, Mode, Standard Deviation, Skewness and Kurtosis) were obtained by the geometric method of moments. The Modes and the percentages of Sand (2000-63 µm), Silt (63-2 µm) and Clay (<2 µm) were also determined.

The mineralogical composition of the <2 µm fraction of fine sediment samples was obtained in oriented samples before and after heating up to 550°C and with ethylene glycol treatment. The mineralogical analyses were carried out by X-ray diffraction, using a Philips PW 3710 X-ray diffractometer, with a Cu tube, at 40 KV and 20 nÅ.

Determinations were carried out at the University of Coimbra (Portugal).

Foraminiferal analysis

Thirty eight samples (36 coincident with the tube samples, 1 sample from the modern Oyambre beach, and 1 sample from the basal boulder gravel) were wet sieved through 2 mm and 63 µm sieves to remove large and fine-grained sediments respectively, at the Micropalaeontological Laboratory of the University of the Basque Country (UPV/EHU). Sand size material (retained in the 63-micron sieve) was oven dried at 60°C and weighed. Foraminifera were concentrated by flotation in trichloroethylene as described by Murray (1979). To ensure statistical representativeness of foraminifera counting, when possible a minimum of 300 individuals per sample were extracted. Otherwise, all individuals present were obtained when the statistical minimum was not reached. The micropalaeontological study was carried out using a stereoscopic binocular microscope Nikon SMZ 645 using reflected light.

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[17] A post-IR IRSL method consists on stimulating with infrared (IR) at a higher temperature, a sample that had previously been stimulated by feldspar infrared stimulated luminescence (IRSL) at low-temperature (~50°C). According to Buylaert et al. (2012: 436) “the resulting post-IR IRSL signal has been shown to have lower fading rates than the conventional IRSL at ~50°C”.

A sea-level rise scenario based on the data from the Oyambre outcrop

The first future sea-level rise scenario is built on the geological results obtained from the Oyambre outcrop that represents a MIS5e sea-level highstand located at +6.901 m above present sea level (referred to BOD).

As noted in Chapter 1, the IPCC AR5 sea-level estimates for this century are between 0.28 and 0.97 m above present level. Another study from Nicholls et al. (2011) estimated a sea level at 0.5-2 m above present for a 4°C rise in global temperature, with a very low probability that the high end is actually reached (although the impacts of such a scenario would be dramatic). Looking beyond 2100, Jevrejeva et al. (2012) estimated a sea-level rise of 0.6–1.1 m by 2100 and between 1.84 and 5.49 m by 2500 (representing the lowest and highest forcing respectively). Therefore, the MIS5e sea-level highstand of +6.901 m would most probably be reached in the forthcoming centuries, but the exact moment remains unknown.

This scenario defined from a geological approach can serve as a source of information of the kind of impacts that could be expected in the long term, beyond 2100.

2.2.2 Sea-level rise scenarios based on the Holocene geological record

Changes in sea level during the Holocene have been reviewed in Section 2.1.2, where it has been explained the use of salt marsh foraminifera as proxies of Holocene sea levels. Several studies carried out in the Basque coast have provided information to build a sea-level-rise curve for the whole Holocene Epoch. The results from these studies have been summarised in Table 2.3. Based on these data, three phases of sea-level change have been identified for the Basque coast during the Holocene. The first phase, from 10,000 cal yr BP to 7,000 cal yr BP is defined by a rapid sea-level rise, as fast as 1 cm yr^{-1}. In the second stage, the rate of change dropped abruptly and almost no increase was measured. Finally, the rate of sea-level rise accelerates in the 20th century to 2.0 mm yr^{-1}.

Table 2.3. Summary of the rate of sea-level rise obtained for the Holocene using foraminifera-based transfer functions in the Basque coast.

Geological time	Years	Sea-level rise rate (mm yr^{-1})	Sedimentary record	Source
Anthropocene	1884 – 1994	2.0 ± 0.3	Ostrada marsh (Plentzia)	Leorri et al. (2008b)
	1936 – 2003	2.3 ± 0.4	Muskiz marsh (Muskiz)	Leorri and Cearreta (2009a)
	20th century	2.0 ± 0.3	Kanala marsh (Urdaibai)	García-Artola et al. (2009)
	20th century	2.0	Murueta marsh (Urdaibai)	Sainz de Murieta (2011)
Holocene	8500 – 7000 cal yr BP	9-12	Bilbao and Urdaibai estuaries	Leorri and Cearreta (2009b)
	7000 – 200 cal yr BP	0.7		
	10,000 – 7000 cal yr BP	22	Bilbao, Urdaibai and Deba estuaries	Leorri et al. (2012)
	7000 – 200 cal yr BP	0.7-0.3		

These data represent the relative sea-level rise, i.e. the relationship "between the ocean surface and the land" and it includes both the eustatic component (changes in global mean sea level) and the isostatic component (changes in the elevation of the land) (Lambeck et al., 2010: 65). This means that the rate of change represents the net rise of sea level in the Basque coast.

All this information has been used to define three scenarios of future sea-level rise. The first scenario is based on the relative sea-level rise rate measured during the 20th century, approximately 2.0 mm yr^{-1}. Data obtained from tide gauges and satellite measurements in the Bay of Biscay for the period 1993-2002 show already an accelerating rise in sea level of 3.09±0.21 mm yr^{-1} (Marcos et al., 2007b), therefore this first scenario represents a conservative choice based on a much longer temporal record.

The second scenario would represent a situation with no recent global warming. Sea level would rise following the general trend of the last 7000 years, so the net increase in 2100 would be 6.3 cm. Finally, the third scenario considers the sea-level rise rate occurred during the early Holocene, from 10,000 cal yr BP until approximately 7000 cal yr BP. It is the scenario with the fastest rate of change and the rise obtained for 2100 is close to the upper bound of the IPCC AR5 scenarios of sea-level rise (Church et al., 2013).

The latest Shared Socio-economic Pathways (SSP) projections of economic growth estimated by reference centres such as the International Institute for Applied Systems Analysis (IIASA, Austria), the Organisation for Economic Co-operation and Development (OECD) or the Potsdam Institute for Climate Impact Research (PIK) define three time periods to be considered: 2010-2030, 2030-2050 and 2050-2100. Following this example, the scenarios in this dissertation have been defined by the years 2030, 2050 and 2100, together with 2080, as a middle point between the last two (Table 2.4).

Table 2.4. Selected future scenarios of sea-level rise based on the palaeodata obtained from the Late Quaternary geological record in different estuaries of the Basque Country.

Scenario - Geological time	Rate of sea-level rise	Year			
		2030	2050	2080	2100
Scenario 1: Anthropocene (1900 – 2010)	2.0 mm yr^{-1}	4 cm	8 cm	14 cm	18 cm
Scenario 2: Holocene 2 (7000 cal yr BP – 1900)	0.5 mm yr^{-1}	1.4 cm	2.8 cm	4.9 cm	6.3 cm
Scenario 3: Holocene 1 (10,000 – 7000 cal yr BP)	10 mm yr^{-1}	20 cm	40 cm	70 cm	90 cm

These three scenarios add to the one that has been previously defined in Section 2.2.1, based on data from the LIG.

2.3 The impacts of future sea-level rise

This section shows the methodology to estimate the potential impacts of sea-level rise on three sites of the Basque coast. In order to do so, we build several flood risk maps, based on the different sea-level rise scenarios discussed in the previous Section 2.2. Flood maps have been defined not only considering changes in sea levels, but also addressing the sedimentary response of salt marshes to these changes. We believe that this is a significative contribution, representative of coastal systems' dynamism.

The case studies have been selected considering the information available but also with the aim of analysing and studying the economic costs incurred in areas with different land uses. The first case study analyses the impacts of sea-level rise on the salt marshes of the Oka Estuary, in the Urdaibai Biosphere Reserve. The second case study is the Butroe Estuary and the objective is to estimate the impacts on the urban area of the Plentzia village. The last case study is located in the municipality of Muskiz, along the Barbadun Estuary. Considering that the biggest oil refinery of Spain is located in this area, it is a very good example to assess the potential economic impacts of sea-level rise on an industrial area with high economic activity.

2.3.1 The response of salt marshes to recent sea-level rise

Salt marshes are dynamic ecosystems located at the highest position of sea level at any time that adapt in response to sea-level variations. This adaptive capacity is determined by the rate of sea-level rise, sediment supply, production of organic matter and land elevation in relation to mean sea level (Morris et al., 2002; Chust et al., 2010). Compared to other estuarine wetlands in the world where organic matter content can reach 20-80% of marsh sediment (Cochran et al., 1998), salt marshes in the southern Bay of Biscay show a smaller proportion of organic matter (below 15%), that concentrates in the upper vegetated zone. Detrital sediments are clearly dominant, indicating that a large input of minerogenic sediments controls its growth (Cearreta et al., 2002, 2013; Sainz de Murieta, 2011; García-Artola, 2013). Besides, sedimentation rates have been found to be linked to elevation with respect to the local tidal range, where lower areas show higher sedimentation rates (García-Artola, 2013).

Several studies in this area indicate that the accretion rate of salt marshes also depends on the conservation status of the ecosystem (see Table 2.5). Natural and regenerated salt marshes show accretion rates ranging from 0.5 to 3.7 mm yr^{-1}. Growth rates are greatest in salt marshes that are in regeneration process, reaching up to 18 mm yr^{-1}. The abandonment of agricultural land (during the 1950s in Urdaibai and the 1970s in Plentzia) led to the entrance of estuarine water in areas previously occupied for agriculture. This water input started a salt marsh regeneration process characterised by high sedimentation rates (average 14-18 mm yr^{-1}) (Cearreta et al., 2013; García-Artola, 2013). The environmental regeneration process was found to last approximately 10 years (García-Artola et al., 2011a).

In this dissertation, the accretion rates will be valuable inputs that will be incorporated into the flood risk maps. This capacity of salt marshes to adapt to (certain rates of) sea-level rise is extremely interesting, particularly when addressing climate change adaptation. While hard infrastructureS for coastal protection (e.g. a dike) are costly and rigid adaptation measures, salt marshes represent a low cost, low regret and flexible option. Besides the direct effects on flood protection, salt marshes additionally provide several co-benefits related to the services offered by these ecosystems, in terms of carbon sequestration, water purification, recreation and nursery and breeding ground for plants, birds and diverse aquatic fauna.

Table 2.5. Average accretion rates measured in different salt marshes of the Basque coast.

Sedimentary Record		Average accretion rate (mm yr^{-1})	Ecological state	Source
Area	Salt marsh			
Urdaibai	Axpe Norte	1.8	Natural	García-Artola (2013)
	Baraizpe	0.9	Regenerated	Cearreta et al. (2013)
		-	In regeneration	
	Busturia	3.5	Regenerated	García-Artola et al. (2011a)
		18	In regeneration	
		3.5	Regenerated	Cearreta et al. (2013), García-Artola (2013)
		14	In regeneration	
	Isla	1.7	Regenerated	Cearreta et al. (2013), García-Artola (2013)
		18	In regeneration	
	Kanala	1.0	Natural	García-Artola (2013)
	Murueta	1.7	Natural	Sainz de Murieta (2011)
		2.1	Natural	García-Artola (2013)
Plentzia	Txipio[18]	0.5-1	Regenerated	Cearreta et al. (2002)
	Ostrada	3.2	Natural	
		3.7	Natural	Leorri et al. (2008b)
	Isuskiza	14-18	In regeneration	García-Artola et al. (2011b)
		14-17	In regeneration	García-Artola (2013)
Muskiz	Barbadun	1.8	Natural	Cearreta et al. (2008)

2.3.2 Flood-risk maps

The LiDAR-based digital terrain model

The rates of change in sea level obtained from the Late Quaternary geological record were used to project future scenarios of sea-level rise in the Basque coast. For doing so, a high-resolution digital terrain model (DTM) of the Biscay coast[19] was used. The DTM was generated from an airborne light detection and ranging (LiDAR) system produced in 2012, and it had a 1×1 m horizontal resolution derived from a density of 2 laser measurement points per m^2 and a vertical accuracy of 0.15 m RMS[20].

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[18] In this case, lower accretion rates seem to be due to the land reclamation occurred in 1860 (Cearreta et al., 2002).

[19] Available at www.geo.euskadi.net/s69-15375/es/

[20] RMS: root mean square error

The use of the LiDAR based DTM allows us to map the sea-level changes and the impacts on the study area at a high spatial resolution and vertical precision (Marcos et al., 2012). DTM values were in orthometric heights above MSL of Alicante ordnance datum, obtained using the IBERGEO95 geoid model, and the ETRS89 coordinate reference system (Marcos et al., 2012a). This Alicante ordnance datum, the general reference used in Spain, is located at 0.34 m below the MSL in Bilbao, according to the vertical levelling of 2008. The LiDAR data were imported into the ESRI ArcGIS™ system (ESRI, Redlands, USA) using Arc Macro Language (AML) standard processing routines.

LiDAR validation process

The LiDAR technology has enabled significant progress in obtaining high-precision and high-resolution elevation data. This technology has proved very useful in urban areas where identifiable landmarks (such as buildings or roads) can be used to calibrate the model and it has also been successfully applied in forest ecosystems. However, its use in salt marsh areas is more complex, due to the lack of accurately recognisable references and particularly because of the characteristics of salt marsh vegetation (Wang et al., 2009). In these coastal ecosystems, the laser shows a lower capacity to penetrate through salt marsh vegetation, leading to elevation errors in the results (Schmid et al., 2011).

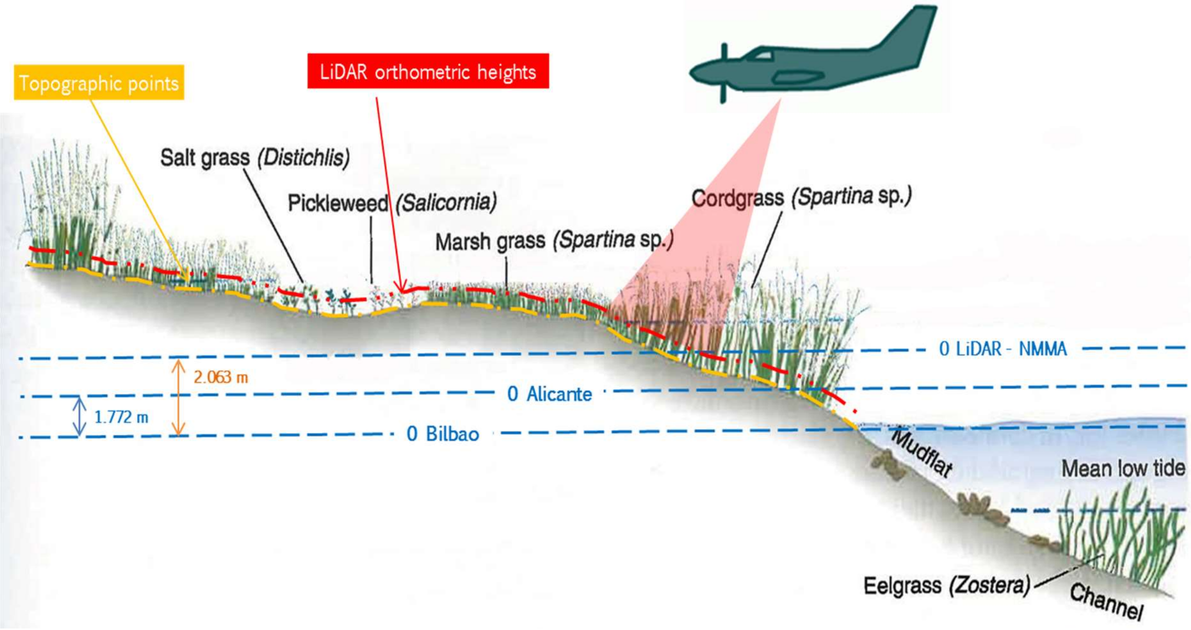

Figure 2.15. Sea-level references (ordnance data of Bilbao and Alicante) and topography. The diagram shows the difference that could exist between the two systems (topographic points *versus* LiDAR heights).

For this reason, we validated LiDAR orthometric heights using topographic points obtained during field works previous to this study, following Chust et al. (2010). We used 100 points in the study case of Urdaibai and 28 points in Muskiz. There was no available information for Plentzia (Figure 2.15).

In the case of Muskiz we obtained a mean difference of 0.0959 m between the two systems (LiDAR heights below topographic points), with 40% of the points found between 0.20 and 0.36 m (middle value 0.28 m). In Urdaibai it was found that the mean difference between the two systems was

0.0898 m, very close to that obtained for Muskiz (LiDAR heights below topographic points). Regarding the distribution of values, 74% of them were between 0.16 and 0.48 m (middle value 0.32 m). See Figure 2.16 for further details. The results from the LiDAR validation process in Muskiz and Urdaibai are shown in Figure 2.16.

As the mean values obtained in both cases are within the error margin of the LiDAR technology (0.15 m vertical accuracy), we decided not to make any correction to the LiDAR based DTM.

Description Data Muskiz	
Count	28
Mean	0.0959
Deviation	0.3196
Variance	0.1022
Kurtosis	-0.1318
Bias	-0.9874
Minimum	-0.6360
Maximum	0.5810
Range	1.2170
Norm (p-valor)	0.0325

Groups 10

Group	Frequency
-0.64	1
-0.48	2
-0.33	2
-0.18	1
-0.03	1
0.12	3
0.28	11
0.43	6
0.58	1
0.73	0

Descriptive Data Urdaibai	
Count	99
Mean	0.0898
Deviation	0.3260
Variance	0.1062
Kurtosis	22.8145
Bias	-4.3188
Minimum	-1.9320
Maximum	0.6410
Range	2.5730
Norm (p-valor)	0.0000

Groups 10

Group	Frequency
-1.93	1
-1.61	1
-1.29	0
-0.97	0
-0.65	1
-0.32	1
0.00	15
0.32	73
0.64	7
0.96	0

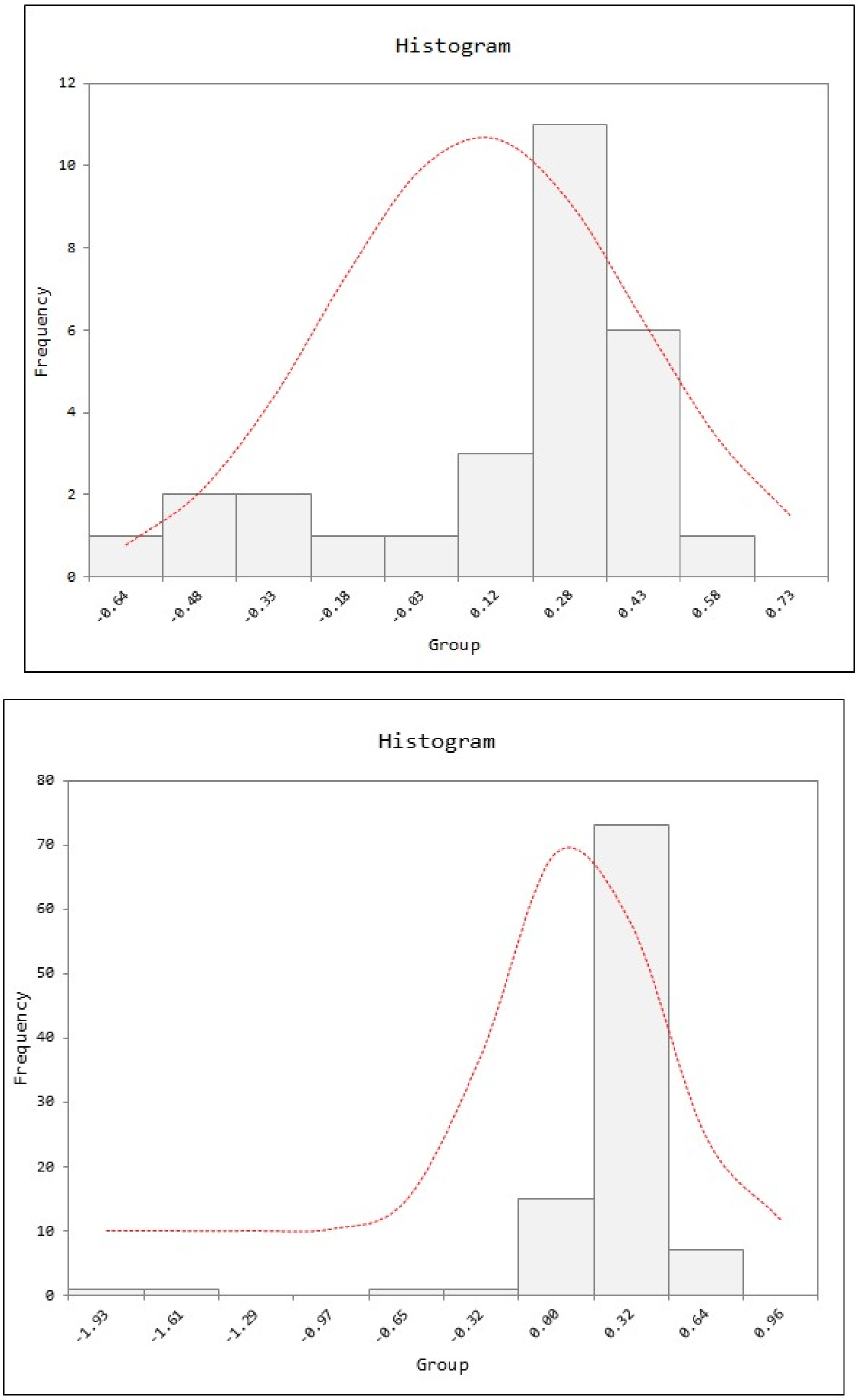

Figure 2.16. Statistical output of the LiDAR validation process. Topographic heights were compared to LiDAR heights. The upper figure shows the results for Muskiz. The lower represents those for Urdaibai.

Identification and digitalization of salt marshes

As explained in previous Section 2.3.1, salt marsh ecosystems have the capacity to adapt to sea-level rise by increasing their height (accretion) thanks to adequate sediment availability in the estuaries. Several previous studies in the Basque coast found that the accretion rate depends on their conservation status. These accretion rates will be an input when developing flood risk maps. In order to do so, existing salt marsh ecosystem areas were delimited using geographic information systems in all three case studies. The identification of salt marshes was carried out by photointerpretation of the 0.25 m spatial resolution aerial photographs from 2012[21] (for example, see Figure 2.17).

Apart from existing salt marsh ecosystems, potential salt marsh areas were also identified. Based on surveys of modern depositional environments, vegetation zones and associated foraminiferal assemblages, Leorri et al. (2012) estimated the height above mean tide level (Bilbao ordnance datum) at which different depositional environments appear in the Basque coast (Table 2.6). The heights for low and high marshes were used to identify potential salt marsh areas and the zones included in the Sectorial Spatial Plan for Wetland Protection (Basque Government, 2004), so wetland areas to be environmentally recovered were also taken into account.

Table 2.6. Indicative topographic positions for different estuarine environments on the Basque coast referenced to Bilbao ordnance datum (BOD). Topographic positions relative to the mean sea level in Alicante have also been included as it is the reference of the LiDAR DTM.

Environment	Above Reference BOD (m)			Above Reference Alicante MSL (m)		
	Lower range	Mid point	Upper range	Lower range	Mid point	Upper range
Fresh water tidal mud flat	5.0	5.5	7.0	2.937	3.437	4.937
High marsh	**3.5**	**4.0**	**4.5**	**1.437**	**1.937**	**2.437**
Low marsh	**3.3**	**3.8**	**4.3**	**1.237**	**1.737**	**2.237**
Tidal creeks and tidal mud flat	2.4	3.1	3.8	0.337	1.037	1.737
Tidal mixed flat	1.6	2.4	3.2	-0.463	0.337	1.137
Tidal sand flat	0.3	1.2	2.1	-1.763	-0.863	0.037
Subtidal	-3.0	0.0	0.2	-5.063	-2.063	-1.863

Source: Leorri et al. (2012)

The total salt marsh surface included in the flood risk areas is the sum of existing salt marshes plus those areas that could be environmentally restored into salt marshes. An example is shown in Figure 2.17.

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[21] Basque Government Cartographic Services: www.geo-euskadi.net

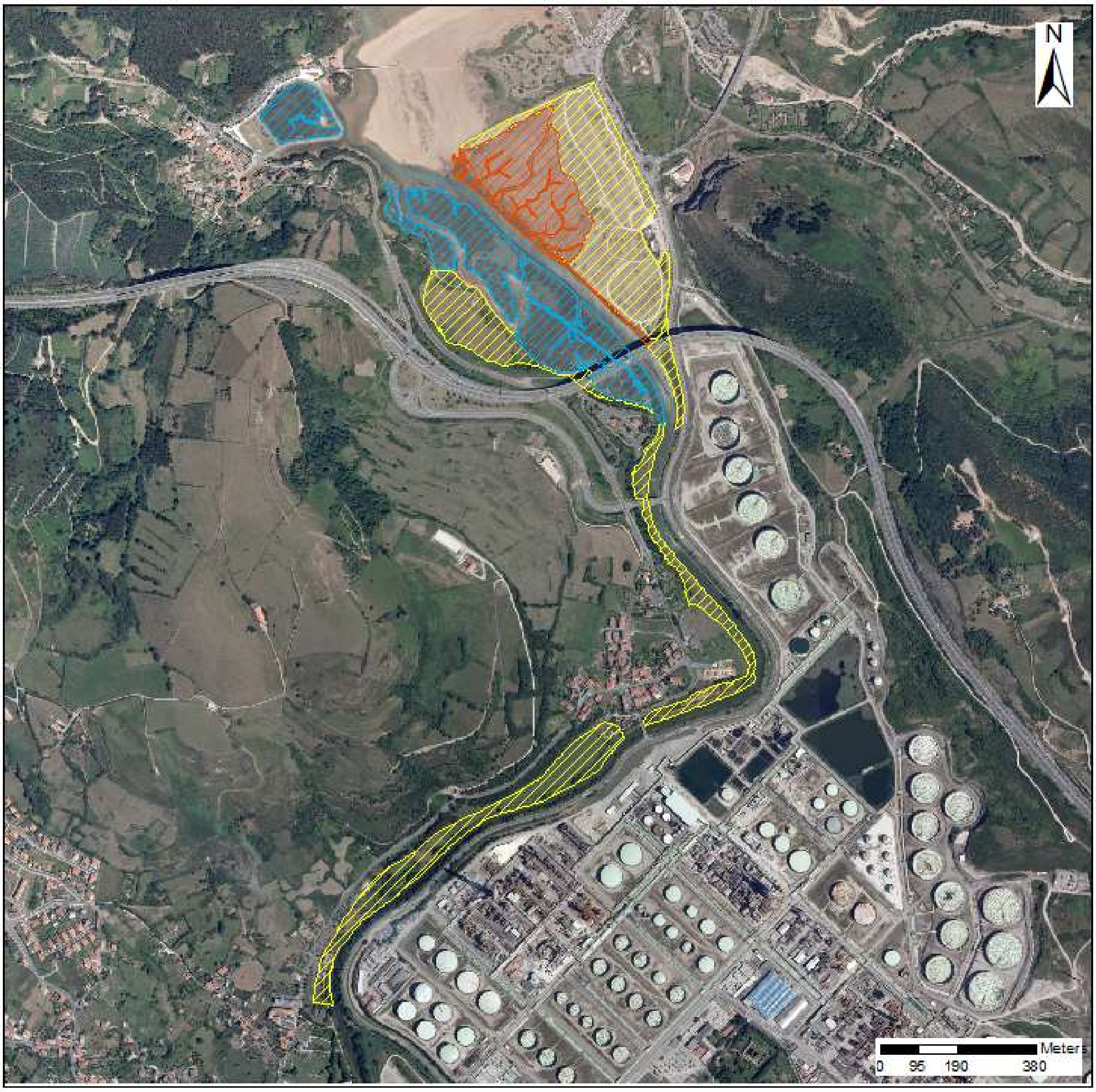


Figure 2.17. Delimitation of salt marsh areas in the Barbadun Estuary. The areas in blue represent current natural marshes, while the red area shows a salt marsh in regeneration process. The yellow areas are potential wetland areas, following the indicative topographic positions described by Leorri et al. (2012) and the zones included in the Sectorial Spatial Plan for Wetland Protection (Basque Government, 2004).

Building flood-risk maps

For each of the sea-level rise scenarios summarised in Table 2.4, two different sea levels were considered:

- MSL: located at 0.340 m above the Alicante Ordnance Datum (mean sea level in Alicante, MSLA). This level is the average value of annual mean levels registered by the Bilbao tide-gauge.
- MAHT level: located at 2.77 m above MSLA. It is defined as the maximum high tide in a 19-year return period and it corresponds to the level of extreme sea events, such as storm surges.

Table 2.7. Tidal parameters of the Bilbao I tide gauge. The heights are represented in centimetres.

Sea levels	Height (above Bilbao 0 m)	Height (above Alicante MSL)
Maximum Observed Level	505	299
Maximum Astronomic High Tide (MAHT)	483	277
Mean Observed Spring High Tide (MOSHT)	440	234
Mean Observed Neap High Tide	321	115
Mean Sea Level	240	34
Mean Observed Neap Low Tide	156	-50
Mean Observed Spring Low Tide	39	-167
Minimum Astronomic High Tide	-11	-217
Minimum Observed Level	-27	-233
Bilbao Ordnance Datum	0	206

Source: based on the reports from Puertos del Estado (2005, 2009) and Chust et al. (2010).

Following Marcos et al. (2012a), flood risk maps were defined using standard geographic information system (GIS) processing routines to estimate the extent of inundation:

1. The coastlines for mean and MAHT sea levels were defined, at 0.34 m and 2.77 m above the mean sea level in Alicante (MSLA) respectively, using the DTM.
2. Sea-level rise scenarios were added, obtaining future mean and MAHT sea levels for the years 2030, 2050, 2080 and 2100.
3. The area between steps 1 and 2 was estimated. A correction process was carried out, removing those zones not connected to the sea water.
4. Salt marsh accretion rates were estimated for each time span.
5. The flooded area for each scenario and time period was then calculated considering salt marsh ecosystems and artificial zones (industrial and urban land, depending on each case study).

2.4 Conclusions

In this chapter we have discussed that the link between past and future changes in sea level is not a straightforward equation. Many factors, such as Earth's orbital parameters, ocean circulation, etc, were different from today's. Nevertheless, many authors argue that the past can be a key to better understand the difference between natural and anthropogenic variability, and to improve the knowledge of the impacts that may be expected. Thus, we have looked at changes in sea level during the LIG and the Holocene as a way to approach future impacts of sea-level rise.

The sea-level rise scenario based on the LIG has been defined on data from a coastal sequence located in Oyambre (Cantabria). Beach deposits at the base of the sequence were found above current sea level, so they correspond to an emerged coastline. Our hypothesis is that these materials represent a MIS5e sea-level highstand. In order to test this initial assumption, we have dated the sediments from the Oyambre outcrop using OSL techniques. The methodology is described in detail in Section 2.4.1. The topographic height of the palaeobeach deposits at +6.901 m above BOD has been used as a reference to define the LIG scenario.

The Holocene curve of sea-level rise was reconstructed based on several studies carried out in Basque salt marshes which used foraminifera as proxies of past sea levels. The curve is divided in three parts, depending of the rate of sea-level rise measured:

- From 10,000 – 7000 cal yr BP sea-level rose at a pace of 10 mm yr^{-1}
- From 7000 cal yr BP to 1900 sea level almost stabilised, and the rate of change dropped to 0.5 mm yr^{-1}
- During the 20th century, from 1900 to 2010, the rate of sea-level rise increased to 2 mm yr^{-1}

Each of these rates of change has been used to define a future scenario of sea-level rise, so three scenarios have been defined for the Holocene and Anthropocene.

Finally, we have described the methodology to translate these four scenarios based on the recent geological record into flood risk maps that will serve to assess potential impacts on three areas of the Basque coast: the Urdaibai Biosphere Reserve, the urban area of Plentzia and the industrial site of Petronor in Muskiz.

3 Results of the geological approach

3.1 Introduction

This chapter presents the results obtained from the application of the methodology explained in Chapter 2 and it is divided in two main parts. The first part focuses on the results from the analysis carried out in the Oyambre outcrop. The sedimentology of the Oyambre sequence is described first, followed by the results of the luminescence dating. The outcome of this analysis is then used to build one of the four sea-level rise scenarios considered in this dissertation, more specifically, the scenario based on the level reached by the sea during the Last Interglacial (LIG-MIS5e).

The second part of this chapter presents the flood-risk maps found on different geological scenarios. Scenarios 1 to 3 correspond to different rates of sea-level rise occurred during the Holocene and Anthropocene, and add to the LIG-MIS5e Scenario. The potential impacts of these four scenarios of sea-level rise have been applied to three sites of the Basque coast, namely the Urdaibai Biosphere Reserve (URB), the Plentzia Estuary and the Muskiz Estuary. The third and last section provides some highlights on the main findings of the geological approach.

3.2 Oyambre

3.2.1 Sedimentology

At the Oyambre outcrop, located topographically above modern beach deposits, a Pleistocene coastal deposit onlaps a palaeocliff cut on soft Oligocene marls. The outcrop has a lithostratigraphy that comprises two well defined units, subdivided in several sub-units (beds). The sedimentary sequence observed in the studied outcrop is shown in Figure 3.1 to 3.13.

The lower unit (2.26 m thick; beds 1 to 3) includes a basal bed of boulder gravel with imbrication, located from 6.901 to 8.42 m above the reference sea level (Bilbao ordnance datum), followed by brown pebbly fine sands (from 8.42 to 9.25 m above sea level). The second unit (10.76 m thick; beds 4 to 26) is formed by sandy layers intercalated by thinner mud layers, extending from 9.25 m to the top of the outcrop (approximately at 22 m above sea level). Bed 4 is characterised by white-grey fine sands. Bed 5 shows a layer of grey mud at the base, then a layer of grey sandy mud, and a final layer of black mud at the top. Bed 6 is made of laminated yellow medium sand. Bed 7 is composed of massive white sand. Bed 8 is of massive yellow medium sand. Bed 9 has an erosive surface at the base, and comprises brown medium sands. Bed 10 is made of grey very fine silt. Bed 11, composed of white medium sand, is followed by yellow and grey fine sands (beds 12 and 13). Laminated brown medium muddy sand appears in bed 14. Beds 15 to 20 comprise yellow to beige medium sands alternating with dark clays. Bed 21 is formed by medium white sands with cross-bedding, that grade upwards to muddy fine sands. The succession ends with a sequence of beige medium sands (beds 24 to 26), with a thin intercalation of a grey muddy sand and a topmost bed of yellow fine sand.

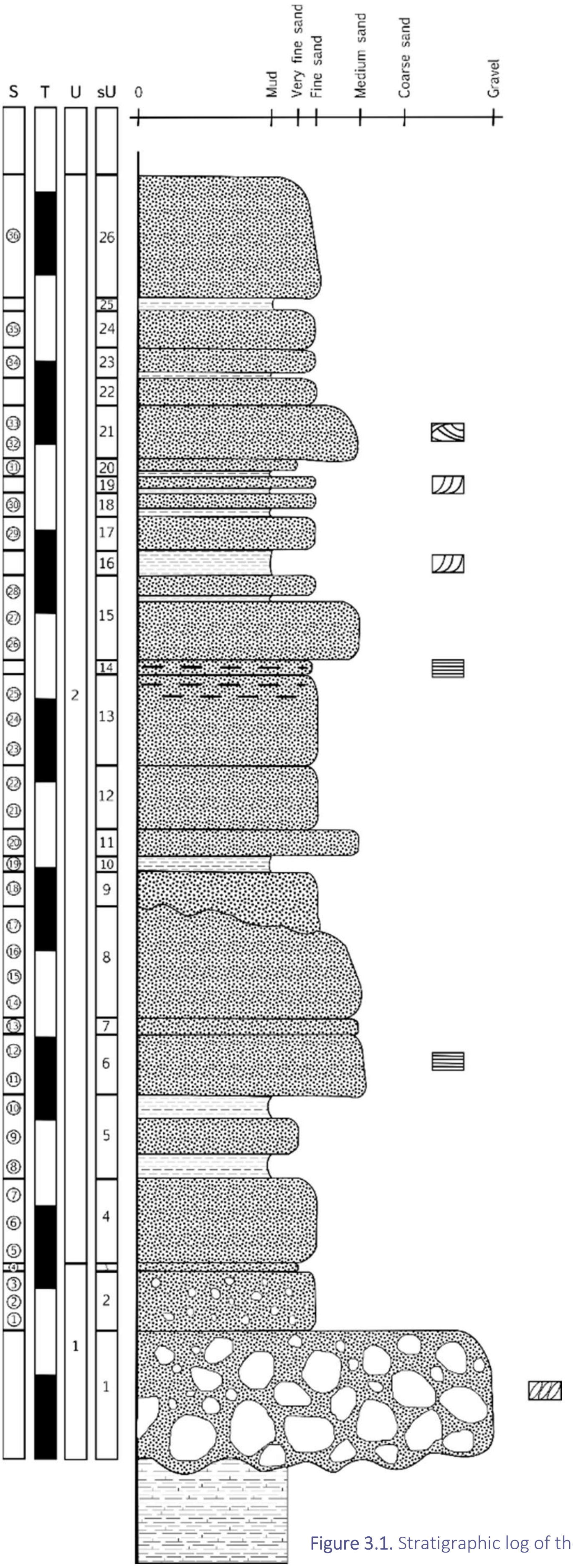


Figure 3.1. Stratigraphic log of the Oyambre outcrop.

Only the sediments sampled for OSL dating were submitted to grain size analysis, carried out with a Coulter granulometer (2 mm to 0.04 µm). This implies that the sand beds and the thicker mud beds of the lower part of the sedimentary succession were analysed.

Figure 3.2. Basal gravels, at 6.901 m above Bilbao ordnance datum, over the soft Oligocene marls.

Figure 3.3. Brown pebbly sands of bed 2 (Ployambre 01-03) and bed 3 (Ployambre 04). Ployambre 05 is located at the base of transitional sediments formed by sandy layers intercalated by thinner mud layers.

Figure 3.4. White-grey fine sands of bed 4 (Ployambre 05-07). Grey sands appear in bed 5 (Ployambre 08-10), with a bed of grey mud at the base and a bed of black mud at the top.

Figure 3.5. Contact between bed 5 (black mud) and subunit 6 (yellow sands).

Figure 3.6. Succession of samples of transitional sediments. The lower sample is Ployambre 12 (bed 6), in a layer of yellow sands. The top sample corresponds to bed 13 (sample Ployambre 25).

Figure 3.7. Detail of bed 6 (Ployambre 12) with yellow sands, followed by massive white sands (bed 7, Ployambre13) and yellow sands again on top (bed 8, Ployambre 14 to Ployambre 15).

Figure 3.8. Detail of yellow and grey sands at the base forming bed 13 (Ployambre 23 to 25), followed by laminated brown medium muddy sands (bed 14) and yellow sands at the top (bed 15, Ployambre 26).

Figure 3.9. Detail of bed 14 (laminated brown muddy sands). Sample Ployambre 25 corresponds to the top of bed 13, and Ployambre 26 is at the base of bed 15.

Figure 3.10. Beds 15 to 21 (Ployambre 26 to 33), composed of yellow and beige sands alternating with thin clay layers.

Figure 3.11. Detail of white sands with cross bedding of bed 21 (Ployambre 32).

Figure 3.12. Beige medium sands with thin intercalations of grey muddy sand (beds 23 and 24, samples Ployambre 34 and 35).

Figure 3.13. Yellow massive fine sands end the sedimentary sequence (Ployambre 36).

Considering the results of the grain-size analysis (Table 3.1, Figure 3.14), together with the field data, it is possible to identify two depositional environments in this sedimentary sequence. The first one is formed by the gravels and the brown pebbly fine sands (beds 1 to 3), representing an ancient beach environment. The sea-level highstand would be represented at the base of the gravels (bed 1). Note that for the grain size analysis of the samples Ployambre 1, 2 and 3 (bed 2) the dispersed pebbles were not considered.

The remaining part of the succession is interpreted as representing deposits of aeolian environment. Medium sands, massive or with cross lamination, intercalated with occasional muddy beds suggests the presence of very small water flows; a tendency of medium sands changing to fine sands is evidenced. The outcrop as a whole is showing sedimentary evolution corresponding to a transgressive episode represented by basal beach environment followed by a relative regressive episode evidenced by the aeolian dune environment.

The results from the grain size analysis suggest that the palaeoenvironments recorded by the outcrop deposits are very similar to the modern ones in Oyambre: beach and sand dunes adjacent to the stream mouth (Arroyo del Capitán). Table 3.1 shows the descriptive grain size statistics of the 38 samples (2 modern and 36 of the outcrop deposits) analysed with a Coulter granulometer (by Prof. Pedro Cunha, Earth Sciences Dept. – University of Coimbra).

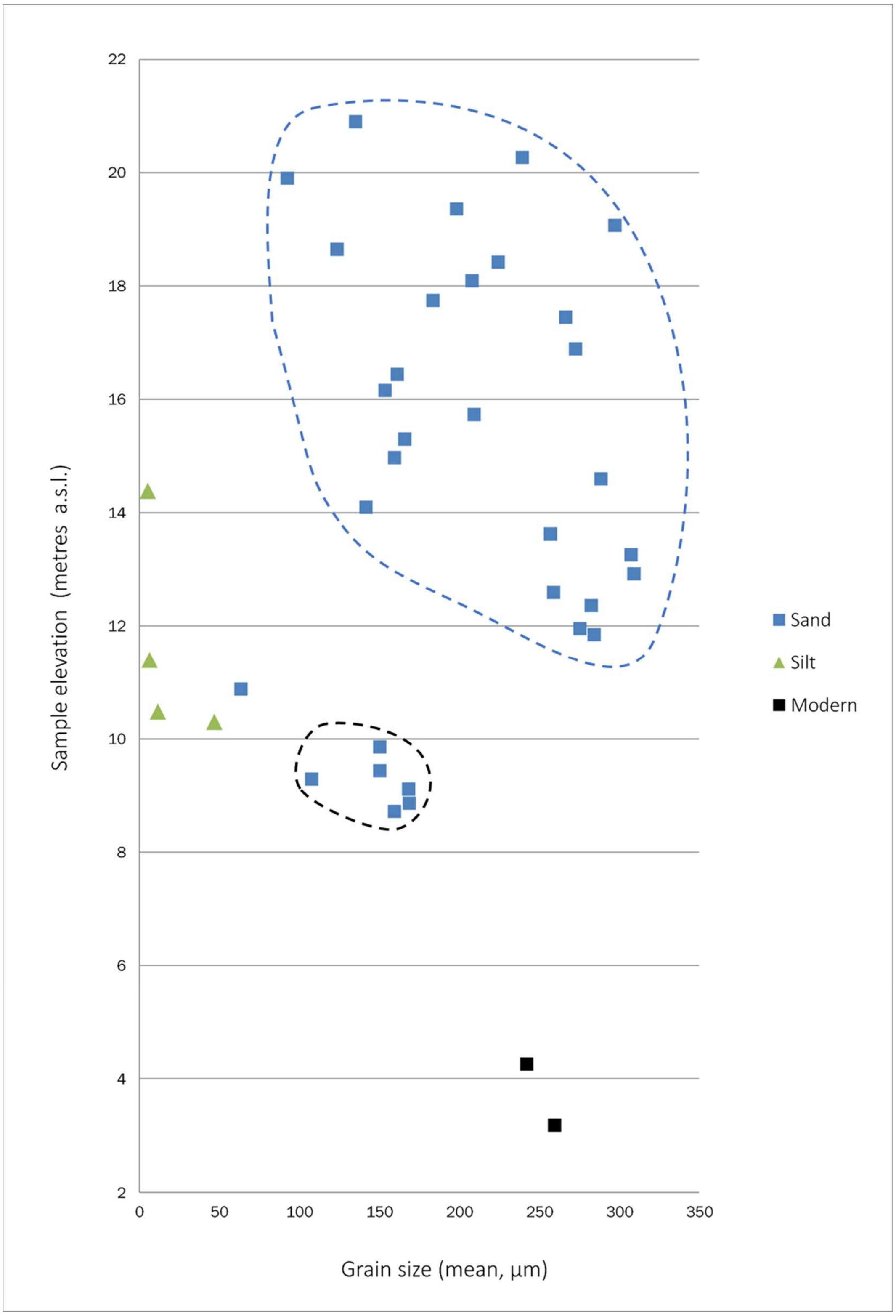


Figure 3.14. Grain size of the sediments plotted *versus* sample elevation.

Table 3.1. Results of the grain-size analysis of the samples obtained at the Oyambre outcrop (Cantabria).

Lab code	Field code	Stratigraphic sub-unit	Mean (µm)	Mean	Median (µm)	Modes (µm)	St. Dev.	Skewness		Kurtosis		Sand (%)	Silt (%)	Clay (%)
122294	Ployambre 36	26	135.3	fine sand	215.9	295.5; 50	3.569	-1.393	Left skewed	2.213	Leptokurtic	75.28	22.39	2.33
122293	Ployambre 35	24	239.5	fine sand	305.2	324.4; 40	2.849	-2.649	Left skewed	8.398	Leptokurtic	90.71	7.91	1.08
122292	Ployambre 34	23	92.5	very fine sand	244.7	295.5; 6 ; 50	6.898	-1.032	Left skewed	-0.383	Platykurtic	69.85	19.14	11
122291	Ployambre 33	21	198.5	fine sand	271	295.5; 45	2.973	-2.252	Left skewed	6.112	Leptokurtic	87.4	11.1	1.5
122290	Ployambre 32	21	297.4	medium sand	324.7	324.4	2.077	-3.69	Left skewed	21.14	Leptokurtic	96.5	2.88	0.62
122289	Ployambre 31	20	123.7	very fine sand	207.7	269.2; 40	3.816	-1.254	Left skewed	1.652	Leptokurtic	71.8	25.58	2.62
122288	Ployambre 30	18	224.4	fine sand	273.5	295.5	2.552	-2.658	Left skewed	9.913	Leptokurtic	91.67	7.27	1.06
122287	Ployambre 29	17	208.1	fine sand	267.6	295.5	2.769	-2.449	Left skewed	7.912	Leptokurtic	90.13	8.58	1.29
122286	Ployambre 28	15	183.7	fine sand	262.7	295.5; 50	3.025	-2.189	Left skewed	5.454	Leptokurtic	85.54	12.89	1.57
122285	Ployambre 27	15	266.7	medium sand	333.1	324.4	3.069	-3.215	Left skewed	11.15	Leptokurtic	94.23	3.39	2.38
122284	Ployambre 26	15	272.8	medium sand	331.4	324.4	2.894	-3.555	Left skewed	14.31	Leptokurtic	94.46	3.24	2.3
122283	Ployambre 25	13	161.3	fine sand	282.4	324.4	4.736	-1.843	Left skewed	2.614	Leptokurtic	82.59	11.59	5.82
122282	Ployambre 24	13	153.7	fine sand	306.7	356.1; 8	5.441	-1.567	Left skewed	1.306	Leptokurtic	79.27	14.33	6.4
122281	Ployambre 23	13	209.4	fine sand	323.2	324.4	4.166	-2.255	Left skewed	4.504	Leptokurtic	87.18	8.61	4.21
122280	Ployambre 22	12	166	fine sand	302.6	324.4; 10	4.894	-1.691	Left skewed	1.925	Leptokurtic	81.59	13.19	5.22
122279	Ployambre 21	12	159.7	fine sand	310.4	356.1; 10	5.33	-1.665	Left skewed	1.579	Leptokurtic	80.28	13.48	6.23
122278	Ployambre 20	11	288.8	medium sand	356.5	356.1	2.95	-3.223	Left skewed	11.97	Leptokurtic	92.25	5.22	2.53
122277	Ployambre 19	10	5.3	very fine silt	5.7	9.371; 50	2.898	-0.032	Left skewed	-0.479	Platykurtic	0.18	60.82	39
122276	Ployambre 18	9	141.8	fine sand	300	356.1; 8	5.908	-1.522	Left skewed	1.025	Leptokurtic	79.54	12.71	7.75
122275	Ployambre 17	8	257.1	medium sand	337	324.4	3.533	-2.766	Left skewed	8.114	Leptokurtic	91.05	5.5	3.45
122274	Ployambre 16	8	307.6	medium sand	339.4	324.4	2.43	-3.939	Left skewed	20.33	Leptokurtic	95.15	2.92	1.93
122273	Ployambre 15	8	309.4	medium sand	360.3	356.1	2.707	-3,659	Left skewed	16.2	Leptokurtic	95.39	2.81	1.8
122272	Ployambre 14	8	259	medium sand	332.3	324.4	3.136	-3.221	Left skewed	11.26	Leptokurtic	92.37	4.58	3.05
122271	Ployambre 13	7	282.7	medium sand	313.8	324.4	2.276	-4.028	Left skewed	22.73	Leptokurtic	96.7	2.16	1.14
122270	Ployambre 12	6	275.6	medium sand	324.3	324.4	2.698	-4.015	Left skewed	18.22	Leptokurtic	1.99	2.09	95.92
122269	Ployambre 11	6	284.4	medium sand	330.7	324.4	2.593	-4.193	Left skewed	20.34	Leptokurtic	96.46	1.71	1.83
122268	Ployambre 10	5	6.4	very fine silt	7	10.3	2.813	-0.192	Left skewed	-0.419	Platykurtic	0.17	68.22	31.61
122267	Ployambre 09	5	63.6	very fine sand	98.7	223.4; 50; 10	4.806	-0.901	Left skewed	0.192	Leptokurtic	59.91	32.94	7.15
122266	Ployambre 08	5	11.6	fine silt	12	12.40; 40; 150	3.804	-0.112	Left skewed	0.499	Platykurtic	10.98	67.39	21.63
122265	Ployambre 07	4	46.8	coarse silt	78.5	269.2; 10; 50	6.587	-0.581	Left skewed	0.876	Platykurtic	52.33	34	13.67
122264	Ployambre 06	4	150.4	fine sand	264.3	295.5	4.5	-1.895	Left skewed	2.796	Leptokurtic	81.93	12.92	5.15
122263	Ployambre 05	4	150.4	fine sand	267.9	295.5	4.843	-1.741	Left skewed	2.241	Leptokurtic	81	13.08	5.92
122262	Ployambre 04	3	107.7	very fine sand	216.2	245.2; 50; 8	5.874	-1.428	Left skewed	0.903	Leptokurtic	77.53	13.12	9.35
122261	Ployambre 03	2	168.4	fine sand	226.8	245.2	3.671	-2,156	Left skewed	5.315	Leptokurtic	88.27	7.9	3.83
122260	Ployambre 02	2	168.9	fine sand	230.1	245.2	3.527	-2.236	Left skewed	5.745	Leptokurtic	88.43	8.26	3.31
122259	Ployambre 01	2	159.5	fine sand	228.5	245.2	3.695	-2.161	Left skewed	4.899	Leptokurtic	86.71	9.37	3.92
-	Ployambre 0	Modern beach sample	259.7	medium sand	254	245.2	1.438	0.47	Right skewed	0.921	Leptokurtic	100	0	0
-	Ployambre dune	Modern dune sample	242.3	fine sand	238.1	245.2	1.36	0.851	Right skewed	2.137	Leptokurtic	100	0	0

3.2.2 Foraminiferal content

Thirty eight samples were collected from the Oyambre outcrop in order to analyse their foraminiferal content. Thirty six of those samples were coincident with the tube samples for luminescence dating, another one was collected from the modern Oyambre beach and the last one was sampled from the basal boulder gravel.

Counting a minimum of 300 individuals per sample is required in order to ensure statistical representativeness. Otherwise, all individuals need to be obtained. This is the case of the 36 samples collected from the Oyambre outcrop, as the foraminiferal content of those samples is extremely low. The results are shown in Table 3.2.

Table 3.2. Results of the foraminiferal analysis of samples Ployambre 1 to 36 obtained at the Oyambre outcrop (Cantabria).

Sample	*T. inflata*	*J. macrescens*	*A. mexicana*	*A. tepida*	*C. excavatum*	*B. gibba*	No. tests	No. species
PLOyambre36							0	0
PLOyambre35	2	1					3	2
PLOyambre34							0	0
PLOyambre33							0	0
PLOyambre32	9		2	1			12	3
PLOyambre31							0	0
PLOyambre30						1	1	1
PLOyambre29							0	0
PLOyambre28							0	0
PLOyambre27							0	0
PLOyambre26							0	0
PLOyambre25							0	0
PLOyambre24							0	0
PLOyambre23							0	0
PLOyambre22							0	0
PLOyambre21							0	0
PLOyambre20		1					1	1
PLOyambre19							0	0
PLOyambre18							0	0
PLOyambre17							0	0
PLOyambre16				1			1	1
PLOyambre15							0	0
PLOyambre14							0	0
PLOyambre13							0	0
PLOyambre12							0	0
PLOyambre11							0	0
PLOyambre10	1						1	1
PLOyambre9							0	0
PLOyambre8							0	0
PLOyambre7	1						1	1
PLOyambre6							0	0
PLOyambre5		2			1		3	2
PLOyambre4							0	0
PLOyambre3							0	0
PLOyambre2							0	0
PLOyambre1							0	0
Total	13	4	2	2	1	1	23	6

More than 300 tests were found in the sample from the modern beach environment. Seventeen species were identified, even though *C. lobatulus* is the dominant species of the assemblage (79%). The results are shown in Figure 3.3.

Table 3.3. Results of the foraminiferal content of the sample from the modern Oyambre beach.

Species	No. tests
C. lobatulus	255
R. anomala	23
M. secans	14
A. mamilla	4
Q. lata	4
S. wrightii	4
R. irregularis	3
E. crispum	2
H. germanica	2
A. inhaerens	2
Q. seminula	2
A. tepida	1
B. gibba	1
C. obtusa	1
C. carinata	1
B. marginata	1
C. williamsoni	1
TOTAL	321

More than 300 individuals were also obtained from the sample of the boulder gravel, which corresponds to the palaeobeach environment. Planktonic foraminifera were abundant (approximately 40%) and Oligocene species were also found. The species assemblage of this sample does not match the one found in the modern Oyambre beach sample and shown in Table 3.3.

3.2.3 Luminescence dating

Thirty six samples were collected from the outcrop for quartz optically stimulated luminescence (Qtz-OSL) dating, namely: four samples of pebbly fine sands representing a beach environment, Ployambre 01 to 04 (NLL codes 122259 to 122262); thirty two samples located above and representing an aeolian dune environment, Ployambre 05 to 36 (NLL 122263 to 122294). Two modern analogues of aeolian dune and beach sands were also collected, Ployambre 0 and dune (NLL codes 122257 and 122258). The luminescence dating results are shown in Table 3.4.

According to the literature, the accuracy of Qtz OSL is reliable up to equivalent dose rates usually between 80 and 250 Gy, depending on the luminescence characteristic of the quartz (e.g. Wintle and Murray, 2006). In the Oyambre outcrop, equivalent doses over saturation (>250 Gy) were measured in the samples Ployambre 01 to 10 (NLL 122259 to 122268), but also in Ployambre 18 and 19 (NLL 122276 and 122277) and consequently the results of these samples were discarded.

The samples with equivalent doses below saturation provided ages varying between 89±8 ky and 191±14 ky, corresponding to samples Ployambre 13 and 31 respectively (see Figure 3.15B). However, a huge scattering can be identified in the results that in some cases are represented by ages that are not according to the stratigraphic order.

It is very probable that these highly scattered age values and respective equivalent doses result from partial bleaching, because the soft Oligocene marls of the basement could have contributed with a considerable amount of quartz grains not sufficiently exposed to sun light during deposition. Therefore, these locally supplied grains would have large residual doses, leading to datings that significantly overestimate the real burial ages.

If only samples in correct stratigraphic position that show lower contamination are selected, then we can derive the conclusion that, once corrected the effect of partial bleaching, the probable depositional age of this outcrop deposits would be ca. 102 ky to 89 ky for the upper aeolian deposits (medium to very fine sands interbedded with few clays) and ca. 116 to 108 ky for the basal beach environment (gravelly fine sands and boulder gravels) (Figure 3.16). So, the sedimentary sequence provided by this coastal outcrop should record the Marine Isotope Stage 5 (MIS5). The base of the marine deposits that indicates the maximum relative palaeosea-level (boulder gravels with sands of bed 1) are today at an elevation of 6.901 m above Bilbao ordnance datum which is in good agreement with the MIS5e highstand that reached around 6.0 m above MSL (Hearty et al., 2007; Rohling et al., 2008).

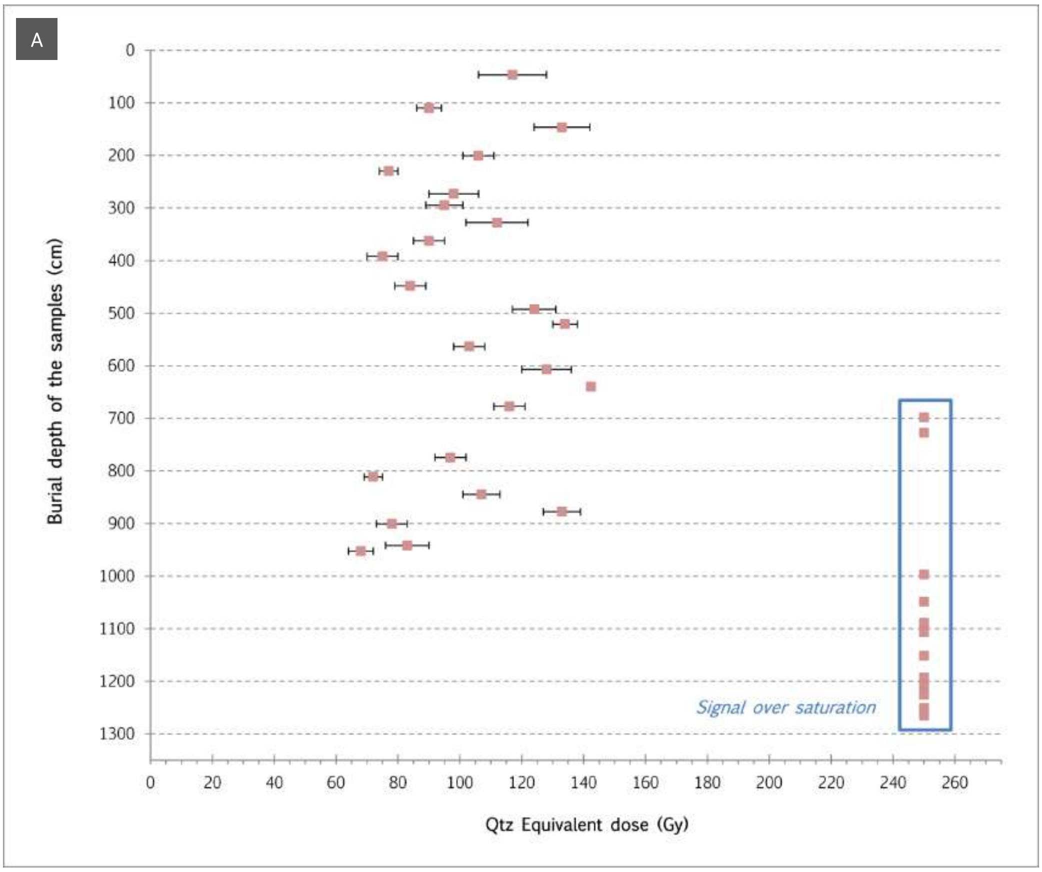
Table 3.4. Summary of quartz optically stimulated luminescence.

