NUI MAYNOOTH

Ollscoil na hÉireann Má Nuad

Coastal vulnerability assessment of Co. Dublin and Co. Wicklow to impacts of sea-level rise

Silvia Caloca-Casado

Thesis submitted in fulfilment of the requirements for the degree of Ph.D.

Irish Climate Analysis and Research Units & Environmental Geophysics Unit

Department of Geography, National University of Ireland, Maynooth

August 2018

ICARUS Irish Climate Analysis and Research Units

Environmental Geophysics Unit

Joint supervisors: Emeritus Prof. John Sweeney & Dr. Paul Gibson

Head of Department: Prof. Gerry Kearns

Table of Contents

List of Figures

List of Plates

List of Equations

Abstract

This research identified the coastal areas of Counties Dublin and Wicklow most vulnerable to impacts of sea-level rise through the analysis of various indicators to provide an index-based assessment. Future vulnerability to potential impacts was also investigated.

A primary challenge in understanding coastal exposure to water-level change was quantifying the important characteristics that make it susceptible to change over the next century. The bulk of the work comes from identification, compilation and quality control of indicators of coastal change, which in this area were found to be regional coastal slope, aspect, geomorphology, cliff type, mean tidal range, shoreline changes, mean significant wave height and relative sea-level rise. A case study to complement shoreline change evaluation was also carried out in south Co. Dublin using multi-temporal digital elevation models to assess volumetric changes on highly responsive, soft unconsolidated cliffs.

High resolution 2D mapping was conducted from two CVI indexed-based maps using six and eight variables. The map showed levels of vulnerability from low to high assigned to different segments depending on their potential susceptibility to physical changes as water levels rise (exposure, sensitivity and adaptive capacity). The CVI showed that high vulnerability areas predominate in the southern areas from Arklow to Greystones. PCA analysis identified the main contributions as coming from cliff type and geomorphology, followed by wave and tidal range and lastly slope, and aspect, with minor contributions from shoreline change.

Future sea level scenarios were derived from local, regional and global trends. A likely scenario showed estimates between 78 and 127cm. An upper limits projection of sea-level rise of 198cm for 2100 was derived for the worst case scenario. These estimates were used to asses the exposure of area to potential flooding when combining tide-surge water levels with local projected sea-level for 2040, 2060, 2080 and 2100. Maximum extreme water levels of 5.76m (0.5% AEP) and 5.67m and 5.58m OD Malin (1% and 2% AEP), were found by 2100.

Two hotspots to the effects of future sea-level rise and storminess were identified in North Dublin (Bull Island and Sutton) and Wicklow from both current and future vulnerability assessments.

A consistent methodology, within a well-defined conceptual framework and the development of a robust specific metric and accuracy of data, was crucial. Adapted methodologies used in this research provide a reference for future development of Irish coastal vulnerability maps nationwide. The work will enable policy makers and stakeholders to easily identify vulnerable areas and target investment for adaptation within realistic timeframes.

To my wonderful family, especially to my father Santiago, daughter Amaia and partner Xavi

Thanks

Acknowledgements

First of all I would like to thank my two supervisors Prf. John Sweeney and Dr. Paul Gibson for their support and mentoring all these years and for their assistance during the research; in particular for taking the time and tedious effort of correcting and reading through this thesis.

I would also like to thank the Geological Survey of Ireland (GSI), especially Brian McConnell (section manager), and also Mary Carter, Monica Lee, and Koen Verbruggen (director) for allowing me to use GSI resources.

I would like to thank my colleagues in the Land Mapping Unit for their assistance, support and encouragement. I am also thankful to Julia Hall, a friend and former ICARUS graduate, for her technical advice and support.

I dedicate this PhD to the memory of my father Santiago Caloca whose example on enduring difficult moments guided me through the project. I would also like to thank my mother Maria Paz Casado and my sister Sandra for their unconditional support during my entire career and particularly during three postgraduate projects.

A very special mention goes to my new born baby Amaia and her father Xavi Monteys. I am grateful to my daughter for bringing so much joy to my life. To my partner Xavi for assisting, advising and dedicating time to comment on results, but above all for his continuous encouragement and support throughout this interesting period! Without him none of this would be possible.

List of Abbreviations

AEP	Annual exceedance probability
AOGCMs	Atmospheric Ocean Global Circulation Models
AR5/AR4	Fifth (Fourth) IPCC Assessment Report with regards to climate change
BGS	British Geological Survey
BN	Bayesian Networks
BP	Before Present
CCFVI	Coastal City Flood Vulnerability Index
CEVI	Coastal Economic Vulnerability Index
CD	Chart Datum
CFRAMs	Catchment Flood Risk Assessment and Management Studies
CFRMPs	Catchment Flood Risk Management Plans
CHERISH	Climate, Heritage and Environments of Reefs, Islands and Headlands
CMIP5	Coupled Model Intercomparison Project Phase 5
CO2	Carbon dioxide
CORINE	Co-ordinated Information on the Environment
CRI-MED	Coastal Risk Index Mediterranean
CVA	Community Vulnerability Assessment
CVAT	Community Vulnerability Assessment Tool
CVI	Coastal Vulnerability Index
CZM	CoastalZone Management
DATUM	A level surface, line or point used as a reference in measuring in elevation
DECLG	Department of Housing, Planning and Local Government
DEH	Department of Environmental Health
DESYCO	Decision support System for Coastal climate change impact assessment
DINAS-COAST	Dynamic and Interactive Coastal Vulnerability Assessment Project
DIVA	Dynamic Interactive vulnerability Assessment tool
DSAS	Digital Shoreline Analysis System
DTM	Digital Terrain Model
ECMWF	European Centre for Medium-Range Weather Forecasts
ECOPRO	Environmentally Friendly Coastal Protection Project
EEA	European Environment Agency
EMODnet	The European Marine Data and Observation Network
ENSO	El Niño–Southern Oscillation
EPA	Environmental Protection Agency
EPICA	European Project for Ice Coring in Antarctica
ERA	European Reanalysis

EUCOM/EC	European commission
EUROSION	European initiative for sustainable coastal erosion management
EPR	End Point Rate
FUND	Framework for Uncertainty, Negotiation and Distribution
GCM	Global Climate Models
GIS	Geographical Information Systems
GEUS	Geological Survey of Denmark and Greenland
GMSL	Global Mean Sea Level
GSM	Geomorphic Stability Mapping
GSI	Geological Survey of Ireland
HADCM	Hadley Centre Coupled Model
HAT	Highest Astronomical Tide
IAE	Irish Academy of Engineering
ICPSS	Irish Coastal Protection Strategy Study
ICZM	Integrated Coastal Zone Management
IG	Irish National Grid
INFOMAR	Integrated Mapping for Sustainable Development of Ireland's Marine
IPCC	Intergovernmental Panel on Climate Change
IPCC WGI	Intergovernmental Panel on Climate Change Working Group
IQR	Inter Quantile Range
ISDR	International Strategy for Disaster Reduction
ITM	Irish Transverse Mercator (ITM)
LAT	Lowest Astronomical Tide
LiDAR	Light Detection and Ranging
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MBES	Multi Beam Echo Sounder
MHWM	Mean high-water mark
MHWS	Mean High Water Springs
MLWM	Mean low-water mark
MLWS	Mean Low Water Springs
MODE	The value that appears most often in a set of date values
NCCAF	National Climate Change Adaptation Framework
NAG	North Atlantic Group
NASA	National Aeronautics and Space Administration
NAO	North Atlantic Oscillation
NOAA	National Oceanic and Atmospheric Administration
NOAA/ESRL	NOAA Earth System Research Laboratory
PCA	Principal Components Analysis
PC 1	First Principal Component

PDO	Pacific Decadal Oscillation
PMSL	Permanent Mean Sea Level
POL	Proudman Oceanographic Laboratory
POLPREDS	An offshore-based tidal computation and visualisation package
OD	Ordnance Datum
OPW	Office of Public Works
OSI	Ordnance Survey of Ireland
OSTM	Altimeters
PVI	Physical Vulnerability Index
Q1-Q3	Inter Quartile Range
r	Pearson’s correlation coefficient
RCMs	Regional Circulation Models
RCP’s	Representative Cumulative Pathways
RICE	Radius of influence to combined erosion and flood
RLR	Revised Local Reference
RLSR	Relative-Sea level rise
RMS	Root mean square, a measure of the magnitude of a varying quantity
RPS	Company involved in planning, design and engineering
RTK GPS	Real Time kinetics Global Positioning
RVA	Regional Vulnerability Assessment
RAV	Risk and Vulnerability assessment
SimCLIM	Software tool for assessing risks from Climate Change
SLCs	Sea-level changes
SLR	Sea-level rise
SRES	Special Report on Emissions Scenarios
SURVAS	Synthesis and Up-scaling of Sea-level Rise Vulnerability Assessment Studies
TE	Thermal Expansion
TOPEX	A satellite mission to map ocean surface topography
UNEP	The United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
USGCRP	The U.S. Global Change Research Program
USGS	United States Geological Survey
VORF	Vertical Offshore Reference Frames
WASA	Waves and Storms in the North Atlantic
WLR	Weighted Linear Regression
WMO	World Meteorological Organization

Chapter 1: Introduction

1.1. Introduction: Global Climate change

According to the philosopher Heraclitus *"Nothing is permanent but change"* and climate and coastal systems are no exceptions. Warming during the last 65 years, triggered by anthropogenic greenhouse gases, is being reflected in observed global changes. Our planet is experiencing changes in extreme and average global air and ocean temperatures, glaciers and ice sheets melting, ocean warming, sea-level rise and fluctuating wind patterns (IPCC, 2007; 2013). Although changes in climate patterns are occurring today, their effects may also be felt in the long term with unpredictable consequences. In addition, interaction between climatic change and natural variability will worsen effects on coastal systems involving coastal erosion, sea-level rise, wave attack, magnitude and frequency of storms/storm surges.

Anthropogenic atmospheric CO_2 is a major contribution to total radiative forcing producing atmospheric concentrations of CO_2 40% higher than pre-industrial levels. CO_2 emissions are translated into temperature increases within a decade. As a consequence, global average temperature has recently increased at an unprecedented rate of 0.2°C/decade (1.3°C last decade in Europe) (IPCC, 2013). Many areas of the eastern North Atlantic, Greenland, and Norwegian Seas are showing record high temperatures (NOAA, 2014).Sixteen of the seventeen warmest years have occurred in this century. The last decade (2001-2010) has been the warmest on record, with the last three decades being warmer than any preceding decade since 1850 (IPCC, 2013).The last three decades are possibly the warmest decades of the last 1,400 years for the Northern Hemisphere (Morice *et al*., 2012)**.** In particular, the period from 2004 to 2013 showed an increase of global mean surface temperature of 0.75°C. 2016 was the warmest year on record (NOAA, 2017) showing an average global surface temperature of 0.94°C above the 20^{th} century average (see Figure 1.1).

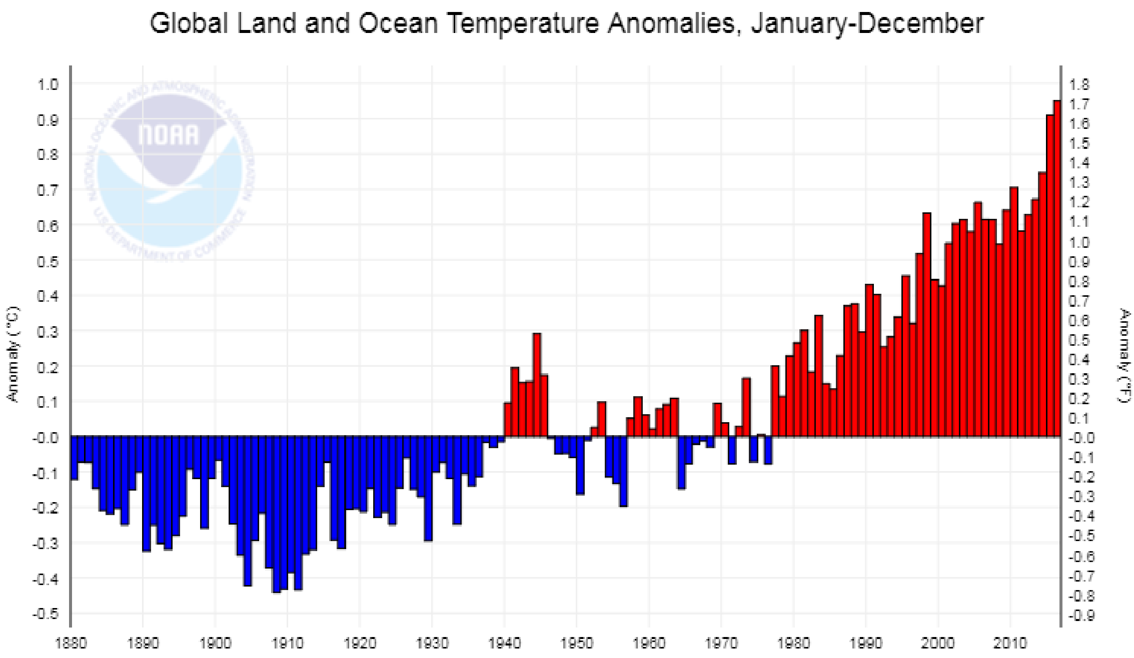


Figure 1.1. Evolution of global land and sea annual surface temperatures anomalies from 1880 to 2017. (NOAA, 2017).

