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Assessment of selected climate change adaptation measures for coastal areas

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ABSTRACT

Climate change and its impacts are already perceptible in many parts of the world and coastal areas are particularly vulnerable to these changes. To address issues arising in the Aquitaine region (south-west France, now administratively part of Nouvelle-Aquitaine), we listed possible measures for adaptation to climate change impacts at the regional level and focussing on coastal hazards. Then we assessed their effectiveness with respect to long-term climate change and to the coastal management practices they are designed for. The assessment is independent of the local context and is therefore valid in most coastal areas.

For this purpose, we conducted a review of the literature to select 51 measures that are potentially applicable to the Aquitaine coast. We then classified these measures combining two approaches. The first was based on the regional management practices applied by the *GIP Littoral Aquitain* (a public interest group for coastal management in Nouvelle-Aquitaine) while the second drew on the IPCC (Intergovernmental Panel for Climate Change) classification based on the physical-environmental, socio-economic or institutional characteristics of adaptation measures. In parallel, ten criteria were defined to assess the current and future efficiency of the measure independently of the local context. Finally, by providing an assessment of the adaptation measures using nine of these criteria, this method allowed objective and easy comparisons between measures.

The results were analysed taking each criterion independently and also through a multi-criteria analysis. Overall, the measures performed well against all the binary criteria except “self-sufficiency” and “synergy with mitigation”. The more detailed analysis of the results highlight the main characteristics of the measures applied in each management approach. The multi-criteria analysis identified a set of essential measures for adaptation to coastal risks in the context of climate change. 19 measures were rated at once as “no regrets”, “robust” and “reversible/flexible”. In general, the study shows that there are many short and medium term possibilities for adaptation (2030–2050, 2080–2100) and emphasises the need to implement some of these as soon as possible. According to our study, measures that generate immediate benefits are overwhelmingly predominant (86%).

1. Introduction

A significant proportion of the world’s population lives in coastal areas, and demographic trends tend to show that more and more people will be living in risk-prone areas in the coming decades (Bunce et al., 2010; Ferro-Azcona et al., 2019). Coastal areas are highly vulnerable to the effects of global changes (Lewis, 2013; Mehvar et al., 2018; Ferro-Azcona et al., 2019). Many coastal communities and cities are aware of the increasing impact of flooding and coastal storms due to sea level rise (Nicholls and Cazenave, 2010; IPCC, 2014; Carson et al., 2016; Wdowinski et al., 2016; van Dongeren et al., 2018; Gibbs, 2019). In addition to its impact on sea level rise, climate change is very likely to affect the frequency and intensity of coastal disasters (IPCC, 2001; Ferro-Azcona et al., 2019).

Mitigation measures aim to reduce greenhouse gas (GHG) emissions and they therefore tackle climate change at source, whereas adaptation measures aim to limit the negative impacts of climate change on human societies (Pielke, 1998; Smit and Wandel, 2006; McNeeley, 2012; Hoegh-Guldberg et al., 2018). There is growing recognition that climate change adaptation and disaster risk reduction are converging for most risks, and that they are increasingly interrelated (Solecki et al., 2011). As highlighted by Birkmann and von Teichman (2010), systematic

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cooperation between projects for climate change adaptation and disaster risk reduction is necessary, but the two fields do not easily work together.

Despite the growing number of adaptation plans adopted, there is still very little actual implementation on site (Berrang-Ford et al., 2011; Eakin and Patt, 2011; Preston et al., 2011; Carmin al., 2012; Bierbaum et al., 2013; Ford et al., 2015; Araos et al., 2016; Gibbs, 2019). As regards disaster risk reduction, many adaptation measures are not specifically designed to address climate change itself, but rather to address natural risks with climate change impacts taken into account (Smit and Wandel, 2006). These measures therefore aim to reduce the levels of risk faced by society. Adaptation can therefore come into play at two different levels: to reduce the vulnerability of goods and people and/or to reduce hazard levels (Allen et al., 2018).

At present, uncertainties remain as to the magnitude, evolution and impacts of climate change at the regional scale in the short (2030–2050), medium (2080–2100) and long term (2100–2300 and beyond) (Wong et al., 2014). In fact, despite major changes in climate models over the last 30 years, uncertainties as to changes up to 2100 have remained similar to those in the first IPCC reports (example: sea level rise between a few tens of cm and more than 1 m).

Roe and Baker (2007) have shown that the magnitude of these uncertainties is related to feedback effects from the climate system that are not always well reproduced by models. Therefore, the uncertainties in projections of all climate variables (temperature, precipitation, sea level) should not be expected to decrease significantly over the next few years. Many questions therefore remain about how adaptation should be understood and put into practice in this highly uncertain context. Jones et al. (2014) show that studies on climate change adaptation and impact assessments need to be conducted together.

Although we selected coastal adaptation measures for their relevance to the Aquitaine region (southwestern France), the approach is independent of the area and the findings are easily transferable elsewhere. This study defines assessment criteria and assesses the selected measures against these criteria in order to assess their sensitivity to climate change and initiate a forward-looking regional approach that could help to apply consistent adaptation strategies across study areas.

2. Material and methods

2.1. Regional context of the listed measures

Changes in climatic and oceanic variables (precipitation, temperatures, sea level, waves) are already perceptible in Aquitaine and will very likely intensify in the future (Le Treut et al., 2013, 2018; Le Cozannet et al., 2016). Natural hazards, directly related to these key variables, are evolving significantly. The Aquitaine region has to cope with many natural risks, particularly in the coastal strip considered for this study. In 2015, Aquitaine became part of the new and larger administrative region of Nouvelle-Aquitaine. In this paper, we will refer to the area under consideration as “Aquitaine”.

In 2013, the regional and national scientific community published a review of current knowledge on the potential effects of climate change at the regional scale (Le Treut et al., 2013). This report stresses the vulnerability of the Aquitaine area to climate change and the need to develop adaptation strategies that are relevant to natural risk management in particular. This study was updated in a 2018 publication (Le Treut et al., 2018). The Paris Agreement signed between the nations at the end of COP21 in December 2015 underlines the urgency and the importance of implementing ambitious public policies for both mitigation and adaptation (Mitchell et al., 2018).

Due to the severe anticipated impact of climate change in Aquitaine, planners, communities and government have high expectations of adaptation studies and options. This paper provides an inventory of possible adaptation measures to be considered in the coastal area for both erosion and coastal flooding risks in Aquitaine.

The 250 km-long Aquitaine coast stretches southwards from the Gironde (Bordeaux area) to the Spanish border. It is exposed to Atlantic swells, a high-energy macrotidal regime and drift currents. The coastline is mainly composed of sandy beaches with coastal dunes. There is also a large tidal basin (Arcachon Basin) and a short length of erodible cliffs with landslide risks along the southern part (Basque country). The areas prone to coastal flooding are mainly located in the Arcachon basin, around estuaries and in the bay of Saint-Jean-de-Luz (Basque Country). The entire coast is highly exposed to coastal erosion and coastline retreat (Fig. 1).

2.2. Method

Assessment of measures for coastal adaptation to climate change involve seven main stages (Fig. 2). The first is to produce an inventory of measures for coastal adaption to climate change focussing on coastal hazards. The second is to classify these measures into two typologies combining the main categories (families) of adaptation measures and existing management approaches. These two typologies are then used to classify the adaptation measures identified (step 3). Relevant assessment criteria are identified and selected separately (step 4). Each adaptation measure is then assessed against the different criteria (step 5). The last stages involve:

- An analysis of the results obtained for each adaptation measure with respect to each criterion (step 6),
- Identification of the most efficient adaptation measures using a multi-criteria analysis (step 7).

These different stages are described in details in the next sections.

2.3. Data collection strategy

First, a review of the literature to list possible adaptation measures was done. Chapter 14 of the 2014 IPCC report (Noble et al., 2014) naturally formed the basis for this review, which was completed with other publications (Linham and Nicholls, 2010) and reports (US AID, 2009; US EPA, 2009), including literature specific to France (MEDDTL, 2010; CDL, 2012; Le Treut et al., 2013; Planton et al., 2015). The review identified many measures, all of which are already implemented or feasible. If the review was made as complete as possible, especially concerning physical-environmental measures, it is not yet exhaustive. From this initial list, only measures adapted to the French Atlantic coast were kept and, when relevant, analysed together with similar measures.

2.4. Classification

Four broad categories were adopted to classify the adaptation measures. These four categories were in turn broken down according to the coastal area management practices applied in the area (Fig. 3), as set out in the national strategy for integrated coastal zone management (MEDDTL, 2012) and in the regional strategy for Aquitaine developed by the *GIP Littoral Aquitaine* public interest group, which is a leading local player in coastal risks management (GIP, 2012; Rocle, 2017; GIP, 2016).