Lab code	Field code	Geographic coordinates	Site	Burial depth (cm)	Qtz equivalent dose (Gy)	(n)[1]	Qtz dose rate (Gy/ka)	w.c.[2]	Qtz age (ky)
122294	Ployambre 36	391588.730 / 4806038.159	Oyambre beach	46.8	117 ± 11	12	1.26 ± 0.05	8	93 ± 10
122293	Ployambre 35	391588.984 / 4806038.045	Oyambre beach	109.9	90 ± 4	17	0.73 ± 0.03	8	124 ± 8
122292	Ployambre 34	391589.140 / 4806037.989	Oyambre beach	146.5	133 ± 9	12	1.18 ± 0.05	8	113 ± 9
122291	Ployambre 33	391589.418 / 4806037.712	Oyambre beach	200.7	106 ± 5	23	0.89 ± 0.04	8	119 ± 8
122290	Ployambre 32	391590.229 / 4806037.123	Oyambre beach	229.9	77 ± 3	12	0.66 ± 0.03	8	117 ± 7
122289	Ployambre 31	391590.506 / 4806037.367	Oyambre beach	273.3	98 ± 8	18	1.09 ± 0.04	9	89 ± 8
122288	Ployambre 30	391591.638 / 4806037.166	Oyambre beach	294.7	95 ± 6	12	0.93 ± 0.04	8	102 ± 8
122287	Ployambre 29	391591.693 / 4806037.254	Oyambre beach	327.7	112 ± 10	12	0.79 ± 0.03	8	141 ± 14
122286	Ployambre 28	391591.798 / 4806037.371	Oyambre beach	362.4	90 ± 5	16	0.79 ± 0.03	8	114 ± 8
122285	Ployambre 27	391592.066 / 4806037.278	Oyambre beach	392	75 ± 5	17	0.74 ± 0.03	8	102 ± 9
122284	Ployambre 26	391592.562 / 4806036.958	Oyambre beach	448.1	84 ± 5	17	0.76 ± 0.03	12	111 ± 8
122283	Ployambre 25	391592.998 / 4806036.867	Oyambre beach	492.8	124 ± 7	18	1.12 ± 0.05	11	110 ± 8
122282	Ployambre 24	391593.248 / 4806036.944	Oyambre beach	521.1	134 ± 4	11	1.17 ± 0.05	11	114 ± 6
122281	Ployambre 23	391593.472 / 4806036.954	Oyambre beach	563.6	103 ± 5	16	0.89 ± 0.03	12	116 ± 7
122280	Ployambre 22	391594.126 / 4806037.197	Oyambre beach	607.2	128 ± 8	22	0.80 ± 0.03	15	160 ± 12
122279	Ployambre 21	391594.401 / 4806037.352	Oyambre beach	639.9	142.4 ± 1.0	24	1.05 ± 0.04	14	136 ± 8
122278	Ployambre 20	391594.638 / 4806037.486	Oyambre beach	677.4	116 ± 5	18	0.73 ± 0.03	15	159 ± 10
122277	Ployambre 19	391595.230 / 4806037.767	Oyambre beach	698.3	> 250*	15	1.69 ± 0.07	22	> 148
122276	Ployambre 18	391595.334 / 4806037.842	Oyambre beach	727.5	> 250*	16	1.24 ± 0.05	13	> 202
122275	Ployambre 17	391595.594 / 4806037.942	Oyambre beach	774.5	97 ± 5	12	0.65 ± 0.03	13	150 ± 10
122274	Ployambre 16	391595.761 / 4806038.017	Oyambre beach	811.4	72 ± 3	12	0.67 ± 0.03	13	108 ± 7
122273	Ployambre 15	391595.942 / 4806038.090	Oyambre beach	844.7	107 ± 6	16	0.76 ± 0.03	17	141 ± 10
122272	Ployambre 14	391596.854 / 4806038.835	Oyambre beach	877.6	133 ± 6	17	0.87 ± 0.04	18	153 ± 10
122271	Ployambre 13	391597.019 / 4806038.953	Oyambre beach	900.8	78 ± 5	16	0.41 ± 0.02	18	191 ± 14
122270	Ployambre 12	391597.197 / 4806039.051	Oyambre beach	941.7	83 ± 7	18	0.58 ± 0.02	19	143 ± 14
122269	Ployambre 11	391597.794 / 4806039.706	Oyambre beach	952.6	68 ± 4	17	0.62 ± 0.03	13	110 ± 8
122268	Ployambre 10	391598.621 / 4806039.894	Oyambre beach	997.3	> 250*	7	0.49 ± 0.03	30	>511
122267	Ployambre 09	391599.221 / 4806040.049	Oyambre beach	1048.9	> 250*	3	1.89 ± 0.08	22	>133
122266	Ployambre 08	391600.387 / 4806040.106	Oyambre beach	1088.7	> 250*	3	2.53 ± 0.10	20	>99
122265	Ployambre 07	391600.457 / 4806039.975	Oyambre beach	1106.8	> 250*	8	1.17 ± 0.05	12	>213
122264	Ployambre 06	391600.911 / 4806040.167	Oyambre beach	1151.4	> 250*	3	1.04 ± 0.05	12	>240
122263	Ployambre 05	391601.670 / 4806039.937	Oyambre beach	1193.1	> 250*	6	0.78 ± 0.03	19	>322
122262	Ployambre 04	391601.790 / 4806040.039	Oyambre beach	1208.2	> 250*	3	1.48 ± 0.06	20	>168
122261	Ployambre 03	391601.841 / 4806040.107	Oyambre beach	1225.7	> 250*	9	1.41 ± 0.06	20	>172
122260	Ployambre 02	391601.934 / 4806040.187	Oyambre beach	1250.8	> 250*	3	1.38 ± 0.06	20	>182
122259	Ployambre 01	391602.168 / 4806040.285	Oyambre beach	1265.2	> 250*	16	1.33 ± 0.06	20	>188

[1] (n) is the number of aliquots measured to estimate the Qtz equivalent dose (Gy).

[2] "w.c." represents the proportion of water content of the samples.

* Natural signals were in saturation (i.e. >86% of the saturation level of the dose response curve).



B

Figure 3.15. Results of the quartz-OSL dating. A. Qtz equivalent dose (Gy) measured for each sample, including the error range. B. Age of the samples (excluding those with an equivalent dose over saturation) in ky and MIS division. The green box represents the MIS5e global sea-level highstand, from 116 to 130 ky, based on Shackleton et al. (2003). Samples are ordered in the vertical axis according to their burial depth.

Figure 3.16. Graphical representation of younger samples in their stratigraphic position. Two groups can be identified: the first one is represented by samples older than 108 ky (within the green field); the second group shows ages from 102 to 89 ky (within the red field).

3.3 Flood risk maps in the Basque Coast

The flood risk maps generated for each of the geological scenarios are described in detail in this sub-section. GBSLR Scenarios 1 to 3 represent Holocene and Anthropocene changes in sea level. GBSLR Scenario 1 (Anthropocene) is built based on a rate of sea-level rise of 2.0 mm yr^{-1}, which translates into an increase of 18 cm by 2100. GBSLR Scenario 2 corresponds to the sea-level rise that had place since the stabilisation occurred at 7000 cal. yr BP until the beginning of the 20th century. The rate of change was very low, 0.5 mm yr^{-1}, so in this scenario the net sea-level rise by the end of the 21st century would be 6.3 cm. Finally GBSLR Scenario 3 takes the rate of sea-level change occurred during the first part of the Holocene, which was as high as 10 mm yr^{-1}. This rate applied to the 21st century translates into a net increase of sea level of 90 cm by 2100.

GBSLR Scenario 4 has been built based on the results from the Oyambre outcrop. As seen in Section 3.2, these results show that the beach sediments of the sequence have a probable age of 130-120 ka and therefore can be correlated with the sea-level highstand occurred during the LIG-MIS5e interglacial. According to the topographic measures carried out in the field, the base of the palaeobeach materials is located at +6.901 m above Bilbao ordnance datum, and this level has been used as a possible far future (but undetermined) sea-level highstand in the Basque coast. All four scenarios are summarised in Table 3.3.

Additionally to the sea-level rise scenarios, the accretion of salt marshes has also been considered when generating flood risk maps. As explained in Chapter 2, salt marshes have the potential to adapt to a certain amount of sea-level rise by increasing their height or "accreting" sediment. Depending on sediment availability and the ecological characteristics of salt marshes, different estimated average accretion rates for the Biscay coast (Cearreta et al., 2002; Leorri et al., 2008a, 2008b; García-Artola et al., 2011b; Sainz de Murieta, 2011; García-Artola, 2013) have been applied: 2.5 mm yr^{-1} for natural salt marshes and 16 mm yr^{-1} for salt marshes in regeneration, until they meet the equilibrium or natural state.

Table 3.5. Summary of future scenarios of sea-level rise based on the palaeodata obtained from the late Quaternary geological record in different estuaries of the Basque Country and the Oyambre coastal sequence.

GBSLR Scenarios - Geological time	Rate of SLR	Future sea levels				
		2030	2050	2080	2100	?
Scenario 1: Anthropocene (1900 – 2010)	2.0 mm yr^{-1}	4 cm	8 cm	14 cm	18 cm	-
Scenario 2: Holocene 2 (7000 cal. yr BP – 1900)	0.5 mm yr^{-1}	1.4 cm	2.8 cm	4.9 cm	6.3 cm	-
Scenario 3: Holocene 1 (10,000 – 7000 cal yr BP)	10 mm yr^{-1}	20 cm	40 cm	70 cm	90 cm	-
Scenario 4: LIG-MIS5e (130-120 ky)	*Unknown*	-	-	-	-	690.1 cm

In order to build flood risk maps, two sea levels have been considered for each scenario:

- MSL, which is located 2.4 m above the Bilbao ordnance datum (Bilbao 0 m).
- MAHT, which is the maximum level reached by an astronomic high tide in a 19-year period. This level, 2.77 m above MSL, was used as an analogue for coastal extreme events[22].

Thus, for each of the four geological scenarios two types of impacts are measured: first, those occurred due to changes in sea level that represent a new permanent environmental condition; second, impacts due to an increase in the MAHT level. The latter shows the potential impacts associated with a coastal extreme event that occurs at the same time as sea level rises. Changes in MAHT levels would not be permanent, but temporal.

These sea-level rise scenarios were applied to three case studies located in the Basque coast (Figure 1.3). The first case study is the Urdaibai Biosphere Reserve (URB) and specifically the salt marshes located in the Oka Estuary, at the heart of Urdaibai. The second case study is the Butroe Estuary, approximately 20 km east of Urdaibai. The third case study assessed the Barbadun Estuary, in Muskiz, in the limit of the Basque Country with the province of Cantabria. The results of the geological approach in terms of flood risk are shown next for each of the case studies and scenarios defined.

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[22] The frequency at which sea level exceeds the MAHT level is "low (once every four years or 0.5 h per year)" (Chust et al., 2010: 116), although its impact can be considerable.

3.3.1 Urdaibai Estuary

Current salt marshes of the Urdaibai Estuary

For the identification of current salt marshes, different cartographic information has been used: the map of EU habitats, the map of EUNIS[23] habitats, the Basque Country vegetation map, and 2012 aerial ortophotographs[24] (Figure 3.17). A total area of 332.7 ha was identified as corresponding to salt marsh environment in this estuary. The size of the study area in Urdaibai is 20 times greater than in the other two case studies (Plentzia and Muskiz), accordingly a slightly different procedure has been followed in this case.

With regard to the vegetation of the estuary, two areas can be distinguished based on the location of vegetation types in relation to the tides:

- In the low marsh, which is daily covered by estuarine waters, salt marsh habitats show a great development and it is worth highlighting the presence of the following species: salty soil vegetation with *Salicornia ramosissima, Spartina maritima*, an association dominated by *Halimione portulacoides* and other halophytic scrubs with *Sarcocornia perennis* and *S. fructicosa*.
- The upper marsh shows a stronger influence of fresh water, and the dominant species is the common reed (*Phragmites australis*), that lives together with other species such as *Thypha latifolia*, *Iris pseudacorus* and *Mentha aquatica*. Unfortunately, invasive shrub species, such as *Baccharis halimifolia*, are also extended in the high marsh zone. In the most humid or even swamp areas rush fields (with *Juncus inflexus*, *Juncus conglomeratus*, *Juncus effussu*, *Trifolium repens*, etc) are abundant. These uppermost areas are often still used as pastures.

Between the marshes there are some areas with a sandy substrate, more or less affected by tides, where the vegetation corresponds to typical coastal sandbanks: *Eryngium maritimum*, *Euphorbia paralias*, *Calystegia soldanella*, *Medicago marina*, *Calike maritima*, *Salsola kali*, *Lagurus ovatus* and *Elymus farctus*, among others (Basque Government, 2006).

The accretion rate of salt marshes in the Urdaibai Estuary

Following the extensive analysis carried out by García-Artola (2013) in the salt marshes of Urdaibai, and also results from Cearreta et al. (2013), most of the salt marshes were classified as natural or regenerated and, accordingly, the accretion rate corresponding to natural or regenerated marshes (2.14 mm yr^{-1}) was applied to these areas. Figure 3.18 shows all the areas identified as salt marshes in the Oka Estuary.

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[23] The European Nature Information System (EUNIS) habitat classification "is a comprehensive pan-European system to facilitate the harmonised description and collection of data across Europe through the use of criteria for habitat identification; it covers all types of habitats from natural to artificial, from terrestrial to freshwater and marine". Definition retrieved from: http://eunis.eea.europa.eu/about).

[24] All the cartographic information is available at www.geoeuskadi.net.

However, there are four areas identified as salt marshes in regeneration process: Mape, Barrutia, Kanala Behekoa and Isla Goikoa. The Mape marsh has followed a singular evolution within the salt marshes in Urdaibai. According to García-Artola (2013), this area evolved from a tidal flat environment to a higher elevation due to the effect of modern deforestation activities, that provided a great amount of sediments that were deposited in this tidal flat, increasing its topographic height. This evolution can also be inferred from historical orthophotographs and other studies confirm the intensive deforestation activities occurred around the Mape River during the last 50 years. Currently the area is characterised as a "low marsh in progress" (García-Artola, 2013: 145), therefore for practical purposes it has been considered as to be in regeneration process. All salt marshes in regeneration have been identified with a pink dot in Figure 3.18.

There is no sedimentary or micropalaentological information on the other three salt marshes, but in the orthophotographs it is possible to identify the evidences of old and abandoned agricultural parcels (in current naturalisation process), so all of them have been considered to be in regeneration. Barrutia is located in the uppermost part of the estuary while Kanala Behekoa and Isla Goikoa are located in the right bank of the lower estuary, close to the town of Gauteguiz-Arteaga. Then, higher accretion rates (16.3 mm yr^{-1}) have been applied to these four salt marshes *in regeneration* for the period 2010-2020; lower accretion rates were assigned from 2020 onwards, as the regeneration process has been determined to take approximately a decade (García-Artola et al., 2011a). See Table 3.6 and Figure 3.18 for further details.

Table 3.6. Accretion rates applied to salt marshes in the Urdaibai Estuary.

Urdaibai salt marshes	Current conservation status	Accretion rate applied (mm yr^{-1})	Source
Axpe Norte	Natural	2.14	García-Artola (2013)
Axpe Sur	Regenerated	2.14	García-Artola (2013)
Baraizpe	Regenerated	2.14	García-Artola (2013) Cearreta et al. (2013)
Barrutia	In regeneration	16.3 (2010-2020) 2.14 (2020-2100)	Orthofotographs
Busturia	Regenerated	2.14	García-Artola (2013) Cearreta et al. (2013)
Isla	Regenerated	2.14	García-Artola (2013) Cearreta et al. (2013)
Isla Goikoa	In regeneration	16.3 (2010-2020) 2.14 (2020-2100)	Orthofotographs
Kanala	Natural	2.14	García-Artola (2013)
Kanala Behekoa	In regeneration	16.3 (2010-2020) 2.14 (2020-2100)	Orthofotographs
Mape	In regeneration	16.3 (2010-2020) 2.14 (2020-2100)	García-Artola (2013)
Murueta	Natural	2.14	García-Artola (2013)
Rest	Natural / Regenerated	2.14	Orthofotographs

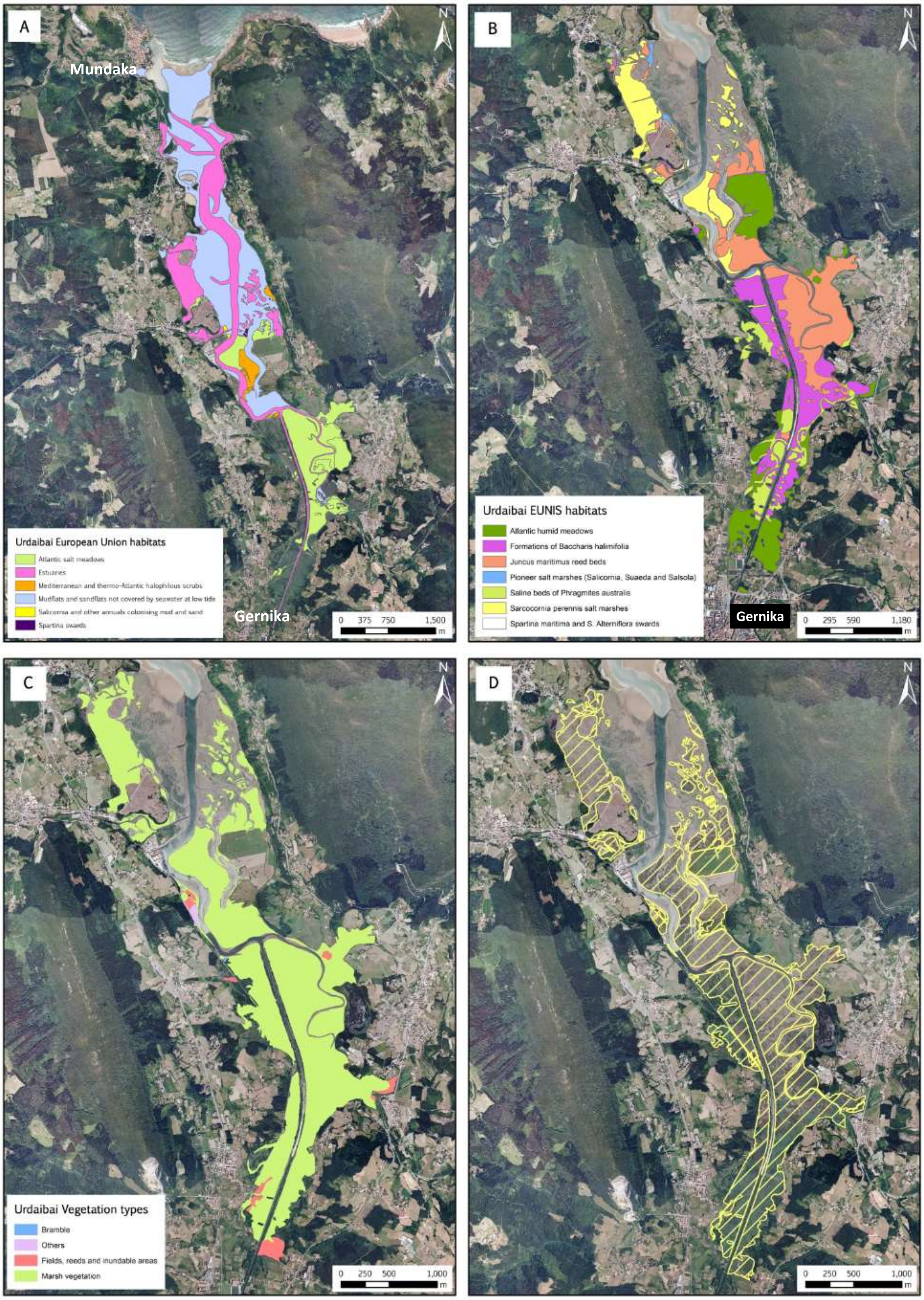


Figure 3.17. Cartographic information used as a base to the identification of current salt marshes in the UBR. A. European Union habitats map; B. EUNIS habitats map; C. Vegetation types map; D. Identified salt marshes.

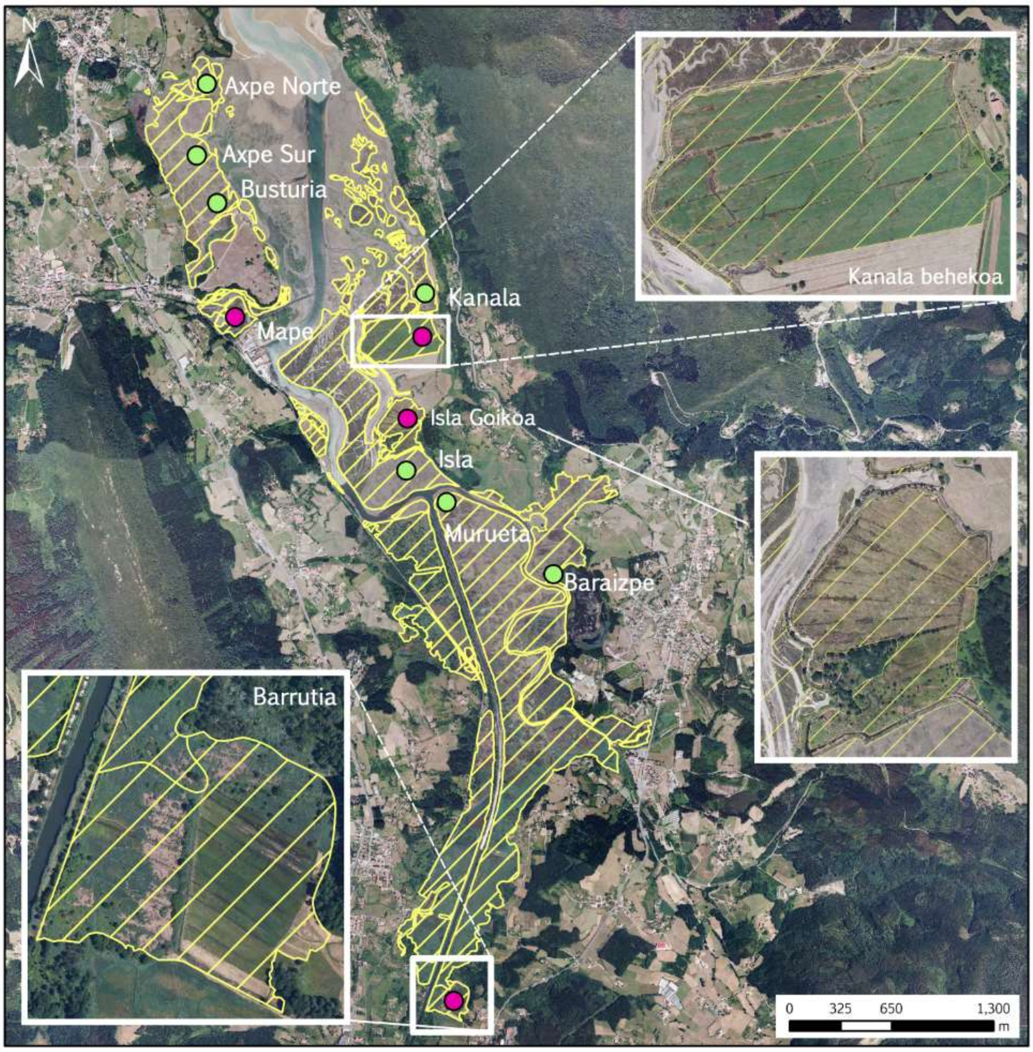


Figure 3.18. Identified salt marsh areas in the Urdaibai Estuary. Green dots represent natural marshes while pink dots correspond to salt marshes in regeneration. Previous agricultural parcels can still be identified in the white boxes for the Barrutia, Kanala Behekoa and Isla Goikoa marshes.

Building flood risk maps in Urdaibai

Sea-flood risk maps have been defined for the Oka Estuary under different sea-level rise scenarios in order to estimate the potential impacts of these changes in sea level on the salt marsh ecosystems.

GBSLR Scenario 1: Anthropocene (1900 - 2010)

During the Anthropocene the rate of sea-level rise in the Basque coast has been 2 mm yr^{-1}. Potential impacts on the Urdaibai Biosphere Reserve have been estimated if sea level would continue to rise at this rate until the end of the century. Two references have been used to estimate these effects: current MSL and the MAHT level. The latter represents the sea level reached in the past when extreme events occurred, so it would represent a non-permanent flooding. The temporal increase in mean sea level turns into almost no additional flooded area. The affected area when sea level reaches the MAHT level is very important, but again, the extra flooding due to a rise of sea level is extremely small (Figure 3.19) and we must keep in mind that we are referring to levels reached due to extreme events, and therefore they would not be permanent.

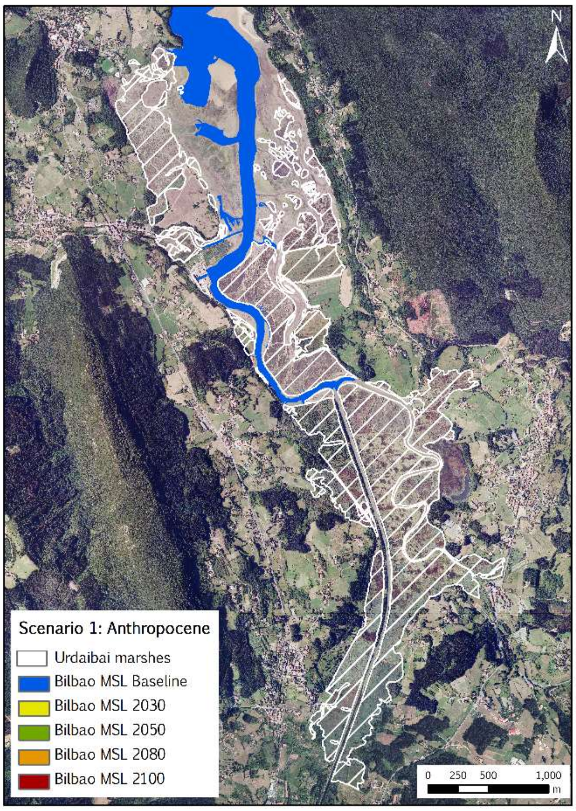


Figure 3.19. Temporal changes in mean sea level (left) and MAHT levels (right) under Scenario 1.

As summarised in Table 3.7, the new flooded area on GBSLR Scenario 1 for temporal changes in MAHT levels would be less than one hectare by the end of the 21st century.

Table 3.7. GBSLR Scenario 1 – Anthropocene. Potentially flooded salt marsh areas in the Urdaibai Biosphere Reserve. Surface areas are given in hectares.

	Non flooded area	Flooded area					
		Mean sea level	MAHT level				
			2010	2030	2050	2080	2100
Urdaibai salt marshes	332.7	0	320.11	320.24	320.25	320.28	320.29

GBSLR Scenario 2: Holocene 2 (7000 cal yr BP - 1900)

The rate of sea-level rise during the second half of the Holocene Epoch was very low (average 0.5 mm yr^{-1}), so the impacts are expected to be smaller than those in Scenario 1. In fact, there are no flooded areas when considering changes in MSL. Changes in MAHT levels translate into a small increase of flooded salt marsh areas (0.13 ha). Flood maps for Scenario 2 are shown in Figure 3.20 and the estimated flooded area for each time span is summarised in Table 3.8.

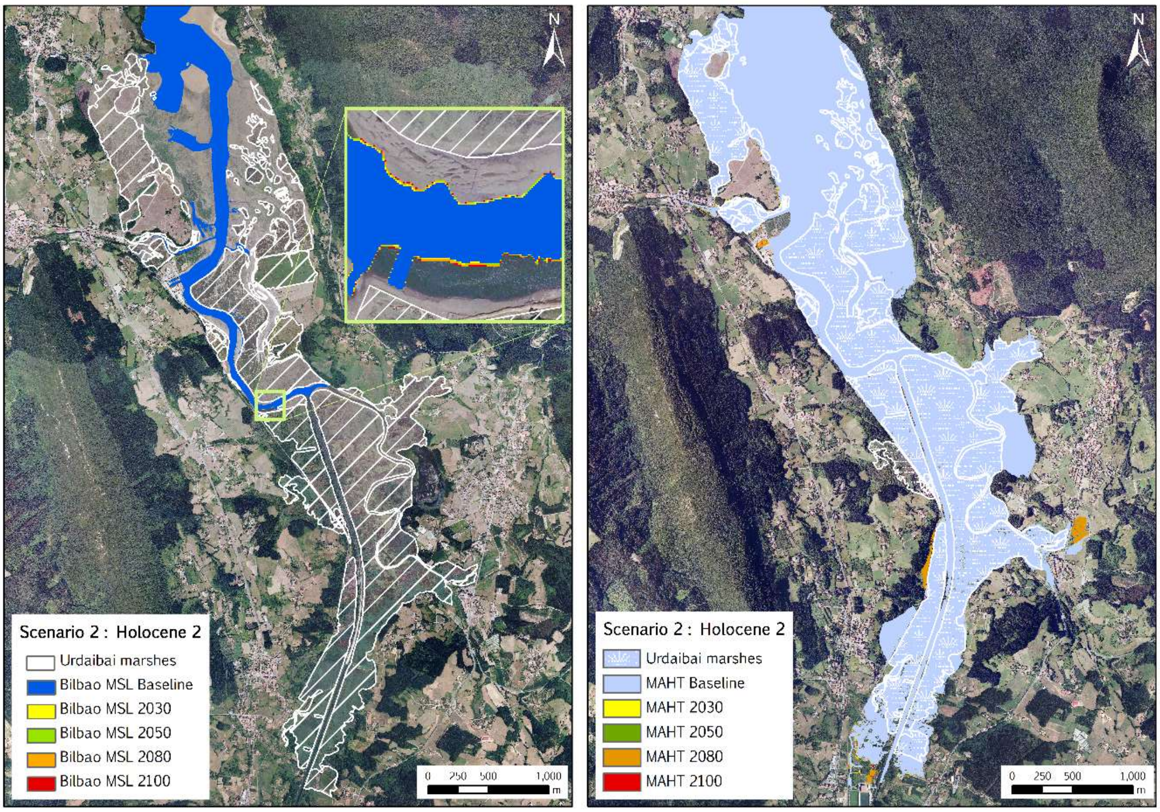


Figure 3.20. Temporal changes in MSL (left) and MAHT levels (right) under GBSLR Scenario 2.

Table 3.8. GBSLR Scenario 2 – Holocene 2. Potentially flooded salt marsh areas in the Urdaibai Biosphere Reserve. Surface areas are given in hectares.

	Non flooded area	Flooded area					
		Mean sea level	MAHT level				
			2010	2030	2050	2080	2100
Urdaibai salt marshes	332.7	0	320.11	320.22	320.23	320.23	320.24

GBSLR Scenario 3: Holocene 1 (10,000 cal yr BP - 7000 cal yr BP)

Flood risk maps in this scenario were estimated using the sea-level-rise rate measured during the first half of the Holocene, 10 mm yr^{-1} (Figure 3.21).

With regard to mean sea level, most of the increases affect the flat areas of the estuary, intertidal zones and salt marshes. However, the temporal increases in mean sea level would significantly affect the Laidatxu beach, in the municipality of Mundaka (Figure 3.22). The retreat has been estimated by measuring the length of the segment represented in Figure 3.22 by a black line. Results are shown in the table attached to the figure.

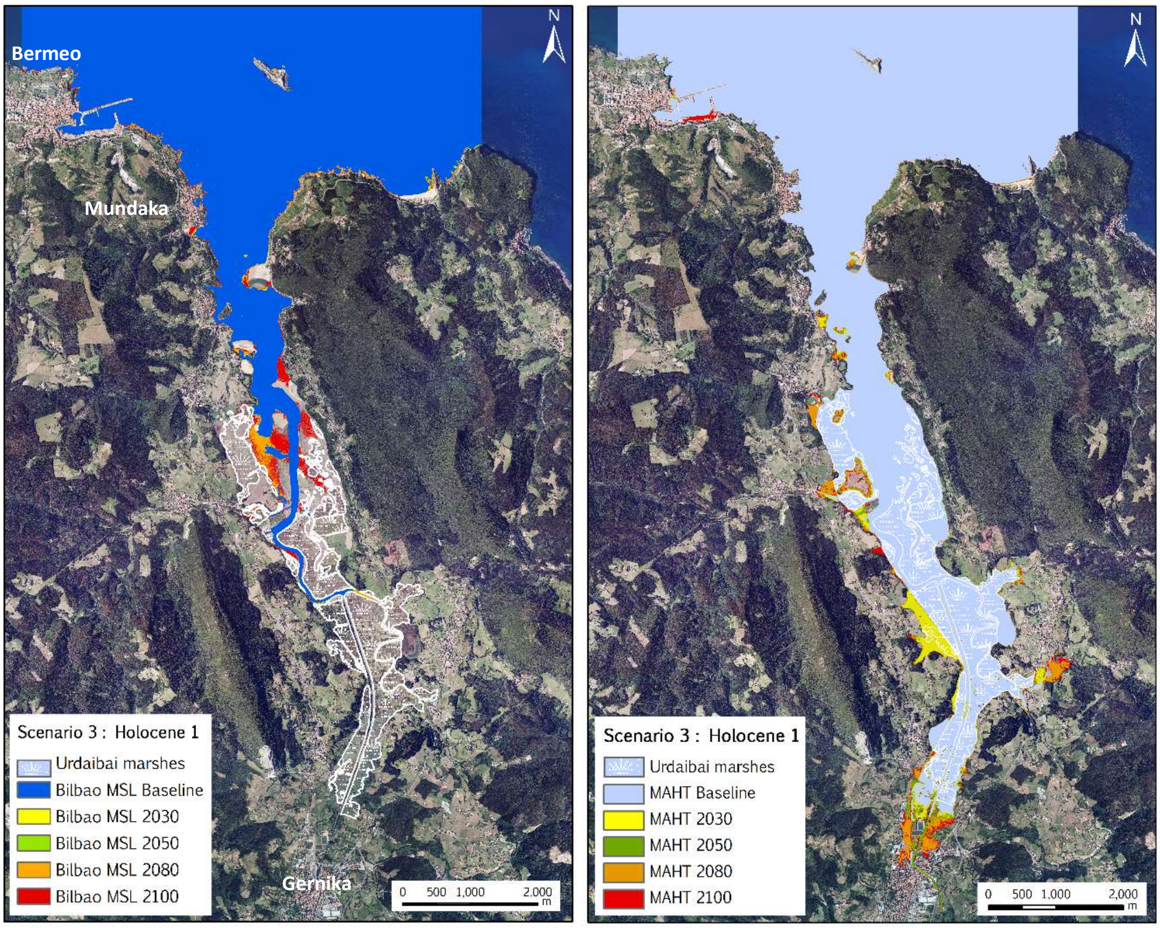
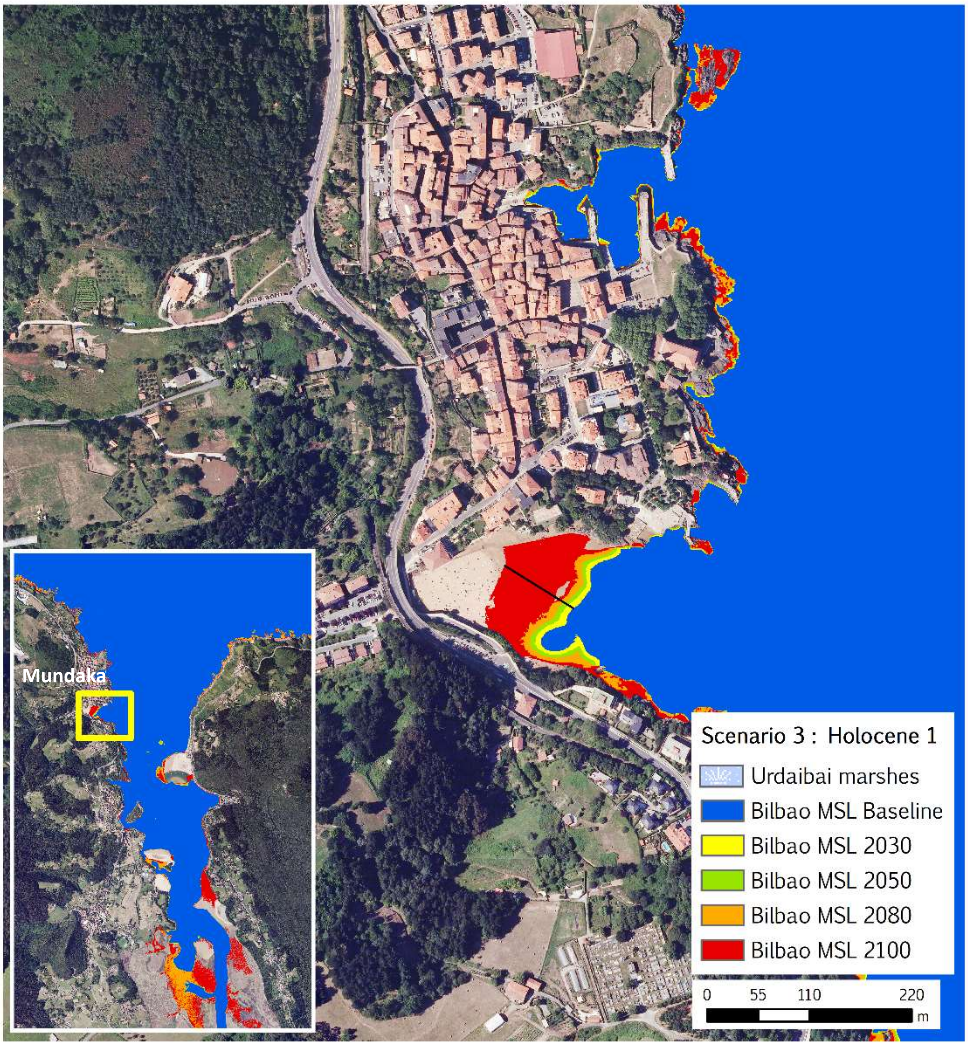


Figure 3.21. Temporal changes in mean sea level (left) and MAHT level (right) under Scenario 3.

When analysing future MAHT levels under GBSLR Scenario 3, potentially flooded areas are much greater, affecting both natural areas of the estuary and urban areas. However, these levels represent an extreme event and therefore, a non-permanent sea-level highstand. Even so, extreme events can cause great impacts both on natural and human systems. Figure 3.23 shows in detail some of the most affected areas due to changes in MAHT levels. From north to south, Figure 3.23A shows how the Port of Bermeo would be affected by flooding only by 2100. Southwards, the next affected areas would be the neighbourhoods of Axpe (Busturia) and San Antonio de Abiña (Sukarrieta). The first is already (potentially) affected by current MAHT levels and these impacts would increase with time. Buildings in the latter case would only be affected after 2080 (Figure 3.23B). The next affected area is located in the same Axpe neighbourhood (Busturia), but further south, near the Axpe train station (Figure 3.23C).



	Potential reatreat in Laidatxu (m)				
	2010	2030	2050	2080	2100
Retreat by scenario	0	6.08	5.89	3.53	70.34
Accumulated retreat	0	6.08	11.97	15.5	85.84

Figure 3.22. Scenario 3 – Holocene 1. Potential retreat of the Laidatxu beach due to the rise of mean sea level.

In the same municipality, several houses of the Larrabe neighbourhood would also be flooded (Figure 3.23D), together with the Murueta shipyard, even by 2030 (Figure 3.23E). The northernmost area of Gernika would also be inundated, particularly from 2080 (Figure 3.23F). On the other bank of the estuary changes of MAHT levels affect smaller areas (Figures 3.23G-J). The greatest area potentially inundated is located in Kortezubi and flooding would mainly affect current crop and pasturelands (Figure 3.23H).

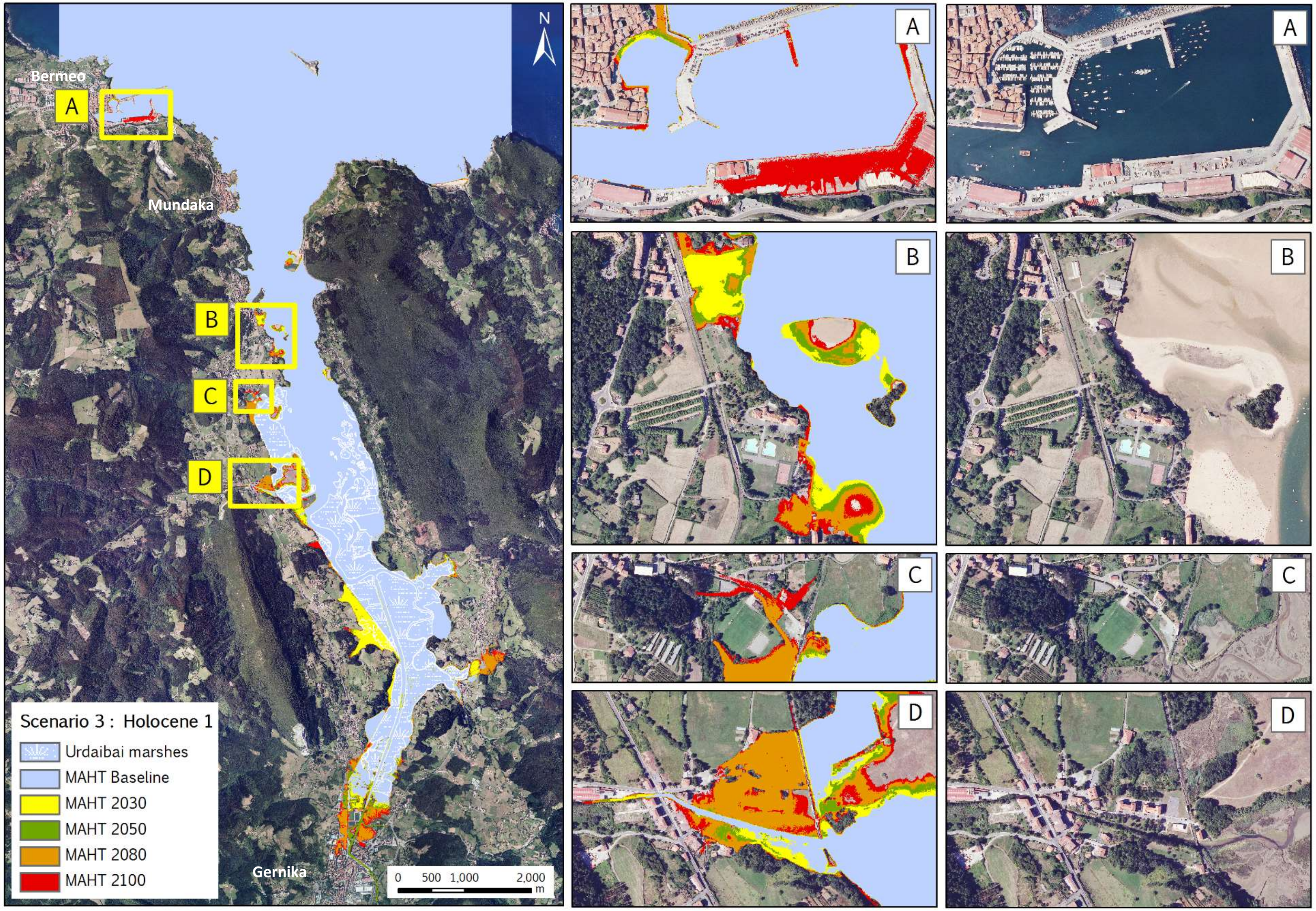


Figure 3.23. GBSLR Scenario 3 – Holocene 1. Temporal changes in MAHT level and potentially flooded areas along the left bank of the Oka Estuary.

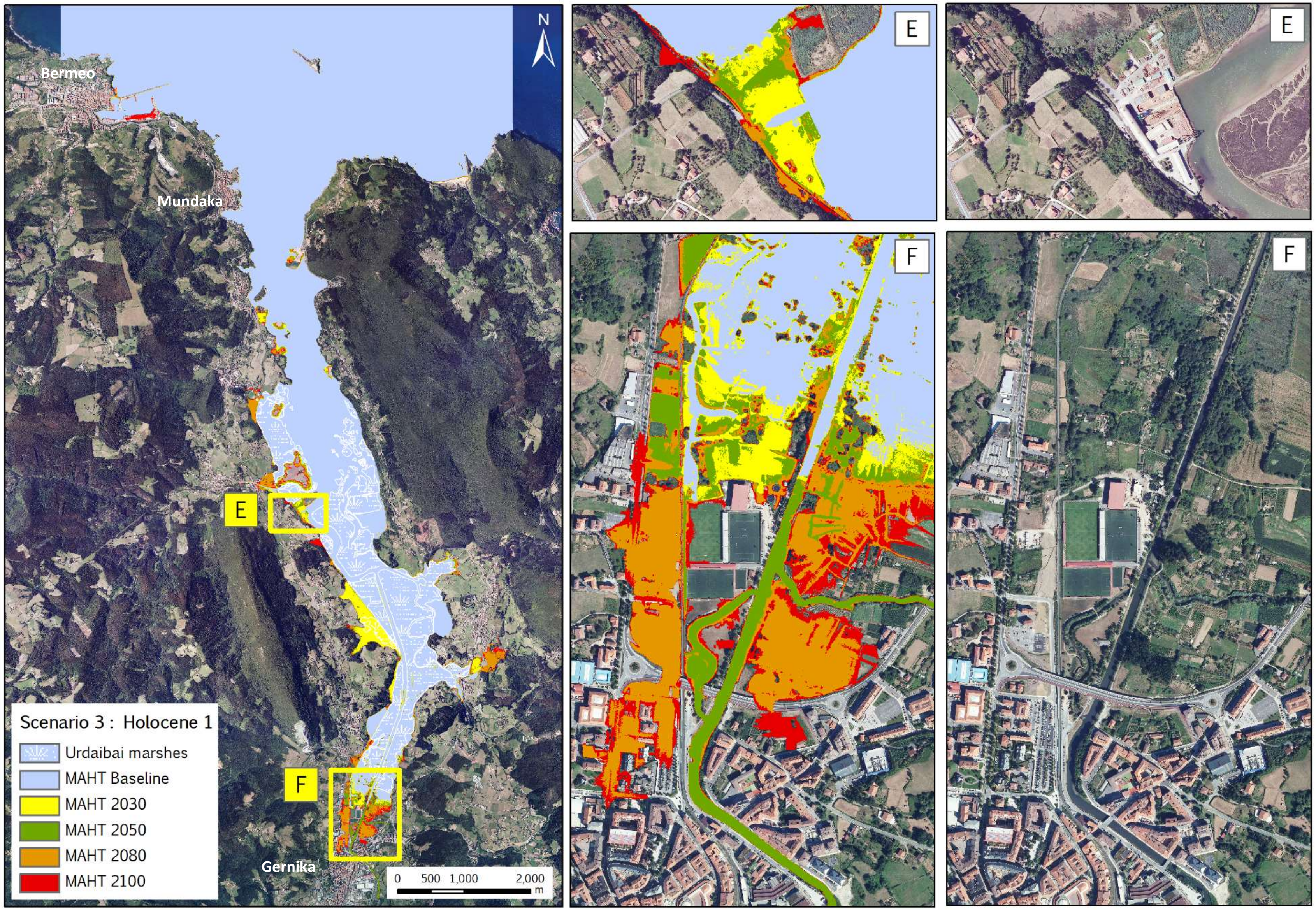


Figure 3.23 (Cont.). GBSLR Scenario 3 – Holocene 1. Temporal changes in MAHT level and potentially flooded areas along the left bank the Oka Estuary.

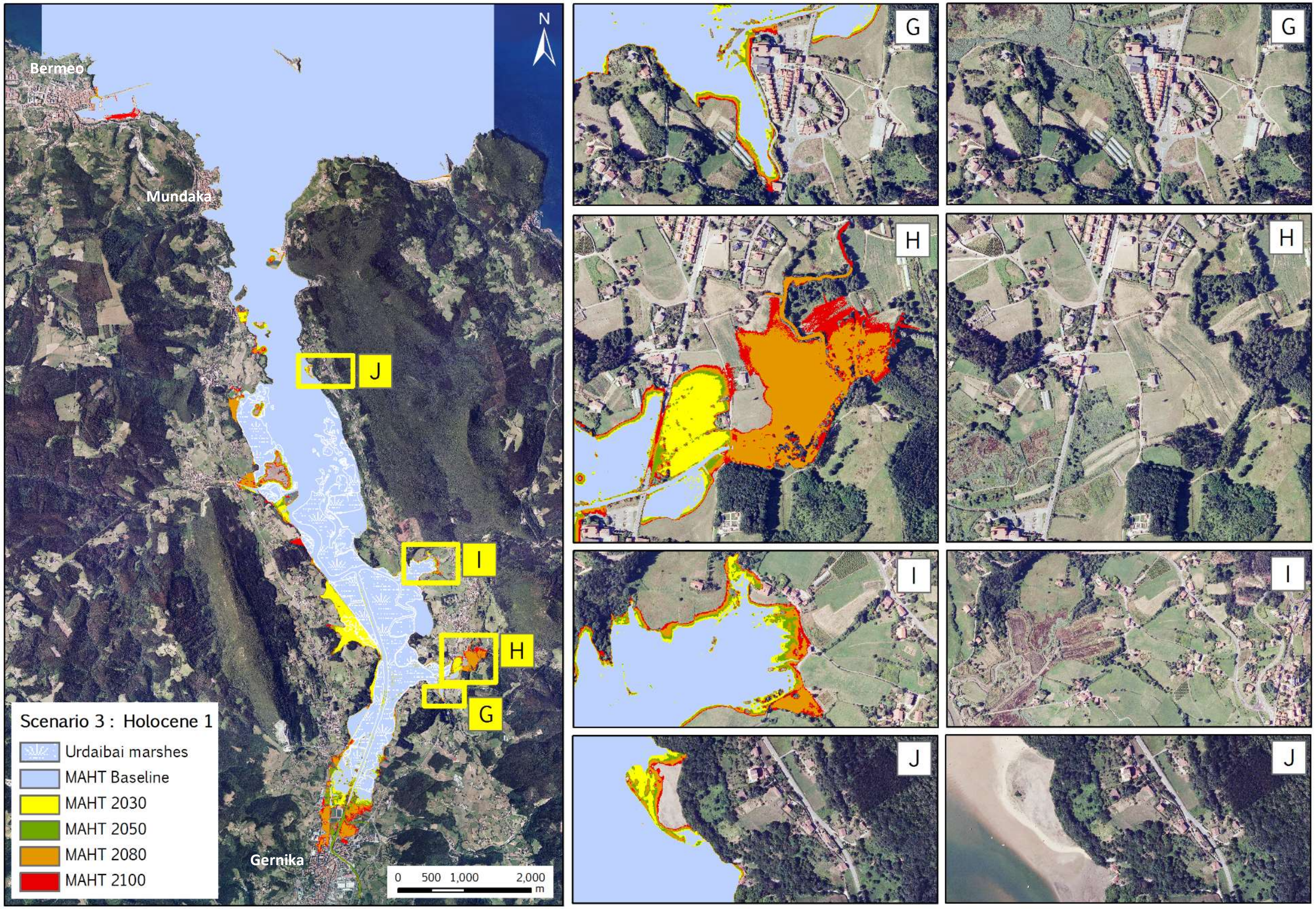


Figure 3.23 (Cont.). GBSLR Scenario 3 – Holocene 1. Temporal changes in MAHT level and potentially flooded areas along the right bank of the Oka Estuary.

GBSLR Scenario 4: LIG-MIS5e sea-level highstand (130-120ky)

Under this scenario Bilbao reference sea level (also known as Bilbao 0 m) would be +6.901 m above current level. We also estimated the new mean sea level (2.4 m above the previous level). Based on these two different sea levels, a new coastline was defined and the corresponding flooded areas were measured.

The results are shown in Figure 3.24, where it can be observed that the complete salt marsh area would be inundated with this new sea level and severe impacts can be expected in both urban and rural areas, but it is remarkable the great area of Gernika, the biggest town of the URB, that would be affected by estuarine flooding. The figure includes current MAHT levels as a reference for the enormous impact that LIG-MIS5e sea levels would represent in Urdaibai.

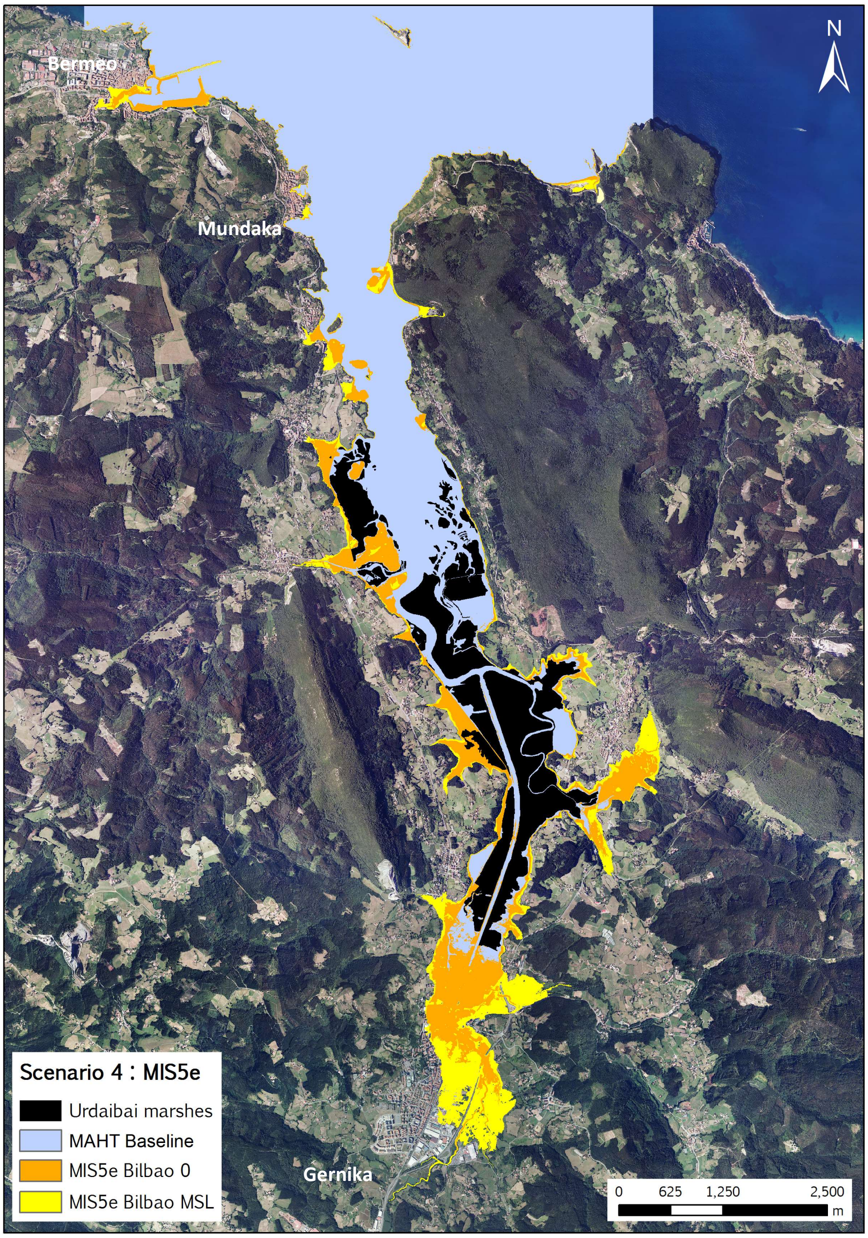


Figure 3.24. Under GBSLR Scenario 4, corresponding to LIG-MIS5e sea levels, the flooded area would increase dramatically. The map shows current MAHT levels (in blue) compared to the new zero (in orange) and the new mean sea level (in yellow).

3.3.2 Plentzia Estuary

3.3.2.1 Current salt marshes of the Plentzia Estuary

The use of orthophotographs was the main method used for the identification of current salt marsh ecosystem areas, afterwards digitalised using a GIS software. Two field visits were also carried out to check *in situ* the defined limits and characterisation of salt marshes, and as a result three marshes were identified: Txipio, Ostrada and Isuskiza (Figure 3.25A, B and C, respectively).

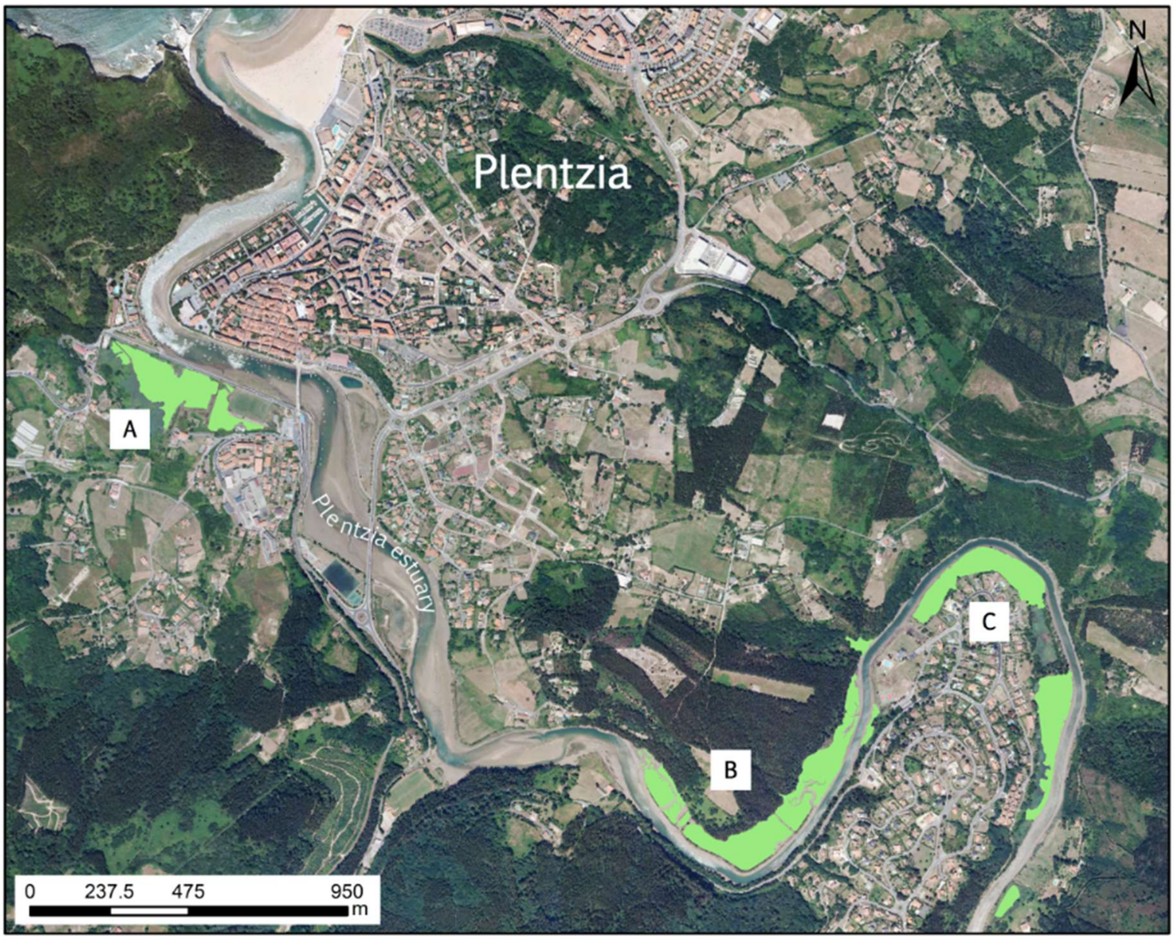


Figure 3.25. Salt marshes in the Plentzia Estuary: Txipio (A), Ostrada (B) and Isuskiza marshes (C).

Starting at the lower estuary, we first find the Txipio marsh, opposite the village of Plentzia. Its northern face is separated from the estuary by a local road built on an ancient dyke, except for a channel that allows tidal fluxes in and salt marsh regeneration to occur. From the mid-19th century until 1960s this area was used for agricultural purposes, and since then a natural regeneration process has taken place (Cearreta et al., 2002). Txipio is separated from the estuary by a road that links Plentzia with Barrika, but a connection that allows water to go in and out exists. On its southern area the salt marsh is limited by the Gatzamina neighbourhood (Figure 3.26).

Figure 3.26. Txipio salt marsh. The picture is taken from the observatory located in the northern part of the salt marsh. The town of Plentzia and the road to Barrika that divides the salt marsh from the estuary can be identified on the left of the picture. The Gatzamina neighbourhood is located at the right of the picture.

The Ostrada marsh is located in the right bank of the upper estuary, limited by a forested area inland and detached from the estuary by several dykes (Figure 3.27). The central area was used during the 1970-1980s for *Eucaliptus* plantation, but the activity was abandoned afterwards for low productivity (Cearreta et al., 2002). On the other hand, the Isuskiza marsh is located in the left bank of the upper estuary, just upstream from the Ostrada marsh. The marsh area, previously occupied by agricultural activity, is now in regeneration process. The marsh is fragmented and divided in three different parts. The western part is partially urbanised and in general, it still shows the agricultural land plots (García-Artola et al., 2011b).

With regard to the flora of the estuary, halophytic plant species distribution is similar to other salt marshes in the Cantabrian coast. It should be highlighted the relative abundance of *Sarcocornia fruticosa* and, in some spots *Limonium vulgare* and *Cochlearia aestuaria.* The endangered halophytic species found in the Plentzia Estuary are *Salicornia dolichostachya, Salicornia lutescens, Salicornia ramosissima, Sarcocornia perennis* subsp. *perennis, Suaeda maritima*, and the most noteworthy, *Apium graveolens* subsp. *butronensis.* The latter is a Basque endemism only known in this estuary (Silván and Campos, 2002). In Txipio, fewer plant species have been found which suggests a semi-natural condition of the marsh, currently in process of plant re-colonization (Onaindia and Amezaga, 1999). In the central part of the salt marsh, these authors found *Arthrocnemum fruticosum*, *Aster tripolium*, *Halimione portulacoides*, *Juncus maritimus*, *Polygonum maritimum*, *Puccinelia maritima*, *Salicornia ramosissima* y *Spartina maritima* as dominant species, while *Elymus pycnanthus* and *Phragmites australis* were found in the more elevated western zone of the salt marsh.

Figure 3.27. Ostrada salt marsh. The picture has been taken from the left bank of the estuary, northwards. Some channels and the well preserved salt marsh vegetation can be observed.