Paleoclimate research on glaciers and ice caps revealed that, in the past, dramatic climatic changes happened very quickly. The Vostok ice core record revealed that, during the previous 800,000 years, atmospheric CO_2 concentrations fluctuated between 170-300 ppm during interglacial and glacial periods (EPICA project/Lüthi*et al.*, 2008) at a maximum rate of 30ppm/1,000 years. However, concentrations have never been as high as at present and have already exceeded levels unprecedented since the Miocene epoch, 10-15Ma (Tripati, et *al.*, 2009). In 2017, CO_2 levels reached 412ppm (Figure 1.2).

Sea-level rise is the most apparent widespread consequence being felt now by human and natural ecosystems, and this will continue into the long term. As the atmosphere warms, sea-level will further rise because of thermal expansion and the addition of fresh water being added from land -based glaciers, such as Greenland and Antarctica (IPCC, 2013). Average global sea-level rose 17cm in the last century at an average rate of 1.7mm/year. Since 1993 this trend has accelerated to 3.3mm/year (Church *et al.*, 2011). Should the warming trend continue, further rises in global sea-levels are expected; exacerbating coastal impacts (Church *et al.*, 2001; Meehl *et al.*, 2007; Nicholls *et al.*, 2007; FitzGerald *et al.*, 2008).

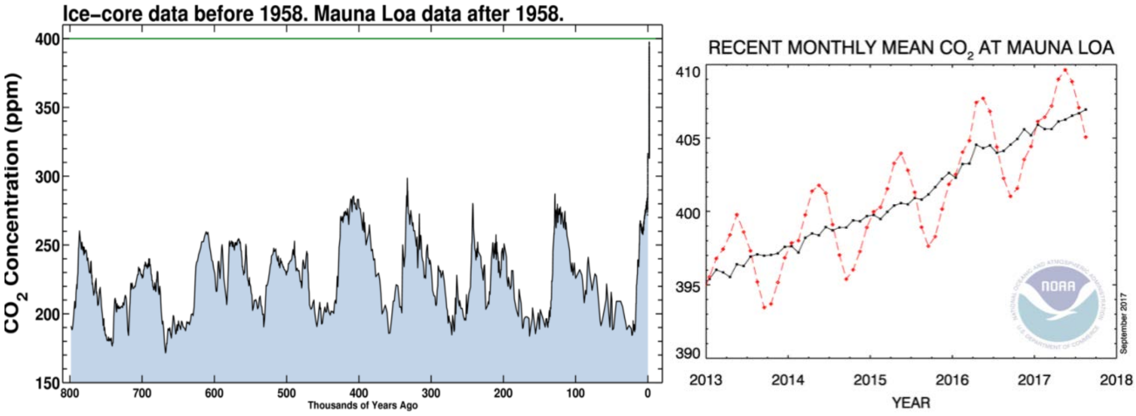


Figure 1.2. Left. Record of CO_2 atmospheric concentrations from ice-core data during the pre-industrial era (Jouzel *et al.,* 2007); right. Recent monthly mean CO_2 concentrations at Mauna Loa (NOAA/ESRL, 2017).

1.2. Global Impacts of Sea Level change

Current research suggests that coastal flooding will be one of the key challenges for the world's populated areas. Sea level increases of up to 0.97m or higher are projected by the end of this century, resulting in increased exposure, especially for urban areas (IPCC, 2013). Exposure is growing also due to rising population and subsidence of land (Dixon *et al.*,2006; Hallegatte *et al.*,2013). Coastal ecosystems, in particular low-lying areas with shallow water tables or areas which are subsiding, are particularly sensitive and are already experiencing changes in erosion, inundation and ecosystem losses (IPCC, 2007; Rotzoll & Fletcher, 2012) .

Impacts of sea-level rise will not be uniformly distributed. some areas will be more at risk due to population increase (Landerer *et al*., 2013). Currently 40M people are exposed to a 1 in-a-100-year event. By 2070 sea-level rise, subsidence, demographic changes will leave 120M unprotected (Hanson *et al.,* 2011).Small increases in sea-level rise would be devastating for those coastal areas where large population centres exist. Even though there were times in Earth history when massive increases in sea level occurred, today 1.2 billion people live within 100km of the coast and below 100m elevation (Small and Nicholls, 2003). 200M people live at only 5m above the sea level, a figure that is estimated to double by the end of the century (Bollmann *et al.,* 2010).

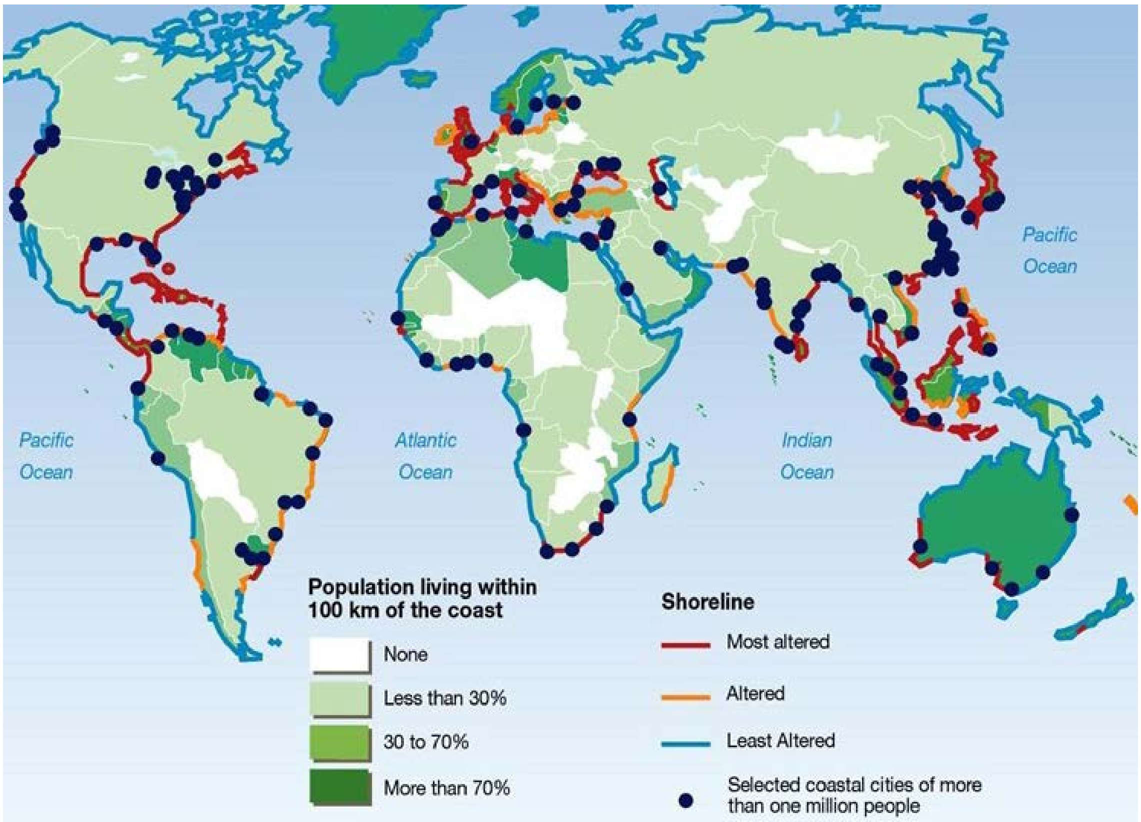


Figure 1.3. Coastal world's population and coastal degradation (Burke *et al.*, 2001).

Under a medium sensitivity emission scenario, by 2100, approximately 147-216M people will live in coastal areas susceptible to inundation (IPCC, 2013). Given current emission trends, between 2.6 and 3.1% of the world's population will be at risk of regular coastal flooding by 2100(IPCC, 2013). A rise of only 1m will affect 100M people around the world, mainly in Asia (Burke *et al.*, 2001) (Figure 1.3). Climate-change-derived impacts on coastal areas will have costly consequences not only because this is home for millions of people, but also due to coastal areas' economic importance for global GDP (Nicholls *et al.*, 2007.For Europe, the non-adapting option will increase costs due to flooding and other events from €100B/year to €250B/year between 2020 and 2050 (EEA, 2012). Changes in two key indicators (mean-sea level rise and storm surge height) have been detected in Western Europe (EEA, 2012). Impacts will be most acutely felt during extreme events. Any change in mean sea level will be enhanced by any increase in wave energy, surge levels and storm frequency and severity (IPCC, 2007). The major storm-surge of 1953 had a great impact in Europe, causing the loss of over 1,800 lives in the Netherlands and 300 in Southeast England (Church *et al.*, 2007).Over the past few years low-lying North-Western European coasts have being experiencing some degree of coastal flooding. Recently, Irish coasts experienced severe flooding when spring tides coincided with a storm-surge in 2002 and again, on a minor scale, in 2004 and 2014 (Met Eireann, 2002; Leahy, 2009; eSurge, 2013).

Figure 1.4. Map showing the aspect of European coasts if all the ice on the Earth melted (National Geographic, 2013).

As shown in Figure 1.4, low-lying European countries like the Netherlands, Denmark, and some parts of the British Isles would be largely affected in the event of a complete loss of polar ice. In this context, calls from Europe have long arisen for an integrated coastal zone management (ICZM) approach (EEA, 2006; 2012) as well as for data collection and provision of relevant information for the development of policy recommendations (Salman *et al.*, 2004; EUROSION, 2004; IPCC, 2007). A recent report from the European Commission on EU Adaptation Strategy on Climate Change encourages EU members to develop strategies for adaptation and vulnerability as part of a joint EU adaptation strategy to establish an approach and alertness at all levels from local to international (EUCOM, 2013). Projects such as the *GEUS* initiative encouraged all the European geological surveys participating in the North Atlantic Group (NAG) to assess changes in coastal geology and processes in the North Sea region (GEUS, 2013). The latest IPCC Assessment Report (IPCC, 2014) urges governments to reduce vulnerability and exposure to present climate variability and to develop vulnerability assessments. Consequently, there is an urgent need for realistic integrated coastal management policies (Bosello et al., 2012) and for the development and application of international standard models and methodologies to assess the vulnerability of coastal systems (McFaden *et al.*, 2007a). To achieve successful adaptation, quantification of vulnerability is essential. Thus, the present research responds to these needs by linking regional coastal research to key international and national development priorities.

1.3. Research aims and procedures

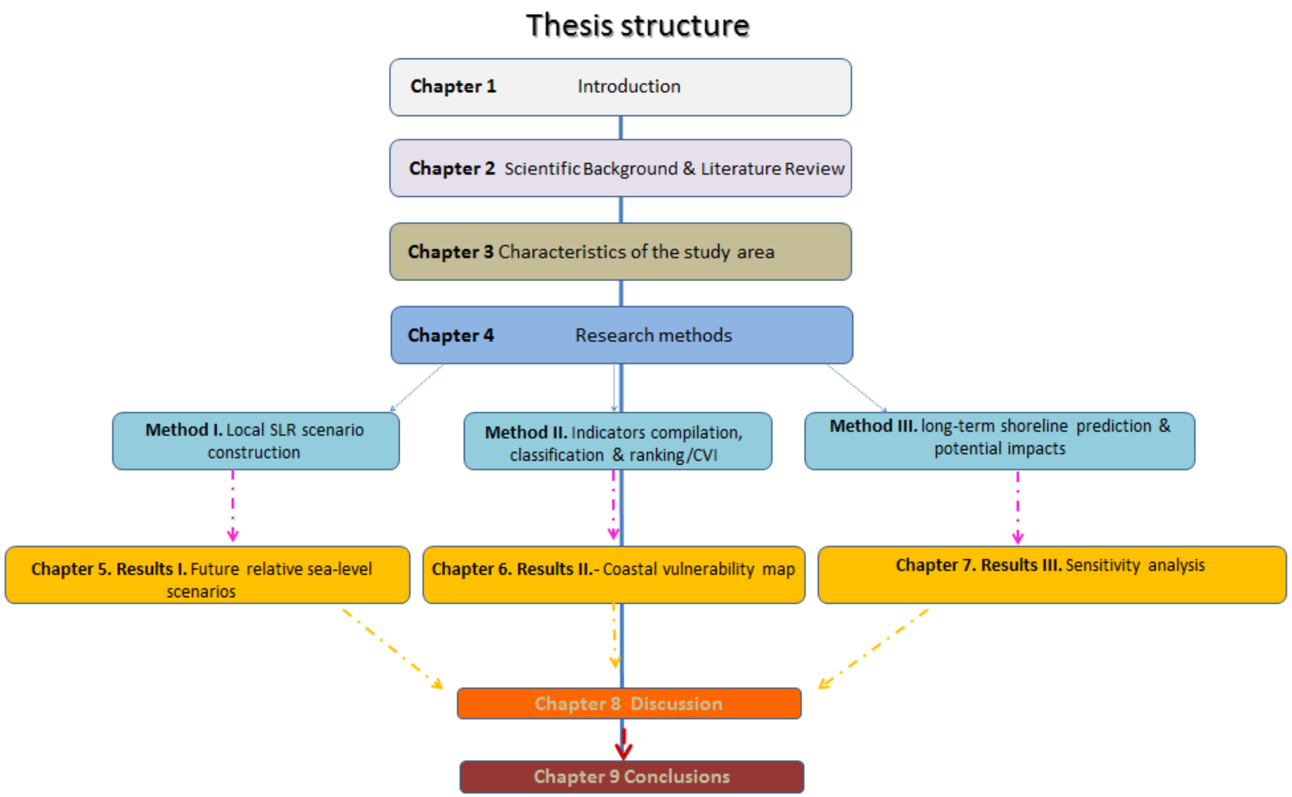
This research aims to assess vulnerability in the coastal area of Co. Dublin and Co. Wicklow. Dublin is an area with substantial socio-economic assets and is prone to flooding and erosion (Martin, 1997; Robinson, 2009; Flood, 2012;).This study will entail the implementation of new methodologies for assessing and quantifying coastal erosion and vulnerability, identifying areas that will more likely experience the negative impacts of sea-level rise. The work is intended to provide a product which will be useful for future adaptation.

