Ca' Foscari University of Venice

Joint Master's Degree programme

in "Sustainable Development"
"CM5-11"

Final Thesis

Climate change risk assessment for the oil and gas industry: identification of potential impacts, vulnerabilities and adaptation strategies in coastal areas.

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Academic Year
2015 / 2016

Index

Summary **3**

Objectives and motivations **5**

Thesis structures **7**

Introduction **9**

1. Literature review of risk assessment tools and methodologies developed for industrial facilities. **11**

1.1 State of the art of risk assessment approaches relevant for the O&G industry. 12

1.2 Discussions and conclusions. 18

2. State-of-the-art of available indicators measuring the effects of climate hazards on O&G exposed systems. **19**

2.1 Review of climate change related indicators for coastal and offshore O&G assets. 20

2.2 The Coastal Vulnerability Index (CVI). 26

3. Planning the risk assessment for the O&G sector: problem formulation and data collection. **34**

3.1 The DPSIR conceptual framework. 35

3.2 Description and Characterization of the case study area. 39

3.3 The available data set. 42

4. Coastal vulnerability index supporting the definition of adaptation strategies for the energy sector. **46**

4.1 Identification of application context: objectives, scale and scenarios. 47

4.2 Indicators' selection and normalization. 49

4.2.1 Physical indicators. 50

4.2.2 Geological indicators. 52

4.2.3 Socio-economic indicators. 54

4.3 Index calculation. 56

4.4 Coastal vulnerability mapping. 57

5. Results and discussions. **57**

5.1 Identification of application context: objectives, scale and scenarios. 58

5.2 Indicators' selection and normalization. 59

5.2.1 Physical indicators. 60

5.2.2 Geological indicators. 69

5.2.3 Socio-economic indicators. 76

5.3 Index calculation. 78

5.4 Overview of adaptation and mitigation options for the O&G industry. 82

6. Conclusions. **86**

References **89**

Websites citations **98**

ANNEX I **100**

ANNEX II **103**

ANNEX III **104**

ANNEX IV **107**

Summary

Climate change is causing serious threats on both natural and human systems worldwide. The expected physical impacts (e.g. sea-level rise, storms, floods, droughts) are already affecting natural and human systems with different intensities and are projected to continue in the future with huge environmental and socio-economic consequences. The Oil and Gas (O&G) industry is particularly exposed to the impact of climate change due to the environment in which industrial complexes and energy infrastructures operate (e.g. offshore regions, low-lying coastal areas, floodplains) and to the susceptibility of the natural resources used in the technological/industrial processes (e.g. water, wind, insolation). More specifically, many coastal energy infrastructures are threatened by sea-level rise and storms through flooding and erosion. Disruptions in supply, transportation and storage of energy may also have global impacts and translate in potential contamination of the natural environment.

Consequently, there is an increasing need to develop appropriate risk based approaches in order to better understand the implications of climate hazards on coastal oil and gas facilities. These methodologies should be used to identify the overall risks and vulnerabilities posed by climate change in different phases of development of oil and gas assets, facilities and operations (i.e. from project design to exploration, processing and transportation).

Starting from a literature review of available tools, methodological guidelines and best practices for conducting climate change risk assessments in the O&G sector, a conceptual framework has been developed in order to show, in a systematic way, the main cause-effect relationships and interactions between: climate-related hazards, pathways of exposure and targets of risk concerning coastal O&G activities and infrastructures. Then, a Coastal Vulnerability Index (CVI) was developed to map the relative vulnerability of coastlines to sea level rise, storm surge flooding and coastal erosion, considering both a baseline (1980-2000) and a future (2021-2050) climate change scenario based on the RCP 8.5 emission scenario.

The analysis, performed in a pilot study within the Mediterranean Region, which is a great example of a coastal system supporting a considerable amount of

energy facilities, allowed to identify and rank coastal segments more prone to erosion and/or inundation. Specifically, the results obtained for the Mediterranean coast of Egypt showed that the Nile Delta region is the area more prone to coastal erosion and permanent/occasional inundations (both in the baseline and the future climate change scenario) compared to the rest of the coastline. Whereas, the area of the Western Desert is characterized by lower vulnerability scores due to its geological characteristics (i.e. rocky/cliffed coasts, steeper coastal slope). Moreover, the results capture the potential exposure of human activities to inundation and erosion, assigning higher vulnerability scores where industrial, urban or agricultural activities are located. Even if it wasn’t possible to integrate in the analysis specific indicators and thresholds to characterize the vulnerability of energy facilities located in the case study area, the CVI outputs (i.e. vulnerability maps and statistics) were finally used to draw some considerations about the potential risks for the energy assets and the adaptations strategies that should developed to protect existing critical infrastructures/operations or upgrade existing design standards for the development of new project plants.

Objectives and motivations

There is a wide consensus among the scientific community that climate change is unequivocal and that is causing a threat on both natural and human systems. Changes are observed (and projected), with different intensities, in all geographical regions: the atmosphere and oceans are warming, the extent and volume of snow and ice are diminishing, and sea levels are rising (IPCC 2013b). The physical impacts of climate change (e.g. sea-level rise, storms, floods, droughts, and different weather patterns) are already affecting natural systems and human assets and are expected to continue in the future (IPCC 2013b).

The O&G sector and the energy companies are particularly vulnerable to climate change impacts due to the areas in which industrial complexes and energy infrastructures operate (e.g. offshore regions, low-lying coastal areas, floodplains), and to the shortage of the resources used during the operational phases (e.g. water, oil, wind, insolation). In fact, changes in climatic features (e.g. temperature, precipitation, windiness, cloudiness, etc.) and variations of magnitude and frequency of extreme weather events (e.g. floods, cyclones, etc) will progressively affect O&G industrial operations, over time (IPCC, 2014a).

As far as coastal areas are concerned, sea-level rise and coastal erosion could have also a great impact on O&G infrastructures, causing equipment losses and relocation (IPCC 2014a). This effect will be obviously amplified by the interplay of several socio-economic factors such as population rise, the socio-economic growth as well as the future policy framework.

Therefore, there is an increasing consensus among the scientific community to develop an appropriate risk based approaches in order to better understand the most likely impacts of climate changes on coastal O&G facilities.

In particular, in order to accomplish this objective, the specific purposes of this study are the following:

a) Review of previous studies concerning climate change impacts on coastal and offshore O&G assets, focusing on the identification of available risk assessment tools and methodologies, key indicators and cause-effect relationships between climate hazards and coastal O&G infrastructures.

b) Definition of a DPSIR (Driving forces, Pressures, States, Impacts, Responses) conceptual framework that includes all the relevant source of risk (threats), the potential exposure pathways between climate-related pressures and states (environmental or O&G targets) and the potential harms (losses or impacts) that might result from exposure to hazard.

c) Development of a Coastal Vulnerability Index (CVI) that allows to map the relative vulnerability of coastlines by identifying and prioritizing hotspot areas and targets at higher risk of sea-level rise storm surge flooding and coastal erosion.

d) Application of the proposed CVI to a pilot case study within the Mediterranean Region, which hosts a great amount of energy infrastructures.

As discussed in the thesis, the output of the analysis will include a suite of tools (e.g. coastal risk maps and indicators) – elaborated by means of Geographic information System – that may help energy companies in the definition and prioritization of potential climate change impacts in the case study area and in the identification of potential solutions for adaptation (e.g. risk reduction or resilience building measures).

Thesis structures

The thesis is structured in six chapters. Chapter 1 and Chapter 2 provide a theoretical background of climate change risk assessment tools, methodologies and key indicators suitable for the vulnerability assessment of the O&G industry. In particular, Chapter 1 critically reviews available risk assessment methodologies and tools for the estimation and prioritization of natural hazards and related risks. Chapter 2 presents the state of the art regarding indicators and indexes useful for the identification of cause-effect relationships between climate pressures and impacts that are most likely to affect coastal O&G infrastructures.

Chapter 3 is aimed at defining a risk assessment procedure suitable for the O&G industry. More specifically, Section 3.1 0presents the DPSIR (Driving forces, Pressures, States, Impacts and Responses) conceptual framework that starts the formalization of all the hypothesized cause-effect relationships between the sources of a hazard, the pathways of exposure and the O&G receptors. Hereafter (Section 3.2) the case study area selected for performing the developed methodology is described, focusing on its natural, administrative and socioeconomic aspects. Finally, the available dataset will described in details according to the spatial domain and data source (Section 3.3).

Chapter 4 is focused on the description of the Coastal Vulnerability Index (CVI) proposed in the thesis to evaluate coastal vulnerability in relation to climate related hazards (e.g. sea-level rise and storm surge anomalies) – considered under different future climate change emission scenarios – and for different physical-environmental indicators (e.g. elevation, slope, land cover).

Chapter 5 describes the main outputs and results of the application of the CVI to the selected case study, including the identification and ranking of those areas more vulnerable to sea-level rise, extreme storm surge events and coastal erosion. Finally, an overview of the potential solutions for the development of adaptation strategies is also provided (Paragraph 5.4).

To conclude, the outputs of this study and the concluding remarks are discussed Chapter 6, highlighting the strengths and the weaknesses of the proposed approach.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) concludes that during the last decades, climate change has caused great impacts on society and on the environment (e.g. sea level rise inundation, change in water quality and availability, drought, loss of biodiversity change, increase in vector borne diseases). Particularly, the increasing emissions of carbon dioxide, related with human activities, are very likely to be the dominant cause of climate variations (IPCC, 2014).

Moreover, climate change is affecting many regions across the world, causing different types of impacts ranging from heavy precipitation, melting of snow and ice, seal-level-rise, increase temperature, heat waves and more frequent/intense extreme weather events (IPCC, 2013b).

Therefore, many key economic sectors are affected by long-term changes in temperature, precipitation, sea level rise, and extreme events, all of which are impacts of climate change. As a consequence, investors and financial institutions operating in most of economic sectors are increasingly interested in developing a business approach to climate change, assessing risks and opportunities related to climate change and identifying the best portfolio of adaptation strategies (IPCC, 2013b).

The O&G industry is mainly triggered by the physical impact of climate change due to the environment in which industrial facilities are located (e.g. offshore regions, low-lying coastal areas, floodplains), and to the susceptibility of the natural resources used in industrial operations (e.g. water, oil, wind, insolation) (IPCC, 2014b).

In particular, many coastal energy infrastructures are threatened by sea-level rise and storms through flooding and erosion. Moreover, extreme weather and storm events may influence the integrity and reliability of pipelines and electricity grids that have been planned for long lifetimes. Disruptions in supply, transportation and storage of energy may also have global impacts and translate in potential contamination of the natural environment. At the same time, projected changes in temperature will have an impact on the energy demand for heating and for cooling in the residential and commercial sectors (IPCC, 2014b). This effect will be obviously amplified by the interplay of several socio-economic factors such as population rise, the socio-economic growth as well as the future policy framework.

In addition to the physical impacts of climate change, policy measures directed at reducing GHG emissions are likely to affect investments in the fields of renewable energy and energy efficiency (IPCC, 2014b).

Consequently, it is time for company leaders and investors in the O&G industry to face the new and adverse challenges posed by climate change.

Generally, risk assessment approaches are mainly focused on the estimation of system failure and on the evaluation of potential cascading sequences of events (e.g. oil spill, blowouts, fire spread) (Alkazimi & Grantham, 2015; Davies & Hope, 2015; Lavasani et al., 2015). Moreover, the majority of the studies are focused on the impacts of climate change on reliable energy supply and demand. Although the considerable amount of scientific literature that has been written on the theme of the prevention from technological accidents (e.g. oil spills, gas releases, fires and explosions) and on the implementation of safety activities (e.g. the petroleum exploration and extraction safety act, Seveso Directive) (Falck et al., 2000; Bolado et al., 2012; Skogdalen & Vinnem, 2012); only a few studies look at climate change as a key factor that may affect facilities integrity and efficiency performance within their entire lifetime (Burkett, 2011; Cruz & Krausmann, 2013).

In order to fill this gap, this thesis is aimed at: 1) reviewing risk assessment methods, tools and indicators that can be used to address the issues posed by climate change on the O&G industry; 2) to select and apply a risk assessment tool (i.e. the Coastal Vulnerability Index) to estimate the potential vulnerabilities and risks related to climate change in a coastal system within the Mediterranean Region supporting a considerable amount of energy facilities.

The main outputs of application include GIS-based maps and statistics which represent useful climate risk products, allowing the classification and ranking of a) current vulnerable regions in which energy facilities are already located, b) areas that are likely to be affected more severely than others in the future in relation to climate-induced sea level rise and storm surge events.

The produced climate risk services can be used O&G companies to mainstream climate adaptation strategies (resilience and risk management) into their business development approach.

1. Literature review of risk assessment tools and methodologies developed for industrial facilities.

The critical review of available risk assessment methodologies and tools is necessary for the establishment of a theoretical background of climate change risk assessments for the O&G sector. In fact, allowing the estimation and prioritization of natural hazards and climate-related risks for various systems, risk analysis can contribute significantly in the effort of reducing, and thus minimizing, the effects of climate variations and impacts during O&G activities (i.e. extraction, production and storage, transport). In order to select the more appropriate risk and vulnerability approach to be developed in the thesis, a review of tools and methodologies applicable for the O&G industry have been performed and is presented below.

Several risk analyses are currently employed by the scientific community to predict, prevent and mitigate the potential hazards due to accidental events that can occur during O&G operation processes (e.g. from project design to exploration, processing and transportation) (Alkazimi & Grantham, 2015; Davies & Hope, 2015; Lavasani et al., 2015).

Even if there are many methodologies and tools already implemented for assessing risk and vulnerability, most of the proposed approaches do not consider climate drivers (e.g. warmer temperature, changes in precipitation patters and extreme weather events) as a primary source of risk for the O&G assets (Falck et al., 2000; Bolado et al., 2012; Skogdalen & Vinnem, 2012).

Thus, the first step of the analysis was aimed at reviewing the most common risk assessment approaches employed by the O&G sector in order to assess industrial system's vulnerabilities to both natural and anthropogenic hazards by considering different steps of O&G development projects (i.e. from project design to exploration, processing and transportation).

Therefore, the following Section is focus on reviewing previous studies concerning risk assessment tools and methodologies generally employed for the O&G industry.

1.1 State of the art of risk assessment approaches relevant for the O&G industry.

A great amount of the reviewed literature deals with tools that help to recognize risks caused by electromechanical failures that may occur during operational processes within the systems. These methods have been developed in order to a) estimate the probability of operational system's failures to occur by considering different types of hazards (e.g. natural fatalities, system fauilures) that may lead to accidental events and determine the likelihood and severity of those situations; b) provide an easy to understand representation of the relationships between the causes of accidental events, their consequences and the strategic measures to mitigate/reduce hazards.

For example Failure Mode and Effect Analysis (FMEA) evaluate equipment security and risks associated with potential equipment malfunction. In addition, FMEA tries to implement corrective actions before the system failures to prevent technological disasters (Petrovskiy et al., 2015).

The FMEA methodology is a bottom-up approach, which plays a central rule in the system design stage, since it increases design safety standards by identifying hazards early in the product lifecycle (Altabbakh et al., 2013). The FMEA tools has been widely adopted in the O&G industry for the risk assessment of inconsistencies, their causes and consequences of equipment involved for example in technological processes of primary and secondary oil refining (Petrovskiy et al., 2015).

Fault Tree Analysis (FTA) estimates the probability of failure of Basic Events (BEs). It is a top-down logic based technique that determines the level of security of complex systems (Lavasani et al. 2015). The FTA starts with the identification of adverse initiating event and proceeds with determining all the potential causes and consequences, that contribute to the top adverse event (Altabbakh et al., 2013). The FTA is a visual model that clearly represents all the possible cause-effect relationship between the initiating and cascading events (Altabbakh et al., 2013).

However, both FMEA and FTA methods are affected by uncertainty associated with failure estimation. Thus, in order to avoid subjective judgments, fuzzy based methods are adopted (Lavasani et al., 2015; Petrovskiy et al., 2015). Therefore, the strength of both approaches is that they deal with ambiguous, qualitatively incomplete and vague information (Lavasani et al., 2015).

Bow-Tie Analysis provides a clear overview of the possible sources of unforeseen events, potential consequence, and actions to take in order to avoid accidental events from occurring and the implementing measures to adopt to limit the possible impacts (Lewis & Smith, 2010; Alkazimi & Grantham, 2015). It is a graphical-based approach, that shows in a easy to understand way the relationships between the causes of accidental events and the measures to be taken in order to control them (Lewis & Smith, 2010; Alkazimi & Grantham, 2015). In the last decade, the bow-tie method has been widely adopted in the O&G industry to support safety reports and health, safety, and environment (HSE) hazards (Lewis & Smith, 2010). For instance, as reported by Lewis and Smith (2010), there are some O&G companies that have pioneered the use of bow-ties diagrams "*to illustrate to the regulator and members of the public that the hazards associated with the operation are recognized, understood and well managed, both from a preventive point of view and for preparedness in the event of an emergency*".

Furthermore, What-if Analysis, Hazard and Operability Analysis (HAZOP) and Layer of Protection Analysis (LOPA) represent other tool aimed at reducing risk and vulnerability of O&G assets/facilities by providing an overview of the all-possible sources of unforeseen events, potential consequences and actions to take in order to avoid accidental events from occurring (Alkazimi & Grantham, 2015; Lewis et al., 2010).

In order to overcome the urgent need of tools able to identify and mitigate potential risks (i.e. operational, mechanical etc.) in the early phase of design, Grantham et al. theorized in 2005 the Risk in Early Design (RED) approach. The RED tool is an original instrument which allows to predict and minimize – at the conceptual design stage – potential accidents from occurring (Grantham et al., 2009). Unlike FMEA and FTA, which require experts to estimate failure probability, RED does not need specialist users because it makes use of historical system's data to outline risk report (Altabbakh et al., 2013). Therefore, engineers lacking of basic system knowledge can also employed this tool (Alkazimi & Grantham, 2015). The risk analysis' outcomes are classified and ranked graphically by the probability of failure and potential consequences on the system (Alkazimi & Grantham, 2015; Saud et al., 2014). The RED software categorizes the outcomes into high, medium, and low risk levels (Alkazimi & Grantham, 2015).

Finally, apart from specific tools developed for reducing the probability of fatalities to occur during O&G operational phases, Bayesian Networks (BNs) represent one of the most promising tools to prevent risks due to oil spill and blowout. In fact, BNs are risk modeling tools that adopt probabilities to define the magnitude and likelihood of fatalities such as oil spill (Davies & Hope 2015; Wu et al., 2015). BNs lead to the integration of different knowledge data by using numerous probabilities, and allow to incorporate different hypotheses in the model (Goerlandt & Montewka, 2015). Thus, BNs are applicable in case of reliable data are missing but expert judgments are available (Wu et al., 2015). In other words, BNs can be still employed in case of lack of data and uncertainty (Davies & Hope, 2015). The results are graphical illustrations, which describe the interaction with all the variables that characterized the system (Davies & Hope, 2015). Hence, BNs are an easy to understand method, by either technical or non-technical stakeholders (Davies & Hope, 2015).

However, none of the reviewed tools were specifically proposed neither applied to assess climate change related risks for the O&G industry. Therefore, the second step of the review process was performed focusing on risk assessment methodologies that can be applied to study natural hazards or climate-related related impacts, vulnerabilities and risks on O&G infrastructures.

A first interesting approach is represented by Quantified/Quantitative Risk Analysis (QRA). QRA is a formal and systematic method that a) evaluates the likelihood and detrimental consequences of hazardous events and b) expresses the results quantitatively as risk to personnel, the environment and facilities through the planning and design phases (Vinnem, 1998; Falck et al., 2000; www.dnvgl.com). This methodology is widely used to investigate risks on: production/processing facilities, high-pressure pipelines, storage and importation sites of O&G facilities (www.dnvgl.com). Quantified Risk Assessment provides valuable insights into the features of the industrial plant, highlighting those aspects where failures may result in harm to operators, members of the public, the environment and or the asset itself. For what concerns the specific case of offshore O&G installations, QRA evaluates blowout, process leaks, fire and explosion hazard probabilities that may occur anywhere in the system (Skogdalen & Vinnem, 2012). In addition, it is also employed as a support tool for decision making process during the design and operation plant stages (Falck et al., 2000; Bureau Veritas, n.d.) Therefore, it gives a further insight into the decision-making procedure by highlighting the accident scenarios that contribute most to overall risk (www.dnvgl.com).

The main goals of this method is to define risk in absolute or relative way by taking into account risk acceptance criteria, to understand the cause-effects relation and to classify potential hazards (Vinnem, 1998). In doing so, QRA approach uses several failure based techniques such as fault-tree and event tree analysis (Skogdalen et al., 2011).

Consequently, QRA approach leads to prioritize risks according to their potential effect on the case study project. Furthermore, in this way it is possible to develop specific resilience and management responses addressing specific risks (www.gpmfirst.com).

Another key approach for the assessment of natural risks triggered industrial infrastructures is given by the pioneering work of Showalter and Myers (1992). They recognized, in fact, the need for a dedicated approach able to evaluate Natural Hazard Triggering Technological Disasters (Na-Tech). Natural disasters (e.g. floods, earthquakes, tsunamis, hurricanes) have the potential to threat directly industrial systems (Piccinelli & Krausmann, 2013). For example, floods are recognized as one of the most frequent natural disasters that may threat O&G pipelines resulting in the release of hazardous materials, fires, and explosions (Piccinelli & Krausmann, 2013). Moreover, Na-Tech risks are expected to increase in the future due to more hazards (climate change, growing number of industries) and higher vulnerability of society (urbanization, interconnectedness) (Piccinelli & Krausmann, 2013). As a result, climate change represents a key parameter that has to be considered because it directly influences the rate at which natural disasters and Na-Tech accidents occur.

Therefore, in the perspective of reducing Na-Tech accidents and reducing their consequences, a unified Na-Tech based framework – called RAPID-N – was recently developed (Girgin & Krausmann, 2013).

RAPID-N is an on-line collaborative risk assessment framework that allows risk assessment of Na-Tech hazards at either local or regional scale. In addition, RAPID-N leads to map Na-Tech accidents even if few data are available (Girgin & Krausmann, 2013). In fact, users contribute directly to update RAPID-N database by entering their own data (e.g. on-site hazard parameter, damage or consequence analysis parameters, rules and equations) with the aim of supporting the risk assessment procedure. In addition, in this way users are allowed to customize the risk assessment calculations according to their needs (Girgin & Krausmann, 2013).

As reported by Girgin & Krausmann (2013), RAPID-N "*incorporates long-term data from the European Mediterranean Seismological Centre (EMSC) and the U.S. Geological Survey (USGS), which is automatically updated once new information becomes available. A basic set of onsite natural hazard parameter estimation equations, damage classifications and fragility curves for plant units collected from the literature are also provided*". RAPID-N also contains the statistics (e.g. parameters and equations) useful for the implementation of consequences analysis. These data are provided by the U.S. EPA's Risk Management Program (RMP) Guidance for Offsite Consequence Analysis methodology (U.S. EPA, 1999).

Finally, RAPID-N risk assessment framework is based on four different modules (Girgin & Krausmann, 2013):

1. The *Scientific module* that includes the property definition and estimation framework that allows the calculation of damage and consequences analyses.
2. The *Natural hazards module* gives information useful to define natural hazards (e.g. extent, frequency and intensity);
3. The *Industrial plants and units module* provides data for the characterization of industrial systems (e.g. types of industrial facilities, their units, categories of hazardous substances);
4. The *Na-Tech risk assessment module* contains: fragility curves, damage and risk states used for the risk assessment process.

To conclude, RAPID-N risk assessment framework allows the screening of all the potential hazards related to the overall Na-Tech scenarios (e.g. toxic release, fire, explosion). Moreover, RAPID-N represents an innovative approach for data input since it makes use of costumer's information in those cases where there is lack of knowledge. In this way, it is possible to conduct both natural hazard damage and consequence assessment by using scientific equations and estimation methods, which can be extended by the users (Girgin & Krausmann, 2013; Salzano et al., 2013).