3.3.2.2 The accretion rate of salt marshes in the Plentzia Estuary

In order to estimate the accretion of salt marshes in the Plentzia Estuary as a response to sea-level rise, the ecological state of the Txipio and Ostrada marshes was considered natural, while the Isuskiza marsh was considered to be in regeneration based on Cearreta et al. (2011). As already explained in Chapter 2 the accretion rate of salt marshes varies depending, among other factors, on their natural state. The values measured in several studies for salt marshes in Plentzia are summarised in Table 2.5. To define future accretion rates, a central value has been taken for both natural salt marshes (2.14 mm yr^{-1}) and salt marshes in regeneration (16.3 mm yr^{-1}). The net potential salt marsh accretion for the different time frames considered is shown in Table 3.7.

Table 3.9. Net accretion rate of salt marshes in the Plentzia Estuary, depending on their ecological state.

Marsh	Ecological state	Surface (ha)	Accretion rate (cm yr^{-1})	Net accretion (cm)			
				2030	2050	2080	2100
Txipio	Natural	3.87	0.21	4.3	8.6	15	19.2
Ostrada	Natural	6.70	0.21	4.3	8.6	15	19.2
Isuskiza	In regeneration	6.01	1.63	18.4	22.7	29.1	33.4

3.3.2.3 Building flood risk maps in the Plentzia Estuary

The tidal part of the Butroe River runs through five municipalities: Plentzia, Gorliz, Barrika, Lemoiz and Gatika, the latter only in the uppermost estuarine area. When estimating the changes in sea level for the Plentzia Estuary potential flooding of urban areas have been assessed together with impacts on salt marshes. Urban flooding has been measured according to the classification of urban land uses. Four main groups have been identified: residential land (1), industrial land (2), general infrastructures (3) and non-developable land (4). Table 3.8 summarises the different land-use types considered and their extensions. This extension represents the total area within the five municipalities the tidal Butroe River goes through. This way, the more extensive land use is non-developable land, followed by general infrastructures. This group is quite diverse and includes basic infrastructures such as those for energy or water supply, communication networks, transport infrastructures, community equipment and recreation areas. Industrial land occupies almost 65 ha, but they are located in areas topographically more elevated, and none of them are located close to the estuary. Finally, residential land has an extension of 60 ha. Figure 3.28 shows the distribution of the different types of urban land in the Plentzia Estuary.

Table 3.10. Urban categories considered for the estimation of flood risk maps in the Plentzia Estuary. The extension occupied by each land use type is the total area within the five municipalities considered (Plentzia, Gorliz, Barrika, Lemoiz and Gatika).

Urban land uses		Short description[25]	Surface (ha)	
Residential land		Land for supporting residential development.	60.1	
Industrial land		Land for industrial purposes.	64.7	
General infrastructures		The general infrastructure category includes:	186.4	
	Basic infrastructures	Infrastructure related to energy supply, water supply and management or waste treatment.		20.9
	Communication and transport	Communication networks, including roads, railroads, ports, etc.		57.2
	Community equipments	General or municipal equipments, such as municipal sports centres, cultural centres, etc.		46.2
	Recreation areas	Green and recreation areas, such as parks or beaches.		62.1
Non-developable land		Land not suitable for urban and development purposes.	5556.7	

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[25] Based on different regulations of the Basque Country (mainly Directrices de Ordenación del Territorio and Ley 2/2006 del Suelo).

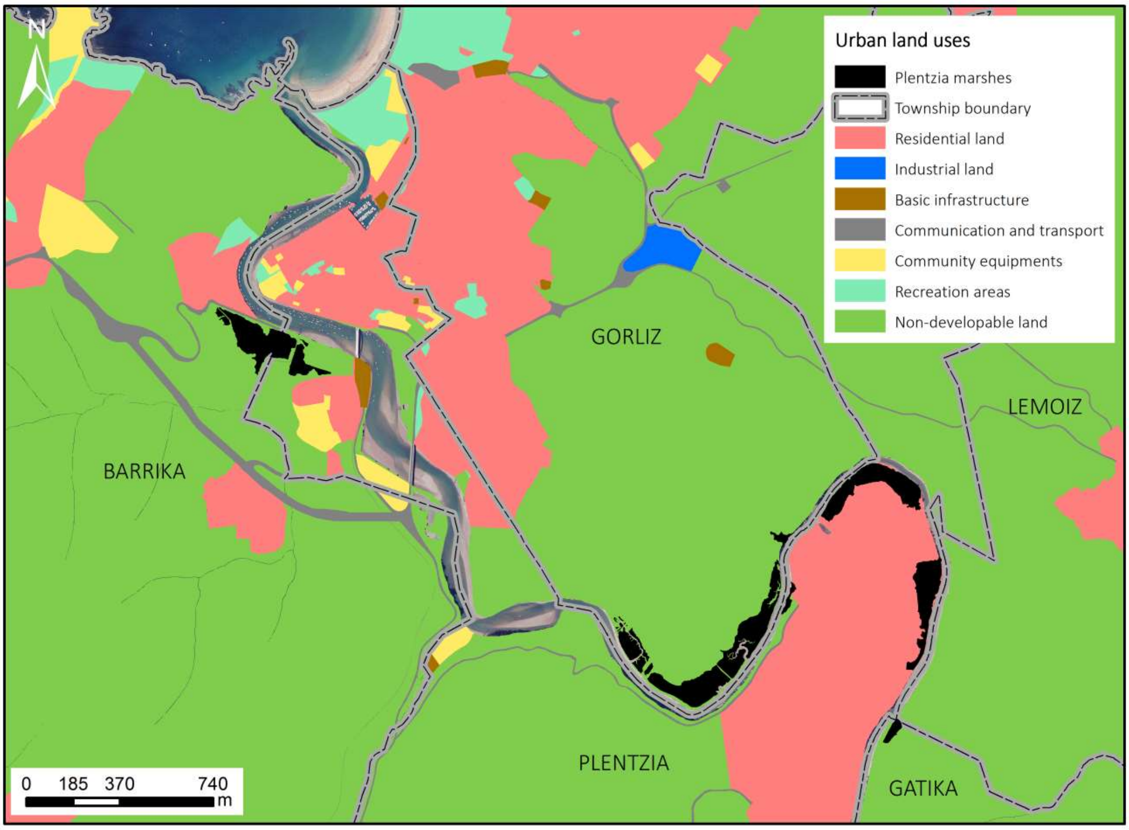

Figure 3.28. Representation of the different urban land uses around the Plentzia Estuary.

GBSLR Scenario 1: Anthropocene (1900 - 2010)

The first scenario represents the rate of sea-level rise occurred during the Anthropocene and measured in 2 mm yr^{-1}. This rate translates into almost no increase in mean sea level, as shown in Figure 3.29. In terms of flooded area, there is no affection to either salt marshes or urban systems.

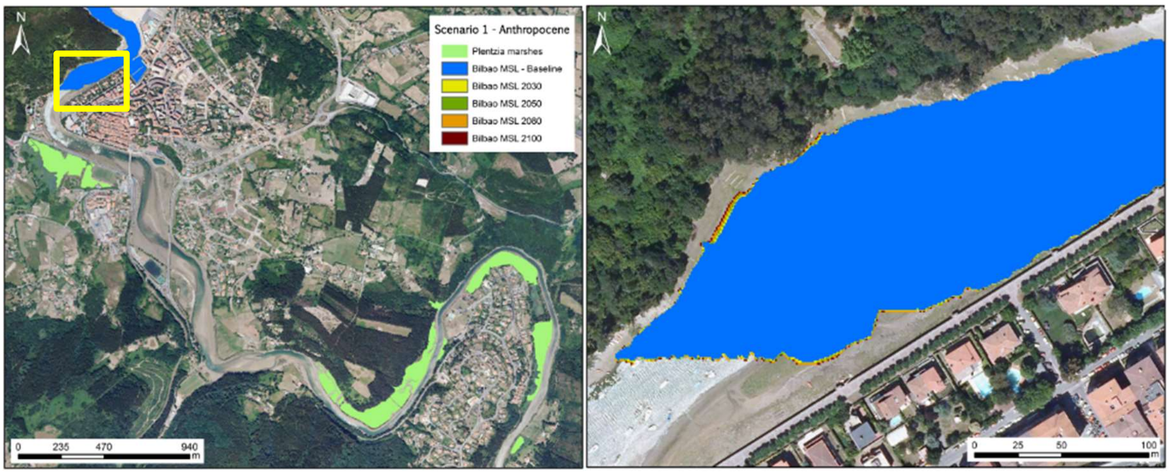

Figure 3.29. GBSLR Scenario 1 - Anthropocene: increase in mean sea level in the Plentzia Estuary.

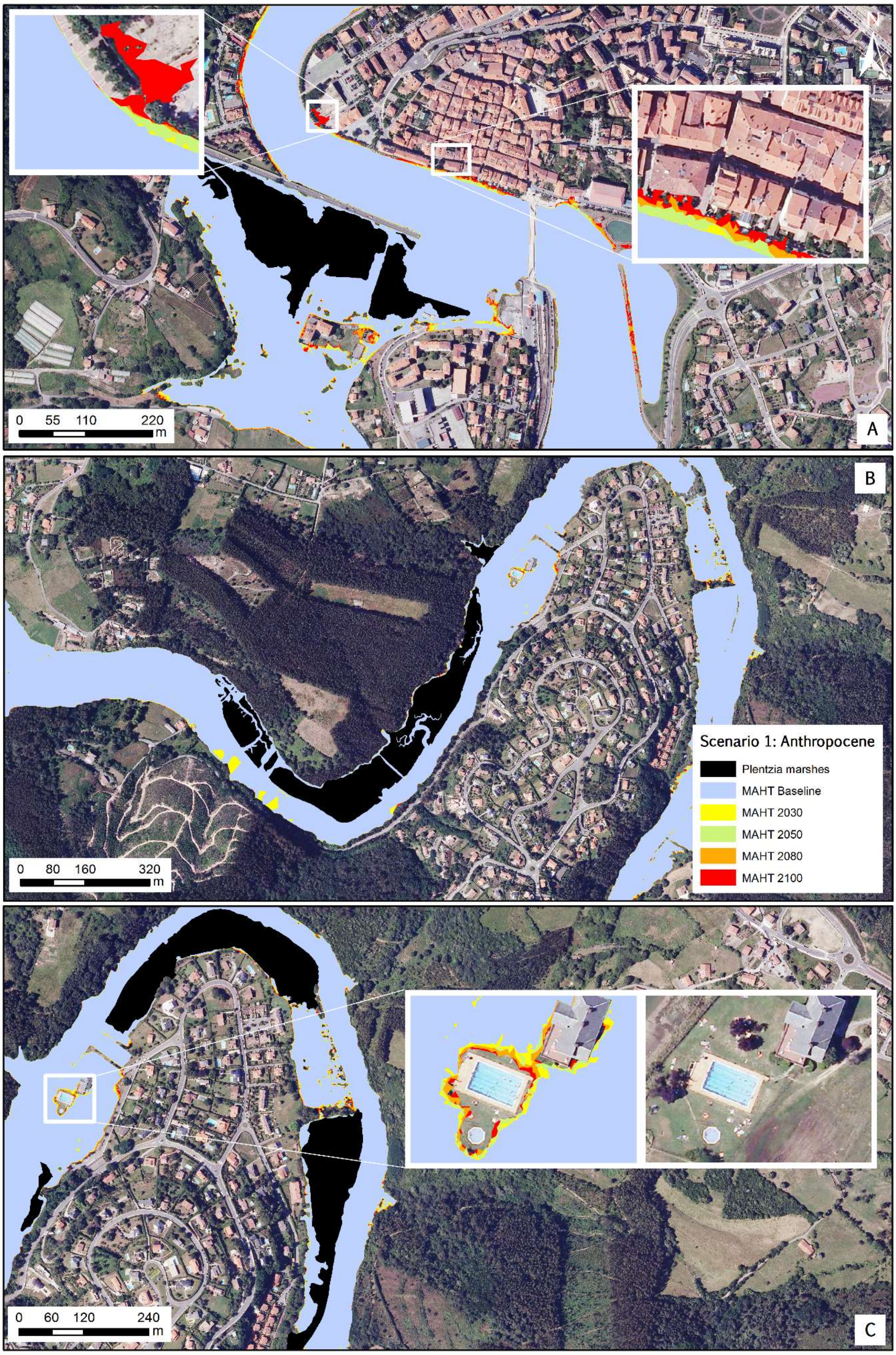

Figure 3.30. Temporal changes in MAHT levels in the Plentzia Estuary for GBSLR Scenario 1. A. Txipio marsh; B. Ostrada marsh; C. Isuskiza marsh. Urban areas potentially affected are also shown in white boxes.

Changes in the MAHT level due to sea-level rise are not significant with regard to salt marsh areas. However, these MAHT level changes do affect two specific urban spots by 2080 and 2100: the first is located in the town centre of Plentzia and the second is in Isuskiza. Details are shown in Figure 3.30 A and C, respectively. The estimated area potentially affected by changes in MAHT level is summarised in Table 3.11 for each of the land use category considered.

Table 3.11. GBSLR Scenario 1 – Anthropocene. Estimated areas potentially affected by temporal changes in MAHT level according to type of land use for different time frames.

Land uses		Baseline: non-flooded surface (m^2)	MAHT level - Flooded area (m^2)				
			Baseline	2030	2050	2080	2100
Salt marsh		165,764	159,068	159,093	158,993	159,001	159,006
Urban land	Residential	601,524	116,667	119,046	121,013	124,695	127,258
	Industrial	646,688	0	0	0	0	0
	Basic infrastructures	208,791	1830	1919	1933	1963	1992
	Communication & Transport	572,005	7561	7577	7607	7733	7808
	Community equipments	462,416	15,789	16,118	16,339	16,691	16,918
	Recreation areas	620,520	40,811	41,169	41,765	42,891	43,698
	Non developable	55,566,825	189,190	191,612	194,882	200,193	203,908

GBSLR Scenario 2: Holocene 2 (7000 cal yr BP - 1900)

During the second half of the Holocene Epoch, the rate of sea-level rise has been measured in 0.5 mm yr^{-1}. If the impacts of GBSLR Scenario 1 were little, impacts of GBSLR Scenario 2 are even smaller.

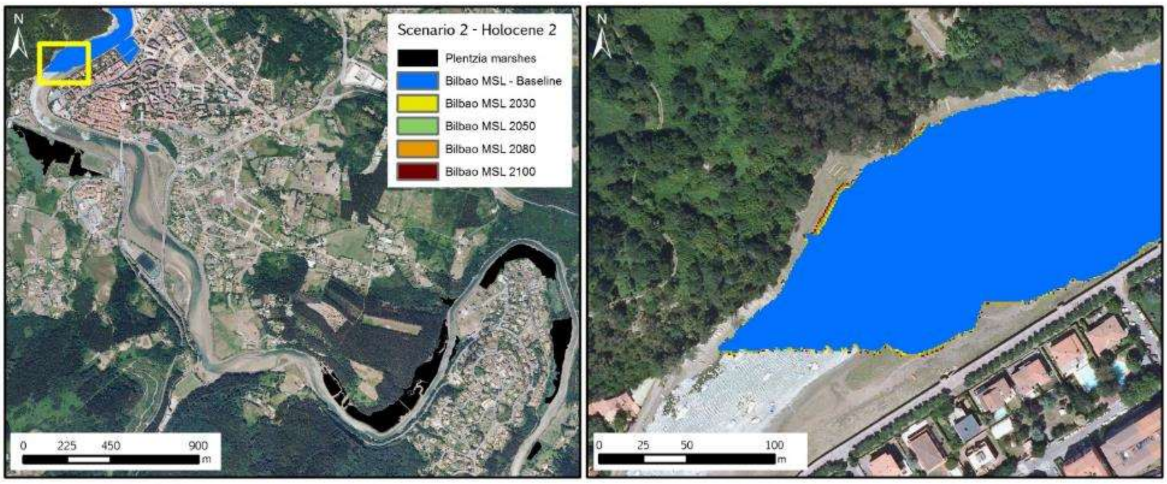

Figure 3.31. GBSLR Scenario 2 – Holocene 2: increase in mean sea level in the Plentzia Estuary.

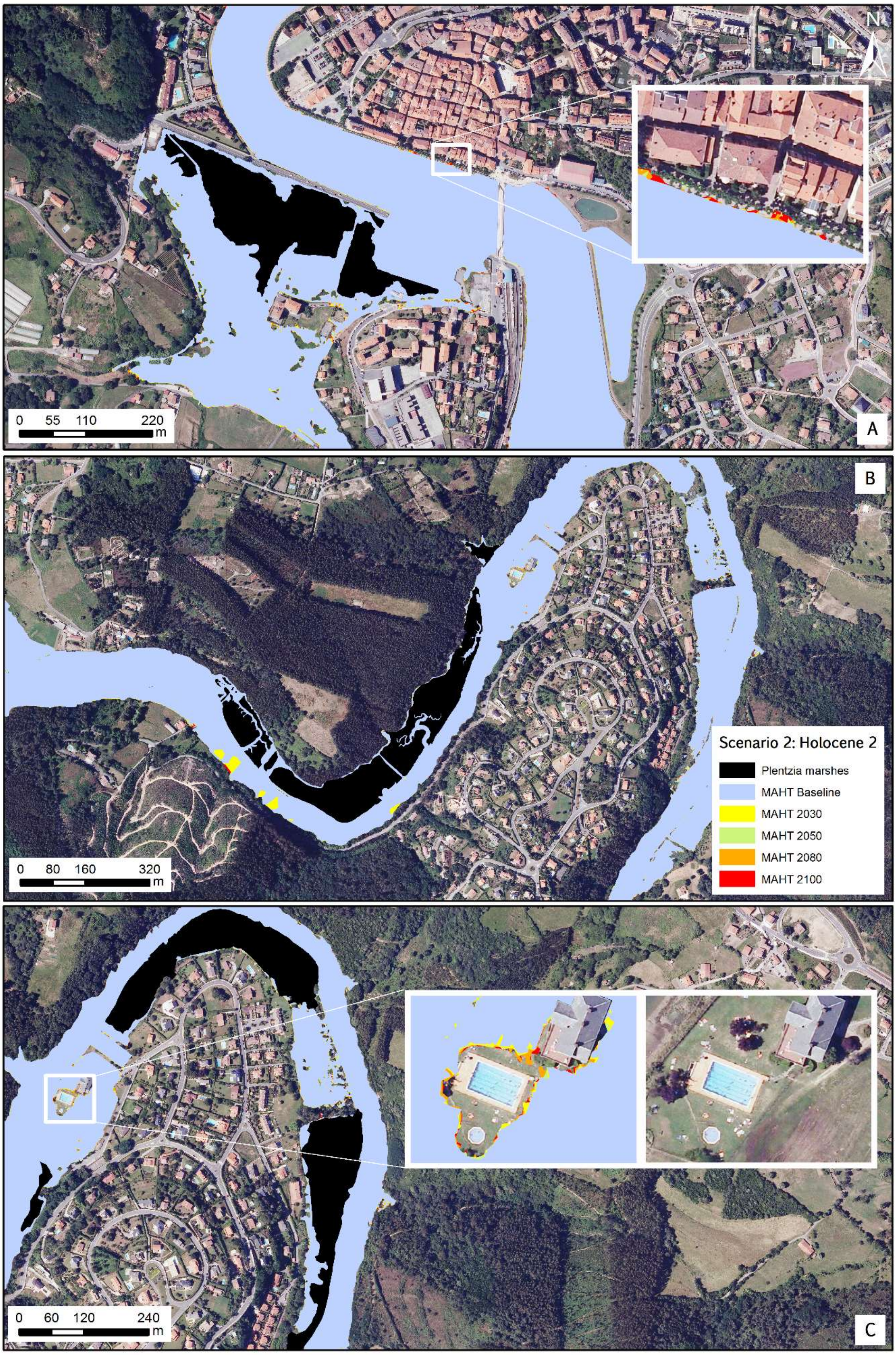

Figure 3.32. Temporal changes in MAHT levels in the Plentzia Estuary for Scenario 2. A. Txipio marsh; B. Ostrada marsh; C. Isuskiza marsh. In this latter case, a household potentially affected is shown in white boxes.

Thus, and with regard to changes in mean sea level, there is no impact on salt marshes or human systems (Figure 3.31), while in the case of changes in MAHT there is a very small increase of the flooding over a household located in the Isuskiza area (Figure 3.32C). In terms of affected extension by land use, Table 3.12 summarises these estimations.

Table 3.12. GBSLR Scenario 2 – Holocene 2. Estimated areas potentially affected by changes in MAHT level according to type of land use for different time frames.

Land uses		Baseline: non-flooded surface (m^2)	MAHT level - Flooded area (m^2)				
			Baseline	2030	2050	2080	2100
Salt marsh		165,764	159,068	159,083	158,973	158,976	158,988
Urban land	Residential	601,524	116,667	117,479	117,994	119,040	119,354
	Industrial	646,688	0	0	0	0	0
	Basic infrastructures	208,791	1830	1904	1909	1919	1925
	Communication & Transport	572,005	7561	7489	7508	7539	7555
	Community equipments	462,416	15,789	15,994	16,037	16,118	16,167
	Recreation areas	620,520	40,811	40,682	40,843	41,128	41,261
	Non developable	55,566,825	189,190	189,191	190,139	191,699	192,428

GBSLR Scenario 3: Holocene 1 (10000 cal BP - 7000 cal BP)

A high rate of sea-level rise occurred during the first half of the Holocene, as high as 10 mm yr^{-1}. This rate would translate into a sea-level highstand of 90 cm by the end of the century.

A. Changes in mean sea level

In the Plentzia Estuary there would not be any significant change for the period up to 2050. However, the rise of mean sea level by 2080 and 2100 would cause considerable impacts to salt marshes, although no urban area would be submerged (see Figure 3.33). Nevertheless, it is important to note that this figure shows the areas under MSL, which is 1.41 m below the mean high tide (Puertos del Estado, 2005).

How these changes in MSL would affect salt marshes and to what extent is shown in detail in the white box of the same figure. The Txipio marsh would be strongly disturbed by daily flooding but only by 2100, while Ostrada and Isuskiza marshes, located in the upper estuary, would not be affected. Urban areas would also experience some flooding. In terms of affected surface, non-developable land and recreation areas would be the most affected, followed by residential areas (Table 3.13).

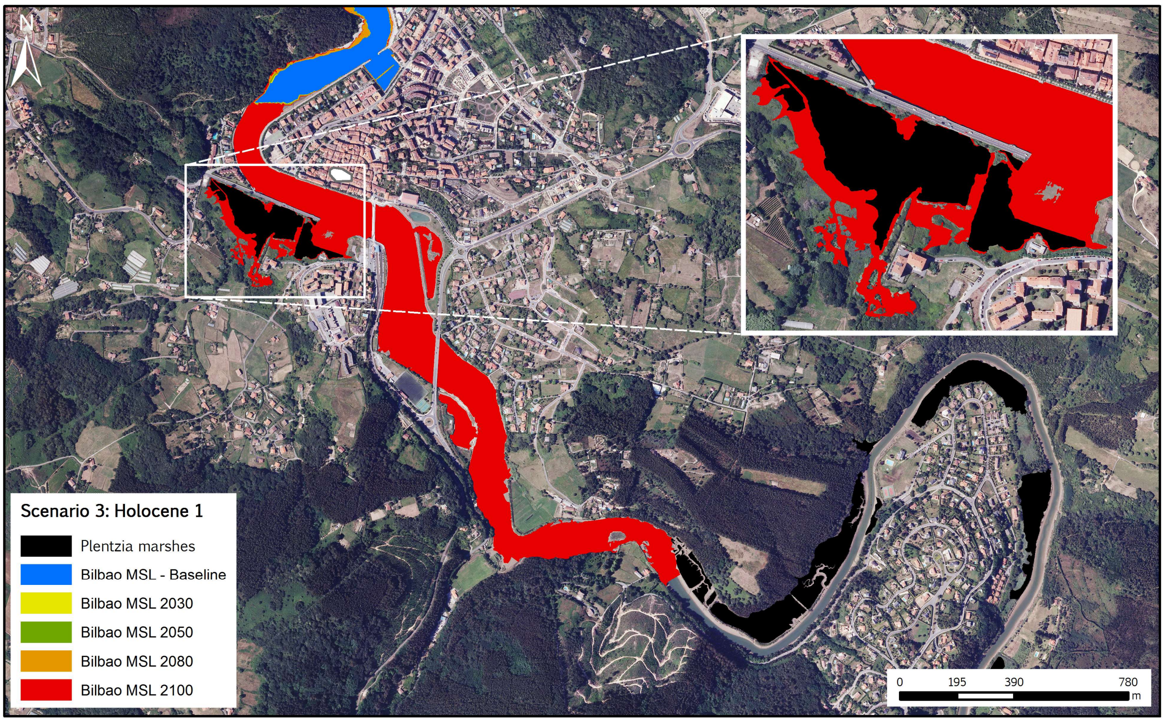

Figure 3.33. Changes in mean sea level in the Plentzia Estuary for GBSLR Scenario 3.

Table 3.13. GBSLR Scenario 3 – Holocene 1. Estimated areas potentially affected by changes in MSL. Flooded areas are shown according to type of land use for different time frames.

Land uses		Baseline: non-flooded surface (m^2)	MSL level - Flooded area (m^2)			
			2030	2050	2080	2100
Salt marsh		165,764	0	2659	29,660	37,808
Urban land	Residential	601,524	0	1467	5142	11,020
	Industrial	646,688	0	0	0	0
	Basic infrastructures	208,791	0	0	432	980
	Communication & Transport	572,005	0	1548	1917	3349
	Community equipments	462,416	0	2215	4689	7866
	Recreation areas	620,520	0	6706	10,161	12,635
	Non developable	55,566,825	0	1026	18,267	71,198

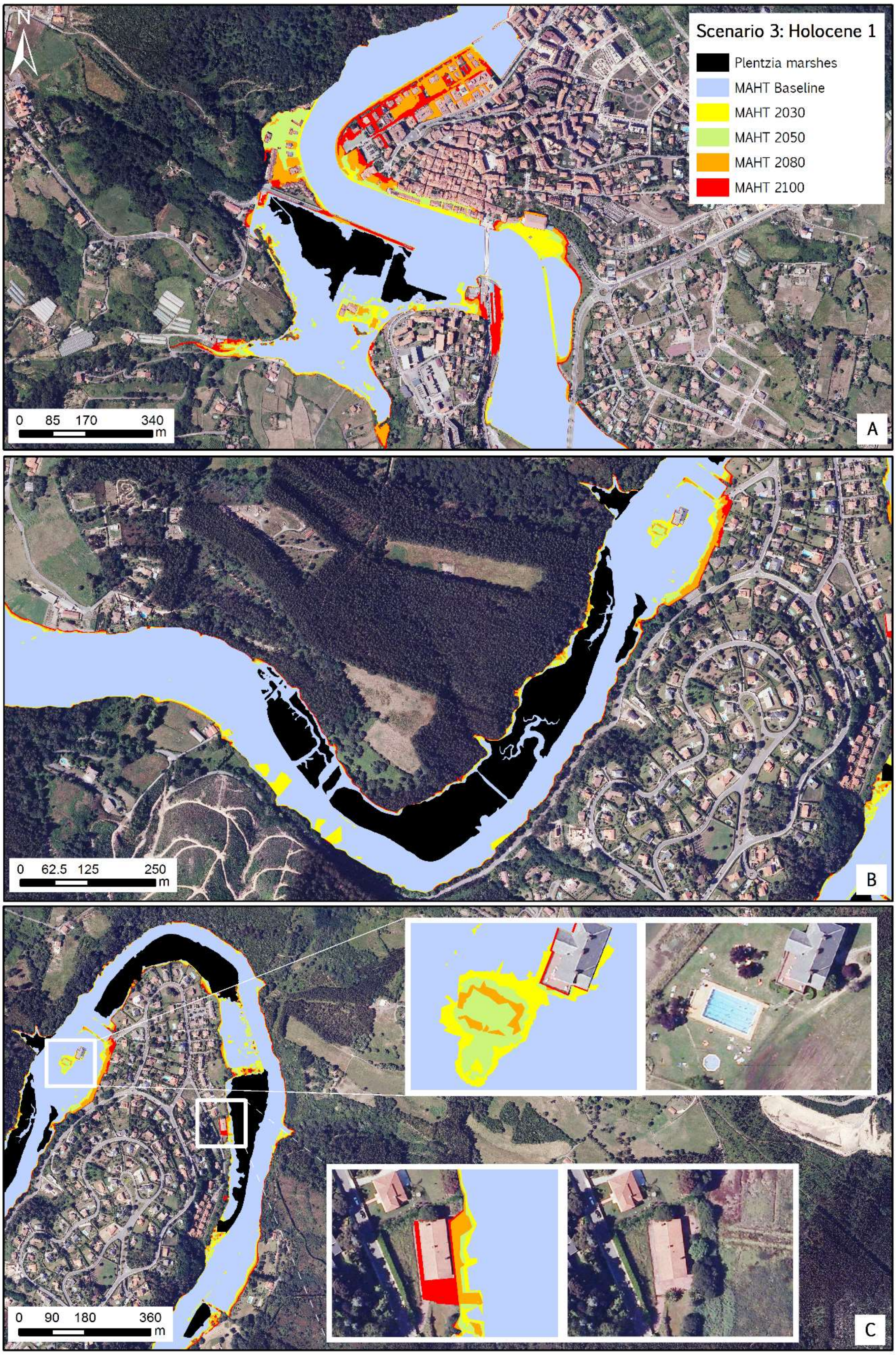

Figure 3.34. Temporal changes in MAHT level in the Plentzia Estuary for GBSLR Scenario 3. A. Txipio marsh; B. Ostrada marsh; C. Isuskiza marsh. In this latter case, two households potentially affected are shown in white boxes.

B. Changes in MAHT level

The main impacts due to changes in the MAHT would affect the lower estuary and the adjacent urban area. Beginning with salt marshes, all of them are currently submerged when the estuary reaches MAHT level, and the same situation occurs in all future scenarios (Figure 3.34).

With regard to urban areas, the flooding would affect two family households in Isuskiza, although one of them, located in the left bank, is also flooded under current MAHT level. However, the most impacted zones would be those in the lower estuary (Figure 3.35). The town centre of Plentzia would be strongly impacted (Figure 3.35A). The southern part would suffer some flooding already by 2030, which will increase by the end of the century. The northern part would not be affected until 2080, but impacts would disturb a greater area. In the same river bank, about 1 km south from the town centre a small area of the Gandia neighbourhood would also be flooded, but no household would be affected until 2100 (Figure 3.35E).

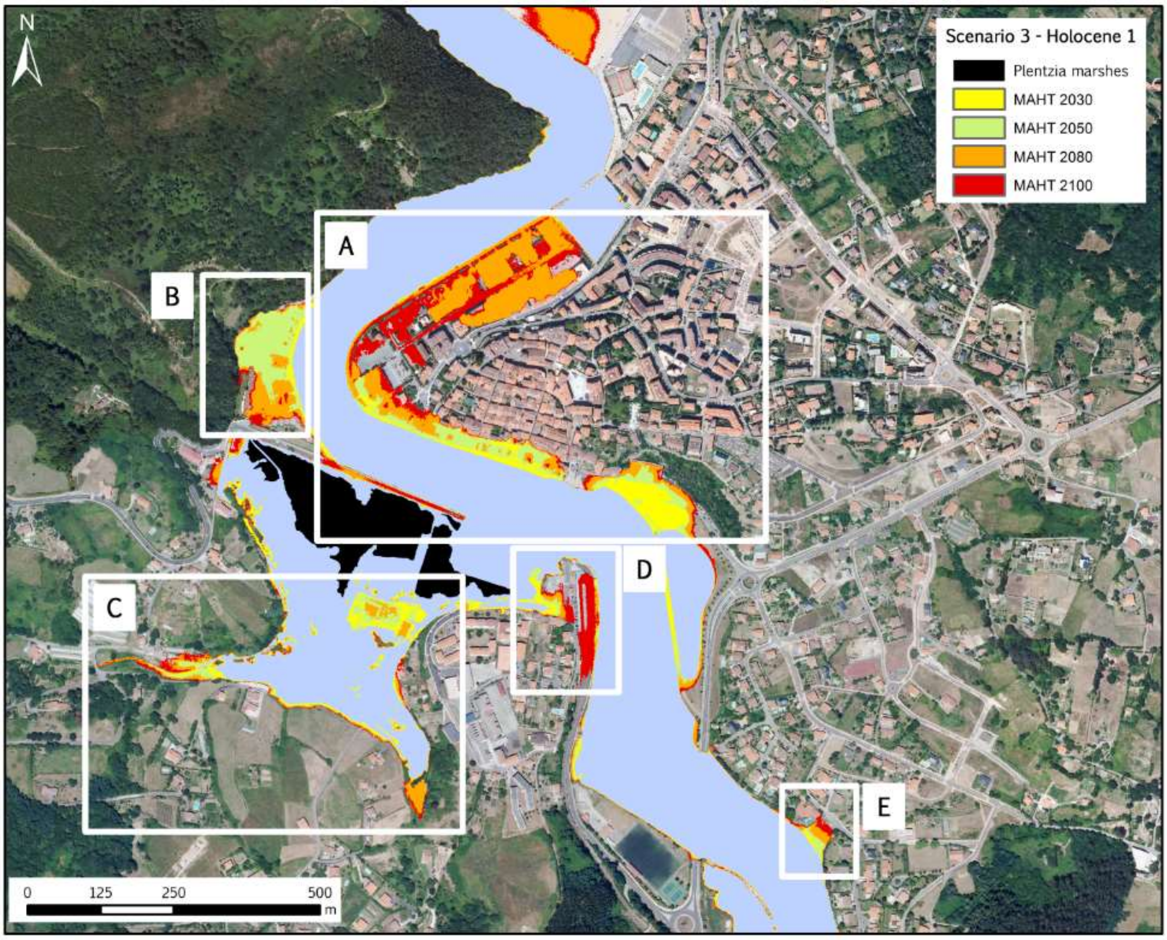

Figure 3.35. Changes in MAHT sea level in the Plentzia Estuary for GBSLR Scenario 3. Main impacted zones are included in white boxes.

In the left bank of the estuary, from north to south, flooding would strongly affect the San Telmo area. Already by 2050 a great part of the neighbourhood would be affected, but damages would increase by 2080 and 2100 (Figure 3.35B). Txipio is located south of San Telmo and by 2050 flooded area would extent up to a few households close to the salt marsh. In fact, the household located closer to the salt marsh area (actually, in an area that was once part of the marsh environment) would experience the greatest flooding, already by 2030 (Figure 3.35C). East of the Txipio marsh, the Plentzia's metropolitan railway station would also get submerged but only at the end of the century (Figure 3.35D). Figure 3.36 shows the affected areas in detail.

With regard to land use categories, non-developable land is affected in a greater extension but proportionally only 0.4% of its total area would suffer from flooding. Relatively, the residential land would have a great part of it flooded (21% in 2030 and in 2100). Basic infrastructure, such as the metropolitan railway station and roads, would also experience damages. The proportion of affected surface is low (up to 3.1% by 2100), but the cost of the damaged infrastructure is expected to be high, not only in economic terms, but also in terms of services to the local population. Table 3.14 summarises the flooded area by types of land use and in different temporal scenarios.

Table 3.14. GBSLR Scenario 3 – Holocene 1. Estimated areas potentially affected by changes in MAHT sea level. Flooded aresa are shown according to type of land use for different time frames.

Land uses		Baseline: non-flooded surface (m^2)	MAHT level - Flooded area (m^2)				
			Baseline	2030	2050	2080	2100
Salt marsh		165,764	159,068	159,363	161,309	163,453	164,195
Urban land	Residential	601,524	116,667	128,993	153,811	193,922	214,679
	Industrial	646,688	0	0	0	0	0
	Basic infrastructures	208,791	1830	2013	2178	2684	6492
	Communication & Transport	572,005	7561	8728	9730	11,380	13,083
	Community equipments	462,416	15,789	17,128	20,105	24,869	27,790
	Recreation areas	620,520	40,811	44,122	47,581	59,936	66,524
	Non developable	55,566,825	189,190	210,618	226,391	246,154	258,055

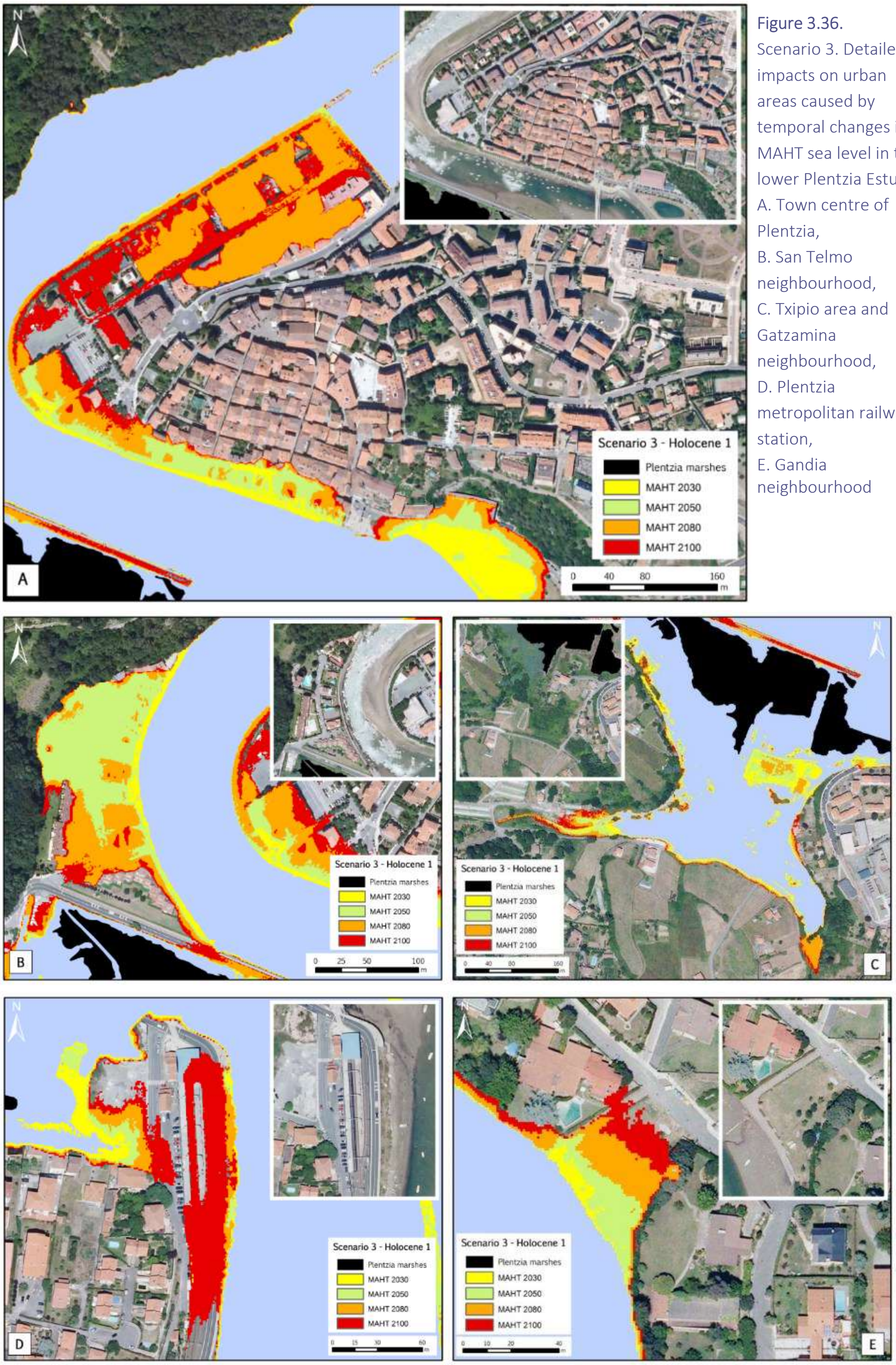

Figure 3.36.
Scenario 3. Detailed impacts on urban areas caused by temporal changes in MAHT sea level in the lower Plentzia Estuary:
A. Town centre of Plentzia,
B. San Telmo neighbourhood,
C. Txipio area and Gatzamina neighbourhood,
D. Plentzia metropolitan railway station,
E. Gandia neighbourhood

GBSLR Scenario 4: LIG-MIS5e sea-level highstand (130-120 ky)

Under this scenario Bilbao reference sea level (also known as Bilbao 0 m) would be +6.901 m above current levels. We also estimated the new MSL (2.4 m above the reference level). Based on these two different sea levels, we estimated the new coastline position and calculated the flooded area.

Table 3.15 shows the flooded area for each of the land use categories considered for the Plentzia Estuary. The data corresponding to flooded area under MAHT levels has also been included as a reference. The submerged area on GBSLR Scenario 4 exceeds by far the impacts when sea level reaches the MAHT level.

Table 3.15. Potentially affected areas under GBSLR Scenario 4 – MIS5e. The impact of both the reference level and the mean sea level on each of the land-use types has been estimated.

Land uses		Baseline (m^2)		MIS5e level – Flooded area (m^2)	
		Non-flooded surface	Flooded area (under MAHT level)	New reference (Bilbao 0)	New mean sea level (MSL)
Salt marsh		165,764	159,068	165,673	165,764
Urban land	Residential	601,524	116,667	273,988	370,522
	Industrial	646,688	0	0	0
	Basic infrastructures	208,791	1830	11,235	15,475
	Communication & Transport	572,005	7561	22,154	44,771
	Community equipments	462,416	15,789	60,240	104,846
	Recreation areas	620,520	40,811	95,680	163,036
	Non developable	55,566,825	189,190	382,465	674,081

The impacts under GBSLR Scenario 4 would be dramatic. With regard to salt marshes, they would be totally submerged, with no possibility of migrating because the topography and different human infrastructures, such as residential areas or roads, would not allow the adaptation. Urban areas would also be strongly hit by this rise in sea level. More than 50% of the residential area in Plentzia would be inundated. Roads, public transport, community equipment and recreation areas, such as the Plentzia-Gorliz beach, would also be dramatically altered. Figure 3.38 shows the overlap between mean sea-level rise under LIG-MIS5e scenario, salt marsh ecosystems and the distribution of land uses.

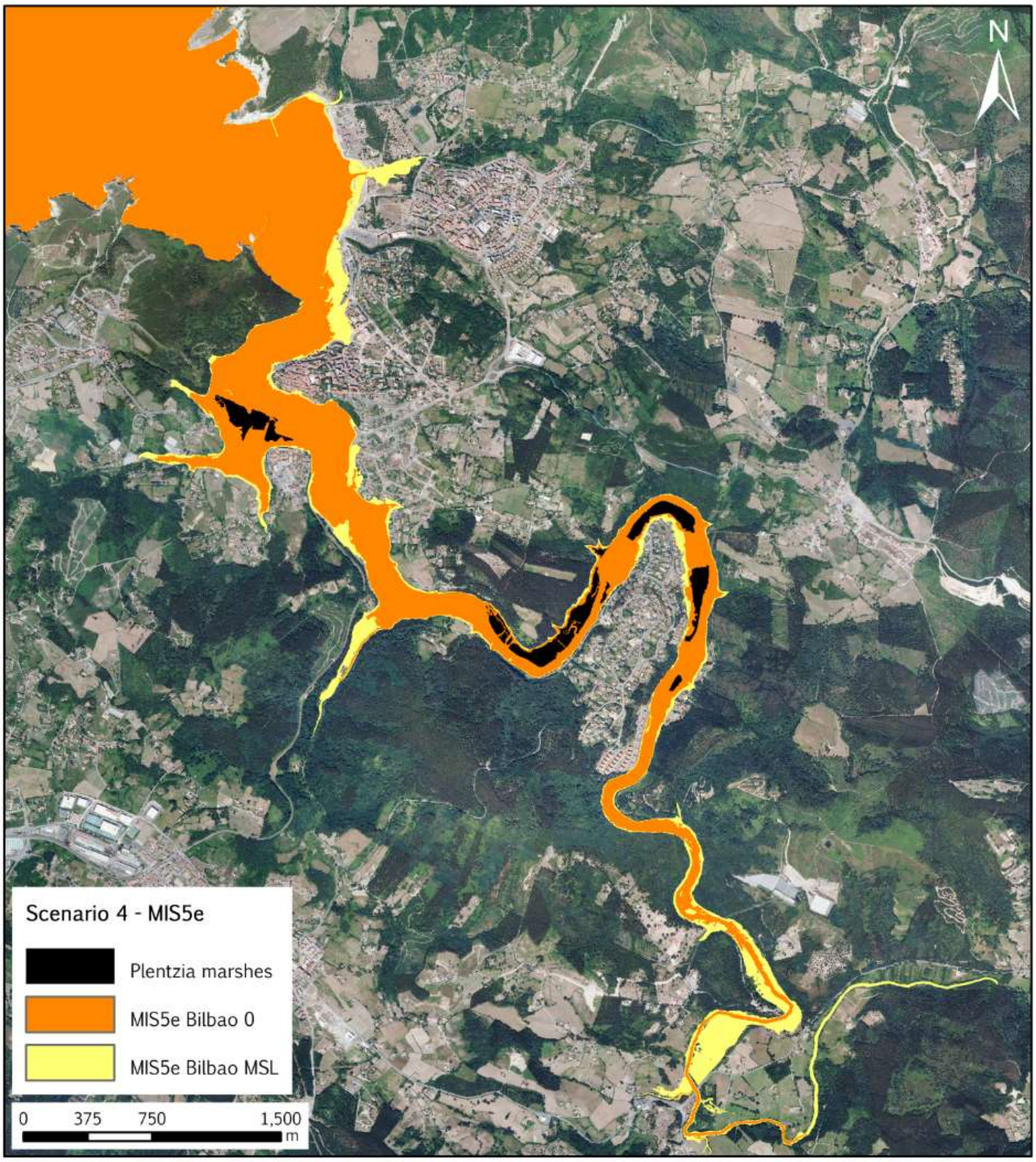

Figure 3.37. Flooded areas under GBSLR Scenario 4 in the Plentzia Estuary. The orange area represents the new Bilbao ordnance datum located at +6.901 m above present levels, while the yellow area reproduces the surface affected by flooding considering mean sea level.

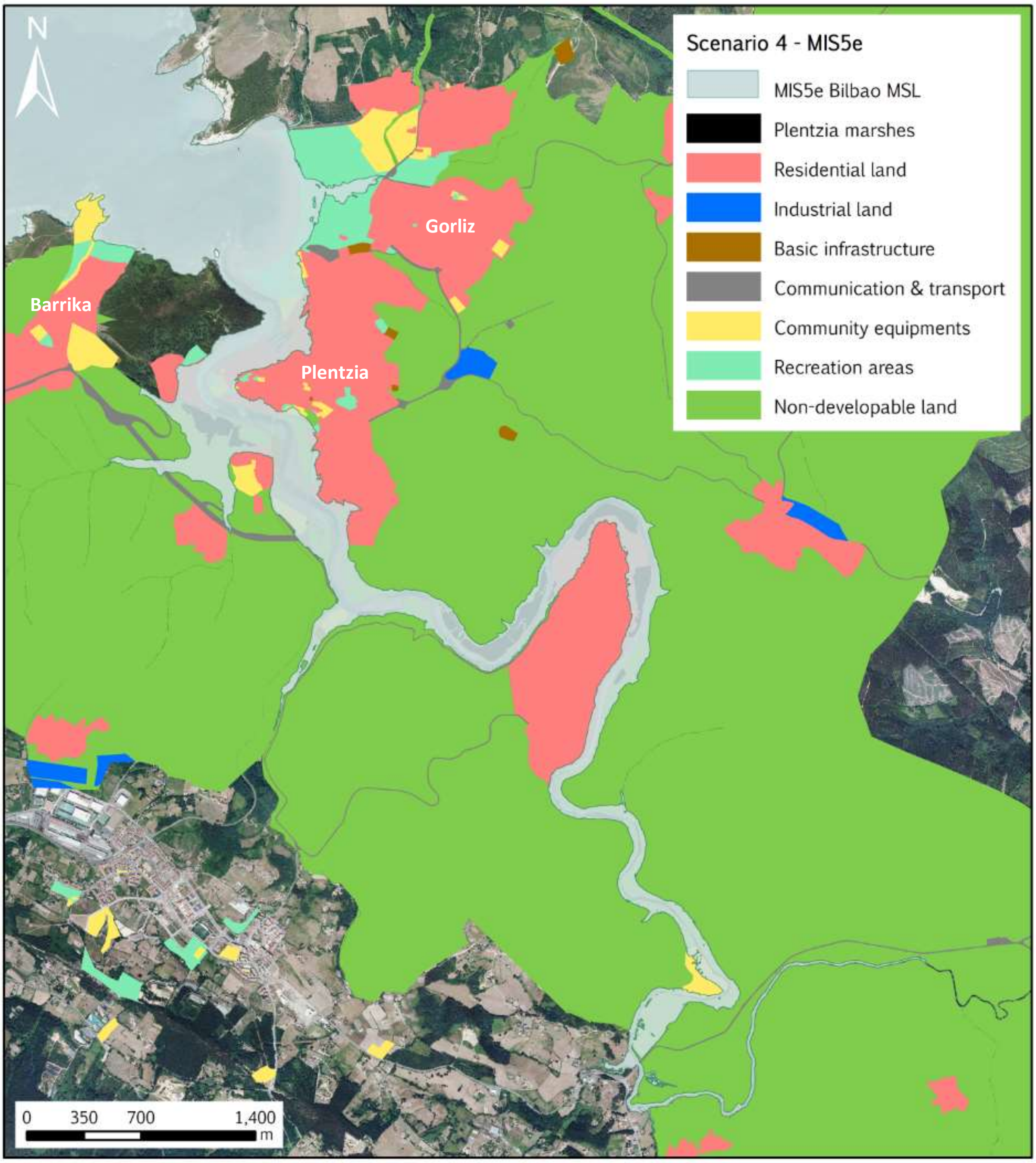

Figure 3.38. Flooded areas under the LIG-MIS5e mean sea-level scenario in the Plentzia Estuary and its impacts on the different land uses.

3.3.3 Muskiz Estuary

3.3.3.1 Current salt marshes of the Muskiz Estuary

The only remains of the original estuarine environments are located in the lower estuary, where there are some salt marsh areas on the left bank (total surface area 15 ha) and a dune field on the right bank (total surface area 10.4 ha) (Cearreta et al., 2008). Figure 3.40 shows the estuary in 1965 and more recently, in 1999, once Petronor and CLH were already built.

Current salt marsh ecosystem areas were delimited in the Barbadun Estuary by means of orthophotographs and GIS technologies. The proposed delimitation was also confirmed on the field. Two well preserved salt marshes can be identified in the left bank, Pobeña and Barbadun (Figure 3.40 A and B). In the right bank where the company CLH was located until 2011, another salt marsh is identified, but in this case the marsh is in regeneration process (Figure 3.40 C).

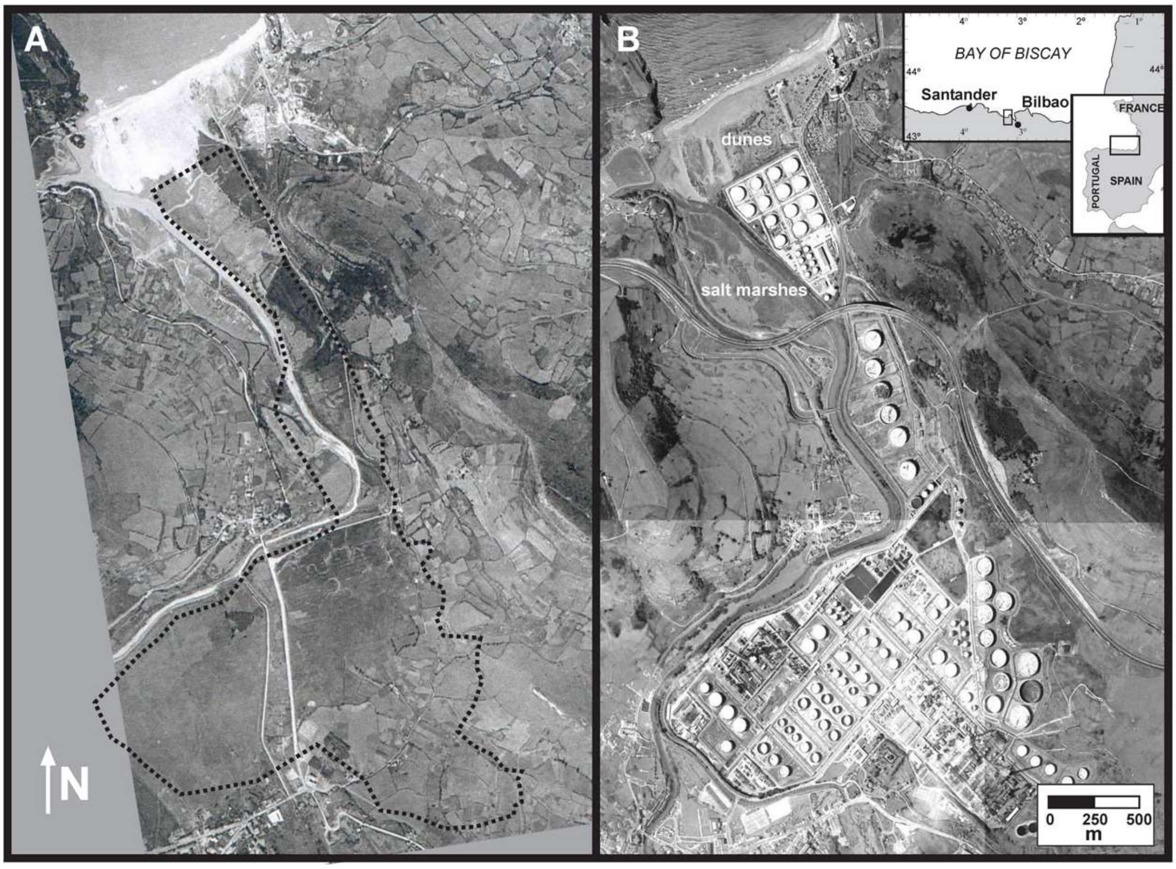

Figure 3.39. Geographic location n of the Muskiz Estuary. A: Aerial photograph showing the estuary in 1965 and the future emplacement of the refinery; B: Aerial photograph showing the estuary in 1999. Source: Cearreta et al. (2008).

The Barbadun marsh shows a mosaic of vegetated areas, mudflats, channels and puddles that allow for a rich fauna (Basque Government, 2004). Pobeña marsh, smaller than Barbadun, is delimited by an artificial enclosing wall.

The CLH marsh is located in the area previously occupied by oil containers of the Compañía Logística de Hidrocarburos (CLH) industrial group. The area was partially restored when the company left this area in 2009. However, it has been observed *in situ* that mostly is a sandy area with little or no vegetation, crossed by a few artificial channels and some built paths. Its topographic height exceeds by far that of natural salt marshes, so a new human intervention would be necessary to recover this environment to its original state (Figure 3.41).

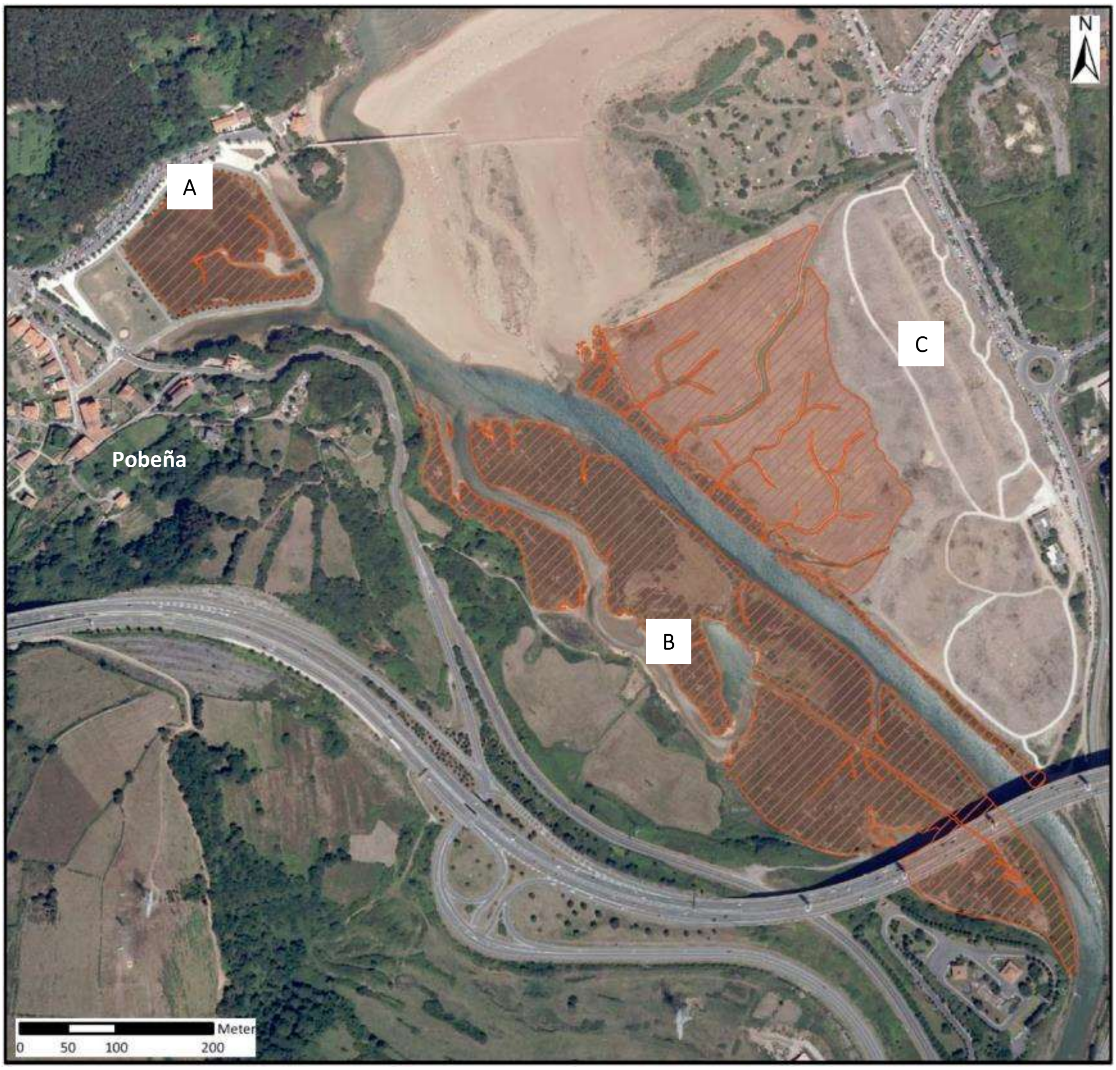

Figure 3.40. Salt marshes in the Muskiz Estuary. A) Pobeña marsh; B) Barbadun marsh and C) CLH marsh. This latter is considered to be in regeneration while the first two are well preserved natural salt marshes.

Regarding salt marsh vegetation, Silván and Campos (2002) found 18 halophytic plant species in the Muskiz Estuary. Especially abundant are *Limonium vulgare* and *Plantago maritima* in those areas daily flooded; the latter can only be found in this estuary and Urdaibai. *Sarcocornia fruticosa* halophytic scrubs are also well represented in the estuary.

Figure 3.41. A. Barbadun salt marsh. Well preserved salt marsh vegetation can be seen and also several old industrial pillars, remnants of the mineral-ore transport activity to the loading bay in Covarón during the 19th century (Montero García, 1988). The buildings at the back are located in Pobeña, very close to the salt marsh of the same name. B. CLH marsh, with artificial gravel sediments, human-made channels and few planted reeds.

In relation to salt marsh accretion rates, following the criteria explained before, various average accretion rates have been used to estimate the net potential salt marsh accretion in the Muskiz Estuary (Table 3.16).

Table 3.16. Net accretion of salt marshes in the Muskiz Estuary, depending on their different ecological state.

Salt marsh	Ecological state	Surface (ha)	Accretion rate ($cm \cdot yr^{-1}$)	Net accretion (cm)			
				2030	2050	2080	2100
Pobeña marsh	Natural	1.66	0.21	4.3	8.6	15	19.2
Barbadun marsh	Natural	9.24	0.21	4.3	8.6	15	19.2
CLH marsh	Natural	0.9	0.21	4.3	8.6	15	19.2
	In regeneration	5.4	1.63	18.4	22.7	29.1	33.4

3.3.3.2 Building flood risk maps

When analysing sea-level rise in the Muskiz Estuary, two different systems have been assessed: salt marsh ecosystems and the industrial area of the Petronor oil refinery. Flood risk maps have been calculated for both areas under three sea-level rise scenarios.

Scenario 1: Anthropocene (1900 - 2010)

The sea-level-rise rate measured during the Anthropocene in Basque marshes (2 mm yr^{-1}) has been used to estimate potential flood maps. As explained in Chapter 2, future sea levels were estimated referred to current Bilbao MSL and the MAHT level. The MAHT[26] level represents the maximum height in a 19 year period; therefore it does not represent a permanent flooding but a highstand as a result of an astronomic extreme event. The net sea-level rise is estimated for the different time periods considered and then added to the sea levels taken as a reference (MSL and MAHT). The results are summarised in Table 3.17.