Part of the work included in this thesis comes as result of work by the author on two Irish funded projects by INFOMAR (Integrated Mapping for the Sustainable Development of Ireland’s Marine Resources) in 2010 and 2012 (Caloca-Casado and Sweeney, 2010; Gibson *et al.*, 2012). The Geological Survey of Ireland (GSI) is seeking to apply these methodologies to map coastal vulnerability at a national scale. The European Marine Data and Observation Network (EMODnet) and CHERISH projects are currently considering methodologies employed in this research for guidance on national vulnerability and risk monitoring assessments with other European partners.

1.4. Thesis Layout

The layout of the thesis is organised as follows (Figure 1.5): *Chapter 1* introduces the context and main aims of the research and is followed by *Chapter 2* which an overview of the background literature is given. In this, special attention is given to mean global trends and sea-level projections; observed effects/impacts of climate change on coastal systems, physical indicators of environmental change and uncertainties. Our view of coastal vulnerability assessment approaches and main sources of uncertainties are also undertaken. *Chapter 3* presents the main characteristics of the study area and the main research methods are discussed in *Chapter 4. Methods I* explores the construction of future sea-level scenarios. *Methods II* describes the methodology used on the indicator compilation and the construction of maps of coastal vulnerability to sea-level changes. *Methods III* analyses long-term shoreline changes from local projected relative sea-level rise, and also evaluates uncertainty in future potential flooding impacts. The results are discussed in three chapters. *Chapter 5* shows results on current and future site specific sea-level scenarios for Dublin. C*hapter 6* focuses on a compilation and analysis of coastal vulnerability indicators, followed by the construction of vulnerability maps to sea-level rise. *Chapter 7* presents results from the sensitivity analysis. Finally, the main findings are discussed in C*hapter 8,* followed by final conclusions and recommendations in *Chapter 9*.

Figure 1.5. The following diagram shows the thesis layout (*Source: Silvia Caloca*).



Chapter 2: Scientific Background & Literature Review

2.1. Introduction: Overview of Global Mean Sea-Level trends & impacts

Global mean sea-level rise projections are one of the key variables for coastal impacts and vulnerability assessments that need to be integrated on coastal planning management. Hence, understanding causes of past sea-level rise is necessary to comprehend coastal vulnerability and will help future projections and scenarios (Devoy, 2015; Nicholls *et al.,* 2007, 2015).

Global sea level was approximately 25-35m higher than during the Pliocene (3M years ago) and 6m during the last interglacial in the Quaternary, 124,000 years ago as a result of temperature rising in response to Milankovitch cycles, while CO_2 remained at 280 ppm. Global sea level was approximately 120m lower 20,000 years ago during the Glacial Maximum; then it rose at up to 20mm/year on occasion until 6-7,000 years ago when it reached relative stability ~2-3,000 years BP, when mean global rates descended to ~1 mm/year (Lambeck *et al.,* 2002; Harvey 2006, Bindoff *et al.,* 2007; Church *et al.,* 2008; Nicholls and Cazenave, 2010; Church and Clark *et al.,* 2014). Since then until 1850-1900, regional sea-level changes only responded to minor fluctuations in solar forcing and the ocean-atmospheric system (Rignot *et al.,* 2008, Rahmstorf, 2010).

In more recent times levels have been inexorably rising, particularly fast in the Atlantic Ocean, imprinting geomorphological changes to our coasts. Presently, ice melting rates are now higher than they have ever been over the past 2,000 years (Kemp *et al*., 2011). Latest observations suggest that rate of sea-level rise is accelerating (Church and White, 2006; Rahmstorf *et al*., 2012) however, not all coastal locations show this accelerating trend (Haigh *et al*. (2011). During the last century average sea level rose 17cm at the rate of 1.8 mm/year. This trend has doubled since the 90’s to 3.4mm/year (Church & White, 2006; Church *et al.*, 2011) from ice melt and thermal expansion contributions (Abraham *et al.*, 2013; Church *et al.,* 2014).

Past century’s extreme sea-levels are entirely attributed to sea-level rise Haigh *et al*. (2010). Some argue about the long-term variability implications, but there is little doubt about the larger contribution from Greenland and Antarctica (Rignot *et al.,* 2008; Sorensen *et al.,* 2011).

Recent satellite altimetry corrections data shows that during the period between 1993-2014 sea-level rose between 2.6-2.9mm. This means that oceans are now not only ~200mm above the levels of 1900 (IPCC, 2013a) but 71mm over 1995 (NASA, 2017) (Figure 2.1).

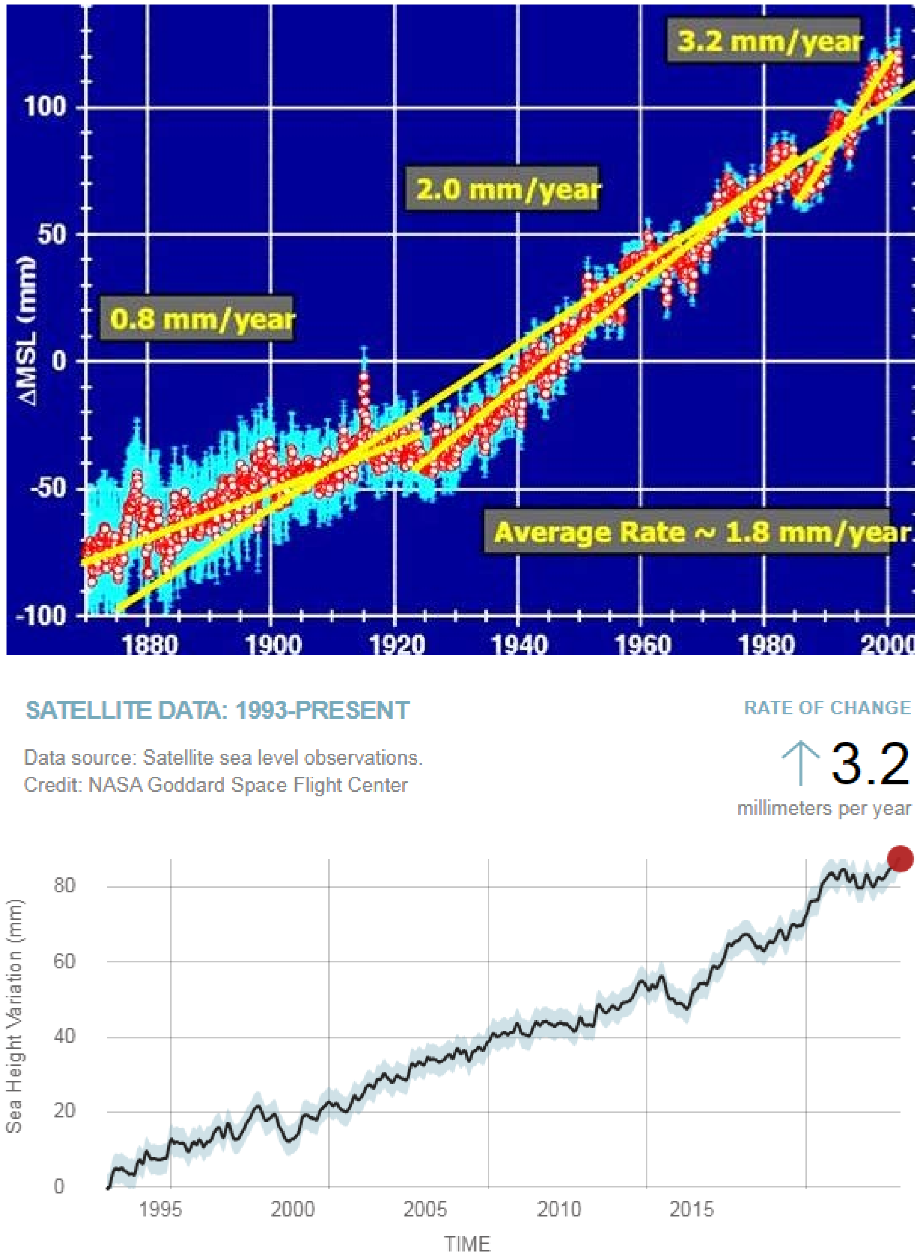


Figure 2.1. Upper. Global mean sea level trends derived from tide gauge observations since 1880 (Church *et al.*, 2006). Lower. Sea-level trends since 1990's from satellites Jason-1 & Jason-2/OSTM altimeters. Source: NASA Goddard Space Flight Centre (NASA, 2017). (Data available at following web UR: https://climate.nasa.gov/vital-signs/sea-level).

2.2. Uncertainties on future sea-level projections

Concerns have risen over future sea-level projections regarding coastal vulnerability and adaptations (IPCC WGI, 2007, 2014; Devoy, 2008; Cooper and Pilkey, 2012; Cooper *et al*., 2014; Muir *et al.,* 2014; Devoy, 2015).

Sea-level rise is not a simple linear process and consequently, if we are to avoid serious damages in populated coastal areas, we must deal with the uncertainty of future tipping points and projections. Progress on future sea-level changes (SLCs) projections evolved from physical process-based General Circulation Models (GCM) and Regional Circulation Models (RCMs) to semi-empirical models. Although those models accurately reproduce past records (Kemp et *al.,* 2011) they do not deal well with complex feedback interactions, that are better represented in process-based model Church *et al.,* 2014), or boundary relationships, and therefore estimates are only approximations (Rahmstorf *et al.,* 2012b).

Regardless of uncertainties and climate models limitations, global projections are apparently always conservative. It seems that the more research data is gathered, the higher the projections get. Initially a likely increase of 23cm was projected by 2100 IPCC (2001); then IPCC (2007) disregarding contribution from Greenland and Antarctica, assumed 0.18-0.59m vs 0.26-0.81m by AR5 in latest IPCC (2013b).

Recent global projections above 1990 levels estimated for the end of the century without considering non-linear contributions range from 0.25-0.5m (Church *et al*, 2001; Meehl *et al*., 2007) and 0.5-1.4m (Rahmstorf, 2007). Other estimates include 0.25-1.5m (Kopp *et al*., 2014); 0.8 to 2m (Pfeffer *et al*., 2008) and up to 5m by Hansen (2007).

Uncertainty about future sea-level rise has increased in AR5 but at least sea-level budgets are now closed (Church *et al*. (2010). Future sea-level rise projections show very likely ranges exceeding 1971-2010 under all Representative Concentration Pathways (RCPs) by 2100 (IPCC, 2013). Recent research obtained from modelling that take into account melting processes from Greenland and Antarctica, give rates of likely increase within the range of 26-81.28cm above 1986-2005 for the period 2081–2100 with increases of 0.98 m by 2100 under the worst scenario of RCP 8.5 (Church *et al.,* 2013; IPCC, 2013b). Unlike other assessments (e.g. NOAA, 2012), IPCC reports do not provide an upper limit. However the report suggests that Antarctica ice-collapsing mechanisms could elevate this value to maximum of 1.2m, or even higher.

Recent projections based on trends from altimeters from 18 (or less) years of data are insufficient to make projections by the end of 2100 as these might be affected by annual or decadal variability (Sallenger, 2012). In this regard, recent satellite altimetry data corrections pointed out that the annual rate of increase in between 1993-2014 was higher than previously thought (2.6-2.9 mm). Therefore it seems we are most likely heading for the upper range of IPCC (2013) projections (1.2m) by 2100 (Watson *et al.*, 2015) (Figure 2.2).