At the country level, the State of Alaska (2009) proposed a specific risk assessment methodology in order to assess the impacts of potential fatalities (both operational and natural) on O&G production assets. This approach leads to evaluate the highest threats of failure and the highest potential consequences of offshore and coastal infrastructures that might affect the safety of the public, industry workers and environment. The proposed methodology identifies potential risks by performing simultaneously operational and natural hazards analysis. Operational hazard assessment estimates risks caused by mechanical failures or human errors; natural hazards assessment evaluates infrastructure and system vulnerability to natural hazard events (e.g. coastal erosion, permafrost thaw, severe storms, flooding, underwater currents, high winds). Both operational and natural hazard assessment procedures categorized potential hazard events for the identified risk categories: *safety*, *environmental,* and *reliability* (Doyonemerland & ABS Consulting, 2009).

The methodology is based on the nodal approach, which leads to analyze the whole initiating events and potential fatalities by assessing the most likely consequences that can occur from a single node anywhere in the system. In other words, global consequences (in both the upstream and downstream nodes) are thus assessed, since initiating events cascade through the entire system of the O&G system (Doyonemerland & ABS Consulting, 2009).

1.2 Discussions and conclusions.

The increasing concern about the potential consequences of climate change on energy facilities and operations in coastal and offshore O&G infrastructure, draw the attention to the definition of common tools and methodologies that can help identifying climate change impacts and vulnerability for this sector.

Most of the reviewed studies focus on physical-environmental impacts related to natural hazards and extreme weather events. Moreover, they concentrate on a single (one to one) hazard analysis (e.g. coastal flood risk for buildings and properties). However, most of the proposed studies barely consider climatic drivers as a key aspect of the risk assessment analysis. Thus, the effectiveness of the approaches is reduced due to the limited extent of which the operational or natural hazards component is considered.

On the contrary, it is widely recognized that a combination of atmospheric, physical-chemical and ocean drivers can lead to a range of direct and indirect impacts on O&G business development (e.g. design and construction, supply chains and logistics, performance and maintenance) (IPCC, 2014c).

Even if the relative importance of key climate drivers will vary across different geographical regions, a comprehensive assessment of risks should be able to consider both extreme (acute) and incremental (chronic) changes in climate-related hazards. Finally, the selection of risk and vulnerability methodologies for different typologies of O&G assets should consider internal company operating and performance metrics and specific indicators in order to capture significant changes that can affect industry's asset design and engineering standards.

Consequently, in order to provide a comprehensive analysis of the state of the art on available risk assessment methods and tools suitable for the evaluation of climate change impacts on the O&G sector, the following section presents an overview of indicators/indexes that can be used to understand the effect of climate change hazards on the O&G infrastructures and/or operation process.

2. State-of-the-art of available indicators measuring the effects of climate hazards on O&G exposed systems.

The theoretical background of risk assessment tools and methodologies developed for industrial facilities previously provided (Chapter 1), is necessary for the establishment of a common understanding of the methods currently applied for the assessment and management of operational and natural hazards risks for various industrial systems. However, other relevant risk assessment tools (i.e. indicators and indexes) can be used to measure the potential effects of climate change on the O&G activities. Accordingly, this Section focuses on the review of indicators (e.g. atmospheric, physical-chemical and ocean parameters) that can help to identify of cause-effect relationships between climate hazards and O&G industry, focusing on the coastal assets.

The overall purpose of the work is to identify the main cause-effect processes to be considered for the development of a DPSIR (Driving forces, Pressures, States, Impacts and Responses) framework (see Section 3.1).

As described in the following paragraphs, reviewed indicators, parameters and functional relationships can be used to assess the range of impacts of climate change on different O&G facilities and operations (i.e. from project design to exploration, processing and transportation).

Even if there are few public documents proposing a methodical and comprehensive assessment of indicators, thresholds and metrics for climate change impacts assessment on coastal and offshore O&G development (Burkett et al., 2011), the reviewed literature provides evidences about how climate change can affect the capacity of developing, expanding and maintaining offshore and onshore O&G facilities.

Key climate pressures and indicators (atmospheric and ocean parameters) - identified based on the results of the literature review are described in the following Section. Whereas, a more comprehensive analysis of climate-related hazards and vulnerability thresholds useful to detect physical and environmental impacts related to climate change and its extremes will be depended in Chapter 3.

2.1 Review of climate change related indicators for coastal and offshore O&G assets.

In general, the use of indicators helps to: reduce the number of parameters that are usually required to represent a complex and dynamic situation; quantify abstract concepts such as vulnerability, resilience or adaptive capacity; simplify the process of communication of risk assessment's results to the final users.

In the specific context of climate change, indicators can be particularly useful to monitor climate variations, characterize spatial and temporal distributions of stressors and pressures, measure exposure and vulnerability factors and finally identify key risks to be addressed.

The main aim of this section is to better understand the implications and cause-effect relationship of climate change on coastal and offshore O&G assets, reviewing the main climate pressures, indicators and associated physical and environmental impacts from recent studies. The results of the analysis are summarized in Table 1 (ANNEX I), and presented below.

As described by Cruz & Krausmann (2013) and Firth (2009) warmer temperature can impact O&G refining, delivery and distribution systems. For what concerns oil refining, higher temperatures reduce steam turbine efficiency and, as a result, energy costs will be much higher. Warmer temperature means also warmer water that can affect plant design and operation requirements and materials, as well as process efficiency. Moreover, higher temperature can cause potential maintenance problems for roads, asphalt pavement and rail tracks, causing indirect impacts to O&G delivery and distribution. Finally, temperature rises may also increase cooling requirements and the related costs (Cruz & Krausmann, 2013).

Increased atmospheric temperature will also have strong effects on coastal exploration and production activities in the Artic region due to the expected decline in sea ice and the thawing of permafrost (Burkett et al, 2011). In fact, sea-ice naturally protects the coast from erosion, sea level rise, waves and storms and the melting of permafrost can affect the transportation routes and foundations of onshore buildings and settlements (U.S. Department of Energy, 2013).

Finally, the presence of permafrost prevents subsurface movement and leakage of drilling wastes in the surrounding environment (Dyke, 2001).

Changes in precipitation patterns can affect both production and transportation phases. On the one hand, increased precipitation leads to extreme weather events such as floods and landslides (Puig et al., 2015). Floods can affect production sites, roads and pipelines transport (where they cross river basins), refinery plants and oil spills (Puig et al., 2015; Arent et al., 2014).

Moreover, peak stream flow can generate damages to roads, bridges, and ports in the coastal floodplain (Burkett, 2011). While, landslides can damage O&G transportation by road and through pipelines. On the other hand, decreasing precipitation levels can affect production and refining processes especially in the case when they depend on the availability of fresh water (Puig et al., 2015). Thus, water scarcity represents a limiting factor and, as a consequence, an important climate related risk for O&G industry (Puig et al., 2015).

Moreover, the combination of higher temperature and declined precipitation poses a threat on water-cooling, water-discharge and storage requirements during extraction and production phases (Cruz & Krausmann, 2013).

Drought events and reduced river runoff can also negatively affect the productivity of estuarine marshes and ecosystems (Nicholls et al., 2007), determining increasing restrictions for O&G activities in stressed coastal environments.

Even if climate projections for wind speed are rather uncertain, strong wind can impact both onshore and offshore O&G systems (Doyonemerland & ABS Consulting, 2009). For example, gales may cause damages on infrastructures and endanger staff working on onshore platforms; severe windstorm can disrupt onshore plant by reducing their accessibility (Puig et al., 2015). Moreover, strong winds can cause a) structural damage to buildings and equipment and b) significant disruption to electric power systems that may feed that infrastructure. Another risk factor related to increased wind speed is the increasing rate of fire spread (Doyonemerland & ABS Consulting, 2009).

A relevant example regarding the use of climate projections in order to support risk assessment for the O&G sector is proposed by Puig et al. (2015). The analysis takes into account two indicators: temperature (maximum values) and precipitation (annual precipitation and annual extreme rain events). In doing so, average temperature and average precipitation data from 1976 to 2005 (historical data) for the locations of the two largest refineries in Colombia were collected. Then, the most probable future trends regarding precipitation, extreme rain and maximum temperature were estimated by using greenhouse gases concentration scenarios to force regional climate models. Climate statistics were made for the year 2025 (corresponding to the average of the projections obtained for the period 2011-2040) and for the year 2050 (corresponding to the average of the projections obtained for the period 2036-2065) according to greenhouse gases concentration scenarios. A threshold based on the analysis of historical heavy rain events was proposed in this study. It was calculated as the daily precipitation level exceeding the highest daily level registered in the top 1 percent wettest days of the reference period (1976-2005) (Puig et al., 2015).

According with the reviewed literature, Sea-Level Rise (SLR) and storm surge can be recognized as key climate-related pressures for coastal and offshore assets.

Over the past few decades the oceans temperature has been warming and average sea level has been rising (IPCC, 2013). Moreover, extreme events (e.g. coastal inundation and storms) are occurring at more frequent rate than previously anticipated. Therefore, O&G infrastructures are especially vulnerable as they often sit on low-lying land (Brown et al., 2014; Carlson et al., 2015). In fact, generally O&G companies present refining assets at or near the coastline; in addition, most facilities (including ports, marinas and gas processing plants) are located on land less than 10 feet above the high tide line meaning that they are exposed to climate variations (Carlson et al., 2015). In the same way, the majority of offshore platforms were not designed to accommodate a permanent increase in mean sea level (Burkett, 2011). In fact, sea level information used for setting design criteria for offshore platforms is usually based on the analysis of data from tide gauge stations, combining tidal and storm surge effects (Bitner-Gregersen and Gramstad 2009). Moreover, the splash zone definition is usually referred to local observed mean sea level and tide conditions, without considering the effect of future sea level rise projections (Bitner-Gregersen and Gramstad 2009).

Expected impacts include flooding and structural damages to drilling and production facilities as well as onshore facilities, resulting indirectly in and disruption of supply chains and a decrease in Gross Domestic Product (GDP) (Brown et al., 2014; Burkett 2011). Moreover, as stated by Carlson et al. (2015) strong winds can make waves larger, increasing storm surge effect on the coast by bringing these waves farther inland. In this way, more structures are exposed to the destructive force of the ocean. Climate change can also affect the strength (intensity and frequency) of coastal storms (Vousdoukas et al., 2016). Finally, climate-warming trend might increase the frequency of occurrence of the most intense-categories hurricanes (IPCC, 2012).

For all these reasons, local sea-level changes and inundation from storm surges have to be considered (Bradbury et al., 2015; Carlson et al., 2015).

It is also important to take into account the effect of temperature variations on SLR and thus storm surge occurrence. In fact, there is a wide consensus among the scientific literature that warmer temperatures have contributed to observed SLR (e.g. expansion in ocean volume and melting of glaciers and ice sheets) (Bradbury et al., 2015). Two relevant studies (Bradbury et al., 2015; Carlson et al., 2015) stress the importance of mapping SLR and storm surge in order to understand the exposure of energy infrastructure to these weather events.

The study conducted by Bradbury et al. (2015) considered three increments of global mean SLR and three hurricane storm strengths. They defined as baseline sea level the average sea levels in 1992. While three increments of future sea-level rise were also taken into account (10 inches of SLR in 2030, 23 inches in 2050 and 32 inches in 2060). This approach leads to identify the existing facilities that can be exposed to greater risk deriving from storm surge, as a result of SLR. Information about the relative exposure of existing infrastructure to hurricanes of varying storm intensities was also carried out. The results of the risk assessment were divided by exposed facilities (e.g. petroleum pumping, oil refineries, oil reserves, natural gas compressor, natural gas storage) and measured both in absolute and relative terms (number of units and percentage).

The study proposed by Carlson et al. (2015) mapped future sea level rise scenarios for the years 2030, 2050, and 2100 based on future greenhouse gases concentration pathway (IPCC, 2013). In this case, inundation from storm surge was estimated by using the model developed by National Weather Service Sea, Lake, and Overland Surges from Hurricanes (SLOSH). The proposed method carries out storm surge maps that give all possible storm paths for a hurricane of a particular strength (5 different hurricanes categories). The results were presented in terms of extent and depth of storm surge flooding in coastal areas.

As remarked by Doyonemerland and ABS Consulting (2009) SLR and storm surge can also cause extensive flooding and beach erosion, especially at high tides. In particular, coastal erosion, including subsidence, can cause loss of building or structural damage to infrastructure items.

Other indicators that are likely to affect offshore platforms are hydrodynamic factors such as waves and currents' velocity.

In fact, changes in prevailing ocean and wave heights as a consequence of climate change will affect offshore facility operation and design. These variations, can cause disruption during operations and supply phases (Firth, 2009; U.S. Department of Energy, 2013). Moreover, wave inundation and underwater wave loads can severely compromise structural integrity of platforms (Cruz & Krausmann, 2013).

Particularly, as remarked by Bitner-Gregersen and Gramstad (2009), extreme (rogue) waves represent a huge threat for ships and offshore structures. Consequently, there an increasing need of developing warning criteria to prevent their damages on marine facilities, equipment and operations. Even if the Benjamin–Feir index, integrating information about strength, frequency and directional spreading of waves, was proposed as a good indicator of the occurrence of rough waves (Janssen, 2003; Bridges & Dias, 2007), their predictability and effect on wave loads for oil platforms and other offshore structures is still highly uncertain. Accordingly, the development of a warning system for rogue waves and its implementation in the design/safety criteria for ships and platforms remains a high priority for future research and for the offshore/shipping industry.

Strong winds play also a key role in this context, in fact, large wind intensity caused by storms and hurricanes, can a) damage offshore pipelines and related equipment b) cause oil spills and c) lift and blow heavy objects against pipelines damaging O&G assets (Doyonemerland and ABS Consulting, 2009). For example, in 2005 Hurricanes Katrina and Rita damaged hundreds of O&G production platforms, as well as offshore assets (U.S. Department of Energy, 2013). This caused great losses of O&G production. Finally, wave heights in coastal bays and lagoons can have secondary effects on coastal wetlands and barrier islands. The impacts can be worse in subsiding areas where pipelines and coastal systems are generally more vulnerable to the effect of wave action (Burkett, 2011).

On the other side, severe currents can cause damage to offshore platforms and underwater pipelines. They can cause collisions between marine vessels and other external impacts (Doyonemerland and ABS Consulting, 2009). Moreover, together with wind forces and storm waves, currents direction and velocity should be evaluated in order to set criteria for the design of offshore structural elements. Particularly, information about wind, currents and wave forces is used to set the hydrodynamic stress conditions (e.g. fatigue and bottom-stability analysis) for offshore fixed structures.

For what concerns other water quality parameters (e.g. carbon dioxide levels, acidity, temperature, and salinity), they can also have important effects on ocean chemistry and ecosystems. In fact, as CO_2 is absorbed at the surface of oceans, the pH of the water lowers with potential adverse impacts on carbonate flora and fauna (Andersson et al., 2003). Moreover, increased CO_2 and temperature can have positive effects on photosynthesis, generating harmful algal blooming, which reduces the light available to seagrasses and available oxygen for fish and shellfish (Short and Neckles, 1999). Even if extensive algal blooms do not affect directly offshore facilities and operations, they could make some changes on the regulatory environment. In fact, extensive algal blooming may affect future exploration and development activities leading to the retirement of facilities (Burkett 2011). In a similar way, changes in physical-chemical water parameters (e.g. temperature, salinity, density) can affect marine growth that is another key environmental factor for the design of subsea infrastructures (Burkett 2011). Particularly, the average salinity and dissolved oxygen content (also affected by climate change) are important factors to set design criteria for cathodic protection against corrosion (Burkett 2011).

The present review represents a starting point for the identification and definition of hazard, exposure and vulnerability indicators to be used in order to identify the potential risks of long-term climate trends and extremes for both coastal and offshore O&G activities/assets.

As this study is aimed at identifying, and consequently ranking, the vulnerability of O&G facilities in the coastal area to climate-relate hazards, the present state of art provides also a synthesis of existing coastal vulnerability indices useful for the assessment of coastal susceptibility to climate related hazards (2.2).

2.2 The Coastal Vulnerability Index (CVI).

Coastlines are dynamic ecosystems characterized by constant variations due to the interactions between atmospheric and hydrodynamic factors such as wave height, wind speed, water depth, removal and transport of sediment, tidal range, rates of relative sea level change, as well as extreme weather event (e.g. intense precipitation, storm surge, flooding). Particularly, sea level rise represents one of the most important climate related pressures for coastal areas. In fact, coastlines are particularly vulnerable to relative sea level change because it can cause major impacts such as coastal erosion, loss of land and permanent inundation (Ramieri et al., 2011). Moreover, coastal ecosystems are also particularly sensitive to the increase in sea surface temperature/salinity, ocean acidification and salt water intrusion (ECT/ACC, 2010). Therefore, low-lying coastal lands are exposed to storm surges, coastal, river and/or pluvial flooding (ECT/ACC, 2010).

As stated by Nicholls et al. (2008), coastal vulnerability analysis related to climate change is mainly focused on absolute/relative sea-level variations and, to a lesser extent, on other climatic pressures and socio-economic aspects.

The Coastal Vulnerability Index (CVI) is one of the most commonly used methods to assess coastal vulnerability to sea level rise, in particular due to erosion and/or inundation (Gornitz et al., 1991).

The traditional CVI approach proposed by Gornitz et al. (1991) provides a ranking of coastal systems according to their ability to change and it is a simple tool supporting decision-makers in identifying coastal areas at higher risk of inundation and/or erosion. A range of variables (including geological and physical processes parameters) is included in the CVI, to assess coastal vulnerability, which are then integrated into a single index for the formulation and implementation of the CVI.

This methodology was widely employed by the U.S. Geological Survey (USGS, 2004) to evaluate and map the relative vulnerability of the Pacific coast to sea-level rise to potential shoreline retreat.

The variables used in the traditional formulation of the CVI (Gornitz, White, and Cushman 1991) are six, classified into geological variables (geomorphology, historical shoreline change rate, regional coastal slope) and physical process variables (relative sea level rise, mean significant wave height, mean tidal range). In particular, the geological variables take into account the shoreline's relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding. The physical process variables contribute to the inundation hazards of a particular section of coastline over time scales from hours to centuries (USGS, 2004).

Schleupner (2005) proposes another significant approach based on the *Coastal Sensitivity Index (CSI)* in order to assess the sensitivity of the coast to flooding and erosion caused by climate change and sea level rise. To evaluate the probability of flooding and coastal erosion, four categories that influence vulnerability are chosen: elevation and morphology of the coast, erodibility, coastal exposition to the wind regime, and natural shelter of the coast. Relative elevation, coastal morphology and erodibility represent geological/geomorphological characteristics of coastal zones (Schleupner, 2005). Coastal exposition to the wind regime may affect coastal erosion and the withdrawal of the coast. Natural shelter of the coast (i.e. if the coast is sheltered by a bay, an island or a coral reef) is also considered a relevant factor protecting the coastline against the direct action of the sea (natural breakwaters function). Relative local subsidence and elevation movements are added to these four categories (Schleupner, 2005).

However, the assessment of coastal vulnerability to inundation and erosion, should consider not only the current physical and geological features of the coast, but also other parameters related to both climatic (e.g. sea-level rise projections, increased storm surge levels) and non-climatic pressures (e.g. population and economic growth, land-use changes) (Nicholls et al., 2008). Thus, coastal vulnerability assessments should be developed by integrating climate change related pressures, human activities and the interdependency between all these factors (Ramieri et al., 2011).

To this end McLaughlin & Cooper (2010) proposed a more complex architecture of CVI, based on the integration of various type of parameters including socio-economic parameters. McLaughlin & Cooper (2010), in their study, expressed, coastlines vulnerability as a function of: "*the physical nature of the coast (which controls its ability to respond to perturbation), the nature (frequency and magnitude) of the perturbation (the forcing factor) and the degree to which such changes impact on human activities or property*". Therefore, vulnerability can be expressed as a combination of three sub-indices:

Vulnerability= *f* coastal characteristics (resilience and susceptibility) + coastal forcing + socio-economic factors

More specifically, the coastal characteristic sub-index assesses the potential vulnerability of a selected area to coastal erosion and inundations. This is evaluated by taking into account: type of shoreline, river solid geology, drift geology, elevation and orientation (McLaughlin & Cooper, 2010).

Whereas, the coastal forcing sub-index estimates the most likely drivers that contribute to determine the degree of which coast is exposed to wave energy. These variables are: significant wave height, tidal range, difference in modal and storm waves and frequency of onshore storms (McLaughlin & Cooper, 2010).

Finally, the socio-economic sub-index takes into account the most probable elements for which coastal erosion poses a risk (e.g. settlement, cultural heritage, roads, railways, land-use, conservation designation) (McLaughlin & Cooper, 2010).

In addition, the vulnerability index proposed by McLaughlin e Cooper (2010) is also multi-scaled because it can be applied at national, regional and local scales. In this way it is, in fact, possible to investigate the implications of spatial scales in the definition of coastal vulnerability. More specifically, ***'global scale'*** allows the implementation of international actions and global policies to be discussed; '***national scale'*** enables the prioritization of resources and plans at national level; finally, ***'local scale'*** is generally implemented in order to carry out practical responses that prevents and protects coastal hazards from occurring (McLaughlin & Cooper, 2010).

Furthermore, McLaughlin e Cooper (2010) highlighted that the process of variables selection must take account of the scale at which vulnerability evaluation is to be addressed. For instance, higher resolution is required at the local compared to the global scale.

In addition, the computation of each sub-index depends on the set of variables selected for the implement of the CVI, and consequently, the number and typology of such variables deals with the considered application scale (i.e. national, regional or local). For example, coastal characteristics and coastal forcing sub-indices can be broadly employed to evaluate the potential vulnerability of a certain region/area to morphologic changes; whereas, socio-economic variables are more suitable for the assessment of national/regional/local vulnerability induced by all the changes in our society (McLaughlin e Cooper, 2010).

However, dealing with numerous and heterogeneous parameters requires to work with high-resolution data (Ramieri et al., 2011). Consequently, the implementation of these methods is very limited within the developing countries.

In order to fill these gaps, Rosendahl Appelquist (2012) has developed a general framework useful for coastal vulnerability assessment that takes into account climate change related hazards as primary pressures. The proposed framework is a graphical tool (Coastal Hazard Wheel, CHW) that does not require excessive data collection or computer processing capacity in order to be applied. The assessment approach is based on geological categorization and it leads the evaluation of coastal climate-related vulnerability at local, regional and national scale. The classification system takes into account the major bio-geophysical variables that allow the characterization of a generic coastal area. The components included are geological layout, wave exposure, tidal range, flora/fauna, sediment balance and storm climate. Moreover, the proposed framework covers the intrinsic hazards related to ecosystem disruption, gradual inundation, salt water intrusion, erosion and flooding (Rosendahl Appelquist, 2012; Rosendahl Appelquist & Halsnæs, 2015). The practical application is made by using the CHW (see Fig. 2.2.1); "*the user starts in the center of the wheel and then moves outwards, ending with the inherent* *hazard evaluations in the outermost circles*" (Rosendahl Appelquist, 2012).