This category covers two coastal management approaches: *natural evolution under monitoring* and *accompaniment of natural processes*.

Natural evolution under monitoring refers to measures designed for natural areas where there are no human issues of concern in the vicinity and is valid for both erosion and flooding. It involves installing coastal monitoring tools to acquire knowledge about the physical processes involved in order to anticipate future developments and a possible transition to other management approaches.

Accompaniment of natural processes includes measures to manage coastal dunes, marshes and cliffs in a flexible manner in order to control erosion. On the sandy coast of Aquitaine, for example, this involves

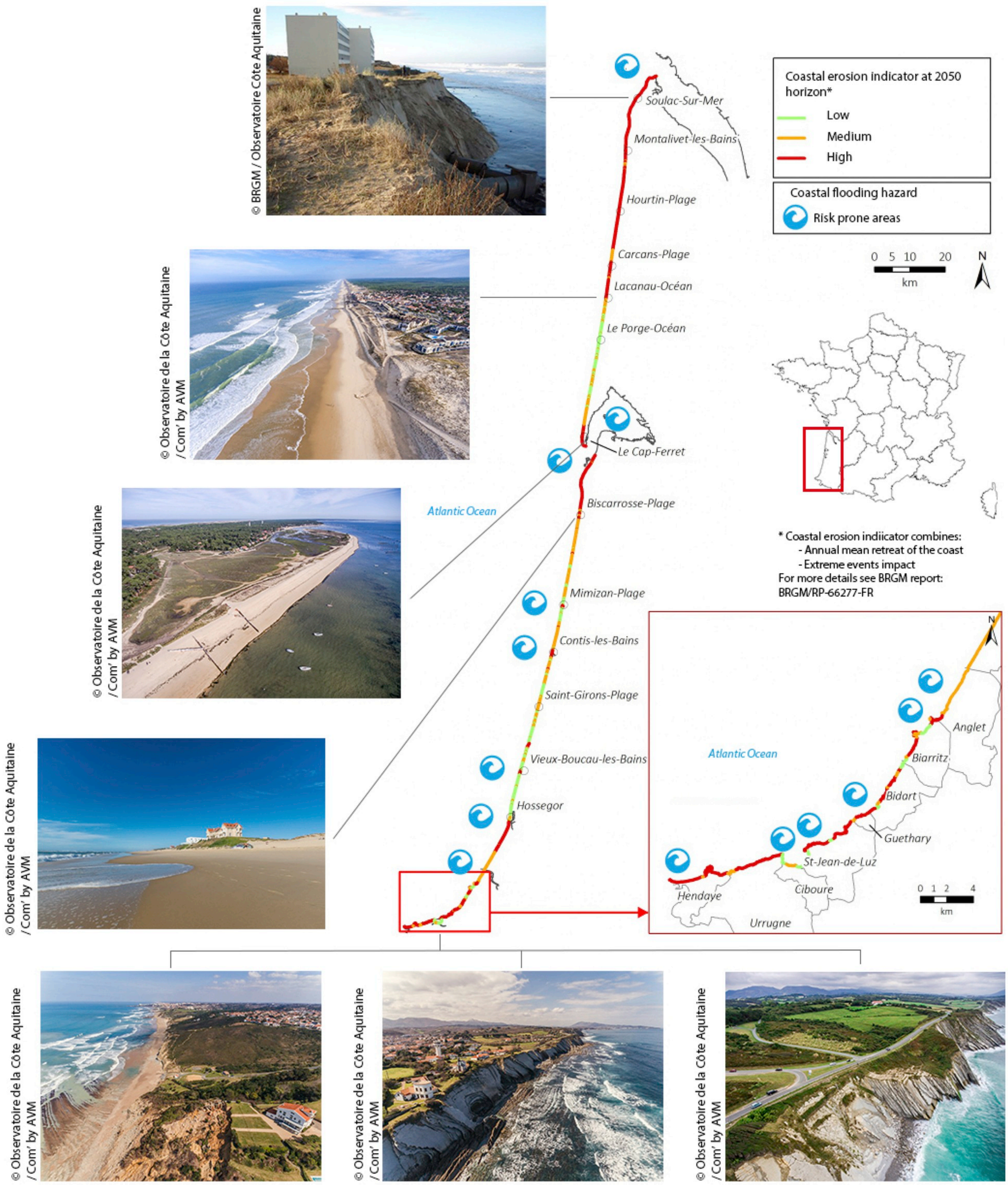

Fig. 1. The aquitaine coast and indicative risk-prone areas. Adapted from Observatoire de la Côte Aquitaine (http://www.observatoire-cote-aquitaine.fr/Les-risques-cotiers-53) and Bernon et al. (2016).

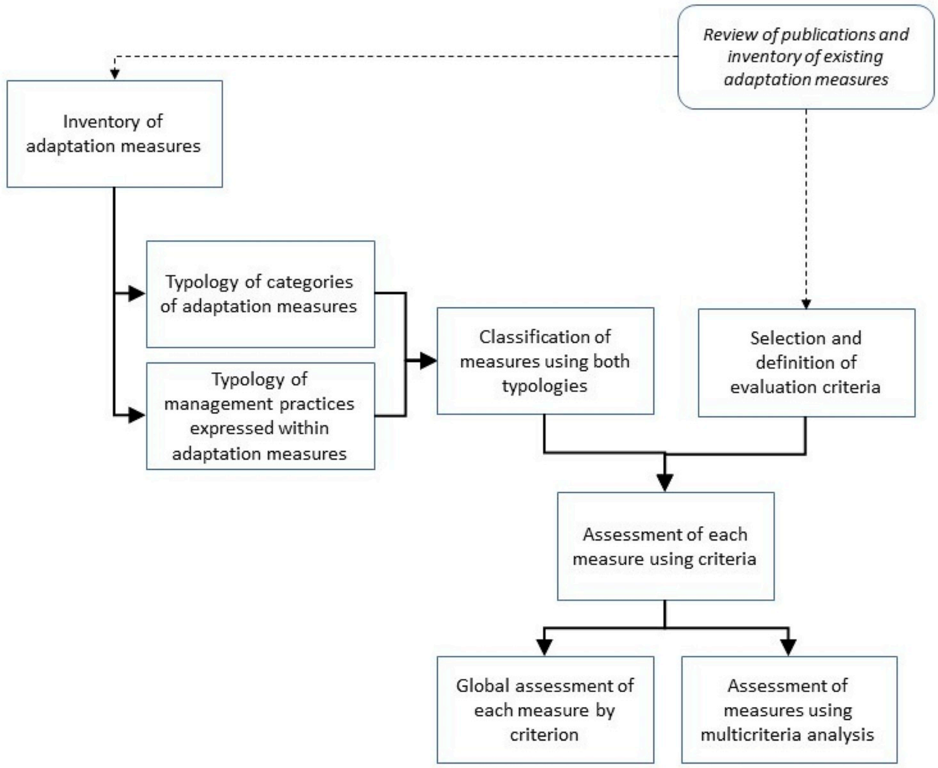

Fig. 2. Method applied to assess measures for coastal adaptation to climate change.

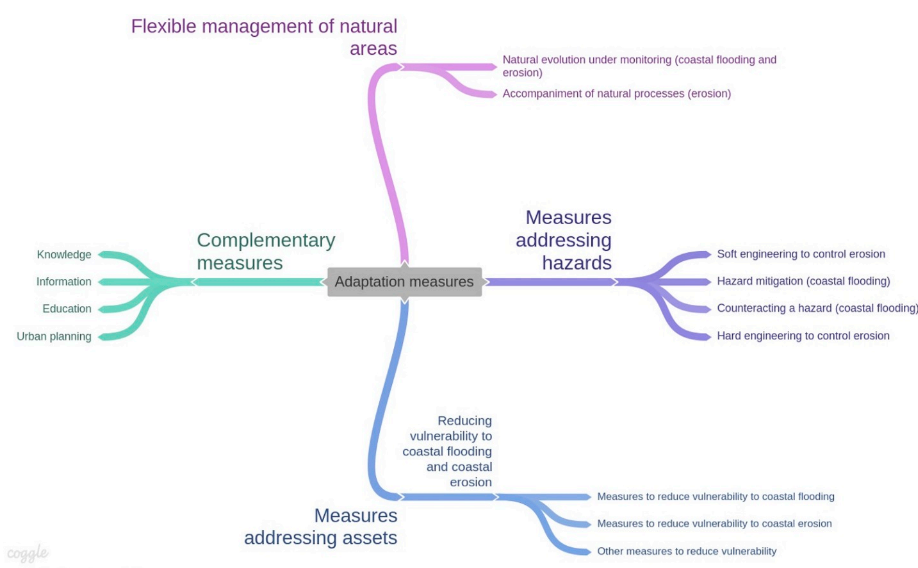

Fig. 3. Classification categories of adaptation measures.[1].

managing dune sand stocks by replanting vegetation or other ecological engineering methods to fix sand and limit wind erosion.