Table 3.17. Net sea-level rise for GBSLR Scenario 1 (Anthropocene) for each of the time periods and sea-level positions considered. Heights are in cm and referred to Bilbao ordnance datum.

Reference	Baseline (2010)	2030	2050	2080	2100
Net sea-level rise (rate = 2 mm yr^{-1})	0	4	8	14	18
Bilbao MSL + SLR	240	244	248	254	258
MAHT + SLR	483	487	491	497	501

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[26] The Maximum Astronomic High Tide (MAHT), as already explained in Chapter 2 and previous sections, is defined as the maximum high tide in a 19-year return period. The level is 483 cm above Bilbao ordnance datum (0 m).

Nevertheless, the impacts due to variations in mean sea level as a result of a changing climate are very small (Figure 3.42). In fact, no additional salt marsh area would be submerged under this scenario, even considering a 18 cm rise by 2100.

Figure 3.42. Sea-level rise in the Muskiz Estuary considering Scenario 1. Anthropocene and Bilbao MSL.

A similar result is obtained when estimating the impacts of sea-level rise on the MAHT level, as shown in Figure 3.43. The flooded area under the MAHT level is much greater than in the previous case, but the changes due to sea-level rise would not be substantial.

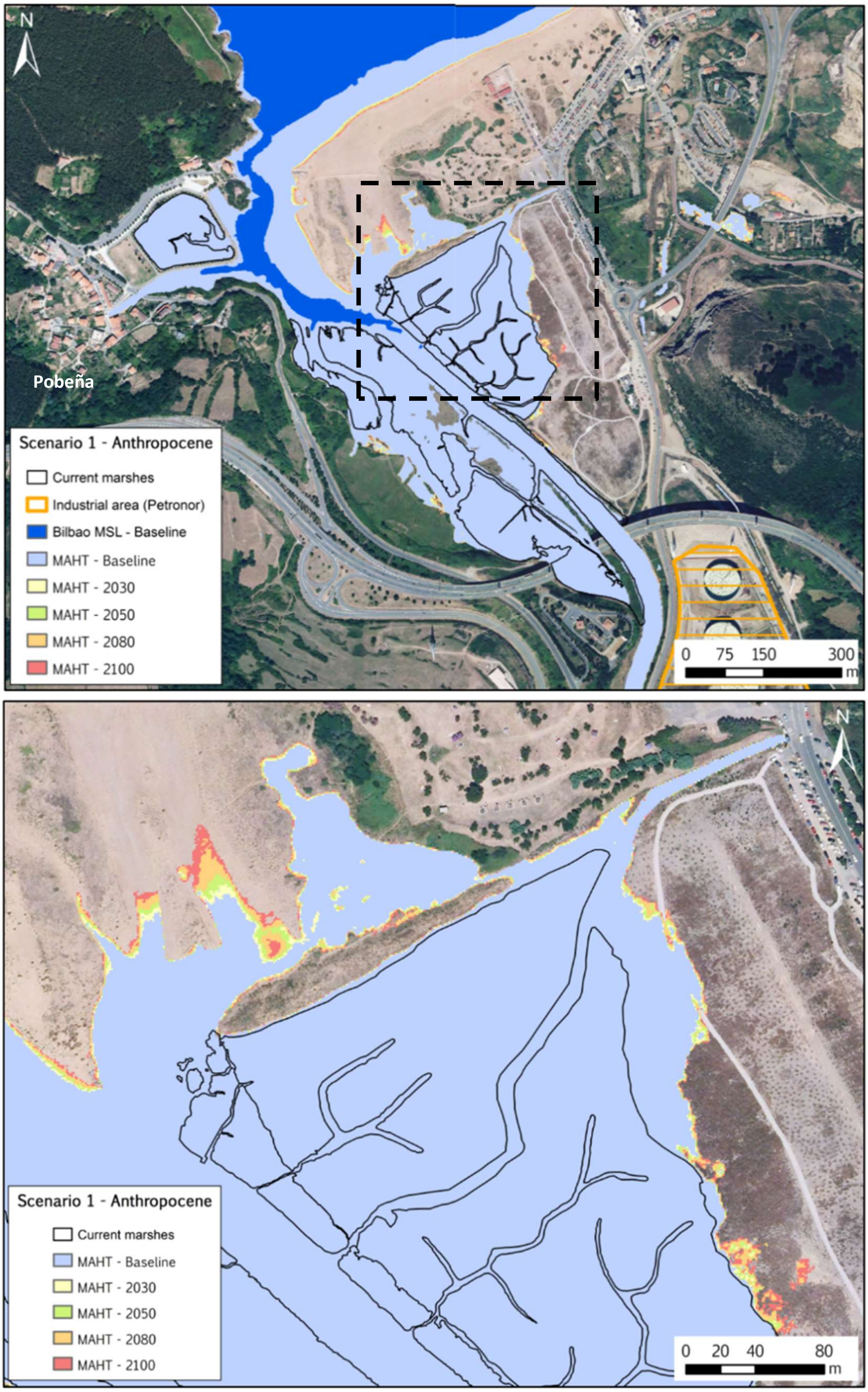


Figure 3.43. Flooded area considering MAHT sea level under Scenario 1. The upper figure shows the salt marsh areas of the Muskiz Estuary. The lower figure shows an enlarged area of the CLH marsh where temporal changes in MAHT levels due to sea-level rise can be observed.

Potential impacts on the industrial area of Petronor have also been estimated and the results show that this oil refinery would not suffer any additional flooding under this scenario (Figure 3.44).

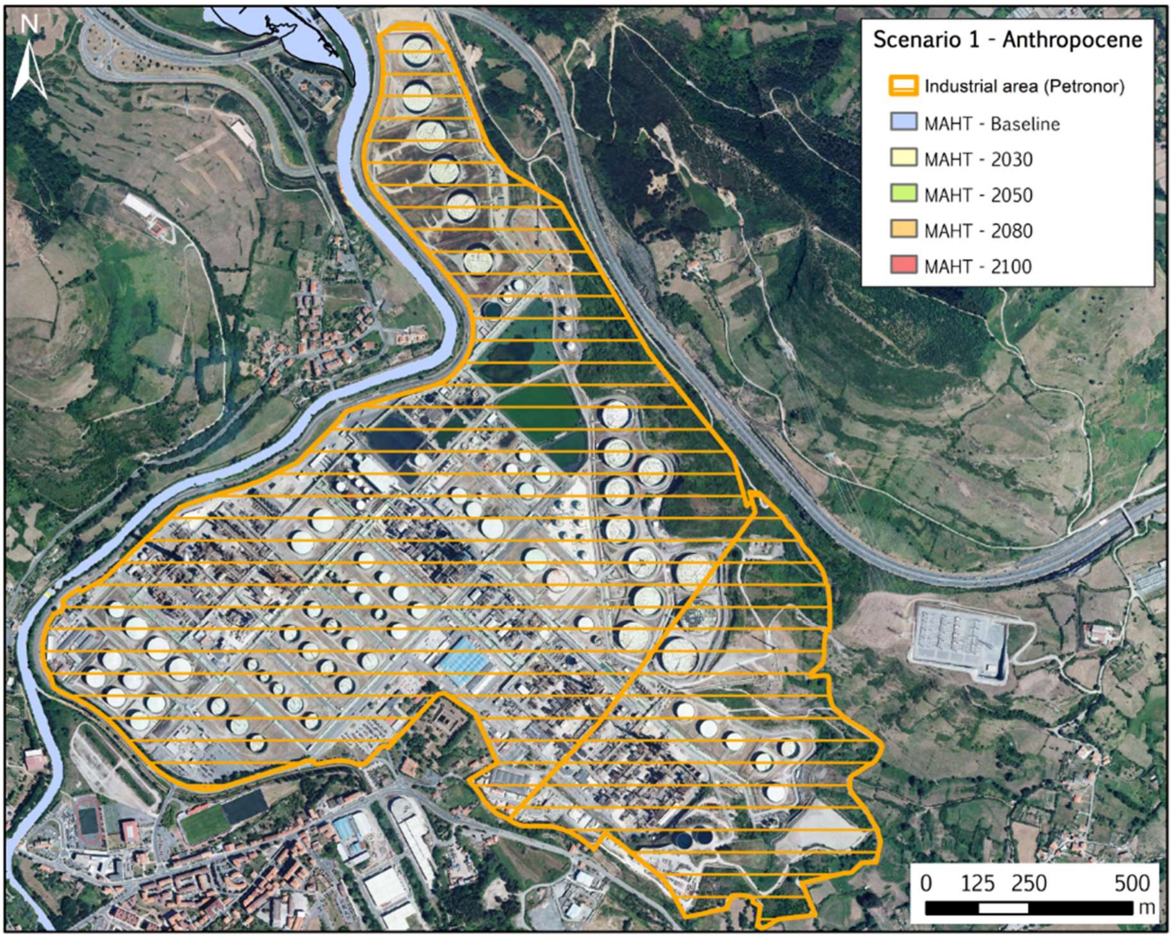


Figure 3.44. Petronor industrial area and the MAHT sea level for each of the time periods considered.

GBSLR Scenario 2: Holocene 2 (7000 cal yr BP – 1900)

In this scenario the rate of sea-level rise considered is that estimated for the second half of the Holocene Epoch, 0.5 mm yr^{-1} (see Table 3.18).

Considering that the rate of sea level used in this scenario is four times smaller than GBSLR Scenario 1, it is easy to predict that under Scenario 2 there will be no new affected areas. The change of mean sea level is shown in Figure 3.45.

Table 3.18. Net sea-level rise under GBSLR Scenario 2 (Holocene 2) for each of the time periods and sea-level positions considered. Heights are in cm and referred to Bilbao ordnance datum.

Reference	Baseline (2010)	2030	2050	2080	2100
Net sea-level rise (rate = 0.5 mm yr^{-1})	0	1	2	3.5	4.5
Bilbao MSL + SLR	240	241	242	243.5	244.5
MAHT + SLR	483	484	485	486.5	487.5

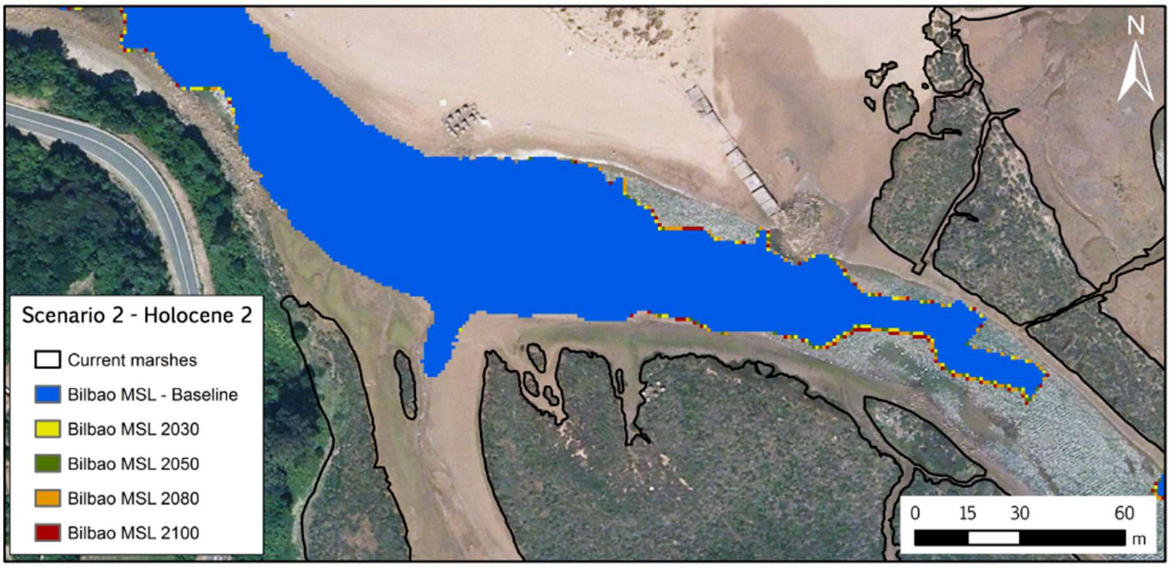


Figure 3.45. Sea-level rise in the Muskiz Estuary considering Scenario 2 (Holocene 2) and Bilbao mean sea level (MSL).

Likewise, the temporal changes in MAHT level are very small and no further salt marsh area is affected. With regard to the industrial area of Petronor, no flooded is expected either considering mean sea level or MAHT level (Figure 3.46).

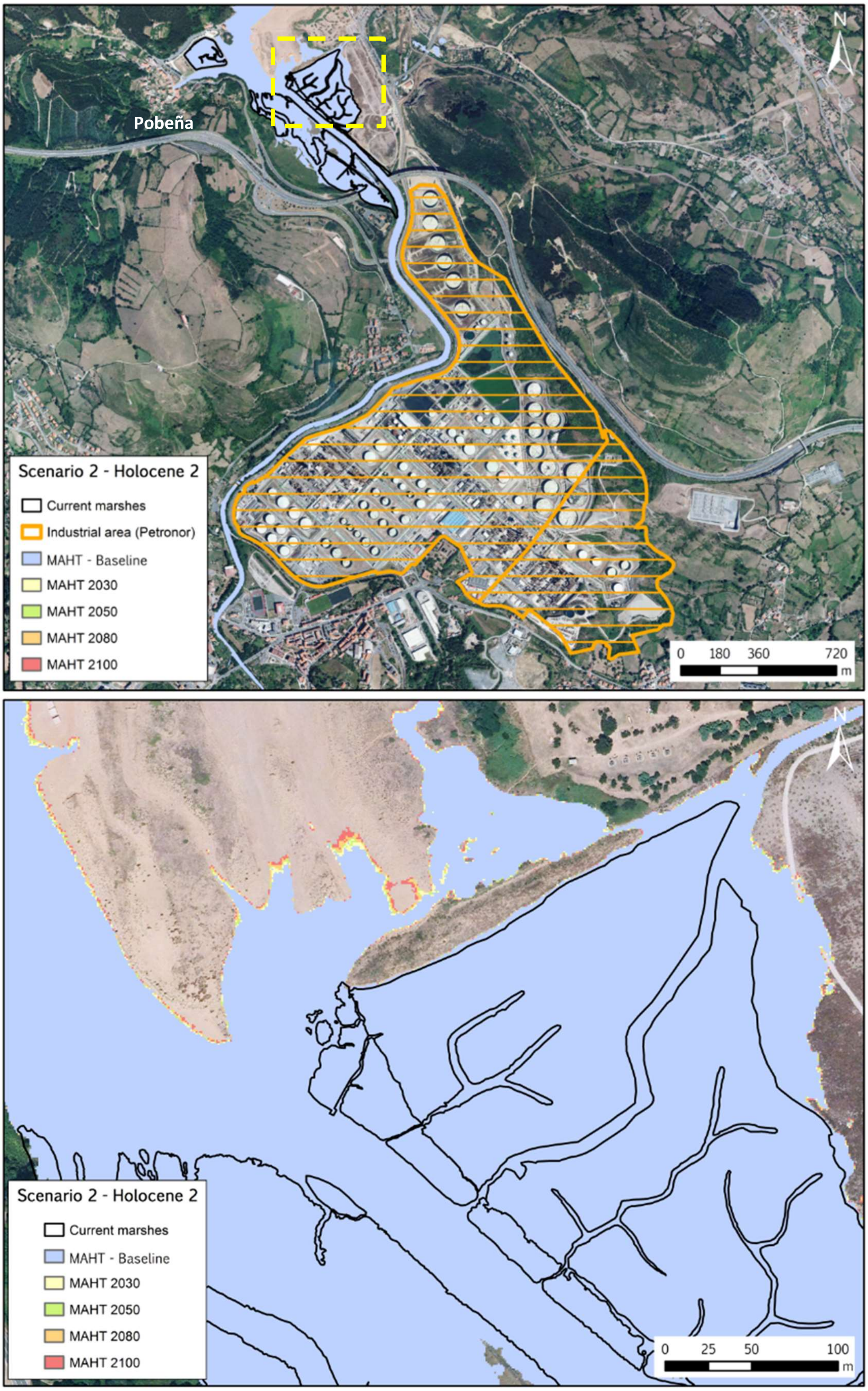


Figure 3.46. Flooded area considering MAHT sea level under Scenario 2. The upper figure shows the salt marsh areas of the Muskiz Estuary and the Petronor oil refinery. The lower figure shows an enlarged area of the CLH marsh where temporal changes in MAHT level due to sea-level rise can be observed.

GBSLR Scenario 3: Holocene 1 (10000 cal yr BP – 7000 cal yr BP)

The rate of sea-level rise considered in this scenario is that estimated for the first half of the Holocene Epoch, which reached an average 10 mm yr^{-1} and by 2100 the sea level would rise by 90 cm. This scenario is close the upper bound estimations for sea-level rise included in the IPCC AR5, that for RCP8.5 ranges from 52 to 98 cm (Church et al., 2013).

Sea level in this third scenario is five times greater than the one measured during the 20th century in Basque salt marshes. Still, the increase in mean sea level would not be translated into permanent flooding of the marshes located in the Muskiz Estuary.

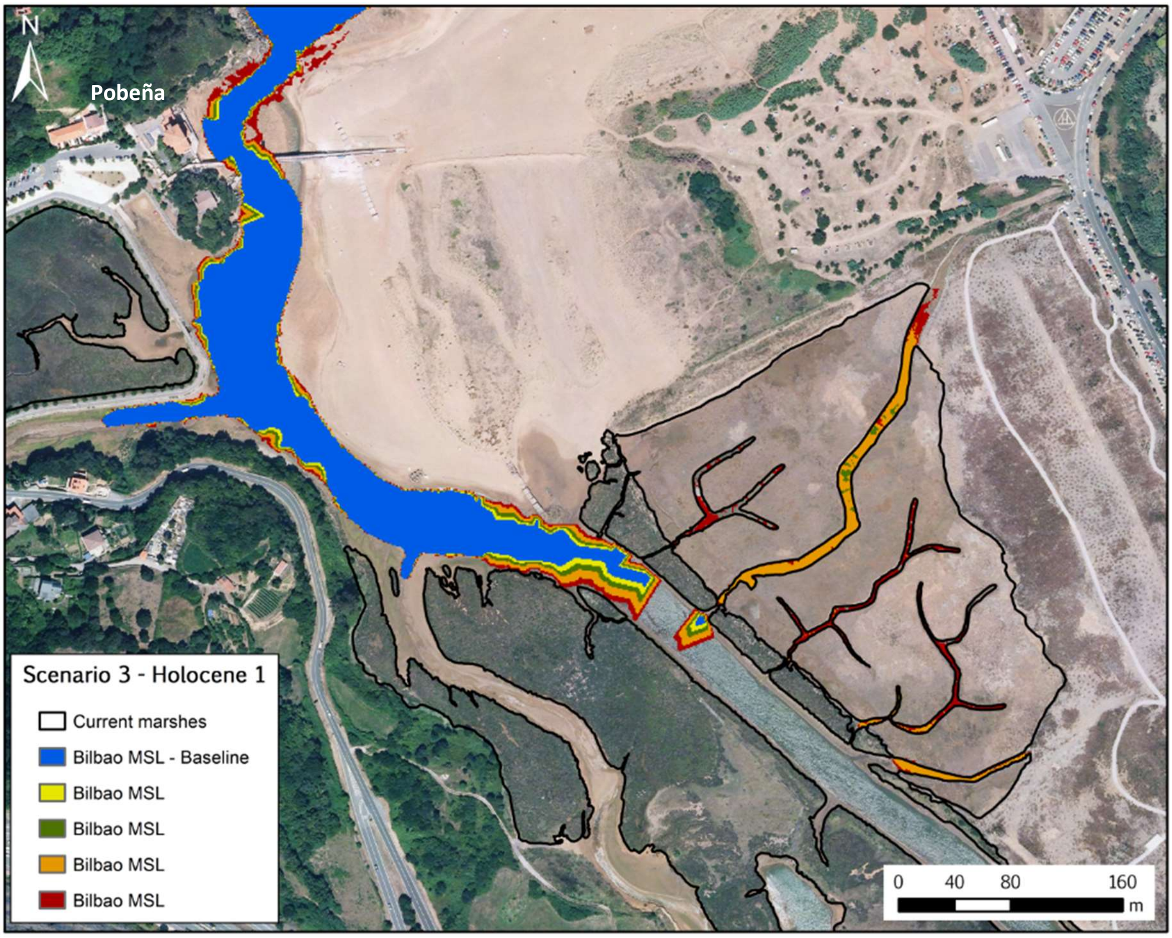
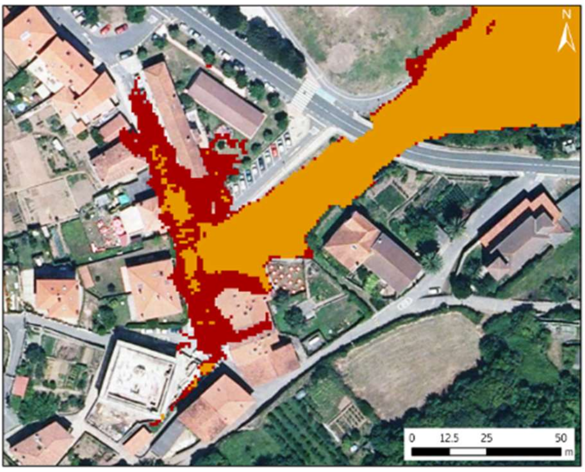


Figure 3.47. Sea-level rise in the Muskiz Estuary considering GBSLR Scenario 3 (Holocene 1) and Bilbao MSL.

However, temporal changes in MAHT level are significant under this third scenario. Although the estimated flooding would not be permanent, higher sea level implies a greater risk of erosion of the salt marshes during extreme events. In fact, the biggest (natural) impacts on coastal wetlands occur during extreme storm tides, when a storm surge adds to the MAHT (Scott et al., 2014).

Currently, when sea level reaches the MAHT level almost the total salt marsh area of the Muskiz Estuary (94%) is submerged. Apart from the La Arena beach and the salt marshes, no other area is



flooded (

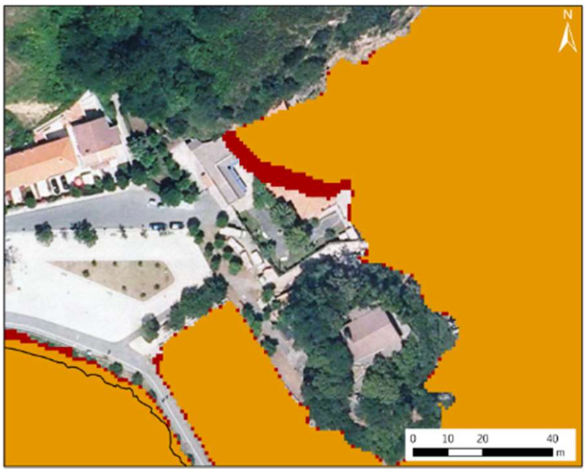


Figure 3.48, blue area). However, under Scenario 3 future MAHT goes beyond salt marshes and a small area of the Pobeña neighbourhood would get affected by the end of the century. Figures 3.48B and C show in detail the expected impacts on the Pobeña area by 2080 and 2100.

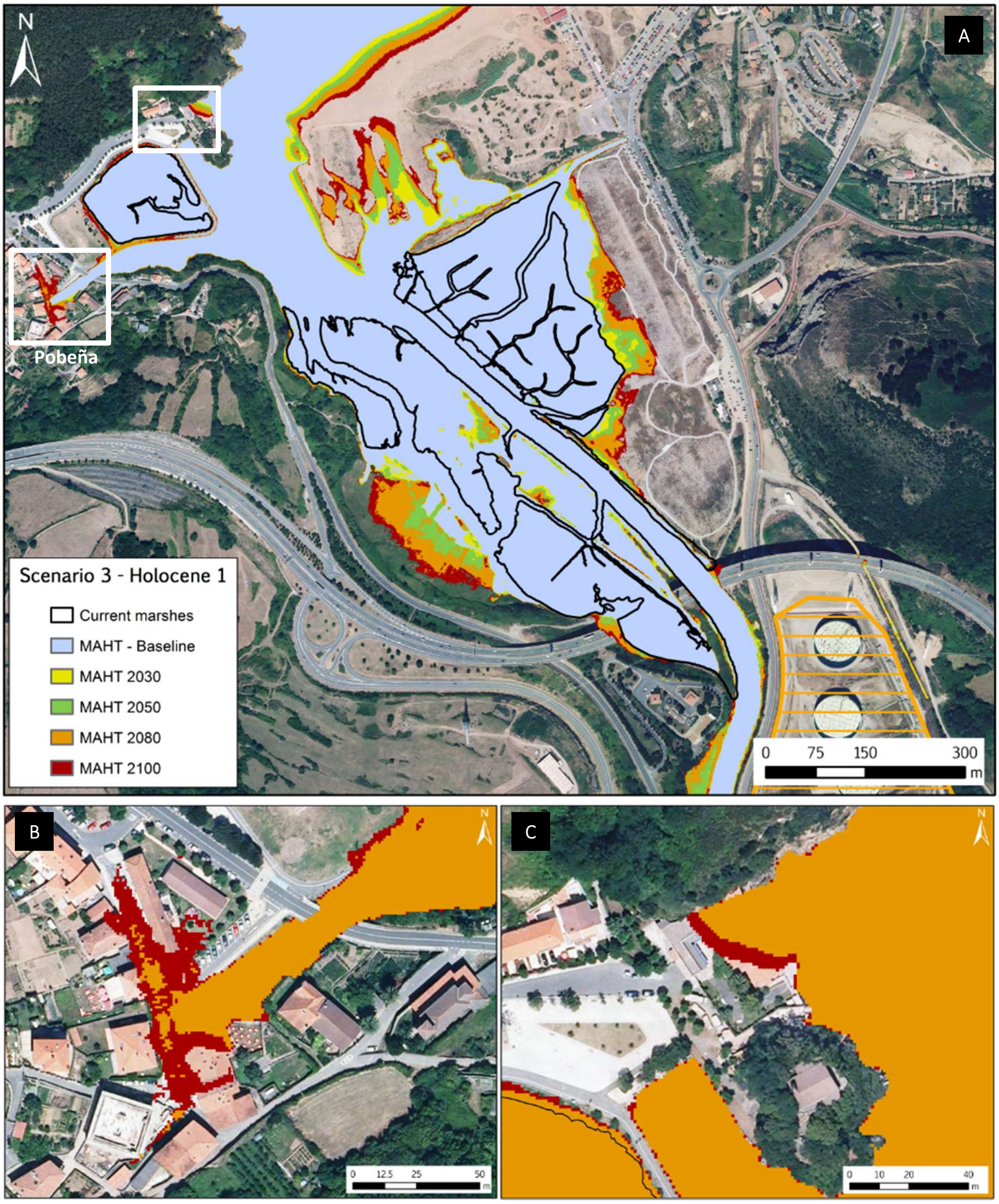


Figure 3.48. Temporal changes in MAHT sea level under GBSLR Scenario 3 in the salt marsh areas of the Muskiz Estuary (A). Maps B and C show the detail of the affected areas in Pobeña.

Results for the Petronor industrial area show that under this scenario the oil refinery would not get submerged (Figure 3.49). Some areas in the left bank of the river would get flooded (Figure 3.49A) but only a few grasslands and vegetation patches would be affected.

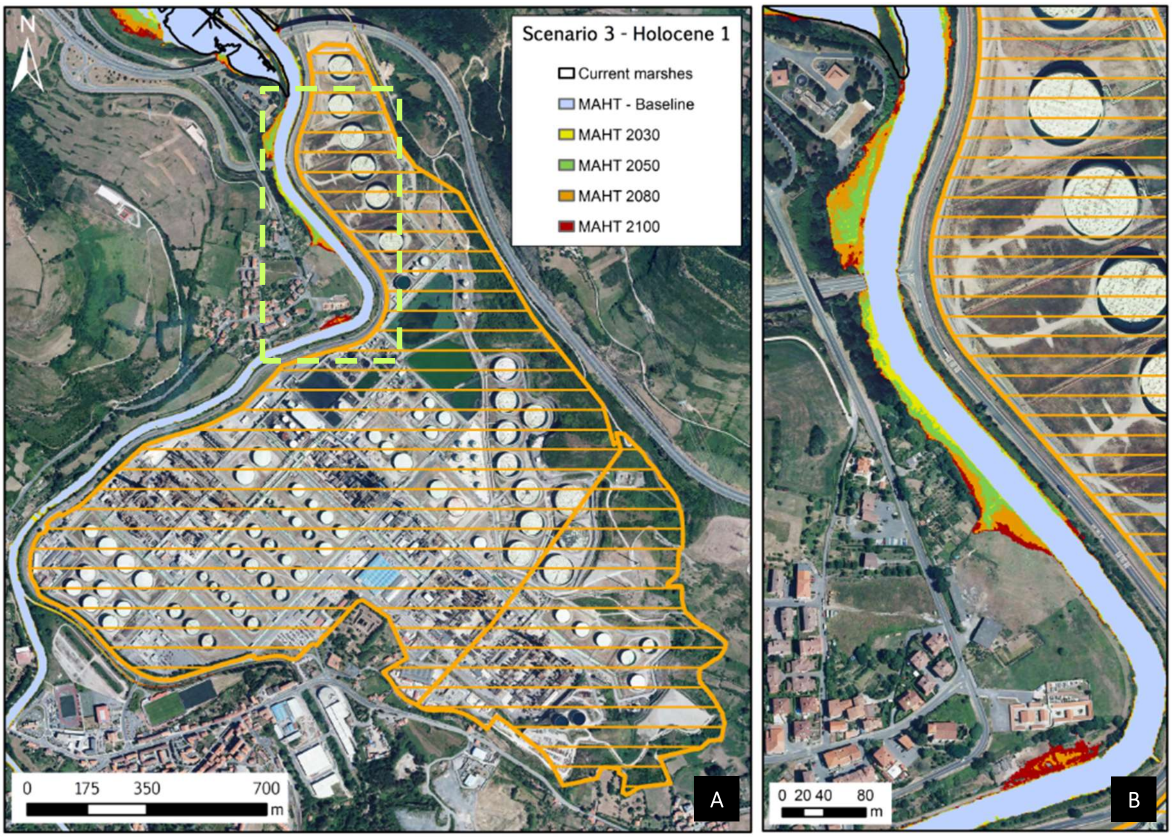


Figure 3.49. Temporal changes in MAHT level around the industrial area. A comprises the whole extent of the area and B shows the detail area in which MAHT level increases more.

GBSLR Scenario 4: LIG-MIS5e sea-level highstand (130-120 ky)

Sea level considered in this scenario is located at +6.901 m above current Bilbao ordnance datum, more than 2 m above the MAHT analysed in the previous scenarios. Figure 3.50 shows the areas affected by the rise in sea levels under this GBSLR Scenario 4. Two levels have been estimated:

- The new reference datum (new 0 m level) has been calculated by adding the LIG-MIS5e level highstand to the current Bilbao ordnance datum. The flooded area in this case is represented in dark-red colour in Figure 3.50. The industrial surface submerged accounts for 5.02 ha, out of a total area of 192 ha, approximately 3% of the current oil refinery area.
- The new mean sea level has been estimated by adding 2.4 m to the LIG-MIS5e 0 m reference. This is the current height difference between Bilbao ordnance datum and Bilbao MSL (Puertos del Estado, 2005). With this new level flooding would affect 87.8 ha, 46% of the oil refinery's total area.

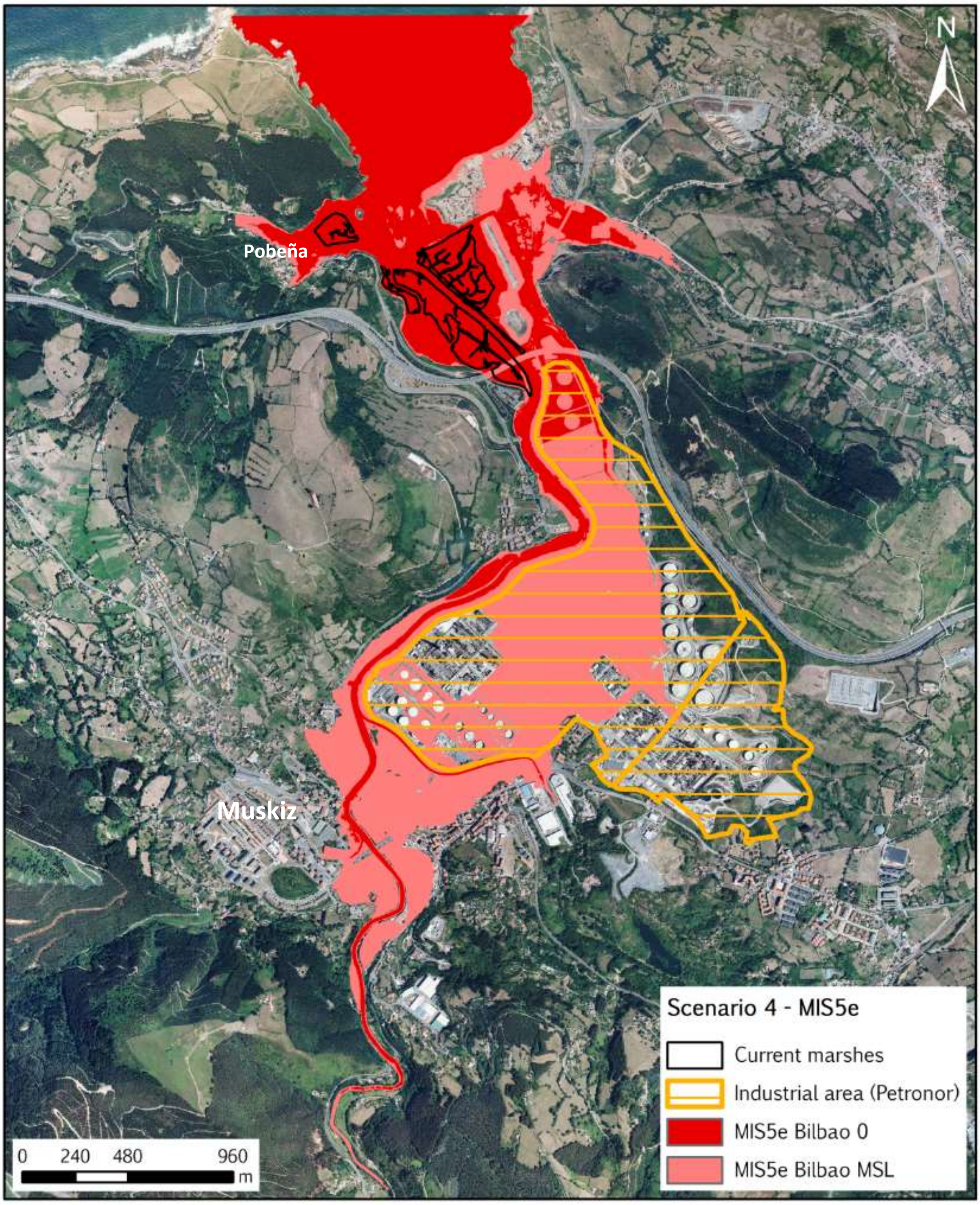


Figure 3.50. Flooded area in the Muskiz Estuary under GBSLR Scenario 4. The dark red area represents +6.901 m above present Bilbao ordnance datum. This would be the new “0 m level”. Taking this new ordnance level as a reference, the mean sea level would cover the light red shaded area.

Impacts due to this great rise in sea level are huge and would not only affect the industrial area. In the lower estuary, the urban area of the Pobeña neighbourhood would almost totally disappear under the estuarine waters and to the upper estuary, quite a big area of the Muskiz village would also get affected by permanent flooding. From an environmental perspective, existing salt marshes would also disappear as topography and human settlements leave no free space for their possible retreat.

3.4 Conclusions

This chapter presents the results of a geological approach to future changes in sea level. Two very distinct parts make up this chapter. The first focuses on the work carried out in the Oyambre outcrop, and the main conclusions can be summarised as follows:

- Based on the sedimentological analysis, two depositional environments can be identified in the Oyambre sequence: an ancient beach environment, formed by gravels and brown pebbly sands (beds 1 to 3), and an aeolian environment comprising by the rest of the succession.
- The dating process provided evidences of partial bleaching, with samples Ployambre 1 to 10 (corresponding to beds 2 to 5) and Ployambre 18 -19 (beds 9 and 10) showing equivalent doses in saturation.
- If only samples located in stratigraphic position that show lower contamination are selected, the probable depositional age of the sequence is ca. 116 ky to 108 ky for the basal beach environment and 102 ky to 89 ky for the upper aeolian deposits. Thus, the probable age of this coastal sequence corresponds to the Last Interglacial, MIS5e.
- The base of the boulder gravels represents the minimum relative palaeosea-level, located today at +6.901 m above Bilbao ordnance datum.

The second part of the chapter presents the flood risk maps built from the geological scenarios, integrating as well the accretion of salt marshes as a response to sea-level rise. The rate of sea-level rise was applied to current Bilbao MSL and to the MAHT level. The latter is used as an analogue of the potential impacts of coastal extreme events, such as storm surges. The main results for each of the case studies are described next:

- Urdaibai case study:
    - The additional flooding in Urdaibai under GBSLR Scenarios 1 and 2 for MSL and MAHT level is extremely small, with almost no new flooded areas.
    - The rise of MSL under GBSLR Scenario 3 would affect mainly intertidal zones and salt marshes. There would be a significant retreat of the Laidatxu beach, ranging from 6.08 m in 2030 to 70.3 m by the end of the century.
    - Temporal changes in MAHT level under GBSLR Scenario 3 would cause significant damages to several human infrastructures located on the left bank of the Oka Estuary. For example, the Murueta shipyard could experience flooding already by 2030. However, most of the impacts would occur by the end of the century, from 2080 onwards, in areas such as the Port of Bermeo, some neighbourhoods of the town of Busturia and the northernmost part of Gernika.
    - Impacts under GBSLR Scenario 4 would be dramatic, especially for Gernika. However, the time frame for this scenario is uncertain and in any case it is expected to go far beyond 2100.

- Plentzia case study:
    - No additional impacts would occur under GBSLR Scenarios 1 and 2.
    - Under GBSLR Scenario 3 changes in MSL would significantly affect salt marshes in the lower estuary by 2080, but no significant damages are expected on human infrastructures.
    - Also under GBSLR Scenario 3, salt marshes and especially human infrastructures would experience important impacts due to temporal changes of MAHT level. The southern part of the centre of Plentzia would suffer from flooding already by 2030, also a great area of the San Telmo neighbourhood in the left bank would by 2050, together with a few households in Txipio. Several roads and the metropolitan railway station would also be affected.
    - Under the long term scenario (GBSLR Scenario 4, LIG-MIS5e) salt marshes and a great part of the lower urban areas would be submerged.
- Muskiz case study:
    - No further impacts are measured for GBSLR Scenarios 1 and 2.
    - Under GBSLR Scenario 3 the rise of MSL does not translate into additional salt marsh flooding. No additional impacts on human systems is expected either.
    - Temporal changes in MAHT level under GBSLR Scenario 3 imply impacts on the Pobeña neighbourhood by 2080. The industrial area of the Petronor oil refinery would not experience any flooding.
    - Under the very long-term GBSLR Scenario 4 salt marhes, most of the Pobeña neighbourhood and a great part of the town of Muskiz would be submerged, as well as 46% of the oil refinery.

PART II.

Economics of climate change adaptation

4 Introduction to the economics of climate change adaptation[27]

So far, in Chapters 2 and 3, a geological approach has been presented to assess the impacts of climate change, more specifically, the consequences of sea-level rise. In this chapter we introduce a different approach that aims at complementing the methodology presented before from a socio-economic perspective. As shown in Chapter 3, climate change threatens not only natural, but also socioeconomic systems. To tackle this enormous challenge, a multidisciplinary approach may prove to be very valuable. In order to carry out this approach, firstly, it is necessary to understand and assess the biophysical effects that are already occurring, as well as those that will happen in the short, medium and long term. This is what in terms of the recent IPCC report on Impacts, Adaptation and Vulnerability (IPCC, 2014) is known as "*hazards*". Secondly, it is necessary to know the degree of vulnerability and exposure of both socioeconomic and natural systems. The sum of these features – hazards, vulnerability and exposure– allows us to determine the "risk" the different systems are facing. Precisely, the geological approach developed in Part I deals with *hazards*, through the definition of different scenarios of sea-level rise, while in Part B the focus will be on *vulnerability* and *exposure*, by identifying those natural and human systems most at risk and valuing the impact in monetary terms.

In order to do so, Chapter 4 reviews the economics of adaptation, including methodological challenges, sectorial approaches and cross-cutting issues. Of all the challenges addressed, Chapter 5 will focus on two issues, economic valuation and the adequate discount rate that should be used in this analysis.

This chapter is structured as follows: section 4.1 provides an introduction to economics of adaption. Section 4.2 summarises the main methodological issues of adaptation economics. Sectorial aspects are covered in section 4.3 and other dimensions of economics in section 4.4. Finally, section 4.5 presents some concluding remarks.

4.1 Introduction

We have argued that climate change is one of the greatest challenges that humanity has never faced, for several reasons, but especially the potential of major life changing and life threatening impacts that it creates and the fact that there is a great deal of uncertainty about the magnitude of these future impacts in different regions and across different ecosystems. The IPCC has clearly stated that there is sufficient scientific evidence regarding the unequivocal warming of the climate on all continents (IPCC, 2007b, 2014c). This change has been more intense during the last century and continues to speed up. The rises in sea level, the disappearance of ice, changes in precipitation and

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[27] This chapter is based on Sainz de Murieta et al., 2014. An introduction to the economics of adaptation to climate change, in: Markandya, A., Galarraga, I., Sainz de Murieta, E. (Eds.), Routledge Handbook of the Economics of Climate Change Adaptation, Routledge International Handbooks. Routledge, New York, pp. 3–26.

increased tropical cyclone activity seem to endorse this fact. The warming is affecting nearly all marine and terrestrial ecosystems, beginning with the Arctic and Antarctic areas and including tropical marine environments. Regional climate changes already affect (or will affect in the near future) nearly all human and natural systems.

While mitigation efforts have dominated the climate change policy debate for more than 20 years, it is more recently, since the beginning of the 21st century, that the United Nations Framework Convention on Climate Change (UNFCCC) has been trying to mainstream adaptation policies. Adaptation policies refer to those groups of instruments designed and implemented to prepare to the changes that are already occurring and will occur; as IPCC (2001: 881) states "adaptation is adjustment in ecological, social, or economic systems in response to current or expected climatic stimuli and their effects or impacts. This term refers to changes in processes, practices, or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in climate."

The growing importance of adaptation has been mainly due to: 1) the lack of satisfactory mitigation efforts and 2) the fact that even if mitigation policies were successful severe impacts will occur in the following century (Parry et al., 1998; Pielke et al., 2007).

It is with the Nairobi Work Programme (NWP) formally approved at the 12th Conference of the Parties (COP 12) held in Nairobi, Kenya, in 2006 that the international community acknowledged adaptation policy as a keystone of the effort to fight climate change. The NWP was agreed on to support all countries, especially developing countries, to: 1) improve their understanding and assessment of impacts, vulnerability and adaptation to climate change, and 2) decide on specific adaptation actions and measures taking as a basis the sound scientific, technical and socio-economic information (UNFCCC, 2007a). The constitution of the Adaptation Fund (AF) was another decisive issue on the adaptation agenda in Nairobi (Sterk et al., 2007), which aims at financing specific adaptation projects and programmes in developing countries that are Parties to the Kyoto Protocol. Following these efforts, it was not until 2010 at the Cancun Summit (COP 16) that the Cancun Accords stated that adaptation "must be addressed with the same priority as mitigation" (UNFCCC, 2011).

The fact that adaptation policies can follow a wide range of typologies, from hard adaptation engineering interventions to softer behavioural alternatives, makes the range of options available very wide. In the literature various classifications of adaptation policies can be found (e.g. Burton, 1993; Stakhiv, 1993; Carter et al., 1994; Smit et al., 1999, 2000; UKCIP, 2007; Agrawala and Fankhauser, 2008; Markandya and Galarraga, 2011; Tompkins and Eakin, 2012) based on different criteria, as shown in Table 4.1.

The growing policy interest in this area has triggered most of the efforts to understand the economic dimension of climate change adaptation, starting with systematic reviews of the existing evidence (Markandya and Watkiss, 2009; Parry et al., 2009; World Bank, 2010a), followed by methodological developments to support decision making efforts in adaptation planning. Estimating the economic impacts of climate change adaptation proves to be a starting point to assess the cost-effectiveness of different policies. We first need to understand the benefits of the measures -in terms of avoided costs- relative to the baseline and the impacts line, estimating later the cost of the policies aimed at identifying those with the highest net benefit.

Table 4.1. Different classifications for adaptation policies according to various criteria.

Classification of adaptation policy	Criteria	Examples
Private vs. public	Nature of agents involved	• Public adaptation takes place when there is an intervention from the government to support adaptation, e.g. Infrastructure building or land-planning. • Private adaptation occurs when the measures are implemented by individuals or private entities, e.g. Insurances for flooding (Tompkins and Eakin, 2012)
Localised vs. widespread	Spatial scope	• Local adaptation refers to those options or measures implemented at a local (or regional) scale, e.g. dike building. • Health National Plans dealing with climate related affections or early warning systems are examples of widespread adaptation.
Short- vs. long-term	Temporal scope	• Short-term adaptation measures are those urgent measures to avoid or moderate the effects of current climate change and variability, e.g. agricultural insurance. • Long-term adaptation deals reducing vulnerability and enhancing resilience to cope with impacts expected in the long-term, for instance, sea-level rise.
Infrastructural, behavioural, institutional, financial and informational	Type of measure	• Infrastructural measures involve climate resilient constructions and engineering options, such as sea-dikes. • Behavioural options are those focused on changing conducts or common practices, such as farming practices or methods. • Institutional responses to climate change include policy, planning or regulatory measures. • Financial options include measures like economic or fiscal incentives for adaptation. • Informational systems, such as early warning systems.
No regret, low regret and win-win	Ability to face uncertainty and/or to address other associated benefits	• No regret options are those measures which represent net benefits even in the absence of climate change; low regret measures are those having comparatively low costs and large benefits, e.g. improving efficiency on water irrigation. • Win-win measures, apart from contributing to adaptation, also provide other social, economic or environmental benefits. For example, improving air quality can contribute to both adaptation and mitigation strategies.

However, several problems arise in this conceptual setting, which have attracted the interest of many scholars and policy makers towards the economics of adaptation. Apart from the methodological issues explored later in this chapter, there are two important problems to be addressed. One is maladaptation, which can be defined as “action taken ostensibly to avoid or reduce vulnerability to climate change that impacts adversely on, or increases the vulnerability of other systems, sectors or social groups” (Barnett and O’Neill, 2010: 211). According to these authors, there could be five types of maladaptation options:

- Measures that increase emissions.
- Actions that affect most those at greater risk.
- Measures whose economic, environmental or social costs are high compared to other alternatives[28].

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[28] From an economic perspective, the term maladaptation is often use for those measures that have high costs in relation to other alternatives, as this definition points out clearly a misuse of resources (Markandya and Galarraga, 2011).

- Options that reduce the incentive to adapt, e.g. by encouraging unnecessary dependence on others.
- Actions that are neither flexible nor reversible but that set dependency paths, such as great infrastructures.

The second problem that arises when assessing the economics of adaptation is related to the adaptation deficit, which represents the lack of adaptive capacity to current climate variability, without considering climate change (Burton, 2004). It is, therefore, closely linked with development deficit[29] (Parry et al., 2009).

The diverse funds established to contribute to adaptation[30] are not directed to cover the costs associated to the adaptation deficit and only take into account the extra costs associated with climate change (Parry et al., 2009). However, authors like Burton (2004) consider that without a successful development to cope with the effects of current climate variability, it would not be possible to implement an effective adaptation to climate change. Hence mainstreaming climate change into development activities is a key imperative.

4.2 Methodological challenges

The economics of adaptation to climate change entails a number of methodological difficulties that have yet to be properly resolved. The problems involved are not new to economics, but the fact that many of them are present in the same discipline presents environmental economists and policy makers with a major challenge.

All these issues, although they are closely related, can be grouped according to Markandya and Watkiss (2009) under the following generic topic headings: (1) uncertainty, (2) fairness and (3) economic valuation. This is the general structure that will be followed in this sub-section (see Figure 4.1). Note that some issues fall under more than one topic heading: for instance, baseline scenarios affect both uncertainty and financial valuation; others, like ancillary benefits, limits of adaptation or public- *versus* private-sector adaptation affect both the equity and financial valuation. They will be addressed as cross cutting issues.

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[29] If *human development* is understood in a broad sense as all elements of a person well-being, from their “health status to their economic and political freedom” (Soubbotina, 2000: 7), the *development deficit* can be defined as the gap between the development goal and the current state of development.

[30] Least Developed Countries Fund (LCD Fund), the Special Climate Change Fund (SCCF) and the Adaptation Fund.

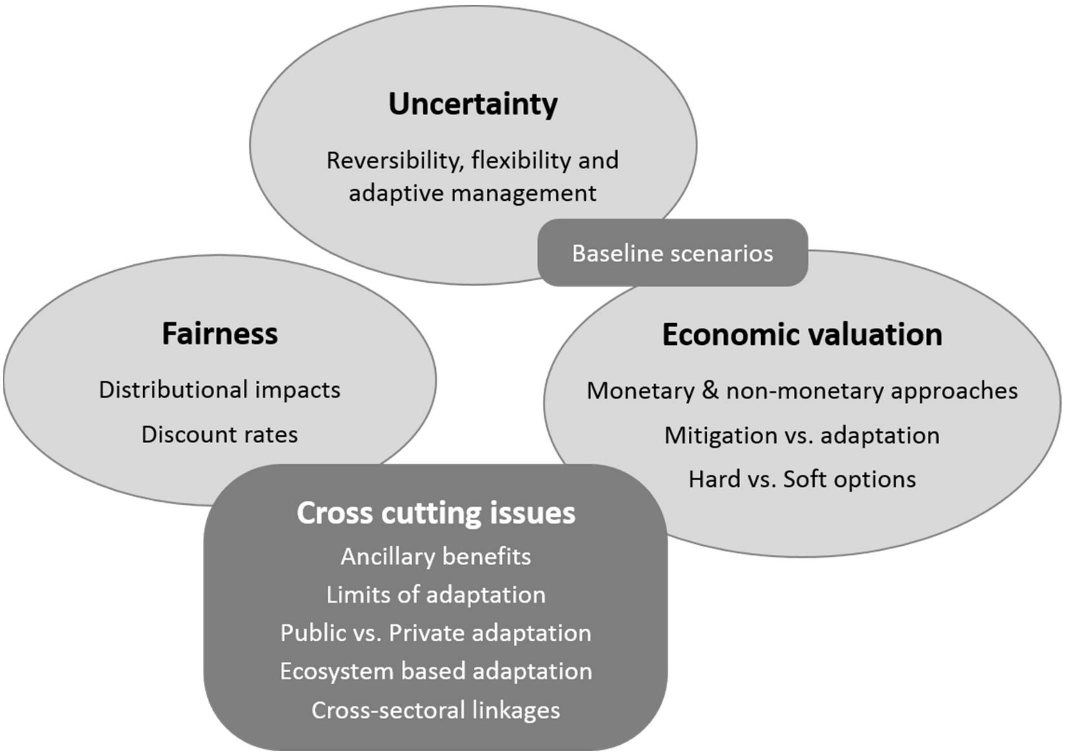

Figure 4.1. Principal methodological issues to be considered in economics of adaptation. Adapted from Markandya and Watkiss (2009).

4.2.1 Uncertainty

Uncertainty is one of the main problems when addressing climate change related issues. For contexts in which adaptation is considered in a wider scope, Markandya (2014) describes the "uncertainty cascade". According to this author, the first level of uncertainty is associated with emission scenarios and the second relates to climate projections which is linked to the socio-economic development associated to each emission scenario as well as to global and regional models. Improving the knowledge has not proven to be sufficient to face the uncertainty related to the first two levels. In fact, better knowledge does not necessarily translate into narrower projection ranges and authors such as Hallegatte (2009) suggest that uncertainty would not disappear even if general circulation models[31] to which emissions are inputs were perfectly accurate.

The third level of uncertainty is related to downscaling climate change projections. Certainly, most available climate models and observations often cannot offer what current decision-making frameworks need to devise adaptation policies, so statistical downscaling is needed to translate those projections into regional climate data and this operation adds additional uncertainty to the results. The fourth level of uncertainty refers to the way both natural and socio-economic systems will respond to climate change and the resulting impacts. Finally, cumulative uncertainties need to be considered as each step (input data, climate modelling, impacts and adaptation…) adds uncertainty to the previous one (Refsgaard et al., 2013).

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[31] General Circulation Models (GCMs) are climate models that "provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available" (IPCC, 2013a: 1450).

Uncertainty, therefore, represents a serious problem on both the local and global scales, and is a significant stumbling block in decision-making. In this context, advocating a preventive approach seems to suggest that especially unfavourable scenarios must be considered when deciding on what actions to take (Weitzman, 2007).

Nevertheless, there are several strategies that decision-makers should consider to deal with uncertainty. With the purpose of keeping as low as possible the cost of being wrong about future impacts of climate change, prioritising reversible and flexible policies when possible is a good strategy (Hallegatte, 2009). Reversibility refers to the possibility of going back to the situation that existed before a policy measure was implemented. The value of the reversibility of a strategy or measure is often known as option value, and this could be used as a tool when assessing the economics of adaptation. The option value refers to the value arising from delaying a decision. An example of this strategy can be the decision not to build a preventive infrastructure now but waiting until new or better information allows for a more efficient design of the infrastructure (Markandya, 2014). However, it will often be impossible to delay a decision indefinitely, so it might be useful to compare adaptation options with different degrees of reversibility (Hallegatte, 2009).

Flexibility allows for adjusting or adapting in the light of new available information, to cope with impacts more or less severe than predicted. If the situation changes progressively, it also allows to adapt incrementally (HMT, 2009). Increasing resilience is another way to deal with uncertainty by designing robust strategies or measures, able to cope with a wide range of future climate conditions. This is closely linked with adaptive management, which “involves an iterative process in which managers learn from experimental management actions. Management actions are applied as experiments, the system is monitored, and actions are then potentially modified to address changes in the state of the system” (Lawler, 2009: 85).

Low-regret measures, defined as those that involve net social and/or economic benefits irrespective of whether or not anthropogenic climate change occurs (IPCC, 2007c), represent another group of actions to incorporate uncertainty into decision making. Examples of such measures include developing a crop insurance scheme or improving water infrastructure. Another option to take uncertainty into account is defining win-win measures, which address climate change but deliver other benefits as well, such as improving air quality or building flood-proofing buildings (HMT, 2009).

Even if there are a variety of methods to take uncertainty into account, we should keep in mind that they will also lead to serious problems for analysis, planning and decision-making (Lempert and Schlesinger, 2000; HMT, 2009).

4.2.2 Fairness and equity

Climate change raises difficult issues of justice and equity, particularly with respect to the distribution of responsibility, burdens and benefits among poor and wealthy nations (Posner and Sunstein, 2009: 93). Distributional impacts at the international scale might be the most evident but it is not the only area in which justice and fairness have an important role. Inequalities within a society could be increased due to climate change and in the long run, consideration of equity between the current and future generations implies a great ethical challenge. This challenge must also be addressed and discount rates can play a major role on how future generations are taken into account.

Distributional impacts

In the past two decades, debates on climate justice have focused on mitigation, and especially the allocation of GHG emissions among countries, due to the urgency to take action to reduce anthropogenic climate change (Paavola and Adger, 2006). Since developed countries have been responsible for the largest share of historical and current global emissions, it seems unfair to require developing countries to have to undertake strong commitments to reduce global GHG emissions (Paavola and Adger, 2006). Additionally, developing countries will suffer the most severe climate change impacts and at the same time stabilizing GHG emissions will not be feasible without their participation. Finding the way for reducing global GHGs in an acceptable way for both developed and developing countries represents one of the biggest challenges of international climate negotiations (Markandya, 2010).

Recently, as the adaptation is gaining importance in climate change policy, fairness and equity related issues have also emerged justice aspects in decision-making on adaptation. For example, there is evidence that a fair global adaptation funding would have positive consequences for both developed and developing countries. This is due to the fact that improving fairness would contribute to building trust among those who feel unfairly treated (some developing countries). Then, this new confidence of developing countries in industrialized ones is expected to have a positive effect on international agreements on mitigation (Rübbelke, 2011). Paavola and Adger (2006) argue that there are four major justice dilemmas of adaptation which include: 1) determining the responsibility of developed countries for climate change impacts, 2) defining the assistance that these countries should grant the developing countries for adaptation, 3) distributing this assistance among the different vulnerable countries and adaptation measures, and 4) implementing procedures to ensure a fair adaptation policy.

Distributional impacts, however, do not exist just in an international context as the adverse effects and benefits of climate change will also affect differently within societies, at national and subnational levels. At the end it will be the poorest and most vulnerable groups and sectors of society who will suffer most from climate change (Thomas and Twyman, 2005). Some authors argue that, from the point of view of equity and justice, the actual adaptation deficit should also be addressed (Adger et al., 2005). In other words, adaptation should reduce existing inequalities and poverty and improve income distribution as a lower vulnerability today will also result in less vulnerability to climate change in the future. Obviously, not all impacts can be avoided, for technical, economic or social reasons. These impacts that will not be avoided are known as “residual damages” and addressing them will be a key issue as they could represent up to two-thirds of all potential impacts in the long term (Parry et al., 2009).

Distributional impacts, therefore, call for the utmost rigour and precision in analysis if they are to be taken into account properly.

Discount rates

In the long term, considerations involving inter-generational equity and safeguarding the rights of future generations are key factors. In particular, discount rates play a key role with respect to both equity and efficiency (Munasinghe, 2000), as they represent the extent to which today's society values costs and benefits to future generations. Zeckhauser and Viscusi (2008) edited a comprehensive special issue entirely devoted to this topic that can be consulted for more information.

Given the length of the periods involved in the climate change context (between 100 and 200 years), the use of discount rates equivalent to those on the market is a critical issue. Some authors suggest rates of around 6% (Nordhaus, 1994), while others opt in favour of rates below 2%, or even close to zero (Cline, 1992; Stern, 2007). However, the use of such low discount rates was one of the main criticisms to the Stern report (Nordhaus, 2007). Other authors, like Weitzman (2001) and Evans et al. (2004), instead, suggest using decreasing rates as impacts become more long-term. In fact it seems that during the last decade a consensus has been reached on social discount rate, which should decline with the longer time horizon (Gollier, 2012). Another approach is presented by Chiabai et al. (2013), who propose a simple rule to estimate different discount rates for different kinds of natural assets in the long term, as many ecosystems will most probably be scarcer in the future. Both Gollier (2012) and Groom (2014) provide further details about discounting in a climate change context.

The valuation of adaptation options, by their nature, will be very much affected by discounting. For instance, if we look at flood prevention, adaptation measures will require strong short-term investments, while the benefits will most probably be received in the mid- or long-term. Also, it is well known that climate change will affect developing countries (and therefore, the global poor) the most so already existing inequalities will be exacerbated, unless adaptation policies counteract this effect. It is clear that discounting opens a whole new field of discussion on ethical issues involving intra-generational and international equity, depending on the considered values or methodologies: the lower the rate used, the higher the valuation of future generations and the greater the present value of expected future benefits from reduced impacts as a result of adaptation measures.

4.2.3 Economic valuation and efficiency

From an economic perspective, adaptation is normally evaluated by determining whether and by how much the benefits of such measures exceed the costs incurred (Agrawala and Fankhauser, 2008). Such an approach is referred to as a Cost-Benefit Analysis (CBA) and essentially involves calculating in monetary terms all of the costs and benefits. An adaptation option would represent a good investment if the aggregate benefits exceed the aggregate costs (Markandya and Watkiss, 2009).

Although CBA is important when designing economic policy, other criteria are also considered when making a decision. This is because CBA, in its simple form, does not cover all aspects: it ignores the distribution of the costs and benefits of adaptation options and it fails to account for those costs and benefits that cannot be reflected in monetary terms, such as some ecological impacts and impacts on health, as well as concerns of welfare, peace and security. Other approaches are often used as a complement or a substitute of CBA. These include, for example, cost-effectiveness analysis and multi-criteria analysis (MCA) (Galarraga et al., 2011c).

Monetary and non-monetary valuations

Valuation of the economic benefits of adaptation has focused on estimating avoided damages in monetary terms. However, not all impacts can be approximated through monetary methods. This is particularly the case for non-market goods and services. In view of this, it has been argued that adaptation decisions should use other metrics or combine a measure of net benefits with an estimate of impacts in physical terms.

This being so, the mixture of monetary and non-monetary values is often necessary, but it greatly complicates the analysis, which is also limited by issues such as the availability of (partial) information and the distribution of impacts. Other methods like cost effectiveness, the risk approach and MCA should also be considered in order to incorporate qualitative information (Barbier et al., 1990).