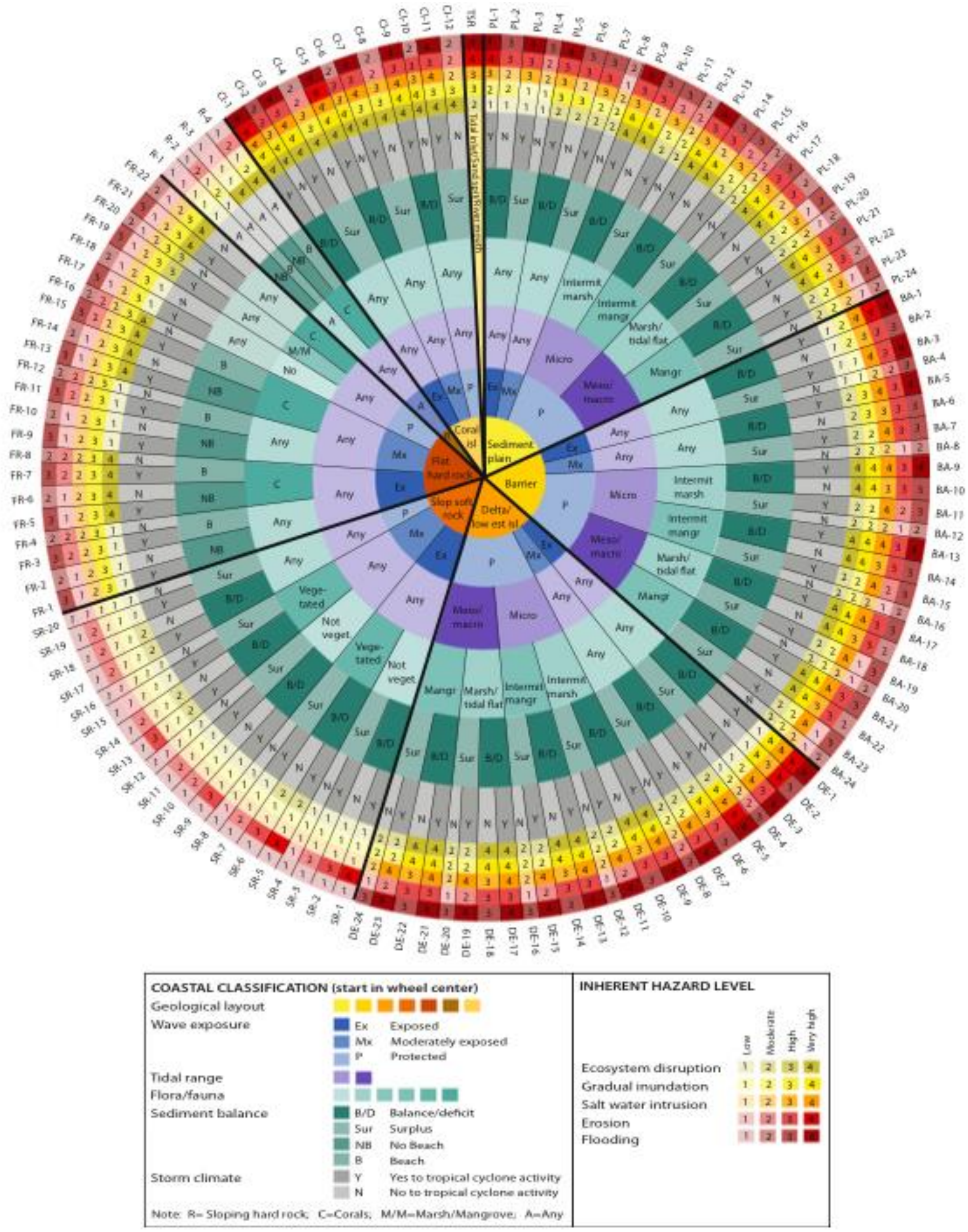

Figure 2.2.1 – The Coastal Hazard Wheel (CHW) (Rosendahl Appelquist, 2012)

It is important to highlight that possible human-induced alterations within or nearby the analyzed coastal system have also to be taken into account during the assessment process (Rosendahl Appelquist, 2012; Rosendahl Appelquist & Halsnæs, 2015).

Together with hazard assessments, the CHW approach can also be employed for identifying suitable hazard management measures to be addressed at different coastal systems. Particularly, Rosendahl Appelquist (2012) defined three types of management options based on the available scientific literature: hard protection measures, soft protection measures and accommodation approaches. Hard protection options consists of traditional approaches useful to protect coastal systems by the use of structural defense (e.g. breakwaters, groynes, jetties, revetments, sea walls, dikes and storm surge barrier), which can resist wave and tide energy (Rosendahl Appelquist & Halsnæs, 2015). Soft protection measures have been implemented as a response to the negative effects of hard defenses. These types of measures are represented by: beach nourishment, dune construction/rehabilitation and cliff stabilization. Additionally, soft protection options allow the natural coastal dynamics to exist (Rosendahl Appelquist & Halsnæs, 2015). Finally, accommodation approaches are aimed at developing adaptation strategies able to increase society's ability to cope with the effects of coastal dynamics and extreme events. However, in order to implement these approaches advanced planning are required. The most common accommodation strategies are, for example, wetland restoration, flood warning systems, flood proofing and coastal zoning (Rosendahl Appelquist & Halsnæs, 2015).

The reviewed coastal vulnerability assessments showed that the traditional formulation of CVI usually express coastal vulnerability as a function of physical-environmental parameters (e.g. geomorphology, coastal erosion, tide range) (Gornitz et al. 1991; Thieler & Hammar-Klose, 2000); whereas, fewer examples take into account also socio-economic parameters (e.g. land cover/use, population) (McLaughlin and Cooper 2010). Nevertheless, there are only few practical studies of CVI aimed at evaluating the vulnerability of coastal infrastructures and/or asset, considering the presence of critical energy facilities/processes.

A relevant example is provided by Dismukes & Narra (2015) that have recently developed a *Coastal Infrastructure Vulnerability Index* (CIVI) including the socio-economic and infrastructure components into the vulnerability assessment process. The CIVI combines physical variables reflecting coastal processes and geological conditions, socio-economic variables, and a full range of critical energy infrastructure lying along coastal systems (Table 2.1).

Table 2.1 **–** The data layer classification proposed by Dismukes & Narra (2015).

Layers	Coastal Factors
Physical variables	- Historical land loss; - Land cover and vegetation types; - Regional elevation; - Sea, Lake, and Overland Surges from Hurricanes (SLOSH) Storm Surge.
Socio-economic variables	- Commercial Buildings; - Population Density.
Energy infrastructure variables	- Oil and gas pipeline volume; - Crude oil refineries; - Electric generation Facilities; - Petrochemical facilities; - Natural gas processing facilities; - LNG terminals; - Natural gas storage facilities; - Port facilities.

Particularly, physical variables reflect a number of dynamic coastal factors such as historical loss, regional elevation and storm surge levels. Socio-economic factors include estimation of population density and the value of commercial buildings located within the investigated area. Finally, critical energy infrastructures are defined as *"those physical and cyber-based systems essential to the minimum operations of the economy and government. They include, but are not limited to, telecommunications, energy, banking and finance, transportation, water systems, and emergency services, both governmental and private"* (Dismukes & Narra, 2015).

After having identified the variables to be included in the CIVI, it is necessary to normalize and aggregate the data because they are measured in differing forms of capacity (Dismukes & Narra, 2015). Therefore, a standardized score is assigned within each component of the CIVI (physical, socio-economic and infrastructures variables) (Dismukes & Narra, 2015).

More specifically, the calculation steps involves the computation of three sub-indices (Dismukes & Narra, 2015):

- **The physical sub-index** → integrating the following parameters: mean regional elevation, SLOSH storm surge, historical land loss and vegetation type;
- **The socio-economic sub-index** →considering the average of population density and commercial building values.
- **The infrastructure sub-index** → calculated by using the simple mean of the standardized density of energy infrastructures as well as pipeline volume density;

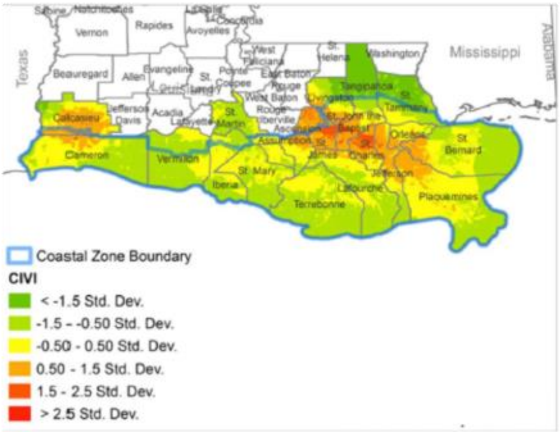

Figure 2.2.2 – Results of the CIVI application to Louisiana (U.S.A) (Dismukes & Narra, 2015).

The outputs are risk maps that reflect the vulnerability of a specific area to climate related hazards (e.g. sea level rise, storm surge), and, as a consequence, identify those energy infrastructures at higher risk of coastal erosion and/or inundation.

To conclude, this CIVI methodology represents an original approach since it combines physical variables – reflecting coastal processes and geological conditions – with socio-economic and critical energy infrastructure variables. Critical energy infrastructures are evaluated in terms of their specific physical energy capacities (Dismukes & Narra, 2016).

Overall, index-based approaches represent common and simple methods to assess coastal vulnerability to sea level rise, in particular due to erosion and/or inundation. In fact, CVIs provide a simple numerical basis for ranking sections of coastline in terms of their vulnerability to heterogeneous type of hazards (e.g. physical, climate-related), which can be used by relevant stakeholders to identify regions where risks may be relatively high (Gornitz et al. 1991; Thieler & Hammar-Klose, 2000).

Although, the majority of the reviewed studies evaluates vulnerability as a function of physical-environmental parameters (e.g. coastal erosion and inundations), none of these takes into account the potential implications posed by climate changes in future scenarios.

Usually, the application of CVI requires a huge amount of data to be implemented at the case study level. Therefore, data availability could be seen as a limiting factor in the CVI applications, determining also the spatial scale (i.e. global, national and local) at which the practical application should be addressed (McLaughlin & Cooper, 2010).

To conclude, despite some limitations, index-based approaches have been recognized as suitable tools for a first risk assessment screening of climate change impacts on coastal energy infrastructures. This because CVIs can be employed even if high-resolution data (and resources) are limited, providing a first step assessment of potential impacts and some considerations for risk management and adaptation.

3. Planning the risk assessment for the O&G sector: problem formulation and data collection.

The aims of this chapter are: i) the define all the potential (theoretical) impacts of climate change on the O&G coastal facilities, infrastructures and processes (e.g. project design, exploration, processing and delivery), ii) to describe the case study area and the available dataset to perform the risk and vulnerability assessment for the O&G sector.

One way to start the formalization of the risk assessment problem, in fact, is by developing a conceptual model useful to represent in a schematized way all the hypothesized cause-effect relationships between the source of a hazard, the pathways of exposure and the receptors. Therefore, hereafter, the DPSIR conceptual framework identifying the potential impacts of climate change on coastal (in-land) O&G activities and infrastructures and on the surrounding environment is described (Section 3.1). Then, Section 3.2 provides a structured synthesis of the case study features and of all the information available at case study level (Section 3.3).

3.1 The DPSIR conceptual framework.

Risk assessment is a rather complex procedure that can help to analyze and manage a wide range of environmental risks, including those related to climate change (Davies & Hope, 2015; Lavasani et al., 2015; Torresan et al., 2016).

Several risk assessment approaches have been developed in many countries and organizations (companies) to deal with the environmental risks associated to the O&G sector (Falck et al., 2000; Bolado et al. 2012; Skogdalen & Vinnem 2012). Most of them propose a stepwise (and cyclic) approach starting from the formulation of the problem, toward the risk identification, analysis and evaluation (ISO, 2009; Defra, 2011)

The final aim of these methodologies, is to provide a road map for decision-makers, toward a structured analysis of the complex array of considerations underlying environmental decisions (Marcomini et al., 2010; Defra 2011).

Particularly, the formulation of the problem, including the identification of all the relevant threats (sources of risk), the potential exposure pathways and the harm (losses) that might result from exposure to hazard (impacts), is the first step for an effective risk assessment. In fact, a clear (unambiguous) definition of the problem, can assist in selecting the level and types of methodology to be used in the following steps of the assessment (Defra 2011).

The development of conceptual frameworks helps to formalize the problem, showing in a systematic way the relationships between the source (S) of risk, the pathways (P) by which exposure might occur and the receptors (R) (Pasini et al., 2012; Iyalomhe et al., 2015). Moreover, conceptual models provide a schematic representation of the limits of the analyzed system (e.g. Defra, 2011) and help to identify all the sources of information (physical, environmental and socio-economic information) needed to evaluate and understand the multidisciplinary nature of risk (Baldi et al., 2010).

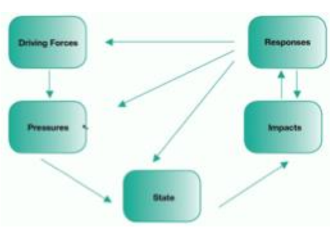

Figure 3.1.1 - The DPSIR framework. (EEA. 1999)

The DPSIR framework developed by the European Environmental Agency (EEA, 1995) with the aim of describing the relationships between the origins and consequences of environmental problems (EEA, 1999; Kristensen, 2004; Khajuria & Ravindranath, 2012) has been widely used to help the conceptualization of risk assessment problems (Kelble et al., 2013). It is an extension of the so called "Pressure-State-Response" (PSR) model, previously developed by the Organization for Economic Co-operation and Development (OECD, 1970) in order to evaluate the environmental performance by using key indicators (Khajuria and Ravindranath 2012).

In principle, the DPSIR framework (Fig. 3.2.1), defines a chain of causal links starting with the identification of the '*driving forces*': the main natural and anthropogenic forces, which can determine variations in the state of the environment and/or human systems. Driving forces, in turn, may exert intentionally or unintentionally '*pressures*' on the environment. Pressures can vary among geographic regions, spatial and temporal scales causing changes in the 's*tates*' of exposed systems. Finally, changes in the state of the system can cause '*impacts*' on environment, human health and activities, eventually leading to '*responses*' (prioritization, target setting, indicators) (Kristensen, 2004). A DPSIR framework is a useful tool first because it helps to classify drivers and pressures at different temporal and spatial scales, and secondly because it provides a first indication of possible response measures.

For this reasons, a DPSIR (Driving forces, Pressures, States, Impacts and Responses) approach is here proposed to formalize the problem at hand, identifying the main cause-effect relationships and interactions between climate-related hazards and offshore and onshore (in-land) O&G activities and infrastructures (Fig. 3.1.2).

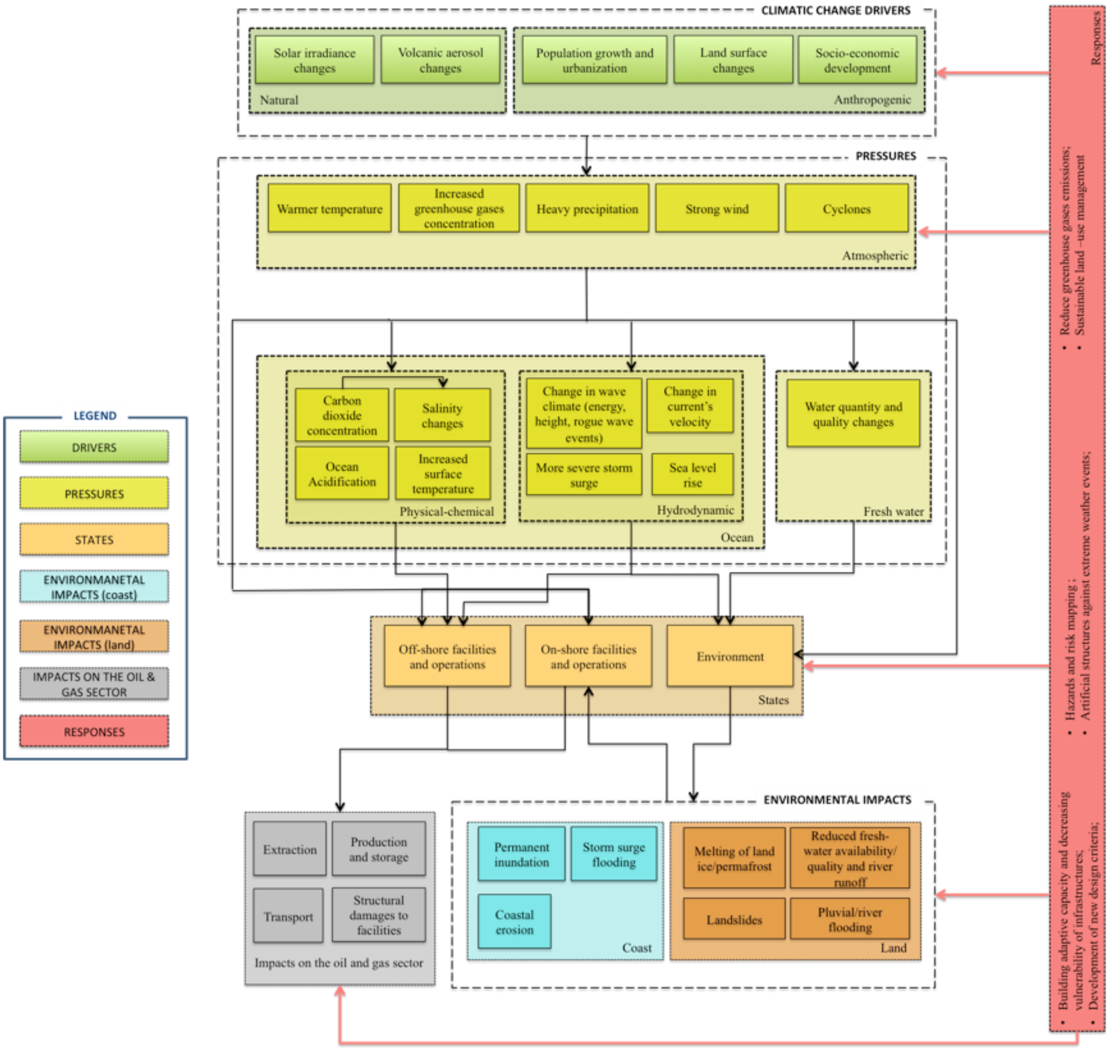

Figure 3.1.2 *- DPSIR conceptual framework describing cause and effect relationships between climate change hazards and offshore and onshore O&G facilities.*

The proposed framework (Fig. 3.1.2) considers, on the top, climate change drivers divided into two classes: natural and anthropogenic. Climate variations are in fact caused by both natural (e.g. solar irradiance and volcanic aerosol changes) and anthropogenic driving forces (e.g. population growth and urbanization, land surface changes, socio-economic development), that contribute to further warming and alter the global climate system (IPCC, 2013). The drivers, in turn, generate a series of pressures including long-term atmospheric processes (e.g. warmer temperature and increased greenhouse gases concentration) determining gradual variations on physical-chemical parameters (e.g. water quality changes, sea level rise, ice melting); and extreme events (e.g. heavy precipitation, strong wind and cyclones), causing more intense changes on waves, wind and storm patterns.

All the potential atmospheric, ocean and freshwater pressures induced by climate change can affect the state of coastal O&G activities and structures (offshore or onshore) and the surrounding environment.

As shown in the DPSIR framework, offshore facilities are mainly affected by atmospheric and ocean physical-chemical pressures. Strong wind can cause structural damages on infrastructures (e.g., lift and blow of heavy objects against pipelines) and can cause oil spills. Moreover changes in physical-chemical parameters (e.g. ocean acidification and salinity), can cause the corrosion of platform cathodic protection. In a similar way, on-shore infrastructures can be affected by a series of climate–related environmental impacts determined by atmospheric, hydrodynamic and freshwater pressures acting on the coastal land surface. Extreme rainfall events can lead to hydrogeological hazards (floods and landslides) affecting roads, bridges, and ports in the coastal floodplain. In addition, flood events and landslides may disrupt transport routes damaging roads and pipelines. On the other hand, decreasing precipitation levels can affect production and refining processes especially when they rely on the availability of fresh water (Puig et al., 2015). Furthermore, sea level rise inundation, storm surge flooding and coastal erosion can affect, for example, refining assets that are generally located along the coastline. In fact, on–shore assets and facilities (e.g. ports, marinas and gas production plant), are especially vulnerable, as they are located near the coastline. Therefore, more structures can be exposed to disruption of supply chains.

In addition, extreme weather events such as cyclones can affect onshore assets and infrastructures, causing great losses for O&G production. Finally, in cold regions (like the Artic), onshore exploration and production activities can be affected by the increased temperature rates, causing a decline in sea ice and the thawing of permafrost.

All the changes in the state of offshore and onshore structures and operations can lead to a range of impacts on different O&G development phases (i.e. extraction, production and storage, transport).

As possible responses, the proposed framework suggests some examples of mitigation and adaptation measures that may be taken to reduce climate related risks, acting at drivers, states and impacts level.

Several measures undertaken at national/international level can reduce greenhouse gases emissions and therefore the anthropogenic drivers of change (e.g. energy taxes, fuel substitution, conversion of land use). Other ones can act directly on the pressures, reducing the intensity of hazard acting on a system (e.g. artificial protections) or the related environmental impacts (e.g. floods, landslides). Another group of responses can mitigate the risks by increasing the adaptive capacity (or reducing the vulnerability) of the exposed system. Which means, for example, the development of new design and operational criteria for coastal and offshore facilities, taking into account the potential changes in intensity or frequency of extreme weather events.

The conceptual framework proposed in this section represent all the theoretical hypothesized relationships between the source of climate change hazard, the pathways by which exposure might occur, and the exposed receptors. The intention is to formalize the problem, clarifying all the potential components involved in the risk analysis. However, not all the risks identified in the framework require comprehensive and detailed assessment. The final choice of the risks to be analyzed in the case study area should be tailored first to the site-specific features of the region (e.g. current impacts and vulnerabilities) and secondly to the available dataset and scenarios.

Therefore, the choice of the risks to be investigated and of the methodology/tools to be applied will be performed by considering the specific characteristics of the case study described below and the available dataset (Paragraph 3.2 and Paragraph 3.3).

3.2 Description and Characterization of the case study area.

The Mediterranean region is a hot spot of climate change and also a very productive region for the energy sector (UNEP/MAP, 2016).

In particular, the Egyptian coastal was chosen as relevant case study for the purposes of this thesis, since it hosts a high concentration of O&G assets, and it is very sensible to climate-related hazards due to the presence of highly productive deltaic areas, lagoons and ecosystems The Egyptian country is located at the northeast corner of the African continent and it is bordered by the Red Sea to the east, Palestine and Israel to the north-east, Libya to the west, and Sudan to the south.

The region Egypt extends over an area of about 1,001,449 km^2 and has a current population of 94,357,585 (http://www.worldometers.info/world-population/egypt-population/; Assed on 13th January 2017). For what concerns the administrative side, Egypt is divided into 27 governorates, which nearly half of them are located along the coastline (http://www.fao.org/ag/agp/agpc/doc/counprof/egypt/egypt.html). The coastal zone of Egypt boosts approximately over 3.000 km along the Mediterranean and the Red Seas. Particularly, the Mediterranean seacoast, selected as case study (Fig.3.2.1), has a length of about 1.100 km and is characterized by deltaic sediments, sand dunes, lakes and lagoons, salt marshes, mud flats, and rocky beaches. From a geologic point of view, it can be divided into four main areas: the Nile Valley and Delta, the Western Desert, the Eastern Desert and the Sinai Peninsula. According with the scientific literature, the Mediterranean coast seems to be susceptible to inundation, shoreline erosion, excessive land use and pollution from oil industry (ETC/ACC, 2010).

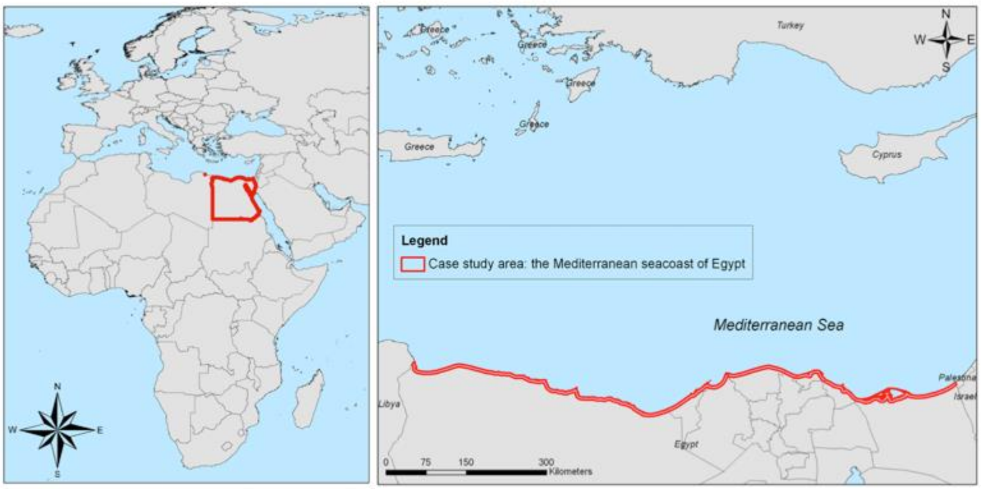

Figure 3.2.1 – The case study area investigated in this thesis.