- Measures addressing hazards

This category covers all four coastal management approaches to *hazard mitigation*, *counteracting a hazard*, *"soft" engineering* and *"hard" engineering*.

Hazard mitigation concerns coastal flooding and includes measures to control runoff in order to mitigate flooding in strategic areas.

Counteracting a hazard also concerns coastal flooding and includes measures to prevent water from entering the area, or to help evacuate water when it does so.

"Soft" engineering concerns erosion along sandy coasts and includes

measures designed to slow or temporarily stop the natural processes of erosion. These measures are referred to as “soft” because they do not involve any radical change in the environment and do not counteract natural processes.

- Measures for flexible management of natural areas

“Hard” engineering measures concern erosion along sandy or rocky coasts and essentially include physical measures designed to stop erosion or fix the coastline. These are referred to as “hard” because they generally modify the environment by disrupting natural processes.

- Measures addressing assets

This category coincides with the coastal management approach referred to as *reducing vulnerability*. This concerns both coastal flooding and coastal erosion and includes measures ranging from action on an individual building to increasing the resilience of a society (e.g. crisis preparation), including strategic retreat. These measures therefore generally involve significant socio-economic and institutional issues.

- Complementary measures

This category includes measures that can be part of any management approach. They are essentially socio-economic or institutional measures (see below), which are not specifically aimed at fulfilling the conditions of a particular management method, but are often necessary to provide a framework and optimum conditions for implementing a particular type of adaptation strategy. They can be divided into four sub-categories according to whether they are targeted to improving knowledge, education, information for citizens or urban planning.

The choice of this classification was discussed and validated with the local stakeholders. It is consistent with the semantics of regional action already undertaken and allows the various measures to be organised according to their objectives and uses as reflected by the management approaches for the coastal zone.

In order to preserve the connection with international practices and provide additional information on the characteristics of the measures, we again used the classification used in the IPCC report (IPCC, WGII AR5, Chapter 14.3 Table 14-1, Noble et al., 2014). The adaptation measures are therefore also labelled according to their “physical-environmental”, “socio-economic” and/or “institutional” nature (see Table 1, Table 2, Table 3, Table 4).

Chapter 14 of the 5th IPCC Report categorises measures in a non-exclusive way (IPCC, WGII AR5, Chapter 14.3 Table 14-1, Noble et al., 2014):

- Structural or physical-environmental measures include technical, technological, engineering, ecosystem-based or service solutions. “This category highlights adaptation options that are discrete, with clear outputs and outcomes that are well defined in scope, space, and time.” (IPCC, WGII AR5 Chap 14.3.1). Examples: protective works, beach nourishment, etc.
- Socio-economic measures include education, information and behavioural solutions (IPCC, WGII AR5 Chap 14.3). These may include risk awareness and its inclusion in education and training, climate services, early warning systems, communication through the media, etc.
- Institutional measures combine solutions based on legislation, public policies or economics (IPCC, WGII AR5 Chap 14.3). Examples of institutional measures include financial incentives including taxes and subsidies or insurance, Risk Prevention Plans, National Plans for Climate Change Adaptation, etc. These measures can be applied at different national, regional or local levels.

The classification adopted here makes it possible to identify both the management approach to which they are related and their characteristics, which informs on the means necessary for their implementation.

We finally selected 51 measures for adaptation to erosion and coastal flooding hazards. These are listed by category in the following tables: Table 1 for “flexible management of natural areas”, Table 2 for “measures addressing hazards”, Table 3 for “measures addressing assets” and Table 4 for “complementary measures".

2.5. Assessment method

The aim is to provide an initial assessment of measures to adapt to coastal risks regardless of the study site. The assessment of the adaptation measures in the light of evolving risks in the climate change context is essentially based on a qualitative multicriteria analysis. The method is based on the one implemented by Hallegatte (2009), in which each adaptation measure is assessed qualitatively against several criteria (Fig. 4). We have extended the number of criteria from six for Hallegatte (2009) to ten in order to have a more accurate assessment.

The ten assessment criteria proposed here (see below) are generic so that they remain independent from the local context.

The approach followed is expert based. Several experts in coastal processes, coastal hazards and risks and climate change have been implicated. Each criteria, which is precisely defined, have been evaluated independently by each expert using its knowledge of coastal processes, adaptation measures and historical cases analysis. During a second phase, each assessment was discussed collectively before defining the final quotation, validated by the expert board.

The overall assessment is done criterion by criterion and does not give an overall score for each measure as this would require a method to aggregate the results that would be difficult to justify beyond any local context. At the local level, however, it may be useful to take stakeholder preferences into account in order to weight the criteria and aggregate the results and thus facilitate decision-making.

2.6. Defining the criteria for assessing the measures

For this study, ten criteria were defined to assess the measures (Fig. 4).

It would have been both useful and, in absolute terms, necessary to have a criterion taking the social, economic and environmental implications of the measures into account (Boruff et al., 2005). However, developing such a criterion would have required the involvement of several different social groups (elected officials, inhabitants, users and tourists, economic players, etc.) and different generations, all with different perceptions. This would have required substantial sociological studies well beyond the scope of this project and the deliberately generic character of the proposed assessment method; therefore, no such criterion was included in this study.

2.6.1. “No regrets” (existence of co-benefits)

This criterion characterises the capacity of an adaptation measure to produce benefits regardless of the level of future climate change and even in the absence of climate change (Hallegatte, 2009).

The benefits are understood here in economic terms, either tangible (e.g. damage avoided) or intangible (e.g. better awareness of erosion in society). These benefits depend on the measure considered, but also on the management approach for which the measure is intended (see classification of measures in section 2 above). For example, the “no regrets” character of an adaptation measure in the “counteracting a hazard (coastal flooding)" approach is assessed for this management approach only. Potentially positive or negative indirect effects on other risks are not taken into account here (see “Possible impact on other risks”

[1] realised with Coggle

Table 1
Characteristics of measures for flexible management of natural areas.

Coastal management approaches	Adaptation measures	Characteristics		
		Physical-environmental	Socio-economic	Institutional
Natural evolution under monitoring (coastal flooding and erosion)	• Creation of monitoring network/ observations	✓	✓	✓
Accompaniment of natural processes	• Sand fences, windbreaks nets, branches, etc.	✓		
	• Cliff foot palisade	✓		
	• Revegetation (on dunes, cliffs, etc.)	✓		
	• Wetland restoration, de-polderisation	✓		
	• Beach access management		✓	✓

criterion, section 2.6.7).

A measure may bring “no regrets” in all cases ('+') or in certain situations only ('+/−'), for example when the “no regrets” character depends strongly on the local context. A measure that is not rated as “no regrets” ('−') will generate significant additional costs if applied in climatic conditions that differ from those for which it was designed, which could be very damaging if climate change takes an unforeseen direction.

2.6.2. Robustness

The robustness of a measure characterises its capacity to be effective in the long term (several centuries), regardless of the way risks might evolve with global warming (Hallegatte, 2009). For example, if its effectiveness is conditioned by a threshold of sea level rise, the measure is generally not robust, because sea level could exceed this threshold in one or more climate change scenarios, making the measure ineffective. This definition is independent of the specific life span of the measure in question; the robustness of a measure is not being assessed with regard to its lifetime, but to its effectiveness regardless of the timing of its implementation in the future (up to 2100–2300).

A robust measure ('+') is therefore effective whatever the climate change scenario and the time horizon considered (e.g. 2030 or 2300). However, a measure is not robust ('−') if there are one or more climate change scenarios for which the measure is no longer effective from a certain date. If the robustness of the measure depends on the local context, it will be classified as ('+/−').

2.6.3. Flexible/reversible

A flexible or reversible measure is a measure that can be dropped overnight without any significant financial impact. The advantage of this type of measure is to keep the cost of misadaptation as low as possible (Hallegatte, 2009). For example, optimising dyke heights for uncertain sea-level rise scenarios (Hunter, 2012) is not a flexible measure because if the sea level does not rise as fast as anticipated in the optimal scenario, the outcome will be over-adaptation. The expenses induced by this over-adaptation would not be recoverable, and in today's context, the cost of partial deconstruction of a structure and the complexity of the social and environmental dimensions to be taken into account make it difficult to reverse the process in most cases.