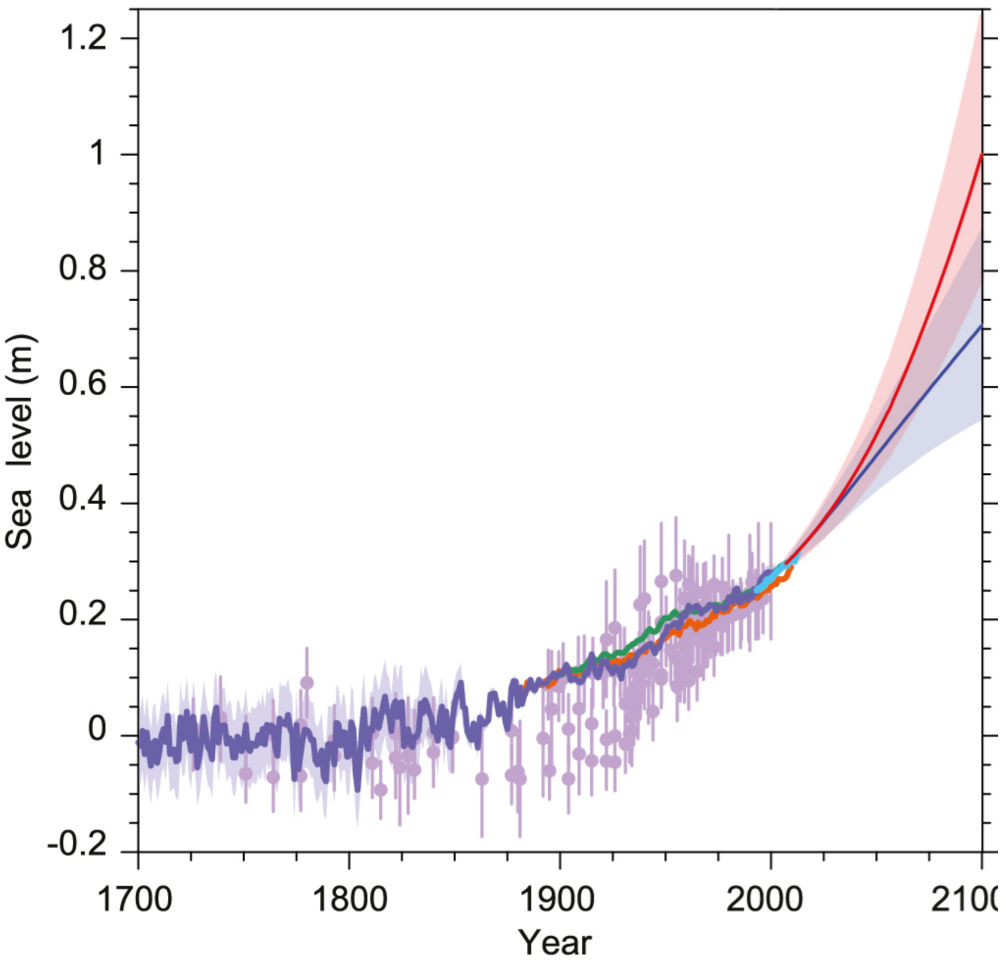


Figure 2.2. Projections of future global mean sea level relative to pre-industrial levels derived from proxy paleo sea-level (light purple), tide gauge (dark pruple) and altimeter data (green, orange and light blue), for low RCP (2.6) in blue and upper (8.5) scenarios in red. Source: (IPCC, 2013b).

On a realistic low-emission scenario, sea-level rise could be up to 30.48 cm from ocean expansion (Yin, 2012) and mountain glaciers would contribute an additional 28cm by 2100 ((Marzeion *et al*.,2012). Probable rise of 40cm (0.2m-2m) by 2050 is being given with very high confidence (NOAA, 2012) predominantly from ocean thermal expansion and glacier melt with important contributions from Greenland and also terrestrial storage changes in Antarctica (Church *et al*.,2010). At the other end, high-emission scenario projections give likely increases ~1.2m (Joughin *et al*., 2010; Rahmstorf *et al*., 2012; Jevrejeva *et al*., 2012; Katsman *et al*., 2011; IPCC, 2013b); or over ~1.8 m by Jevrejeva *et al.* (2014). See Table 2. 1.

Study	21st Century Sea Level Rise (m)	Comment
IPCC		
IPCC AR4[4]	0.18–0.59 m	Without future acceleration of Greenland and Antarctic dynamic term
IPCC AR4[4]	Up to 0.76 m	With future acceleration of Greenland and Antarctic dynamic term
A (Semiempirical Models)		
Rahmstorf[114]	0.5–1.4 m	Semiempirical, derived using observations
Horton et al.[115]	0.54–0.89 m	Semiempirical, derived using simulated past temperature and sea level rise. Excludes high end emission scenarios (A1FI). Not including statistical uncertainty in the fit
Vermeer and Rahmstorf[116]	0.75–1.9 m	Semiempirical, derived using observations
Jevrejeva et al.[117]	0.6–1.6 m	Semiempirical, derived using observations
Grinsted et al.[118]	0.72–1.6 m (based on Moberg temperatures) or 0.96–2.15 m (based on Jones and Mann temperature)	Semiempirical, derived using observations
B (Physical Evidence)		
Pfeffer et al.[39]	2 m possible. 0.8 m more plausible	Based on physical constraints of deglaciation
Rohling et al.[119]	1.6 ± 0.8 m	Based on combining coral data with sea-level reconstruction using stable oxygen isotope records during last interglacial period (a palaeo-climate analogue)
Kopp et al.[120]	0.56–0.92 m	Ice sheet component only based on sea level indicators spanning the last interglacial stage (a palaeo-climate analogue)
New York Panel on Climate Change,[121]	1 m	Ice melt component only based on the average rate of sea-level rise during the last deglaciation
Grant et al.[122]	1.2 m	Sea-level reconstruction using stable oxygen isotope records over the last 150,000 years, including the last interglacial period (a palaeo-climate analogue). Rates are averaged over a millennium, so do not constrain rates over shorter periods
C (Expert Elicitation)		
Bamber and Aspinall[123]	0.84 m (95th percentile)	Ice melt term only, to which other sea-level components need to be added
D (Combined)		
UKCP09[14]	0.12–0.76 m from IPCC range, and up to 2 m (H++)	Based on IPCC and physical reasoning. Numbers are for the UK without land movement
Katsman et al.[15]	0.55–1.15 m (global)	Based on IPCC and physical reasoning

Table 2. 1. Sea-level projections summary for the 21st century using different models (Nicholls, 2014).

Intermediate scenarios with limited information about ice sheet dynamics and ocean warming are often too optimistic (Schaeffer *et al*., 2012). Yet an optimistic medium emission scenario of 0.5m will cause serious impacts. On the other hand, socio-economic scenarios, might be overestimating the future growth of some developing countries but underestimating other issues (Allen Consulting Group, 2005).

Low-probability, high-impact range of sea-level rise scenarios (H^{++}) in the UK projected increases of 0.93-1.90m by 2100. From an impact and adaptation view, those high-end scenarios should be seriously considered (Ranger *et al.*, 2013; Nicholls *et al.*, 2014b; Hinkel *et al.*, 2015; Le Bars *et al.*, 2017).

Temperature's contribution (thermal expansion) only constitutes 50% of the expected SLCs. There are significant uncertainties on emission scenarios. The key is how sensitive the system is to those increases and how large ice sheets will respond. Globally temperature rise is likely to exceed 1.5° C for most of RCP scenarios, reaching 4-5°C for RCP 8.5 over 1986-2005 values by 2081-2100 (IPCC, 2014). In Europe, this could be translated into a temperature rise of 4.1°C (RCP (8.5) for 2071–2100 with respect to 1971–2000 (Van der Linden *et al.*, 2009).

Wu et *al.* (2012) found that ocean warming rates of subtropical western currents (including the Gulf Stream) are several times faster than the mean since the beginning of the last century. Warming diminishes the ability of the oceans to absorb CO_2. As oceans do not respond quickly, sea-levels will continue to rise for centuries (Solomon *et al*., 2009).

In order to keep a temperature rise to less than 2°C, long-term cumulative global carbon emissions should fall dramatically (IPCC, 2013) (Figure 2. 3). Even though, global sea levels would still increase between 1.5-4 m by 2300 even if the global mean temperature stabilized at 2°C (Schaeffer *et al*., (2012)).

Contribution from Greenland and Antarctica ice sheets has doubled up from 2003 (Chen *et al.,* 2009; NASA, 2015); IPCC, 2013). In the worst case scenario some consider that current emissions are enough to see Greenland melt over the coming centuries (Robinson *et al*., 2012). While the amount of change in sea level heavily depends on Greenland and Antarctica melting processes, only a few models deal with the climate forcing effect on ice dynamics (Moore *et al.*, 2013; Church *et al.*, 2013a; Bindschadler *et al.*, 2013; Nick *et al.*, 2013; Hinkel *et al.*, 2014).

Time-scales are crucial. Changes can be expected in small tropical glaciers within years, larger glaciers and small ice caps over centuries and on ice sheets over millennia. Even though timing is difficult to predict, large changes within decades or sooner cannot ruled out (Hansen *et al.*, (2005b; 2007).

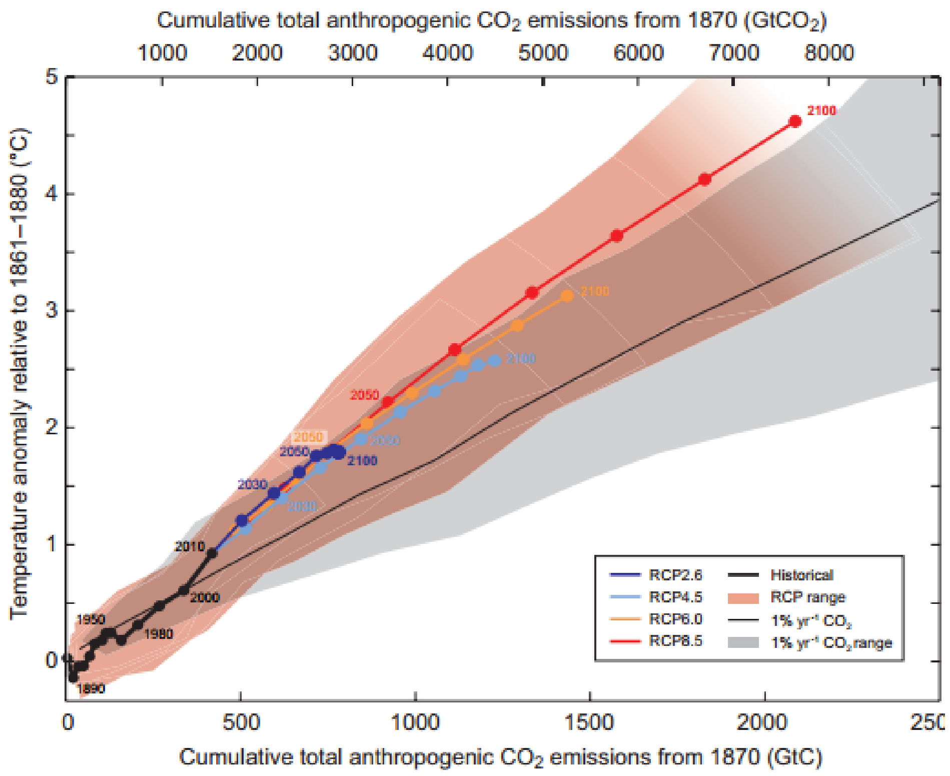


Figure 2. 3. CO_2 cumulative emissions (Gt) from 1870 and associated global temperature increase for 1861-1880 and projected for high emission scenarios by 2100 (IPCC, 2013).

Right now the big uncertainty falls on the Antarctica ice sheet (IPCC, 2013b). Glaciers and ice sheets in West Antarctica are undertaking irreversible changes that together with associated positive feedbacks will impact on global rising sea-levels for hundreds of years (Rignot *et al.*, 2014). Melting processes in West Antarctica are happening faster than predicted (Bromwich *et a*l., 2013; Pritchard *et al.*, 2012), and glaciers that feed ice sheets increasing (Steig *et al.*, 2012). Even small changes in temperature can alter summer snow melting rates and ice stability (Abraham *et al.*, 2013).

Excessive warming from doubling CO_2 concentrations could make West Antarctica deglaciate within the next decade according to the latest research (Khazendar *et al.*, 2015).

The likelihood and speed of a West Antarctic Ice Sheet (WAIS) collapse is still uncertain but it is believed that exponential disintegration due to highly responsive patterns to warming could result in sea-level rises of 5–6 m by 2100 (Mercer, 1978; Oppenheimer, 1998). Antarctic bottom water slowing mechanism is believed to be behind those rapid changes of sea-level rates in the past (interglacials) that occasioned changes in coastal areas, and some argue that that could be repeated (Silvano *et al.*, 2016).

Despite the fact that models cannot deal with rapid changes from ice sheets, current models suggest that the biggest contribution will come from thermal expansion followed by mountains glaciers (Church and White, 2010); 15-21 cm by 2100 from ocean dynamics (Yin *et al.*, 2009) and then Greenland and the West Antarctic ice sheet (Church *et al.*, 2010; Gornitz, 2013) which could contribute up to 1m (Church *et al.*, 2013). Sea-level rise from rapid ice melting will vary regionally depending on distance from the source but it could reach 4-5mm/year by 2050 with significant consequences for coastal areas (European Commission, 2013).

Hence improvement of new climate models to accommodate changes from Greenland and Antarctica ice sheets will be fundamental for coastal flooding assessments.