Although sea level rise in the Mediterranean Sea is not expected to be as high as in the oceans, low-lying areas and estuaries (located between 0 to 1m above sea level), and key urban centers and coastal wetlands in the Aegean-Levantine Sea will be threatened by the increase of mean sea level (ETC/ACC, 2010 ; UNDP, 2011; El-Hattab, 2015).

Particularly, the Nile Delta, is a vital system, containing, most of the agricultural fields, much of the industry, residential areas and tourism, is the most vulnerable area in Egypt to sea level rise (Attia, 2007; Abdrabo and Hassaan, 2014). In fact, as stated by the World Bank (2014), sea level rise will inundate areas lying below one meter in elevation, and as a result, 12-15% of agricultural fields may be lost. For example, the data collected by the Coastal Research Institute of Alexandria and the work carried out by using Radar satellite show that the city of Alexandria has experienced a land subsidence of about 1.6 mm/ year, Al-Burullus, 1.0 mm/year and Port Said 2.3 mm/year (El-Hattab, 2015).

Relative sea level rise and the consequent inundation of low-lying areas can therefore cause disruption of urban areas, industrial facilities and damage to equipment as well as loss of ecosystems and their services (UNDP, 2011).

Furthermore, energy and mineral resources as well as major industrial and economic centers are mainly located near the Nile Delta region also know as the Exclusive Economic Zone (EEZ) (http://www.indexmundi.com/egypt/maritime_claims.html). Specifically, the area hosts many O&G facilities, including offshore and onshore (in-land) coastal assets.

In addition, the intensification of Storm Surge (SS) events due to climate change could cause more damaging flood conditions over the coastal zones of Egyptian country and, in turn, low-lying areas could experience more severe flood events with potential inundation risk for additional 2.67 million people (Elsharkawy et al. 2009; Dasgupta et al. 2009)

The complexity and relevance of the case study area from the natural and socio-economic point of view and the importance of the issues linked to climate change and natural hazards (e.g. expected sea level rise, high tidal waves, floods, coastal erosion, cyclones and tsunamis), ask for a comprehensive (integrated) approach to climate risk management and adaptation (UNDP, 2011). However, specific measures and plans aimed at reducing climate change risks for coastal and offshore energy infrastructures are still missing (UNDP, 2011).

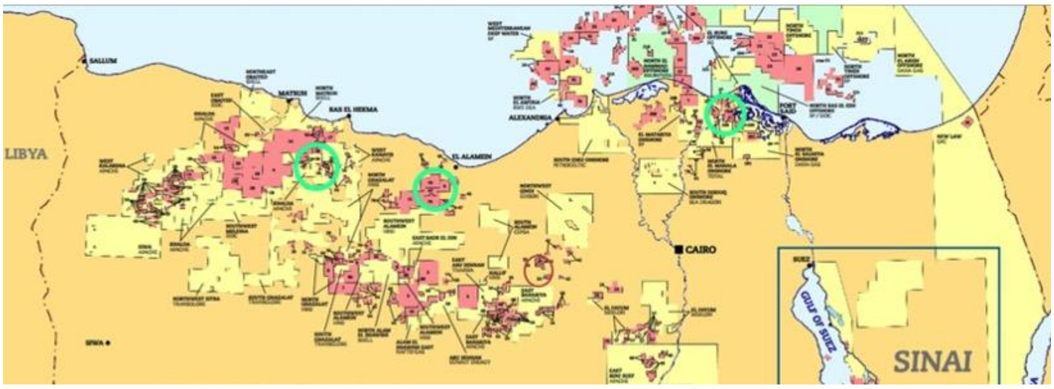

Figure 3.2.2 – The O&G facilities along the Mediterranean cost of Egypt (http://palisade-research.com/technology-the-next-oil-superpower/).

Therefore, the issues of coastal inundation and erosion are of particular relevance in this area, also considering the high concentration of offshore and onshore industrial facilities in the region (Fig. 3.2.2).

3.3 The available data set.

The assessment of climate change impacts at the regional scale involves the collection of a huge amount of data in order to define the scenarios, indicators and parameters that have to be included into the coastal vulnerability calculation. Consequently, a survey of available information and dataset concerning physical, geological and socio-economic characteristics was performed for the Egyptian Mediterranean seacoast.

Therefore, in order to identify site-specific targets and indicators of vulnerability to permanent/occasional inundations and coastal erosion impacts in the area of concern, available territorial and environmental data were investigated and collected. Available data include ocean data for present and future scenarios (se-level rise scenarios and storm surge levels), site-specific wave height and tidal range information for the baseline period, physical-environmental indicators useful to characterize the nature of the landforms of the coast (geomorphology, elevation, erosion) and socio-economic indicators useful to localize the presence of the human activities and infrastructures (land cover/use, administrative areas) were collected.

Most of the available data were retrieved from various free database in or electronic format compatible with GIS (e.g. shapefiles), however, some indicators (e.g. geomorphology characterization, shoreline erosion/accretion pattern) were note available in electronic format and were retrieved as maps (images) from a recent analysis developed by Hereher in 2015.

Table 3.1 shows the dataset that was collected and used in the present thesis, organized in the following fields: type of parameter, model/dataset name and domain, spatial resolution, time scenario, format and source.

Table 3.1 - Available datasets for the case study area.

Type of indicator	Model/dataset name and domain	Spatial resolution	Time scenario	Format	Data source (reference)
Sea-level rise	SSALTO/DUACS dataset (Egypt); CMCC-Regional Climate Model (Mediterranean region);	Atmosphere component: 0.8-2 degrees; 80 km	Observed period: 1993-2011 Future period: 2021-2050 and 2041-2070 (under RCP4.5 and RCP 8.5 scenarios)	Shapefile	SSALTO/DUACS (Segment Sol multi-missions dALTimetrie, d'orbitographie et de localisation precise system (http://www.aviso.oceanobs.com/en/data/product-information/duacs/); OrientGate project (http://www.orientgateproject.org/indicator.php?id=36)
Storm surge level	Delft3D-Flow hydrodynamic model (Europe coastline)	Atmospheric component: 0.2°	Baseline period: 1970-2000; Future period: 2010-2040 and 2070-2100 (under RCP4.5 and RCP 8.5 scenarios)	xls; Shapefile	Vousdoukas et al., 2016; JRC (http://data.jrc.ec.europa-eu/collection/LISCOAST)
Geomorphology	Mediterranean seacoast of Egypt	/	/	Images (PDF)	Hereher, 2015
Digital Elevation Model (DEM)	Mediterranean seacoast of Egypt	Spatial resolution: 30m	/	Raster	USGS, 2016 (http://earthexplorer.usgs.gov/)
Coastal slope	Mediterranean seacoast of Egypt	Spatial resolution: 30m	/	Raster	Calculated by using the 30m DEM, 2016

Type of indicator	Model/dataset name and domain	Spatial resolution	Time scenario	Format	Data source (reference)
					(http://earthexplorer.usgs.gov/)
Shoreline erosion/ accretion	Mediterranean seacoast of Egypt	/	/	Images (PDF)	Hereher, 2015
Mean tide range	Sea ports of Egypt	/	/	xls	Egyptian Maritime Consultant Office, 2009 (http://www.emco-shipping.com/egypt_main_port.aspx)
Mean wave height	Third generation ocean model (WAM); Mediterranean Basin	Atmospheric component: 1/16°	Reference period: 2001-2010	Netcdf	Liberti et. al, 2013; ENEA (http://www.enea.it/en/home-luglio-2015?set_language=en&cl=en)
Land cover	Global Land Cover 2000 (GLC 2000) (Egypt)	Spatial resolution: 30°	/	Raster	Open Street Map, 2000 (http://download.geofabrik.de/index.html)
Administrative areas	Egypt	/	/	Shapefile	Global Administrative Areas (GDAM), 2015 (http://www.gadm.org/download).

4. Coastal vulnerability index supporting the definition of adaptation strategies for the energy sector.

As introduced in Chapter 3, coastal vulnerability indexes represent a common and simple method to assess the susceptibility of coastlines to potential shoreline retreat, inundation and erosion (Thieler & Hammar-Klose, 2000; McLaughlin & Cooper, 2010; Hereher, 2015).

Considering the specific vulnerabilities of the case study area to sea-level rise, storm surge flooding and erosion (Paragraph 3.2), and the availability/accessibility of data in the southern Mediterranean region (Paragraph 3.3), the Coastal Vulnerability Index (CVI) proposed in this thesis was therefore selected as suitable tool to: 1) make a screening assessment of potential environmental impacts associated to climate change in coastal area and, 2) draw some preliminary considerations about the potential impacts and adaptation options for the O&G industry.

In fact, as depicted in the conceptual risk framework (Paragraph 3.1), the assessment of the physical-environmental impacts of climate change in coastal systems is a necessary step for the identification and evaluation of potential risks on coastal (inland) energy facilities (e.g. O&G processing and refinery plants, storage facilities, pipelines). In addition, the hydrodynamic pressures such as sea-level rise and storm surge flooding could impact directly offshore assets (e.g. O&G extraction platforms, floating production and storage assets).

As described in the following sections, the CVI proposed in this thesis was therefore developed for the assessment and prioritization of climate change impacts on the coastal environment and the related energy infrastructures.

Key steps for the development and application of the CVI include:

1. Identification of the application context: objectives and scenarios.
2. Indicators' selection and normalization.
3. Index calculation.
4. Coastal vulnerability mapping.

The theoretical steps for the implementation of CVIs will be presented in the following paragraphs (4.1, 4.2, 4.3 and 4.4). Finally, Chapter 5 will be focused on the application of the CVI approach at the case study level, including recommendations for the development of adaptation strategies.

4.1 Identification of application context: objectives, scale and scenarios.

The overall aims of the CVI developed within this thesis are:

- to evaluate the (actual) coastal vulnerability to inundation and erosion, based on site-specific physical, geological, socio-economic and critical energy infrastructures variables;
- to evaluate the potential (future) vulnerability based on future climate change scenarios (e.g. sea-level rise and storm surge projections);
- to provide some recommendations about the potential impacts and adaptation strategies for the energy infrastructures located in coastal zones.

Therefore, the objectives of the proposed methodology are: firstly, the identification and prioritization of coastal segments along the coast, which are more likely to be affected by coastal inundation and erosion within the analyzed region, both in present (baseline) and future (e.g. climate change induced) scenarios; and secondly, provide a relative prioritization of the potential impacts for the energy sector, and for the implementation of adaptation strategies, based on the current distribution and typology of existing assets or on future projects for infrastructure design.

Compared to the traditional formulation of CVI applied for coastal vulnerability assessment/management (Gornitz et al., 1991; Thieler & Hammer-Klose, 2000), and the more recent applications in Europe (McLaughlin & Cooper, 2010; Rosendahl Appelquist, 2012) and in the Mediterranean region (Hereher, 2015), the proposed CVI was designed by considering a multi-dimensional set of physical, geological and socio-economic variables able to characterize coastal vulnerability to inundation and erosion for the O&G energy sector. Moreover, the CVI proposed in this thesis allows to:

- Considering future and state-of-art climate change scenarios available on the regional (Mediterranean) scale (e.g. OrientGate and JRC projects);
- Use of open-source/free-access physical, geological and land cover datasets, allowing the application of the methodology also in developing countries;
- Integrate asset's design standard metrics and indicators into the CVI formulation.

Thus, the developed index is proposed as a suitable risk assessment tool for a) the identification of most likely impacts affecting O&G facilities in coastal zones and b) the definition of a preliminary set of adaptation strategies that should be considered by energy companies in order to manage climate related risks in costal zones.

In addition to a clear explanation of the objectives, the definition of the application context for the CVI should include the selection of the appropriate spatial scale of the assessment.

In fact, as mention in Paragraph 2.2, the vulnerability assessment can be performed at various spatial scales: global-scale assessments enable international approaches to be coordinated and global policies to be debated; national scale assessments allow the definition of national level policy and the prioritization of resources; local scale studies are commonly implemented to define the practical response to coastal hazards (McLaughlin & Cooper, 2010). Thus, the CVI calculation should consider what data are available at the spatial scale of interest, moreover, a higher resolution is usually required at the local compared to the global scale.

Even if investors in the O&G sector may be interested in the development of specific adaptation plans/options at the local (i.e. project level) scale, they should also consider the surrounding area, including access routes to the plant and key related infrastructures (e.g. production and processing plants, refineries, offshore platforms) (CoastAdapt, 2016). Therefore, in some instances, the scale of risk assessment associated with climate change can be greater than the project design scale, and therefore more useful for broader strategic decisions rather than individual project/infrastructure management (CoastAdapt, 2016).

Finally, another key feature of the proposed CVI is that it is suitable for integrating information about future climate change scenarios that is essential for the implementation of climate change impact and risk assessments (Willows & Connell, 2003; IPCC 2013b).

4.2 Indicators' selection and normalization.

The proposed CVI formulation is based on the aggregation of indicators belonging to 3 main categories: physical indicators, representing the nature of coastal processes (sea-level rise, storm surge flooding, tide range and wave height); geological indicators, representing the resistance or susceptibility of coastlines to physical variations (geomorphology, elevation, coastal slope, inland buffer and shoreline erosion/accretion); socio-economic variables (land cover and presence/absence of critical energy infrastructure) reflecting the distribution of human activities exposed to climate related hazards along coastal systems (Gornitz et al., 1991; Thieler & Hammer-Klose, 2000; McLaughlin & Cooper, 2010).

Compared to the traditional CVI formulation including 6 or 7 variables (geomorphology, coastal slope, shoreline erosion/accretion rates, relative sea-level rise, mean tidal range and mean wave height) (Gornitz et al., 1991; Thieler & Hammer-Klose, 2000), the proposed CVI formulation considers also socio-economic variables representing the distribution of human activities (e.g. land cover) and the presence/absence of existing or future critical energy infrastructures. In fact, it is assumed that the presence of human assets can influence the distribution and local severity of consequences (damages) associated with climate-related hazards.

Each indicator selected for the CVI is characterized by different attributes (e.g. quantitative or qualitative information) and measurement units, therefore, in order to aggregate all the indicators in a single index, they need to be normalized in a common scoring system. This process requires first the classification of the variables according to their capacity of determining detrimental changes to coastlines (and therefore vulnerability); and secondly the assignation of a score from 1 to 5 to each class where 1 has a very low contribution to vulnerability, whereas 5 corresponds to a very high contribution of that class to the final vulnerability score.

Hereafter, all the indicators included in the CVI equation will be described, providing some guidelines for their classification and scoring procedure.

4.2.1 Physical indicators.

Physical indicators take into account all the coastal processes (sea-level rise, storm surge flooding, tide range and wave) that could impact and, therefore, modify the nature of the coast. Four physical indicators including sea-level rise, storm surge flooding, mean tide range and mean wave height are considered for the CVI formulation (Table 4.1).

Table 4.1 **–** Physical indicators, classes and scores proposed for the CVI calculation.

Physical indicators	**Vulnerability classes and scores**				
	Very low	**Low**	**Moderate**	**High**	**Very high**
	1	**2**	**3**	**4**	**5**
Sea-level rise (mm/yr)	< 1.8	1.8 – 2.5	2.5 – 3.0	3.0 – 3.4	> 3.4
Storm surge flooding (m)	< 1.0	1.0 – 1.6	1.6 – 2.2	2.2 – 2.8	> 2.8
Mean tide range (m)	>6.0	4.1 – 6.0	2.0 – 4.0	1.0 – 1.9	< 1.0
Mean wave height (m)	<0.55	0.55 – 0.85	0.85 – 1.05	1.05 – 1.25	>1.25

Specifically, ***Sea Level Rise (SLR)*** is defined as the potential increase of mean sea level that may cause permanent/occasional inundation of low-lying coastal areas (Özyurt 2007; IPCC 2012b).

Recent estimations of future sea-level rise suggest that global mean sea level exceeded 5 m during the last 3 million years (IPCC 2013c). Thus, sea-level rise will have a large impact on coastal evolution, causing for example coastal erosion and temporal/occasional inundation (Gornitz et al., 1991).

The vulnerability classes proposed for this indicator follow the traditional CVI thresholds (Gornitz et al., 1991; Thieler & Hammar-Klose, 2000; Hereher, 2015) where a value of 1 (lowest score) was assigned to sea-level rise (< 1.8 mm/yr), while a score equal to 5 (highest score) was assigned of higher rate of sea-level rise (> 3.4 mm/yr) (Table 4.1).

For what concern ***storm surge flooding***, it can be defined as “*the temporary increase, at a particular locality, in the height of the sea due to extreme meteorological conditions (e.g. low atmospheric pressure and/or strong winds)*”

(IPCC, 2012). The proposed storm surge indicator, therefore, corresponds to the height reached by sea level during an extreme event of a specific return period (e.g. 5, 10, 20, 50 or 100 years).

Although, there is a wide amount of literature about the negative impacts of storm surge events on both natural and anthropogenic systems. There is no consensus in the scientific literature about how to classify the storm surge hazard based on common thresholds. Therefore, the classification method that is proposed in this thesis follows the one developed by the USA National Hurricane Center (http://www.nhc.noaa.gov/) for storm surge inundations caused by hurricanes that identifies four classes of hazard (heights above ground) on the basis of historical storm surge flooding (http://www.nola.com/hurricane/index.ssf/2014/12/national_hurricane_center_unve.html). Particularly, a score equal to 1 was assigned to lower storm surge levels (heights < 1 m), whereas a score equal to 5 was assigned to higher storm surge levels (> heights 2.8 m) (Table 4.1).

Mean ***tide range*** is the vertical difference in height between the high water and low water during a tidal cycle (Rosendahl Appelquist 2012). As stated by Gornitz et al. (1991), high tidal range is determined also by stronger tidal currents that in turns may cause erosion and transport of sediment. In addition, micro-tidal coasts (<1 m) are considered more vulnerable than macro-tidal regions (> 4 m) (Gornitz et al., 1991). Consequently, coastlines characterized by low tidal range are considered highly vulnerable, whereas high tidal range coasts are considered less susceptible (Table 4.1).

Finally, ***mean wave height*** variable represent the difference in elevation between the wave crest and wave trough, and it represents the applied measure for incoming wave energy (Rosendahl Appelquist, 2012). The classification adopted in this analysis follows the one suggested by Thieler & Hammar-Klose (2000).

Coastlines experiencing high wave heights are classified as more vulnerable comparing with coastlines exposed to lower wave heights (Murali et al., 2013). In fact, higher wave height results in an increase in wave energy, which subsequently may cause loss of land and human resources due to erosion and inundation events (Murali et al., 2013).

4.2.2 Geological indicators.

Geological indicators deal with the resistance of coastlines to erosion/accretion trend, and their susceptibility to flooding and erosion. Table 4.2 gives an overview of the geological indicators suggested for the CVI calculation together with their vulnerability classes and scores.

Table 4.2 **–** Geological indicators, classes and scores proposed for the CVI calculation.

Geological indicators	Vulnerability classes and scores				
	Very low	Low	Moderate	High	Very high
	1	2	3	4	5
Geomorphology (non numerical)	Rocky, cliffed coast	Medium cliffs, indented coasts	Low cliffs, alluvial plains	Cobble beaches, estuary, lagoon	Barrier beaches, sand beaches, salt marsh, mud flats, deltas
Elevation (m)	>30	20 to <30	10 to <20	5 to <10	<5
Coastal slope (%)	>11.5	11.5 – 5.5	5.5 – 3.5	3.5 – 2.2	<2.2
Inland buffer (m)	Up to 300	/	50 to 300	/	0 to <50
Shoreline erosion/ accretion (m/yr)	>2.0 Accretion	1.0 – 2.0 Accretion	(-1.0) – (+ 1.0) Stable	(-1.1) – (-2.0) Erosion	< (-2.0) Erosion

Coastline ***geomorphology*** play a major role in determining the impact of sea-level rise on shoreline changes (Hereher, 2015). This variable, in fact, determines relative resistance (or erodibility) of different landform types to marine inundation and erosion (Thieler & Hammar-Klose, 2000; Özyurt, 2010; Gaki-Papanastassiou et al., 2010). As shown in Table 4.2, this indicator leads to qualitatively identify all the geomorphologic structures of the investigated coastal system (e.g. muddy, deltaic, sandy, rocky and low cliffed coasts), corresponding to different vulnerability scores. Hard rocky and cliffed coasts are generally less vulnerable to inundation/erosion whereas sedimentary (unconsolidated) coasts (e.g. barrier, beaches, sand beaches, salt marsh, mud flats and deltas) are the more vulnerable to shoreline changes.

The ***elevation*** indicator is generally defined as "the average elevation of a particular area above mean sea level" (Murali et al., 2013). It represent a crucial variable in identifying and estimating the extent of land threatened by future climate change scenarios (McLaughlin & Cooper 2010; Murali et al., 2013). According to McLaughlin & Cooper (2010), low-lying coasts are more susceptible to permanent/occasional inundation events caused by the increasing of mean sea level and more extreme storm surge flooding; whereas, higher coasts are less vulnerable to the possible impacts of climate change. Consequently, coastal regions having higher elevations (>30 m) were assigned a score equal to 1 (less contribution to vulnerability), while those having lower elevations (<5 m) were assigned a score equal to 5 (higher contribution to vulnerability) (Table 4.2).

The ***coastal slope*** indicator represents the steepness or flatness of a coastal region, and it can be expressed both in percent or degree (Murali et al., 2013). The coastal slope indicator leads to evaluate the relative risk of inundation and also the potential velocity of shoreline retreat. The susceptibility of the coast due to inundation by flooding and the associated land loss is a direct function of coastal slope (Thieler and Hammer-Klose, 2000). In fact, gently-sloping coastline may retreat faster than steeper regions (USGS, 2004) (see Table 4.2).

The ***inland buffer*** indicator was selected for the calculation of the CVI, to represent the decreasing susceptibility of the coastal area to inundation and erosion, with increasing distances from the coastline. The classes and scores adopted for this indicator follow the ratings proposed by McLaughlin & Cooper (2010) for the CVI calculation at the regional (i.e. sub-national scale).

Finally, the indicator ***shoreline erosion/accretion*** is defined as “the physical removal of sediment by wave and current action” (Özyurt, 2007). In other words, it indicates the dynamics of the coastline and the rate at which it has changed in the past. Accreting coastlines are defined less vulnerable, as they result in the addition of land areas by moving towards the ocean (Murali et al., 2013). Therefore the minimum score (equal to 1) was assigned to these types of coast. Instead, eroding coastlines are considered highly susceptible because they are already subjected by loss of natural and the related human resources due to shoreline retreat (Murali et al., 2013). Hence, a score equal to 5 were assigned to this class. Table 4.2 can be consulted for the complete classification.

4.2.3 Socio-economic indicators.

Socio-economic indicators reflect, on the one hand the distribution of human activities (land cover), and on the other hand the presence/absence of exiting energy infrastructures located near the coast (McLaughlin & Cooper, 2010; Dismukes & Narra, 2016). In fact, human assets can influence the distribution and local severity of consequences (damages) associated with climate-related hazards. Hereinafter, the proposed socio-economic indicators and general criteria for their classification and scoring are proposed and discussed.

Table 4.3 **–** Socio-economic indicators, classes and scores proposed for the CVI calculation.

Socio-economic indicators	**Vulnerability classes and scores**				
	Very low	**Low**	**Moderate**	**High**	**Very High**
	1	**2**	**3**	**4**	**5**
Land cover (non numerical)	Water bodies, Marsh/bog and moor, Sparsely vegetated areas, Bare rocks	Natural, grassland, coastal areas	Forest	Agriculture	Urban and industrial infrastructure

Regarding the ***indicator land cover***, it helps to understand the distribution of human activities in the coastal territory, representing a proxy of the 'value' of the coast (McLaughlin & Cooper 2010). Therefore, as shown in Table 4.3, urban/industrial areas located along the shoreline makes the region more vulnerable to the potential damages related to inundation and erosion than the presence of natural or semi-natural environments. Land cover vulnerability classes and scores were assigned according with the classification scheme provided by Table 4.3.