Thus, a flexible/reversible measure ('+') does not entail large costs if it is finally abandoned, while an irreversible measure ('−') generates significant over-costs and/or simply cannot be abandoned.

The potential impacts of a measure on the environment, hydrodynamics, sediment transport, landscape, and so on are not taken into account in this criterion because their reversible/irreversible nature strongly depends on the local context. The analysis here is as general as possible.

2.6.4. Short decision horizon

Uncertainty about future climate conditions and their impacts on weather-ocean variables increases rapidly over time (Hallegatte, 2009). Reducing the lifetime of investments makes it possible to change strategies when the measure needs to be renewed, whether for inherent reasons or because it is no longer adapted to the prevailing environmental conditions. This reduces uncertainties about potential impacts and associated costs (compared to a measure that is no longer in line with the observed environmental changes).

A measure with a short decision horizon ('+') is a measure whose implementation demands a financial commitment over less than 10 years (from the moment it is operational). Conversely, a measure with a long decision horizon ('−') is a measure that demands commitment over more than 10 years.

2.6.5. Synergy with mitigation

The “synergy with mitigation” criterion reflects the impact of the measure's implementation on the overall aim of reducing greenhouse gas (GHG) emissions (Hallegatte, 2009). Thus, a measure in synergy with mitigation ('+') promotes the reduction of GHG emissions. Conversely, a measure that counteracts mitigation ('−') generates significant overproduction of GHG on a continuous basis or at the time of implementation. A measure can also be neutral with respect to GHG emissions or not affect GHG emissions significantly ('NA[2]') and in some cases the measure cannot be determines ('Indet.').

2.6.6. Immediate benefit

This criterion is applied to assess whether a measure is effective with respect to the management method for which it is implemented as soon as it is put in place ('+'), or if there is a delay between implementation of

Table 2
Characteristics of measures addressing hazards.

Coastal management approaches		Adaptation measures	Characteristics		
			Physical-environmental	Socio-economic	Institutional
Hazard mitigation (flooding)		• Retreat or removal of existing defences	✓		
		• Wetland restoration, de-polderisation	✓		
		• Second line levee / dyke	✓		
Counteracting a hazard (flooding)		• Dunes restoration or reconstruction / artificial sand dunes	✓		
		• Adjustment/increased height/ creation of hard engineered structures ○ Walls ○ Backshore riprap ○ Breakwaters (natural, artificial, submerged or not; including artificial reefs) ○ Stakes ○ Dykes, dyke embankments, multi-line dykes, etc. ○ Hybrid solutions	✓		
		• Temporary defences	✓		
		• Temporary storm surge dams	✓		
		• Limiting actions liable to cause subsidence (water, gas and oil pumping, etc.)	✓		✓
Soft engineering to control erosion		• Beach and/ or dune nourishment	✓		
		• Beach drainage	✓		
Hard engineering to control erosion	Sandy coast	• Adjustment/increased height / creation of hard engineered structures ○ Groynes ○ Breakwaters (natural, artificial, submerged or not) ○ Stone walls ○ Fence at dune foot ○ Backshore riprap ○ Stakes ○ Dykes ○ Hybrid solutions	✓		
		• Retreat or removal of existing defences	✓		
		• Geotextiles, geotextiles tubes & geobags[1]	✓		
	Rocky coast	• Reprofiling	✓		
		• Adjustment/ increased height / creation of hard engineered structures ○ Riprap at cliff foot ○ Retaining walls ○ Groynes ○ Stone walls ○ Cliff strengthening ○ Terraces building	✓		
		• Cliff drainage	✓		
		• Anti-runoff and anti-infiltration devices at cliff top	✓		

[a]The geotextile material, consisting of natural fibers and biodegradable polymers could be considered as "soft" adaptation measures when used in layers filled with local sand (geocontainers) or sand-filled containers (geotubes). However

independently of how they are used and before degradation, which can take several decades, geotextiles aim at stopping erosion or fixing the coastline. That is why they are classified as "hard" measures according to our definition (see section 2.4).

the measure and the associated benefits ('−').

This criterion is sometimes difficult to assess, in particular for adaptation measures in the "complementary measures" category (Fig. 3). These "complementary measures" can be applied in all coastal management approaches, but scoring for this criterion inherently depends on the management approach considered.

We therefore considered that for the measures in the "complementary measures" category, this criterion assesses the capacity of the measure to be effective as soon as it is implemented, in terms of the objective defined by the subcategory to which it belongs (i.e. improving knowledge, education, information for citizens, urban planning).

2.6.7. Possible impacts on other risks

This criterion takes into account the indirect effects of an adaptation measure on risks for which it is not initially intended. A classic example is a longitudinal protection structure at the top of the beach. The structure is intended to prevent coastal flooding and/or coastline retreat, but has the indirect effect of increasing erosion at the ends and the base of the structure. In this case, the indirect effects will be considered negative ('−').

We thus distinguish between:

- a measure that decreases risks for which it is not initially intended (referred to as positive indirect effects: '+'),
- a measure that has no indirect positive or negative effects on other risks ('NA'),
- a measure that may have a negative impact on other risks ('−').

2.6.8. Self-sufficiency

Many adaptation measures require the implementation of other adaptation measures to be effective.

In order to take this into account, a specific criterion was established to distinguish between self-sufficient measures ('+') and measures whose effectiveness depends on the implementation of other measures ('−'). When the evaluation of the criterion depends on the local context, a third attribute is used ('+/−').

This criterion, like the "Immediate benefit" criterion (section 2.6.6), can be difficult to attribute to some adaptation measures in the "complementary measures" category, since their rating depends on the management approach considered. As with the "Immediate benefit" criterion (section 2.6.6), we therefore considered that this criterion assesses the capacity of a measure to be self-sufficient in the subcategory it belongs to (i.e. improving knowledge, education, information for citizens, urban planning, see Fig. 3).

2.6.9. Life expectancy

This criterion was adopted to take the "effective period" concept into account in assessing the measures: once implemented, when should a measure be renewed or replaced by a different one?

This criterion corresponds to the lifetime of the measure considered as a single action. For example, "beach nourishment" as an adaptation measure would have a life expectancy of around five years (or less, depending on the rate of erosion of the beach). The life expectancy of a measure is its intrinsic lifetime, modulated by local environmental conditions (e.g. annual erosion rate, extreme events occurrence(s)).

If the environmental conditions in which the measure is implemented are not disturbed by any external circumstances, the criterion corresponds to the value of the measure's lifetime. Following the recommendations of Le Cozannet et al. (2016), sea level rise is considered here as the major external disturbance having an impact on erosion along soft coasts and on coastal flooding in the medium to long term, and therefore on the measure's life expectancy.

This criterion can thus be given three kinds of values[3]:

- life expectancy expressed in number of years if it is short enough for the effectiveness of the measure not to be affected by sea level rise or if the effectiveness of the measure is independent of sea level rise;
- "Function of SLR" if sea level rise is likely to constrain the lifetime of the measure and to reduce its effective period;
- "Infinite" if the effectiveness of the measure does not depend on the sea level rise and is virtually perennial.

2.6.10. Implementation costs and/or maintenance costs

This is the only quantitative criterion in the evaluation grid. The information filled in is based on examples from the literature. It was not possible to provide figures for all the measures identified.

The point of this criterion is to provide orders of magnitude for the costs generated by the implementation of a measure. These are given for information purposes only and are not intended to influence the overall assessment of a measure in the context of this study. This is because the actual total cost of implementing a measure is inherently related to the local context, which means that taking this criterion into account when working at the local level will be crucial.

3. Results

The full assessment table is available in Garcin et al. (2018) and provided as supplementary materials.

3.1. Overall analysis

The general measures score favourably against all criteria except "self-sufficiency" and "synergy with mitigation" (Fig. 5). Different tendencies appear for the different families of measures. Not surprisingly, *measures addressing hazards* is the family with the most drawbacks in respect of our criteria (Fig. 6) and to a lesser extent *measures addressing assets* (Fig. 7). Conversely, *complementary measures* (Fig. 8) and *measures for flexible management of natural areas* (Fig. 9) meet most of the criteria, but they are seldom self-sufficient. Figs. 5–9 consist in a general analysis to show how families of measures behave regarding the criteria. It gives an overview of their efficiency.

The results are detailed by assessment criterion in the following sections.

3.1.1. "No regrets"

A large majority of measures are rated as "no regrets" (72%) and nearly 14% of the measures as "no regrets" under certain conditions (+/−). In contrast, 14% of the measures do not rate as "no regrets" (−). These measures do not produce benefits in all climate change scenarios and are likely to generate additional costs if applied in conditions that differ from those they were designed for, which could be very damaging if climate change proceeds in an unforeseen direction.