2.3. Potential effects of sea-level rise on coastal areas

In the light of above, natural systems are already experiencing some changes (IPCC, 2014). In Europe extreme weather events are more evident now than over the last century, exacerbating impacts (Nicholls and Cazenave, 2010; Weisse *et al.*, 2014). Barrier islands, deltas, bays, estuaries, wetlands are the most vulnerable coastal forms and highly sensitive even to minor changes. There are already undergoing erosion and will be more exposed in the future to the attack of higher water levels and storms (Tebaldi *et al.*, 2012; Devoy, 2015). Additional factors such as groundwater inundation could double the predicted flooding from rising seas (Rotzoll & Fletcher, 2013).

In a warmer world, coasts will become more dynamic and exposed. More frequent flooding and inundation are expected to shape low-lying coastal areas (Betts *et al*., 2004).

Direct potential impacts associated with sea-level rise such as coastal erosion, inundation, salt intrusion into groundwater, estuaries and wetlands submersion, flooding from changes in extreme water levels, will be exacerbated (Church *et al*,. 2006; Nicholls *et al.*, 2007). Any alteration of mean sea levels will be reinforced by increases in wave energy or surge. Changes in sea level and storm frequency and severity pose major threats to coastal habitats and endanger people and their infrastructure (Church *et al.*, 2006; Baxter *et al.*, 2010; Perini *et al.*, 2016; Sierra *et al.*, 2016;).

Some impacts such as inundation, coastal flooding and erosion, higher wave over-topping and rainfall runoff will be relevant in the short-term while, in the long-term, wave and wind climate processes affecting sediment budget and coastal adjustment will more relevant (Nicholls, 2007; 2014; IPCC, 2014).

Coastal low-lying areas with shallow water tables are certainly at risk (Rotzoll & Fletcher, 2012). Further flooding by rising water tables are expected and this contribution could double that of the rising sea, impeding drainage into the ocean and causing further damage in delta areas. The closer to shore the higher the pressure exerted on groundwater in some areas.

Total uncertainty over a system is difficult to quantify (McCarthy, 2001; Lowe & Gregory, 2005; Carter *et al.*, 2007). Uncertainties on future climate outcomes globally and locally, vulnerability and exposure, and how humans and systems will respond to it are large. The current uncertainty in future projections can also be extrapolated to the magnitude of the impacts (Nicholls & Cazenave, 2010; IPCC, 2014; Devoy, 2015; Hinkel *et al.*, 2015; Nicholls, 2015;).

The climate system's response to natural variability makes sea level vary from place to place and also in time (IPCC, 2007). Given the different rates of oceanic thermal expansion, future sea-level changes will be subjected to local patterns generally caused by land vertical movement or local response to ice sheets (Kopp *et al*.,2014) (Figure 2.4). Nonetheless, all 95% of the coastal areas will very likely experience some positive sea-level rise close to average and nearly 70% of the world's coastlines will experience severe changes (IPCC, 2013b). By 2050 approximately 30% of the world's coastal wetlands will be either eroded or inundated (Church et al., 2010; Church et al., 2014) and by 2100, 50% of the population will leave below 1m (MSL) in coastal areas stressed by squeeze (Nicholls *et al.*, 2007, 2011; Wong and Losada, 2014; Cooper and Pilkey, 2012).

In regional assessments of coastal impacts, it is important to estimate when will the anthropogenic signal be physically translated into regional changes, and what percentage of a particular contribution will emerge first at this particular region (Lyu et *al.*, 2014). Therefore, coastal impacts will be felt much earlier than expected for should the higher emission scenarios materialize. That is why for impact analysis it is advisable to consider wider ranges (Burkett *et al.*, 2012; Parris *et al.*, 2012; Hinkel *et al.*, 2015, Nicholls *et al.*, 2013; Ranger *et al.*, 2013; Le Bars *et al.*, 2017).

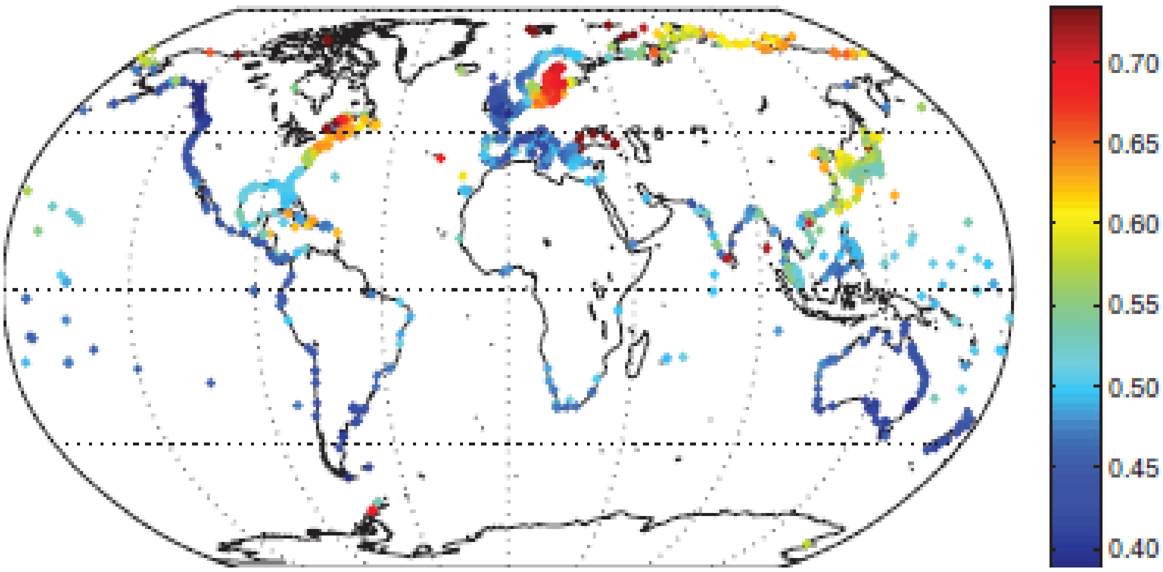


Figure 2.4. Likely local sea-level rise (m) projections for RCP 8.5 scenarios (Kopp *et al.*,2014).

System's sensitivity proxy indicators play an important role on anticipating potential impacts as many systems can be resilient to climate changes below a threshold and then very fragile over it to even small changes. Small changes in average conditions or minor shifts of storm direction and intensity will have a strong impact on sensitive coasts (Slott *et al.*, 2006; Burkett, 2012) and displace the shoreline further than projections from sea-level alone (Ruggiero *et al.*, 2010b). This together with increases in wave energy will have noticeable impacts on coastal infrastructures, water supply, erosion/flooding events and sediment transportation.

However, due to complex interactions with bathymetry and coastal topography there is not a direct proportionality between sea-level rise and storm surge impacts. This non-linearity is clearly evidenced in deltaic areas, where small increases in sea level could cause 2-3 times higher storm surges, leading to shorter return period of high water levels (Smith *et al.*, 2010; Wolters and Kuenzer, 2015).

Qualitative risk studies in the UK have quantified annual damages by combining diverse coastal management practices and different scenarios of flooding and erosion and detected growing sensitivities to sea-level rise over 4.5mm/yr (Dawson *et al.*, 2009).

Impact on levels and regularity of inundations are still uncertain (Kirshen *et al.*, 2008). Risks of damage along the coast will depend on storm itself, but also on its physical, demographic and assets coastal exposure and coping ability. There are still uncertainties on how sea-level rise will affect storms during this century, but it is quite clear that sea-level rise will aggravate the storm-associated risks at the coast (Burkett, 2012). Again, concerns about the complexity and non-linearity of climate systems, tipping points and potential impacts will also be an issue for adaptation (IPCC, 2014; Dawson *et al.*, 2009).

Given the uncertain impact scenarios it might seem challenging to accurately deliver accurate projections for the near future. On the one hand we don’t know whether in the long-term the ice-sheets will collapse and then reach a balance, whereas in the short-term the largest source of sea level uncertainty lies in their behaviour. On the other hand, the response of the coastal system regarding the action of waves and tides is also uncertain.

2.3.1. Changes on extreme and storminess

Pronounced cyclical changes in frequency linked to the behaviour of the North Atlantic Oscillation (NAO) have occurred since the 1940s, almost at a decadal level (Lozano & Devoy, 2000, Lozano *et al.*, 2004). Monthly mean and maximum wave height and annual mean significant wave height (2.2 cm/year) in the NE Atlantic and higher latitudes have increased (Carter & Draper, 1988; Bacon & Carter, 1991). However initially the anthropogenic role versus natural variability is not clear, there is a relation between warming and a northward shift of the storm tracks (Gulev and Grigorieva, 2006; Wang *et al.,* 2006; 2009).

Higher extremes sea-levels in combination to intense storms are a concern (Church *et al.,* 2013). Future evolution of storm tracks and wave height in North Western Europe varies with the model performance, data acquisition and natural variability. Extremes storm events have definitely intensified since the 70's in and it is believed that its destructive capacity will increase in North Atlantic and North Pacific (Emanuel, 2005; Webster *et al*., 2005). Changes in extreme coastal levels generally reflect global sea-level trends (Marcos *et al*. 2009; Haigh *et al.,* 2010; Menendez and Woodworth, 2011). Several coupled general circulation models projected changes in baroclinicity associated with excessive warming in Polar Regions (Yin, 2005). This weakens the gradient between poles and middle-latitudes and hence shifts in storm tracks northwards in the Northern Hemisphere, lowering mid-latitude storm frequency. Changes in circulation patterns due to warming are affecting extra-tropical cyclones making them more intense in high latitudes (Stone & Orford, 2004). It is likely that the number of intense cyclones and associated strong winds will increase in the North Atlantic (Lozano *et al.,* 2004; IPCC, 2013). The lower gradient can also weaken the westerlies around the British Isles, favouring more frequent easterlies wind events that will enhance coastal erosion over certain areas on eastern coasts (Devoy, 2008).

Changes in extreme wind speed and mean sea-level pressure will affect extreme and return values of surge heights. Average of wind speed strength could increase up to 10% by 2050 (IAE, 2009). In the eastern Irish Sea, Brown *et al.,* (2009) projected increases in peak surge elevation due to enhanced wind velocities and sea-levels in a warmer world. Changes in storminess and mean sea level mainly will derive changes in the 10-year and 50-year return values of annual maximum wind speed and return periods of surge heights across the UK and Irish coasts (Lowe and Gregory, 2005; Wang *et al.,* 2008; 2009). Despite uncertainty, there is robust scientific evidence of an increase in extreme events associated with anthropogenic influence (Peters *et al.,* 2011).

Even if tropical storm frequency does not increase, maximum cyclone wind speeds will (IPCC, 2013).

2.4. Conceptualization of vulnerability

Climate risks management must be assessed firstly in relation to current risks by addressing what kind of level of damage or loss a community or nation can endure. Vulnerable areas, those highly exposed and quite sensitive, with limited adaptive capacity, must be identified and quantified before estimating potential changes.

There are different ways of defining risks and vulnerability, and therefore various methods for assessing the vulnerability of a system. According to Chambers (1989) vulnerability is the opposite to security and relates to exposure to external unexpected events and continuous, cumulative predictable stresses over a system. Vulnerability and exposure are not the same as risk. Risk refers to the likely potential losses or damages originated by particular hazard over a long period of exposure (Schneiderbaner *et al.*, 2004; EC, 2013). As stated by Wamsley *et al.* (2015), risk involves hazard plus vulnerability plus the effects or impacts of the threat (hazard) over the system. Depending on the vulnerability the system, the hazard might or might not have an effect on the system. The system will mitigate to a certain extent but risks cannot be avoided totally.

The concept of resilience relates to a system's ability exposed to hazards to recover or to resist or modifying itself in order to maintain an acceptable functioning (Pelling 2003; Merriam-Webster, 2013). Thus, some refer to both terms as separate, while others regard resilience as part of the adaptive capacity, and therefore of vulnerability (Linkov et *al.*, 2013).

On probabilistic risk assessments, vulnerability relates to a probability of an adverse effect to occur. A risk assessment would evaluate the regularity of flooding events; identify prone areas affected previously and consequently the more vulnerable and exposed (Benassai *et al.*, 2015).

According to Fussel (2007), a vulnerable situation involves defining the system (natural or social system) or a coupled human-environment system (e.g., geographic region) potentially threatened by exposure to a hazard, while considering its characteristics, the magnitude of the hazard, and period of interest. This hazard can also be natural or anthropogenic, continuous (e.g., sea-level rise) or discrete (e.g., a storm).

New vulnerability definitions differ from the old definitions of risks by introducing adaptation and sensitivity concepts. In the climate context, vulnerability relates to the amount of climate variability and extremes, and represents a function of the system's exposure, sensitivity and adaptation to them.

Vulnerability can also be described is terms of susceptibility of a system to change or to damage. Sometimes vulnerability does not only rely on susceptibility but also on what is called secondary vulnerability, that it is the lack of resources to respond (Alexander, 2000) or incapacity to accommodate changes (Pelling, 2003). Hence it can be defined as 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes' (McCarthy, 2001; IPCC, 2007b, 2014).