As far as industrial infrastructures are concerned, the CVI should include some indicators related to the presence or absence of different types of ***critical energy infrastructures*** related to O&G industry. In fact, the geographic configuration of energy facilities can influence the distribution and local severity of impacts associated with hazard events (e.g. sea level rise, storm surge flooding and coastal erosion) (Thatcher et al., 2013; Dismukes & Narra 2016). The scientific review conducted on available index-based approaches (Paragraph 2.2), shows that the most common energy infrastructures included in coastal vulnerability or impacts assessments are natural gas/crude oil drilling and production plants, processing facilities, electric generation facilities and ports/service bases (Dismukes and Narra 2016). Table 4.4 presents an overview of such critical energy infrastructures.

Table 4.4 – Energy infrastructure typologies.

Energy infrastructure typologies
Oil and gas pipeline volume
Crude oil refineries
Electric generation facilities
Petrochemical facilities
Natural gas processing facilities
LNG terminals
Natural gas storage facilities
Port facilities

However, the selection of infrastructure to be considered in the assessment depends on the specific objectives of the assessment, the local characteristics of the O&G assets and the site-specific available information. A limiting factor for the consideration of this indicator is that data related to O&G infrastructures are not available on free access dataset, and therefore is necessary to have access to internal data and information of energy companies. In addition to the localization of the critical energy infrastructure, the CVI can integrate some physical infrastructures' indicators determining the relationship between the potential physical damages of industrial assets/equipment and the severity of hazard events. Some examples of these indicators are listed in Table 4.5.

Table 4.5 – Overview of physical infrastructure indicators for different energy facilities.

Facility typology	Vulnerability indicators	Vulnerability classes
Pipelines	Product transported, length, diameter, and volumetric capability.	High, medium and low
Storage tanks	Total capacity, empty and full operating weight	High, medium and low
Wells	Years placed in service, location, record of past damages from natural hazards/extreme weather events	High, medium and low

Facility typology	Vulnerability indicators	Vulnerability classes
Offshore production facilities	Platform location maps, engineering description of components/equipment/main structures	High, medium and low
Processing plants	Location maps, number of associated wells/pipelines, type of fluids, record of past damages from natural hazards/extreme weather events, processing facility capacity, refining/distillation capacity	High, medium and low

However, there are not common guidelines for the selection, classification and scoring of these indicators in the CVI formulation. Therefore, the implementation of these indicators in the index requires, firstly, an assessment of their significance (prioritization) based on expert/engineering knowledge of the specific system at risk; and secondly, the definition of high, medium or low vulnerability scores should be possibly based on the contingency thresholds used for the design of energy infrastructures.

4.3 Index calculation.

Once key indicators are selected, classified and scored, they have to be combined in a single index. There are different ways to calculate the CVI in the scientific literature, however, for the purposes of this thesis, the square root of the product mean proposed by Gornitz et al., (1991), and then employed by for example Thieler & Hammar-Klose (2000) and Hereher (2015) is applied:

$$CVI = \sqrt[2]{\frac{(x_1 * x_2 * x_3 \ldots x_n)}{n}} \qquad \textit{Equation 1}$$

where n= number of selected indicators.

4.4 Coastal vulnerability mapping.

The final step deals with the classification of the CVI score in *n* different classes (e.g. 3, 4 or 5), using for instance n-1 percentiles as limits (e.g. 25%, 50%, 75%) (Thieler & Hammar-Klose, 2000). This classification enables the evaluation of the relative coastal vulnerability of the different studied coastal segments (such as sub-areas included in a wider coastal system) (Thieler & Hammar-Klose, 2000).

Risk maps produced through the application of the CVI methodology at the case study level will be presented in Chapter 5. These maps identify most vulnerable areas to inundation and erosion, providing a support for decision makers to establish relative priorities for intervention.

5. Results and discussions.

The results of the CVI procedure described in Chapter 4 were classified and processed by using the ArcGIS software in order to obtain maps that spatially represent the relative vulnerability of Egyptian coastline to inundation and erosion.

Moreover, through GIS tools, several statistics (e.g. percentage and surface of coastal areas associated to different vulnerability classes, percentage and surface of high vulnerability classes in each administrative unit) were calculated in order to synthesize relevant information coming from the CVI outputs.

Data for all the selected CVI indicators were assembled from a variety of digital and analogue sources in a single GIS geo-workspace in order to spatially represent them into layers, which represent vulnerability maps useful for stakeholders to a) establish relative priorities for intervention on the already existing infrastructures; b) identify suitable areas for the design of future O&G infrastructures.

The step-by-step application of the CVI, including the results and maps obtained for each individual indicator and the final vulnerability index will be presented and discussed in the following paragraphs.

5.1 Identification of application context: objectives, scale and scenarios.

As anticipated in Paragraph 4.1, the application of the CVI approach at the case study level was performed with the aim of identifying and prioritizing coastal segments at higher risk of coastal inundation and erosion in relation with future climate scenarios.

However, since it was not possible to retrieve free dataset concerning the presence, localization and typology of energy infrastructures in the case study region, the CVI application was performed by aggregating the following indicators:

- Physical indicators (sea-level rise, storm surge flooding, mean tide range and mean wave height);
- Geological indicators (geomorphology, elevation, coastal slope, inland buffer, shoreline erosion/accretion);
- Socio-economic indicators(land cover).

In particular, as described in the following sections for some indicators (i.e. sea-level rise and storm surge), it was possible to consider not only a baseline scenario, representing the current vulnerability situation (1970-2010) but also a potential future scenario related to climate change impact in the considered timeframe (2010-2050). The choice of the future timeframe was performed considering that a mid-term horizon (the next 30 years) can be relevant both for the current management decisions of existing infrastructures and for the strategic decisions about the future infrastructure investments in the O&G sector.

The spatial scale of the assessment includes the Mediterranean coast of Egypt, and is delimited by the areas located within 5km from the shoreline. In fact, as highlighted in a recent study (Hereher, 2015), this region represents the area potentially influenced by coastal erosion and flooding in Northern Egypt coast. The 5km coastal strip was defined by using the Buffer command of the ArcGIS software and is represented in Fig. 5.1.

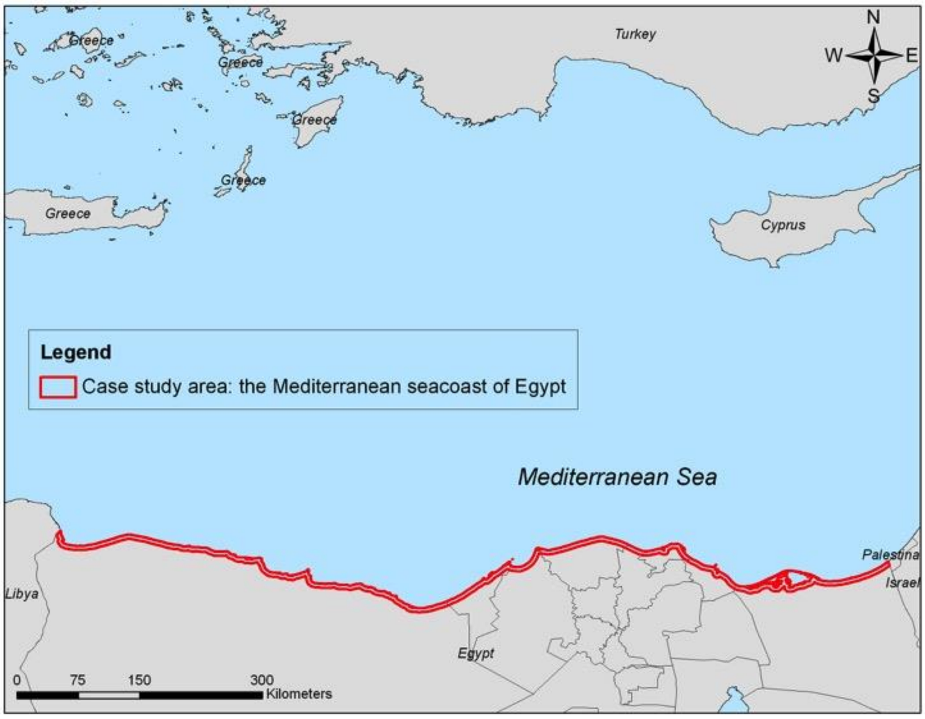

Figure 5.1 – The case study are of the Mediterranean seacoast of Egypt.

The assessment of coastal vulnerability to coastal erosion and inundations should be performed considering high resolution and high vertical accuracy topographic datasets. However, this was not possible for the area of concern, because only few accessible free-datasets, characterized by high spatial resolution ,were retrieved. Particularly, the vulnerability assessment process was done by considering as spatial units of measurements (e.g. grid cells) the most detailed available dataset for the raster analysis (e.g. 30m DEM).

5.2 Indicators' selection and normalization.

The aim of this Paragraph is to present the physical, geological and socio-economic vulnerability indicators calculated for the case study area in order to show their spatial pattern and the relevant statistics leading to the final vulnerability index later described in Section 5.3.

5.2.1 Physical indicators.

Physical indicators were selected as relevant proxies of ocean processes acting on the coast that may cause property or infrastructure damage, loss of livelihoods and services, social and economic disruption, or environmental damage.

As described below, useful information for the calculation of physical indicators was retrieved from:

a) The output of ocean, waves and hydrodynamic models (e.g. derived both from the baseline period and for future climate change scenarios).
b) The analysis of past observations of climate or ocean variables (e.g. tide gauge data, return periods of extreme waves and storm surge events).

In particular, it is worth to note that for the analysis of storm surge levels and sea level rise indicators it was possible to rely on future projections compliant with recent RCP emission scenarios[1]. Whereas, the analysis of wave height and tidal range was based on observed or modeled distribution of data for the baseline scenario.

Considering that the information concerning physical indicators was available for sea grid points located in front of the case study shoreline, the Inverse Distance Weighted (IDW) function of ArcGIS was applied to correlate the value of each grid point along the Mediterranean coast of Egypt to the corresponding nearest pixel inland.

In order to estimate the classes and scores for the ***sea-level rise*** indicator, several sources of information were considered in the analysis.

First, data representing the sea level anomalies under the RCP4.5 and RCP8.5 emission scenarios for two future time frame periods (2021-2050 and 2041-2070) compared with the reference year (2005) were retrieved from the Regional Climate Model developed by CMCC with a regular grid of about 80 km for the Euro-Mediterranean region (Scoccimarro et al., 2011). Particularly, 12 model grid points were selected in front of the Mediterranean seacoast of Egypt (Fig. 5.2.1).

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[1] The RCPs are widely used to represent the approximate total radiative forcing in year 2100 relative to 1750 (IPCC 2013b). Each RCP is built upon a combination of reasonable assumptions and scientific knowledge about energy resource stocks, socio-economic and demographic trends and technological base information (Riahi et al. 2011). They include one mitigation scenario leading to a very low forcing level (RCP2.6), two stabilization scenarios (RCP4.5 and RCP6), and one scenario with very high greenhouse gas emissions (RCP8.5) (IPCC 2013b).

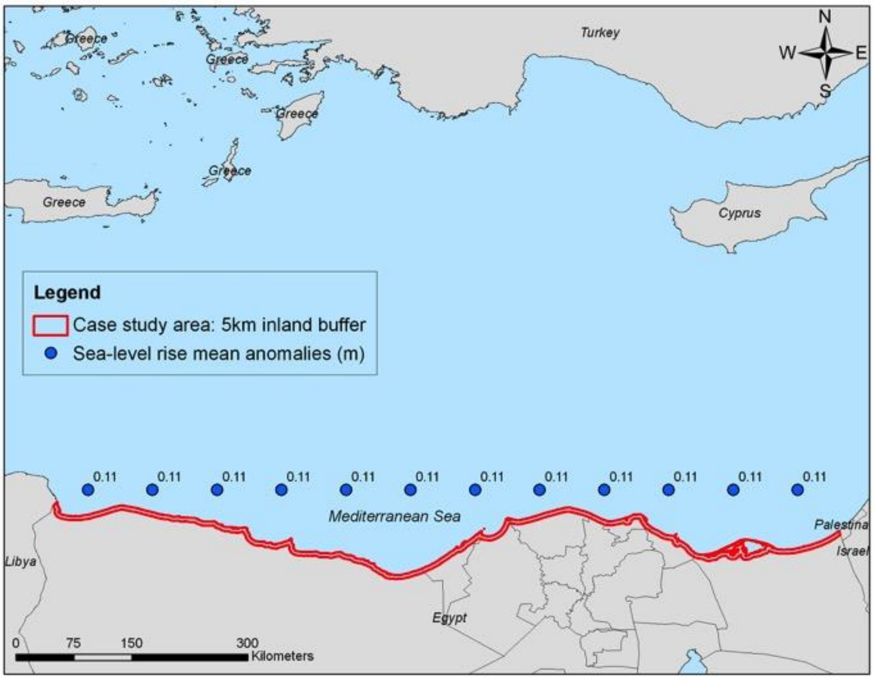


Figure 5.2.1 **-** Grid points selected for the analysis of sea-level anomalies in the Mediterranean seacoast of Egypt.

For each of the 12 grid points, several statistics representing the sea level rise anomaly were downloaded from the dataset made available by the OrientGate Project (http://www.orientgateproject.org/), including: 1) "max-min", difference between the maximum of the considered period and the minimum of the baseline period (full precautionary circumstance); 2) "mean", difference between the mean of the considered period and the mean of baseline period; 3) "median", difference between the median of the considered period and the median of baseline period; 4) "pct", difference between the 90th percentile of the considered period and the 10th percentile of baseline period (highly precautionary circumstance). Table 1, ANNEX II summarizes the statistics (mean, median, max-min, median and pct) for sea-level anomalies calculated at the 12 grid points in the two investigated timeframes and emission scenarios.

The values are quite uniform among the different grid points included in the case study area. However, the analysis was focused on the results obtained under the RCP8.5 scenario for the 2021-2050 timeframe period, selected as the worst case scenario, characterized by mean sea level anomalies of about the 10.7 cm along the analyzed coast compared to the reference year (2005), which means about 2.4 mm/yr.

Even if the projection of sea-level anomalies includes both the dynamic component (e.g. wind and ocean circulation variations) and the steric component (e.g. temperature and sea surface salinity changes); any dynamical ice-sheet component is not taken into account in the CMCC-Regional Climate model. Therefore, observational estimates of the land ice melting have to be considered as an additional component of sea-level rise, in order to have a conservative assessment of the potential future sea-level changes.

According to the most recent scientific literature, land ice melting component ranged from 1.0-1.2 mm/year during the decades 1993-2003 (Meier et al. 2007; Meehl et al. 2007; Slangen et al., 2012; Radic & Hock 2011). However, the land ice-melting rate could amount to more than 2 mm/year by the end of the 21st century (Meier et al. 2007; Meehl et al. 2007; Slangen et al., 2012; Radic & Hock 2011). Hence, a component equal to 2mm/yr was added to the CMCC-Regional Climate model output, in order to have a more conservative estimate of future sea levels.

Thus, according to the sea level rise classification proposed in Table 4.1 the maximum score equal to 5 was assigned to this indicator in the case study area, because the thresholds is projected to be exceeded (>3.4 mm/yr) in the considered future climate change scenarios (Fig. 5.2.2).

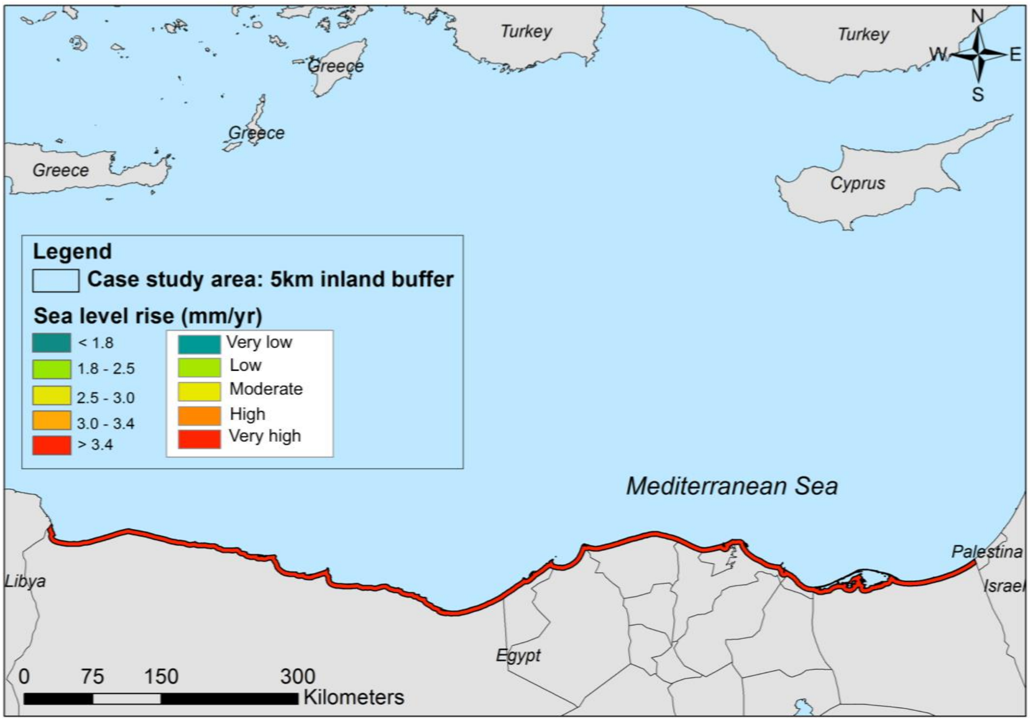


Figure 5.2.2 – Vulnerability map of sea level rise indicator showing the expected rate of sea-level in the case study region, under future climate change for the timeframe 2021-2050.

The future scenario for the sea level rise indicator, considering the potential effect of climate change, is worsen than the scenario of sea level height calculated for the baseline period (1993-2011) by using data extracted from the SSALTO/DUACS dataset (http://www.aviso.oceanobs.com/en/data/product-information/duacs/). In fact, in this case, the distribution of data for the Egyptian coastline shows a sea level increase of about 3 mm/yr and therefore a slightly lower vulnerability score equal to 4 was assigned.

As far as ***storm surge levels*** are concerned, data for the classification and scoring of the indicator were retrieved from a public-access dataset of extreme storm surge level (SSL) in order to evaluate the SSL along the Mediterranean coast of the investigated area (available at: http://data.jrc.ec.europa.eu/collection/LISCOAST).

Particularly, extreme SSL projections have been generated by using the Delft3D-Flow hydrodynamic model forced by surface wind and atmospheric pressure fields from the 6-h output of 8 climate models (CMIP5 forcing) within the European coastline for a baseline period (1970–2000) and the RCP4.5 and RCP8.5 emission scenarios for the following time frame periods: 2010–2040 (short scenario) and 2070–2100 (long term future scenario) (Vousdoukas et al., 2016).

Extreme SSL values were estimated for eight different return periods (5, 10, 20, 50, 100, 200, 500, 1000) by using the Peak-Over Threshold (POT) method, that lead to identify extreme events for each 30-year time frame periods (Vousdoukas et al., 2016). The employed models present a regular grid of 0.2° resolution for Europe and North Atlantic sea.

Specifically, 42 grid points were selected in front of the Mediterranean seacoast of Egypt to analyze storm surge level data within the case study area (Fig. 5.2.3).

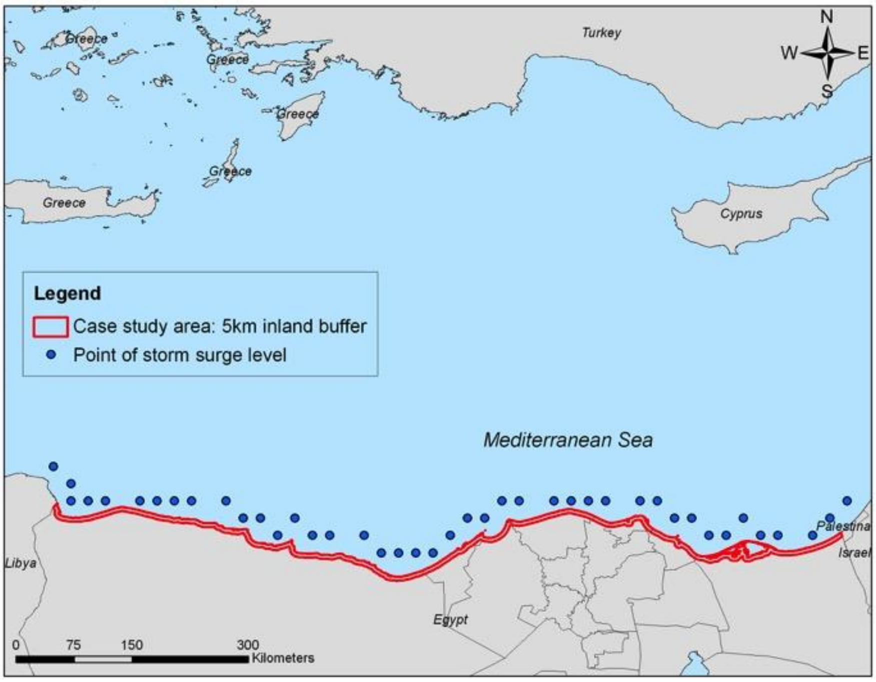


Figure 5.2.3 - Grid points selected for the analysis of storm surge level in the Mediterranean seacoast of Egypt.

Specifically, storm surge level values along the case study area for the mid-term timeframe (2010-2040) range from 0.43m (class 1) for the RP5 to 1.76m (class 3) for the RP100 (Table 2, ANNEX II). However, in order to apply a precautionary approach in the coastal vulnerability assessment, the scoring of SSL values was done by selecting the maximum value of each grid point among all the five return periods (RP5, 10, 20, 50, 100) (see Table 1-2, ANNEX III). Therefore, with respect to the classification discussed in the previous paragraph (Table 4.1, Paragraph 4.2.1), SSL along the Egyptian seacoast resulted in the range 0.63m - 1.60m and therefore in the vulnerability classes 1 (very low) and 2 (low) (Fig 5.2.4).

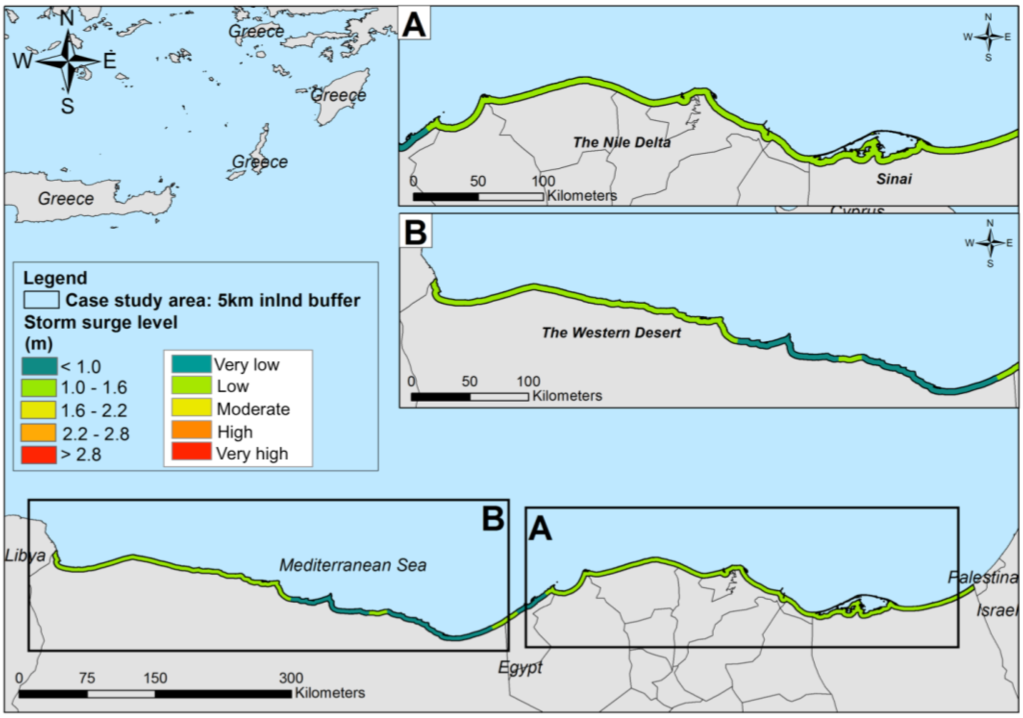


Figure 5.2.4 **–** Vulnerability map of storm surge level indicator, showing the expected rate of storm surge level in the case study region under future climate change for the timeframe 2010-2040.