In detail, *measures for flexible management of natural areas* are all rated as "no regrets", as are the *complementary measures*. Of the *measures addressing assets*, 50% are rated as "no regrets" and 38% as "no regrets depending on context" (+/−). 65% of the adaptation measures addressing a particular hazard are rated as "no regrets" and thus produce benefits even in the absence of climate change; 29% of the measures in this category are not rated as "no regrets".

Table 3
Characteristics of measures addressing assets.

Coastal management approaches		Adaptation measures	Characteristics		
			Physical-environmental	Socio-economic	Institutional
Reducing vulnerability to coastal flooding and coastal erosion	Actions on buildings (coastal flooding)	• Flood-proofed buildings (dry or wet)	✓		
		• Floating or amphibious anchored houses	✓		
		• Elevated ground floor	✓		
		• Stilt buildings	✓		
		• Removable buildings	✓		
		• Boat houses	✓		
		• Water and salt insensitive materials	✓		
		• Suitable positioning of utilities networks (electrical, drinking water, sewage …)	✓		
	Actions on buildings (coastal erosion)	• Removable buildings	✓		
	Other measures to reduce vulnerability	• Building standards adapted to hazard exposure			✓
		• Artificial raising of ground (e.g. artificial islands, mounds under buildings)	✓		
		• Strategic retreat	✓	✓	✓
		• Establishment of land management program (e.g. for land exchanges)		✓	✓
		Crisis management plan :			
		• Council protection plan			✓
		• Height of emergency exits of buildings adapted to the water level expected for a given hazard level	✓		✓
		• Emergency roads raised above the water level expected for a given hazard level	✓		✓
		• Protection of strategic or risk-prone buildings or areas	✓		✓

3.1.2. Robustness

The analysis for all types of adaptation measures indicates that about 51% of the overall measures are robust, that is to say, effective regardless of the climate change scenario considered and in the long term (i.e. to any date in the future up to 2300). However, nearly 37% of the measures are not robust and 12% are robust in some cases only.

In detail, considerable variability appears according to the category of measures. For example, 33% of the *measures for flexible management of natural areas* are rated as robust, and 24% of the *measures addressing hazards*. Nearly 50% of the measures from these two categories are not robust. On the other hand, 50% of *measures addressing assets* appear to be robust and those classified as *complementary measures* are all robust.

3.1.3. Flexible/reversible

Of all the measures, nearly 65% are flexible and reversible, while 35% are not.

A more detailed breakdown shows disparities: 100% of the measures for *flexible management of natural areas* and *complementary measures* are

Table 4
Characteristics of complementary measures.

Coastal management approaches		Adaptation measures	Characteristics		
			Physical-environmental	Socio-economic	Institutional
All	Knowledge	• Monitoring network and/or coastal observatories	✓	✓	✓
		• Hazard and vulnerability mapping		✓	✓
		• Sediment management plan at the hydro-sedimentary cell scale			✓
		• Research network and conferences		✓	
	Education	• Natural risk and climate change training		✓	
		• Research network and conferences		✓	
		• Risk awareness, urban planning, strategic retreat, etc.		✓	
	Information	• Creation of early warning systems	✓	✓	✓
		• Climate services	✓	✓	✓
		• Consultations		✓	
		• Media communication		✓	
	Urban planning	• Integration of climate change and its effects on coastal hazards in urban planning and documents		✓	✓
		• Prohibit building in hazardous areas and preserve buffer zones		✓	✓

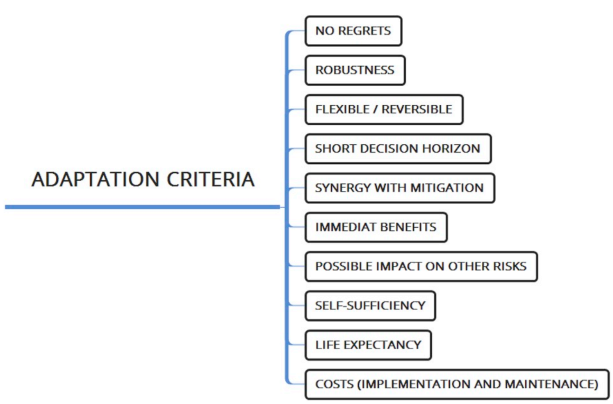

Fig. 4. List of the assessment criteria developed.

rated as reversible, while only 41% of the *measures addressing hazards* are assessed as reversible, the majority (59%) being considered irreversible. *Measures addressing assets* are equally divided between “reversible” and non-reversible".

3.1.4. Short decision horizon

More than half of the overall measures (53%) have a short decision horizon, while the remaining 47% demand commitments of more than 10 years.

A large majority of *flexible management measures* have a short decision horizon (83%). Of the measures in the *measures addressing hazards* and *measures addressing assets* categories, 65% and 75% respectively have a long decision horizon. Once again, the *complementary measures* stand out, with 100% having a short decision horizon.

3.1.5. Synergy with mitigation

This criterion was sometimes difficult to evaluate because it often depends on the scale of the actions to be carried out according to the context of each site. Only by systematically calculating the full carbon footprint of each adaptation measure would it be possible to quantify and confirm the qualitative assessment made in this study. Positive synergy with mitigation of GHG emissions remains very marginal overall, being promoted by only 10% of the measures. However, this criterion does not apply to 43% of the measures (e.g. *complementary measures* category), and they would generate GHG emissions in 35% of cases. In about 12% of cases, no synergy between adaptation and mitigation could be determined.

Regarding *flexible management measures*, 33% appear as rather positive as regards reducing GHG emissions, while this criterion is not applicable to the remaining 67%. In contrast, the *measures addressing hazards* tend to perform unfavourably by counteracting mitigation, with 64% of the measures rated as negative, as compared to 18% positive. About 12% of the measures could not be assessed against this criterion. *Measures addressing assets* never favour mitigation; 44% of them counteract synergy with mitigation, 31% are not concerned by this criterion and 25% are indeterminate. Finally, we considered that the criterion for synergy with the mitigation of GHG emissions is not applicable to any of the *complementary measures*.

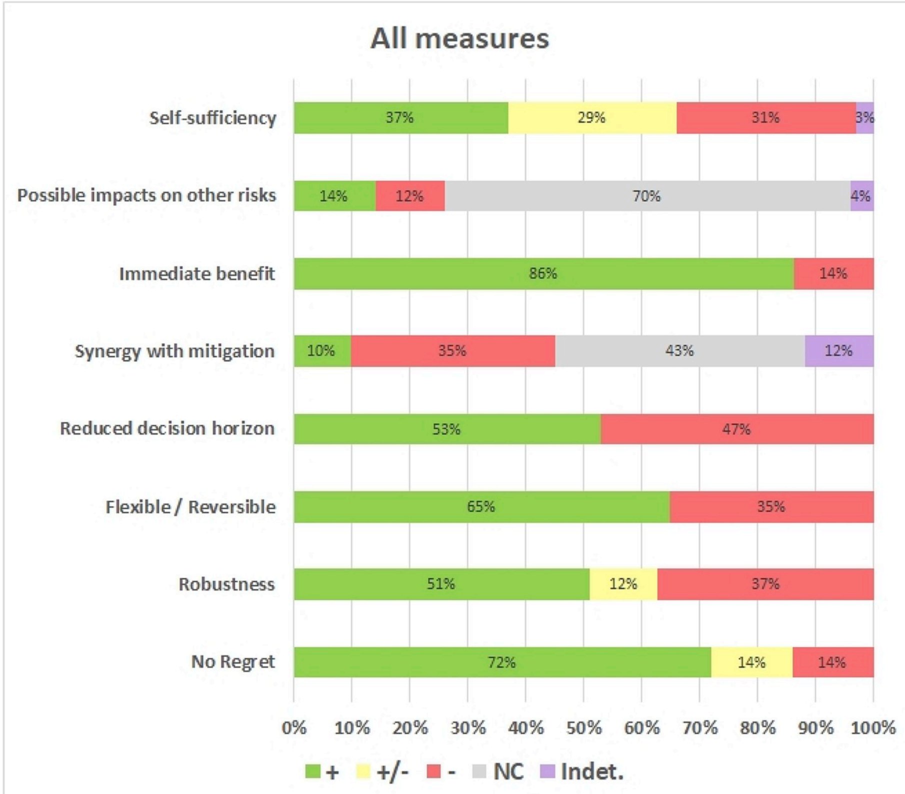

Fig. 5. Analysis of adaptation measures used in all coastal management approaches.