Interrelationships between mitigation and adaptation

The relationship between adaptation and mitigation is complex and highly important, and it needs to be taken into consideration. In fact, the IPCC addressed this issue on its 2007 report (AR4) where a chapter on the interrelationship between the two forms of climate action was included (Klein et al., 2007). Assessing the links between adaptation and mitigation was an important step forward of AR4.

As previously stated, due to the long history of past emissions and the inertia of the climate system, it will not be possible to completely avoid the effects of climate change even with the effective implementation of the most ambitious mitigation policies (Parry et al., 1998). Adaptation is, thus, not only necessary but unavoidable. However, if there is no progress in mitigation the amount of climate change that is likely to happen will make adaptation impossible or extremely costly for some natural and human systems (Klein et al., 2007; Stern, 2007). Therefore, an effective climate policy should include a portfolio of both adaptation and mitigation options.

Adaptation and mitigation policies work at different spatial (local or regional *versus* international), time and institutional scales, hence it will not be always possible to develop synergies among them. In some cases adaptation and mitigation might represent a trade-off when designing the climate policy and distributing climate funds (Abadie et al., 2013) whereas in other situations synergies might exist. Opportunities for such synergies are present in some sectors (agriculture and forests, urban infrastructure), while in others the options are more limited (coastal, energy) (Klein et al., 2007). For example, Aaheim and Garcia (2014) analyse the inter-relationships between adaptation and mitigation to see the extent at which REDD+ programs can actually represent a successful option for both kinds of climate change policies.

Hard *versus* soft adaptation measures

Hard measures involve the construction of infrastructures and protective barriers, while soft measures are associated with changes in the behaviour and habits of socio-economic agents. According to Markandya and Watkiss (2009) there has been a tendency to focus on hard engineering options as they are easier to cost than behavioural or policy measures, but soft measures need to be given greater consideration. In fact, this preference towards structural measures may create a distortion adversely affecting potentially critical soft measures needed to enable adaptation (such as better land-use planning, early warning systems or insurance schemes) and lead to inappropriate and expensive adaptation measures. It could also result in overestimation of adaptation costs (Agrawala and Fankhauser, 2008). Nevertheless, the classification hard / soft does not necessarily imply that hard options are technology-based while soft options are not. In fact, there are many examples of green infrastructure (e.g. wetland restoration or landslide prevention by tree planting) that can be considered soft and at the same time have an important innovative and technological component (Markandya and Galarraga, 2011).

An important aspect of this discussion is that soft adaptation options are easier to reverse, which makes them more suitable to deal with a highly uncertain future (Hallegatte, 2009).

4.2.4 Cross-cutting issues

Baseline scenarios

One of the most difficult aspects when analysing the economics of adaptation to climate change is the definition of the baseline scenario. Ideally, the baseline represents what would happen to the fundamental variables in the absence of climate change. But a future baseline scenario with no climate change is not as simple as looking at historic trends. Instead, it is a complex reconstruction of changes in population, economy, development, behaviour patterns and a number of other factors that are highly uncertain and even more in the long term (Markandya and Galarraga, 2011: 32). Baseline scenarios are, therefore, inexorably associated with high levels of uncertainty (Markandya and Watkiss, 2009). The HTM Green Book (2007) proposes several methodologies to deal with baseline-related uncertainty: probability distribution, and when these are not available, sensitivity analysis, the consideration of scenarios for baselines and, sometimes, the use of Monte Carlo Analysis as well (Markandya, 2014).

Ancillary benefits

Ancillary benefits, sometime also known as co-benefits are “the positive effect that a policy or measure aimed at one objective might have on other objectives, irrespective of the global effect on global welfare” (IPCC, 2014d). That is, adaptation to climate change often has benefits apart from lessening the impacts of climate change. For instance, many adaptation measures contribute to reducing actual vulnerability with respect to current climate variability or extreme events. Other examples include environmental regeneration of ecosystems, improvements in air quality, the positive impact on health of changes in transportation and life habits, etc. These benefits which accrue as a positive side effect of adaptation measures and were not among the main objects of those measures are known as ancillary or secondary benefits (EEA, 2007).

According to some authors (for example, Van Ierland et al., 2007) a distinction should be made between no regret options and ancillary benefits. No regret options are those adaptation measures for which non-climate related benefits arise in such a way that the implementation of those measures would be beneficial irrespective of future climate change taking place. Ancillary benefits on the other hand are co-benefits associated with another primary policy and may or may not be enough to justify the measures on their own.

Some ancillary benefits may result difficult to assess in monetary terms, improved health or increased ecosystem resilience, for example. Some attempts to estimate these ancillary benefits exist and, besides the difficulties, this issue should not be left aside when assessing costs and benefits of adaptation.

As future climate change will affect particularly the more disadvantaged and vulnerable groups of society, the distribution of ancillary benefits should also be taken into account in the analysis (Markandya and Watkiss, 2009).

The limits of adaptation

The limits of adaptation and the need to reduce the exposure of ecosystems to impacts and increase their resilience must also be taken into account. There is an incipient body of literature concerned with the definition of this concept, which is open to important nuances depending on what systems are being analysed. In fact, we can analyse the limits of adaptation from two different perspectives: the *exogenous* or analytical approach, which primarily examines the objective limits of adaptation, including ecological or biophysical limits, economic limits and technological limits. Most studies conducted so far focus on this approach. In contrast, Adger et al. (2009: 338) propose an *endogenous* approach that “emerges from inside society”. Considering how societies are organized, social limits of adaptation “depend on the goals, values, risk and social choice”, and therefore are “mutable, subjective and socially constructed”. Likewise, Dow et al. (2013) propose an actor-centred and risk-based (*endogenous*) approach for defining limits to social adaptation (Markandya and Galarraga, 2011).

Other references that need to be considered on this issue include the papers of Holling (1973), which first defined the concept of resilience in environmental terms, Perrings (1998), which redefined the concept, and Walker et al. (2010) which provides an example of operationalizing resilience in the Australian context.

Public *versus* private sector adaptation

Adapting to climate change may involve different levels of society, from individuals, firms and civil society, to public institutions and governments at local, regional, national and international scales (Adger et al., 2005). Even if many studies focus on public adaptation, both public and private adaptation need to be considered (Markandya and Watkiss, 2009).

Sectors such as engineering or construction most likely will have to adapt, at least to some extent, their building methods and they will most certainly contribute to climate-proofing existing infrastructure as well. Insurance policies are another important form of private-sector adaptation. Telecommunication companies, media and new technologies can play an important role in relation to the monitoring and communication of hazards, while companies of the primary sector should also consider how to adapt to new climate conditions to ensure food security and the financial sector could also play a main role, for instance, in relation to the financing of adaptation measures. These are just a few examples that show the key role that the private sector could have regarding adaptation (Agrawala and Fankhauser, 2008).

In some cases public-sector adaptation can be considered as a disincentive to private adaptation, particularly to autonomous (or unplanned) adaptation, so there is clearly a need for coordination between the public and private sectors (Markandya and Watkiss, 2009). Clearly, public policies have an important responsibility in providing adaptation as a public good where private activities might not occur due to externalities or other failures. At the same time, there are many cases where the effectiveness of adaptation could be improved if public and private sectors would act jointly. This public-private partnership can be implemented through concessions (which is a long-term contract) but also full divesture, where the private agent takes possession of the assets (Agrawala and Fankhauser, 2008). For example in Spain, concessions are very common for sectors such as energy (e.g. hydro-energy), transport (e.g. highways), or water resources (e.g. for agriculture). Full divesture has been used in the case of the energy distribution network.

The role of economic modelling

As already said before, the study of climate change has some features that make it particularly challenging as we have already noted. First, there is still great uncertainty regarding the future impacts at global, regional and local levels; second, the impacts, although some of them are already visible today, will have very long term consequences, to 2050, 2100 and beyond; finally, the impacts will not be evenly distributed, neither among countries nor between different social groups (Galarraga and Markandya, 2009). All these make the analysis and modelling effort particularly difficult.

Despite this, it is possible to estimate important features of the social dimension of climate change through integrated assessment models (IAMs) that combine economic, environmental and climate information at different scales.

Among the top-down integrated assessment approach, there are three major types of models used in the economic analysis of climate change: Computable general equilibrium models (CGEMs), that offer an explicit representation of domestic and international trade; dynamic growth models, which have been used primarily in the context of energy and emissions reduction policies; and macroeconomic models that assess the relationship between different variables from past observations (time series) rather than economic theory. Top-down IAMs have been traditionally used in mitigation policies.

Bottom-up models, also known as engineering or partial equilibrium models, have been usually applied to estimate the cost of mitigation policy, but research on the costs and benefits of adaptation has been also conducted through bottom-up studies due to its predominantly local/regional nature. However, the growing interest to assess the economic impacts of both mitigation and adaptation policies has resulted in a very recent, but growing body of literature that addressed these issues through macroeconomic approaches (Agrawala et al., 2011).

Ecosystem-based adaptation

Ecosystem-based adaptation (EbA) considers the use of biodiversity and ecosystem services[32] as an instrument to help human communities adapt to the adverse impacts of climate change. Ecosystem-based approaches include activities of sustainable management, conservation and restoration of ecosystems (Colls et al., 2009).

So far, most adaptation initiatives have focused (as noted) on the use of "hard" adaptation options but the role of EbA as a complement -and sometimes substitute- of infrastructure investments is being increasingly recognized (Colls et al., 2009; McKinnon and Hickey, 2010). EbA contributes to reduce vulnerability to climate impacts across several human sectors, including disaster risk reduction (e.g. salt marsh ecosystems provide coastal protection against storm surge-events, coastal erosion and sea-level rise), livelihood diversification and food security (ensuring access to natural resources) and sustainable water management (flood protection, improving water quality) (Colls et al., 2009; Jones et al., 2012). EbA often represents a more cost effective alternative than hard adaptation initiatives (Ojea, 2015). According to Moberg and Rönnbäck (2003), the value of coastal protection from erosion provided by reefs can reach 1 million US dollars/km of coastline over a 25 year period in areas with major infrastructure, while artificial ways of coastal protection can cost from 246,000 up to 5 million US dollars/km.

Ecosystem-based approaches have additional advantages over hard initiatives: first, there are multiple ancillary benefits or co-benefits they can deliver, such as carbon storage, biodiversity conservation or sustainable economic development (Munang et al., 2013). On the contrary, few hard interventions provide extra benefits beyond the adaptation option for which they were designed; furthermore, sometimes they can even generate negative impacts on surrounding natural and human systems. Second, while hard adaptation measures are usually permanent, EbA approaches are potentially more flexible and have no-regret character (Jones et al., 2012). Consider, for instance, estuarine wetlands that can migrate upwards and inland as sea level rises (assuming that there is available land for migration) (Cearreta et al., 2013). Third, EbA adaptation initiatives can create synergies with other adaptation initiatives, development goals and mitigation strategies (Munang et al., 2013).

EbA, however, also faces a range of barriers -such as insufficient finance, land use conflict or community opposition- and limitations related to the degree of future climate change and the ecological limits of nature (Colls et al., 2009). Mainstreaming EbA as a basic approach to climate change adaptation and decision making therefore still remains a challenge (Munang et al., 2013).

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[32] *Ecosystem services* are “the benefits people obtain from ecosystems” (MEA, 2005).

4.3 Sectorial approach to the economics of adaptation

Existing studies regarding the economics of adaptation can be classified into two main groups: first, global aggregated assessments that are relatively abstract and include some simplifying assumptions that are difficult to apply when devising adaptation policies at smaller scales; second, more disaggregated sectorial and project level studies that provide much more detailed and accurate spatial (regional, national, local) and sectorial scales (Galarraga et al., 2011c). According to Agrawala and Fankhauser (2008), sectorial level studies should be the base upon which higher order assessments are carried out.

From an economic perspective, there is a large amount of information available at the sectorial level especially in relation to the costs and benefits of adaptation. However, it is also true that this information is unevenly distributed across sectors (Agrawala and Fankhauser, 2008), as discussed below. In this section we offer an overview of the economics of adaptation for each of the main sectors involved in climate change adaptation.

4.3.1 Energy

The energy sector is one of the main contributors to GHG emissions with 64% of global emissions related to human activities (Emberson et al., 2012) and, therefore, to climate change. Hence most of the studies related to it have focused so far on mitigation (Ansuategi, 2014). However, this sector is not only a contributor to climate change but also highly vulnerable to its impacts for several reasons (Ebinger and Vergara, 2011). First, climate change can potentially affect energy availability. This will be especially relevant in cases such as hydropower or biofuels. The results from a recent study on the hydropower sector in Costa Rica showed a significant reduction in the hydropower production, estimated between 5% and 12%, by 2100 in all IPCC scenarios considered (A2, A1B, B1) (Sainz de Murieta et al., 2015). The potential impact on other renewable sources –wind, solar, waves…- will be site dependant. Obviously, fossil fuels will not be directly affected, although exploration and access to them could also be affected, for instance, by the strike of extreme events. Second, climate change and especially extreme events, may also affect energy supply systems, both at energy production sites or disruption of transmission infrastructures (for further details on extreme events see IPCC (2012a) and Mitchell et al. (2014). Last, consumption patterns may also be altered by climate change. Isaac and van Vuurem (2009) estimated a global reduction of 34% in the demand for heating under climate change by the end of the century, while the demand for cooling would increase by 72%.

All these impacts could lead to major economic impacts worldwide. In the USA, energy costs could increase due to climate change up to 140.7 billion US dollars by 2100 in a business-as-usual scenario (Ackerman and Stanton, 2008). Thus, as well as in mitigation, it is clearly a priority to include the energy sector in the context of adaptation policies to climate change more than it has been so far, and further research should also be carried out to fill in the gaps of knowledge regarding this important issue.

4.3.2 Agriculture

There is a lot of literature analysing the economic benefits of adaptation in the agricultural sector (Agrawala and Fankhauser, 2008). The impacts of climate change include a mixture of positive and negative impacts depending on where the agricultural zone is, the crop analysed and the planting techniques. Generally speaking, climate change may lead to increases in yields at mid- and high latitudes and to decreases in tropics and sub-tropics, although many exceptions exist, particularly where expected increases in monsoon intensity will raise precipitation. Particularly in South Asia and Africa the risk of hunger appears to increase as a result of climate change depending, of course, on the number of vulnerable people in these regions among many other factors. Studies such as Parry et al. (2005, 2009) are some good research papers on the topic.

There is still quite a lot of uncertainty related, for instance, to the beneficial effects of CO_2 on crop growth but there is evidence that high temperatures will limit future crop productivity (Bruckner et al., 2014; Gallejones, 2014). Anyhow, adaptation strategies will be very site specific but can include changing planting seasons, and/or crops, new infrastructure such as irrigation systems, improved insurance system or other type of support for farmers. Markandya and Watkiss (2009) state that, "in practice support to farmers will be strongly driven by a combination of cost benefit analysis and the needs of providing sustainable livelihoods to poor farmers – i.e. distributional considerations will be very important".

4.3.3 Health

From infectious diseases to malnutrition and disaster-related injuries, climate change will influence human health in several ways; most of them adverse, even if few would be beneficial, e.g. reduced seasonal mortality in high latitude developed countries due to more benign winters (IPCC, 2007b). The climate-health connection associated with thermal stress, extreme weather events, physical hazards and some infectious diseases are the easiest to analyse. This is the reason why most of the research produced so far has given preferential attention to these issues, together with future regional food yields and hunger prevalence. However, there is an emerging approach that considers health risks in a broader way, including those related to social, demographic and economic impacts of climate change (McMichael et al., 2006: 859-860).

According to the IPCC (Confalonieri et al., 2007), health impacts will be greater in low-income countries, but the more vulnerable social groups in developed countries will also be affected (e.g. the elderly and children, the urban poor, etc.). Hence, adaptive capacity needs to be addressed globally; impacts of recent hurricanes (Katrina, Sandy) and heatwaves (e.g. the 2003 heatwave in Europe) show that even high income countries are already in need to improve their response to extreme events (Confalonieri et al., 2007: 393).

Several approaches can be used to prioritize goals in health adaptation and identify the most appropriate set of measures, the most popular being the cost-effectiveness analysis (CEA), cost-benefit analysis (CBA), and the multi-criteria analysis (MCA) (Chiabai and Spadaro, 2014). Current estimates of the costs of adaptation in the health sector vary greatly depending on the methodology, the available information, the health issues assessed, as well as the world regions under analysis. For instance, a study by the UNFCCC (2007b) estimated that health adaptation costs would range from 4-12 billion US dollars per year in 2030. However, even if the study was based in the best available information for developing countries it clearly underestimates the total health costs, as not all countries, activities nor diseases were included in its scope (Parry et al., 2009).

4.3.4 Coastal areas

There are many impacts related to climate change in coastal areas where most of the population worldwide live. The main driver of these impacts is sea-level rise and an increase in the intensity and frequency of extreme events, including storms. There are a number of potential effects, which complicates comparison as Nicholls et al. (2006) show.

The impacts are largely in terms of loss of the services of land and several estimates of loss of services under climate change have been made (see Hinkel and Klein (2009) for the methodology; Hinkel et al. (2010) for Europe; Markandya and Mishra (2011) for India; Galarraga et al. (2011c) for a local case study in the Basque Country). Sea-level rise and coastal damage is perhaps one of the better quantified areas of impact, including studies dealing with costs and benefits on adaptation, as shown in the review by Agrawala and Fankhauser (2008). However, Losada and Diaz-Simal (2014) argue that most of these analyses do not consider regional relative sea-level rise. Of course, adaptation measures can reduce the losses associated with sea-level rise. The net benefits are then measured in terms of the cost per hectare of the adaptation measures relative to the avoided losses per hectare as a result of these measures.

There are also distributional impacts in poor countries where sea-level rise can affect livelihoods of poor people. Here decisions may need to compare alternative livelihoods.

But sea-level rise is not the only climate associated impact on coastal zones (IPCC, 2014b). Other important issues exist such as extreme sea events, seawater intrusion, storm surges, coastal erosion or increasing sea temperature among others. How to incorporate all these potential impacts into decision making in order to design effective adaptation policies remains a challenge.

4.3.5 Flood risk

The frequency and intensity of river floods is inevitably linked to rainfall. In the context of climate change the amount and distribution of precipitation is expected to influence the frequency and severity of floods. In fact, more intense precipitation events have already been observed and this trend is expected to continue in the future (Milly et al., 2002). Note that, even if projections point to a reduction in total rainfall, increases in extreme precipitation may occur which will raise the risk of river flooding (Kundzewicz and Schellnhuber, 2004).

Yet, climate is not the only factor that can exacerbate flood risk: land-use planning, the existence – or not– of early warning systems, the overvaluation of structural defences (such as dikes and channellings) are examples of other type of factors that could intensify flood hazards (Kundzewicz and Schellnhuber, 2004). However, adaptation can contribute to reduce most of the climate change-induced increases in river flooding risks at relatively low costs. A case study from the Netherlands (EEA, 2007) show that optimal flood defence investments could reduce climate-induced flood damage from 39.9 billion to 1.1 billion euros over the 21th century at a relatively modest cost of around 1.5 billion euros. This case study is also especially interesting as it represents an example of a new policy approach to flood risk management: spatial solutions are identified with the objective to create “room for the river”, together with more traditional technical measures. Another interesting example of adaptation to flood hazards is the TE2100 Plan[33] that “sets out the strategic direction for managing flood risk in the Thames estuary to the end of the century and beyond”. It includes real options analysis, which allows to consider uncertainty and flexibility in the analysis (Galarraga et al., 2011c).

4.3.6 Economic impacts and inter-sectorial relationships

As already mentioned, sectorial assessments have the advantage of providing detailed information about the economic impacts of climate change, but they have a more limited scope when assessing national or global adaptation policies. Indirect and induced impacts must not be forgotten, and nor must the usefulness of general equilibrium models that take into account relationships between different sectors of activity. Multi-sectorial estimates have been carried out in three fronts: (1) at the national level, especially among least developed countries (LDC) as part of the National Adaptation Programmes of Action (NAPAs); (2) at the regional level through projects like PESETA[34], that assesses the impacts of climate change across several sectors in Europe; and (3) at the global level, where international agencies, such as UNFCCC, World Bank, UNDP or Oxfam, have valued the global costs of adaptation (Agrawala and Fankhauser, 2008).

Perry and Ciscar (2014) review several studies based on multi-sectorial, bottom-up and top-down approaches to understand the influence of climate change in the economy and how adaptation could minimise its impacts. They conclude that bottom-up approaches add more value as they provide greater detail and also include the interactions between some physical and economic variables. However, and for this same reason, bottom-up studies require much more input information and further research is needed so as to be able to cover the scope of current top-down approaches.

4.4 Other dimensions of adaptation

4.4.1 International cooperation

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[33] Available at: http://www.environment-agency.gov.uk/homeandleisure/floods/125045.aspx

[34] PESETA is a project coordinated by the European Commission Joint Research Centre (JRC). More information available at: http://peseta.jrc.ec.europa.eu/

As it has been already noted, the early work on climate change has focused on mitigation; adaptation started to receive some attention mostly after COP16 in Kenya in 2006 and the publication of IPCC's AR4 where adaptation was recognised as meriting the same level of attention as mitigation (Mertz et al., 2009). Unlike mitigation, that requires global cooperation, adaptation has a strong local component and this is one of the reasons to explain why it has also been virtually absent in international negotiations.

However, an efficient and fair adaptation policy may need a certain level of international cooperation (Pickering and Rübbelke, 2014). This is especially true considering that low- and middle-income countries that contributed less to GHG emissions will suffer the most severe impacts from climate change; at the same time, most of these countries also have great difficulties to obtain the necessary resources for adapting to climate change. Additionally, international cooperation on adaptation may also have positive side effects, contributing to a climate of trust among developing countries with respect to developed countries, which in turn could contribute to global mitigation efforts. And the other way around: developing countries have asked for adaptation reinforcement as a previous requirement for getting involved in a global compromise for emissions reduction. Therefore, a lack of clear international support for adaptation could also obstruct an international agreement on mitigation (Rübbelke, 2011; Pickering and Rübbelke, 2014).

4.4.2 Fast growing countries and adaptation

The term Fast Growing Countries (FGC), although there is no universally accepted definition, refers to those nation states with particularly good performance in terms of economic growth. According to Virmani (2012: 5), "most studies of fast growing economies use 5% average growth in per capita Gross Domestic Product (GDP) to identify fast growing economies", but the author proposes an alternative definition by which FGC would include those "countries that had an average growth rate of per capita GDP of 7 per cent or more, for a continuous period of 10 years or more". BASIC (Brasil, South Africa, India, China) or BRIC (Brasil, Russia, India, China) are common FGC groups (Zheng and Pan, 2014).

Most FGCs have not the same level of human development as the so called developed countries, so institutions and governance need to be strengthened, along with industrial policy and urban planning; these policies and measures will involve a certain energy and resource consumption (Pan and Zheng, 2011). However, overpopulation and rapid growth may involve an increase in the exposure and vulnerability to climate impacts. For instance, the most densely populated coastal zones developed in recent years are those with highest risk for extreme events (Shi, 2011). In recent periods more than 70% of the economic loss due to natural disasters in China was climate-related (Luo, 2011).

The general increase in climate vulnerability has generated a strong need for adaptation in FGCs. In fact, adaptation can contribute to achieve development goals in the short-term, together with reductions in vulnerability over the long-term (World Bank, 2010a). So, even if international funding might be a constraint for implementing adaptation policy, all the FGCs have reached a consensus on the idea that adapting to climate change may lower the cost of development (Zheng and Pan, 2014).

4.4.3 Adaptation in low-income countries

As mentioned before, climate change impacts are expected to be higher in developing countries. There are several reasons for this: first, the pre-existing high level of poverty in these countries; second, many of these economies largely depend on weather and climate (for example, the agricultural sector); third, they have a lower adaptive capacity, and often, lack of political will and difficulty in accessing resources and funding as well (Atta-Krah, 2012; Tol, 2005).

Despite this unfavourable starting point, some adaptation initiatives at the national and community levels are already underway. However, the implementation of these measures requires a major economic effort, which will increase as the impacts of climate change get more severe. According to the World Bank (2010b), the cost to developing countries of adapting to a 2° C warmer climate by 2050 could range between 75 billion to 100 billion US dollars per year. This cost represents the economic impact of additional adaptive capacity needed to face future climate change and is, therefore, additional to the costs of development.

In a situation of financial constraints and big development/adaptation challenges, economic tools such as CBA can be very useful to help decision- and policy-makers identify priorities (Chambwera and Stage, 2010). Newer approaches propose a stakeholder-based CBA for low- and middle-income countries, which allows considering the qualitative aspects of CBA. For instance, how cost and benefits of adaptation is distributed among vulnerable groups (Lunduka et al., 2014).

In any case, adaptation should be considered as an opportunity to enhance development, rather than a separate issue (Chambwera and Stage, 2010). In this way, low- and middle-income countries should prioritise those adaptation measures that contribute to achieve the development goals, over others addressing solely the impacts of climate change.

4.4.4 The role of regional and local governments in adaptation

Climate policy requires global compromises and coordination. However, regional (sub-national) and local governments can play an important role to set up the measures and policies to address climate change, especially if we look at adaptation. According to the United Nations, many regions are already involved in climate policy design, both at national and international scales, indeed more than ever before (UNDP-UNEP-EMG-ISDR, 2008).

Regional governments in many parts of the world are responsible for many of the policy areas involved in climate policies (i.e. energy, special planning, transport, industry, housing, environment, etc.) so they are key actors to implement the policy actions for both adaptation and mitigation (Galarraga et al., 2011a).

If we focus on adaptation, there are several reasons to underline the role of regional and local governments with regard to this issue: first, climate change impacts can vary significantly from one region to another, so adaptation should be especially designed to respond to regional vulnerability. Second, regions are closer to its citizens, therefore being able to identify the specific context, the strengths and difficulties that may arise during the implementation process. Third, this proximity is also a good tool to facilitate social participation and public information and awareness. Actually, this could even guarantee a better implementation process (Galarraga et al., 2011a).

Nevertheless, some difficulties may also arise when working at the regional and local scales, difficulties in most cases related to state-region and inter-regional coordination.

4.4.5 The role of technology in adaptation

In the literature on climate change, technological advances have been traditionally addressed from the perspective of reducing emissions. However, technology can also be very useful for adapting to climate change and, in fact, most adaptation options include some form of technology or technique (Christiansen et al., 2011). Efficient cooling systems, desalination technologies or increasingly advanced weather forecasts that anticipate extreme events are examples of how technology can enhance adaptive capacity.

Although technological capacity and innovation can be considered a fundamental element of adaptive capacity, many technological solutions are specific to a sector or are associated with a particular impact (Adger et al., 2007). For example, Clements et al. (2011) provide a range of technological systems to improve adaptive capacity in developing countries from an agro-ecological approach. The proposed series of technologies contribute to building long-term resilience while enhancing productivity at the same time. Klein et al. (2001) identify four main groups of technological options for reducing the vulnerability of coastal zones: technologies for information and awareness, for planning and designing adaptation strategies, for implementing those and, finally, for monitoring and evaluating their effectiveness. Elliot et al. (2011) address adaptation technologies and practices for developing countries in the water sector. The authors propose an Integrated Water Resource Management (IWRM) as an overall decision-making framework, as adaptation in the water sector should be addressed as part of an inter-sectorial strategy to guarantee the sustainable and safe use of water resources.

Nevertheless, technology by itself is not enough to respond to the challenges of climate change adaptation, for several reasons: first, the framework for decision-making in situations of great uncertainty may constrain the development or implementation of technological options. Second, some technological solutions might not be a suitable option from a cultural, local or economic perspective. Third, the local context is very important when addressing adaptation, consequently technologies proven to be successful in one place, may not be so in another (Adger et al., 2007).

Finally, it is important to stress that the adaptive capacity is not only influenced by the economy and technology, but also by social factors such as human capital and institutional capacity (Adger et al., 2007).

4.4.6 Adaptation and extreme events

According to the IPCC, climate disasters are defined as "*severe alterations in the normal functioning of a community or a society due to hazardous physical events interacting with vulnerable social* *conditions, leading to widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs and that may require external support for recovery*" (IPCC, 2012b: 3). As follows from the definition, the severity of the disaster not only depends on the characteristics of the extreme event itself, but also the exposure and vulnerability of the affected areas, which in turn depend upon various other factors, such as anthropogenic climate change, natural climate variability and socio-economic development. Adaptation focuses on reducing exposure and vulnerability by increasing resilience to the potential impacts of extreme events due to climate change (IPCC, 2012b).

Disasters occurred around the globe during the last decades have driven a growing interest of researchers and policymakers to assess the economic impacts of extreme events. Significant progress has been made since, but research has been mostly carried out in developed countries context (Okuyama, 2008). However, there is a general consensus that macroeconomic effects are expected to be more severe in low- and middle-income countries (Lal et al., 2012).

The specific characteristics of each hazard and its associated damages represent a major challenge for economic modelling of the impacts of extreme events. Okuyama (2008) offers an exhaustive review of methodologies for disaster impact analysis, such as input-output (IO), social accounting matrix (SAM), CGE and econometric models, each method showing strong and weak features (e.g. IO and SAM tend to overestimate economic impacts while CGE may lead to underestimations). Mitchell et al. (2014) assess the way disaster losses threaten future economic development in a climate change context and how mainstreaming risk management into economic and fiscal policy can be a key issue to increase resilience, reducing the exposure and vulnerability to extreme events.

4.5 Conclusions

This chapter shows that economics can provide very useful information for decision making on adaptation to climate change. However, this economic approach is not without difficulties.

From a methodological perspective, the main challenges are related to the treatment of uncertainty, fairness and equity and the limitations of economic valuation. The literature on how economic tools can be used, the difficulties they present and how these difficulties can be overcome is relatively young but growing fast. Particularly important are the boundaries of the economic analysis and how it can complement other methods of assessment.

The sectorial approach is not exhaustive, but reviews the problems faced by adaptation in five main sectors of activity:

- Energy: important impacts are expected in this sector, in terms of energy availability and supply as well as consumption patterns, but major gaps exist in relation to adaptation in this sector.
- Agriculture: in this sector both positive (in some mid- and high latitudes) and negative impacts (tropics and subtropical areas) are expected, therefore adaptation measures are very site-dependent at the regional and local scales.

- Health: climate change is expected to produce and exacerbate many negative impacts on health, ranging from thermal stress to some infectious diseases, depending on the area under analysis. There is a wide literature addressing the costs and benefits of health adaptation and in general greater impacts are expected in developing countries, often linked with adaptation deficit.
- Coastal areas: impacts on this sector are among the best quantified, even though sea-level rise is the major impact considered compared to extreme events, seawater intrusion or coastal erosion. Adaptation costs greatly vary of the type of measure and the site.
- River flood risk: even if it is not a sector itself, extreme events related to flood risk are one of the main concerns in developing and developed countries. Even if the total precipitation is reduced, the change in rainfall patterns is expected to increase flood risk. There are many studies addressing the costs and benefits of adapting to river flooding, with quite different risks.

Finally, other dimensions of adaptation have also been analysed, such as international cooperation, which is closely linked to distributional issues. The role of fast growing countries is gaining increasing attention in relation to adaptation, but low income countries should not be forgotten, as they are to suffer most the impacts of climate change. This adds to the fact that many developing countries still have a significant adaptation deficit, which should be addressed together with adaptation to climate change. Another interesting issue that requires some attention is the role of regional and local governments, as often they are be in charge of many of the policy areas involved in climate change adaptation. Technology can play a key role for adaptation, but it presents several limits related to uncertainty or transferability. In relation to extreme events we conclude that most of the research has been carried out in developing countries, while macroeconomic impacts are more likely to be greater in mid- and low-income countries.

Of all the different issues reviewed in this chapter, Chapter 5 presents an application of two of the challenges described in relation to the methodology: economic valuation and discounting. This application is then used to assess the costs of impacts of sea-level rise and coastal extreme events in three sites of the Basque coast.

5 Valuing the costs of sea-level rise in the Basque coast

5.1 Introduction

Two of the methodological issues related to the economics of adaptation reviewed in Chapter 4 will be analysed in this chapter, namely, discounting and economic valuation. In relation to discounting, climate change has raised a substantial debate among economists about the best way to address long term -and often intergenerational- decision-making, due to its ethical and economic complexities. Decision-makers will have to determine which policies should be implemented in the short term and which should be delayed based, among other criteria, on their relative costs and benefits. In this context, discounting, which is used to estimate how much future costs and benefits are worth today, has become a key element of the analysis (Agrawala and Fankhauser, 2008). The economic appraisal of implementing a specific project or adaptation measure today will depend largely on the discount rate applied. Section 5.2 will review the role of discounting and how a different approach to classical discounting methods can be helpful to address decisions under climate change.

As the aim of this dissertation is to estimate the potential economic impacts of sea-level rise, economic valuation techniques need to be considered for each of the case studies. The goods and services provided by salt marshes are not traded in the market, so an ecosystem service valuation approach is followed in order to measure the economic costs associated with the loss of salt marsh areas. This approach, which is applied to all three case studies, is described in depth in Section 5.3. Alternatively, a market based approach is used to measure the economic impacts of coastal flooding on the urban area of Plentzia and the industrial area of Muskiz, addressed in Sections 5.4 and 5.5 respectively.

5.2 Discounting and the economic impacts of climate change

Decisions with consequences that occur over the future are known in economics as *intertemporal choices*. From an economic perspective, intertemporal choices have been assessed during the last 80 years using the discounted utility (DU) model formulated by Samuelson (1937). The DU model is based on the assumption that people make decisions by assessing its (positive or negative) consequences in a similar way to how the market evaluates gains and losses: “exponentially discounting the value of an outcome” depending on how far in time this outcome occurs (Berns et al., 2007: 1). In other words, the model is based on the assumption that society prefers to receive short-term benefits while delaying costs to the future. Thus, the weight given to future welfare decreases with time (Gowdy et al., 2010).

But how much should the value of a future outcome be discounted? Which discount rate should be used? Lower discount rates imply a higher valuation today of a future outcome and, the other way around, higher discount rates entail a lower value for the future. Let us imagine that a region needs to decide if, as a result of climate change, it would be necessary to invest in the construction of a new sea-dyke to protect its coastal zone from storm-surge events, and in case it is considered necessary when this investment should take place. The use market-based discount rates would lead to a lower present value of future economic impacts related to storm-surge flood events and therefore, the decision to invest might be abandoned or delayed. Conversely, using lower discount rates will provide a higher present value of these future economic costs. In this case, action might need to be taken sooner than in the previous case.

Following the example, a low discount rate involves greater economic sacrifices to the current generation *versus* future ones, which, according to general economic theory, will be richer. In contrast, a higher discount rate could lead to an underestimation of future impacts (Philibert, 2006). This is why the classical framework for representing intertemporal choices based on discount rates observed in the market has been criticised, especially when assessing global environmental issues such as climate change or biodiversity loss. Several authors have defended the need for a change in the framework of intertemporal choices (Graaff, 1987; Bromley, 1998; Spash, 2002; Gowdy, 2004), but the Stern Report, which proposed a discount rate close to zero, has been a major milestone regarding this issue. A heated debate followed its publication (Groom, 2014), which initially focused on the appropriate discount rate, as seen in Nordhaus (2007), for example. Nevertheless, several leading economists, such as Dasgupta (2007) or Weitzman (2009), have also concluded that the standard traditional framework is inadequate to address environmental problems characterised by irreversibility, uncertainty and long-term horizons (Gowdy et al., 2010). Other authors agree on the need for action on climate change, but consider the Stern Report to be incomplete and its conclusions to be incorrect from an economic perspective (Tol, 2006; Tol and Yohe, 2006).

Nordhaus (2007), in his review of the Stern Report, points out that discounting comprises two concepts that should not be confused. The first concept is the "real interest rate"[35] defined as "the annual percentage increase in the purchasing power of a financial asset" and is calculated as "the nominal or market interest rate on that asset minus the inflation rate[36]" (Frank and Bernanke, 2007b: G-5). These values are, in principle, observable in the market. For instance, the real return of Spanish Treasury securities in June 2014 varied between 1.52% (5 year securities) and 4.52% (30 year securities).

The second concept, often known as "pure rate of social time preference", is related to the economic welfare of households or generations across time. That is, it "refers to the discount in future welfare", not future goods or investments. Discount rates closed to zero, as applied in the Stern Report, would mean that present and future generations are considered equally, while a positive discount rate implies a reduction ("discounted") of welfare of future generations compared to the present one (Nordhaus, 2007: 690). Thus, the choice of either alternative is not trivial and may have a decisive influence when assessing the economics of climate policy (Beckerman and Hepburn,

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[35] It is also known as real return, the opportunity cost of capital, or the real return on capital.

[36] The rate of inflation is the annual percentage rate of change in the price level, as measured, for example, by the Consumer Price Index (CPI) (Frank and Bernanke, 2007b: G-5).

2007). Nordhaus (2007) supports the use of real (market) interest rates close to 6% per year in contrast to the framework proposed by Stern.

An intermediate approach is defended by authors such as Beckerman and Hepburn (2007). These authors opt for alternative methods to reveal social preferences through, for example, stated preference surveys, behavioural surveys, etc. Philibert (2006) suggests the use of declining discount rates when valuing environmental assets that cannot be substituted or reproduced. This viewpoint is also defended by other authors such as Cropper and Laibson (1998), Gollier (2008) and Groom (2014). A similar approach is used by Chichilnisky (1996) who argues that no generation should prevail over the other, so she proposes to use a conventional discounting approach in the near-future and a zero-rate after an inflexion point.

During the last decade, it seems that a non-official consensus has been reached in favour of social discount rates which should decrease in the long term (Groom, 2014). Nevertheless, the debate is not closed yet. In fact, Weitzman (2007) argues that choosing the discount rate is one of the biggest uncertainties related to the economics of climate change.

5.2.1 The Equivalency Principle

Following the previous discussion, two main conclusions can be drawn regarding discount rates: on the one hand, that it is a problem with significant ethical implications in relation to intergenerational equity, that is, with the way we value future generations. Prioritising the welfare of the current generation might have a significant impact on that of future generations.

On the other hand, the selected discount rate has a direct influence on the policies under analysis, i.e. the result of a cost-benefit analysis will change significantly depending on the discount rate used. For instance, when applying a positive discount rate to GHG mitigation policies or measures it may turn out that from an economic perspective is best to postpone taking action; however, that might not be the case when using a close to zero discount rate. This is precisely one of the conclusions of the Stern Report, which advocates the need for action, especially in the area of mitigation, to avoid enormous economic impacts (between 5 and 20% of global GDP) in the future.

As stated before, this approach based on the use of low discount rates is not only applicable to climate change, but also to assess other global environmental issues. In a context of land planning, the price of land depends greatly on whether it has been granted permission for development. This way, two identical pieces of natural land located in the same area may have totally different prices if one of them has the permission to be built upon. This situation generates an anomaly with deep ethical and environmental implications, as it will always be cheaper to artificialise natural land than use or restore existing urban land. Chiabai et al. (2013) argued that both pieces of land should be valued similarly, as the long term value of both pieces of land is at least equivalent; accordingly future generations would probably give them equal utility and economic value. In this context, these authors developed a rule based on an alternative approach to discounting as a way of making both valuations equivalent. The so-called *Equivalency principle* can be applied when two conditions are met:

1. Past decision making by the administrative unit[37] of reference on development *versus* protection of natural assets has been socially optimal, so that "the marginal present value of the preserved land is equal to the marginal present value of the adjacent developed land" (Chiabai et al. 2013: 6).
2. Future generations may be affected in the long run by the decision taken on the land under analysis.

For the case studies assessed in this dissertation it is, therefore, assumed that the allocation of developed and undeveloped land has been socially optimal. It is also reasonable to believe that future generations, especially under climate change, could be affected in the long run by decisions involving the study areas. Accordingly, it is presumed that the case studies presented here meet the two conditions required for the application of the equivalency principle.

For illustrative purposes, let us imagine two pieces of natural land, namely N_1 and N_2, located in the same area and have identical environmental and geographical characteristics, such as slope, ecosystem, proximity to infrastructures, etc. (see Figure 5.1). Having both the exact same characteristics today, the current price of both pieces of land would be the same. If their features do not change and both plots remain in a natural state in the long term, their utility is expected to be the same. However, if one of the lands is granted development permits, its market price will automatically increase, while it is most likely that the value of the natural piece of land is not fully recognised by the market. In this situation, Chiabai et al. (2013) argue in favour of using the discount rate to ensure that the present value of both plots is made equivalent, regardless whether they are classified as natural, residential or industrial land. This assumption is the ground for the development of the so called Equivalency Principle (EP).

Figure 5.1. Two pieces of natural land (N1, N2) of equal properties selected to illustrate the application of the Equivalency Principle.

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[37] Chiabai et al. (2013) define administrative unit as "the public administration having the responsibility for land use planning and for granting building permits in a specified area".

In practical terms, when a land plot N_1 is classified as urban (U), either for residential or industrial uses, then N_1 = U; while N_2 remains as natural land on its original state (N). In this situation, the price of the urban parcel would be greater than that of the natural piece of land ($P_{N1} = P_U > P_{N2}$) and this change could have significant implications for future generations. The value of N2 is usually estimated as the present value per hectare (PVN) by non-market valuation methods. This value should represent the total economic value (TEV) of the natural land that comprises use and non-use values as explained before. Using the conventional equation for the present value, the EP is expressed as follows:

$$PVN = \sum_{t=1}^{T} \frac{V_N (1+g)^t}{(1+d)^t} \tag{5.1}$$

Where PVN is the discounted flow value of the natural land in time; V_N is the TEV of the natural land in time t; d is the discount rate to be applied on the natural land; PU is the price per hectare of the land with the right to be built upon and g stands for the growth rate or appreciation of benefits of the undeveloped land over time.

In the long term, it can be assumed that the land provides benefits in perpetuity. For infinite time scales, the equation changes as follows:

$$PVN = \sum_{t=1}^{T} \frac{V_N (1+g)^t}{(1+d)^t} \approx \sum_{t=1}^{T} \frac{V_N}{(1+d-g)^t} \tag{5.2}$$

When time tends to infinity the formula can be simplified to the following expression:

$$PVN = \frac{V_N}{(d-g)} = PU \tag{5.3}$$

The main purpose of the EP is to find the appropriate discount rate g that provides a balance to the different value given to each piece of land based on their land-use classification, i.e. natural vs. residential or industrial. Solving Equation 5.3 we obtain the rule to be applied:

$$d = \frac{V_N}{PU} + g \tag{5.4}$$

Equation 5.4 shows the principle to estimate the discount rate considering increasing flows of benefits over time. If growth is not taken into account, g would be equal to zero.

In this dissertation, V_N represents the flow of benefits (euros per hectare per year) provided by salt marsh ecosystems, obtained from the value transfer model for the Basque Country later explained in Section 5.3; PU is the price of industrial or residential land available for each site and g represents the per capita GDP growth, following socio-economic scenario SSP2 (see Section 5.2.2 for further details). A scenario with no economic growth has also been considered.

For the case study of Plentzia, the price (P_U) of urban land is obtained from the statistics of the Spanish Ministry of Public Works and Transport for prices of urban land by population size[38]. In the case of Muskiz, the price (P_I) of industrial land (I) is based on estimations from Sprilur[39]. The growth rate is estimated using quantitative projections of the so-called Shared Socioeconomic Pathways (SSPs) and explained in detail in the following sub-section.

5.2.2 Future economic growth

The IPCC (2013a) defines a scenario as "a plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces and relationships". It is important to note that scenarios are not forecasts but a description of how the future may be regarding different fundamental areas (society, economy, environment, greenhouse gas emissions, etc). In the context of climate change, scenarios help us to analyse the contribution of human activities to climate change, the response of the natural systems to these activities, the impact of mitigation or adaptation policies, etc.

So far, the scenarios were based on the Special Report on Emission Scenarios (IPCC, 2012c). These were baseline scenarios, meaning that future climate policy was not considered. Also, the development approach followed a sequential process in which different socio-economic options were translated into GHG emissions and these into changes to the climate system. However, this process was not responding to the demands arising among climate change researchers, namely the need for more detailed information as inputs to the newest climate models, an increasing need to explore the impact of alternative climate policies and the interest in including the effect of different adaptation and mitigation options into future scenarios (Capellán-Pérez et al., 2014).

Recently, the IPCC decided to change its approach developing scenarios in a parallel coordinated process rather than sequentially (Figure 5.2). The starting point of this new approach is a set of four scenarios based on different radiative forcings[40], the so-called "representative concentration pathways" (RCPs). The term representative is used because each RCP shows only one of several possible scenarios, while the word pathway stresses the importance of the trajectory followed to reach a specific GHG concentration, and not only the concentration value reached. The change in the approach is, therefore, substantial: rather than going from a set of socio-economic scenarios, the four radiative forcing scenarios can be achieved through different socioeconomic and technological options. Also, it is possible to address the role of different adaptation and mitigation strategies (Moss et al., 2010).

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[38] Available at http://www.fomento.es/be2/?nivel=2&orden=36000000.

[39] From a conversation with Mikel Oregi in charge of strategy and planning of Sprilur, the Public Society of the Basque Government responsible for providing companies with access to developed land for industrial use, industrial buildings, and offices (www.sprilur.es).

[40] Radiative forcing is defined as "*the change in the balance between incoming and outgoing radiation to the atmosphere caused by changes in atmospheric constituents, such as CO_2*" (Moss et al., 2010).

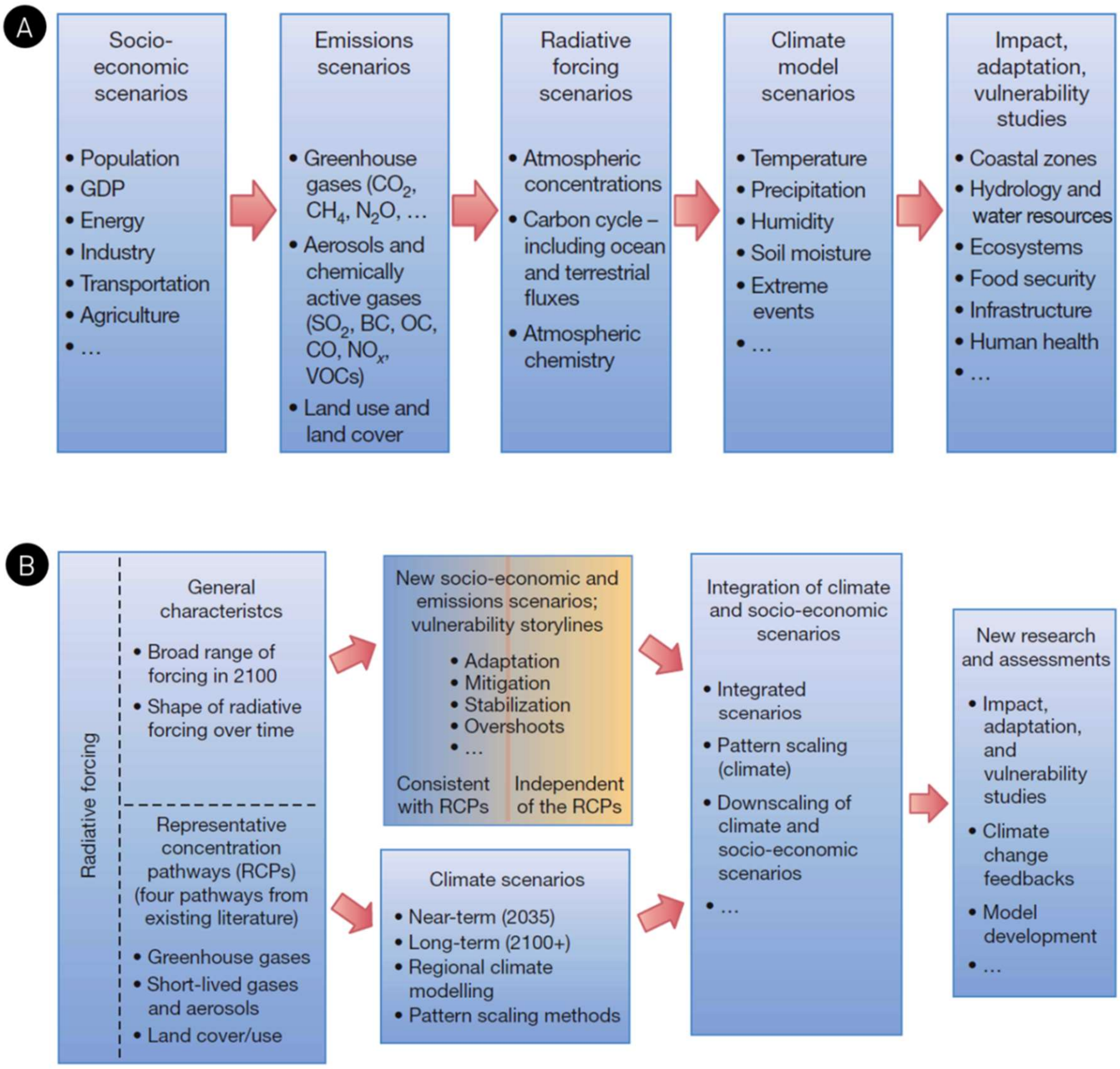

Figure 5.2. Building climate change scenarios. The sequential approach that followed to the development of the SRES scenarios (A) compared to the parallel process based on the four RCPs (B) that is currently being used. In the parallel process climate and integrated assessment modellers work simultaneously (Moss et al., 2010).

In any case, future projections are a complex task and are not without uncertainty. One major cause of uncertainty is the different time scales of climate, energy and economic policies. For example, long term economic projections may go as far as a decade, while climate policy often considers a 50-100 year timeframe (Capellán-Pérez et al., 2014).

As part of the new framework adopted by the climate research community, several SSPs have been developed based on different technological, socioeconomic and policy trajectories. SSP storylines have been built up along two axes: the vertical axis corresponds to the intensity of climate policies that will be necessary to prevent a certain level of climate change (mitigation); the horizontal axis represents the needs to cope with a certain level of climate change (adaptation). For example, SSP1 faces low challenges, SSP2 represents a middle of the road scenario and SSP3 implies high socio-economic challenges for both adaptation and mitigation policies (see Figure 5.3). Further details on each socio-economic pathway are shown in Table 5.1.

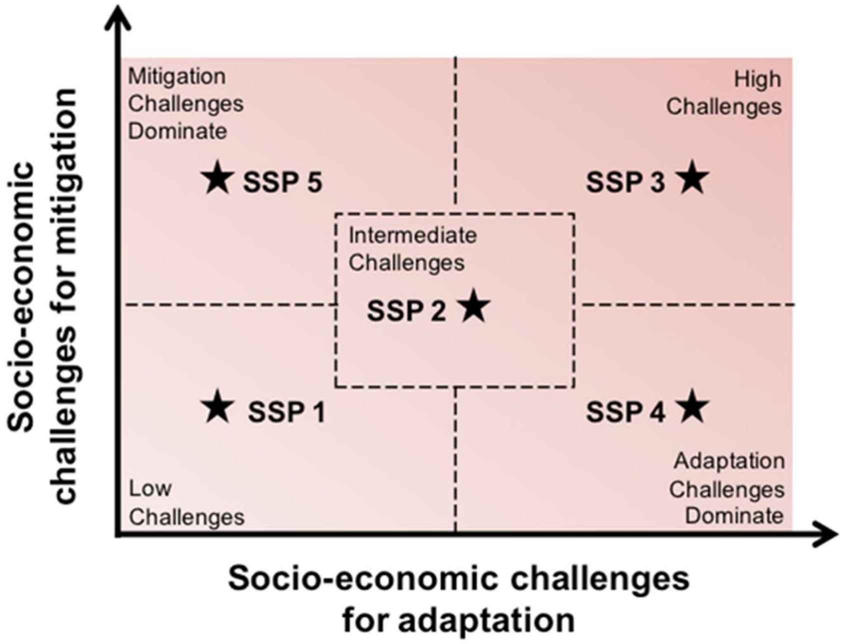

Figure 5.3. Five Shared Socioeconomic Pathways (SSP) storylines constructed around two axis representing the challenges of mitigation and adaptation policies. Source: http://climate4impact.eu/, adapted from IPCC (2012d).

The so-called "matrix architecture" that can combine different RCPs and SSPs open new opportunities for research on impacts, adaptation and vulnerability. This structure allows comparing a certain level of climate change (a single RCP) with different socio-economic futures (several SSPs). It is also possible to assess the potential impacts of different degrees of climate change (various RCPs) on a single socio-economic scenario. Additionally, facing different SSPs with the RCPs the effectiveness of adaptation could be measured, as well as residual damages or related costs and benefits (van Ruijven et al., 2014).

In order to estimate future economic impacts of climate change in the Basque Country, growth rates need to be included in the estimations, which can be derived from different SSPs. In this dissertation the SSP2 "middle of the road" scenario has been selected. Estimates from Capellán-Pérez et al. (2014) for this scenario show a moderate global growth of per capita GDP in the short term of around 3%, that slowly declines stabilising at 1.8-2% global growth rate in the long term.

Table 5.1. Illustrative example of narratives underlying the SSPs described in Figure 5.3.

SSP1 - Sustainability	The world is reasonably well suited to both mitigate and adapt, could be one in which development proceeds at a reasonably high pace, inequalities are lessened, technological change is rapid and directed toward environmentally friendly processes, including lower carbon energy sources and high productivity of land. Similar to SRES B1 scenario.
SSP2 – Middle of the road	Intermediate case between SSP1 and SSP3. Current trends continue with moderate progress on income convergence. Some emerging economies catch up relatively quickly whereas growth is much slower in the least-developed countries, at least in the first decades. Global emissions are projected to follow business-as-usual trends. There are substantial challenges for mitigation and adaptation, but neither is particularly severe. Similar to SRES B2 scenario.
SSP3 – Fragmentation	Large challenges for both mitigation and adaptation could be a world in which unmitigated emissions are high due to moderate economic growth, a rapidly growing population, and slow technological change in the energy sector, making mitigation difficult. Investments in human capital are low, inequality is high, a regionalized world leads to reduced trade flows, and institutional development is unfavourable, leaving large numbers of people vulnerable to climate change and many parts of the world with low adaptive capacity. Similar to SRES A2.
SSP4 – Inequality	Mitigation might be relatively manageable while adaptation would be difficult and vulnerability high, could describe 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.
SSP5 – Conventional Development	Large challenges to mitigation but reasonably well equipped to adapt. 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. Similar to the SRES A1FI scenario.

Source: IPCC (2012d), Appendix I, Box 2; Capellán-Pérez (2014).

Projections of economic growth in terms of GDP per capita based on purchasing power parity (PPP[41]) for scenario SSP2 have been estimated[42] by different organisms[43] for 32 world regions. In the case of the Basque Country estimates for the European Union have been used. This group includes member states prior to 2004, leaving outside the countries that recently joined the European Union as they may have a different growth path. Table 5.2 shows growth rates estimated by three organisms (International Institute for Applied Systems Analysis (IIASA), Organisation for Economic Co-operation and Development (OECD), Potsdam Institute for Climate Impact Research (PIK)), the average values and those growth rates selected for the Basque Country, calculated by rounding off average growth rates.

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[41] PPPs are defined as “convert different currencies to a common currency and, in the process of conversion, equalise their purchasing power by eliminating the differences in price levels between countries”(European Commission and Eurostat, 2012: 13).

[42] Available at: https://secure.iiasa.ac.at/web-apps/ene/SspDb/dsd?Action=htmlpage&page=about

[43] International Institute for Applied Systems Analysis (IIASA), the Organisation for Economic Co-operation and Development (OECD) and Potsdam Institute for Climate Impact Research (PIK).

Table 5.2. Growth rates estimated by IIASA, OECD and PIK and the selected average values to project future economic growth in the Basque Country.

Organism	2010-2030	2030-2050	2050-2100
IIASA	2.5	2.01	1.05
OECD	1.5	1.51	1.26
PIK	1.9	1.35	0.89
Average	2.0	1.6	1.1
Basque Country	*2.0*	*1.5*	*1.0*

Note that the selected growth rates are long term estimates that do not consider short term economic cycles. Although the Basque Country (as a great part of Europe) is coming out of a serious economic crisis that does not conform to trends in long-term growth, the decision to exclude short-term economic cycles is justified to avoid additional uncertainty to that inherent to long-term future economic projections.

5.3 Economic valuation of the impacts of sea-level rise on salt marshes in the Basque coast

5.3.1 The economic value of ecosystems and their services

As early as 1970s, Westman (1977) published an article on the value of the services provided by nature in which he gathered the concern of policy-makers on how much services such as clean air and water or wildlife were worth. He already stressed the importance of accounting for the benefits of nature's services in decision-making. The term Ecosystem Services (ES), was first used a few years later by Ehrlich and Ehrlich (1981), but it was not until the late 1990s that the concept got widespread attention with the publications by Costanza et al. (1997) and Daily (1997) (TEEB, 2010). Costanza et al. (1997) estimated an average value for the services provided by the biosphere of 33 trillion US dollars per year. But more important that the economic estimation itself was the role this paper played as an influential element of raising awareness.

The Millennium Ecosystem Assessment (MEA), which popularised the term ecosystem services, defined them as "the benefits people obtain from ecosystems" and classified these benefits into four groups as described in Table 5.3. The first group represents provisioning services, such as food, water and timber; the second group includes regulation services, for example flood prevention, soil retention or climate regulation, etc.; the third group comprises cultural services that offer recreational, spiritual and aesthetic benefits; finally supporting services such as soil formation, photosynthesis and nutrient cycling are included in the fourth group (MEA, 2005; TEEB, 2010). Humans, despite cultural differences and technological advances, are essentially dependent upon the services provided by ecosystems (MEA, 2005; Markandya and Pascual, 2014).

Table 5.3. Categorisation of ecosystem services.

Category	Services	Examples
Provisioning Services	1. Food	Fish, game, fruit
	2. Water	Drinking, irrigation, cooling
	3. Raw Materials	Fibre, timber, fuel wood, fodder, fertiliser
	4. Genetic resources	For crop-improvement and medicinal purposes
	5. Medicinal resources	Biochemical products, models & test-organisms
	6. Ornamental resources	Artisan work, decorative plants, pet animals, fashion
Regulating Services	7. Air quality regulation	Capturing (fine) dust, chemicals, etc.
	8. Climate regulation	Carbon sequestration, influence of vegetation on rainfall, etc.
	9. Moderation of extreme events	Storm protection and flood prevention
	10. Regulation of water flows	Natural drainage, irrigation and drought prevention
	11. Waste treatment	Water purification
	12. Erosion prevention	
	13. Maintenance of soil fertility	Including soil formation
	14. Pollination	
	15. Biological control	Seed dispersal, pest and disease control
Habitat Services	16. Maintenance of life cycles of migratory species	Including nursery service
	17. Maintenance of genetic diversity	Gene pool protection
Cultural & amenity Services	18. Aesthetic information	
	19. Opportunities for recreation & tourism	
	20. Inspiration for culture, art and design	
	21. Spiritual experience	
	22. Information for cognitive development	

Source: TEEB (2010).

This way to understand, appreciate and value nature, biodiversity and ecosystems to the extent that they provide some benefits to humans has been widely criticised, with some justification. Firstly, the concept of ecosystem services is anthropocentric and from an ethical point of view, biodiversity has a value in itself, not just in terms of the services provided to humans. Also, ecosystems offer some intrinsic benefits that cannot be valued in economic terms, such as some of the services included in the third and fourth groups: aesthetic or spiritual benefits, supporting services, etc. Another challenge of the economic valuation of ecosystem services is that related to the monetization of biodiversity, as so far it only considers a part of its total value, and therefore result an underestimation of it (Markandya et al., 2008). Unfortunately, some studies include "conceptual errors, oversimplified biophysical models or lack of social and technological context [...]" (Lele, 2009) and others focused in obtaining an economic value, often missing other types of values crucial to understand the human-nature interrelationship (TEEB, 2010). In this connection, some authors argue about the risks of the commodification of nature, which could cause inequalities in the access to services currently considered to be public goods (Gómez-Baggethun and Ruiz-Pérez, 2011; Chiabai, 2015).

However, and despite the criticisms to the ES concept and its economic valuation, it should be acknowledged its usefulness as a decision-making tool (Chiabai, 2015). In fact, the definition of plans or projects with impacts on biodiversity and ecosystems implies implicitly attaching a value to the affected ecosystem, which often is close to zero. In these cases, an economic valuation can help bring out, at least, part of the value of these ecosystems.

Moreover, it cannot be managed what it has no defined value and concepts such as "invaluable" or "priceless" have failed to halt biodiversity loss (Liu et al., 2010). Therefore the key question might be making society aware of the value of ES. According to TEEB (2010: 187), "economics, as the study of how to allocate limited resources, relies on valuation to provide society with information about the relative level of resource scarcity". Thus, ecosystem services valuation (ESV) is a way to integrate ecological and economic considerations, "putting natural capital into the equation of economic 'development' and on the agenda of policy-making" (Chee, 2004: 550).

In conclusion we can say that the ecosystem service approach has changed our paradigm of the interdependency between humans and nature and that is surely of benefit to nature itself (Markandya and Pascual, 2014).