Compared to the same grid points analyzed for the baseline period (1970-2000) (Table 2, ANNEX III) the SSL shows a decreasing trend in the future climate change scenario (2010–2040). In fact, as reported by Lionello et al. (2012), projected SSL along the Mediterranean coastline shows minimal changes or even a small decreasing trend by the end of the century.

However, the difference in SSL for the future and baseline scenarios was not so relevant to determine different vulnerability scores for the SSL indicator in the two temporal scenarios.

Regarding ***mean tide range*** indicator, data were retrieved from tide gauge stations obtained from the Egyptian Maritime Consultant Office website (http://www.emco-hipping.com/Home_Egyption_Maritime_Consultant_Office.aspx; latest update: July 2013) for the six ports of Alexandria, Dekheila, Abu Qir, Damietta, Portsaid and Arish, where water-level gauges are placed to monitor tidal variation along the Mediterranean coast of Egypt (Fig. 5.2.5).

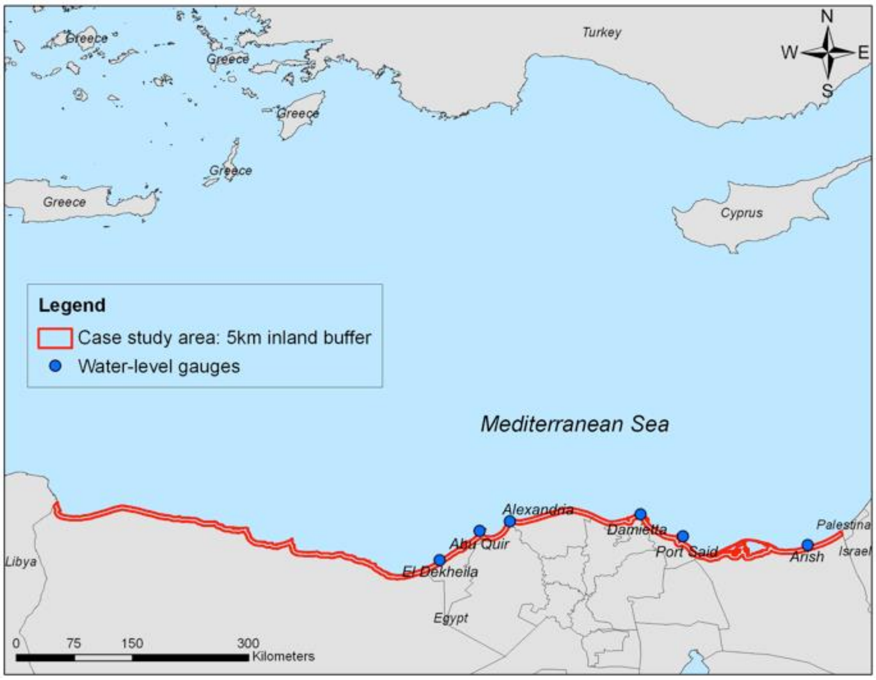


Figure 5.2.5 – Water-level gauges along the Mediterranean seacoast of Egypt.

The data reveal a tidal range between 0.30 m and 0.65 m for the yearly values (Table 1, ANNEX IV). Therefore, according to the proposed classification (Table 4.1, Section 4.2.1), a value of 5.0 is assigned for this parameter in the CVI equation to the entire Egyptian coastline. Figure 5.2.6 displays the vulnerability scores for the mean tidal range in the case study area, for the baseline scenario.

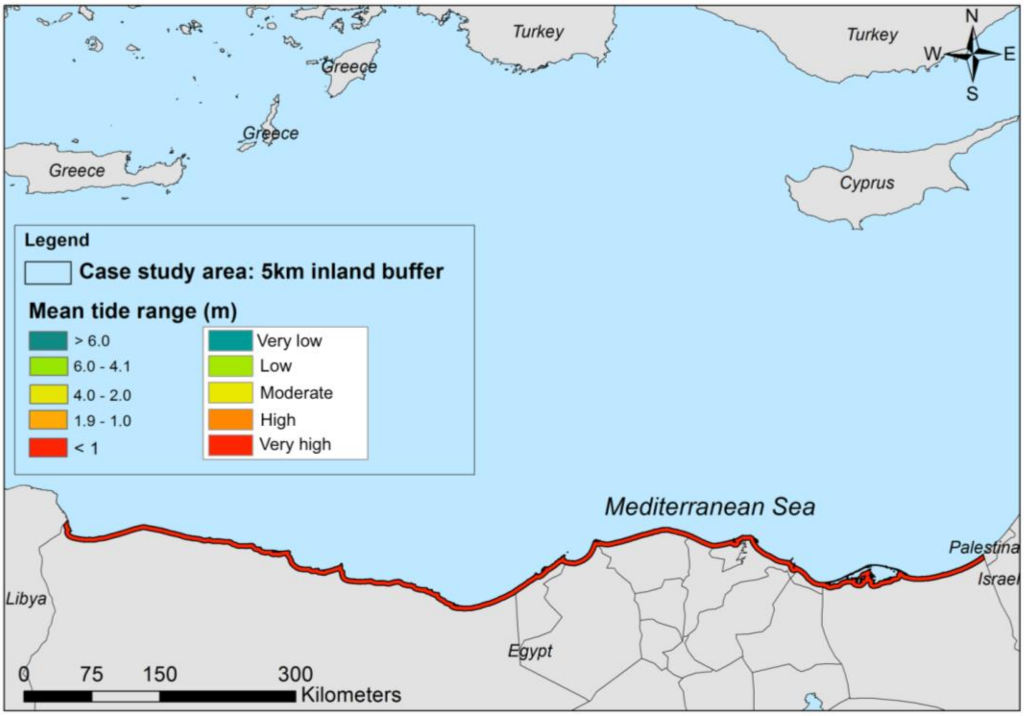


Figure 5.2.6 – Vulnerability map of mean tide range indicator, showing the mean tide range in the case study region for the observed period (2009).

The results obtained for this indicator are in line with the tidal range classification proposed by Rosendahl Appelquist (2012) and Hereher (2015), where the Egyptian coast is characterized by a micro-tidal pattern, with a low and high level of 0.20 m and 0.88m respectively (Hereher, 2015).

Even if future projections of the tidal range according to climate change scenarios were not available for the present assessment, it is known that this parameter is not expected to change significantly under the climate forcing, because it is mostly related to astronomical factors.

The analysis for the ***mean wave height*** indicator at the case study level was performed considering data regarding significant wave heights (H_S) retrieved from the wave energy atlas for the Mediterranean Sea and the WAM (Wind Wave Model) wave model Cycle. The wave model provided H_S values for the 10 years period 2001-2010 with a uniform spatial resolution of 1/16° (corresponding to a linear mesh size of 5-7 km) (Liberti et al., 2013). WAM is a high-resolution model for the Mediterranean sea since its outputs were validated against most of the available wave buoy and satellite altimeter data, including the Mediterranean coastline of Egypt. The H_S parameter was extracted from the model domain every 3 hours for both mean and seasonal (i.e. spring, summer, autumn, winter) statistics for the area of concern. Higher values of H_s were recorded during the winter season (ranging from 0.42m to 1.32m), this trend is due to the seasonal distribution of the Mediterranean sea states which is characterized by a more dynamic condition of wave energy during winter and fall seasons, as reported by Liberti et al. (2013). Whereas, spring and summer seasons present a calmer sea states. However, in this analysis mean wave height values are considered according to the traditional CVI formulations based on the annual mean H_s values (Table 4.1).

The assessment of H_s values in front of the Egyptian Mediterranean coast (Fig. 5.2.7) revealed that significant wave height (H_s) values ranges from a minimum of 0.37 m (vulnerability class 1) to a maximum of 1.04 m (vulnerability class 3). Specifically, as shown in Fig. 5.2.7, higher values mainly occur along the western corner of the region (Fig. 5.2.7A). Therefore, overall, Egypt's coastline shows a relatively moderate vulnerability to the analyzed parameter, with the majority of the territory belonging to class 2.

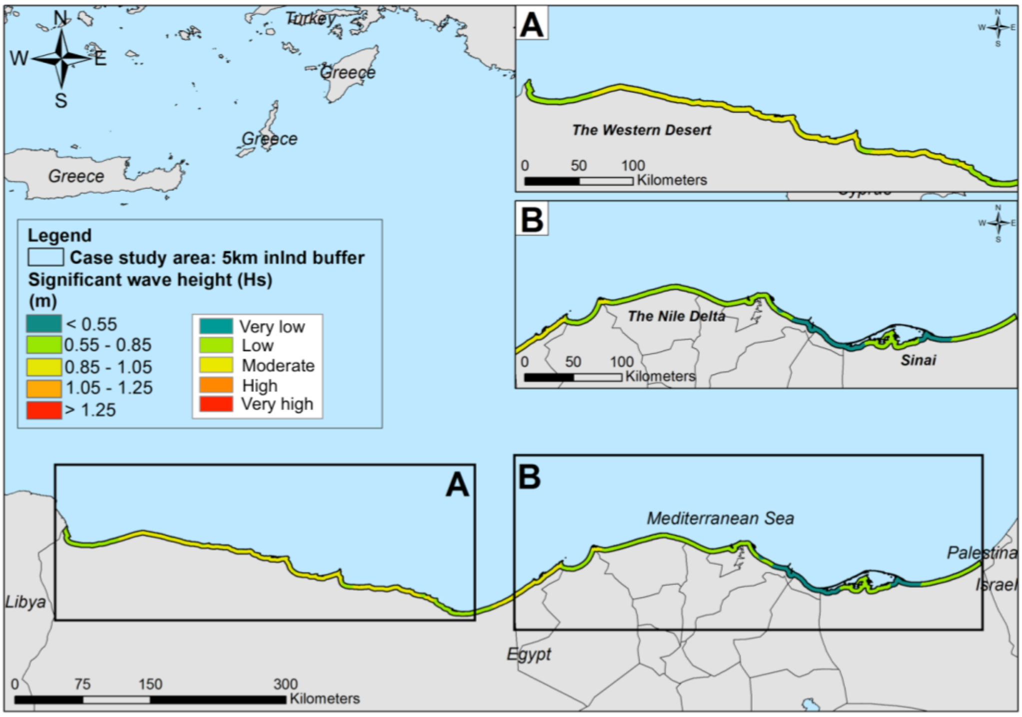


Figure 5.2.7 – Vulnerability map of significant mean wave height (Hs) indicator, showing the mean wave height values in the case study region for the baseline period (2001-2011). Details of the Western Desert sub-region (A) and the Nile Delta area (B).

Even if the current assessment was performed only on the wave dataset available for the baseline period (2001-2010) in the Mediterranean region, future projections of wave climate according to the recent RCP scenarios should be included in the CVI calculation in order to capture the potential future variations in wave dynamics and the related consequences on shoreline changes.

5.2.2 Geological indicators.

The geologic indicators are used to represent the nature of the landforms of the coast and the relative resistance (susceptibility) of the coastal territory to flooding and erosion.

Input data used for the elaboration of the geological indicators are summarized in Table 4.3 (Paragraph 3.3). The maps and statistics obtained from the application of geological indicators to the case study are presented and discussed below.

Figure 5.2.8 depicts the ***geomorphology*** of the Mediterranean coast of Egypt according to the vulnerability classes described in Paragraph 4.2.2. Particularly, by comparing Fig. 5.2.8 and 5.2.9, it is possible to see that the North Coast extending from Alexandria until the Libyan border is a rocky cliffed coast; the region between Alexandria and El-Alamine is a low cliffy coast; the Nile Delta area and the seacoast of the North Sinai are characterized by flat deltaic sediments and finally it has to be mentioned the Bardawil Lagoon in North Sinai.

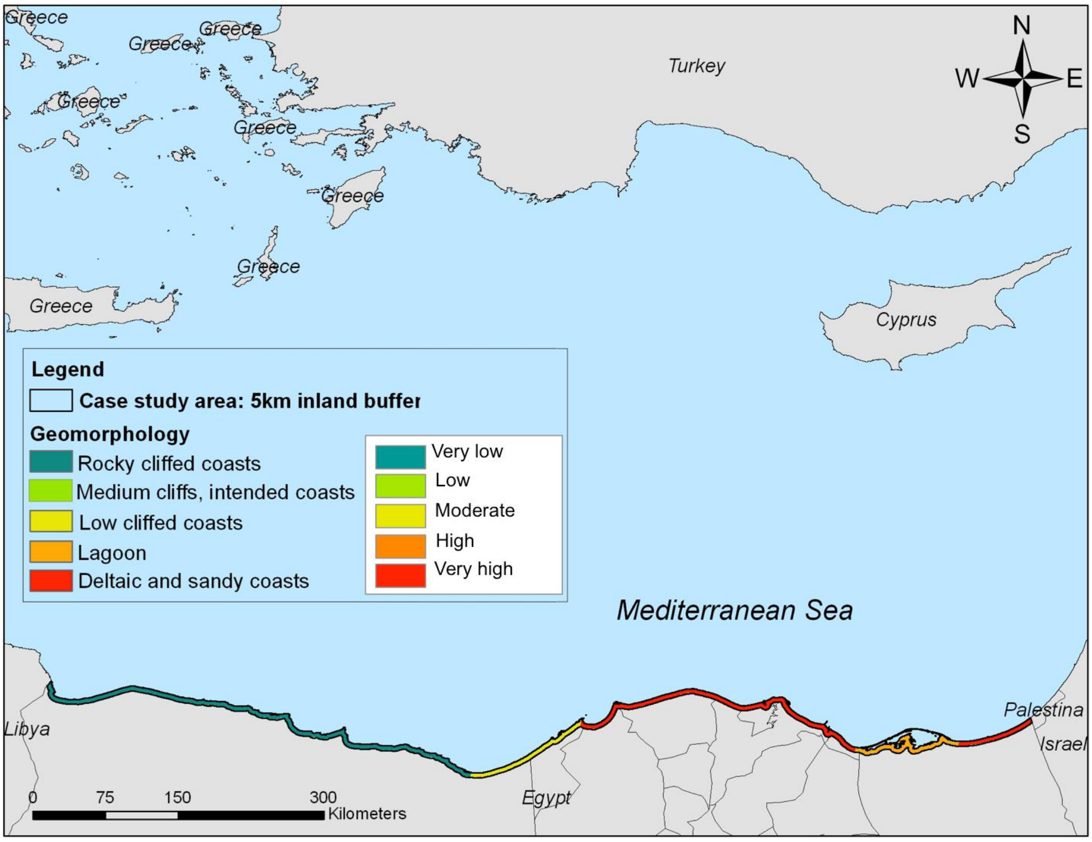


Figure 5.2.8 – Vulnerability map of geomorphology indicator for the case study region.

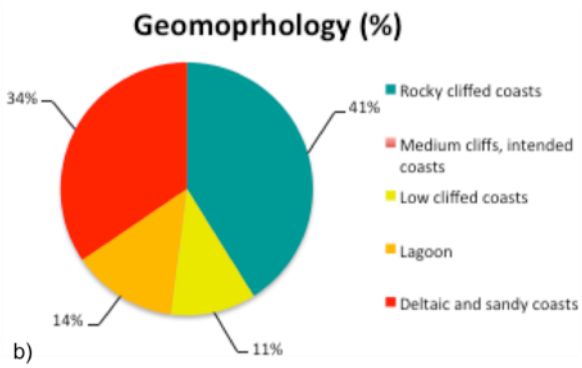
Figure 5.2.9 – The Mediterranean seacoast of Egypt.

Since it was no possible to retrieve a free-access dataset of the Egyptian geomorphology, the classification for this indicator was performed according to the classification employed in the recent study of Hereher (2015) for the same case study area.

Based on the geomorphology map, several statistics representing the territorial surface (km^2) and the percentage (%) of the investigated region in each vulnerability class were calculated (Figure 5.2.10).

Score	Class	Km^2
1	Rocky cliffed coasts	1998.58
2	Medium cliffs, intended coasts	/
3	Low cliffed coasts	531.09
4	Lagoon	655.71
5	Deltaic and sandy coasts	1676.38

a)



b)

Figure 5.2.10 – Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each vulnerability class for geomorphology indicator.

The deltaic and sandy coasts, representing the most vulnerable class to coastal inundation and erosion cover a relevant percentage of the territory (34%). Low cliffed coasts and lagoons representing the medium and high vulnerability classes cover 11% and 14% of the total surface of the case study area, respectively. However, the majority of the territory (41%) is characterized by rocky cliffed coasts, corresponding to the lower vulnerability score.

Figure 5.2.11 depicts the ***elevation*** of the Egyptian coastline according the vulnerability classification discussed in Paragraph 4.2.2 (Table 4.2). Lowlands occur mostly within the Nile Delta region (Fig. 5.2.11A) and in the Sinai Peninsula. While steep coasts are located in the western part of the region (Fig. 5.2.11B).

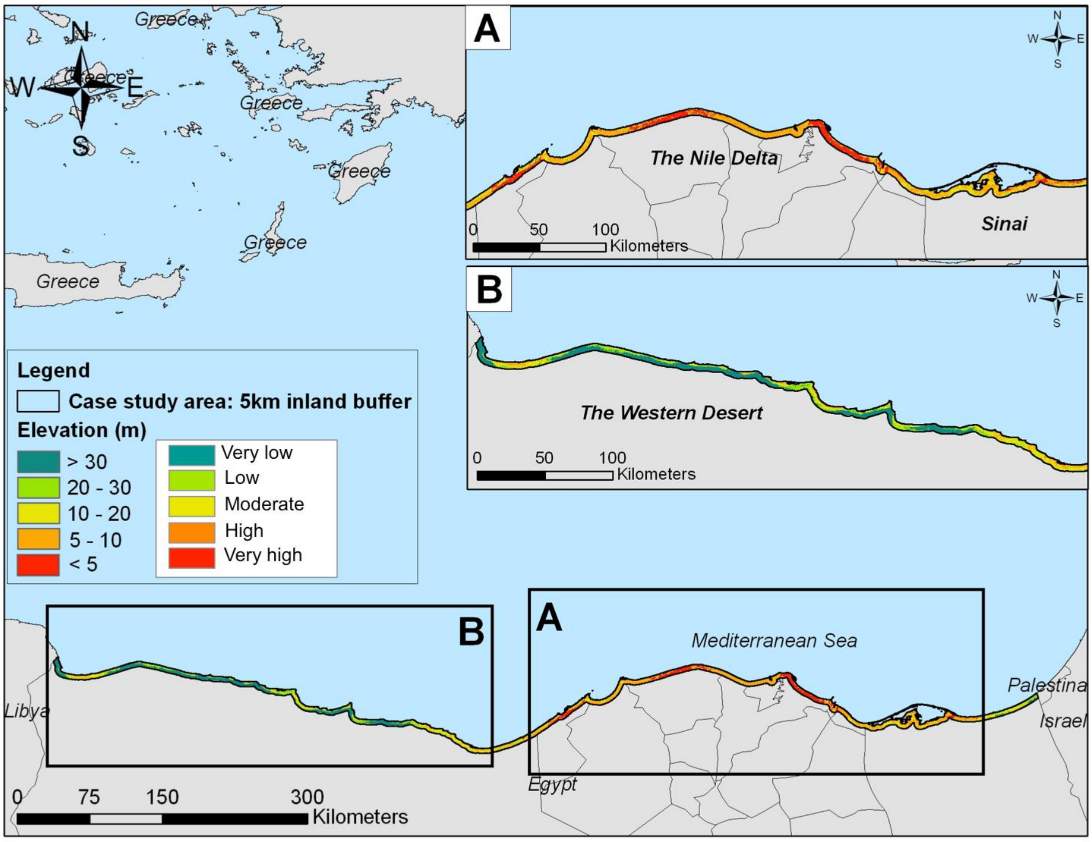
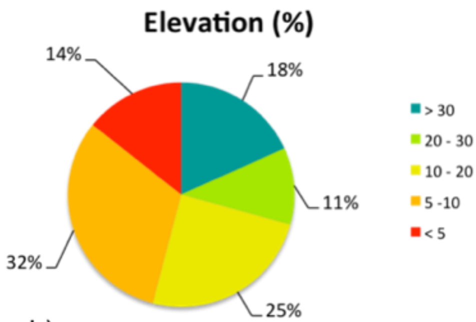


Figure 5.2.11 - Vulnerability map of elevation indicator for the case study region. Details of the Nile Delta area (A) and the Western Desert sub-region (B).

Moreover, Fig. 5.2.12 reveals that higher vulnerability class (< 5m) presents the higher percentage of the territory with a total value of 46%. Whereas only the 18% of the surface belongs to the low vulnerability class (> 30m). In addition, a relevant percentage of the territory occurs in the moderate vulnerability class with a percentage of 25%. Finally, only the 11% of the case study area is included in vulnerability class 2 (20m – 30m).

Score	Classes (m)	Km^2
1	> 30	886.57
2	20 - 30	538.87
3	10 - 20	1202.51
4	5 -10	1538.90
5	< 5	694.80

a)



b)

Figure 5.2.12 - Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each vulnerability class for elevation indicator.

The statistics were calculated based on a 30m Digital Elevation Model (DEM) downloaded by the United State Geological Survey (USGS) dataset (http://earthexplorer.usgs.gov/), which allow to find out lowlands at higher risk of sea-level rise and storm surge flooding.

On the basis of the DEM, the ***coastal slope*** indicator was also calculated for the case study area. Figure 5.2.13 reveals that steep to moderate slope coasts, occur mostly along the Western Desert area (Fig 5.2.13B) and along the easternmost of Sinai Peninsula (Fig. 5.2.13A). While low to very low slope coasts, occur along the entire Nile Delta coast (Fig. 5.2.13A) and the rest of Sinai coast. Finally, gentle slope coasts are also located along the city of Baltim and Damietta within the Nile Delta region (Fig. 5.2.13A and 5.2.9). These coasts take the value of 5.0 and are considered the more vulnerable class with the higher potential to be inundated by sea level rise or storm surge.

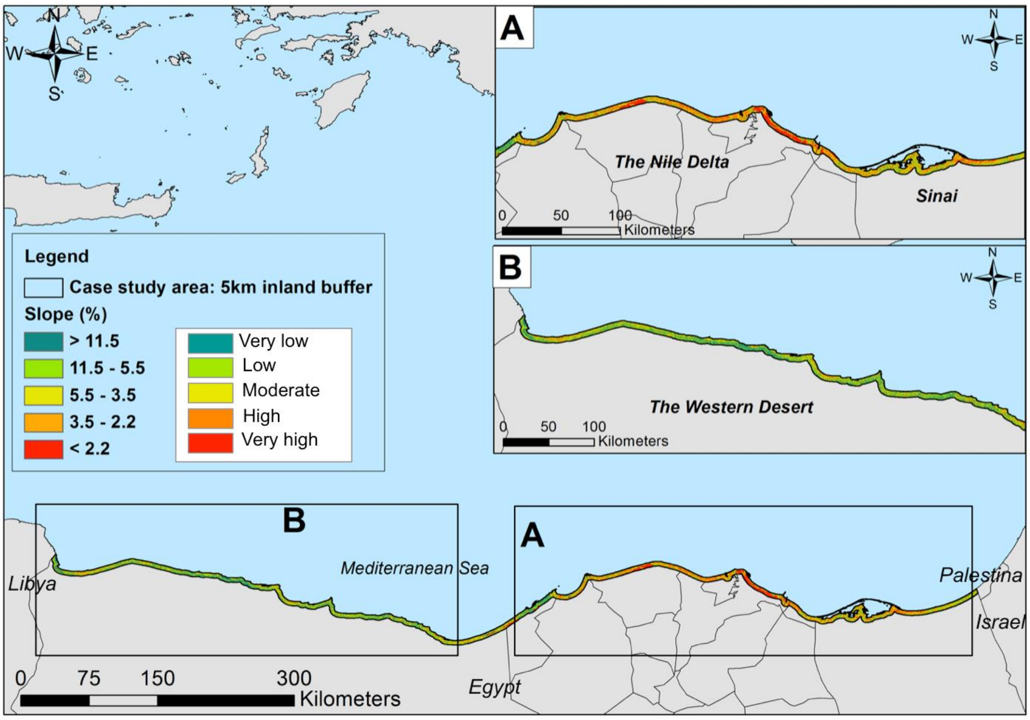


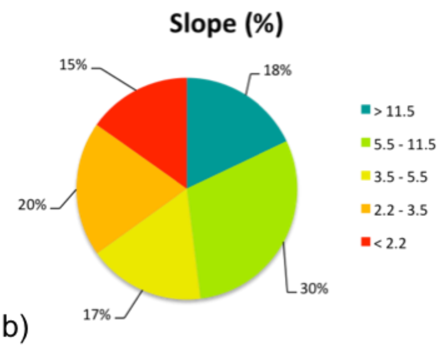
Figure 5.2.13 - Vulnerability map of coastal slope indicator for the case study region. Details of the Nile Delta area (A) and the Western Desert sub-region (B).