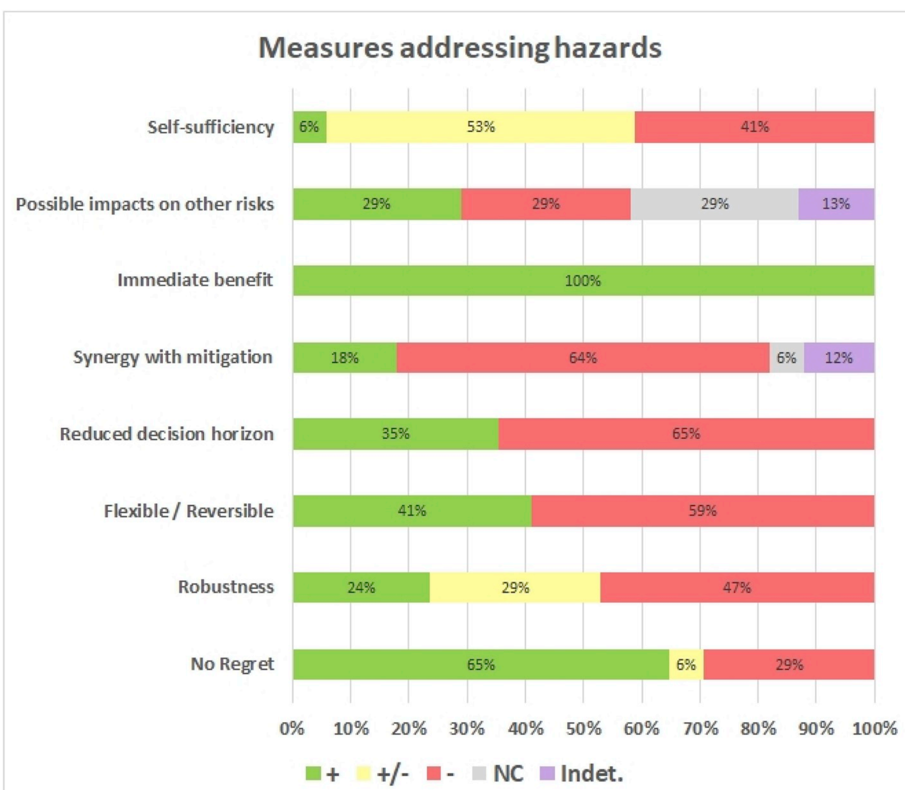

Fig. 6. Analysis of adaptation measures addressing hazards.

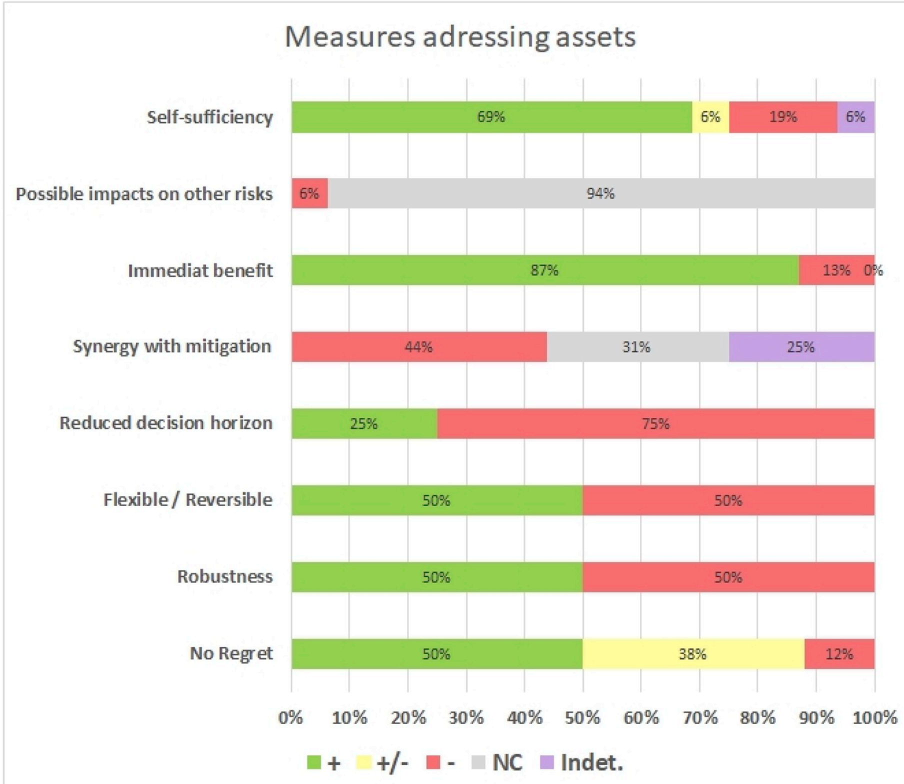

Fig. 7. Analysis of adaptation measures for addressing strategic assets.

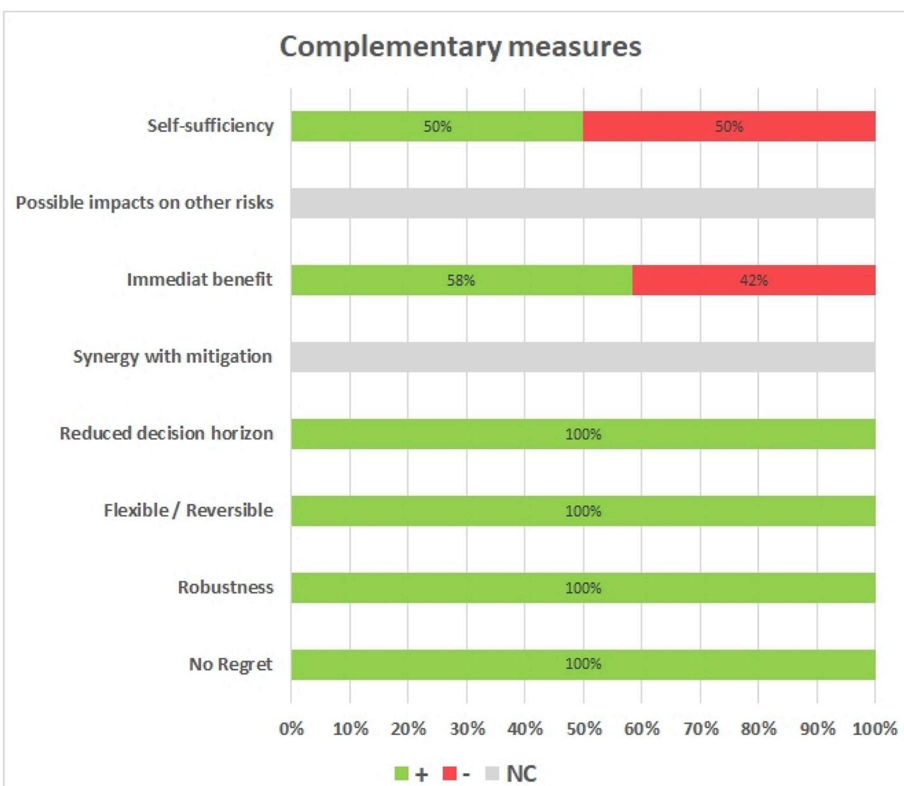

Fig. 8. Analysis of complementary adaptation measures.

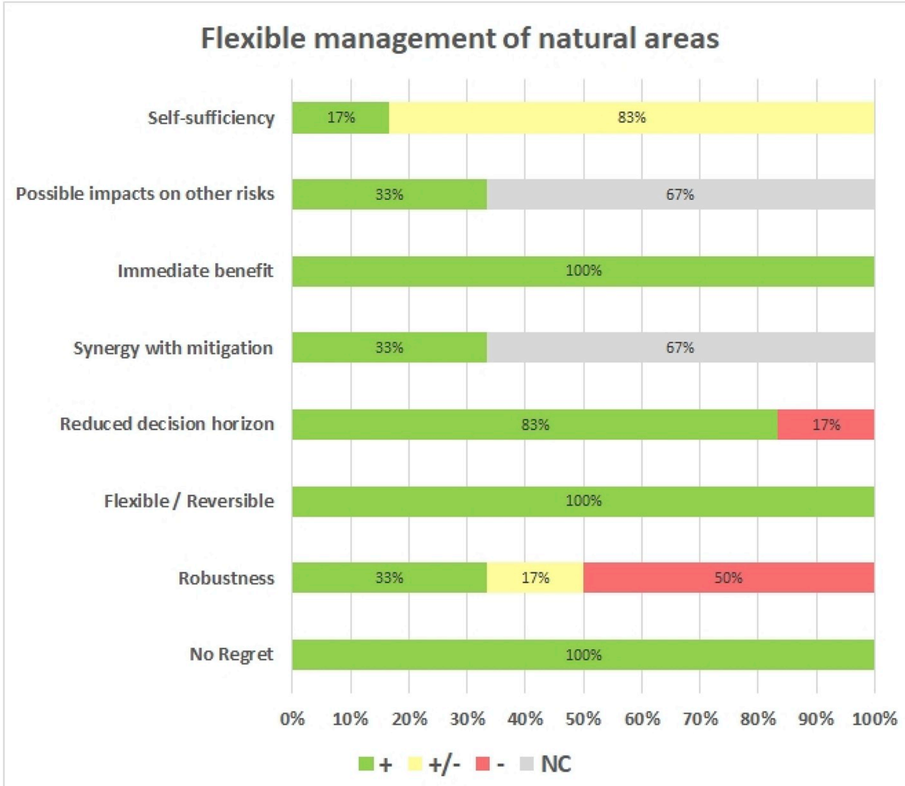

Fig. 9. Analysis of adaptation measures for flexible management of natural areas.