5.3.1.1 Salt marsh ecosystems: what is their value?

Coastal salt marshes are transition zones between marine and terrestrial environments (Basque Government, 2004). Even if they represent a small percentage of Earth's land surface, salt marshes provide a wide variety of ecosystem goods and services that have an important global socio-economic value (Spencer and Harvey, 2012). In fact, salt marshes can be considered one of the most productive and valuable ecosystems (Costanza et al., 1997; Barbier et al., 2011).

The most important benefits from salt marshes are coastal protection, erosion control, water purification, maintenance of fisheries, carbon sequestration, provision of unique habitats for fish and birds, tourism, recreation, education and research (Barbier et al., 2011; Spencer and Harvey, 2012). The values of some of these important services have been estimated at different scales. In the UK, for instance, the goods and services provided by coastal margin ecosystems have been estimated at 48 billion sterling pounds, which represents 3.46% of the UK's national income (Jones et al., 2011). Barbier et al. (2011) carried out a review of several salt marsh valuation studies that has been summarised in Table 5.4. Note that the values vary greatly depending on the ecosystem service assessed and also of the valuation method used. For example, coastal protection has been measured in terms of avoided damages from hurricanes along the US East coast, while the availability of raw materials reflects the annual net income from grazing livestock in a natural reserve on England's West coast. Significant differences can also be found within the same ecosystem service. The value for fisheries maintenance can reach 6,471 US dollars per acre in the East coast of Florida in terms of recreational fishing, but the value of an additional acre of salt marsh for the US Gulf coast blue crab fishery is below 2 US dollars per acre. Moreover, values can vary greatly within the same area.

Table 5.4. Salt marshes: ecosystem services, processes, and functions and examples of values.

Ecosystem services	Ecosystem processes and functions	Ecosystem service value examples	Sources
Raw materials and food	Generates biological productivity and diversity	15.27 sterling pounds/ha·yr net income from livestock grazing, UK	King and Lester (1995)
Coastal protection	Attenuates and/or dissipates waves	8236 US dollars/ha·yr (average) in reduced hurricane damages, USA	Costanza et al. (2008)
Erosion control	Provides sediment stabilization and soil retention in vegetation root structure	Estimates unavailable.	-
Water purification	Provides nutrient and pollution uptake, as well as retention, particle deposition	785–15,000 US dollars/acre capitalized cost savings over traditional waste treatment, USA	Breaux et al. (1995)
Maintenance of fisheries	Provides suitable reproductive habitat and nursery grounds, sheltered living space	6471 US dollars/acre and 981 US dollars/ acre capitalized value for recreational fishing for the east and west coasts, respectively, of Florida, USA. 0.19–1.89 US dollars/acre marginal value product in Gulf Coast blue crab fishery, USA	Bell (1997) Freeman (1991)
Carbon sequestration	Generates biogeochemical activity, sedimentation, biological productivity	30.50 US dollars/ha·yr	Chmura et al. (2003)
Tourism, recreation, education and research	Provides unique and aesthetic landscape, suitable habitat for diverse fauna and flora	31.60 sterling pounds/person for otter habitat creation (UK) 1.20 sterling pounds /person for protecting birds (UK)	Birol and Cox (2007)

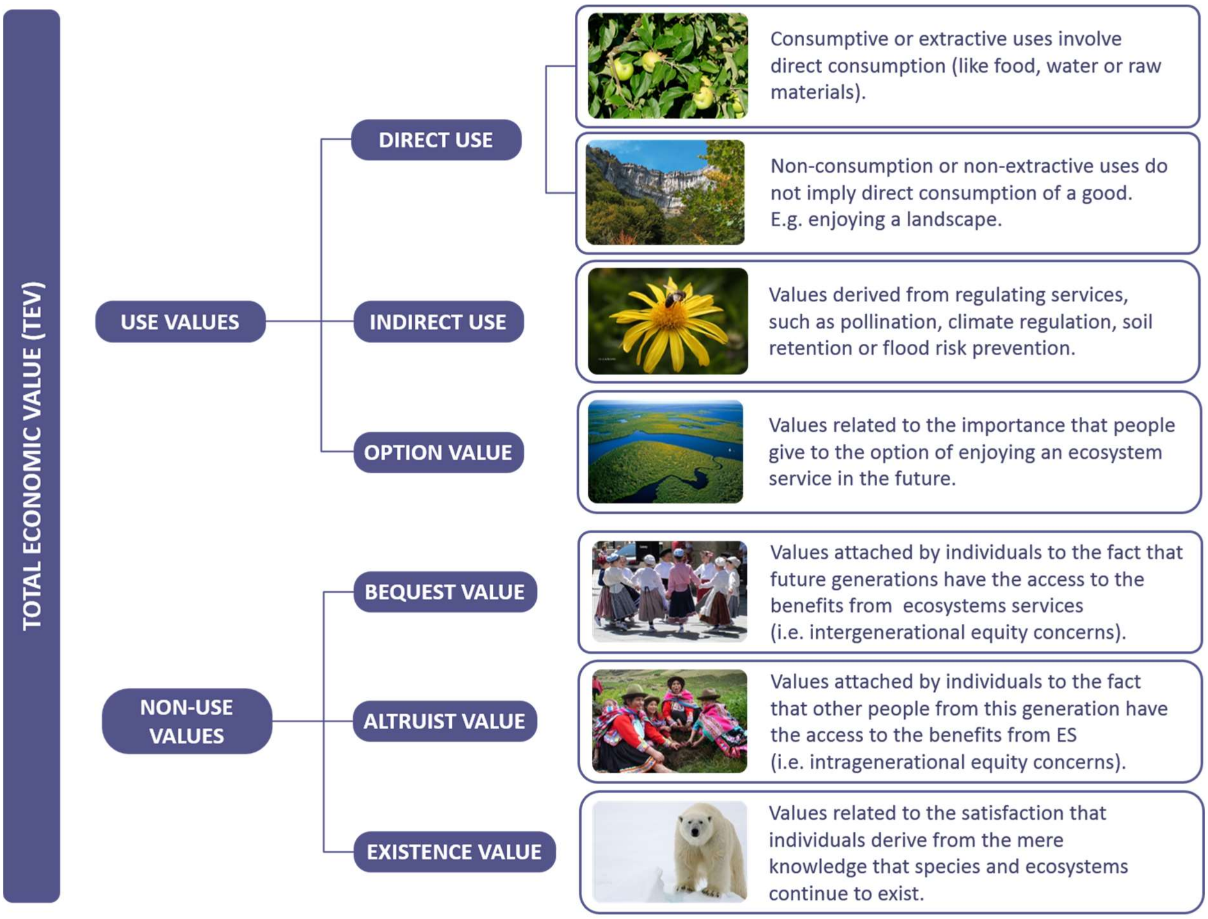
Source: Barbier et al. (2011) for full references.

Despite the important ecosystem services they provide, globally salt marsh areas have lost 25% of their original extension due to human activities and the current loss rate is estimated to be between 1% and 2% per year (Secretariat of the Convention on Biological Diversity, 2010). Additionally, up to 50% of salt marshes worldwide have been deteriorated (Barbier et al., 2011). The future does not look much brighter: salt marsh ecosystems will need to face processes such as climate change, sea-level rise, development, marsh reclamation, invasive species or deterioration of water quality (Spencer and Harvey, 2012).

5.3.2 Methods for ecosystem service valuation

The economic valuation of ecosystem services allows, first, to provide a monetary estimate in terms of specific benefits generated to humans, and second, to estimate the economic impacts of human activities on the basis of the damage produced on ecosystems and related services.

If biodiversity and ES in economic terms are seen as part of our natural capital, then the flows of ES would be equivalent to the interest that society receives on that capital (Costanza and Daly, 1992; TEEB, 2010). Accordingly, the total economic value (TEV) can be defined as "the sum of the values of all ecosystem service flows that natural capital generates both now and in the future – appropriately discounted" (TEEB, 2010: 188). TEV encompasses *use values* and *non-use values*. The first consists of the sum of the *direct use* of ES (obtaining food or enjoying a landscape, for example), *indirect uses* derived from regulating services, such as flood prevention or climate regulation, and *option values* (the value people place on protecting biodiversity for the future). Non-use values relate to the importance given merely to the fact that a certain ecosystem or species exists (*existence value*). Non-use values also include the value of an ecosystem for being available for future generations (*bequest values*) or even other people from the current generation (*altruist value*) (TEEB, 2010). The components of TEV are summarised in Figure 5.4.



Consumptive or extractive uses involve direct consumption (like food, water or raw materials).

Non-consumption or non-extractive uses do not imply direct consumption of a good. E.g. enjoying a landscape.

Values derived from regulating services, such as pollination, climate regulation, soil retention or flood risk prevention.

Values related to the importance that people give to the option of enjoying an ecosystem service in the future.

Values attached by individuals to the fact that future generations have the access to the benefits from ecosystems services (i.e. intergenerational equity concerns).

Values attached by individuals to the fact that other people from this generation have the access to the benefits from ES (i.e. intragenerational equity concerns).

Values related to the satisfaction that individuals derive from the mere knowledge that species and ecosystems continue to exist.

Figure 5.4. Types of values included within the concept of Total Economic Value (based on TEEB, 2010; Table 5.1. and Figure 5.3).

Most of these values can be measured in monetary terms through economic valuation methods that can be classified into three main categories, although this classification changes depending on the authors (see, for example, de Groot et al., 2002; Liu et al., 2010; TEEB, 2010):

- **Market based approaches** most often use market values, so they reflect real preferences or costs to individuals, and this is, actually, the main virtue of this approach: using data from actual markets, data which are available and can be relatively easy to gather. This is the case for agricultural or timber markets.
- **Revealed preference approaches** are based on the observation of individual choices through which people show their preferences in relation to the ES under valuation.
- The **stated preference approach** is used to simulate a market for ES by using surveys "on hypothetical (policy-induced) changes in the provision of ES".

The ecosystem service valuation methods included in each of these three main groups are summarised in the table below.

Table 5.5. Summary of main ecosystem service valuation (ESV) methods (based on de Groot et al., 2002; Barbier, 2007; Liu et al., 2010; TEEB, 2010).

Approach	Valuation Methods	Meaning and examples
Market based	Market price based	Valuations are obtained directly from what people are willing to pay for a good or service in the market where the ES under valuation is exchanged; e.g. timber, food.
	Cost-based	**Avoided costs** methods are based on the extent to which a costly negative impact is avoided due to the presence of ES; e.g. flood prevention by wetlands.
		Replacement cost methods are based on what it would cost to replace an ES by technology; e.g. carbon capture and storage by forests.
		Restoration costs are those necessary to restore ES that have been previously lost or damaged; e.g. restoring coastal ecosystem affected by an oil spill.
	Production function	Based on the fact that ecosystems may be inputs into the production of goods or services that are marketed; e.g. water provision for hydro energy.
Revealed preferences	Travel costs	Mainly used to estimate recreational values, are based on the fact that the use of ES may require travel, thus travel costs are used as the implied value of the service.
	Hedonic prices	The value of an ES is estimated by considering what people are willing to pay for the service through purchases in surrogates markets. A typical example is the higher price of a house close to the beach.
Stated preferences	Contingent valuation	People are directly asked about their willingness to pay (or accept compensation) for a change in the provision of an ES through a social survey questionnaire.
	Discrete choice experiments	People are asked to choose or rank several scenarios that consider different levels of ES provision. Often one of the alternatives is the money people would be willing to pay for the service.
	Group valuation	Derived from social and political theory, this method is based on the fact that public decision making should be a result of an open public debate, and not the sum of individual preferences.

ESV methodologies have a number of limitations worth considering yet these methods can provide fundamental inputs for decision making when any other alternative do not exist. In this regard, Kumar et al. (2013) recommends that policy makers integrate the information provided by economic valuation, but being aware of its limitations and TEEB (2010: 187) suggests that valuation should be used not to substitute but to complement "other legitimate ethical or scientific reasoning and arguments relating to biodiversity conservation".

In practice, it is necessary a great deal of economic and ecological information in order to apply any of these methodologies. When this information is not available, carrying out studies to obtain it can be costly and time-consuming, so it is not always possible. In this case, a reasonable alternative is using a **benefit transfer approach**. This method is not a valuation method itself but allows transferring an existing valuation estimate from a similar ecosystem to the site for which there is a lack of information (Galarraga et al., 2004; TEEB, 2010).

5.3.2.1 The benefit transfer method

Where no previous economic information is available on the value of an environmental good or service, there are several methods that could be used, as it has been previously exposed. However, resources or time constraints may limit or prevent undertaking new primary valuation studies; instead, a benefit transfer (BT) method could be used. Although the reliability of the benefit transfer over other methods of ESV, it does allow to have economic estimates that can be used as a reference in decision-making processes (Galarraga et al., 2004).

A benefit transfer consists in taking an estimate from previous research (i.e. the value provided by salt marsh ecosystems in a certain location) and transferring it to value an analogous ecosystem (Smith et al., 2002). The site from which values are taken is known as "study-site" and the place where values are being transferred to is called "policy-site" (Galarraga et al., 2004).

There are three ways in which a benefit transfer can be developed:

- The more basic approach, called **unit BT**, consists on the assumption that the single value of an ES in the study-site is approximately equal to that in the policy-site. This value is thus directly transferred, making some adjustments when necessary (currency, income…).
- In the **value function transfer**, the whole benefit (or damage) function is transferred, not only the value obtained at the study-site. From a conceptual point of view this is a more rigorous procedure as more information is used for the value transfer. In this way the valuation function used as the study-site is applied at the policy-site by introducing information and parameters from the area under study.
- Finally, the **meta-analytic function transfer** can be used. The difference with the previous approach relies on the fact that this function is built based on multiple values from different studies. That is, the value for the study-site estimated with this approach is not obtained from one single study but from a compilation of values obtained from a meta-analysis (Galarraga et al., 2004; TEEB, 2010).

This last approach will typically incorporate a wide range of socio-economic and physical attributes of the study-sites, including different valuation methods, that cannot be taken into account when undertaking value function transfers based on a single primary valuation study (TEEB, 2010). It is considered to be a more accurate way to transfer values between sites (Brander et al., 2012). Nevertheless, Lindhjem and Navrud (2008) found that for international benefit transfers the reliability of meta-analytic function transfer approaches is not necessarily greater than that of a value function transfer.

Despite imperfections of the benefit transfer method, we believe that having a reference value is better than having no value at all, as in these cases the implicit value will often be negligible.

5.3.3 Applying a benefit transfer approach to salt marshes in the Basque coast

Several primary economic valuation studies have been developed in the Basque Country. For example, Pascual (2007) carried out an economic valuation of Basque forests and Ayala et al. (2015) valued changes in landscapes in the context of the European Landscape Convention. Other studies have focused on specific sites. That is the case of two Natura 2000 network sites, namely Mount Jaizkibel (Hoyos et al., 2007) and the site of community interest (SCI) Garate-Santa Barbara (Hoyos et al., 2012). However, no primary valuation study has been undertaken on salt marshes.

Regarding the benefit transfer method, this is not a new approach, but it has been often used in the Basque Country for economic valuation of ecosystems and their services. For example, Galarraga et al. (2011c) estimated the impacts of SLR in several coastal ecosystems of the Basque Country. In order to do so, they first estimated the economic value of the ecosystems under assessment. In the case of wetlands and salt marshes, the economic value was obtained through the combination of data from a single example of restoration costs and a value transfer.

Based on this example and in the absence of available valuation studies focusing on salt marshes in the Basque Country, a meta-analytic transfer function has been carried out to estimate the value of three salt marsh areas in the Basque coast: the Oka Estuary, located in the Urdaibai Biosphere Reserve; the Butroi Estuary in the municipality of Plentzia; and the Barbadun Estuary in Muskiz.

5.3.3.1 Case studies (policy sites)

From a biophysical and geological perspective, the three case studies considered in this dissertation share some common features: they are estuaries with presence of salt marsh areas, which show a different conservation status. But despite their common features, they represent different geographical contexts that translate into different impact and valuation approaches for each case study.

Urdaibai is a Biosphere Reserve which includes the most important salt marsh area of the Basque Country. Coastal wetlands, such as the ones existing in Urdaibai, were drained for agricultural uses since the 17th century, and abandoned during the mid-20th century, coinciding with the rise of industrialisation in the Basque Country. Natural, regenerated and a few still-reclaimed salt marshes represent around 65% of the whole estuarine area of the Urdaibai Biosphere Reserve (Cearreta et al., 2013).

Quite different is the case study of the Plentzia Estuary, where current salt marsh areas occupy 14% of the total surface of the estuary. During the last two centuries urban occupation strongly modified the lower estuary, while agricultural uses transformed the upper estuary and also some areas of the lower zones (Cearreta et al., 2002). Although agricultural decline has driven the regeneration of salt marsh areas, urban area in the lower estuary is consolidated.

In Muskiz only 19% of the original surface of the estuary is preserved today and 90% of the lost land is due to the human action (Rivas and Cendrero, 1992), and more specifically to the establishment in 1968 of one of the largest oil refinery in the Iberian Peninsula (Petronor, Repsol Group). The only remains of the original estuarine environments are located in the lower estuary, where there are some salt marsh areas on the left bank (total surface area 15 ha) and a dune field on the right bank (total surface area 10.4 ha) (Cearreta et al., 2008).

5.3.3.2 Data for the benefit transfer

The reference study for wetland valuation used as a basis for the value transfer was defined by Brander et al. (2012) who developed a meta-analysis combined with spatial data to estimate the value of the ecosystem services of wetlands. The meta-analysis contains 222 independent observations from 120 primary valuation studies of temperate climate zone wetlands (mainly from Europe and the USA). In the absence of primary valuation studies, this study is considered the best available reference to estimate the economic value of Basque salt marshes.

The application of the meta-analytic function transfer to salt marshes in the Basque coast has been done following the next steps:

a. Identification of variables from the original meta-analytic function transfer that can be applied to the policy sites in the Basque Country
b. Estimation of variables from the Basque policy sites
c. Currency and income adjustment: purchasing power parity (PPP)
d. Inflation adjustment

The transfer process is described in detail next.

Identification of variables from the original meta-analytic function transfer

The meta-analytic transfer function developed by Brander et al. (2012) is based on the meta-analysis performed by Ghermandi et al. (2010). The value transfer by Brander (2012) was applied to assess European wetlands only, so a subset of the full original meta-analysis was used to build the value function.

The meta-analytic regression model defined by Brander et al. (2012) is shown in Equation 5.5.

$$\boldsymbol{ln(y_i) = a + b_S X_{Si} + b_W X_{Wi} + b_C X_{Ci} + u_i} \qquad (5.5)$$

The dependant variable y represents the flow value of wetlands (in 2003 US dollars per hectare per year), a is the constant term; b_S, b_W and b_C are the coefficients of the explanatory variables and u is a vector of residuals.

The explanatory variables are divided in three groups (Table 5.6). The first group, study characteristics (X_S), includes those variables related to the valuation studies, such as the method used, the year of publication or the type of value obtained (marginal or average).

Table 5.6. Variables originally included in the meta-regression model developed by Brander et al. (2012).

Variable group	Variable		Type	Statistically significant
Study characteristics (X_S)	Valuation type	Contingent valuation	Binary (0-1)	✗
		Choice experiment	Binary (0-1)	✗
		Hedonic pricing	Binary (0-1)	✓
		Travel cost method	Binary (0-1)	✗
		Replacement cost	Binary (0-1)	✗
		Net factor income[44]	Binary (0-1)	✗
		Production function	Binary (0-1)	✗
		Market prices	Binary (0-1)	✗
		Opportunity cost	Binary (0-1)	✗
	Type of data	Marginal valuation	Binary (0-1)	✗
Wetland characteristics (X_W)	Wetland type	Inland marshes	Binary (0-1)	✗
		Peatbogs	Binary (0-1)	✓
		Salt marshes	Binary (0-1)	✓
		Intertidal mudflats	Binary (0-1)	✗
	Size	Wetland size	Ln (ha)	✓
	ES	Flood control and storm buffering	Binary (0-1)	✗
		Water supply	Binary (0-1)	✗
		Improved water quality	Binary (0-1)	✗
		Commercial fishing and hunting	Binary (0-1)	✗
		Recreational hunting	Binary (0-1)	✓
		Recreational fishing	Binary (0-1)	✗
		Harvesting of natural materials	Binary (0-1)	✗
		Fuel wood	Binary (0-1)	✗
		Non-consumptive recreation	Binary (0-1)	✗
		Amenity and aesthetics	Binary (0-1)	✗
		Natural habitat and biodiversity	Binary (0-1)	✓
Context variables (X_C)		GDP per capita	Ln (US dollars)	✓
		Population in 50 km radius	Ln (Pop)	✓
		Wetland area in 50 km radius	Ln (ha)	✗

The second group contains those characteristics related to wetlands (X_W), specifically the type and size of the wetlands considered. Five types of wetlands are defined: inland marshes, peatbogs, salt marshes, intertidal mudflats and saline wetlands. Most of the wetlands for which value estimates are available are medium to large size wetland areas. Although the majority of the valuation studies are focused on large sites, small wetlands are also represented (less than 100 ha). The ecosystem services provided by wetlands are also included within this second group through valuation studies assessing those ES.

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[44] "Assign value as revenue of an associated product(s) net of costs of other inputs" (Brander et al., 2006).

The third group of variables (X_C) relates to the socio-economic and geographical context: GDP per capita, population living in a radius of 50 km around the wetland assessed, and wetland abundance are the variables included in this group. The values of GDP per capita used in the meta-regression are estimated in US dollars referring to the year 2003, while population has been calculated using GIS techniques. The explanatory variable representing wetland abundance is estimated by measuring the wetland area in a radius of 50 km around the wetland of reference. According to Ghermandi et al. (2008: 10), this variable reflects "the uniqueness of a wetland environment and may explain the influence of people's perceptions and preferences due to the presence of other sites that can act as a substitute for some of the services provided".

Only statistically significant variables were taken into account in the transfer function for the case studies. None of the first group variables related to the study characteristics (X_S) are included in the function transfer. The reason is that the only study addressing wetland valuation in the Basque Country (Galarraga et al., 2011b) uses restoration, regeneration and cleaning costs. These categories were not among the valuation methods included in the original meta-analysis from Brander et al. (2012), as shown in Table 5.6.

The second group of variables included in the regression (X_W) referred to the type and size of the wetlands considered. Salt marshes, the kind of wetland to be assessed in the Basque Country, represent 16% of all the study sites considered in the regression. The variables GDP per capita and population from the third group (X_C) have also been introduced in the meta-analytic transfer function. Table 5.7 summarises the variables included in the meta-analytic transfer function for the Basque Country and the associated statistical coefficient and *p* value.

Table 5.7. Variables used in the benefit transfer function for Basque salt marshes, based on the meta-regression model developed by Brander et al. (2012)

Variable group		Variable		Coefficient	*p* value
Group 1	Study characteristics (X_S)	*Not applicable*		-	-
Group 2	Wetland variables (X_W)	SM	Salt marshes (dummy)	0.073	0.901
		S	Wetland size, ha (ln)	-0.218	0.000
Group 3	Context variables (X_C)	GDP	Real GDP per capita, US dollars (ln)	0.430	0.004
		P	Population in 50-km radius (ln)	0.503	0.000

As a result, the meta-analytic value transfer model for the Basque coast is defined as follows:

$$\boldsymbol{ln(V_{Basque}) = a + b_{SM}ln(SM) + b_{Size}lnS + b_{GDP}ln(GDP) + b_P lnP + u_i} \tag{5.6}$$

The notation V_{Basq} is the estimated flow value per hectare per year for Basque salt marsh ecosystems (in US dollars 2003); SM represents the dummy variable[45] corresponding to salt marshes;

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[45] A dummy variable is a binary type of variable that takes the value 0 to indicate absence or 1 meaning presence.

S is the size of the salt marsh measured in hectares; GDP indicates the GDP per capita in the Basque Country, and P denotes the population within a 50 km radius from the salt marsh assessed.

Estimation of variables from the case studies (policy-sites)

The first two variables needed in the transfer model are SM and S. As explained before, the first is a dummy variable which indicates presence or absence of salt marshes by taking value 1 or 0 respectively. As this section focuses salt marshes, this variable will always have a value of 1.

The second variable represents the size of the salt marsh area in each case study, which has been measured using geographical information systems (GIS): salt marshes in Urdaibai occupy 332.7 ha, 16.58 ha in Plentzia and 17.2 ha in Muskiz.

The next dependant variable is the GDP per capita in the Basque Country. The study from Brander et al. (2012) used data in US dollars (2003), so previous to any estimation, the data of the Basque per capita GDP from the study year (2003) was converted into the reference monetary unit considering purchasing power parity (PPP)[46].

The last dependant variable that had to be estimated was the population within a 50 km radius from the salt marsh areas. The estimations were calculated using spatial information systems together with statistical information on population of the Basque Autonomous Community and the adjacent provinces of Burgos and Cantabria[47]. The final data is the sum of the population of each the municipalities that falls within the 50 km buffer area around each of the wetlands under assessment (Figure 5.5).

The dependant variables for each of the case studies are summarised in Table 5.8. The dummy variable SM and GDP are the same in all cases, however there is a big difference on the size of salt marsh areas: Urdaibai is a protected area in which most of its wetland area has been preserved, while the estuaries of Plentzia and Muskiz show fragmented and reduced salt marsh areas. Population is also higher in Urdaibai and smaller in the case of Muskiz.

Table 5.8. Explanatory variables used in the transfer model and the corresponding values estimated for Basque salt marshes. Beta coefficients are those taken from the meta-analytic regression carried out by Brander et al. (2012).

Variable	Beta coefficient	Urdaibai	Plentzia	Muskiz
Presence of salt marshes (dummy), SM	0.073	1	1	1
Wetland size in hectares, S	-0.218	332.7	16.58	17.2
Real gross domestic product per capita, US$$_{2003}$, GDP	0.430	32,018.62	32,018.62	32,018.62
Population in 50 km radius, P	0.503	1,486,517	1,380,698	1,278,733

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[46] PPP index was only available at country level so that of Spain was used for the Basque Country. [46] The information on Basque GDP was obtained from the Basque Statistics Institute (Eustat, 2015) (see subsection 0. Currency and income adjustment: purchasing power parity (PPP) for further details on the procedure).

[47] The information on Basque population was obtained from the Basque Statistics Institute (Eustat, 2015) and the population from Burgos and Cantabria was taken from Spanish Statistics Institute (INE, 2015). All data is from the 2011 population census.

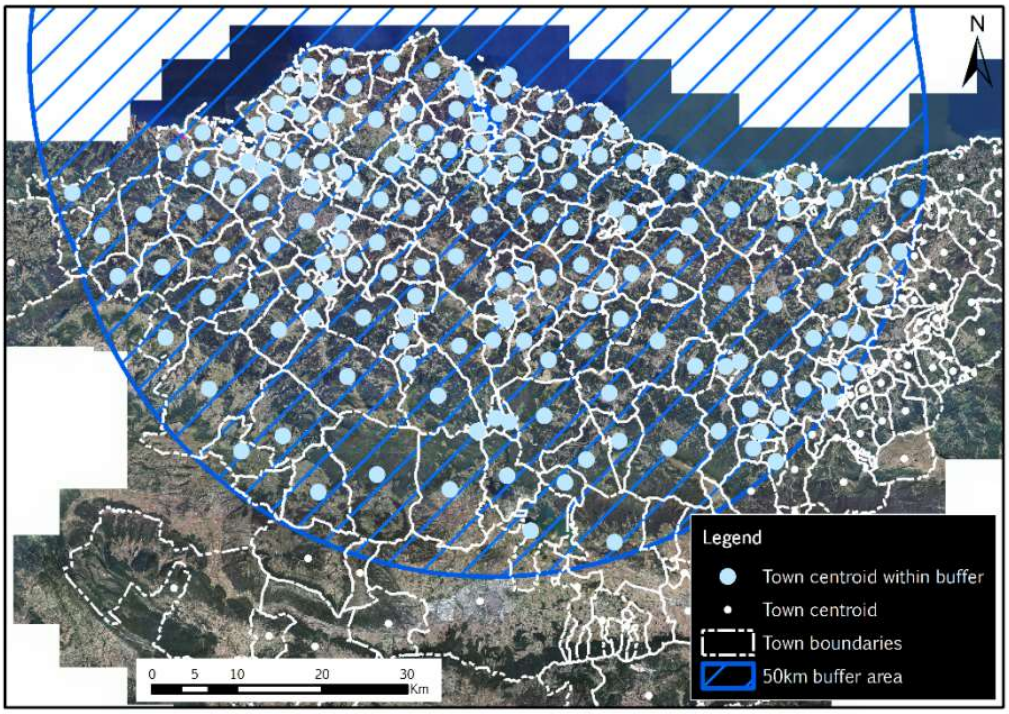

Figure 5.5. The blue circle indicates the 50 km buffer area around the salt marshes of Urdaibai. The dots represent the central point (centroid) of each municipality. White dots are outside the 50 km buffer area while the light blue dots represent the towns within the area.

Currency and income adjustment: purchasing power parity (PPP)

It has been shown in Equation 1 that measuring the economic value of Basque salt marshes requires data about the GDP, which is provided in euros. However, the meta-analytic transfer function carried out by Brander et al. (2012) used US dollars (2003) instead as the reference currency, so the Basque GDP that is provided in euros (2003) needs to be translated into US dollars.

An option to do this is using official US dollar/euro exchange rates, but this method does not account for the real purchasing power of both currencies. Transformation factors that reflect the actual purchasing power of different countries by removing differences in price levels have been developed within the International Comparison Program (ICP) of the World Bank and OECD (OECD, 2011). These are the so-called Purchasing Power Parities (PPP), which are available per country and for several year at the OECD website[48].

No PPP data is available for the Basque Country, so the one corresponding to Spain was used to translate Basque GDP (in euros) into US dollars.

$$\boldsymbol{GDP_{US\ dollars\ 2003} = GDP_{euros\ 2003} * \frac{PPP_{US\ 2003}}{PPP_{Spain\ 2003}}} \tag{5.7}$$

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[48] The OECD Purchasing Power Parity data can be downloaded at: http://www.oecd.org/std/prices-ppp/purchasingpowerparitiesspppsdata.htm

Note that only the currency changes in this process, but not the reference year. Once the Basque GDP was estimated in the correct units, the transfer model for the Basque Country can be used to measure the economic value of salt marshes in this region.

Inflation adjustment

The result of applying the transfer function to the Basque context is expressed as V_{Basq}, the economic value of salt marshes of each case study, measured in US dollars (2003) per hectare. This value needs to be translated into euros, following the process explained in the previous subsection.

$$V_{Euros\ 2003} = V_{US\ dollars\ 2003} * \frac{PPP_{Spain\ 2003}}{PPP_{US\ 2003}} \tag{5.8}$$

Once the value of salt marshes is in euros (2003) it also needs to be updated in time, so the next step is to convert the data in the year of the study, 2003, to the reference year (2013). Commonly, data from different years can be adjusted to a reference year by using the Consumer Price Index (CPI)[49], which reflects the effect of inflation[50], as shown in Equation 6:

$$V_{Euros\ 2013} = V_{Euros\ 2003} * \frac{CPI_{Spain\ 2013}}{CPI_{Spain\ 2003}} \tag{5.9}$$

The OECD provides information on CPI for different countries and time periods[51], but again, only information for Spain was available.

5.3.4 The benefits provided by salt marshes in the policy sites

The results of the value transfer for each of the case studies is shown in Table 5.9. Salt marshes in Urdaibai show the lowest value per hectare, 12,276.29 euros per year[52], but this is explained by the fact that the total area of salt marshes in Urdaibai is 20 times bigger than that of Plentzia and Muskiz. In fact, the total economic value provided by salt marshes in Urdaibai during a year is ten times greater than the ones in Plentzia or Muskiz, reaching 4 million euros.

The flow values per hectare of the ecosystem services provided by salt marshes in Plentzia and Muskiz is 22,744 euros and 21,708 euros, respectively. The total benefits provided in a year range from 377,101 euros in Plentzia to 373,393 euros in Muskiz.

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[49] The Consumer Price Index (CPI) "measures the cost of a standard basket of goods and services relative to the same basket of goods and services in a fixed year; called the base year" (Frank and Bernanke, 2007b: 150).

[50] The inflation rate of a country is the "annual percentage rate of change in the price level, as measured, for example, by the CPI" (Frank and Bernanke, 2007b: 150).

[51] Consumer price indexes available at: http://stats.oecd.org/Index.aspx?DataSetCode=MEI_PRICES

[52] From now on, the monetary values shown in this dissertation correspond to the reference year 2013, unless otherwise indicated.

Table 5.9. Value per hectare per year of the salt marshes in the three case studies: Urdaibai, Plentzia and Muskiz.

SALT MARSHES	VBasque (US$$_{2003}$/ha·year)	PPP (2003) Spain (€/US$)	CPI (2003)	CPI (2013)	VBasque (€$_{2013}$/ha·year)	VBasque (M€$_{2013}$/year)
Urdaibai	12,663.53	0.702	93.86	121.0	**12,276.29**	**4.08**
Plentzia	23,461.79	0.702	93.86	121.0	**22,744.35**	**0.38**
Muskiz	22,393.71	0.702	93.86	121.0	**21,708.93**	**0.37**

5.3.4.1 The benefits provided by salt marshes in the future

Discounting is used to measure how much future benefits are worth today. The rate at which present value of salt marsh ecosystem is discounted in the future has been estimated through the methodology based on the equivalency principle (Chiabai et al., 2013), explained in detail in Section 5.2.1, following Equation 5.4. The price of urban land P_U has been taken from the statistics of prices of urban land by province and municipality size provided by the Spanish Ministry of Public Works and Transport[53]. In the case of Urdaibai, the two main municipalities, Gernika and Bermeo, both have populations above 10,000 inhabitants, therefore the price of urban land corresponding to municipalities of that size was selected. This average price in 2013 was 278.18 euros. In the case of Plentzia, the price of urban land corresponding to municipalities with a population between 1,000 and 5,000 inhabitants was selected. The average value for 2013 was of 219.20 euros per square metre. Finally, the price corresponding to municipalities with a population ranging from 5,000 to 10,000 was chosen for Muskiz. In 2013, the average price was of 292.94 euros/m^2.

Discount rates have been estimated considering both constant and increasing flows of benefits. The estimates with constant flows do not account for economic growth, only discount rate is considered. The assessment using growing flows estimate the future benefits considering that the economy is going to grow, and this growth has been estimated taking the SSP2 economic scenario presented in Table 5.2 as a reference. Results show that the discount rate for Urdaibai considering constant flows is 0.42%, while when introducing the growth parameter the discount rate is 1.79%. In both cases, the resulting rates are well below market references (Table 5.10).

Table 5.10. Summary of variables and estimates of the discount rates for the case studies.

Variables		Urdaibai	Plentzia	Muskiz
Benefits provided by salt marshes in euros (2013) per hectare per year, V_{SM}		12,276.29	22,744.35	21,708.93
Price of urban land in euros (2013) per m^2, P_U		278.18	219.20	292.94
Growth rate of benefits of the undeveloped land over time, g		2% (2010-30); 1.5% (2030-50); 1% (2050-2100)		
Discount rate, d_{SM}	Constant prices	0.44%	0.96%	0.74%
	Increasing flows of benefits (including g)	1.82%	2.33%	2.12%

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[53] The data is publicly available at: http://www.fomento.es/be2/?nivel=2&orden=36000000.

Once the discount rates have been obtained for each case study, then we proceed to estimate the present value of benefits (PVB) provided by salt marshes to the future, following Equation 5.10:

$$PVB = \frac{B*g}{(1+r_{SM})^t} \tag{5.10}$$

Where PVB is the present value of benefits; B is the benefits in the baseline year (2013); g represents the growth rate, but only appears for the case in which increasing flows have been considered; d_{SM} is the discount rate to be applied on salt marshes and t is the time period, in years. These benefits correspond to the situation with no climate change, where no flooded areas have been considered and the results are shown in Table 5.11.

The greatest benefits are provided by salt marshes in Urdaibai, which was expected as this area includes the biggest salt marsh area. The total benefits for the period 2013-2100 vary substantially depending on whether growth is accounted for or not. In the first case benefits reach 184 million euros, while considering constant flows benefits increase 62%, up to almost 300 million euros.

In absolute terms the difference is not that big for Plentzia and Muskiz, but proportionally the trend is similar. Benefits are 54% greater in Plentzia if constant flows are selected, 21.9 million euros compared to 14.25 million euros when increasing flows are included. In Muskiz, total benefits range from 15.38 million euros with increasing flows to 24.25 million euros when growth is not taken into account, which is 58% more benefits when constant growth is applied.

Table 5.11. Estimated economic benefits provided by salt marsh ecosystems. Benefits are measured in millions of euros.

Salt marsh	Area (ha)	Growth (g)	r_{SM}	Present value of benefits provided by salt marshes by period (M€)					TOTAL
				2013-2029	2030-2049	2050-2079	2080-2099	2100	2013-2100
Urdaibai	332.7	Increasing flows (SSP2)	1.82%	61.42	51.75	49.60	20.95	0.86	**184.57**
		Constant	0.44%	67.05	72.71	97.74	58.34	2.78	**298.63**
Plentzia	16.58	Increasing flows (SSP2)	2.33%	5.43	4.11	3.42	1.24	0.05	**14.25**
		Constant	0.96%	5.91	5.75	6.67	3.43	0.15	**21.92**
Muskiz	17.2	Increasing flows (SSP2)	2.12%	5.49	4.38	3.91	1.53	0.06	**15.38**
		Constant	0.74%	5.99	6.15	7.67	4.25	0.20	**24.25**

In the period 2013-2100, the benefits provided by all three salt marsh areas assessed range from 214.2 to 344.8 million euros.

5.3.5 Salt marsh loss due to sea-level rise: what is the cost?

If the rate of sea-level rise is higher than the capacity of salt marshes to adapt to the new level, the wetland area will be reduced due to flooding. This loss would imply a reduction of the flow of benefits provided by salt marshes to the society. This way, the costs of sea-level rise can be calculated in terms of the loss of salt marsh areas.

Salt marsh areas are considered lost only when flooded permanently, as these ecosystems have the capacity to support and gradually recover from extreme events that would cause occasional damages (inundation and erosion). Therefore, only flooded marshes under mean sea level (MSL) have been considered. The salt marsh surface submerged under each GBSLR scenario have already been estimated in Chapter 3. No permanent loss of wetland surface occur under GBSLR Scenario 1 nor would 2, while there be some impacts on GBSLR Scenario 3 and 4. However, the costs associated to GBSLR Scenario 4 are not addressed due to its long term characteristics, and therefore only impacts under GBSLR Scenario 3 are examined.

The next step is to calculate the economic costs of flooded salt marsh areas. The hectares are multiplied by their discounted economic value. Following section 5.3.4.1, discount rates have been estimated considering both constant and increasing flows. The costs are measured as avoided benefits, i.e., the benefits that the flooded salt marsh areas will not provide when flooded.

The results for Urdaibai are summarised in Table 5.12. The first three rows show the change in salt marsh surface in Urdaibai. Note that the table shows the accumulated loss of salt marsh area for each time period, i.e., under GBSLR Scenario 3 salt marsh areas in Urdaibai will lose 1.87 hectares by the end of the century. Next, the costs of sea-level rise are presented. The first estimates consider increasing flows of benefits, and the corresponding discount rate (1.82% for Urdaibai). The second group of cost estimates have been calculated with constant flows of benefits and therefore the discount rate of 0.44%.

Table 5.12. Costs of sea-level rise due to loss of salt marshes under GBSLR Scenario 3 in Urdaibai.

	2030	2050	2080	2100	TOTAL
(A) Salt marsh surface no CC, hectares	332.7	332.7	332.7	332.7	-
(B) Salt marsh surface with CC (GBSLR Scenario 3), hectares	332.2	332.2	331.8	330.8	-
(A-B) Salt marsh surface loss, accumulated	*0.48*	*0.53*	*0.88*	*1.87*	-
1. Costs with increasing flows of benefits. Discount rate: 1.82%					
(A) No climate change, millions of euros	61.42	51.75	49.60	21.81	184.57
(B) ES Benefits with CC, millions of euros	61.37	51.67	49.49	21.72	184.26
(A-B) Costs due to CC, euros	*42,196*	*78,175*	*101,745*	*87,748*	*309,865*
2. Costs with constant flows of benefits. Discount rate: 0.44%					
(A) No climate change, millions of euros	67.05	72.71	97.74	61.13	298.63
(B) ES Benefits with CC, millions of euros	67.00	72.60	97.54	60.88	298.02
(A-B) Costs due to CC, euros	*47,709*	*110,104*	*203,916*	*250,479*	*612,208*

The present value of these costs reach 612,000 euros when considering constant flows, and approximately half of it if economic growth is taken into account (almost 310,000 euros). These costs account only for 0.1% of all the economic benefits provided by salt marsh ecosystem services. This is fundamentally because the loss of hectares is also small in relation to the whole salt marsh area: 1.9 hectares by 2100, barely 0.006% of the current surface.

According to the results obtained for GBSLR Scenario 3 (see Chapter 3), the Plentzia Estuary would lose almost 23% of its current surface by 2100, and as a consequence the goods and services provided by marshes would also be reduced. The services provided by salt marshes in this area have been estimated in 22,744 euros per hectare and per year. Multiplying this value by the total wetland surface we get that salt marshes in Plentzia provide services valued in more than 380,000 euros per year. By 2100 they would have provided between 14.3 and 21.9 millions of euros, depending on the discount rate used. However, these services would be reduced under GBSLR Scenario 3 due to the change in sea level. The costs, measured as the loss of benefits provided by these coastal ecosystems, would range between 0.3 and 0.6 million euros for the whole period (Table 5.13).

Salt marshes in this area would suffer no permanent flooding in any of the scenarios considered. Thus, sea-level rise would generate no costs in terms of the loss of ecosystem services.

Table 5.13. Costs of sea-level rise due to loss of salt marshes under GBSLR Scenario 3 in Plentzia.

Plentzia	2030	2050	2080	2100	TOTAL
(A) Salt marsh surface no CC, hectares	16.58	16.58	16.58	16.58	-
(B) Salt marsh surface with CC (GBSLR Scenario 3), hectares	16.58	16.58	16.31	13.61	-
(A-B) Salt marsh surface loss, accumulated	*0.00*	*0.00*	*0.27*	*2.97*	-
1. Costs with increasing flows of benefits. Discount rate: 2.41%					
(A) No climate change, millions of euros	5.43	4.11	3.42	1.29	14.25
(B) ES Benefits with CC, millions of euros	5.43	4.11	3.37	1.06	13.96
(A-B) Costs due to CC, euros	0.00	0.00	54,859	233,141	288,000
2. Costs with constant flows of benefits. Discount rate: 1.04%					
(A) No climate change, millions of euros	5.91	5.75	6.67	3.58	21.92
(B) ES Benefits with CC, millions of euros	5.91	5.75	6.57	2.94	21.16
(A-B) Costs due to CC, euros	0.00	0.00	107,045	648,636	755,682

Table 5.14 presents a summary of the results of this sub-section, focusing on the impacts of climate change in relation to the loss of salt marsh areas and the associated economic impacts that have been previously presented in Table 5.12 and Table 5.13.

The last column shows the percentage loss referred to the estimates with no climate change. In Urdaibai the losses, both in terms economic and extension, are insignificant. The surface potentially lost in Plentzia is very important, as almost one quarter of the already reduced salt marsh area would be submerged. However, the expected economic costs are small, between 2% and 3.5%.

Table 5.14. Summary of impacts of sea-level rise in each case study, in terms of the loss of salt marsh areas and the reduction of the benefits provided by these ecosystems.

Case study	Climate change impacts		2013-2029	2030-2049	2050-2079	2080-2100	TOTAL	
Urdaibai	Salt marsh surface loss (ha)		0.48	0.05	0.34	0.99	**1.87**	*<0.01%*
	Costs due to climate change (euros 2013)	Increasing flows (r = 1.82%)	42,196	78,175	101,745	87,748	**309,865**	*0.17%*
		Constant flows (r = 0.44%)	47,709	110,104	203,916	250,479	**612,208**	*0.21%*
Plentzia	Salt marsh surface loss (ha)		0.00	0.00	0.27	2.70	**3.78**	*23%*
	Costs due to climate change (euros 2013)	Increasing flows (r = 2.41%)	0	0	54,859	233,141	**288,000**	*2%*
		Constant flows (r = 1.04%)	0	0	107,045	648,636	**755,682**	*3.5%*
Muskiz	Salt marsh surface loss (ha)		0	0	0	0	**0**	*0*
	Costs due to climate change (euros 2013)	Increasing flows (r = 2.12%)	0	0	0	0	**0**	*0*
		Constant flows (r = 0.74%)	0	0	0	0	**0**	*0*

5.3.6 Discussion

The economic values obtained from the meta-analytic value transfer for the policy sites are lower than others estimated for different areas and ecosystems in the Basque Country. For example, the valuation carried out by Hoyos et al. (2007) for the coastal and terrestrial ecosystems of Mount Jaizkibel provided estimates of 72,000-224,000 euros (2006) per hectare. Galarraga et al. (2011c) estimated a value of Basque coastal wetlands in 60,700 euros (2006) per hectare, but this is not a primary valuation study but the result of a combination of restoration costs[54] and a unit value transfer.

The lack of specific primary studies valuing salt marshes makes difficult to compare the results, but the difference is still significant. Galarraga et al. (2011c) argue that in the case of passive use values, a way to explain the high values they obtained, not only for wetlands, but also for several other coastal ecosystems, can be found in the Basque idiosyncrasy. In fact, Hoyos et al. (2009) found that cultural identity had a significant influence in willingness to pay valuation studies addressing the protection of natural areas. As the meta-analytic transfer function does not capture the effect of the cultural identity, this could also be a possible explanation for the low values obtained for salt marshes in Urdaibai, Plentzia and Muskiz.

Another issue for discussion is the effect of the size in the economic values obtained for the case studies. The values per hectare per year in Urdaibai are approximately 45% lower than the results for Plentzia or Muskiz. This result is in general agreement with the literature on economic valuation (see for example Ojea et al., 2015). From an economic perspective it can be explained with the law of supply and demand: the higher the supply, the lower the price, and the other way around. As the

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[54] These costs were based on a local restoration project undertaken by the Department of the Environment of the Basque Government.

salt marsh areas in Plentzia and Muskiz are scarcer, their value is higher. However, in terms of ecosystem functioning the rule is not straight forward. Actually, a greater salt marsh area such as that in Urdaibai, which is also better preserved and less fragmented, is expected to provide more and higher quality ecosystems services per hectare than a small relict salt marsh area. And thus, the economic value of the services provided by salt marshes in Urdaibai should have been higher. Developing an alternative economic approach is out of the scope of this dissertation but it is an interesting issue for further research.

Regarding the results obtained for the present value of future benefits of salt marshes, these results show loser benefits when the discount rate is higher. This result was expected, but it serves to stress the importance of selecting the appropriate discount rate when assessing future costs and impacts, as it will condition the assessment significantly.

Finally, the losses due to sea-level rise are found to be small. As summarised in Table 5.14, in Urdaibai losses would range between 310,000 euros and 612,000 euros by the end of the century depending on the discount rate. In Plentzia the economic impacts would vary between 288,000 euros and 756,000 euros, also according to the discount rates applied. There are two causes that can explain these low results. The first is related to the fact that the net loss of salt marsh areas is not very high. In Urdaibai only 1.8 hectares would be permanently lost under GBSLR Scenario 3 and in Plentzia 3.8 hectares would get permanently submerged. The second cause leading to low economic costs is that most of the physical impacts occur from 2050 onwards, as shown in Figure 5.6.

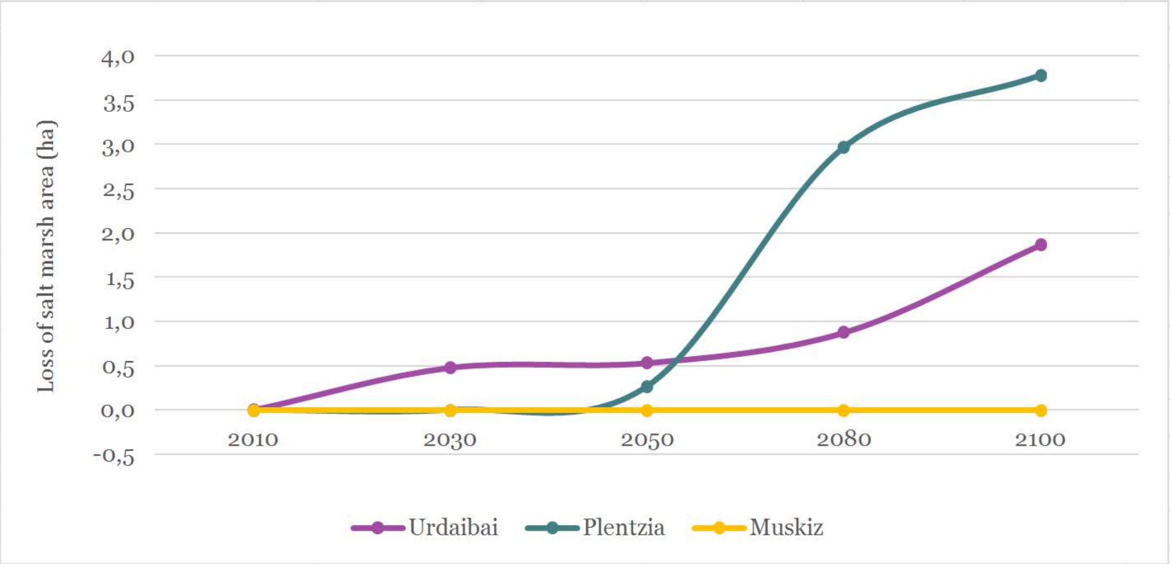

Figure 5.6. The loss of salt marsh areas for each case study under GBSLR Scenario 3 – Holocene 1.

In Urdaibai the flooded areas increase after 2050 but most of the losses are expected during the last two decades of the 21st century. In Plentzia the acceleration steeply increases in the mid-21st century and declines slightly at the end of the century. This means that ecosystem services would be fully supplied during the first half of 21st century and their benefits would be reduced only during the second half of the century.

5.4 Estimating the costs of flooding in urban areas

5.4.1 Introduction

The first reference to flood events in the Basque Country goes back to 1406. In that year 39 catastrophic flood events were recorded only in Bilbao. Since this first reference, similar events in other places of the Basque territory, such as Laudio, Donostia or Tolosa, have also been registered (Fernández Gómez, 1993).

No doubt, the coast of the Basque Country is an area with high-risk, not only due to natural flood hazard (generated by high precipitation, strong slopes and steep valleys) but also because of its high vulnerability, with most of the low-lying areas densely urbanised (Ibisate et al., 2000). Climate change will most probably make this situation worse, as the intensity and frequency of extreme events are expected to increase in the following decades (Benito et al., 2005).

In this context, there is a growing body of scientific literature analysing the effects of climate change on extreme precipitation and flood frequency (e.g. Knox, 2000; Palmer and Räisänen, 2002; Kundzewicz et al., 2014). Other studies assess the change in flood risk due to climate change (e.g. Hall et al., 2005) and research on the economic impacts of flooding is abundant as well, even in a small region such as the Basque Country (e.g. Basque Government, 2007; Osés Eraso, 2009; Galarraga et al., 2011c).

Even though the literature is more abundant for river flood risk, there are several studies assessing the impacts of sea-level rise and coastal extremes in the Basque coast (see, for example, Marcos et al., 2007a, 2009, 2012b; Chust et al., 2010; Liria et al., 2011). However, these studies focus on the expected effects in terms of flooded areas and affected habitats, rather than the resulting economic damages.

In this section, both approaches are combined with the aim of measuring the economic impact of sea-level rise in the urban area around the Plentzia Estuary. In order to do so, the methodology already used to assess the economic impacts of river-flood risk in the Basque Country (Basque Government, 2007; Osés Eraso, 2009) have been adapted to the flood impacts associated with sea-level rise developed in Chapter 3.

5.4.2 Methodology

From an economic approach, flood risk is usually assessed as a combination of the probability or frequency of a flood event and the damage caused by the event (Osés Eraso, 2009). This can be made following a three-step methodology:

a. Determination of the physical attributes of flood events
b. Identification of assets exposed to the risk of flooding
c. Estimation of the potential economic damages

In this subsection, the three-step methodology to estimate the economic costs of flooding that has been previously applied in several case studies in the Basque Country, has been adapted to the sea-level rise scenarios developed in Chapter 3. The details of how this has been undertaken are explained next.

a. Determination of the physical attributes of flood events

Flood-risk maps developed in Chapter 3 for each GBSLR scenario are the starting point to measure the physical attributes of flood events, as the areas potentially inundated by flooding have already been identified through those maps. However, the damage associated with an extreme flood event depends upon several factors, e.g. inundation duration, flow velocity, contamination load or water depth (Osés Eraso, 2009). Among them, the latter is considered to be the key factor in most assessments (Boettle et al., 2013).

In this work the duration of the event, its flow velocity or the contamination load are unknown variables but water depth can be measured, as the rate of sea-level rise for all GBSLR scenarios and each case studies is known, both considering MSL or MAHT level. To illustrate how depth is estimated, let us consider the areas affected by MAHT levels currently and under GBSLR Scenario 3, as presented in Figure 5.8. The buildings shown in the figure would not be currently affected by MAHT levels, represented by the area in blue. However, due to sea-level rise, MAHT levels would rise significantly by 2030 (yellow area), reaching some of the households. As the rate of sea-level rise under GBSLR Scenario 3 is 10 mm yr^{-1}, in the period from 2010 to 2030 sea level would rise 20 cm. Consequently, water depth in the yellow area would be equal to or lower than 20 cm. This way, GIS systems were used to estimate water depth for every GBSLR scenario and each asset at risk in the different time periods considered.

Figure 5.7. Estimation of affected assets by overlapping flood maps on urban land plots.

b. Identification of assets exposed to the risk of flooding

Once the physical characteristics of coastal floods under each scenario are known, all the assets at risk need to be identified. In order to do so, the official cadastral information for the province of Biscay[55] was used as a first reference. However, a great amount of information was not available from the cadastre, such as the specific commercial premises in each building or the type of assets located at ground level, so this additional information was obtained in the field.

According to the different uses, a first division between residential and non-residential assets was made. Within the first group four types of houses were found: detached, semi-detached, terraced houses and apartment buildings. Parking spaces was also considered as a separate sub-category. Non-residential properties include commercial ownership, public facilities, such as the city hall or the municipal sports centre, and health related elements.

The detailed classification is presented in Table 5.15 and the full list of elements at risk has been included in Appendix I.

Table 5.15. Classification of assets at risk based on their uses (residential or non-residential) and the individual typology.

USE	Typology	Description
Residential	Detached houses	Free standing residential building, in principle, used by a single family. Around the Plentzia Estuary these houses usually have garden and sometimes other infrastructure such as swimming-pools or tennis-courts.
	Semi-detached houses	Pairs of houses sharing one exterior wall. Most usually, they also have a garden.
	Terraced houses	Also known as row houses, they share two exterior walls with each other, except those houses in the ends that share one single wall.
	Apartments	Large building divided in several apartments.
	Garages	A separate sub-category has been used to assess garages.
Non-residential	Commercial	This group includes all the properties where an economic activity is being carried out. The following sub-categories have been identified: • Shops • Banks • Offices • Premises • Restaurants • Hotels • Bars
	Public facilities	This group includes the City hall, the public sports centre and the tourist office.
	Sanitation	Public health facilities have been identified as a specific sub-category.

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[55] The cadastre is an administrative record of urban and rustic land ownership in the province of Biscay. The data of the urban cadastre includes descriptions of urban properties (parcels and buildings), stating surfaces, location, etc. The database and GIS maps of the cadastre was provided, under request, by the Cadastral Office of the Regional Government of Biscay on January 2015.

c. Estimation of the potential economic damages

Two studies have assessed the economic costs of flooding in the Basque Country: the first is a study commissioned by the Basque Government in 2007, which provided a methodology to estimate the cost of climate change impacts and specifically addressed flood risk in Bilbao (Basque Government, 2007). The second assesses the impacts of floods on the Urola River Basin (Osés Eraso, 2008). Both studies have been developed by using methodologies defined for the UK, as this country has a long history of assessing economic impacts of floods (e.g. DETR, 1999; DEFRA, 2003, 2004, 2006). Additionally, where no local costs were available, the costs from British studies have been transferred to the Basque Country. These two reference studies addressing flood impacts in Bilbao and the Urola River Basin, together with the so-called Multi-coloured Manual (Penning-Rowsell et al., 2006), have been used as the main reference to estimate the economic damages of flooding in the urban areas of the Plentzia Estuary.

Considering the available information for the case studies, the following categories of impacts have been defined:

Direct impacts on properties

The costs of direct impacts have been estimated based on data from the UK (Penning-Rowsell et al., 2006), and then transferred to the Basque Country by using the consumer price index and the PPP index for Spain[56]. The Multi-coloured Manual (Penning-Rowsell et al., 2006) provides information on different types of costs that vary with flood depth and duration[57]. The document follows a different approach for residential and non-residential properties.

In the case of residential properties, direct damages of a flood are divided in three main categories: damages to the building fabric, damages to household inventory and clean-up costs. Each of these categories includes several subcategories, as shown in Table 5.16. The costs for each of these sub-categories depend on two variables: water depth and the type of household (detached, semi-detached, terraced or apartments). Costs are given in euros per square metre, so an average surface of households in the case study site was used in the calculations.

Some elements not specified in the Multi-coloured Manual were also included in the assessment. This is the case of garages, basements or household entrances in apartment buildings. To estimate these costs without specific data, some assumptions had to be made. In relation to garages, when the surface could not be measured using GIS services (in the case of underground garages, for example), an average of 25 m^2 were assigned. This surface would include the parking spot and the proportional share of the corresponding commons spaces. With regard to the costs, only those related to damages in the building and clean-up were included.

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[56] CPI and PPP indexes were obtained from the OECD statistics at http://www.oecd.org/std.

[57] As coastal extremes are being assessed, only events with a duration below 12 hours have been considered.

Table 5.16. Classification of direct damages to residential properties, based on the Multi-coloured Manual (FHRC, 2006).

Direct cost category	Level	Sub-categories of costs
A. Damages to building fabric	A.1. Household	External main building
		Plasterwork
		Floors
		Joinery
		Internal decorations
		Plumbing and electrical
	A.2. Gardens & Exteriors	Paths and paved areas
		Gardens/fences/sheds
B. Damage to household inventory items	B.1. Household	Domestic appliances
		Heating equipment
		Audio/video
		Furniture
		Personal effects
		Floor coverings/curtains
	B.2. Garden	Garden/DIY/leisure
C. Clean-up cost	Household	Domestic clean-up

Often, especially in apartment buildings, first floor houses are elevated so only basements, garages and house entrances are at flood risk. In relation to basements, the surface of the building was considered in these cases and it was assumed that the costs of these assets were 20% of those corresponding to households, as it is expected that many appliances and inventory items would not be found here. As in the previous case, only building-related and clean-up costs were considered. Regarding building entrances, an average of 20 m^2 was estimated and again, only building-related and clean-up costs were taken into account.

Flooding costs to non-residential properties can be estimated based on four variables, as shown in Figure 5.8. The first variable is related to the economic activity developed in each property at risk. The Multi-coloured Manual provides damage costs[58] for a wide range of economic activities, but only those identified, which are listed in the figure, have been used in this study.

The second variable refers to those elements that can result damaged and are also taken into account when estimating the costs and these can be related to the building structure, its services, the moveable equipment, the fixtures and fittings and the existing stock. Water depth is the third variable that determines the damages of a flood event, which is known as it has been measured when determining the physical characteristics of floods; the fourth and last variable is the susceptibility, which is a factor, estimated for each of the elements at risk, that is then multiplied by the average value of each of the elements. Elements with a higher susceptibility are expected to have greater damages. E.g., a warehouse where the stock is kept underground or at ground floor level presents a higher susceptibility to flooding and is expected to suffer greater damages. The Multi-coloured Manual provides maximum, minimum and average susceptibilities for each of the elements at risk and only average susceptibilities have been accounted for.