This parameter was calculated based on the 30m DEM by using the Slope function of ArcGIS software. Basically, for each grid cell the Slope tool calculates the maximum rate of change in elevation over the distance from that cell to its neighbors (http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-slope-works.htm). Coastal slope can be calculated either in degree (°) or percent (%); in this analysis the percent has been chosen as unit of measurement (Thieler & Hammar-Klose, 2000; Hereher, 2015).

Moreover, based on the costal slope map produced for the case study area, further relevant statistics were also calculated. Figure 5.2.14 shows that the extensive percentage (30%) of surface occurs in the moderate slope coasts. The remaining vulnerability classes (i.e. steep, low, very low and gentle) are fairly distributed with percentage ranging from 20% for low slope coast to 15% for gentle slope coasts. Specifically, all the vulnerability classes present considerable surface of territories in the medium/low risk classes.

Score	Classes (m)	Km^2
1	> 11.5	872.99
2	5.5 - 11.5	1461.88
3	3.5 - 5.5	828.93
4	2.2 - 3.5	958.93
5	< 2.2	739.02

a)



b)

Figure 5.2.14 **-** Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each vulnerability class for coastal slope indicator.

As already explained before (Section 4.2.1), the CVI calculation was performed also considering the decreasing susceptibility of coastal areas to inundations and erosion according to increasing distance from the shoreline (***inland buffer*** indicator). In fact, the more a coastal cell is far from the coastline, the less it is affected by the impacts coastal erosion and permanent/occasional inundations.

Figure 5.2.15 reveals four classes of coasts in terms of stability and ***erosion/accretion pattern.*** The majority of the coast (53%) includes stable coasts due to their rocky nature. Specifically, the west coast of the Western Desert and the easternmost area of the Sinai Peninsula occur in vulnerability class 1 (stable coasts).

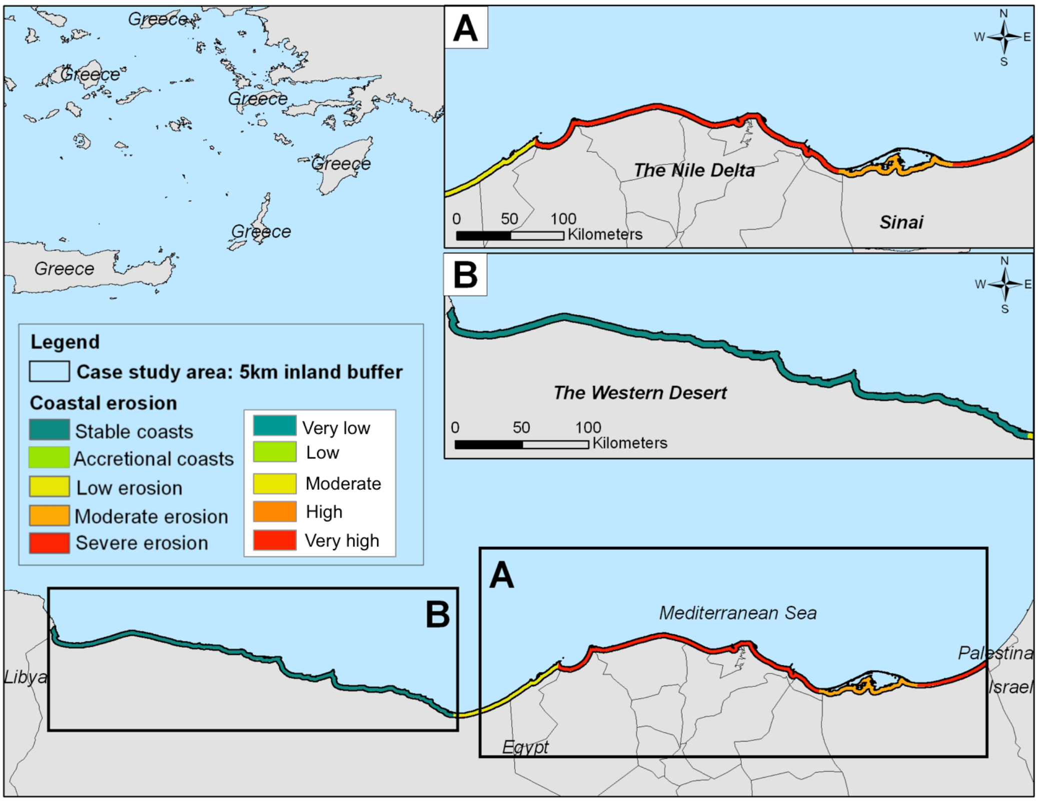
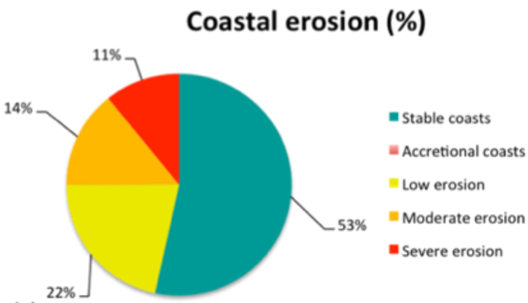


Figure 5.2.15 – Vulnerability map of coastal erosion indicator for the case study region. Details of the Nile Delta area (A) and the Western Desert sub-region (B).

As depicted in Figure 5.2.16, low-erosion coasts represent the 22% of the entire coastline, and are mainly located along the North Sinai (Fig. 5.2.16).

Score	Classes	Km^2
1	Stable coasts	2598.16
2	Accretional coasts	/
3	Low erosion	1045.93
4	Moderate erosion	693.25
5	Severe erosion	524.41

a)



b)

Figure 5.2.16 - Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each vulnerability class for coastal erosion indicator.

Moreover, near to Alexandria (eastward) there is also a small area that is part of this category. Moderately eroding coasts (vulnerability class 4) occur at four different locations within the Nile Delta area. Severe erosion was observed in five different places either in the Nile Delta region or in the Sinai Peninsula. These are the most dangerous and vulnerable locations to coastal erosion; hence, a score of 5 is assigned in the CVI equation. These categories account for the 14% and 11% respectively. Finally, accretional coasts have not been observed throughout the entire Mediterranean coast of Egypt.

Considering that it wasn’t possible to retrieve a free-access dataset for the shoreline erosion accretion indicator for the investigated area. The classification for this indicator was made with reference to the dataset already employed in the study of Hereher (2015).

5.2.3 Socio-economic indicators.

The socio-economic indicators are used to represent the distribution of human activities and the potential damages/disruption to industrial activities caused by adverse weather events (e.g. flooding and erosion).

As anticipated in Section 5.1, only the land cover variable has been selected to represent the socio-economic indicators. In fact, as mentioned before (see Section 4.2.3) no available dataset was retrieved for the characterization of energy infrastructures’ vulnerability.

Input data used for the elaboration such indicator are summarized in Table 4.3 (Paragraph 3.3). Hereafter, maps and statistics resulting from the application of socio-economic indicators to the case study area are presented and discussed.

Figure 5.2.17 reveals that the analyzed coast presents four different classes of land cover.

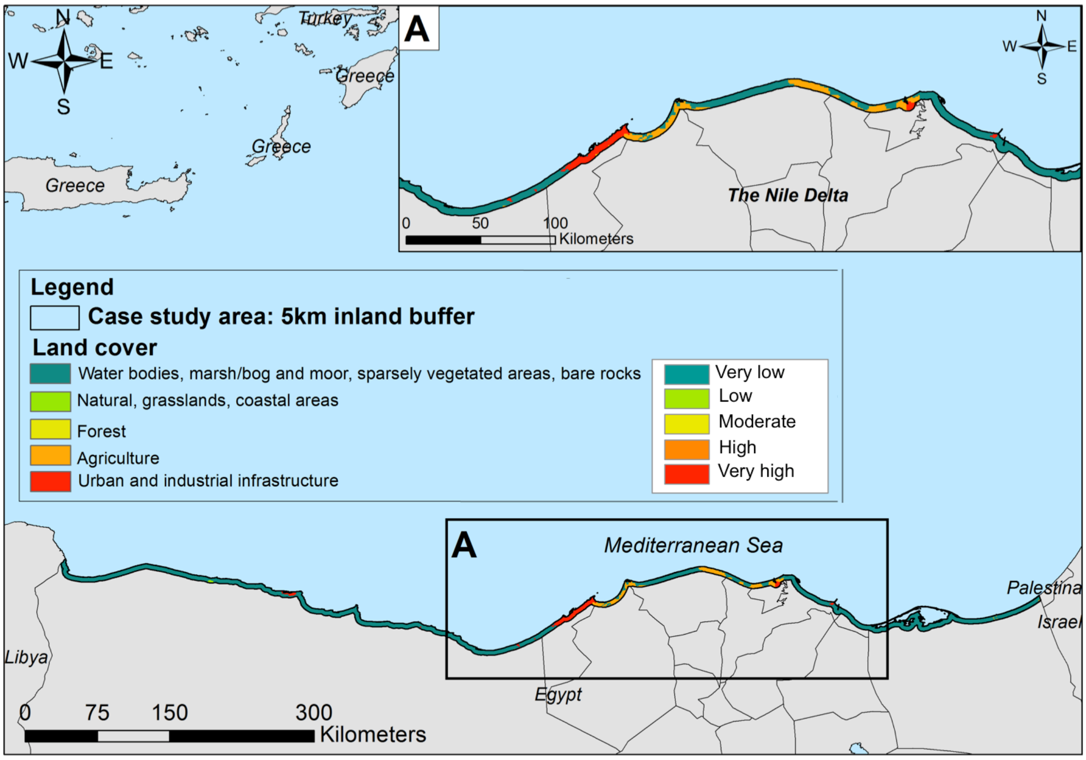


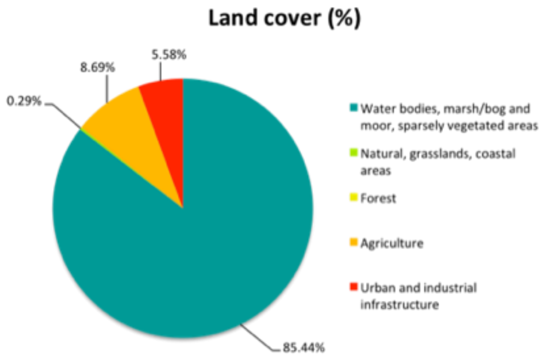
Figure 5.2.17 – Vulnerability map of land cover indicator in the case study region. Details of the Nile Delta area (A).

Most of the analyzed region (85%) is characterized by water bodies, marshes and vegetated areas. Specifically, the west coast of the Western Desert and the easternmost area of the Sinai Peninsula belong to this class, thus, a value of 1 is assigned to these regions in the CVI equation.

As shown in Fig 5.2.18, agricultural land represents the 8.69% of the overall territory, while the 5.58% of the analyzed area is covered by urban and industrial infrastructure. These regions, mainly located in the Nile Delta area (Fig 5.2.17), were therefore scored 4 and 5 respectively, according to land use classification proposed in the CVI (Table 4.3, Section 4.2.3). Only the 0.29% of the territory hosts natural/grasslands areas. Finally, forest ecosystem has not been observed throughout the entire Mediterranean coast of Egypt.

Score	Classes	Km²
1	Water bodies, marsh/bog and moor, sparsely vegetated areas	4084.37
2	Natural, grasslands, coastal areas	13.80
3	Forest	/
4	Agriculture	415.61
5	Urban and industrial infrastructure	266.59

a)



b)

Figure 5.2.18 **-** Distribution of the territorial surface (km^2) a) and of the percentage of surface b) associated with each vulnerability class for land cover indicator.

Land cover data were retried by the Global Land Cover 2000 (GLC 2000) project which adopt the European CORINE land cover classification (see Table 4.3, Section 4.2.3).

5.3 Index calculation.

Once vulnerability scores (1 to 5) were assigned to each of the selected indicators, the coastal vulnerability index was calculated using Equation 1 (Paragraph 4.3) for both the baseline and future timeframe scenarios.

Figure 5.3.1 shows the CVI map developed for the RCP8.5 climate change scenario in the timeframe (2010-2050). It displays the CVI score, which ranges from 2 to 433.

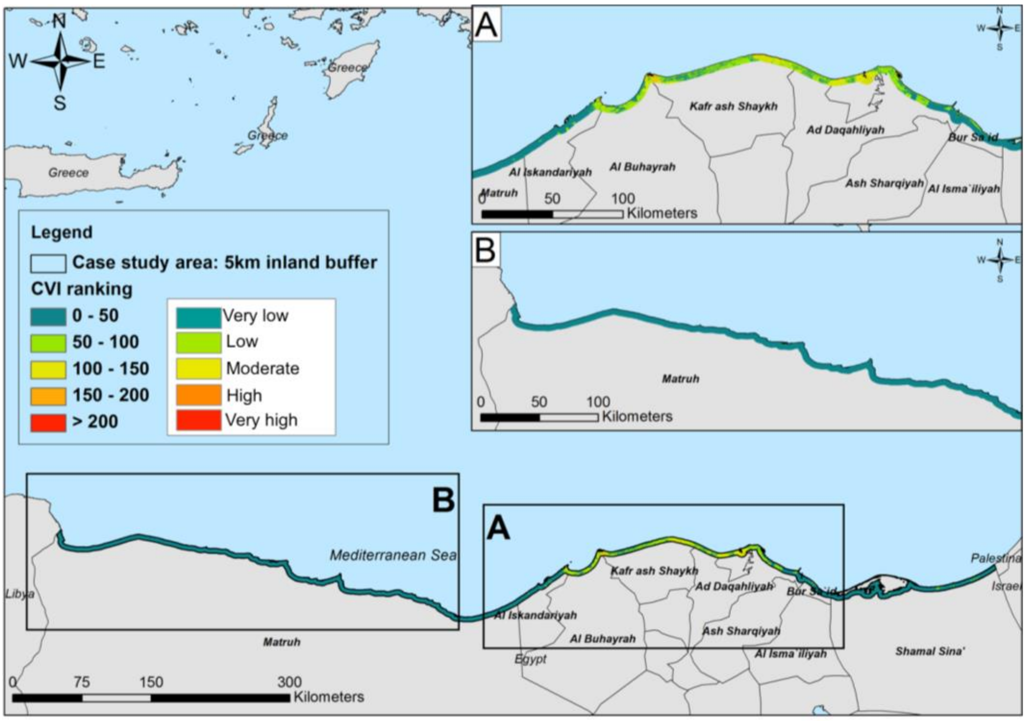


Figure 5.3.1 **–** Map of the resulting CVI score for the case study region, showing the governorates along the Mediterranean seacoast.

The CVI output, were first classified in 4 classes equal in size, in order to better visualize moderate values of CVI ranging from around 2 to 200. Then, a separate class was defined for the higher CVI values, restricted in small areas of the case study (e.g. Rosetta and Damietta), in a unique class ranging from 200 to the maximum value equal to 433.

The results show that Nile Delta (Fig. 5.3.1A) is the area more prone to the impacts of coastal erosion and permanent/occasional inundations compared to the rest of the coastline. In fact, the Nile Delta region is a lowland sandy coast which hosts several human activities (agricultural and industrial) that make this area particularly vulnerable to the potential damages associated with permanent/occasional inundations and erosion.

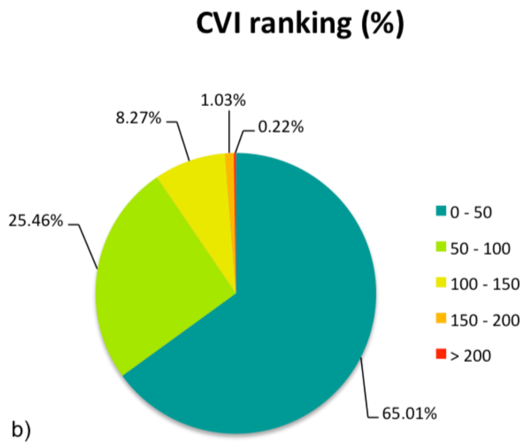
The area of the Western Desert, instead, even if characterized by moderate wave heights, higher than the other coastal segments, is characterized by lower vulnerability scores mainly due to its geological features (i.e. rocky/cliffed coasts, steeper coastal slope) (Fig. 5.3.1B).

Finally, in some coastal zones (near the Sinai Peninsula), even if all the geological indicators are characterized by relatively high vulnerability scores (from moderate to very high) the final CVI score is low due to the relatively low vulnerability of the land cover, the wave height and storm surge level.

Based on the coastal vulnerability map (Fig. 5.3.1), further relevant statistics were also calculated for the case study area. Therefore, Fig. 5.3.2 shows the territorial distribution (km^2) and the percentage (%) of the Egypt's coastline surface in each vulnerability category.

Score	Classes	Km^2
1	0 - 50	1773.66
2	50 - 100	694.71
3	100 - 150	225.53
4	150 - 200	28.14
5	> 200	6.11

a)



b)

Figure 5.3.2 - Distribution of the territorial surface (km^2) a) and the percentage of surface b) associated with each score of the coastal vulnerability index for the case study region.

Only the 1.03% percent of the mapped shoreline is classified as highly vulnerable to inundation or erosion. Whereas, a relevant percentage (≅65%) of the total surface belongs to very low vulnerability classes, followed by the 25.5% of the territory classified with low vulnerability. Finally, the 8.27% is classified as moderately vulnerable.

Fig 5.3.3 shows the distribution of vulnerability scores (1 to 5) for the eight Egyptian governorates located along the Mediterranean seacoast (Fig. 5.3.1).

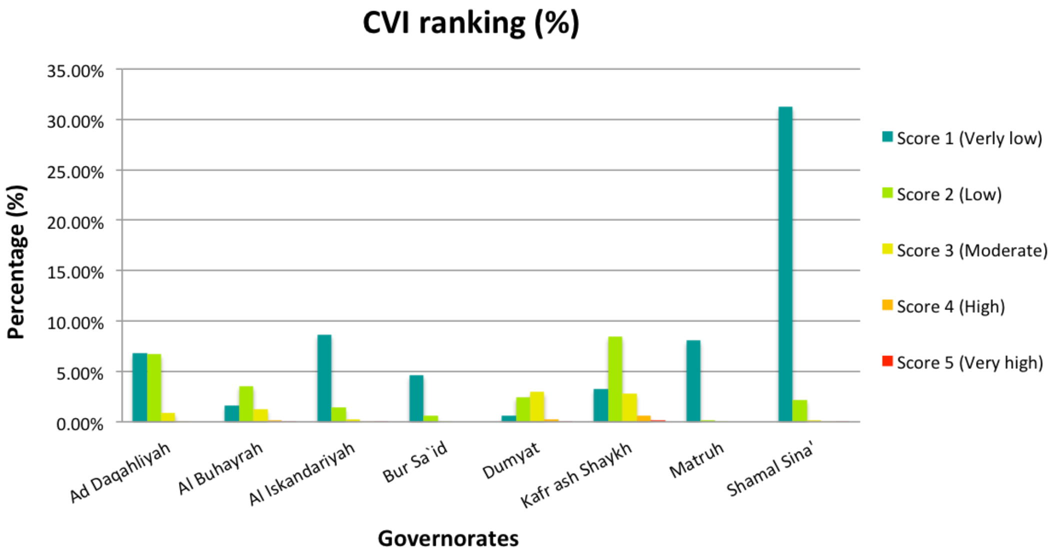


Figure 5.3.3 – Distribution of CVI scores for Egypt's governorates located along the Mediterranean seacoast.

Overall, the bar graph highlights that the majority of governorates are characterized by very low and low vulnerability classes. Particularly, Shamal Sina' is the governorate with the relatively low vulnerability, with almost the total surface in vulnerability class 1. While, Dumyat and Kafr ash Shaykh (near the Nile river Delta) have the relatively higher percentages of the coastline in the moderate vulnerability class (Fig. 5.3.3). However, the other governorates present relatively low percentages of the territory in the higher vulnerability classes (from 3 to 5).

Finally, it is important to remark that the total CVI score assumed the same values (minimum and maximum) for the two investigated time frame periods (baseline and future). In fact, values of SLR and SSL result to be very similar under the baseline and the future scenarios. In addition, projected SSL shows minimal changes or even a small decreasing trend. This tendency can be explained considering that the future scenario (2021–2050), does not record remarkable climate-related changes, which, instead, can be observed after the second half of the century (IPCC, 2014).

The CVI presented in this thesis allows to relate together physical, geological and socio economic variables in a quantifiable way, which leads to identify the relative vulnerability of the analyzed coastline to inundation and erosion. Even if it was not possible to consider the indicators representing the critical energy infrastructure, as suggested in the methodology explanation (Chapter 4), the results highlight relevant information about the physical and environmental impacts that can occur on the shoreline, considering future climate change scenarios, and can be used to provide some preliminary considerations on the potential impacts and adaptation options for the energy infrastructures exposed in the region.

Therefore, the following section is aimed at presenting the potential impacts caused by climate variations on the O&G facilities and/or operations (i.e. from the extraction to the distribution and delivery processes) and possible adaptation/mitigation options that could be implemented into the business approach of O&G companies.

5.4 Overview of adaptation and mitigation options for the O&G industry.

As described in Chapter 2. State-of-the-art of available indicators measuring the effects of climate hazards on O&G exposed systems., climate change could determine increased rates of sea level rise and variations in the frequency and severity of extreme wave and storm surge events, posing a serious threat on coastal O&G facilities and operations. Moreover, most of the reviewed studies (Chapter 1) agree that O&G facilities/processes located in low-lying coastal areas are particularly vulnerable to climate related hazards.

Therefore, the energy companies are increasingly asking for information about the potential impacts of climate change on O&G facilities in order to underpin the definition of adaptation strategies.

Overall, company's business plan should include adequate contingency planning, emergency-response and recovery planning to be well prepared against climate change impacts in order to ensure the safety of the environment and the O&G facilities/operations as well (Acclimatise, 2009).

As reported by Cruz & Krausmann (2013) "*adaption measures include, for example, improvements in engineering design and construction methods and materials, regular maintenance and monitoring of infrastructure conditions, and improved planning and preparations for service delays or cancellations*".

In fact, new plant and equipment design standards could be required in order to be prepared against the occurrence of extreme weather events. In addition, it could be also necessary to upgrade existing design criteria of O&G facilities/equipment for more adequate response and recovery planning (Cruz & Krausmann, 2013; Acclimatise, 2009).

The comparison between the outputs of the CVI application (Fig. 5.3.1) and the O&G concession map (Fig. 3.2.2), confirms that the Nile Delta is the more vulnerable area to the future impacts of the considered climate-related hazards (i.e. coastal inundation and erosion). Moreover, this region is characterized by a relevant presence of inland O&G assets, therefore, it is essential to increase the awareness of energy companies about the potential risks and adaptation strategies that could be required.

For example, storm surge events can flood oil drilling and production platforms causing structural damages as well as disruption of onshore support facilities (Burkett, 2011). In addition, coastal drilling and production platforms, as well as onshore support facilities, can be also damaged due to the increasing of wave heights/loads (Burkett, 2011).

Figure 5.4.1 – Example of exposed pipeline. Source: http://www.dailynewsegypt.com/2014/10/20/egypt-israel-gas-deal-wont-happen-without-states-approval-petroleum-ministry/

For what concerns pipelines (Fig.5.4.1), which are generally employed to transport crude oil and natural gas, they seems to be particularly vulnerable to the effects of wave action especially in areas where significant subsidence occurs (Burkett, 2011).