3.1.6. *Immediate benefits*

Measures with immediate benefits are overwhelmingly predominant (86%), while 14% require a delay after implementation before they become effective. This means that in the vast majority of cases, climate change adaptation measures bring immediate benefits to society in terms of the purpose for which they are implemented, regardless of any other factor.

In detail, all the *measures for flexible management of natural areas* and *measures addressing hazards* bring immediate benefits. *Measures addressing assets* bring immediate benefits in 87% of cases. Finally, 58% of the *complementary measures* bring immediate benefits, but 42% do not.

3.1.7. *Possible impacts on other risks*

Only 14% of the measures reduce risks other than the one(s) for which they are implemented. Furthermore, 12% of the adaptation measures potentially have a negative effect on other risks. In 70% of cases, the measures have no impact on other risks.

Looking into the detail, this criterion is not applicable to the *complementary measures*. *Measures for flexible management of natural areas* do not interfere with other risks (67%) or have a potentially positive impact (33%). On the other hand, 29% of *measures addressing hazards* may have negative effects on other hazards. 58% of these measures either have a positive impact or are not concerned by this criterion. The remaining 13% could not be assessed against this criterion. *Measures addressing assets* have no impact on risks in 94% of cases; only 6% could have a negative impact.

3.1.8. *Self-sufficiency*

About 37% of the measures are self-sufficient, while a similar number (31%) are not; 29% will be self-sufficient in some cases only, and finally, this criterion could not be determined for 3% of the measures.

With regard to *flexible management measures*, their self-sufficiency generally depends on the local context (83%), the remaining measures being considered as self-sustaining. The effectiveness of *measures addressing hazards* depends on other measures or on the local context in the majority of cases (94%). Nearly 70% of the *measures addressing assets* are self-sufficient, while 19% need to be accompanied by other measures to be effective. Finally, the *complementary measures* are equally divided into self-sufficient measures and measures that need to be complemented by others to be effective.

3.1.9. *Life expectancy*

The overall analysis of this criterion (Fig. 10) shows that 40% of general measures have a life expectancy that depends on the rise in sea level (or on climate change in general). This means that the intrinsic life span of 40% of the adaptation measures considered in this study is liable to vary with the effects of climate change. This finding has two consequences: on the one hand, it emphasises the need to contextualise assessments of adaptation measures and, on the other hand, it highlights the importance of refining local hazard projections. This implies estimating the likelihood of local shoreline retreat or coastal flooding as a function of climate change scenarios and probabilistic models. This would make it possible to specify the life expectancy of measures and thus develop relevant adaptation pathways.

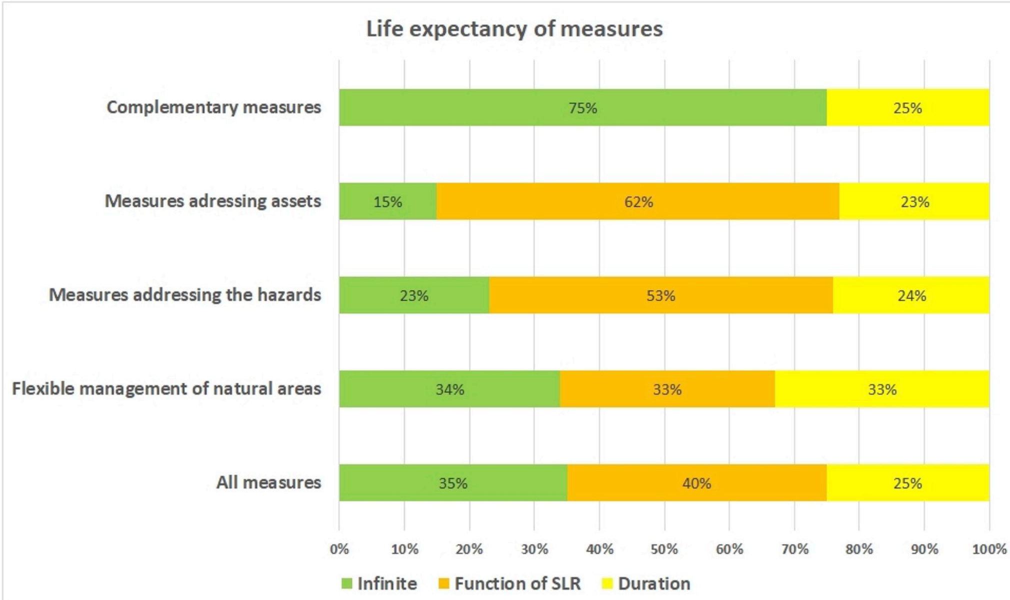

Fig. 10. Analysis of adaptation measures for the life expectancy criterion. (Infinite: the efficiency of the measure is not limited in time; Function of SLR: the lifetime of the measure is directly influenced by sea level rise rate and climate change; Duration: the lifetime of the measure is limited and independent of sea level rise, it is for example 5 ou 10 years.)

3.2. Multicriteria analysis

The analysis of all measures rated at once as “no regrets”, robust and reversible/flexible produces 19 adaptation measures that meet these criteria. Of these 19 measures, 11 are *complementary measures*, four are *measures addressing assets*, two are *measures addressing hazards* and two are *measures for flexible management of natural areas*. These 19 measures are listed in Table 5. They bring tangible or intangible benefits to society independently of climate change. They are relevant and effective regardless of the direction taken by climate change up to any time in the future. They do not induce significant extra costs if they are ultimately abandoned. These measures are of particular interest for climate change adaptation planning because they offer good options in a context of uncertainty.

The *complementary measures* all meet these three criteria. This is mainly because they are not physical-environmental measures and are therefore independent of climate change and systematically flexible. It should nevertheless be emphasised that *complementary measures*, as their name indicates, are additional to other measures implemented in one or more management approaches, depending on the site studied. They are therefore not sufficient in themselves as components of adaptation plans for coastal risks in the context of climate change. It is interesting to note that the management approaches referred to in the *measures addressing hazards* category as “*hazard mitigation (coastal flooding)*, *“soft” engineering measures (sandy coast erosion)* and *“hard” engineering measures (erosion)* do not include any measure that meets the three criteria mentioned above.

If we add the “short decision horizon” and “immediate benefits” constraints to the three previous criteria, 13 adaptation measures meet the criteria. The majority of these measures (seven) are *complementary measures*, two are *measures addressing assets*, two are *measures addressing hazards* and two are *measures for flexible management of natural areas*. In comparison with the 19 measures identified above, these 13 measures do not demand commitments for more than 10 years, which makes it possible to change a strategy when it is no longer suited to the current environmental conditions. They also produce immediate benefits, in terms of the management method or the purpose for which they are intended, as soon as they are implemented. These 13 measures may be considered as key measures for adaptation to climate change.

Finally, if we add the self-sufficiency criterion to those above, only four measures remain that meet these conditions:

- creation of a surveillance/observation network, for the “natural evolution under monitoring” approach;
- construction of removable buildings, for the “reducing vulnerability” approach;
- creation of climate services (complementary measures - information to citizens);
- communication via the media (complementary measures - information to citizens).

For each of the objectives or management approaches concerned, these four measures may be considered as the minimum to be implemented in applying a climate change adaptation strategy. For example, if the aim is to reduce the vulnerability of an area, the minimum is to opt for removable buildings in areas potentially exposed to hazards.

The robustness of a measure characterises its relevance and effectiveness in all climate change scenarios and at any date in the future. Robust measures are therefore of particular interest in the context of adaptation to climate change. However, non-robust measures with a short decision horizon are also of interest because they allow strategies to be changed as soon as they are no longer in line with current

Table 5
Multicriteria analysis of adapation measures.