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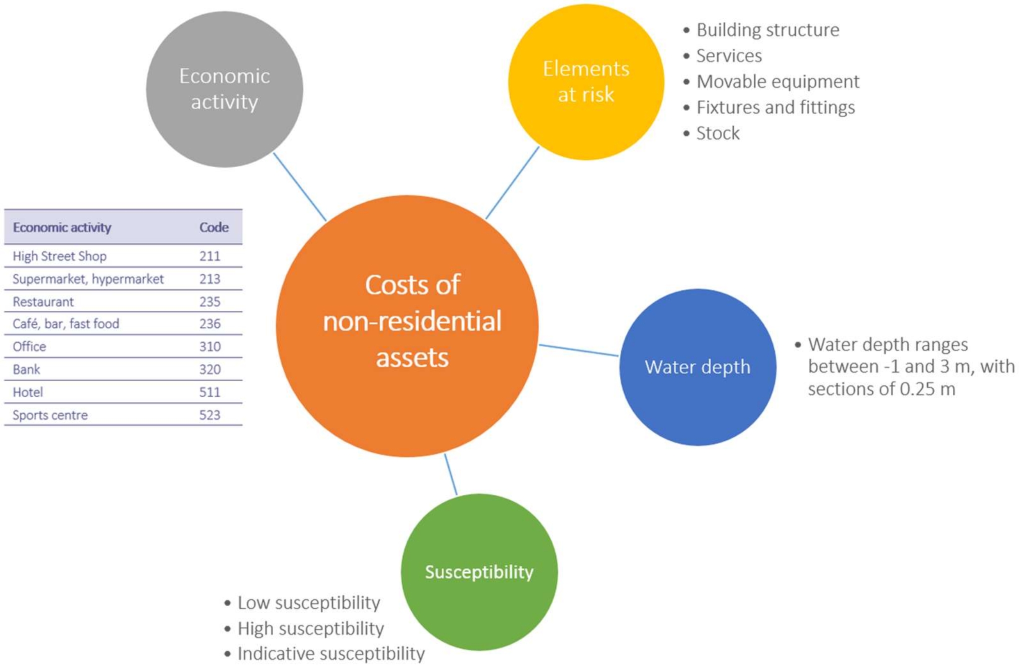
[58] Costs are originally provided in sterling pounds (2003) per square metres and have been transformed into euros (2013) per square metre, with CPI and PPP indexes.



Economic activity	Code
High Street Shop	211
Supermarket, hypermarket	213
Restaurant	235
Café, bar, fast food	236
Office	310
Bank	320
Hotel	511
Sports centre	523

Figure 5.8. The costs of non-residential assets depend on four variables related to the economic activity developed in the property, the elements at risk, the susceptibility and the water depth.

Indirect impacts

There are many types of indirect costs that can be analysed but only impacts on households and non-residential buildings are considered.

Residential properties

When a household is flooded, the people living there might need temporary relocation. Studies carried out for the UK provide references to estimate these effects (Penning-Rowsell et al., 2006) and the Basque Government (2007) transferred these values to the Basque Country. According to these estimates, when flooding exceeds 30 cm, 50% of the households would need relocation for an average period of 30 days.

Besides, affected households will need to use dehumidifiers to help the household-drying process. The extra cost due to the electricity consumed by this equipment was obtained following the British reference. For water depth below 10 cm, 4 dehumidifiers are needed during 28 days and the period doubles for water levels above 10 cm. The average consumption of the dehumidifiers is calculated to be 3 kW per hour. However these are estimates for UK household sizes (52 m^2), which have been adapted to this case study.

Non-residential assets

Apart from the direct damages caused by flooding, some commercial activities may be forced to stop their activities for some time. Based on references from the FHRC Multi-coloured Manual (Penning-Rowsell et al., 2006), the Basque Government (2007) estimated that non-residential buildings (shops, warehouses, offices…) would suffer an average loss of 116 $\text{euros}_{2005}/\text{m}^2$ for floods exceeding 1.5 m depth. However, this depth is not measured in any of the GBSLR scenarios under assessment (only in Scenario 4, whose economic appraisal has been discarded due to its long-term nature), therefore this cost category is not applicable to this study.

Impacts on human health

Floods may cause important damages to human health, going from death or physical injuries, to psychological effects, such as anxiety caused by the event itself, loss of personal belongings, the stress of the risk of future events or the tension associated to dealing with insurance reclamations or repair works in the household.

The methodology to assess the first kind of impacts requires data on the velocity of water when a flood occurs. Unfortunately, data that are not available for the present case studies (Osés Eraso, 2009). Therefore, only indirect effects on health will be assessed, based on a study of the British Department of Environment (DEFRA, 2004), adapted to the Basque Country by the Basque Government (2007).

Table 5.17 shows some of the results of those data obtained for the Basque Country (Basque Government, 2007). Indirect health impacts are considerable particularly for river floods with return periods of 100 and 500 years and they can exceed 8000 euros per event only due to anxiety derived from the flooding.

Table 5.17. Economic estimates of health impacts due to anxiety for different flood-return periods (RP). Column 3 shows the data as an annual flow value while column 4 shows the estimates per event.

Flood return period (RP) (1 in X years)	Annual flood probability (1/RP)	Health damages at RP (euros/household·year)	Health damages at RP (euros/household·event)
10	0.1	8	207
100	0.01	349	8,234
500	0.002	348	8,216

Source: Basque Government (2007).

Note: damages originally in euros (2005) have been transformed into euros (2013) using the corresponding CPI index.

However, this study does not look at river flooding and neither does it consider probability in terms of different return periods. Instead, coastal flooding is estimated through the GBSLR scenarios. If indirect impacts on human health were to be considered, an analogy between river-floods in Plentzia and GBSLR scenarios was necessary. The Basque Water Agency provides open access to official flood-risk maps, for different return periods. By using GIS systems, these maps were examined in contrast to the coastal flood-risk maps developed in Chapter 3. Two characteristics of both maps were then analysed:

- The extension of the flooded areas
- The different flood depths

In summary, indirect health costs were estimated based on the analogy between coastal flood scenarios developed in Chapter 3 and official river flood-risk maps.

Other impacts

Many other impacts can be considered, such as the disruption of railway transport and the use of emergency services. In this case we follow on:

Disruption of rail transport

The costs of the disruption of the railway as a result of a flooding have also been considered in this analysis. In order to calculate these impacts, the number of passengers is first determined. As the company Metro Bilbao has not established economic compensations due to delays caused by flooding, the compensation policy of the British Railtrack has been used.

To estimate the time of disruption we should go again to the document by the Basque Government (2007), which indicates that a 48-hour disruption can be expected for a 100 year return period (RP), and this time increases up to 195 hours for the floods with 500 year RP. The final cost will be the product among the cost per hour and the number of hours during which the service is delayed.

It is important to note that these costs will only be applied when the railway system is affected by flooding.

Emergency costs

The estimates are based on the data from the FHRC Multi-coloured Manual (Penning-Rowsell et al., 2006) which estimated that the total costs related to the emergency services represent 10.7% of the direct total losses on households, and this is the reference used.

Impacts NOT considered

Due to the lack of data, there are many impacts that have not been considered, but it is worth noting for further research. The most relevant impacts that could not be considered in this study were:

- Direct impacts on human health
- Direct physical damages to public infrastructure and flood protection infrastructure.
- Disruption of road transport.
- Second order impacts on neighbouring zones.
- Disruption of public services.

5.4.3 Results: the cost of coastal flooding in Plentzia

Based on the results presented in Chapter 3, coastal flooding would only affect the urban area along the Plentzia Estuary when considering MAHT level on GBSLR Scenarios 1 and 3. Coastal flooding associated to MAHT levels in this dissertation represents the level reached by an extreme event when the nature of flooding would not be permanent, but temporary. More precisely, in order to estimate the economic damages of this extreme event, it has been assumed that flooding has duration less than 12 hours.

In this context, there are five main areas vulnerable to coastal flooding along the Plentzia Estuary. These areas, presented in Figure 5.9, are the following:

- In the lower estuary:

  A. San Telmo neighbourhood (municipality of Barrika).
  B. Ibiltokia area in the northern Plentzia urban centre.
  C. Erribera area, in the southern part of the Plentzia urban centre.
  D. Txipio area, close to the salt marsh of the same name (Plentzia).

- In the upper estuary:

  E. Isuskiza residential area (Plentzia).

San Telmo (Figure 5.9, A) is a small household area located in the municipality of Barrika. The neighbourhood is placed on the left bank of the lower estuary and consists mainly of a small number of detached and semi-detached houses, with a couple of apartment buildings. The area identified as Ibiltokia is located in the northern part of the Plentzia urban centre (Figure 5.9, B). The focus of the analysis will be on the households located in the Ibiltokia and Labasture Streets, as these are the areas most at risk of flooding. Different types of residential buildings can be found in this area: apartment buildings are predominant in Labasture Street, while detached and semi-detached houses dominate in Ibiltokia Promenade. Even if this is not a commercial area, some non-residential properties can also be found.

Erribera is a low-lying area located in the southern part of Plentzia's urban centre (Figure 5.9, C). Zugaitz bidea promenade and Erribera Street go parallel to the estuary and are the main areas at risk, together with other relevant public infrastructures such as the City Hall and the sports centre. In contrast with San Telmo and Ibiltokia, this area is dominated by apartment buildings, with varied commercial activity at ground floor level. The Txipio salt marsh, located in the left bank of the lower estuary, has given its name to the surrounding area. In this area there is a small town centre, mainly formed by apartment buildings, and several sparse country houses (Figure 5.9, D), linked with the rest of Plentzia's urban area through a pedestrian bridge that crosses the estuary. Plentzia's Railway Station is also located in this neighbourhood.

The last area is located in the upper estuary, in the zone limited by the river meander and known as Isuskiza (Figure 5.9, E). One single detached house has been found to be at risk of flooding in this area, already under the current MAHT level. The rest of houses do not get affected by flooding under any of the scenarios considered.

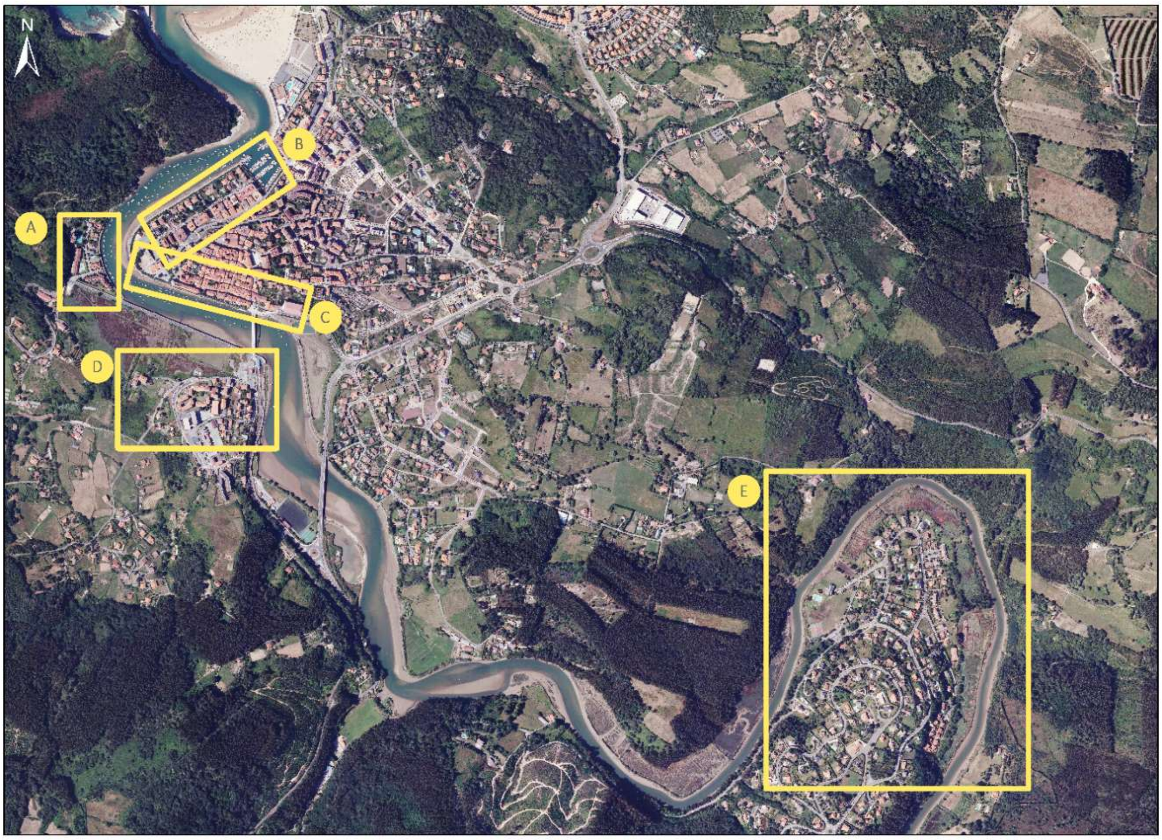


Figure 5.9. Urban areas potentially affected by flooding in the Plentzia Estuary. A. San Telmo. B. Ibiltokia. C. Erribera. D. Txipio. E. Isuskiza.

The information from the regional cadastre has been the base to identify the assets exposed to the risk of coastal flooding. This information was complemented with the data gathered on the field in relation to the typology and location of residential and non-residential properties in the town of Plentzia[59]. The fieldwork consisted in the identification and photo report of all the residential and non-residential properties located in those areas potentially affected by flooding, according to the flood-risk maps built in Chapter 3. The full list of assets exposed to the risk of flooding has been included in Appendix I.

A. Damage costs on GBSLR Scenario 1

GBSLR Scenario 1 represents a rate of sea-level rise equal to that registered in the Basque coast along the 20th century, i.e., 2 mm yr^{-1}. No damages are expected in Plentzia only due to the rise in mean sea level. However, this increase in MSL would contribute to more severe extreme events, represented in this study by MAHT-level flood events. The risk of MAHT flooding concentrates in three specific areas under GBSLR Scenario 1: Txipio, Isuskiza and Erribera, even though the latter is only affected in a few frontline houses by the end of the century.

The damage estimates are evaluated for each category of costs described in the previous section.

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[59] The San Telmo neighbourhood located in the left bank of the lower estuary belongs to the municipality of Barrika, and therefore cadastral data from this town have also been consulted.

Direct impacts on properties

The economic costs associated with damages to residential properties under GBSLR Scenario 1 (Anthropocene) are presented in Table 5.18. A low and high estimate is provided for each area and time period considered. Damages by 2030 are equal to those of the baseline, and increase slowly from 2050 onwards. The impacts on Isuskiza are limited to a single detached household, so the higher costs occur in Txipio, where a larger area is affected. A small zone in Erribera would be affected by the end of the century, but flood depth would be below 4 cm, so the costs are estimated to be very low.

Table 5.18. Summary of the estimated (undiscounted) costs of coastal flooding on the residential properties of Txipio, Isuskiza and Erribera areas under GBSLR Scenario 1. Data are in euros per extreme event (undiscounted).

RESIDENTIAL		Erribera		Txipio		Isuskiza		TOTAL	
		Low	High	Low	High	Low	High	Low	High
Baseline		0	0	136,375	237,544	63,570	63,570	199,944	301,113
Scenario 1	2030	0	0	136,375	237,544	63,570	73,046	*199,944*	*310,589*
	2050	0	0	237,544	268,848	63,570	73,046	*301,113*	*341,894*
	2080	0	0	237,544	268,848	73,046	82,523	*310,589*	*351,371*
	2100	2509	36,651	276,221	405,439	73,046	82,523	*351,776*	*524,613*
	TOTAL	**2509**	**36,651**	**887,683**	**1,180,678**	**273,231**	**311,138**	**1,163,423**	**1,528,468**

In the case of non-residential properties impacts are limited to Erribera and Txipio. In the Erribera area damages would only occur by 2100 and even then flooding would only affect a small frontline area so the costs would be low. Non-residential assets in Txipio are scarce thus even if flooding affects this neighbourhood under current MAHT levels, damage costs would be small. Considering the high range in GBSLR Scenario 1, the total costs of a coastal extreme event that reaches the MAHT level in Plentzia would range from almost 9000 euros[60] currently to 87,426 euros in 2100. Further details are provided in Table 5.19.

Table 5.19. Damage costs of coastal flooding on non-residential properties located in Txipio and Erribera areas (Plentzia). Data are in euros per extreme event (undiscounted).

NON-RESIDENTIAL		Erribera		Txipio		TOTAL	
		Low	High	Low	High	Low	High
Baseline		0	0	4270	8942	4270	8942
Scenario 1	2030	0	0	4270	8942	4270	8942
	2050	0	0	4270	8942	4270	8942
	2080	0	0	8942	13,906	8942	13,906
	2100	34,332	73,520	8942	13,906	43,274	87,426
	TOTAL	**34,332**	**73,520**	**26,424**	**45,696**	**60,756**	**119,216**

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[60] All damage costs in this chapter are estimated in Euros (2013).

Indirect impacts on residential properties

As explained previously in Section 5.4.2, when flood-level exceeds 30 cm it is estimated that 50% of the residential households will need relocation for an average period of 30 days. In the Erribera area flood depth would be limited to 4 cm, so no relocation would be needed.

In the Txipio neighbourhood floods would only exceed the 30 cm threshold by 2100 and this impact would be limited to four specific households. One of them has an elevated entrance and only the basement is located at ground floor level, so the need for relocation is discarded in this case. Accordingly, only 3 households are finally taken into account. According to Eustat, the average cost of a rental accommodation in Biscay in 2013 was 838.8 euros per month, approximately 28 euros per day. Indirect costs due to relocation in GBSLR Scenario 1 can be estimated multiplying this accommodation cost by the number of households in Txipio that would need relocation. The total cost would be 2516.40 euros.

Another indirect cost to take into account is that related to the need of using dehumidifiers after a flooding whose depth exceeds 10 cm. According to Eurostat (2013), the average price of the kilowatt per hour in Spain in 2013 was 0.2251 euros. A cost of 10,514 euros was obtained for Txipio on the basis that 4 dehumidifiers would need to be used per household during 28 days (Osés Eraso, 2008). The average house size in Plentzia[61] is 100.4 m^2, which represents a consumption of 5.8 kW per hour and household. This cost would remain constant for the baseline and each year considered in the scenario, as the number of houses affected by flooding would not increase.

Indirect impacts on human health

No impacts are expected under GBSLR Scenario 1.

Disruption of rail transport

Plentzia Railway Station would not be affected by flooding on GBSLR Scenario 1.

Emergency costs

Emergency costs can be estimated as a 10.7% of the total direct losses on households. For GBSLR Scenario 1 the average emergency costs range from 27,314 euros (2013) in 2030 to almost 47,000 euros (2013) by the end of the century. Details are shown in Table 5.20.

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[61] Eustat, 2013. Basque family household statistics by province according to structural characteristics. Dataset.

Table 5.20. Total emergency costs in Plentzia for coastal extreme events occurring under GBSLR Scenario 1. Data are in euros per extreme event (undiscounted).

RESIDENTIAL		TOTAL DIRECT LOSSES		EMERGENCY COSTS		
		Low	High	Low	High	Average
Baseline (2010)		199,944	301,113	21,394	32,219	26,807
Scenario 1	2030	199,944	310,589	21,394	33,233	27,314
	2050	301,113	341,894	32,219	36,583	34,401
	2080	310,589	351,371	33,233	37,597	35,415
	2100	351,776	524,613	37,640	56,134	46,887

Summary of economic impacts under GBSLR Scenario 1

The results of the monetary impacts of a coastal flood event in Plentzia under GBSLR Scenario 1 for different years are presented in Table 5.21. The data are estimated using 0%, 3% and 6% discount rates.

Damage costs vary greatly depending on the discount rate applied. For undiscounted estimates, the impacts increase gradually and damages reach 0.4-0.7 million euros for a MAHT level flood event by the end of the century. When applying larger discount rates, the highest impacts are measured in 2030 and then decrease, being negligible by 2100.

Table 5.21. Present value of the damage costs due coastal flooding in Plentzia under GBSLR Scenario 1. The present value has been estimated using 0% (undiscounted), 3% and 6% discount rates. All the results are in thousands of euros.

Types of impacts		2030			2050			2080			2100		
		DR 0%	DR 3%	DR 6%	DR 0%	DR 3%	DR 6%	DR 0%	DR 3%	DR 6%	DR 0%	DR 3%	DR 6%
a. Direct impacts	Residential	200-311	121-188	74-115	301-342	101-115	35-40	311-351	43-48	3-7	352-525	27-40	2-3
	Non-residential	4-9	2-5	1-2	4-9	1-3	0	9-14	1-2	0	43-87	3-6	0
b. Indirect impacts	Relocation	0	0	0	0	0	0	0	0	0	3	0	0
	Dehumidification	11	6	3	11	3	1	11	1	1	11	1	1
c. Indirect impacts on human health		0	0	0	0	0	0	0	0	0	0	0	0
d. Other impacts	Railway transport disruption	0	0	0	0	0	0	0	0	0	0	0	0
	Emergency costs	31-33	12-18	7-10	32-37	10-11	3-4	33-38	4-5	1	38-56	3-4	0
Total costs		**236-363**	**141-217**	**85-131**	**348-398**	**115-132**	**39-44**	**363-413**	**50-56**	**8-9**	**446-681**	**33-51**	**3-4**

B. Damage costs on GBSLR Scenario 3

GBSLR Scenario 3 represents the highest rate of sea-level rise for the next century, measured in 10 mm yr^{-1}. According to the results from Chapter 3, the increase in mean sea level under this scenario is important, but no urban areas are expected to suffer from direct flooding. However, when considering MAHT level the expected impacts are very important. All the urban areas in Plentzia would be affected by this extreme sea level, although not all of them at the same degree.

Direct impacts on properties

Direct impacts have been evaluated and the estimated losses are presented in Table 5.22. The biggest losses are expected in Ibiltokia, even though flooding would not affect this area until 2080. In this year, losses would range between 2.4 and 2.5 million euros (2013). The next area most affected would be the San Telmo neighbourhood. Impacts range from 0.9 in 2050 to 1.7-1.9 million euros by the end of the century. In these two areas detached, semi-detached and terrace houses, which have higher damage costs, are proportionally abundant compared to Erribera and Txipio. Also, flood depths up to 90 cm are expected by the end of the century and damages increase considerably with depth.

Table 5.22. Summary of direct costs on residential assets under GBSLR Scenario 3. Data are provided in millions of euros per extreme event (undiscounted).

RESIDENTIAL		San Telmo		Ibiltokia		Erribera		Txipio		Isuskiza		TOTAL	
		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Baseline		0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.24	0.06	0.06	0.20	0.30
Scenario 3	2030	0.00	0.00	0.00	0.00	0.20	0.20	0.30	0.34	0.07	0.08	0.58	0.62
	2050	0.89	0.91	0.00	0.00	0.85	0.90	0.44	0.48	0.08	0.08	2.27	2.38
	2080	1.61	1.76	2.41	2.51	1.05	1.15	0.57	0.61	0.09	0.09	5.73	6.11
	2100	1.76	1.85	2.90	3.19	1.19	1.24	0.67	0.70	0.09	0.10	6.60	7.08
	TOTAL	4.26	4.52	5.31	5.69	3.30	3.49	0.00	2.13	0.33	0.35	15.18	16.18

Damage costs would be highest in Erribera, due to the fact that there are several semi-detached and terraced houses on its frontline, which show higher damage costs than other residential assets, such as apartment buildings. The Txipio neighbourhood is exposed even to current MAHT-level extremes but, the neighbourhood grows westwards on a hill, and only households located in the lower lying areas closer to the Txipio marsh would suffer the impacts of a coastal extreme event of this nature. Significant impacts are expected in Isuskiza considering that a single house is at risk of flooding.

The main impacts in relation to non-residential properties are concentrated in the Erribera area. This was an expected result as this is the main commercial area of Plentzia. By 2050 losses in Erribera could reach between 0.5 and 1.3 million euros per extreme event. In 2080 the costs raise up to 2.1 million euros and by the end of the century the high estimate provides losses of 3.3 million euros only in this small area of Plentzia. Results are shown in Table 5.23.

Table 5.23. Costs of coastal flooding on non-residential properties in the Plentzia Estuary. Data are in millions of euros per extreme event (undiscounted).

NON- RESIDENTIAL		San Telmo		Ibiltokia		Erribera		Txipio		Isuskiza		TOTAL	
		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Baseline		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Scenario 3	2030	0.00	0.00	0.00	0.00	0.01	0.02	0.01	0.01	0.00	0.00	0.02	0.04
	2050	0.00	0.00	0.00	0.00	0.53	1.28	0.01	0.02	0.00	0.00	0.55	1.30
	2080	0.00	0.00	0.16	0.26	2.10	2.15	0.02	0.02	0.00	0.00	2.28	2.43
	2100	0.00	0.00	0.27	0.33	2.49	3.31	0.04	0.08	0.00	0.00	2.80	3.72
	TOTAL	0.00	0.00	0.43	0.59	5.14	6.77	0.08	0.13	0.00	0.00	5.65	7.49

Indirect impacts on properties

Two types of indirect impacts are measured on residential assets. The first is related to the need to relocate the people living in a household due to the damages suffered during the flood. As explained for GBSLR Scenario 1, 50% of all residential households need relocation for an average of 30 days when flood-level exceeds 30 cm. The results have been calculated by multiplying the number of households affected by floods deeper than 30 cm by the average cost of a rental accommodation in Biscay, which in 2013 was 838.8 euros per month. Total relocation costs range from little more than 2000 euros in 2030 to 23,000 euros by 2100 (Table 5.24).

Table 5.24. Estimation of total relocation costs. Half of the houses affected by floods exceeding 30 cm have been included as subject to relocation. All cost estimates are provided in euros (undiscounted).

Scenario 3	San Telmo		Ibiltokia		Erribera		Txipio		Isuskiza		Total Relocation Costs
	Houses	Cost	Houses	Cost	Houses	Cost	Houses	Cost	Houses	Cost	
2030	0	0	0	0	0	0	1.5	1258	1	839	**2097**
2050	1	839	0	0	4	2936	1.5	1258	1	839	**5872**
2080	8	6710	9	7130	5	4194	2	1678	1	839	**20,551**
2100	8	6710	9	7130	6	5033	2	1678	1	839	**21,389**

The second kind of indirect impact is based on the need for installing dehumidifiers when a household is affected by a flood surpassing 10 cm in depth. Table 5.25 shows the total electricity costs per year and urban area. The areas with more apartment buildings where households are usually not located at ground level show the lowest costs, namely, Erribera and Txipio. The opposite happens in the sites where more detached, semi-detached and terraced houses can be found, i.e. San Telmo and Ibiltokia.

Table 5.25. Estimation of total relocation costs. Half of the houses affected by floods exceeding 30 cm have been included as subject to relocation. All cost estimates are provided in euros (undiscounted).

Scenario 3	San Telmo		Ibiltokia		Erribera		Txipio		Isuskiza		Total Electricity Costs
	Houses	Cost	Houses	Cost	Houses	Cost	Houses	Cost	Houses	Cost	
2030	0	0	0	0	4	3355	3	10,514	1	3505	**17,374**
2050	13	45,562	0	0	11	38,552	3	10,514	1	3505	**98,133**
2080	16	56,076	17	59,581	12	42,057	4	14,019	1	3505	**175,237**
2100	16	56,076	21	73,600	12	42,057	4	14,019	1	3505	**189,256**

Indirect impacts on human health

Indirect impacts on health after a flood event, such as anxiety and stress associated with the tasks post-event, are very common and can be valued in economic terms. As explained in Chapter 5, the report by the Basque Government on the costs of flooding in Bilbao (Basque Government, 2007) includes some estimates of the costs linked to indirect impacts on health. These costs vary according to the return period of floods, so an analogy between coastal flood scenarios from Chapter 3 and river floods has been carried out (see Table 5.12). Based on this analogy, costs were calculated using the data from the report by the Basque Government (2007). According to the result shown in Table 5.26, costs during the first half of the 21st century would be zero or negligible, but would reach 243,000 euros in 2080 and 436,000 euros by 2100.

Table 5.26. Estimation of indirect health costs. All cost estimates are provided in euros (undiscounted).

Scenario 3	San Telmo		Ibiltokia		Erribera		Txipio		Isuskiza		Total Health Costs
	Houses	Cost	Houses	Cost	Houses	Cost	Houses	Cost	Houses	Cost	
2030	0	0	0	0	4	0	3	0	1	0	0
2050	13	2693	0	0	11	2279	3	0	1	0	4972
2080	16	3315	17	139,977	12	98,807	4	829	1	0	242,927
2100	16	131,743	21	172,912	12	98,807	4	32,936	1	0	436,398

Disruption of rail transport

The first step to estimate the economic impacts associated with the disruption of rail transport is to determine the number of passengers. According to Metro Bilbao[62], in 2010 Plentzia Railway Station had 642,488 passengers, which makes 1760 every 24 hours. The next table shows the cost estimates for Plentzia, based on the report by the Basque Government (2007) which calculated 21 euros per passenger and delayed hour and 12 euros per cancellation, taking as a reference the compensation

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[62] Metro Bilbao (2015). [Comparative table of passengers per station - Tabla comparativa de viajeros y viajeras por estación]. Retrieved from https://www.metrobilbao.eus/conocenos/metro-en-cifras-viajeros-y-calidad/datos-de-viajeros-y-viajeras.

policy of the British Railtrack for delays associated to flooding events[63]. When a flooding occurs, approximately 40% and 60% of the services are cancelled or delayed, respectively (Basque Government, 2007). This translates into a cost of 523 euros per hour for cancelled services and 622 euros per hour for disrupted services.

To estimate the total disruption costs a 48-hour disruption has been considered for a 100 year RP, and this time increases up to 195 hours for the floods with 500 year RP (Basque Government, 2007). The final cost is the product of the cost per hour and the number of hours during which the service is delayed.

In the case of Plentzia, the Railway Station would only get flooded under Scenario 3 and under 500 year RP river flood events. However, flood depth would reach approximately 31 cm, so using the disruption time related to 500 year RP seems excessive, and that of the 100 year RP has been used. The total costs obtained for Plentzia under Scenario 3 by 2100 reach 55,000 euros (2013).

Table 5.27. Estimated costs of railway transport disruption in Plentzia.

Plentzia Railway Station	Passenger journeys				Costs per hour		Costs per event		Total costs
	2010	2010	Cancelled	Disrupted	Cancelled	Disrupted	Cancelled	Disrupted	
	year	24 h	60% /h	40% /h	euros/h	euros/h	euros/event	euros/event	euros/event
1/10 year RP	642,488	1760	44	29	523	622	25,083	29,865	54,948

Source: adapted from Basque Government (2007).

Emergency costs

As in GBSLR Scenario 1, emergency costs are calculated as the 10.7% of the total direct losses on households. In Scenario 3 emergency costs would range from 64,000 euros (2013) in 2030 up to 732,000 by 2100, as shown in Table 5.28.

Table 5.28. Total emergency costs in Plentzia for coastal flooding under GBSLR Scenario 3. Data are shown in euros (undiscounted).

RESIDENTIAL		TOTAL DIRECT LOSSES		EMERGENCY COSTS		
		Low	High	Low	High	Average
Baseline		199,944	301,113	21,394	32,219	26,807
GBSLR Scenario 3	**2030**	581,735	624,769	62,246	66,850	64,548
	2050	2,266,102	2,375,032	242,473	254,128	248,301
	2080	5,728,964	6,105,311	612,999	653,268	633,134
	2100	6,603,383	7,077,181	706,562	757,258	731,910

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[63] Metro Bilbao has not established economic compensations due to delays caused by flooding.

Summary of the costs of flooding under GBSLR Scenario 3

The costs of flooding under GBSLR Scenario 3 are significantly greater than those calculated for Scenario 1. Even if the commercial area is affected greatly under this scenario, the biggest impacts are associated with damages to residential properties, as in Scenario 1. The results obtained for each category of impacts is summarised in

Table 5.29, considering discount rates of 0%, 3% and 6%.

Undiscounted costs during the first half of the 21st century are quite low. In 2030 the costs range between 0.69 and 0.75 million euros for the whole urban area along the estuary. By 2050 the damage costs raise to 3-4 million euros but the greatest increase occurs at 2080, when impacts more than double in relation to 2050. By 2100 the impacts of an extreme event that reached MAHT levels would rise up to 11-12 million euros. Results vary considerably when market-based discount rates are applied. With a 3% discount rate damage costs increase slowly up to 2080 when they reach 1.2 million euros and then start to decrease. The evolution of the costs associated with a coastal extreme event when applying a 6% discount rate reaches the highest peak by 2050, and then slowly decline. The highest total costs per extreme event when using a 6% discount rate reach 1.1 million euros by mid-century.

Table 5.29. Present value of the damage costs due to coastal flooding in Plentzia under GBSLR Scenario 3. The present value has been estimated using 0% (undiscounted), 3% and 6% discount rates. All the results are in millions of euros.

Types of impacts		2030			2050			2080			2100		
		DR 0%	DR 3%	DR 6%	DR 0%	DR 3%	DR 6%	DR 0%	DR 3%	DR 6%	DR 0%	DR 3%	DR 6%
a. Direct impacts	Residential	0.6	0.3-0.4	0.2	2.3-2.4	0.7	0.2	5.7-6.1	0.7-0.8	0.1	6.6-7.1	0.5	0
	Non-residential	0	0	0	0.5-1.3	0.2-0.4	0.1	2.3-2.4	0.3	0	2.8-3.7	0.2-0.3	0
b. Indirect impacts	Relocation	0	0	0	0	0	0	0	0	0	0	0	0
	Dehumidification	01	0	0	0.1	0	0	0.2	0	0	0.2	0	0
c. Indirect impacts on human health		0	0	0	0	0	0	0.2	0	0	0.4	0	0
d. Other impacts	Railway transport disruption	0	0	0	0	0	0	0	0	0	0.1	0	0
	Emergency costs	0.1	0	0	0.2-0.3	0.1	0	0.6-0.7	0.1	0	0.7-0.8	0-0.1	0
Total costs		**0.7**	**0.3-0.4**	**0.2**	**3.2-4.0**	**1.0-1.2**	**0.3**	**9.1-9.6**	**1.1-1.2**	**0.2**	**10.8-12.3**	**0.8-0.9**	**0.1**

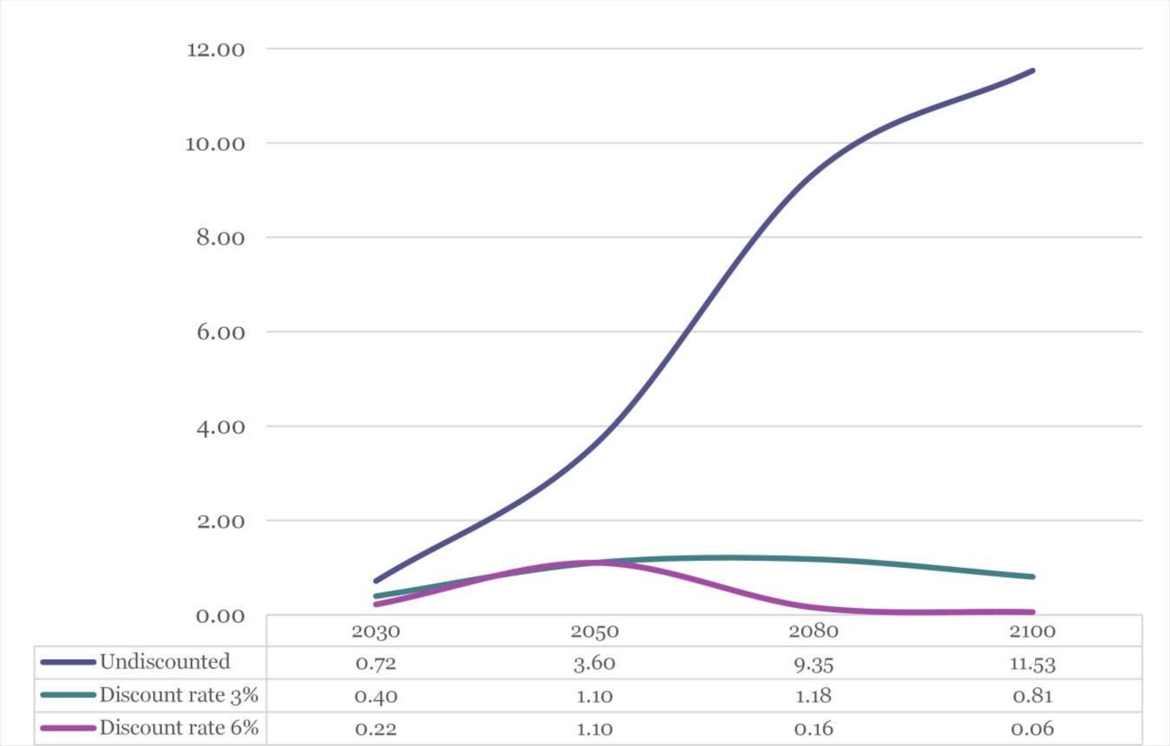
5.4.4 Discussion

The estimated economic impacts for the urban area of the Plentzia Estuary vary greatly depending on two main factors. The first factor relates to the GBSLR scenario. GBSLR Scenario 1 is built based on sea-level rise rates of 2 mm yr^{-1}, while GBSLR Scenario 3 is 5 times greater, therefore the risk is very different in each case. Under GBSLR Scenario 1, mainly the Txipio and Isuskiza areas are affected, and Erribera only by the end of the century. The affected area but also the flood depth are much smaller in this first scenario, and accordingly, economic impacts are also smaller, around two orders of magnitude.

The second factor is related to the discount rate applied. The calculations have been made undiscounted but also considering two market-based discount rates, a lower (3%) and a higher rate (6%). Not only the results are different in absolute terms depending on the discount rate, but the evolution of the impacts are also different. In GBSLR Scenario 1 undiscounted damage costs increase progressively until the end of the century, which is explained by the fact that as sea level rises, the damages are greater. When market based discount rates are applied, the highest costs would occur by 2030 and then decrease gradually to become negligible by 2100. The evolution of costs associated to MAHT-level extreme events under GBSLR Scenario 3 are shown in Figure 5.10. The curve representing undiscounted costs shows a similar shape of that of salt marsh loss presented in Figure 5.6: the impact would increase considerably from 2050 to 2080, and then the trend slows down. This result could suggest that sea-level rise in this period might exceed some threshold in the Plentzia Estuary. The economic impacts when discount rates are applied also follow different trends. For the lower discount rate the costs would increase from 0.4 to 1.2 million euros in 2080, and then the impacts would decrease by the end of the century. When using a 6% discount rate, however, the highest costs are reached in 2050 and then start to reduce. By 2100 the impacts would barely reach 65,000 euros for a MAHT level flood event.

Regarding previous results of other studies carried out in the Basque Country, average annual damage costs linked to extreme flood events in Bilbao estimated in the study commissioned by the Basque Government (2007) were revealed to be much higher: between 225 and 275 million euros (2005) by 2080 in the baseline scenario, that did not include socio-economic changes nor climate change. These damages would increase in 56% due to the effect of climate change. Osés Eraso (2009) estimated the impacts of climate change on the risk of flooding in the Urola watershed (Gipuzkoa, Basque Country). The expected annual damages ranged from 7600 euros (2005) in the municipality of Zumarraga to 29,000 euros (2005) in Zestoa. In some cases, the effect of climate change more than doubled the costs under the baseline scenario. In Amurrio (Araba, Basque Country) annual average damages were estimated to be 56,000-64,000 euros (2005) and climate change was estimated to increase these costs by 15% (Galarraga et al., 2011c).

Obviously there are more valuable assets at risk in Bilbao than in Plentzia, or other small municipalities such as those located along the Urola River, and this is one of the reasons for having much higher damage costs in Bilbao. Anyway, coastal and river-flood risk are not easily comparable. As observed in Plentzia when comparing river-flood risk maps with GBSLR Scenarios is that fluvial extreme events are more severe, especially regarding water depth. Also, damage costs when assessing river-flood risk is usually given in terms of annual average damage, while the costs estimated for Plentzia are provided for each MAHT level flood event.



	2030	2050	2080	2100
Undiscounted	0.72	3.60	9.35	11.53
Discount rate 3%	0.40	1.10	1.18	0.81
Discount rate 6%	0.22	1.10	0.16	0.06

Figure 5.10. Increasing damage costs of extreme flooding in the Plentzia Estuary under GBSLR Scenario 3 (MAHT level). The data represents the costs associated with an extreme flood event that reaches MAHT levels following the sea-level rise rate of GBSLR Scenario 3.

Nevertheless, there are similarities between previous studies and the analysis of Plentzia: damages on residential properties are, by far, the main contribution to total costs. Damages related to emergency services and the impacts on non-residential properties are also significant, but the rest contribute very little to the total damage costs. In the studies assessing river-flood risk, direct health impacts played an important part of the total damages, but these could not be measured in Plentzia because the speed of the flood was not available.

5.5 The costs of flooding on industrial areas: the case study of Muskiz and the oil refinery of Petronor

Muskiz is a town located in the Biscayan Mining Zone. This area supported a major industrial activity and was decisive in the industrial development and spectacular economic growth of Biscay during the 19th century (Montero García, 1988). The economic activity that emerged from iron mining led to important advances, such as the development of shipping and rail infrastructure, the creation of the first iron and steel industry in the left bank of the Bilbao estuary (1882) or the development of a new bourgeois class (Montero García, 1988), which represented the basis for the economic activity in Biscay during the 19th and 20th centuries.

The modern sectorial distribution of the economy in the Muskiz municipality follows the general trend of Biscay and the Basque Country. Thus, the tertiary sector brings the highest percentage of the population, followed by construction and industry, although the percentage of population working for the industrial sector is slightly above the Biscayan rate. Moreover, Muskiz has a per capita GDP 64% above the mean for Biscay and the municipal tax collection per capita is enormous compared to the mean of the province and the Basque Country. All these indicators are capturing the impact of the Petronor oil refinery on the local economy. But the influence of the refinery is not limited to Muskiz, as its activity has a strong role on the regional economy as well. Taxes, for instance, and other associated economic activities.

However, the company is not out of question. Protests by environmental groups[64] and other social platforms[65] have intensified after decision of the company to implement a new project to refine fuel subproducts (new Units for Reduction of Fuel, also known as Coke treatment unit).

All these reasons make interesting to centre the economic assessment of this case study on the potential impacts of sea-level rise on the Petronor oil refinery.

5.5.1 Petronor in numbers

The Petronor Company was constituted in 1968 and the oil refinery was set up on the Muskiz Estuary in 1970. Currently it covers an area of 148 ha, 75% of the original estuary and is one of the largest oil refineries in the Iberian Peninsula (Cearreta et al., 2008). Today, 85.98% of the company is owned by the Spanish multinational Repsol and 14.02% by Kutxabank.

Petronor has an average annual production of 9.28 MTn, where diesel, fuel and gasoline represent around 85% of all products. Sales in 2013 reached 9.4 MTn, the national market representing 63% of all sales, compared to 37% of sales in the foreign market (Petronor, 2013). The same year, a total of 914 people were working at Petronor. In 2012 the URF (Units for Reduction of Fuel) project was set up, after an inversion of 850 million euros. With this new infrastructure the refinery transforms the heaviest components of oil, otherwise used to the production of fuel, into lighter products that

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[64] See, for example, Ecologistas en acción: http://www.ecologistasenaccion.org/article28268.html.
[65] Plataforma anticoke: http://coordinadoraanticoke.blogspot.com.es/

have a greater demand: liquefied gases (propane, butane), gasoline and diesel (Petronor, 2013). However, and despite this new activity line, during the last year Petronor had, for the first time in its history, negative economic results. In 2012 the revenues before taxes were -17.07 million euros, being even worse in 2013, when the company lost 87.51 million euros. Expanded data are shown in Appendix II.

Since the beginning of the economic crisis in 2008, demand has dropped both in Spain and Europe. Two are the key factors to explain the negative results of the last two years: the first, a weak demand[66] in a context of excess capacity; the second is related to the boom of non-conventional hydrocarbon in the USA that has forced a production and export increase of traditional oil products at lower prices. As a result, several oil refineries shut down in Europe during 2012 and 2013 (Petronor, 2012). In this context of severe crisis, the company has identified three main challenges: the new refining process (particularly since the URF unit is operating), cost reduction and innovation. Cost reduction focuses, largely, on CO_2 emission reduction. First, a 15% emission reduction was planned by 2016 but, as this objective was achieved during 2013, Petronor defined a new objective of 20% emission cuts by 2016. Also, the company explicitly states that environmental and energy efficiency measures are conceived as a competitiveness factor, instead of an irremediable expense (Petronor, 2013).

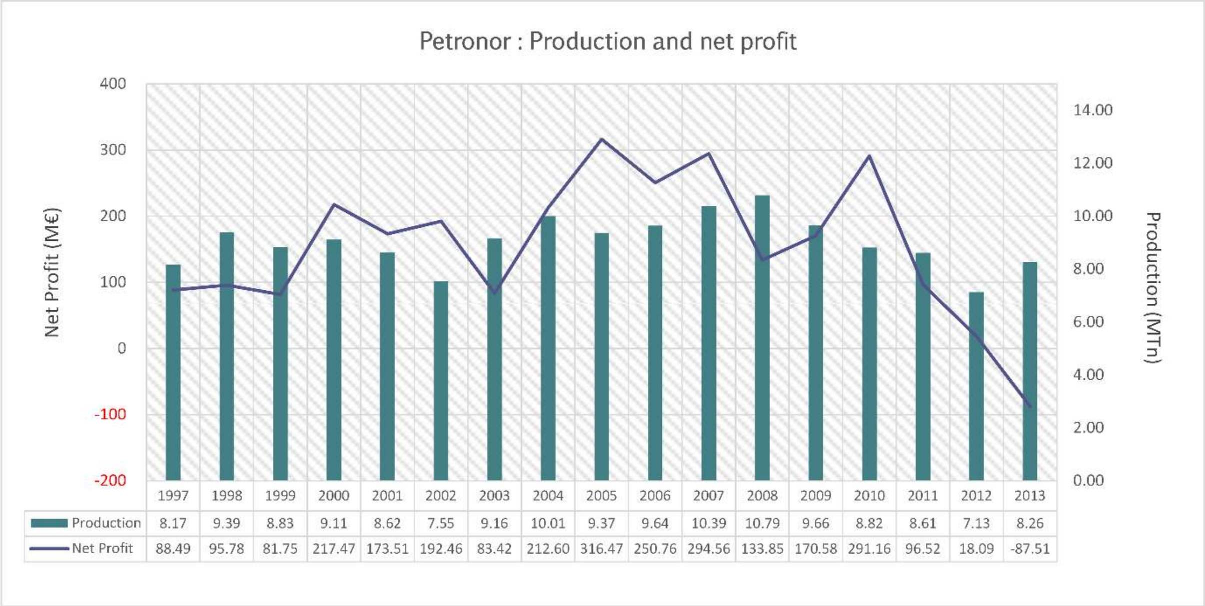

Figure 5.11. Evolution of the production (in million tons, right vertical axis) and net profit after tax (in million euros, left vertical axis).

However, climate change is not mentioned even once in the activity reports of Petronor, and it is most probable that climate policy will play a decisive role in the future of oil refineries in general, and Petronor in particular.

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[66] Petrol (gasoline) consumption dropped by 26% during the period 2007-2012 (Petronor, 2012).

5.5.2 Climate change and the future of fossil fuels

In the Cancun Summit celebrated in December 2011 the United Nations for the first time officially agreed that global temperature increase should stay below 2°C if irreversible and severe impacts are to be avoided (Galarraga et al., 2011b). The question is, how much CO_2 is possible to emit before exceeding the 2°C limit?

Meinshausen et al. (2009) estimated that in order to have a 75% chance of keeping warming below 2°C throughout the 21st century, carbon emissions for the period 2000-2050 should be limited to ~1000 gigatonnes of CO_2. They also calculated that "emitting the carbon from all proven fossil fuel reserves would vastly exceed the allowable CO_2 emission budget for staying below 2°C" (Meinshausen et al., 2009: 1160). This has been confirmed by a recent study from McGlade and Ekins (2015), which suggested that "globally, a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2°C." This message seems to be reaching the financial arena and policy arena as well. For example, in September 2014 the Rockefeller Fund announced the sale of fossil fuel assets and its future strategy in favour of renewable technologies[67]. More recently, Norway's Government Pension Fund Global (GPFG), world's biggest sovereign wealth fund worth 850 billion US dollars and founded on the nation's oil and gas wealth, revealed the removal of investments on coal, tar sands, cements and gold-mining on an environmental and climate basis[68].

In the Basque Country, the Energy Strategy 2020 includes among its long-term goals the progressive decarbonisation of the energy system to reach the goal of zero oil by 2050 and zero fossil fuels in 2100. Moreover, the Basque Ministry of the Environment proposed an institutional alliance to accomplish the zero CO_2 emission target by 2050. Therefore, it seems clear that climate policy is going to play a major role in the future of fossil fuels in general and of Petronor in particular.

5.5.3 River flood risks in Petronor: an illustrative example

The flood risk maps obtained in Chapter 3 for the Muskiz Estuary show that flooding due to sea-level rise would not affect the activity of the oil refinery of Petronor, even considering MAHT levels. Coastal flood risk increases significantly under the most extreme scenario (GBSLR Scenario 4, corresponding to the LIG-MIS5e), but the economic appraisal on this scenario has been discarded due to its long-term nature.

However, the industrial area of Petronor it is identified as a river-flood prone area by the Basque Water Agency (ARPSI ES018-BIZ-BAR-01). The 100 year return period floods potentially affect almost 20% of the refinery area, and this surface expands even further when analysing the 500 year return period (Figure 5.12). The Water Agency estimates that in the Muskiz Estuary there are almost 150

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[67] Schwartz, J. (2014, September 21). Rockefellers, Heirs to an Oil Fortune, Will Divest Charity of Fossil Fuels. Retrieved from www.thenytimes.com

[68] Carrington, D. (2015, February 5). World's biggest sovereign wealth fund dumps dozens of coal companies. The Guardian. Retrieved from www.theguardian.com

ha at risk, including the risk to human health, infrastructure and industrial activities. In fact, during the 20th century five flood events were registered in this area (in 1908, 1909, 1915, 1953 and 1977).

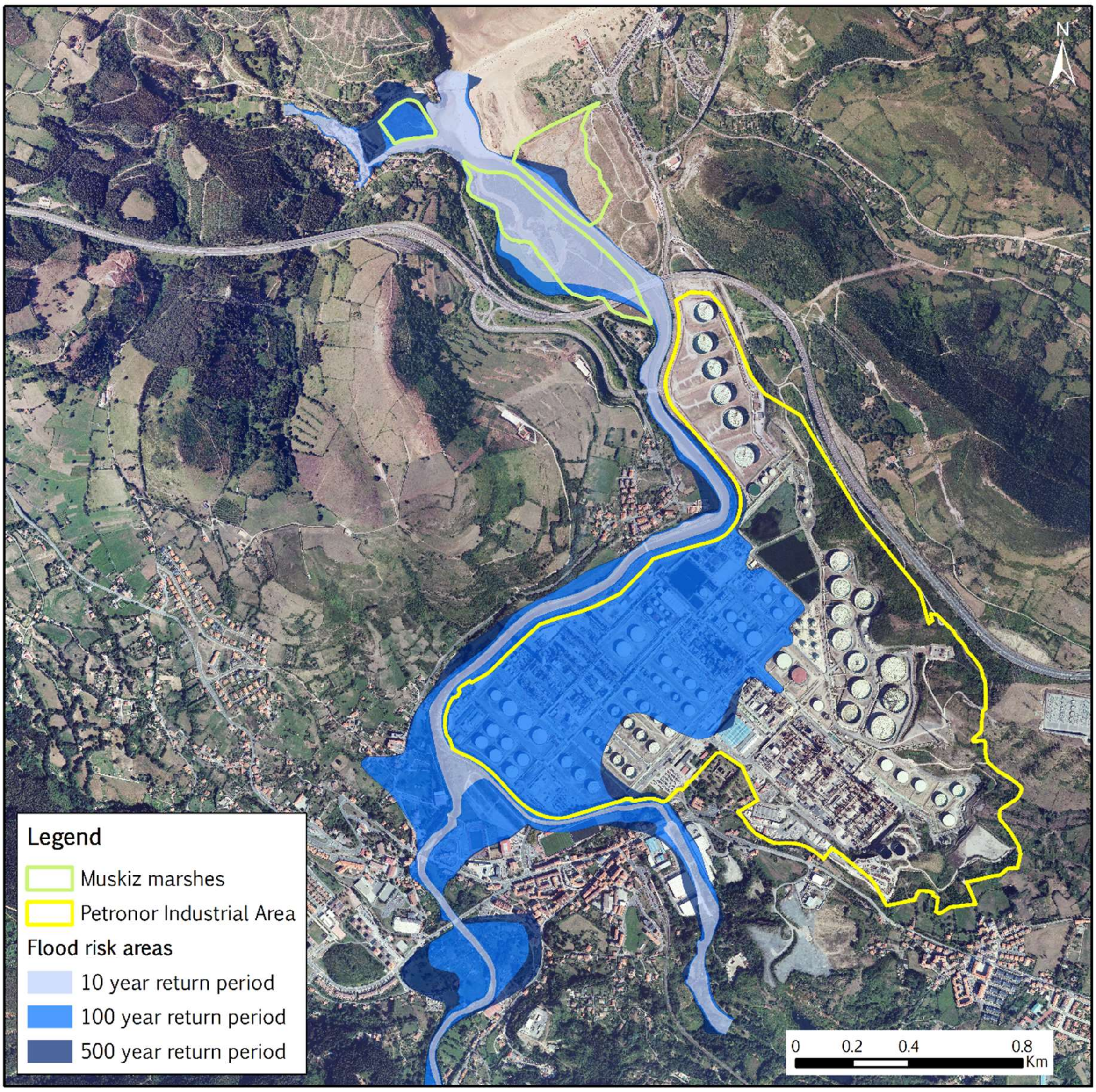

Figure 5.12. Current river-flood risk areas in the Muskiz Estuary and the Petronor oil refinery. Source: cartographic services of the Basque Water Agency.

In an estuary such as Muskiz, cummulative impacts between sea-level rise and river floods could be expected. Additionally, extreme events at the global level are expected to be more frequent and intense (IPCC, 2012c), and even though a general reduction in precipitation has been projected for Spain, this trend regarding extreme flood events is likely to happen also in this country (Benito et al., 2005). Anyway, this analysis on the interrelation between river floods and sea-level rise is beyond the objectives of this dissertation, although it is an interesting topic for further research. Nevertheless, a simple calculation of the potential damages of a river flooding has been estimated only with the purpose to illustrate the magnitude of the economic impacts resulting from an extreme flood event in this area.

The costs associated with a river-flood event in Petronor are estimated using the British FHRC Multi coloured Manual (2006) as a reference that foresee that for flood depths above 2 m factories would stop their activity during 3 days. However, floods risk in Petronor is high and it could affect an area of 66 hectares. This is why we have considered a range of days during which Petronor would stop its activity. The upper range is defined by the number of days (90) that a high-tech company would need to cease its activity (Penning-Rowsell et al., 2006). Once the number of stop days are known, the losses during these days can be estimated based on the average turnover and net revenues for the period 2000-2013 (see Appendix II). The results are presented in Table 5.30.

Table 5.30. Estimated costs of river flooding on Petronor, based on a range of days during which the refinery would need to cease its activity. Economic references (turnover and net revenues) are taken from the activity reports of Petronor (available at www.petronor.com). Data are undiscounted.

Ceasing operation (days)	Average Turnover		Average Net Revenues		Total profit loss (M€)	
	(M€/year)	(M€/day)	(M€/year)	(M€/day)	(ref. Turnover)	(ref. Net Revenues)
Low estimate (3 days)	4934.8	13.52	168.85	0.463	40.53	1.39
Medium estimate (45 days)					608.4	20.84
High estimate (90 days)					1216.8	41.67

5.6 Conclusions

In this chapter an in-depth description of the methodologies followed in the economic part of this dissertation has been presented. The main points addressed can be summed up as follows:

- The economic impacts of sea-level rise in the Basque Coast are addressed through three case studies: the natural salt marsh areas of the Urdaibai Biosphere Reserve, the urban area of the Plentzia Estuary and the industrial area of Muskiz. All three case studies share a common feature, the presence of salt marshes, but have other differences that lead to different approaches to estimate the costs of sea-level rise.

- Discounting has great economic and ethical implications in contexts of climate change. However, there is no single view on the discount rate that should be applied. An alternative approach to discounting, based in the Equivalency Principle defined by Chiabai et al. (2013), is used to estimate the rates to be applied to Basque salt marshes.

- The economic value of salt marsh ecosystems have been measured through a value transfer function developed by Brander et al. (2012) for wetlands in temperate regions of Europe and North America. The transfer function was adapted to the Basque context introducing specific information from the case studies. The value of salt marsh ecosystem services in Urdaibai was found to be 12,276 euros per hectare per year, 22,744 euros per hectare per year in Plentzia and 21,709 euros per hectare per year in Muskiz.

- Once the value of Basque salt marshes had been obtained, the economic damages derived from the rise of sea level were measured by estimating the loss of salt marsh areas in the three case studies. In Muskiz no losses are expected, while the impacts of sea-level rise in Urdaibai reach 310,000-612,000 euros by the end of the century. The losses are greatest in Plentzia, were almost 23% of the salt marsh area would disappear. The costs of this loss would vary between 288,000 and 756,000 euros by 2100. Both in Plentzia and Urdaibai impacts remain low up to mid-century, but losses are triggered from 2050 onwards.

- A framework commonly used to assess the economic impacts of river flooding has been applied to estimate the damage costs related to sea-level rise in the urban area of Plentzia. Impacts would only occur for MAHT levels. A detailed identification and classification of the assets at risk was done based on information from the cadastre and other data gathered on the field. Valuation data from the Multi-Coloured Manual (Penning-Rowsell et al., 2006) was transferred to the Basque Country and applied to each category in order to estimate the total damage costs. The results vary significantly depending on GBSLR and the discount rate used:

    - For GBSLR Scenario 1, economic impacts are very low, up to 0.7 million euros for floods in 2100 for zero discount rates, but are negligible when applying 3% and 6% discount rates.

    - Under GBSLR Scenario 3, undiscounted results show that the costs increase 15 times from 2030 until 2100. Using a 3% discount rates, the costs reach 1.2 million euros in 2080 and then decline. For the higher discount rate (6%), economic impacts of MAHT level floods occurring in 2050 would reach 1.1 million euros, but then the costs decline to become almost negligible by the end of the century.

- Based on the results from Chapter 3, sea-level rise is not expected to cause any direct impacts on the industrial area of the Muskiz Estuary. For illustrative purposes, a simplified river-flood-risk analysis has been used to see the magnitude of the potential impacts of climate change in Muskiz.

6 General discussion

Among the multiple changes that global warming has already triggered, sea-level rise represents a major threat for coastal areas across the world, as a great part of global population and socioeconomic infrastructures concentrate, precisely, in those areas (Revi et al., 2014). About one third of the mega-cities with population above 5 million people are located in low lying coastal areas and in the last 40 years the population at risk of a 100 year return period coastal extreme event has increased by 95% (Wong et al., 2014).

The Basque Country is a small region in Europe, with steep landscapes that northwards end at the Cantabrian Sea. Most of the Basque population live in low-lying estuarine areas. In fact, the Basque coast concentrates 60% of the total population and the 33% of the industrial activities, even though it represents only 12% of the area of the Basque Country (Cearreta et al., 2004). Thus, sea-level rise may represent one of the major risks for this coastal region.

In this dissertation we have approached sea-level rise from a double perspective:

- A geological approach, developing four scenarios of sea-level rise based on data from the recent geological record, i.e. based on data from past changes in sea levels occurred in the eastern Cantabrian coast.
- An economic approach, carrying out an economic assessment of the impacts derived from the GBSLR scenarios.

The first part of the study, therefore, focuses on building different alternatives for future sea-level rise. Note that GBSLR Scenarios in this dissertation are not defined as predictions or forecasts, but instead as potential ways in which sea-level could change and the different impacts that it may cause in the Basque coast.

The physical impacts associated with the defined GBSLR scenarios are estimated building flood risk maps for three sites of the Basque coast: the Urdaibai Biosphere Reserve, located along the Oka Estuary; the coastal town of Plentzia, in the Butroe Estuary, and the industrial area of Muskiz, placed in the lower Barbadun Estuary.

The second part of the dissertation addresses the impacts of these GBSLR scenarios from an economic perspective, by using two different methodologies:

- A benefit transfer to estimate the costs due to the loss of salt marsh ecosystems. This has been complemented with an alternative method to discounting.
- A flood risk assessment, to measure the costs of flooding on urban areas.

Following the general structure of the dissertation, in the following sections both parts are discussed separately.

Part I. A geological approach to sea-level rise

The first three GBSLR scenarios developed are based on the rates of change occurred during the Anthropocene and Holocene. GBSLR Scenario 1 has been defined applying the current rate of sea-level rise measured in the Cantabrian coast during the 20th century, i.e. represents the rate of sea-level rise of the Anthropocene. The impacts of sea-level change under this scenario are estimated based on the rate of sea-level rise during the 20th century in the Cantabrian coast, which has been measured in 2 mm per year, so by 2100 regional mean sea level would be 18 cm above the present level.

However, an acceleration of the rate of sea-level rise is likely to occur during the 21st century (Nicholls, 2010). In fact, even the IPCCs lowest projections estimate higher changes in global sea levels (Church et al., 2013). Moreover, observed sea-level rise so far has been faster than the changes projected by models (Rahmstorf et al., 2007), so Scenario 1 represents a conservative estimate of future changes in sea level.