Furthermore, the increasing rate at which sea level is rising may limit their accessibility and the proper use of valves during operations activities (https://www.fhwa.dot.gov/environment/climate_change/adaptation/ongoing_and_current_research/gulf_coast_study/phase2_task3/task_3.1/page06.cfm).

Finally, storm surge flooding can expose buried pipelines by eroding the surrounding land, particularly in the case study area where soil erosion may represent a greater issue (Cruz & Krausmann, 2013).

Figure 5.4.2 – Example of oil refinery located in the Nile Delta region. Source: http://quality-macs.com/projects/

Whereas, oil refineries (Fig. 5.4.2) are prone to sea level rise and extreme storm surge events, since they are generally located at or near the coastline (e.g. less than 3m above the high tide line) (Carlson et al., 2015).

In fact, coastal erosion and inundations may cause more frequent disruption events to refining operation processes (e.g. reduced refining utilization rates, flooding of electrical equipment, power failure) (Carlson et al., 2015; (Cruz & Krausmann, 2013).

Finally, transport facilities (e.g. ports, roads, highway, rails) can also be affected by climate related impacts. For instance, inundation of coastal areas can cause loss of transportation routes and foundations of onshore assets (Cruz & Krausmann, 2013; Burkett, 2011).

Considering the complex nature of the envisaged impacts in the coastal zone, the conflicts of uses for the limited coastal space and the long-term implications of climate change, the definition of coastal adaptation strategies should involve multiple actors: public (national, regional and local) management authorities, private companies (including O&G businesses) and the local stakeholders (e.g. non-governmental organizations, environmental associations).

Hereafter some examples of broad adaptation responses that can be applied by governmental bodies to manage the risks related to inundation and erosion in the coastal zone are proposed (Ramieri et al. 2011; CoastAdapt, 2016):

1. avoidance
2. managed retreat
3. accommodation or limited intervention
4. hold the line
5. do nothing

'Avoidance' measures do not allow the development of new private/public infrastructures/assets without robust planning strategies in vulnerable coastal zones. Moreover, they could include higher standards for public concessions, to ensure

more resilient/adaptive industrial facilities such as buildings with piled construction (CoastAdapt, 2016). The *'managed retreat'* strategies encourage local stakeholders to relocated existing structures highly vulnerable to climate hazards (CoastAdapt, 2016). Whereas, accommodation/limited intervention options can be aimed at distributing funds for redeveloping existing urban/industrial areas to minimize impacts caused by erosion/inundations (CoastAdapt, 2016). *'Hold-the-line'* measures are proactive measures that consist on building defensive structures (e.g. barriers, dikes) for protecting existing and future development and threatened habitats/infrastructures. Finally, '*do-nothing'* options means that no adaptation/mitigation plans are considered, because the envisaged risks are deemed acceptable (i.e. do not exceed the tolerance threshold) (CoastAdapt, 2016).

As far as O&G companies are concerned, they should integrate coastal vulnerability and adaptation information to: improve strategic investments decisions (e.g. the choice of new areas suitable for the energy facilities); adapt the design of new infrastructures to future climate change scenarios; manage the predicted risks on existing infrastructures.

Some adaptation options (e.g. waterproofing of buildings/equipment and elevation of facilities/processes based on sea-level rise and storm surge projections) can be applied to protect the energy assets functionality from coastal flooding (Cruz & Krausmann, 2013).

Furthermore, there are also a set of strategies that could be adopted at project level stage in order to increase assets' resilience of both existing and future infrastructure: huge investments to upgrade facilities/equipment; selection of the most appropriate location for assets; the implementation of emergency protocols for protecting critical infrastructures/operation from climate change and extreme weather events (Acclimatise, 2009; IPIECA, 2013).

Even if the proposed options should match the specific objectives of the O&G company, it is important to consider any opportunities that might come from the selected adaptation strategies and any co-benefits that can be achieved (CoastAdapt, 2016). Therefore, a strict cooperation with relevant stakeholders (e.g. coastal policy authorities, O&G companies) is envisaged for the selection of the more relevant risks to be addressed, the retrieval of missing information for vulnerability assessment, and the selection of the more suitable adaptation option to be adopted.

To conclude, the proposed CVI is a screening (first-level assessment) tool that can be used to identify more vulnerable regions where a more detailed vulnerability assessment could be required. A comprehensive assessment should be performed in order to define all the relevant climate-related issues that need to be addressed, assess the vulnerability of critical energy infrastructure based on local information, and take appropriate measures to prevent, mitigate and prioritize any potentially negative effects deriving from climate changes.

6. Conclusions.

The thesis was aimed at the assessment of the potential impacts of climate change on the O&G facilities and infrastructures. Specifically, the thesis focused on the development of a CVI methodology for the assessment of key risks and vulnerabilities related to climate change in the Mediterranean seacoast of Egypt. The proposed methodology can be used to: consider climate change emission scenario for sea level rise and storm surge levels; identify and prioritize those areas along the coastline highly vulnerable to inundation or erosion; localize the critical infrastructure exposed to the coastal hazards (e.g. industrial areas, O&G infrastructures/item) and assess their vulnerability.

Due to data constraints, the CVI values calculated for the case study area basically reflects the physical and geological vulnerability of the considered coastline. However, the results capture the potential exposure of human activities (e.g. industrial areas) to inundation and erosion, and were used to provide some preliminary considerations about potential impacts and adaptation strategies for the O&G sector.

In line with recent results obtained from the application of coastal vulnerability indexes in Mediterranean coastal areas (Hereher, 2015; Satta et al., 2015; Torresan et al., 2016) the proposed approach does not attempt to provide absolute predictions about the impacts of climate change; rather, it is aimed at supporting semi-quantitative evaluation and relative ranking of areas and targets potentially affected by both climate-related pressures.

The elaboration with Geographic Information Systems (GIS) tools allowed a detailed analysis of the results and the estimation of several indicators and statistics for the analyzed parameters (e.g. km^2/percentage of the territory distribution in each vulnerability class).

The strength of the proposed methodology is represented by the possibility to integrate a broad number of physical, geological, socio-economic and infrastructure-specific parameters into the final CVI equation. Moreover, differently from the majority of CVI applications that are usually based on the analysis of past data, future climate change scenarios for sea level rise and storm surge were processed and employed as input data in the assessment. This, in turn, makes the approach flexible to be applied in different coastal regions and for multiple climate and timeframe scenarios. Hence, the results of this study could be improved considering further climate change scenarios (e.g. using the outputs coming from different climate models) and extending the analysis to longer timeframe periods (e.g. 2070-2100), in order to provide an estimate of the uncertainty associated to the effect of climate change that is a relevant information for planning and management purposes.

Moreover, the CVI approach can be easily up-scaled to evaluate the consequences of climate-related impacts at a broader regional scale, as well as down-scaled by using more detailed datasets for the characterization of coastal vulnerability (e.g. high resolution data, information about the energy infrastructures/item, localization of the O&G facilities). Finally, the proposed approach can also be in principle applied to other receptors of interest for the stakeholders (e.g. offshore platforms).

Overall, the methodology outputs (i.e. vulnerability maps, statistics for the analyzed parameters) can be considered as a first-pass assessment for the spatial identification of areas and consequently targets at higher risk from inundation and erosion events.

Nonetheless, the developed methodology and the resulting outputs, present some limitations mainly due to the difficulty to retrieve specific indicators and vulnerability thresholds for different types of energy facilities, and to the coarse available data used to characterize the geological indicators (e.g. 30m DEM, geomorphology, sediment budget). Higher spatial resolution and high vertical accuracy datasets would be required to provide a better estimate of coastal vulnerability to inundation and erosion processes. For overcoming this gap, a more fruitful participation of relevant stakeholders in the case study area is envisaged in order to: integrate the specific knowledge about existing threats, past/observed hazards or vulnerability; select and localize the critical energy infrastructures at risk; characterize their vulnerability according to the standards applied in the specific projects' design.

Finally, the complexity of the problem at hand, should consider the significance (prioritization) of the vulnerability assessment process based on the stakeholders' perceptions and knowledge of the specific system at risk (i.e. the O&G facilities and operations), aimed at creating a product tailored to the stakeholders' requests and that could be easily incorporated into the business approach of O&G companies.

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ANNEX I

Table 1: Overview of climate change pressures, indicators and impacts for coastal and offshore O&G development.

Climatic pressures	Indicator (units)	Impacts		References
		Physical and Environmental	Oil and Gas assets	
Atmospheric Temperature	Average temperature (degree centigrade)	- Increased fire risk; - Decline in sea ice and thaw of permafrost.	- Reduced efficiency and performance of power plants and water-cooling; - Increased operational costs for cooling water; - Effects on plant design and operation requirements; - Maintenance problems for transportation assets; - Disruption and delay of O&G distribution and production; - Possibility of extension of fire risk in operational sites located in fire prone areas; - Loss of transportation routes and foundations of onshore assets in the Artic region.	- Burkett, 2011; - Cruz & Krausmann, 2013; - Dyke, 2001; - Firth, 2009;
Precipitation	Average changes of precipitation and precipitation intensity (mm/year; mm/day)	- Increased risk of flooding and landslides; - Increased risk of drought; - Reduced river runoff.	- Reduced fresh water availability; - Poorer water quality and increased costs for water treatments; - Increased flood risk for assets and transportation routes located in coastal areas and on river floodplains; - Disruption and delay of operational/production/distribution processes; - Drainage systems can be compromised; - Increased restrictions of O&G production in coastal areas.	- Burkett, 2011; - Cruz & Krausmann, 2013; - IPCC, 2014; - Nicholls et al., 2007; - Puig et al., 2015; - USGCRP, 2009;

Climatic pressures	Indicator (units)	Impacts		References
		Physical and Environmental	Oil and Gas assets	
Wind	Speed (m/s)	- Increased high wind; - Increased risk of wind storm; - Increased risk of fire.	- Disruption and black out of onshore plants and electric power systems; - Disruption and delay of O&G distribution; - Structural damage to onshore and offshore infrastructures and equipment; - Increased work related injury.	- Doyonemerland & ABS Consulting, 2009; - Puig et al., 2015
Sea Level Rise (SLR) Storm surge	Heights (m) Height (m) Return period (years)	- Increased risk of coastal flooding; - Increased risk of coastal erosion/loss of land; - Increased risk of saltwater intrusion.	- Increased flood risk for O&G assets located in low-lying land; - Increased risk for offshore facility operation and design processes; - Disruption of supply chain and logistic systems; - Damage to infrastructure items, building and ports. - Loss/opens of navigation routes. - Reduced freshwater availability.	- Brown et al., 2014; - Burkett 2011; - Bradbury et al. (2015); - Carlson et al., 2015; - Firth, 2009; - Doyonemerland and ABS Consulting (2009); - IPCC, 2012; IPCC, 2013; - U.S. Department of Energy, 2013) - Vousdoukas et al., 2016
Wave	Wave Heights (m) Wave Energy ((N/m^2) Return period (years)	- Increased risk of more intense tropical storms; - Increased risk of hurricanes; - Subsiding areas will be more vulnerable to higher wave heights.	- Increased risk for operation and design systems; - Disruption and delay of assets operations and supply chain process; - Damage to structural integrity of platforms/ports; - Damage to offshore pipelines and related equipment; - Increased risk of oil spills; - Loss/opens of navigation routes.	- Bitner-Gregersen and Gramstad, 2009; - Burkett, 2011; - CCSP, 2008; - Cruz & Krausmann, 2013; - Firth, 2009; - Stone et al, 2003) - U.S. Department of Energy, 2013;
Current	– Direction (°N);		- Damage to offshore platforms and pipelines.	- Doyonemerland and

Climatic pressures	Indicator (units)	Impacts		References
		Physical and Environmental	Oil and Gas assets	
	– Velocity (m/s)			ABS Consulting, 2009
Ocean Temperature; CO_2; acidity; salinity	- Changes in temperature (°C) - CO_2 concentration - pH	- Changes in flora and fauna; - Poorer water quality; - Changes in sea surface temperature; - Extensive algal bloom.	- Damage to exploration and development systems; - Increased corrosion.	- Andersson et al., 2003 - Burkett, 2011 - Short and Neckles, 1999

ANNEX II

Table 1 **–** Sea level rise future projection under the RCP4.5 and 8.5 for the mid and the long term time frame periods (2021-2050 and 2041-2070) in the case study region (http://www.orientgateproject.org/indicator.php?id=36).

EMISSION SCENARIOS	TIME FRAME	STATISTIC	MEAN m	MIN m	MAX m	SD m	VAR m
RCP 4.5	2021 - 2050	MEAN	0.098	0.097	0.100	0.001	8.88E-07
		MEDIAN	0.091	0.090	0.094	0.001	2.23E-06
		MINMAX	0.462	0.448	0.490	0.016	2.44E-04
		PCT	0.253	0.248	0.262	0.005	2.03E-05
	2041 - 2070	MEAN	0.190	0.190	0.192	0.001	6.46E-07
		MEDIAN	0.190	0.189	0.192	0.001	7.83E-07
		MINMAX	0.506	0.490	0.533	0.017	2.99E-04
		PCT	0.333	0.326	0.348	0.008	6.28E-05
RCP 8.5	2021 - 2050	MEAN	0.107	0.107	0.108	0.000	1.19E-07
		MEDIAN	0.091	0.090	0.094	0.001	2.23E-06
		MINMAX	0.408	0.399	0.424	0.010	1.09E-04
		PCT	0.260	0.255	0.270	0.006	3.51E-05
	2041 - 2070	MEAN	0.190	0.190	0.192	0.001	6.46E-07
		MEDIAN	0.190	0.189	0.192	0.001	7.83E-07
		MINMAX	0.549	0.537	0.579	0.014	2.00E-04
		PCT	0.379	0.372	0.392	0.007	4.42E-05

Table 2 **–** Projection of extreme storm surge level along the Mediterranean coast of Egypt for the mid period (2010-2040) under the two RCPs (4.5 and 8.5) considering eight return periods (RP 5, 10, 20, 50, 100, 200, 500 and 1000 (http://data.jrc.ec.europa.eu/collection/LISCOAST).

EMISSION SCENARIOS	RETURN PERIOD	MEAN m	MIN m	MAX m	SD m	VAR m
RCP 4.5	RP5	1.15	0.44	1.62	0.33	0.11
	RP10	1.18	0.45	1.65	0.34	0.11
	RP20	1.21	0.47	1.69	0.35	0.12
	RP50	1.25	0.48	1.72	0.36	0.13
	RP100	1.28	0.49	1.75	0.37	0.13
	RP200	1.31	0.50	1.78	0.37	0.14
	RP500	1.35	0.52	1.82	0.38	0.15
	RP1000	1.38	0.53	1.86	0.39	0.15
RCP 8.5	RP5	1.16	0.43	1.63	0.32	0.10
	RP10	1.19	0.44	1.66	0.33	0.11
	RP20	1.22	0.45	1.69	0.34	0.11
	RP50	1.26	0.46	1.73	0.35	0.12
	RP100	1.28	0.48	1.76	0.36	0.13
	RP200	1.31	0.49	1.79	0.36	0.13
	RP500	1.34	0.50	1.83	0.37	0.14
	RP1000	1.37	0.51	1.85	0.38	0.14

ANNEX III

Table 1 – Classification of SSL points along the Mediterranean seacoast of Egypt for the baseline period (1970-2000), considering different return periods (RP5, 10, 20, 50 and 100).

LAT	LONG	SSL RP5	SSL RP10	SSL RP20	SSL RP50	SSL RP100	MAX VALUE SSL	SCORE
		m	m	m	m	m		
32.1	25.1	1.637	1.670	1.701	1.739	1.765	1.765	**3**
31.7	25.3	1.302	1.324	1.347	1.376	1.398	1.398	**2**
31.9	25.3	0.896	0.915	0.933	0.957	0.975	0.975	**1**
31.7	25.5	1.426	1.451	1.474	1.504	1.524	1.524	**2**
31.7	25.7	1.465	1.495	1.523	1.559	1.585	1.585	**2**
31.7	26.1	1.564	1.596	1.626	1.665	1.693	1.693	**3**
31.7	26.3	0.830	0.849	0.865	0.885	0.899	0.899	**1**
31.7	26.5	1.462	1.499	1.535	1.581	1.614	1.614	**3**
31.7	26.7	1.307	1.340	1.372	1.414	1.445	1.445	**2**
31.7	27.1	1.513	1.558	1.601	1.653	1.690	1.690	**3**
31.5	27.3	1.272	1.295	1.318	1.345	1.365	1.365	**2**
31.5	27.5	0.999	1.019	1.038	1.062	1.079	1.079	**2**
31.3	27.7	0.538	0.554	0.567	0.581	0.590	0.590	**1**
31.5	27.9	0.930	0.947	0.963	0.983	0.999	0.999	**1**
31.3	28.1	0.592	0.607	0.621	0.638	0.650	0.650	**1**
31.3	28.3	1.255	1.279	1.302	1.332	1.354	1.354	**2**
31.3	28.7	0.633	0.650	0.664	0.680	0.690	0.690	**1**
31.1	28.9	0.954	0.979	1.003	1.032	1.052	1.052	**2**
31.1	29.1	0.439	0.452	0.463	0.476	0.485	0.485	**1**
31.1	29.3	0.554	0.569	0.583	0.599	0.611	0.611	**1**
31.1	29.5	1.255	1.283	1.310	1.342	1.366	1.366	**2**
31.3	29.7	0.522	0.537	0.550	0.564	0.574	0.574	**1**
31.5	29.9	0.469	0.484	0.496	0.510	0.519	0.519	**1**
31.5	30.1	1.428	1.469	1.507	1.554	1.586	1.586	**2**
31.7	30.3	1.464	1.511	1.553	1.603	1.636	1.636	**3**
31.7	30.5	1.448	1.493	1.534	1.582	1.614	1.614	**3**
31.7	30.9	1.448	1.487	1.521	1.560	1.586	1.586	**2**
31.7	31.1	1.345	1.383	1.417	1.457	1.484	1.484	**2**
31.7	31.3	1.271	1.309	1.344	1.385	1.412	1.412	**2**
31.7	31.5	1.344	1.381	1.415	1.456	1.486	1.486	**2**
31.7	31.9	1.371	1.414	1.455	1.504	1.539	1.539	**2**
31.7	32.1	1.304	1.344	1.382	1.432	1.468	1.468	**2**
31.5	32.3	1.267	1.313	1.357	1.411	1.451	1.451	**2**
31.5	32.5	1.017	1.042	1.066	1.096	1.118	1.118	**2**
31.3	32.7	1.317	1.368	1.413	1.466	1.501	1.501	**2**
31.3	32.9	1.356	1.412	1.462	1.521	1.560	1.560	**2**
31.5	33.1	1.289	1.326	1.361	1.404	1.435	1.435	**2**

LAT	LONG	SSL RP5	SSL RP10	SSL RP20	SSL RP50	SSL RP100	MAX VALUE SSL	SCORE
		m	m	m	m	m		
31.3	33.3	1.307	1.357	1.403	1.457	1.494	1.494	**2**
31.3	33.5	1.259	1.311	1.359	1.416	1.456	1.456	**2**
31.3	33.9	1.179	1.230	1.277	1.336	1.378	1.378	**2**
31.5	34.1	1.163	1.208	1.253	1.312	1.357	1.357	**2**
31.7	34.3	0.950	0.978	1.005	1.040	1.066	1.066	**2**

Table 2 – Classification of SSL points along the Mediterranean seacoast of Egypt under the RCP8.5 emission scenario for the mid timeframe period (2010-2040), considering different return periods (RP5, 10, 20, 50 and 100).

LAT	LONG	SSL RP5	SSL RP10	SSL RP20	SSL RP50	SSL RP100	MAX VALUE SSL	SCORE
		m	m	m	m	m		
31.1	28.9	0.999	1.023	1.047	1.076	1.098	1.098	**2**
31.1	29.1	0.428	0.440	0.451	0.465	0.475	0.475	**1**
31.1	29.3	0.569	0.583	0.597	0.614	0.626	0.626	**1**
31.1	29.5	1.276	1.304	1.330	1.363	1.387	1.387	**2**
31.3	27.7	0.522	0.536	0.548	0.562	0.572	0.572	**1**
31.3	28.1	0.608	0.621	0.634	0.650	0.662	0.662	**1**
31.3	28.3	1.274	1.298	1.321	1.351	1.373	1.373	**2**
31.3	28.7	0.646	0.662	0.676	0.693	0.704	0.704	**1**
31.3	29.7	0.537	0.550	0.563	0.578	0.590	0.590	**1**
31.3	32.7	1.302	1.355	1.403	1.460	1.499	1.499	**2**
31.3	32.9	1.363	1.421	1.473	1.534	1.576	1.576	**2**
31.3	33.3	1.295	1.348	1.398	1.457	1.497	1.497	**2**
31.3	33.5	1.255	1.309	1.359	1.420	1.463	1.463	**2**
31.3	33.9	1.180	1.232	1.281	1.342	1.385	1.385	**2**
31.5	27.3	1.285	1.308	1.330	1.360	1.381	1.381	**2**
31.5	27.5	1.019	1.040	1.060	1.085	1.104	1.104	**2**
31.5	27.9	0.905	0.921	0.937	0.958	0.974	0.974	**1**
31.5	29.9	0.474	0.487	0.499	0.514	0.525	0.525	**1**
31.5	30.1	1.434	1.474	1.512	1.559	1.593	1.593	**2**
31.5	32.3	1.254	1.297	1.337	1.385	1.419	1.419	**2**
31.5	32.5	1.033	1.060	1.086	1.119	1.143	1.143	**2**
31.5	33.1	1.294	1.331	1.368	1.414	1.447	1.447	**2**
31.5	34.1	1.173	1.217	1.261	1.320	1.366	1.366	**2**
31.7	25.3	1.257	1.279	1.301	1.329	1.349	1.349	**2**
31.7	25.5	1.372	1.397	1.421	1.453	1.477	1.477	**2**
31.7	25.7	1.466	1.495	1.522	1.555	1.578	1.578	**2**
31.7	26.1	1.567	1.598	1.625	1.658	1.681	1.681	**3**
31.7	26.3	0.840	0.857	0.874	0.897	0.914	0.914	**1**
31.7	26.5	1.461	1.498	1.535	1.585	1.623	1.623	**3**
31.7	26.7	1.316	1.348	1.379	1.422	1.455	1.455	**2**

LAT	LONG	SSL RP5	SSL RP10	SSL RP20	SSL RP50	SSL RP100	MAX VALUE SSL	SCORE
		m	m	m	m	m		
31.7	27.1	1.520	1.564	1.607	1.660	1.700	1.700	**3**
31.7	30.3	1.465	1.512	1.554	1.605	1.640	1.640	**3**
31.7	30.5	1.450	1.494	1.534	1.583	1.617	1.617	**3**
31.7	30.9	1.439	1.478	1.514	1.555	1.582	1.582	**2**
31.7	31.1	1.323	1.362	1.397	1.440	1.469	1.469	**2**
31.7	31.3	1.257	1.295	1.330	1.370	1.398	1.398	**2**
31.7	31.5	1.326	1.361	1.392	1.427	1.451	1.451	**2**
31.7	31.9	1.354	1.397	1.438	1.488	1.523	1.523	**2**
31.7	32.1	1.296	1.334	1.370	1.417	1.451	1.451	**2**
31.7	34.3	0.975	1.003	1.031	1.068	1.097	1.097	**2**
31.9	25.3	0.912	0.929	0.946	0.969	0.986	0.986	**1**
32.1	25.1	1.626	1.660	1.692	1.733	1.762	1.762	**3**

ANNEX IV

Table 1 **-** Mean tidal range for the seaport of Egypt along the Mediterranean Sea.

Port	Longitude	Latitude	Tidal range
Alexandria	Long 29°49/E	Lat 31°08/N	0.40m
Dekheila	Long 29°49/E	Lat 31°08/N	0.40m
Abu Qir	Long 30°40/E	Lat 31°19/N	0.40m
Damietta	Long 31°48/E	Lat 31°23/N	0.61m
Port said	Long 32°18/E	Lat 31°15/N	0.3m
Arish	Long 33°49/E	Lat 31°09/N	0.65m