Measure	Criteria		
	No Regrets / Robust / Reversible	*No Regrets / Robust / Reversible / Short decision horizon / Immediate benefits*	*No Regrets / Robust / Reversible / Short decision horizon / Immediate benefits /Self-sufficiency*
Creation of monitoring network	✓	✓	✓
Access management	✓	✓	
Temporary defences	✓	✓	
Limiting actions favouring subsidence	✓	✓	
Removable buildings	✓	✓	✓
Building standards adapted to hazards	✓		
Land management program	✓		
Local area protection plan	✓	✓	
Hazard and vulnerability mapping	✓	✓	
Sediment management plan	✓	✓	
Research network and conference	✓		
Natural risk and climate change training	✓		
Risk awareness	✓		
Early warning	✓	✓	
Climate services	✓	✓	✓
Consultations	✓	✓	
Media communication	✓	✓	✓
Integration of climate change and its effects on coastal hazards in urban planning and documents	✓		
Ban on construction in risk-prone areas	✓	✓	

environmental conditions. It is considered that variations in environmental conditions due to climate change are not perceptible over periods of less than 10 years. Table 6 lists eight measures that meet this case. For example, they include all ecological engineering measures for beaches or dunes. It is worth noting that these eight measures also generate immediate benefits, in terms of the management method in question, which reinforces their value.

4. Discussion

Assessments of natural risks in the future and in the climate change context must take changes in both risks and vulnerability in the area concerned into account. How risks will evolve in the future is linked to changes in parameters and forcing factors, which are dependent on greenhouse gas emission reductions on the worldwide scale. There is

Table 6
Non-robust adaptation measures with a short decision horizon.

Coastal management approach	Measure
Accompaniment of natural processes (erosion)	Sand fences, windbreak nets, branches, etc.
	Cliff foot palisade
	Plant cover (on dunes, cliffs, etc.)
Counteracting a hazard (coastal flooding)	Dune restoration or reconstruction
Soft engineering measures against erosion	Beach or dune nourishment
	Beach drainage
Hard engineering measures against erosion[1]	Geotextiles
Reducing vulnerability	Sealed buildings

[a]See Table 2.

still a great deal of uncertainty as to how far mitigation measures will be applied in the coming years. Adding to these uncertainties are those concerning the responses of the climate system, due to its complexity and to feedback effects that are still difficult to model. It would also be necessary to carry out prospective socio-economic studies so that the simultaneously occurring social changes that are among the main components of the problem can be taken into account. A prospective study of this kind would involve exploring possible futures by co-constructing different qualitative and quantitative scenarios to anticipate future changes in an area's vulnerability and inform planning decisions. The assessment of adaptation measures proposed here does not include these considerations for several reasons:

- Firstly, the time-scales for which the prospective socio-economic scenarios have predictive value seldom exceed a few decades (generally 20–30 years) because of the increasing uncertainties weighing on the realism of these scenarios as we project ourselves into the future. In the context of climate change, this is a short-term horizon, given that sea-level rise will very likely continue for several centuries (Clark et al., 2016). An assessment of adaptation measures over the medium and long term (beyond 30 years) can only be done through comparisons with anticipated changes in the hazard and not risk as societal changes cannot be taken into account.
- Secondly, changes in the coastal fringe, particularly where land use planning is concerned, are inherently linked to the regulations in force. Under current conditions (without any changes in regulations), massive densification of urbanisation in coastal sites is unlikely. Nevertheless, recent parliamentary debates in France and a series of proposals for laws on the coastal fringe to take into account erosion in a climate change context for urban planning tend to show that the situation could evolve in the near future. The uncertainty over this regulatory context and the aims of future public policies to limit urban sprawl are not conducive to co-developing scenarios with stakeholders.
- Finally, our method for assessing adaptation measures is generic (see section 2) and is therefore virtually independent of the local geographical context (only the necessary maritime, climatic or geomorphologic context is taken into account). Prospective socio-economic data are necessarily local and therefore difficult to exploit in such an approach.

This inventory of measures to adapt to coastal erosion and flooding risks is intended to be representative but not exhaustive, in particular as regards the *complementary measures* category. These can be extremely diverse and highly dependent on the prevailing economic, political and legislative context at the local, regional and/or national levels.

Moreover, some measures have been grouped together under the same label (engineered structures, for example) for better readability of the results. These are measures with points in common: they are similar in nature and, most importantly, their scores are the same for all the assessment criteria. Conversely, a few measures seem to recur in different management approaches (for example, creation of a monitoring network/observations). This is because they are assessed in terms of each management method, so their evaluation might be different for the same criteria. This work focusses on coastal hazards (erosion and flooding), but the same methodology could be applied for other climate sensitive hazards affecting the coastal area, such as for example river flooding or drought.

The adaptation measures selected here have been assessed by experts. The assessment is virtually independent of the local context so that they can all be compared in the same analysis grid and according to objective criteria. The assessment therefore provides general lessons, but is not sufficient in itself to support operational decision-making for a particular site. This is because adaptation measures can have different consequences and impacts, depending on the site in which they are applied. As a result, any operational decision will have to take the local context into account.

In our analysis, no overall integrated score is given, because this would necessarily mean prioritising the criteria in order to weight them, which can only be done in close consultation with stakeholders to define the weighting procedure. Moreover, indirect effects on the environment, biodiversity, landscape, tourism or wider economic activities are not considered, because these all depend on the local context and can only be assessed on a case by case basis. Any more detailed assessment of the different adaptation options at the local level will therefore have to take these points into account.

These reservations notwithstanding, the following main points emerge from our study. Whatever their category, measures that generate immediate benefits are overwhelmingly predominant (86%, Fig. 5). This implies that implementing climate change adaptation measures as soon as possible can only be beneficial to society, regardless of future climate changes. However, measures that require a delay between their implementation and the expected benefits must also be considered and anticipated in adaptation planning.

Very few physical-environmental measures are robust, in other words effective, in any given climate change scenario and over long time scales (several hundred years). This is consistent with conclusions of Antunes do Carmo (2019): after some time effort will have to focus on retreat to safe places as protecting high-risk areas will become extremely costly in both terms of defence and loss rates. On the other hand, there are many possibilities for adaptation in the short and medium term (2030–2050, 2080–2100).

Measures with a short time horizon for decisions are of interest in the uncertain context of climate change impacts because they allow a change in strategy as soon as the need arises. It should also be noted that relatively few adaptation measures are in synergy with GHG mitigation, although this is a priority in any attempt to limit global warming. Among other conditions, the rate of sea level rise, both ongoing and at a given time, has a major influence on coastal flooding, coastal erosion and shoreline retreat hazards (Wong et al., 2014; Planton et al., 2015; Le Cozannet et al., 2016). Many measures have a life expectancy that depends on sea level rise, which is itself constrained by climate change scenarios. This means that the inherent lifetime of the measure is long enough for sea level rise to potentially reduce its period of effectiveness. To specify the effective life expectancy of these measures, risk projections must be refined at the global, regional and local scales. It then becomes possible to develop adaptation pathways that are best suited to the study site (Lavery and Donovan, 2005). The *complementary measures* have the advantage that they are not mutually exclusive, unlike other measures in many cases. It is already obvious that these measures provide a necessary and favourable framework for the development of any adaptation strategy implementing one or more management approaches. It must be kept in mind, however, that none are usually sufficient in themselves as plans for adaptation.

5. Conclusions

The method applied in this research work builds on recent experiences in the Netherlands and the English-speaking world and is presented by the IPCC as the most appropriate for responding effectively to the challenges of climate change adaptation. This approach focuses on solutions (adaptation measures), which facilitates decision-making in the highly uncertain context of evolving risks.

51 adaptation measures, based on an international literature review and an analysis of existing on-site approaches, were listed for this study. We identified 10 climate-change-related criteria to assess the different measures. Our analysis of the results highlights the main characteristics of the measures applied in each management approach and enabled us to identify a set of essential measures to adapt to coastal risks in the climate change context. In general, the study shows that there are many possibilities for adaptation in the short and medium term (2030–2050, 2080–2100) and stresses the need to anticipate and plan adaptation, in particular when there is a delay between implementing a measure and its expected benefits. The development of adaptation pathways suited to local geographical contexts needs to be based on more detailed hazard projections in order to specify the life expectancy of the measures applied.

This assessment of proposed adaptation measures is mostly independent of the local context so that all the adaptation measures identified can be compared on the basis of the same analysis grid and according to objective climate-change-related criteria. It is therefore valid in most coastal areas. This type of general assessment, however, is not sufficient in itself to support decision-making on adaptation choices for any particular site. Any decision on adaptation measures must take the local context into account to make an in-depth assessment of the different criteria chosen.

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Appendix A. Supplementary data

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