The three main components to be considered to effectively assess the vulnerability of a system to impacts of climate change (Fussel, 2007; Nicholls *et al*., 2007) are: **exposure** (physical climate variability) which refers to stimuli, environmental assets or background climate conditions that impact on a system; **sensitivity** which is a response of a system to changes in climate compared to its current state (resilience or ability towards recovery or lack of preparedness); and finally **adaptability** which tells how the system deals with exposure and sensitive to a particular hazard such as sea-level rise, by either copying or taking advantage of the new conditions (Allen Consulting Group, 2005; Nicholls and Klein, 2005; Green and McFadden, 2007; IPCC, 2014).The socioeconomic factors shape the coastal system as much, the natural system and sea-level rise are shaping the socioeconomic system (Lazarus *et al.*, 2014). See Figure 2.5.

Exposure and sensitivity will determine the potential impacts over the system (IPCC, 2001, 2007; Fussel, 2007). In costal assessments to sea-level rise, adaptive capacity is usually poorly represented compared to exposure or sensitivity (Nguyen et *al.*, 2016). Considering that future sensitivity depend on current adaptive capacities and associated measures, sensitivity and adapt capacity components are not easily separated (Brooks *et al.*, 2005).

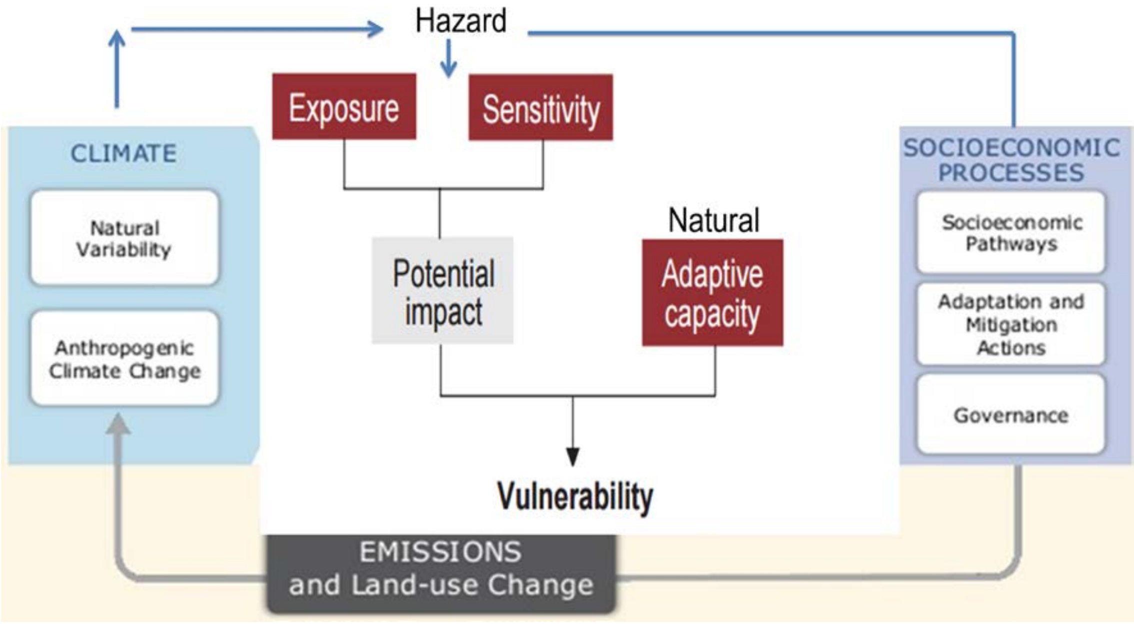


Figure 2.5. Conceptual model of vulnerability to climate change (adapted from Allen Consulting (2005), Füssel (2007) and IPCC (2014)).

In terms of sensitivity it is advisable to quantify it before prioritising risks. For instance, if an area is struggling to cope with adverse effects of recurrent storms it would be interesting to evaluate the effects of future increases on frequency and severity compared to current situation. Sometimes sensitivity is obvious whereas in others it is not so. In those cases it is recommended to consider potential future changes of circumstances and quantify when the changes will derive on a catastrophic situation, identifying thresholds at which change is detected and also by determining when that point will be reached (Broadleaf Capital International, 2006).

In the light of the above, when framing management risks, vulnerability can be merely addressed based on the physical character of the area together with coastal forcing variables, focusing on the damage of environment-human systems when exposed to climatic changes (Hahn, 2003; Polsky *et al.*, 2003; White *et al.*, 2005; IPCC, 2007). However, it is usually is the notion of a risk within the social or economic damages context that makes us to protect that area by implementing management measures (Gornitz *et al.*, 1993). Consequently, in the climate change context, many authors recommend combining physical, socio-economic (non-climatic) and environmental factors (Moss *et al.*, 2001; United Nations; 2004; ISDR, 2004; Brooks *et al.*, 2005; Adger, 2006; Fussel and Klein, 2006; Nicholls *et al*., 2007; Devoy, 2008; Harvey and Woodroffe, 2008; UNEP, 2008; Balica *et al*., 2012; Lazarus *et al.*, 2014). Others focus on the sensitivity of system to respond to future climate related hazards (De Leon, 2006; Gutierrez *et al.*, 2011, 2015).

2.4.1. Evolution of vulnerability climate change assessments

Climate change vulnerability assessments have evolved, responding to growing public demands and improved scientific knowledge. Their main function is to better understand climate sensitive-systems in a changing world (anthropogenic-derived climate change) and to inform stake-holders and policy makers concerning mitigation and/or adaptation (Füssel & Klein, 2006).

The conceptual development of climate change vulnerability assessments was initially more focused on the physical responses of the systems involved. Impact based assessments were reliant on quantitative scenarios of climate change. Impacts were not considered to be the main cause of systems vulnerability, but it contributed to it (Preston *et al.*, 2007). Later, vulnerability-based assessments (first and second generation) appeared. Vulnerability assessments focus on the physical characteristics and interactions as well as the external stressors (Ribot, 1995). These were mainly orientated to understand coastal behaviour from the analysis of climate model outputs together with multiple indicators from different vulnerability components and their relative influence on coastal responses (Preston *et al.*, 2007). The first generation introduced non-climatic factors and raised awareness to adaptation. The second generation focused on adaptive capacity. These expanded from impact assessments as they did not only quantitatively assess the changes but also evaluated the relevance of the magnitude and distribution of future potential impacts.

Fundamentally, impact assessments shifted to vulnerability assessments by focusing on climate variability, non-climatic factors and adaptation considering stakeholder involvement, and relied on multi-dimensional scenarios to provide a comprehensive picture of the system (UNFCCC, 2005). Impact assessments quantified changes of physical or socioeconomic indicators but vulnerability assessment located the vulnerable areas, which is more a relevant measure (Downing *et al.*, 2001).

Finally adaptation-policy assessments for policy-makers provided recommendations and adaptation strategies to protect populations (Füssel & Klein, 2006; IPCC, 2001; IPCC, 2007; IPCC, 2013). Figure 2.6 shows the conceptual progression of knowledge on climate change impact, vulnerability, and adaptation assessments.

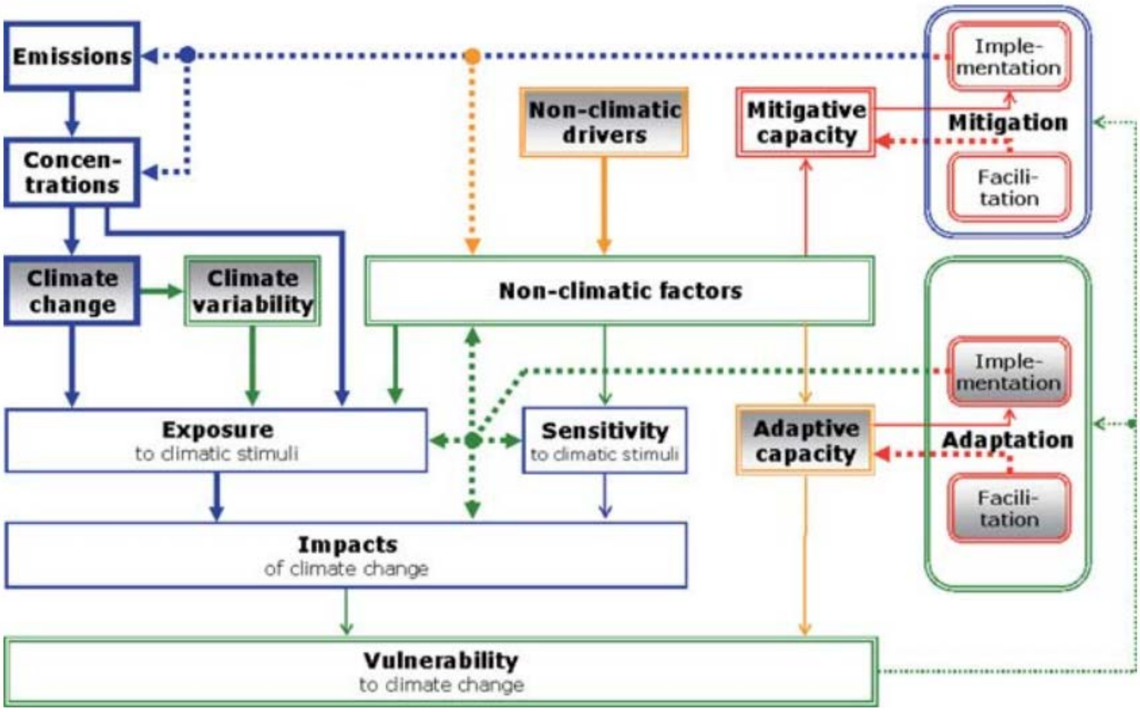


Figure 2.6. Conceptual network showing the evolution of key concepts on climate change impact, vulnerability, and adaptation assessments: blue for impact assessments, green (1st generation vulnerability), orange (2nd generation vulnerability) and pink (adaptation-policy assessments) (Füssel & Klein, 2006).

2.5. Synthesis of coastal vulnerability studies

2.5.1. GIS-tools for coastal management assessments

Currently, coastal vulnerability assessments to climate change impacts as a tool for decision making are becoming popular (USGCRP, 2011). GIS-based studies around the world have developed coastal vulnerability maps using multi-variable index approaches, physical information and numerical model information. Although there is not one single appropriate method for undertaking a vulnerability assessment, diverse vulnerability approaches and dedicated tools have been developed in recent years.

Multivariate tools from qualitative to quantitative methods have been integrated for visual and statistical analysis for ICZM for predicting models regarding future scenarios of climate change (Allen Consulting Group, 2005) and coastal mapping analysis (Doukakis, 2005). In general GIS packages have revealed as an ideal platform in environmental studies to locate hazardous coastal zones, displaying, analysing spatial and evolution processes and variable processing (Miller *et al.,* 2005; Rodriguez *et al,.* 2009). GIS visualisation techniques are also a powerful tool for visualisation to the general public and stakeholders (Dawson *et al.*, 2009).

For instance, Nicholls & de la Vega-Leinert (2000) under the SURVAS project (Synthesis and Up-scaling of Sea-level Rise Vulnerability Assessment Studies) developed a common methodology for global assessment of vulnerability to sea-level rise identifying key indicators for susceptibility, socio-economic vulnerability and resilience to impacts of climate change, linked to an international network of experts on vulnerability and adaptation.

UNFCCC (2008) and McFadden *et al., (*2007a) recommended some specific tools designed to explore national, regional and global vulnerability and impact integrated assessment in coastal areas to climate change and sea-level rise: FUND (Climate Framework for Uncertainty, Negotiation and Distribution) integrated assessment model for climate change; the EU-funded DINAS-COAST project developed a coastal database for impact and vulnerability assessments to sea-level rise using DIVA (Dynamic and Interactive Coastal Vulnerability Assessment) tool. DIVA's tool would reduce the uncertainty for coastal impact modelling concerning future coastal flooding scenarios, erosion and adaptation by splitting the coast into manageable units for physical and socio-economic analysis' behaviour (Hinkel, 2005, 2009; Hinkel and Klein, 2007; 2009; Hinkel *et al.,* 2013). Likewise, Nicholls *et al*., (2008) and Torresan *et al*., (2008) demonstrated the applicability of their GIS-based decision support system for community vulnerability and adaptation assessment at the regional and local level using DIVA's tool for comparing a set of indicators in Europe to estimate coastal vulnerability indicators.

Some other examples of tools for coastal evolution are the Climate Change Research's Coastal Simulator tool developed by the Tyndall Centre designed to predict coastline under future scenarios of change and management plans (Nicholls *et al.,* 2005; 2008a); the Community Vulnerability Assessment Tool (CVAT) (Flax *et al.,* 2002) developed by the National Oceanic and Atmospheric Administration's Coastal Services Center, which deals with socioeconomic and environmental factors overlaying different hazard maps .

In recent years specific tools such as DSAS (GIS-based) developed by the US Geological Survey Woods Hole Science Centre for coastal erosion has been successfully applied to CVA (Thieler and Danforth, 1994; Thieler *et al.,* 2009).

The Simulator of CLIMate Change Risks and Adaptation Initiatives developed under the SimCLIM Open Framework Software System (SimCLIM, 2013) generates sea-level scenarios to aid decision-making. This tool together with the DIVA, the Regional Vulnerability Assessment (RVA) (Torressan *et al.,* 2010) and the DEcision support SYstem for COastal climate change impact assessment (DESYCO) tools, was very successful (Torressan *et al.,* 2012).