GBSLR Scenario 2 has been built based on the changes in sea level recorded during the second part of the Holocene Epoch, from 7000 cal yr BP up to the 20th century. The geological record in Basque salt marshes have shown that during this interval the rate of sea-level change dropped to 0.3 - 0.7 mm yr^{-1}. If Scenario 1 was a moderate estimate of future sea-level rise, Scenario 2 represents a slowdown that, according to most of the studies and the instrumental record, is not happening at present (Watson et al., 2015) and it is not likely to occur in the future (Church et al., 2013; Church and White, 2006). That is, it represents the situation before and without climate change.

A higher rate of sea-level rise has been used to define GBSLR Scenario 3, which is based on the acceleration occurred during the first part of the Holocene Epoch, from 10,000 to 7000 cal yr BP. This rapid rise in sea-level has been measured in the Basque coast in 10 mm yr^{-1}. This rate is five times faster than current changes in sea level and outlines a future in which sea level could reach 90 cm higher than today by 2100. Serious consequences could be expected from such a rapid change in sea level over a short period of time (less than a century), but it is not out of the question: sea-level rise according to the IPCC’s RCP8.5 storyline could range from 0.53 to 0.98 m by 2100.

A comparison between the GBSLR scenarios and the IPCC 5AR global projections is shown in Figure 6.1. The chart on the left shows the three GBSLR scenarios compared with the IPCC’s lowest estimate, which corresponds to RCP2.6. It can be observed that Scenarios 1 and 2 are well below the more optimistic projection while Scenario 3 lays high above it. In the chart on the right GBSLR scenarios are compared to the highest IPCC projection, RCP8.5. Scenario 3 runs above the highest estimate until approximately 2080, when it enters within the RCP8.5 range. That is, Scenario 3 considers a constant rate of sea-level rise, while RCP8.5 shows an acceleration in the rate of change towards the end of the century. This comparison is important to show that the GBSLR scenarios are actually not only reasonable, but feasible and within the IPCC’s expected ranges.

Results from semi-empirical models show changes in global sea-levels ranging from 75 to 190 cm by the end of the century (Vermeer and Rahmstorf, 2009). As discussed in Chapter 2, semi-empirical models accurately reproduce sea-level changes occurred during the last millennium, as opposed to process-based models. However, there is no certainty that the relationship between sea-level rise and temperature in the future will remain the same as it has been during the last millennia, so this represents a serious limitation of these models (Rahmstorf, 2010). Anyway, there seems to be a consensus in the scientific community that the IPCC's upper sea-level rise projection could be reached by 2100 (Losada et al., 2014), thus the results from Scenario 3 should not be ruled out.

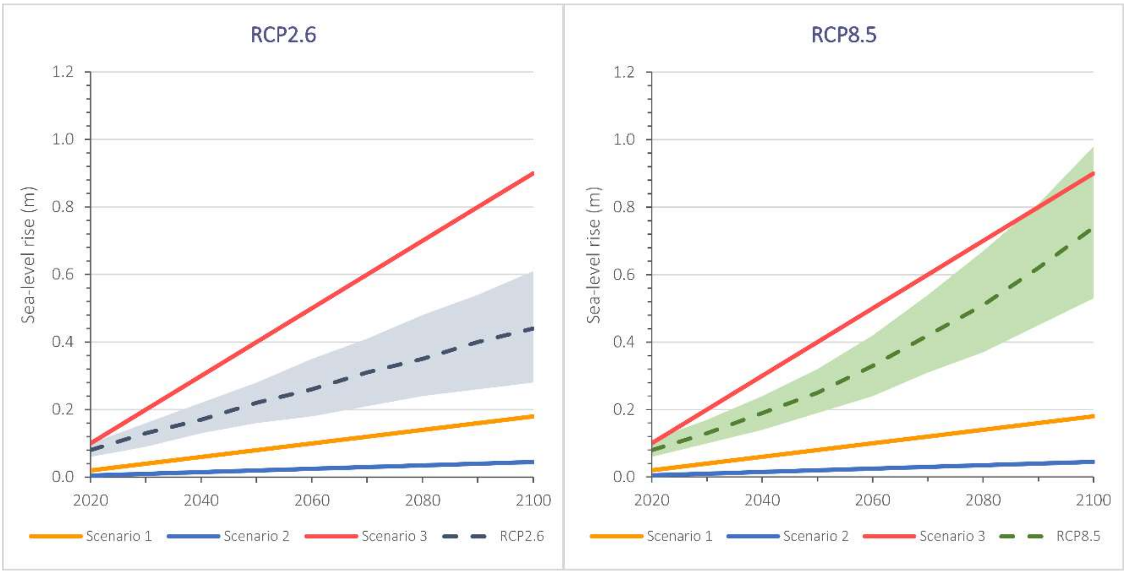

Figure 6.1. Comparison between the geological sea-level rise scenarios for the Basque coast and the IPCC low and high projections (RCP2.6 and RCP8.5).

Sea-level rise projections at the regional level are less abundant than global ones (Losada et al., 2014). Chust et al. (2010) produced regionalised scenarios of sea-level rise for the Basque coast, based on the previous IPCC scenarios A1B and A2. Their results showed an increase in mean sea-levels for the Bay of Biscay between 28.5 and 48.7 cm by 2100. Their findings are very much within the range of IPCC AR4 projections, according to which the change in global sea level in 2095 would be of 18-59 cm. The updated IPCC estimations provide a range of global sea-level rise significantly higher, between 28 cm and 97 cm by 2100, so it would be reasonable to expect a higher sea-level rise if the regionalised projections for the Basque coast were updated following the latest IPCC report. However, based on a recent study by Slangen et al. (2014) that regionalise sea-level rise projections globally, Losada et al. (2014) calculated a change of 41 cm and 57 cm for the eastern part of the Bay of Biscay during the period 2081-2100, under RCP4.5 and RCP8.5, respectively.

GBSLR Scenario 4 was built based on the sea level existing during the LIG, thus it represents a specific sea level rather than a rate of sea-level change. The information to build Scenario 4 was obtained from a coastal terrace located in Oyambre (Cantabria). There, a palaeobeach deposit was identified more than four metres above present mean sea level. A sedimentological and palaeontological analysis was carried out on the samples taken in the Oyambre outcrop. Next, the samples were dated using OSL dating techniques. The results from the dating process showed that the likely age of the basal beach environment is 116 to 108 cal ky BP, corresponding to the MIS5e. The topographic height of the palaeobeach was measured at +4.501 m above current MSL (reference Bilbao ordnance datum), which is in agreement with the findings of other studies. For example, Kopp et al. (2009) estimated that sea level during the LIG was, with a probability of 95%, at least 6.6 m higher than today. Hearty et al. (2007) determined a highly variable sea-level rise curve for the LIG stage, with levels ranging from +2.5 m during the first half of the interglacial up to +6 – 9 m reached in rapid shifts occurred at the end of the LIG.

The height of the palaeobeach deposits in Oyambre was used to define the sea level on GBSLR Scenario 4. A rise in sea level above 2 m by 2100 is highly improbable (Jevrejeva et al., 2014) so Scenario 4 represents a sea level highstand that could be reached during the following centuries (Jevrejeva et al., 2012).

Once the four GBSLR scenarios were defined, flood risk maps were produced using GIS systems. First, a high-resolution airborne laser altimetry data (LIDAR) was used to derive a Digital Terrain Model (DTM) of 15-cm vertical resolution. Next, the rates of change defined for each GBSLR scenario were added to two reference sea levels: Bilbao MSL and MAHT. While the first is the common reference used in most regional sea-level rise studies, the latter was used as a reference for coastal extreme events. Currently, MAHT level is 243 cm above MSL and 43 cm above spring tide level (see Table 2.8). Marcos et al. (2012b) on their assessment of sea-level extremes in the Basque coast found that the main control factor on these events was the long term rise of MSL, assuming no changes in tidal contribution. Following their results, sea-level rise is the only driver considered to estimate future changes in MAHT level and its associated impacts.

The last step before producing the flood-risk maps is related to the services provided by salt marsh ecosystems. Coastal wetlands, and more specifically salt marshes, offer a wide range of ecological services such as coastal wave protection, erosion control, maintenance of fisheries, carbon sequestration, among others (Barbier et al., 2011). It is less known the capacity of these ecosystems to adapt to (certain) changes in sea levels. The dynamic evolution of salt marshes as a function of sea-level change has been studied in the estuaries of Urdaibai, Plentzia and Muskiz during the last 15 years (see for example Cearreta et al., 2002; Leorri et al., 2008a; García-Artola et al., 2015) and the results show that natural salt marshes tend to accrete at an average rate of 2.0 mm yr^{-1} (Cearreta et al., 2013). Salt marshes in regeneration receiving sufficient sediment supply accrete several times faster, between 14 and 18 mm yr^{-1}, until they are fully regenerated (García-Artola et al., 2011b). The regeneration process has been estimated to last approximately 10 years (García-Artola et al., 2011a).

This capacity of salt marshes to maintain their relative height with respect to sea level is a very interesting adaptive feature that has been incorporated into the elaboration of flood-risk maps. Observe that an average accretion rate of 2 mm yr^{-1} would neutralise the sea-level rise considered in GBSLR Scenarios 1 and 2 and it would reduce that of Scenario 3. Unfortunately, such an adaptation measure is not fully operative in Basque estuaries, as anthropogenic activities have reduced importantly the extension of salt marshes. In Plentzia, the surface of the estuary has been reduced by 37% due to human impacts and in Muskiz only 19% of the original estuarine surface remains today (Rivas and Cendrero, 1992). Quite different is the situation of Urdaibai: even though it has lost 29% of its original surface (Rivas and Cendrero, 1992), it was declared Biosphere Reserve by the UNESCO in 1984 and has been a protected area since then. In the future, salt marshes, especially in Urdaibai, could play a major role as an ecosystem-based adaptation measure to cope with sea-level rise.

Once salt marsh accretion levels were incorporated into flood-risk maps, results show that potential impacts depended on three variables: the GBSLR scenario, the sea level considered (MSL or MAHT) and the case study under assessment.

Under GBSLR Scenario 1, changes in MSL are negligible for all case studies. When considering MAHT level impacts on Urdaibai would be insignificant especially considering that these impacts would not be permanent: the additional flooded salt marsh area would be less than a hectare. In Plentzia, some urban areas would be affected under Scenario 1. Flooding would affect the neighbourhoods of Txipio and Isuskiza and the frontline row of the Erribera area, even if the latter only by 2100. Under GBSLR Scenario 1 the expected rise in sea level was 18 cm by 2100, so all this is the maximum height reached by the floods in these areas. In fact, in Erribera the estimates are even lower, barely 5 cm, so impacts under this scenario are small.

Sea-level rise under GBSLR Scenario 2 results in no additional flooding in any of the case studies. It should be kept in mind that both GBSR Scenario 1 and 2 are below the most conservative IPCC sea-level rise scenarios (RCP2.6). This is the main reason to explain the low impacts measured in these scenarios.

The situation changes under GBSLR Scenario 3, which is close to the upper projection of the IPCC. Changes in MSL represent a situation of permanent flooding. Fortunately, these changes are negligible for Plentzia and Muskiz. In Urdaibai, changes in MSL would significantly affect the beaches of Laida and Laidatxu. The extension of both beaches would be importantly reduced. The retreat in the Laidatxu beach ranges from 6 m in 2030 to 85 m by the end of the century. No other urban areas nor salt marshes would be affected by MSL rise.

The MAHT level represents the height reached by a potential extreme coastal event and therefore it does not imply permanent flooding. In Urdaibai salt marshes are already flooded under current MAHT level and they would also be in the future. However, the additional flooding due to sea-level rise in the first half of the 21st century concentrates on the rural land located close to the estuary. Some infrastructures, such as the Murueta shipyard, would be greatly affected by flooding already by 2030. Nevertheless, the most important damages would occur at the end of the century. From 2080 onwards, coastal floods would reach some urban areas of Bermeo, Busturia and even Gernika, located in the upper estuary.

The impacts of changes in MAHT level would affect all of the urban areas around the Plentzia Estuary, to varying degrees and at different times. In the left bank of the estuary, both the neighbourhoods of Txipio and San Telmo would be flooded. Txipio is already affected to some extent by current MAHT level, but this situation would worsen greatly due to sea-level rise, both in relation to the extension of the area and the depth of the water layer. In San Telmo some impacts are expected by mid-21st century but these would increase dramatically by 2080 and beyond.

In the right bank of the Plentzia Estuary, the area named Ibiltokieta would be inundated only by 2080, but then flooding would affect most of the households of this area. Water depths would reach 30 cm in 2080 and 50 cm by the end of the century. Some frontline houses in the Erribera area would already be damaged by 2030, but impacts would be very important from 2050 onwards. At the end of the century flooding would affect almost the whole low-lying zone of the town centre of Plentzia, including its city hall, sports centre and most of the buildings located in the Ibiltokia and Erribera areas. Fortunately, the town centre of Plentzia has developed up a mild hill, so the lower zone by the estuary is not very vast. In the upper Plentzia Estuary, the most western area of the neighbourhood of Isuskiza is already affected by current MAHT level. Under Scenario 3 the impacts are greater in extension and water depth, but limited to a single detached household.

No additional flooding is measured under GBSLR Scenario 3 in the oil refinery of Petronor, located in the Muskiz Estuary.

The changes in sea-level under the long-term and most extreme GBSLR Scenario 4 would cause critical damages in all three case studies. In Urdaibai, large areas of the biggest towns in the area, namely Gernika and Bermeo, would be inundated, together with several other rural and urban areas. Obviously, all salt marsh areas would be submerged. In Plentzia, more than 50% of its residential area would be flooded under Scenario 4 MSL. Many roads and transport infrastructure (as the Metropolitan Railway Station of Plentzia) would also be affected by permanent flooding, together with other natural systems such as the salt marshes or the Plentzia-Gorliz beach. In Muskiz, half of the oil refinery area would be inundated but damages would also affect the urban areas of the Pobeña neighbourhood and even Muskiz in the upper estuary.

Part II. The costs of sea-level rise

Global damage costs associated with coastal flooding are expected to increase significantly not only due to the rise of global sea level, but also due to the increase of the number and value of assets at risk from coastal flooding worldwide (Wong et al., 2014). For a global sea level between 25 and 123 cm higher than today, the associated annual costs could reach 0.3-9.3% of global GDP (Hinkel et al., 2014). Observe that the worst case estimate of this study represents almost half of the global costs of climate change calculated by Stern (2007). The impacts of sea-level rise in 83 developing countries was carried out by Dasgupta et al. (2009), whose results show a loss of global GDP ranging from 1.3% to 6.05% for sea-level rise of 1 m and 5 m respectively.

In 2005, flooding caused in the main coastal cities in the world global losses of around 6 billion US dollars per year, but this estimate could rise by 2050 to 52 billion US dollars annually only due to socio-economic change. If climate change and subsidence is added and no adaptation is implemented, losses could reach 1 trillion US dollars per year (Hallegatte et al., 2013b).

In the last 10 years, the United States have suffered two of the most catastrophic coastal extreme events of their recent history. In 2005, the city of New Orleans was hit by hurricane Katrina and the damage costs were estimated in 142 billion US dollars (2010), the highest costs ever measured for a coastal extreme event. The death of almost 1800 people should be added to this number (Nicholls and Kebede, 2012). In 2012, another coastal extreme event hit the East Coast of the US. Only in New York City, damage costs were estimated in 19 billion US dollars, additionally to 43 human lives lost and thousands of people affected (Steffen et al., 2014). An assessment of the risks of coastal extremes to the coast of California estimated that a 1.4 m increase in sea level by the end of the century could cause damage costs of more than 100 billion US dollars and the population at risk would be close to half a million people (Heberger et al., 2011).

In Australia, Steffen et al. (2014) reviewed the literature on the costs of sea-level rise using three different approaches. The first approach was based on the value of the infrastructure at risk of coastal flooding, which in Australia reaches 226 billion dollars (2008 prices) for a sea-level rise of 1.1 m. This rise in sea-level is a high end IPCC projection by 2100, 20 cm above the GBSLR Scenario 3 used in this dissertation. In the second approach the observed economic damages of previous coastal flood events were used. Damages for the period 1967-1999 reached 28.6 billion dollars (2008), considering events of major flooding, tropical cyclones and severe storms. The third approach reviewed deals with the future costs of coastal flooding. The present cost of a future event is estimated using discount rates, as it has already been done in this dissertation. One of the examples for Australia assessed the impacts of future coastal flooding in Gosford. The findings show that for a sea-level rise of 0.4 m by 2100, damage costs valued in 13.5 million dollars (adjusted to 2010 prices) were generated (Lin et al., 2014).

Brown et al. (2011) found that, in the absence of mitigation or adaptation, coastal flooding in Europe, together with other impacts linked to sea-level rise, such as coastal erosion, would produce annual damage costs of 11 billion euros (2005 prices) by 2050. These costs, measured for middle-of-the-road emission scenario A1B, would increase up to 25 billion euros (2005) by 2080. Apart from to direct costs, other impacts were also included in this estimate, such as salinization, land loss and the cost of moving. At the country level, these authors found great differences among European countries. The Netherlands would suffer the greatest economic damages, followed by France, the UK, Germany and Belgium. For these countries annual damage costs vary between 0.3 and 12 million euros per kilometre of coast. Following closely the estimates for Belgium but well below the top four, Spain would be the sixth country in the ranking, with expected annual damage costs of around 1.2 billion euros (2005) by 2080.

Considering the impacts of 0.5 and 1 m sea-level rise by 2100 in Greece, Kontogianni et al. (2012) estimated the total long-term costs on agriculture, wetlands, forests, and housing and tourist infrastructure using 1% and 3% discount rates. For the lower discount rates, the impacts range between 154 and 265 billion euros (2012). With the higher discount rate the present value of the total financial loss would vary between 25 and 45 billion euros (2012).

At the local scale, the total damage costs on three small coastal communities of Maryland was estimated in 27.2 million US dollars (3% discount rate), for a sea-level rise of 0.6 m. For changes in sea level of 0.9 m the losses rise to 47.1 million US dollars (Michael et al., 2003).

Lichter and Felsenstein (2012) calculated the potential costs of sea-level rise and coastal extremes in Tel Aviv, Haifa and 6 small municipalities of the Northern coastal strip of Israel. GIS systems were used as a basis of the study, complementing the socio-economic information. Direct costs were measured in terms of damages to residential and non-residential buildings, equipment value at risk and road systems. Damages to the cities on the Northern strip were found to be small for sea-level rise up to 1 m, but in all scenarios and all cases, except one under all scenarios, the cost to residential buildings is at least twice the damages on non-residential buildings, similar to the results in Plentzia.

Hallegate et al. (2011) found that sea-level rise would exacerbate the costs of the 100 year storm-surge return period in Copenhagen. If damage costs of such an event currently would cause damages of 3 billion euros, a 50-cm rise in sea levels would increase the cost by 55% to 4.8 billion euros. If sea level rose by 1 m, the costs of a coastal extreme event could reach 6.9 billion euros.

Losada et al. (2014) found that in the Cantabrian coast the provinces of Cantabria, Biscay and Guipuscoa would suffer most from extreme events. Combining the effects of permanent flooding and extreme events, the two Basque provinces would be the ones to suffer most. Using a 3% discount rate, the costs of permanent flooding in Biscay by 2040 represent 1.2% of the GDP of the province in 2008. The damage costs produced by extreme events for Biscay in the same period would represent 2% of the GDP (2008). These estimates are based on an extrapolation of the historical trend followed by sea-level rise from 1950 that would cause a sea level close to 1 m higher than today's by 2040. Projections of other socio-economic variables have also been considered.

In this dissertation, the damage costs of coastal extreme events in the urban area around the Plentzia Estuary has been estimated for two GBSLR scenarios. For Scenario 1, the present average value of flood damages by 2050 are 112,000 euros (2013) and 42,000 euros (2013), for discount rates of 3% and 6% respectively. By the end of the century, the present value of coastal flood damages would be 42,000 euros (2013) using a discount rate of 3% and 3800 euros (2013) for a discount rate of 6%. Note that GBSLR Scenario 1 represents a very optimistic rate of sea-level rise, increasing only in 18 cm by 2100.

When considering GBSLR Scenario 3, damages in Plentzia increase significantly. In 2050 the present value of the potential damages of a coastal extreme event could reach 1.1 million euros (2013), using a discount rate of 3%, and 350,000 euros (2013) applying a discount rate of 6%. By the end of the century, damages would reach 800,000 euros (2013) for a market-based discount rate of 3% while the costs drop to 61,000 euros (2013) if using a discount rate of 6%. Obviously, the net impact is much smaller than the results obtained by Losada et al. (2014) for Biscay, but this was expected as Plentzia is a tourist coastal town of less than 5000 inhabitants. However, proportionally the results are quite similar, as by 2050 damages could reach between 1% and 2% of the local GDP (2012), depending on the discount rate used (6% and 3%, respectively).

In terms of flooded areas, Chust et al. (2010) estimated that 110.8 hectares of the Basque coast would be affected by flooding for a sea-level rise of 48.7 cm under SRES scenario A2 by 2100. Also, sandy beaches would experience a considerable retreat, between 25% and 40%. Under GBSLR Scenario 3 in Plentzia, MAHT level would inundate 59 ha of urban land by the end of the century, although 44% of it would be non-developable land. If the non-developable land category is not considered, 33 hectares of developed urban land[69] would still be affected by coastal extreme flooding.

GBSLR Scenario 4 would cause catastrophic impacts around the Plentzia Estuary, inundating 44% of the urban area[70]. However, long-term economic assessments have huge uncertainties associated. Scenario 4 has been considered to be a probable scenario for the following centuries (Jevrejeva et al., 2012), so it was left out of this economic valuation.

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[69] Following Chapter 3, urban land includes the following categories: residential, industrial, basic infrastructures, communication and transport, community equipments, recreation areas and non-developable land.

[70] Non-developable land was not included in the estimate of flooded surface. See Note 69.

Additionally to urban areas, sea-level rise and coastal extremes are also expected to cause significant damages to coastal ecosystems. Globally, a 1 m sea-level rise, together with other human activities, could affect 50% of world's Ramsar wetlands. A study assessing the impacts of sea-level rise in coastal wetlands of 78 developing countries found that more than 60% of them would be at risk for a 1 m rise in global sea level. The economic value of the ecosystem services provided by these wetlands is around 630 million US dollars (2000 prices) per year (Blankespoor et al., 2012).

In Greece, the impacts of a 0.5 m sea-level rise on coastal wetlands was estimated in 56.3 million euros (2010) and 9.7 million euros (2010) for discount rates of 1% and 3% respectively. The costs due to a sea-level rise of 1 m would increase to 100.9 million euros (2010), with a discount rate of 1%, and 17.3 million euros (2010) applying a discount rate of 3% (Kontogianni et al., 2012). However the estimates are based on a value of 4.8 per square metre of coastal wetland, significantly higher than the results obtained in this dissertation for Basque salt marshes.

The assessment of Losada et al. (2014) showed that salt marshes of the Basque coast are among the most threatened by sea-level rise of the Cantabrian coast. Even the strongly urbanised estuary of Nervion in Bilbao, would experience critical wetland loss under the most severe scenarios. In Guipuscoa, a rise in sea level of 49 cm by 2100 would cause the loss of 3.9 hectares of salt marshes (Chust et al., 2011).

Results from Chapter 3 show that in Urdaibai, permanent salt marsh loss only occurs under GBSLR Scenario 3 and it only represents 0.5% of total salt marsh area (barely 2 hectares would be inundated). Following the same scenario, the Plentzia Estuary would lose 23% of its current surface, almost 4 hectares. In Muskiz, no flooding would affect permanently its salt marsh areas.

The loss of salt marsh areas have also been assessed from an economic perspective. First, the current value of each salt marsh was estimated using a benefit transfer method. The annual value per hectare provided by Basque salt marshes was found to be 12,486 euros (2013) for Urdaibai, 22,583 euros (2013) for Plentzia and 21,169 euros (2013) for the Muskiz Estuary. The future impacts were estimated applying two discount rates in each case study, one considering constant flows and the second, higher than the previous, including economic growth based on SSP2. In Urdaibai, the total losses due to sea-level rise under GBSLR Scenario 3 range from 310,000 euros (2013) to 612,000 euros (2013) by the end of the century, depending on the discount rate applied. In Plentzia, the costs vary between 277,000 euros (2013) for the lower discount rate and 755,000 euros (2013) using the higher discount rate.

As far as we know, there is no similar assessment of the economic costs of sea-level rise due to the loss of salt marsh areas to which our results could be compared with.

Limitations

In relation to coastal extreme events, MAHT level has been used as a reference of these events. Thus, several assumptions were undertaken. The relationship between the different sea levels should not necessarily remain the same in the future, but potential changes in tidal characteristics were not considered. Marcos et al. (2012b) found that the frequency of extreme events by the end of the 21st century would be smaller and the intensity similar to current events, so these features were not taken into account either.

Another initial assumption is related to the rate of sea-level rise. As Holocene rates have been used to build GBSLR Scenarios 1 to 3, the rate applied was constant. However, sea-level rise is known to have been accelerating during the last decades of the 20th century and the latest IPCC projections show accelerated rates of sea-level change (Church et al., 2013), as shown in Figure 6.1.

Wetland accretion was taken into account, based on empirical data obtained for the salt marsh areas addressed. However, no inland-migration was consider. However, this should be a small limitation to the results as the steep valleys and human infrastructures would limit in most cases, if not all, any natural migration of these ecosystems (Chust et al., 2011).

In relation to the second part of the dissertation, no adaptation measures were considered when assessing future coastal floods and no socio-economic scenarios were made when estimating the damage costs on the urban area of the Plentzia Estuary. This area was considered to be fully developed and as a result, it was not expected that the population at risk would increase in the future.

Finally, the economic analysis was carried out as a complex combination of economic methods, geological scenarios and GIS calculations. The economic costs and benefits provided by salt marshes as well as the damage floods on urban areas were estimated over a one-hundred year period. Therefore the results should be considered carefully, evaluating the uncertainty linked to each method and dataset. Nevertheless, we consider that the outcome provides a scale of both biophysical and economic damages that can be useful for addressing adaptation policies and measures in the Basque coastal areas.

Further research

The three case studies are areas currently at risk of river flooding, however the present analysis has been done focusing exclusively in coastal flooding. It would be extremely interesting, academically as well as from a policy perspective, to assess the cumulative effects of both threats.

It would also be interesting to extend the assessment to other estuaries and coastal areas of the Basque Country, even if empirical data on salt marshes is not available. On the one hand, estimating the economic losses associated to the loss of salt marsh areas in the Basque coast would be a step forward to recognise the value of the services provided by these ecosystems. Also, it would be useful to raise awareness of the impacts that we may expect from climate change in the following decades. On the other hand, it would be very valuable from a policy perspective to know the range of economic impacts that could be expected by sea-level rise in bigger and more populated areas, such as Bilbao or San Sebastian.

Nevertheless, further research does not need to be limited to the Basque Country. The same methodologies could also be applied to other coastal areas. The main limitation would be data availability in relation to salt marshes, sea-level rise or the value of different assets at risk.

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Appendix I. Assets at risk of coastal flooding in the Plentzia Estuary

The information from the regional cadastre together with the data gathered on the field in relation to the typology and location of residential and non-residential properties in the town of Plentzia and Barrika is included in this Appendix I. The fieldwork consisted in the identification and photo report of all the residential and non-residential properties located in those areas potentially affected by flooding, according to the flood-risk maps built in Chapter 3. This Appendix is structured following the areas at risk of coastal flooding in the Plentzia Estuary, as defined in Section 5.4.

A. San Telmo

San Telmo is located in the lower estuary and belongs to the municipality of Barrika. Less than 20 buildings have been identified, mainly detached, semi-detached and terraced houses and one single apartment building. The next figure shows some of the frontline households.

Figure 0.1. Frontline of the San Telmo neighbourhood in Barrika.

The full list of residential properties presented in Table 0-1, and the detail of the cadastral parcels and buildings is shown in Figure 0.2.

Table 0-1. List of residential properties located in the San Telmo neighbourhood.

Use	Type	Town	Code Street	Street name	Number	Other features		
						Garden	Tennis	Swimming pool
Residential	Terraced	Barrika	10	San Telmo	1	X		
Residential	Terraced	Barrika	10	San Telmo	2	X		
Residential	Terraced	Barrika	10	San Telmo	3	X		
Residential	Terraced	Barrika	10	San Telmo	4	X		
Residential	Terraced	Barrika	10	San Telmo	5	X		
Residential	Apartments	Barrika	10	San Telmo	6	X	X	X
Residential	Apartments	Barrika	10	San Telmo	7	X	X	X
Residential	Apartments	Barrika	10	San Telmo	8	X	X	X
Residential	Apartments	Barrika	10	San Telmo	9	X	X	X
Residential	Apartments	Barrika	10	San Telmo	10	X	X	X
Residential	Semi-detached	Barrika	10	San Telmo	11	X	X	X
Residential	Semi-detached	Barrika	10	San Telmo	12	X	X	X
Residential	Semi-detached	Barrika	10	San Telmo	13	X	X	X
Residential	Semi-detached	Barrika	10	San Telmo	14	X	X	X
Residential	Detached	Barrika	10	San Telmo	15	X		
Residential	Detached	Barrika	10	San Telmo	16	X		
Residential	Detached	Barrika	10	San Telmo	17	X		X
Residential	Detached	Barrika	10	San Telmo	18	X		
Residential	Garages	Barrika	10	San Telmo	1			
Residential	Garages	Barrika	10	San Telmo	2			
Residential	Garages	Barrika	10	San Telmo	3			
Residential	Garages	Barrika	10	San Telmo	4			
Residential	Garages	Barrika	10	San Telmo	5			
Residential	Garages	Barrika	10	San Telmo	6			
Residential	Garages	Barrika	10	San Telmo	7			
Residential	Garages	Barrika	10	San Telmo	8			
Residential	Garages	Barrika	10	San Telmo	9			
Residential	Garages	Barrika	10	San Telmo	10			
Residential	Garages	Barrika	10	San Telmo	15			
Residential	Garages	Barrika	10	San Telmo	16			
Residential	Garages	Barrika	10	San Telmo	17			
Residential	Garages	Barrika	10	San Telmo	18			

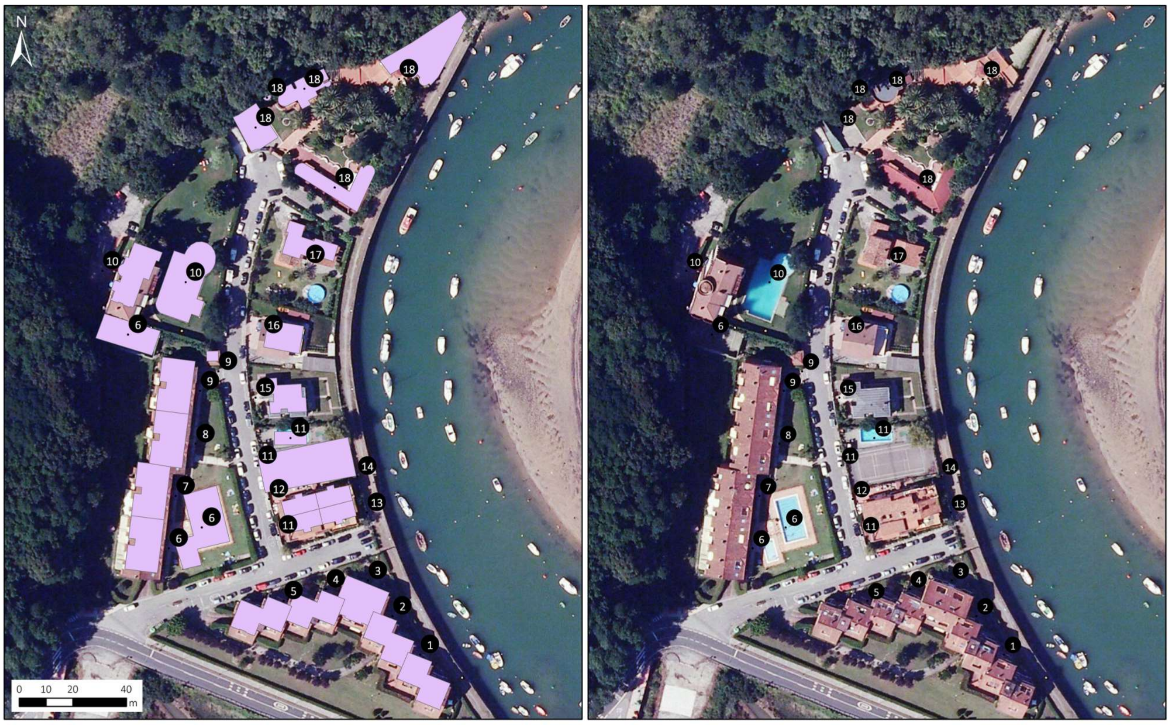

Figure 0.2. Detail of San Telmo neighbourhood, including street numbering. Source: official street map of Barrika, Provincial Council of Biscay.

B. Ibiltokia area

This area is characterised by great detached and semi-detached properties in the Ibiltokia Promenade, while the second row is dominated by more modern apartment buildings. Examples of some residential properties found in this area are shown in the next pictures (Figure 0.3 and Figure 0.8).

A number of non-residential assets are also located in this zone, such as the local Health Centre and a few shops, which is presented in Figure 0.5.

The cadastral map of Ibiltokia can be seen in Figure 0.6 and the full list of residential and non-residential ownerships are listed in Table 5.14 and Table 0-3, respectively.

Figure 0.3. Apartments building in 2 Labasture Street.

Figure 0.4. Semi-detached house located in 12 Ibiltokia Promenade.

Figure 0.5. Local Health Centre at 4 Frontoi Street.

Figure 0.6. Ibiltokia area in the north part of the Plentzia urban centre. The numbers represent the official street numbering of households and buildings.

Table 0-2. List of residential properties located in the Ibiltokia area.

Use	Type	Town	Cod Street	Street	Number	Ground level	Garden	Swimming pool
Residential	Apartments	Plentzia	13	Areatza	1	Household		
Residential	Apartments	Plentzia	13	Areatza	11	Basement		
Residential	Apartments	Plentzia	13	Areatza	13	Basement		
Residential	Apartments	Plentzia	13	Areatza	15	Basement		
Residential	Apartments	Plentzia	63	Arraun	1	Entrance		
Residential	Apartments	Plentzia	63	Arraun	2	Entrance		
Residential	Apartments	Plentzia	21	Frontoi	2	Household, garden		
Residential	Apartments	Plentzia	16	Labasture	1	Elevated entry	X	
Residential	Apartments	Plentzia	16	Labasture	2	Household, garden		
Residential	Apartments	Plentzia	16	Labasture	4A	Garden, no flooding		
Residential	Apartments	Plentzia	16	Labasture	4B	Garden, no flooding		
Residential	Apartments	Plentzia	16	Labasture	6	Household (U)		
Residential	Apartments	Plentzia	16	Labasture	8	Household (U)		
Residential	Apartments	Plentzia	16	Labasture	10	Entrance (U)		
Residential	Apartments	Plentzia	16	Labasture	12	Entrance (U)		
Residential	Apartments	Plentzia	16	Labasture	14	Basements (U)		
Residential	Apartments	Plentzia	16	Labasture	16	Household		
Residential	Apartments	Plentzia	16	Labasture	16	Entrance		

Use	Type	Town	Cod Street	Street	Number	Ground level	Garden	Swimming pool
Residential	Apartments	Plentzia	16	Labasture	18	Entrance		
Residential	Apartments	Plentzia	16	Labasture	20	Entrance		
Residential	Apartments	Plentzia	16	Labasture	22	Entrance		
Residential	Detached	Plentzia	21	Frontoi	1	Household	X	
Residential	Detached	Plentzia	5	Ibiltokia	2	Household	X	X
Residential	Detached	Plentzia	5	Ibiltokia	3	Household	X	
Residential	Detached	Plentzia	5	Ibiltokia	4	Household	X	X
Residential	Detached	Plentzia	5	Ibiltokia	6	Household	X	X
Residential	Detached	Plentzia	5	Ibiltokia	7	Household	X	X
Residential	Detached	Plentzia	5	Ibiltokia	8	Household	X	X
Residential	Detached	Plentzia	5	Ibiltokia	10	Household	X	
Residential	Detached	Plentzia	5	Ibiltokia	11	Household	X	
Residential	Detached	Plentzia	16	Labasture	9	Household	X	
Residential	Semi-detached	Plentzia	5	Ibiltokia	5A	Household	X	
Residential	Semi-detached	Plentzia	5	Ibiltokia	5B	Household	X	
Residential	Semi-detached	Plentzia	5	Ibiltokia	12	Household	X	
Residential	Semi-detached	Plentzia	5	Ibiltokia	13	Household	X	
Residential	Semi-detached	Plentzia	5	Ibiltokia	14	Household	X	
Residential	Semi-detached	Plentzia	5	Ibiltokia	15	Household	X	
Residential	Semi-detached	Plentzia	16	Labasture	3A	Garden	X	
Residential	Semi-detached	Plentzia	16	Labasture	3B	Garden	X	
Residential	Garages	Plentzia	13	Areatza	1	Garage		
Residential	Garages	Plentzia	13	Areatza	3	Garage		
Residential	Garages	Plentzia	13	Areatza	5	Garage		
Residential	Garages	Plentzia	13	Areatza	7	Garage		
Residential	Garages	Plentzia	13	Areatza	9	Garage		
Residential	Garages	Plentzia	63	Arraun	1	Garage		
Residential	Garages	Plentzia	63	Arraun	2	Garage		
Residential	Garages	Plentzia	21	Frontoi	1	Garage		
Residential	Garages	Plentzia	16	Labasture	1	Garage	X	
Residential	Garages	Plentzia	16	Labasture	1	Garage	X	
Residential	Garages	Plentzia	16	Labasture	2	Garage		
Residential	Garages	Plentzia	16	Labasture	6	Garage		
Residential	Garages	Plentzia	16	Labasture	8	Garage		
Residential	Garages	Plentzia	16	Labasture	9	Garage	X	
Residential	Garages	Plentzia	16	Labasture	10	Garage		
Residential	Garages	Plentzia	16	Labasture	14	Garage		
Residential	Garages	Plentzia	16	Labasture	16	Garage		
Residential	Garages	Plentzia	16	Labasture	18	Garage		

Table 0-3. List of non-residential properties located in the Ibiltokia area.

Type	Town	Cod. Street	Street	Number	Code. EqType	EqType	Groundfloor
Commercial	Plentzia	63	Arraun	1	211	High Street Shop	Shop
Commercial	Plentzia	16	Labasture	4B	213	Superstore	Supermarket
Commercial	Plentzia	63	Arraun	2	236	Café, Fast food	Bar
Commercial	Plentzia	63	Arraun	1	310	Office (non specific)	Local Postal Service
Commercial	Plentzia	63	Arraun	2	310	Office (non specific)	Physiotherapist
Commercial	Plentzia	63	Arraun	2	310	Office (non specific)	Port Authority
Commercial	Plentzia	16	Labasture	22	310	Office (non specific)	Office
Commercial	Plentzia	16	Labasture	22	310	Office (non specific)	Office
Commercial	Plentzia	16	Labasture	22	310	Office (non specific)	Premises
Commercial	Plentzia	16	Labasture	20	311	Office (non specific)	Insurance office
Commercial	Plentzia	16	Labasture	20	312	Office (non specific)	Office
Commercial	Plentzia	63	Arraun	2	320	Bank	Bank
Sanitation	Plentzia	21	Frontoi	4	620	Health Centre	Local Health Centre

C. Erribera area

The Erribera area is the one with the highest commercial activity of the five zones under assessment. Residential properties are mainly three or four-storey apartment buildings. Many of them still keep the traditional aspect of old Basque village buildings (see Figure 0.11, below). Plentzia’s City Hall, located by the riverside in the Astillero Square can also be seen in Figure 5.21 (below).

The list of the residential and commercial buildings located in Erribera area is provided in Table 5.15 and Table 5.16, respectively. The cadastral map of this area is presented in Figure 0.8.

Figure 0.7. In the upper figure, Plentzia's City Hall. A typical apartment building with a small groceries shop at 25 Erribera Street is shown below.

Table 0-4. List of residential properties located in the Erribera area.

Use	Type	Town	Cod_Street	Street	Number	Groundfloor
Residential	Apartments	Plentzia	4	Barrenkale	1	Garden
Residential	Apartments	Plentzia	22	Erribera	6	Building entrance
Residential	Apartments	Plentzia	22	Erribera	8	Building entrance
Residential	Apartments	Plentzia	22	Erribera	9	Household, garden
Residential	Apartments	Plentzia	22	Erribera	10	Building entrance
Residential	Apartments	Plentzia	22	Erribera	12	Building entrance
Residential	Apartments	Plentzia	22	Erribera	14	Building entrance
Residential	Apartments	Plentzia	22	Erribera	15	Household, garden
Residential	Apartments	Plentzia	22	Erribera	17	Household, garden
Residential	Apartments	Plentzia	22	Erribera	18	Building entrance
Residential	Apartments	Plentzia	22	Erribera	25	Household
Residential	Apartments	Plentzia	22	Erribera	26	Building entrance
Residential	Apartments	Plentzia	22	Erribera	28	Building entrance
Residential	Apartments	Plentzia	22	Erribera	30	Building entrance
Residential	Apartments	Plentzia	22	Erribera	33	Household, garden
Residential	Apartments	Plentzia	22	Erribera	34	Building entrance
Residential	Apartments	Plentzia	22	Erribera	35	Household, garden
Residential	Apartments	Plentzia	22	Erribera	44	Building entrance
Residential	Apartments	Plentzia	22	Erribera	46	Building entrance
Residential	Apartments	Plentzia	22	Erribera	48	Building entrance
Residential	Apartments	Plentzia	22	Erribera	19A	Household, garden
Residential	Apartments	Plentzia	22	Erribera	19B	Household, garden
Residential	Apartments	Plentzia	46	Plazatxoa	1	Household, garden
Residential	Apartments	Plentzia	46	Plazatxoa	2	Building entrance
Residential	Apartments	Plentzia	46	Plazatxoa	4	Building entrance
Residential	Apartments	Plentzia	46	Plazatxoa	2A	Building entrance
Residential	Semi-detached	Plentzia	4	Barrenkale	47	Household, garden
Residential	Semi-detached	Plentzia	22	Erribera	3	Household, garden
Residential	Semi-detached	Plentzia	22	Erribera	5	Household, garden
Residential	Semi-detached	Plentzia	22	Erribera	7	Household, garden
Residential	Semi-detached	Plentzia	22	Erribera	11	Household, garden

Table 0-5. List of non-residential properties in the Erribera area.

Type	Cod. Street	Street	Number	Code EqType	EqType	Groundfloor
Commercial	22	Erribera	2	211	High Street Shop	Shop
Commercial	22	Erribera	6	211	High Street Shop	Shop
Commercial	22	Erribera	9	211	High Street Shop	Shop
Commercial	22	Erribera	12	211	High Street Shop	Shop
Commercial	22	Erribera	14	211	High Street Shop	Shop
Commercial	22	Erribera	14	211	High Street Shop	Bookshop
Commercial	22	Erribera	18	211	High Street Shop	Pharmacy
Commercial	22	Erribera	18	211	High Street Shop	Bakery
Commercial	22	Erribera	20	211	High Street Shop	Shop
Commercial	22	Erribera	21	211	High Street Shop	Shop
Commercial	22	Erribera	22	211	High Street Shop	Flower Shop
Commercial	22	Erribera	24	211	High Street Shop	Clothing Shop
Commercial	22	Erribera	25	211	High Street Shop	Grocery shop
Commercial	22	Erribera	28	211	High Street Shop	Shop
Commercial	22	Erribera	44	211	High Street Shop	Stationery shop
Commercial	22	Erribera	46	211	High Street Shop	Optician's shop
Commercial	4	Barrenkale	3	235	Restaurant	Restaurant
Commercial	4	Barrenkale	3	235	Restaurant	Restaurant - Terrace
Commercial	22	Erribera	13	235	Restaurant	Restaurant
Commercial	22	Erribera	13	235	Restaurant	Restaurant - Terrace
Commercial	22	Erribera	27	235	Restaurant	Restaurant
Commercial	22	Erribera	27	235	Restaurant	Restaurant - Terrace
Commercial	8	Kristo eskilara	13	235	Restaurant	Restaurant
Commercial	22	Erribera	30	236	Café, Fast food	Bar
Commercial	22	Erribera	8	310	Office (non specific)	Physiotherapist
Commercial	22	Erribera	15	310	Office (non specific)	State agency
Commercial	46	Plazatxoa	2A	310	Office (non specific)	Office
Commercial	22	Erribera	21	320	Bank	Bank (BBK)
Commercial	22	Erribera	25	320	Bank	Bank (BBVA)
Commercial	22	Erribera	34	320	Bank	Bank (La Caixa)
Commercial	22	Erribera	48	320	Bank	Bank (Laboral Kutxa)
Commercial	22	Erribera	13	511	Hotel	Hotel
Commercial	22	Erribera	27	511	Hotel (Pension)	Hotel
Commercial	22	Erribera	29	310*	Office (non specific)*	Premises
Commercial	22	Erribera	4	310*	Office (non specific)*	Premises
Commercial	22	Erribera	10	310*	Office (non specific)*	Premises
Commercial	22	Erribera	17	310*	Office (non specific)*	Premises
Commercial	22	Erribera	28	310*	Office (non specific)*	Premises
Commercial	22	Erribera	32	310*	Office (non specific)*	Premises
Commercial	46	Plazatxoa	2	310*	Office (non specific)*	Premises
Commercial	46	Plazatxoa	4	310*	Office (non specific)*	Premises
Commercial	46	Plazatxoa	2A	310*	Office (non specific)*	Premises
Commercial	46	Plazatxoa	2A	310*	Office (non specific)*	Premises
Public facility	43	Astillero Square	1	310	Office (non specific)	City Hall
Public facility	22	Erribera	21	310	Office (non specific)	Tourist Office
Public facility	46	Plazatxoa	2B	523	Sports, leisure centre	Sports centre

* The records with an asterisk represent premises that currently have no economic activity.

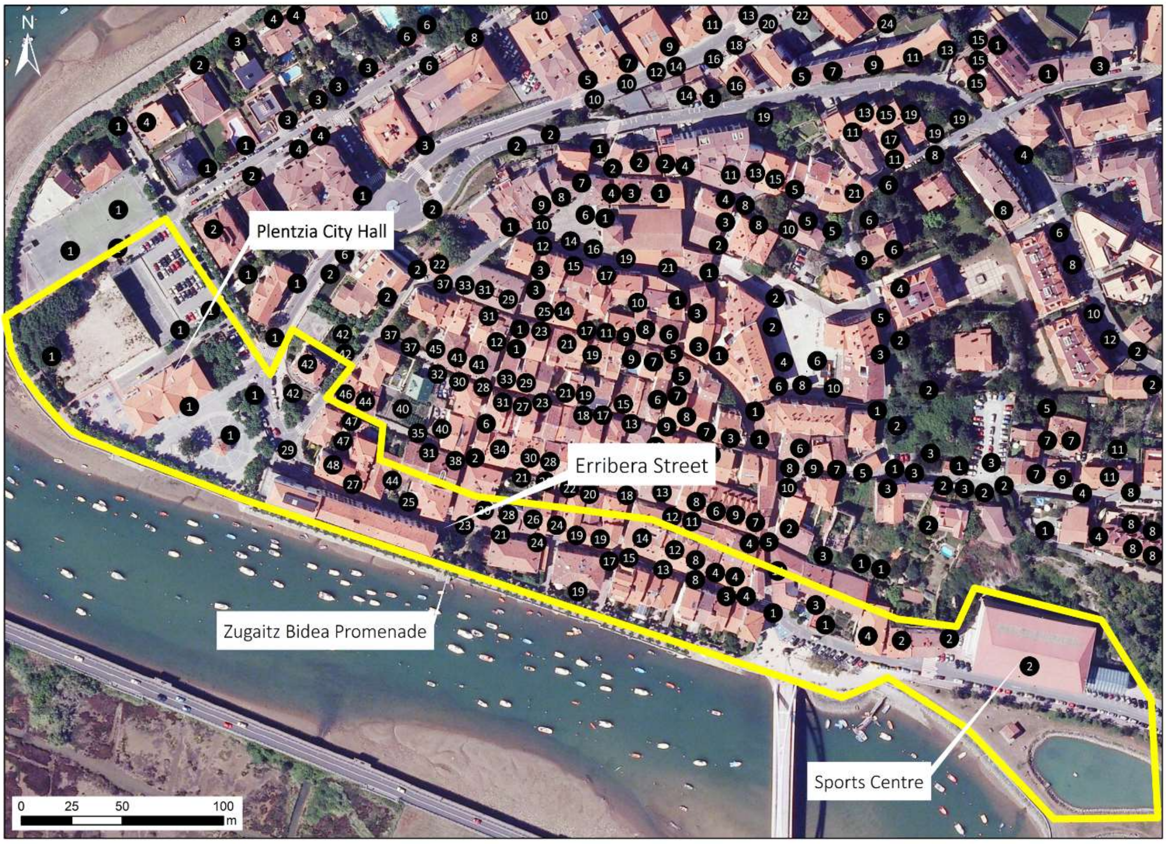

Figure 0.8. Erribera area in the southern part of the Plentzia urban centre.

D. Txipio area

A few traditional detached or semi-detached houses coexist in the Txipio neighbourhood with more modern apartment buildings (Figure 0.9). In a discordant way, a few hundred metres west from the Txipio neighbourhood, two isolated apartment buildings located in an area that not so long ago belonged to the Txipio salt marsh (Figure 0.10). In fact, this is one of the areas most at risk of flooding in the Txipio area.

The cadastre map of Txipio is shown in Figure 0.11 and the complete list of properties is detailed in Table 0-6 (residential assets) and Table 5.19 (non-residential ownerships).

Figure 0.9. Different types of buildings found in the Txipio neighbourhood.

Figure 0.10. Two apartment buildings adjacent to the Txipio salt marsh.

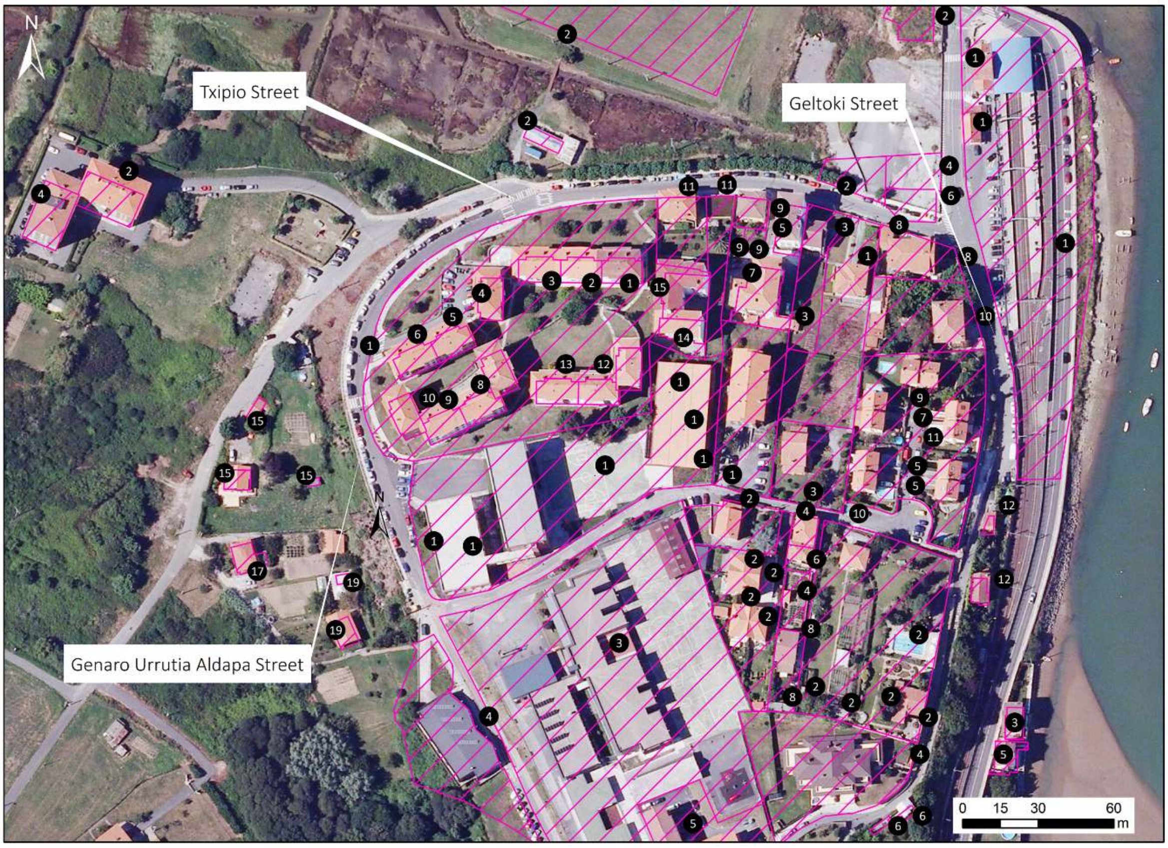

Figure 0.11. Aerial view of the Txipio neighbourhood, including cadastral parcels and street numbers.

Table 0-6. List of residential properties in the Txipio neighbourhood.

Use	Type	Town	Cod_Street	Street	Number	Infrastructure at groundfloor level
Residential	Detached	Plentzia	33	Txipio	1	Household, garden
Residential	Apartments	Plentzia	33	Txipio	2	Building entrance
Residential	Apartments	Plentzia	33	Txipio	3	Household, garden
Residential	Apartments	Plentzia	33	Txipio	4	Basement
Residential	Apartments	Plentzia	33	Txipio	9	Household
Residential	Detached	Plentzia	33	Txipio	11	Basement, garden
Residential	Detached	Plentzia	33	Txipio	15	Household, vegetable garden
Residential	Detached	Plentzia	33	Txipio	17	Household, vegetable garden
Residential	Detached	Plentzia	11	Geltoki	3	Household, garden
Residential	Detached	Plentzia	11	Geltoki	5	Household, garden
Residential	Detached	Plentzia	11	Geltoki	8	Household, garden
Residential	Detached	Plentzia	11	Geltoki	10	Household
Residential	Garages	Plentzia	33	Txipio	2	Garages (16)
Residential	Garages	Plentzia	33	Txipio	5	
Residential	Garages	Plentzia	33	Txipio	9	
Residential	Garages	Plentzia	33	Txipio	11	

Table 0-7. List of non-residential assets in the Txipio neighbourhood.

Type	Town	Cod. Street	Street	Number	Code EqType	EqType	Groundfloor
Commercial	Plentzia	33	Txipio	5	310*	Office (non specific)*	Premises
Others	Plentzia	11	Geltoki	1	310	Office (non specific)	

* The records with an asterisk represent premises that currently have no economic activity.

E. Isuskiza area

The assets at risk in Isuskiza are limited to one single household, at risk of flooding under current MAHT level. The property includes a detached house with garden and swimming-pool (Figure 0.12).

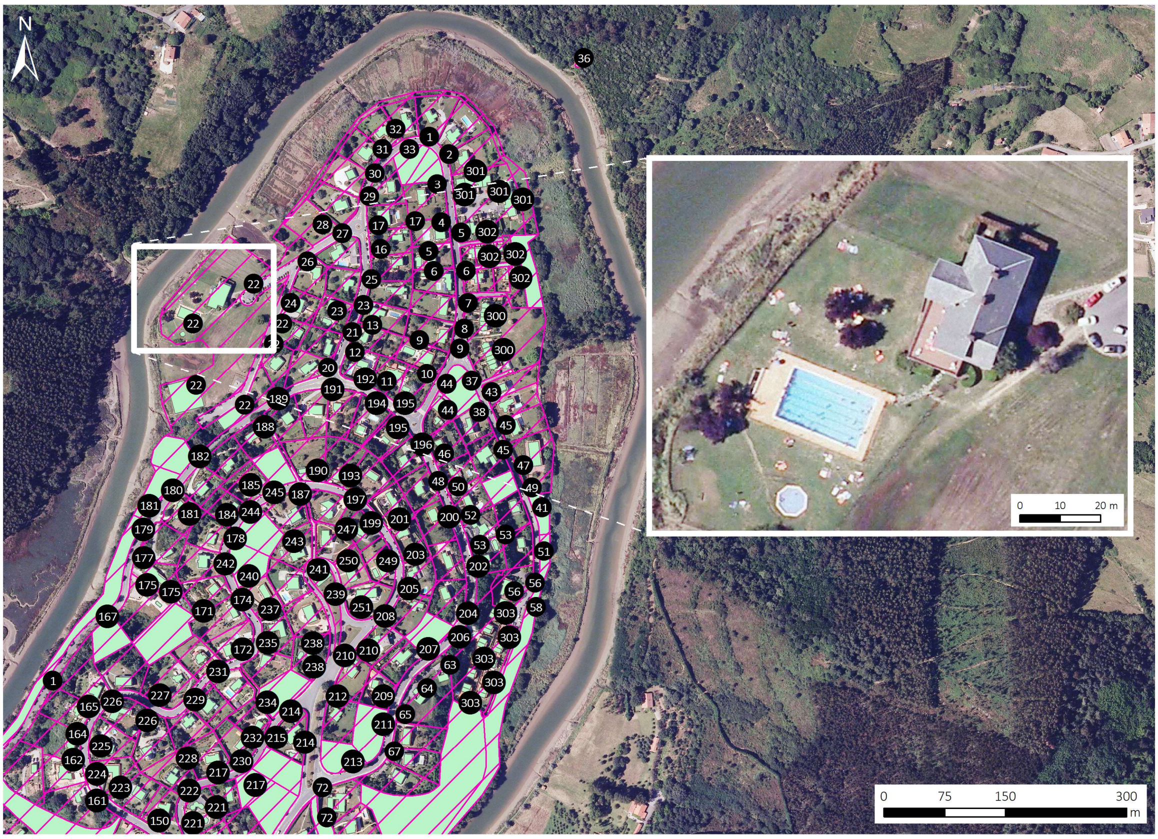

Figure 0.12. Aerial view of the Isuskiza area, including buildings and street numbers. The white box zooms into the only property potentially affected by flooding according to the results presented in Chapter 3.

The cadastral information on this household can be summarised as follows:

Use	Type	Town	Code Street	Street name	Number	Garden	Swimming-pool
Residential	Detached	Plentzia	38	Isuskiza	22	X	X

Appendix II. Economic and productive data of Petronor oil refinery (1997-2013)

Table 0-1. Economic and finantial evolution of Petronor (million euros).

Year	Net Turnover	Revenue (before taxes)	Taxes	Net Profit(2)	Net Operating Result	Inversions
1997	2231.54	119.43	30.93	88.49	65.68	3651(1)
1998	2056.93	132.43	36.64	95.78	108.98	4856(1)
1999	2292.81	99.56	17.81	81.75	76.49	13,302(1)
2000	3611.22	299.89	82.42	217.47	269.16	8936(1)
2001	3108.51	210.86	37.36	173.51	136.65	31.61
2002	2801.13	207.26	14.79	192.46	31.37	18.68
2003	3287.91	105.73	22.31	83.42	79.14	15.45
2004	3728.41	298.45	85.85	212.60	254.88	40.32
2005	4896.67	454.33	137.86	316.47	430.00	81.35
2006	5353.90	345.71	94.95	250.76	253.53	57.98
2007	5584.24	362.52	67.97	294.56	248.72	101.70
2008	6436.10	143.25	9.40	133.85	115.10	170.70
2009	4335.90	154.93	15.65	170.58	83.50	280.40
2010	5348.40	304.35	-13.19	291.16	95.80	262.37
2011	6951.80	77.98	18.53	96.52	30.20	232.25
2012	6793.70	-17.07	35.16	18.09	-39.00	90.03
2013	6849.30	-162.34	74.83	-87.51	-160.10	54.16

(1) Inversions from 1997 to 2000 are given in pesetas.

(2) Net profit up to 2008 is calculated by subtracting the taxes to the revenue before taxes; from 2008, it is the sum of both concepts.

Table 0-2. Production of the refining activities and national and international sales.

REFINING ACTIVITY				INTERNATIONAL CONTEXT		STAFF
Production (MTn)	National Sales (MTn)	International Sales (MTn)	Total Sales (MTn)	Brent average (US dollars/barril)	US dollar/euro average change	
8.17	5.63	2.74	8.37			
9.39	6.20	3.70	9.90			792
8.83	6.40	2.74	9.14			787
9.11	6.36	2.74	9.10			769
8.62	6.63	2.21	8.84			774
7.55	6.68	1.56	8.24			771
9.16	7.85	1.93	9.77			776
10.01	7.50	2.62	10.12			837
9.37	7.83	2.34	10.17			861
9.64	7.62	3.00	10.62			878
10.39	7.31	3.50	10.81	72.39	1.37	874
10.79	7.01	3.60	10.61	97.26	1.47	885
9.66	6.25	3.51	9.76	61.67	1.39	896
8.82	5.95	3.34	9.29	79.50	1.33	921
8.61	6.23	3.51	9.74	111.26	1.39	919
7.13	5.71	3.11	8.82	111.67	1.28	914
8.26	5.93	3.47	9.40	108.70	98.05	914