2.5.2. Coastal Vulnerability Indexed-based approaches

Early methods to assess SLR-induced coastal retreat were based on the Brunn Rule model. Over time the applicability of simplistic approaches to estimate the effects of sea-level rise were questioned for coastal change evaluation (Pilkey *et al.,* 1993; Thieler *et al.,* 2000). Some authors suggested incorporating factors such as the sediment budget and geologic setting (Stolper e*t al.,* 2005). Different models were traditionally used to investigate local changes on coasts. But those were not suitable at regional scales due to the complexity of calculations; for example, numerical process-based inundation models for flooding assessment (Xia *et al.,* 2011; Lewis *et al.,* 2012) or morphodynamic models (Jiménez *et al*., 2009).

Studies to evaluate the natural coastal system's susceptibility to change began to proliferate in the 90s (Gornitz, 1990; Thieler & Hammar-Klose, 1999; 2000a, b). Later, new information on sea-level rise within the climate context stressed the importance of protecting the coast. Intergovernmental Panel on Climate Change (IPCC, 1991) set guidelines for common methodology for coastal vulnerability assessments and that was a milestone for coastal vulnerability studies.

Relative vulnerability mapping is the first step to assess coastal vulnerability to climate change, and potential impacts (Preston *et al.*, 2008). In this sense coastal vulnerability indices are very useful and can serve different purposes: mapping and ranking different attributes of the system, targeting specific policy adaptation and comparisons with other studies (Dwarakish *et al.*, 2009). In this context, the application of vulnerability index-based approaches was considered as an effective and robust method for characterizing the relative vulnerability of different segments along the coast according to its natural ability to adapt and its susceptibility (Abuodha & Woodroffe, 2006; 2010; Gutierrez *et al.*, 2007).

Gradually, coastal vulnerability indices and indicator-based approaches for vulnerability mapping began to emerge. Global and regional impact and coastal vulnerability assessments mainly started to focus on drivers such as relative sea level rise and extreme sea level for coastal protection from impacts such as erosion, inundation, submergence (Nicholls and Tol, 2006; Anthoff *et al.*, 2010; Hinkel *et al.*, 2013).

Most of the initial approaches only dealt with geo-physical dynamics (geomorphological processes) or physical impacts such as the exposure to permanent/impermanent to flood events (Dasgupta *et al.*, 2009; 2011; Bosom and Jimenez, 2011; Yin *et al.*, 2012; Kebede and Nicholls, 2012; Boateng, 2012) while the more complex also introduced economic and social vulnerability aspects (Abuodja and Woodroffe, 2006; Nicholls *et al.* 2008).

Some authors acknowledge the importance of integrating several vulnerability drivers for coastal assessments, involving hybrid approaches addressing both biophysical and social dimensions (Preston *et al.*, 2008; Soares *et al.*, 2012), particularly the policy-driven assessments (Füssel and Klein, 2006; Nicholls *et al*., 2007). The application of non-climatic drivers and future scenarios as contributors of coastal change in conjunction with environmental chances could provide valuable information to regional coastal vulnerability studies (Polsky *et al*., 2003, Nicholls *et al*., 2008, Torresan *et al*., 2008; Bjarnadottir *et al*., 2011; Li and Li, 2011; Yoo *et al*., 2011).

However, there is little consensus in literature on socio-economic variables compared with biophysical indicators. Although socioeconomic factors like population or assets location are important in local or global studies (Boruff, Emrich, and Cutter, 2006; Brooks, Adger, and Kelly, 2005; McLaughlin *et al.,* 2002; Birkman, 2007; Yoo *et al.,* 2014; Wolters and Kuenzer, 2015, Wamsley *et al.,* 2015) many studies on coastal vulnerability to climate change do not consider them (Torresan *et al.,* 2012). This could be due of the lack of data and heterogeneity, scales issues plus it is not clear which variables best represent the capacity of that community to cope (Nguyen *et al.,* 2016).

The first attempt of applying a Coastal Vulnerability Index (CVI) to assess coastal vulnerability was that of Gornitz and Kanciruk (1989). Sea-level rise was initially introduced as a climatic effect within the following physical setting of variables: geology, geomorphology, elevation, shoreline change rate and wave and tide regime (Gornitz, 1991). Gornitz made the method suitable for a global context and also considered storm frequency for inundation and susceptibility to erosion. He also suggested incorporating economic factors and population at risk into the index (Gornitz *et al.,* 1991). Gornitz and White (1992) and Gornitz *et al.,* (1994) developed these ideas further.

Those approaches were adopted by Thieler and Hammer-Klose index (1999, 2000a, b) to map US coastal vulnerability. This CVI yields coastal relative system natural vulnerability to sea-level rise by evaluating system's susceptibility to change together with system's natural variability to adapt. This approach has more recently been applied (Thieler *et al.,* 2000; Thieler *et al.,* 2002; Pendleton *et al.,* 2004a, 2004b; 2005). Later Pendleton *et al.* (2010) created a coastal vulnerability index (CVI) to evaluate a coast's potential susceptibility to physical change as sea levels rise in the United States and the northern Gulf of Mexico, which was strictly based on local physical characteristics. Gutierrez *el at.,* (2009; 2011) used CVI derived data to explore future changes in shoreline for the same areas.

Similarly, a sensitivity index were employed by Shaw e*t al.,* (1998) to explore coastal sensitivity in Canada and by Sankari *et al.,* (2015) in India.

Some authors combined a Social Vulnerability Index (SoVi) that contained storm and socio-economic data (Boruff *et al.*, 2005), with Thieler and Hammer-Klose (2000) CVI into the Coastal Social Vulnerability score (CSoVi) to examine the vulnerability of the U.S. coast to erosion (Boruff, Emrich, and Cutter, 2005). Likewise, Thatcher *et al.*, (2013) applied a Coastal Economic Vulnerability Index (CEVI) to the northern Gulf of Mexico area to identify low-lying coastal areas vulnerable to flooding from storms and relative sea-level rise, including those physical characteristics identified by Pendleton *et al.* (2010), but also economic loss.

A Physical Vulnerability Index (PVI) was also employed in Morocco to map the relative coastal vulnerability to sea-level rise and storm events, also considering socio-economic data such as land use (Raji *et al.*, 2013).

In Australia several approaches were conducted to assess vulnerability to impacts across several regions from geomorphic and storm surge vulnerability mapping and probabilistic approaches to determine future patterns of coastal erosion (DEH, 2000; Abuodha & Woodroffe (2006, 2007, 2010); Harvey & Woodroffe, (2008); (Preston *et al.*, 2007; 2008). Gornitz *et al* (1991) and Thieler and Hammar-Klose (1999, 2000a, b) indices were also adapted to the Australian coast to evaluate patterns of shoreline change (Abuodha and Woodroffe, 2006) and to characterise susceptibility by means of Coastal Sensitivity Index (CSI) (Abuodha and Woodroffe, 2010b).

Sano *et al.* (2015) integrated vulnerability assessments with adaptation progress from coastal Local Governments.

In Tasmania, Sharples (2004) performed the first mapping of beach vulnerability assessing inundation risk. Later Sharples (2006) carried out a Geomorphic Stability Mapping (GSM) based on landforms and substrate characteristics to determine to potential climate change impacts on coasts such as sea-level rise and accelerated erosion. Similar to Gornitz (1991), Sharples (2006) exclusively employed physical factors but did not apply CVI.

Balica *et al.* (2012) developed a Coastal City Flood Vulnerability Index (CCFVI) to assess future vulnerability and compared the impact of climate change on cities in the long term.

In the European context, different tools for coastal mapping have been applied at different spatial-temporal scales (Ramieri *et al.*, 2011) ranging from index-based derived from US approaches to GIS-based decision supporting systems for mitigation and adaptation (Mocenni et al., 2009; Schirmer et al., 2003) or dynamic computer models (Hinkel, 2005; Hinkel *et al.*, 2010).

Locally sensitivity index in Ireland was also developed by Carter (1990) assessing the vulnerability of the coast from slope, coastal features and structures, and land use. It was also carried out in the UK by Pethick and Crooks (2000) using storm data (frequency and recovery time). Devoy (2008) analysed the vulnerability for Ireland by 2100 to 1m of relative SLR based on socio-economic components. Sustainability and adaptation case studies were carried out in vulnerable areas of Ireland and compared with other coast-like types in Europe (Sánchez-Arcilla *et al.*, 2016).

Vulnerability assessments based on natural vulnerability, socio-economic and institutional vulnerability (institutional responsibilities) (Angell and Stokke, 2014). Hammerfest (2010a) carried out a Risk and Vulnerability (RAV) assessments to plan and prepare for local adaptation at municipality scale considering extreme weather, storm surges and socio-economic factors.

McLaughlin (2001, 2002), developed a GIS-based vulnerability index for Northern Ireland evaluating physical coastal characteristics, coastal forcing and socioeconomic characteristics towards erosion and wave attack. McLaughlin and Cooper (2010) discussed the application of multi-scale coastal vulnerability indices and their scale relevance when developing metrics.

The British Geological Survey (BGS, 2017) produced a Coastal Vulnerability Index (CVI) that consists of some GIS-based set of layers rather than a single map that identifies susceptible areas to flooding and coastal erosion. The backshore layer was derived through an erosion susceptibility assessment considering the geological engineering properties of cliff. The foreshore dataset contains coastal geomorphological features (beaches, tidal flat deposits, saltmarshes or wave-cut platforms) that would potentially dissipate wave and currents energy at the cliff front, decreasing rates of erosion. Layers with cliff top height and prone inundated areas were also provided.

Satta *et al.* (2017) developed a Coastal Risk Index (CRI-MED) that assessed coastal risks and vulnerabilities from physical and socio-economic impacts of the Mediterranean. CRI-MED is a spatial risk index, which combines multiple data layers) representing facets of risk.

2.6. Limitations of CVI approaches: spatio-temporal constraints

Vulnerability assessments for coastal evolution analysis require a substantial amount of knowledge from different disciplines. Coastal vulnerability indices for vulnerability assessments are also disadvantaged by the lack of available data, coastal protection information and from the diversity of methods in use. When estimating risks, no method will identify the same hotspots (Hinkel 2008, Klein and Hinkel 2009). As a result, processes of quality data control, selection of indicators, weighting of variables, ranking of variables, construction of indices, interpretation, etc. are challenging (Moss *et al.*, 2001; Schmidtlein *et al*., 2008).

It is very important to be able to compare with other studies at a national scale or if possible, internationally (Eakin and Luers, 2006). Besides, some show a lack of focus or theoretical and conceptual framework (Eriksen and Kelly, 2007; Wamsley et al 2015) that determine how robust they are towards validation.

At a European level, the MOVE project (2008) or EUROSION project (2004) made attempts to unify vulnerability methods and quality criteria requirements in order to create a general framework and methodology for assessment of vulnerability to natural hazards in Europe. Nonetheless, international standard methodologies have not yet been enforced. There is still a lack of coordination regarding approaches for coastal vulnerability assessments. If vulnerability assessments have nothing in common (approach, result, or data used, metrics), it is difficult to compare or distinguish trends (Wolters & Kuenzer, 2015).

Vulnerability assessments are scale-dependent in space and time (McLaughlin and cooper, 2010; Yoo *et al.,* 2011) and these constraints should not be too broad or narrow (Pendleton *el at.,* 2005; Dawson *et al*., 2009). Different tools and methods could address coastal vulnerability at different spatial and temporal scales depending on goals and context. Introducing these two factors is relevant as they determine the amount of time and the type of exposed coastal elements (susceptibility), and therefore their vulnerability (Bonetti *et al.*, 2012).

CVI calculations are not predictive instruments and their information is limited by to short period of time or static (McLaughlin and Cooper, 2010). One of the current limitations of CVI and rank-based techniques applied to climate change is that they do not generally include climate impact model projections (Füssel, 2010). A coastal vulnerability index is useful in prioritising decisions. However, predictive tools are rather static and do not provide absolute predictions about the impacts of sea-level rise. They locate the areas within a region most likely to be affected. The validity of the CVIs can be tested against observed shoreline changes within a particular time frame since variables are subjected to time-spatial restrictions (Abuodha and Woodroffe, 2006).

Coastal processes span from hours (tides) to millennia (tectonic) and threats (SLR) from short to long term. Hence it is difficult to differentiate between current and future vulnerability due to the lack of data on future projections of sensitivity and adaptive capacity (Schauser *et al.*, 2010). Consequently, many studies are based on current vulnerability (less than 10 years) and do not account for future adaptation strategies (Masselink and Russell, 2013).

Uni-temporal studies are common. However, decision makers would benefit from multi-temporal assessments, evaluating what degree of vulnerability we are facing and identifying trends in this (Wolters and Kuenzer, 2015). When the hazard is supposed to change over time, the time horizon on which we are assessing vulnerability has to be specified (Wamsley *et al.*, 2015). These vulnerability assessments could address current vulnerability (Wang *et al.*, 2011a), or by introducing future scenarios (Thatcher *et al.*, 2013). Temporal variability should be reflected by the variables used (Bonetti *et al.*, 2012). Some studies introduce the barrier type to capture millennial scale trends of progradation or erosion (Abuodha and Woodroffe, 2010b).

Indices that consider large amounts of variability are more useful for long-term planning, and enhance resiliency. Sometimes some components of vulnerability reflect the current conditions (socioeconomic data) and others the future (sea-level projections).

Economic conditions such as population, houses, and roads will change over time, but it is difficult to predict how these variables will change. If vulnerability analysis in one area is only based on current conditions it will somehow underestimate future vulnerability to sea-level rises (Wu *et al*., 2002); whereas if future predictions are included in CVI then the validity of the vulnerability map would be extended in time (Thatcher *et al.,* 2013; Jimenez *et al.*, 2017**).**

Several research studies have assessed the impacts of climate change on Mediterranean coasts at national to regional scale (Torresan *et al.,* 2012; Jimenez *et al.,* 2017) or local scale (Sanchez-Arcilla *et al.,* 2011, 2016).

Indicator-based approaches constitute an efficient way to locate vulnerable areas at the local scale, which is the scale at which adaptation usually operates. Their metrics are developed for the purpose of their study and are consequently spatially scale-dependent (Wamsley *et al.,* 2015; Wolters & Kuenzer, 2015).

Different scales respond to different purposes and priorities and therefore show different information. The spatial resolution increases at a local and regional scale; a greater level of detail (and less perspective) is required to distinguish between areas of vulnerability, and some information only becomes evident at that scale. Going to larger areas would also add information on some variables as perspective is gained. In addition, the gradient of a particular metric may differ depending on the scale of the analysis; some metrics might not be relevant at one scale but valuable at another. It could happen that some variables become obsolete at a particular resolution. Results cannot be easily compared across scales directly or sometimes from different variables from components at the same scale. However, index values can be normalised, so each value is relative to the full range of values for that scale (McLaughlin and Cooper, 2010).

If operating at national level, important information at the county level could be masked (Adger *et al.,* 2004). Global scale methods do not apply directly to local areas, so local methods need to be adapted (Yoo *et al.,* 2014). When comparing to wider areas the same metrics should apply (Hinkel, 2011). Therefore, studies are sometimes not comparable either internationally or with other areas nationally where similar CVI methods has not been employed. Thus, some authors advocate a national-scale approach (Abuodha and Woodroffe, 2006). A general view could be useful for general assessment e.g. implementing to assess help, distribute EU funds and allocate money per counties, and then refine the target and resources (ie: focusing on vulnerable structures) when higher resolution assessments becomes available. However other authors recommend operating at small scales and then aggregating data into a simplified larger scale as the other way around is not a possibility if high resolution data has not been compiled in the first place (McLaughlin and Cooper, 2010).

2.7. Coastal processes and feedback mechanisms

Coastal dynamics respond to geomorphological and oceanographical factors through adjustments and process at different time- space scales (Cowell et al., 2003a, b); Patterns of Sea-level and sea surface changes (SLCs) constitute the main driver in coastal systems' evolution, which are exposed to processes operating at several varying timescales (Church and Clark *et al.*, 2014; Devoy, 2015). SLCs range from microscale to macroscale temporally and spatially (ICS, 2013). Short term (~10 years) to rapid (days-hourly) movements in sea levels, are caused mainly by meteorological and coupled Earth atmosphere ocean drivers (storms, wave movement or currents). Long term movements in SLC are driven by earth crustal land movement and ocean shape (10^{6-7} years). Intermediate short-term SLCs respond to glacial forcing (e.g. Quaternary (10^{5-6} years) (Lambeck, 2001; Church *et al.*, 2010).

However due to the multiple drivers operating at the coast, it is difficult to link those drivers to sea-level rise impacts (Nicholls *et al.*, 2009; Wong *et al.*, 2014). Sometimes human activity overcomes natural processes (Syvitski *et al.*, 2009). Also, the natural variability makes difficult the identification of impacts of climate changes. Therefore, beaches showing evidence of recent erosion does not mean that sea- level rise is the primary driver (Balica *et al.*, 2012).

To extrapolate climate change-related shoreline changes is difficult given the complexity of multiple contributing factors and interactions. Coastal systems such as estuaries, barriers and tidal flats will retreat in response to sea-level and wave climate changes. Earlier methods to assess SLR-induced coastal retreat were based on the fact that beach profiles will respond to sea-level rise by trying to maintain their relative position and shape based in the Brunn Rule (Brunn, 1969). Nonetheless coastal change process is locally variable and subject to a complex interaction of site specific factors (Masselink, & Russell, 2013). The proportionality between SLR and shoreline retreat established by the Bruun Rule only accounts for less that 50% of the likely changes at the coast (Nicholls *et al.,* 2007; Devoy, 2008; Church *et al.*, 2010) whereas the remaining retreat is subjected to climate-driven rainfall and river-discharge factors. Also SLR contributes to feedbacks associated to coastal processes like coastal-sediment flux and sedimentary infilling of coastal-accommodation spaces (de Groot *et al.,* 2012), which are responses connected to human interactions, and therefore influence the effectiveness of SLR in driving landward retreat (Bindoff *et al.,* 2007; Nicholls *et al.,* 2007; Church *et al.*, 2014). Moreover, erosion at one point will likely cause accretion elsewhere. In that sense, local (or regional) predictions in would be more useful than national to capture these processes (Montreuil and Bullard, 2012).

Novel multidisciplinary approaches on risk and vulnerability assessment models evaluate the joint probability from several impacts, typically concentrating on one variable's response, such as shoreline. These approaches look at the probability and magnitude of a particular hazard or perturbation that will affect the exposure of the system (Turner *et al.,* 2003). Recent coastal vulnerability studies have successfully applied innovative probabilistic methods based on Bayesian network calculations to analyse the shoreline sensitivity to sea-level rise. These were able to effectively validate it by hind-casting past shorelines, which made this method suitable for assessing the potential retreat of the coastline associated with future sea-level rise changes. (Gutierrez *et al*., 2011; 2015) included predicted probabilities of specific geomorphic characteristics using Bayesian networks (BN). Gutierrez *et al.* (2015) integrated BN data representing longer-term processes (shoreline change), short-term vulnerabilities (dune erosion) and anthropogenic modifications to the coast. One of the limitations is that these techniques mainly focused in one isolated physical aspect (i.e. shoreline evolution) instead of the overall system, and it could happen that the coastline might be stable when ecosystems or societies are already under pressure (Hinkel, 2011).

In order to understand erosion, multi spatial-temporal data at various resolutions, inundation levels, and erosion are necessary to understand the processes behind sediment transport and budget for numerical modelling (Bonetti *et al.*, 2010). Research has evaluated long-term shoreline responses, monitoring and modelling sea-level rise at decadal (Anthoff *et al.*, 2010) or millennial timescales (Woodroffe and Murray-Wallace, 2012); and also short-term adjustments to annual or seasonal events (Van Rijn *et al.*, 2003; Davidson *et al.*, 2010)

Regarding future scenarios of inundation, rising the sea by a certain amount does not mean all the areas below certain elevation will be inundated (Gesch *et al.*,2009; Thatcher *et al.*, 2013). The reason is the intricate physical processes that intervene on RSLR impacts (storm impacts, barrier island migration, wetland accretion, shoreline erosion, etc).

Some approaches used inundation mapping and numerical modelling to evaluate the impacts of short-long term processes on barrier islands (Gutierrez *et al.*, 2009; FitzGerald *et al.*, 2008). Long-term shoreline changes associated with sea-level rise were combined with human interventions on dune building and beach nourishment to derive long-term or short-term variability of coastal geomorphology (Plant *et al.*, 2014). Shoreline change was investigated under the worst case scenario of sea-level rise in sensitive areas to flooding (Bonetti *et al.*, 2012; Jimenez *et al.*, 2017).

Surface changes coupled with storminess patterns deeply affect the coastal evolution and processes (erosion, inundation and river discharge changes (Nicholls *et al.*, 2007; Kremer *et al.*, 2013)). In the long term, sedimentary coasts will adjust to rise in the mean sea level by retreating (Nicholls and Cazenave 2010). Sandy beaches recover rapidly after a storm as the sediment moved offshore during the storm and into a bar is returned to the beach. A beach comprised of primarily cohesive material does not have this characteristic (Wisely *et al.*, 2015).

In general, there is a lack of information in different contributors to SLRs, and feedbacks involved needed for validation of model outputs (IPCC WGI, 2007, 2014; Church *et al.*, 2010, 2013). Introducing ensembles of Atmosphere and Ocean General Circulation Models (AOGCMs) and the wider use of Regional Circulation Models

(RCMs) improves the knowledge of the constraints on systems contributing to SLC, but there are still large uncertainties (IPCC WGI, 2014).

Decadal scale climate change variability has an effect on storminess and sea level (Wang *et al.*, 2009; Phillips and Crisp, 2010) and consequently on coastal movement. Sea-level fluctuations patterns at the local-regional context (e.g.,Bindoff et *al.*, 2007; Nicholls *et al.*, 2007; Church *et al.*, 2014) are possibly driven by short-term sea-surface change factors, such as salinity density; steric effects, local currents, and El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO) and North Atlantic Oscillation (NAO) variability.

Connection between the NAO and changes in erosion and coastal process impacts in the North Atlantic has been identified (Stone and Orford, 2004). Also, geomorphological changes on soft cliffs (spatial and temporal variation), sediment supply and transport rates have been linked to NAO variability in the East Anglian coast (Brook and Spencer, 2014). Unprotected soft cliffs respond to NAO variability over decadal and multi-decadal timescales as opposed to shorter term variability in water levels associated with tides sea level rise as the main driver.

As shoreline changes are oscillating, so this type of analysis requires sufficient data records that at least cover the long-term mean rate of change. Consequently, in the future, rates of sea-level change as the main factor of coastal change (FitzGerald *et al*., 2008; Gutierrez *et al.*, 2009) should not diminish the importance of other significant forcing factors such as of variability in storminess. Policymaking and coastal management practices should take this into account (Brook and Spencer, 2014).

Coastal erosion comes as a result of natural and human-induced factors acting at different scales (Bonetti *et al.*, 2012). Coastal change is difficult to assess in between storms and accretion/fore dune building periods (Abuodha and Woodroffe, 2010b). Storm impacts occur at short time scales (days to weeks) but storm recovery could take months to years. Inter-storm recovery is a crucial parameter when it comes to determine long-term coastal resilience to climate change, storminess variability and sea level rise (Brooks *et al.*, 2016). Low-frequency, high-magnitude storms will sometimes have a greater impact on the coast than sequent smaller storms. But if those are too frequent, a threshold might be crossed and the area will not recover (McLaughlin and Cooper 2010).

Morphodynamic responses come from a combination of shore face bathymetry, sediment availability and inshore hydrodynamics. In the regional context, storm impacts will be different depending on shoreline characteristics. The primary controls for beach recovery and shoreface gradient are the tidal range, migratory sub-tidal and intertidal bars. Sufficient drying times for sand and also aeolian transport requires winds above 8 m s^{-1} (Masselink *et al.,* 2006; Houser, 2009), If strong winds coincide with falling tides, exposed sand is prone to dune building**.** Over time, this barrier recovery potential from storm impacts will determine the future survival of coastal ecosystems, communities and infrastructures on high-energy coasts. Gathering knowledge of time-space dynamics, dune growth and barrier recovery processes, can be highly beneficial in future coastal management planning with projected sea-level rise and storminess (Brooks *et al.*, 2016). It is also important to understand the spatio-temporal dynamics of storms, surges and extreme waves and their impact upon morphology (Spencer *et al.*, 2014; Masselink *et al.,* 2015).

In this regard GIS-based studies have evaluated shoreline movement, profile analysis and field measurements, monitoring barrier responses, after storms and during non-storm, to analysis future shoreline responses to rising sea levels and storm variability (Brooks *et al.*, 2014; 2016). However more multidisciplinary approaches with quantitative predictions of storm impacts and post-storm recovery are needed (Wang *et al.*, 2015).

According to Nicholl (2015), adaptation should be analysed in a context that includes driver’s effects and complex interaction and feedbacks that might aggravate impacts, in response to future sea-level rise and associated storminess (Wong *et al.*, 2014). Rising sea levels will be accompanied by other coastal processes, apart from submergence, such as wetland loss and change, erosion of beaches and soft cliffs, saltwater intrusion into groundwater, and direct and indirect human impacts (Nicholls, 2015). That is why some author recommends including them in impact and adaptation assessments (Wong *et al.,* 2014). For instance some studies have assessed drivers, pressures, coastal state, impacts, and responses of local systems so flexible adaptation strategies can be developed in respect of long term trends and for short terms events (Sanchez-Arcilla *et al.*, 2016).

Nonetheless, this would add an extra challenge to already complex coastal vulnerability assessments.

2.8. Best practice for Coastal management. Knowledge gaps

Techniques to assess vulnerability of coastal communities should plan to mitigate vulnerability. Coastal vulnerability and impacts assessment lack uniformity (Harvey and Woodroffe, 2008) and consistency in methods (Pled *et al.*, 2010; Hinlkel, 2011). Currently there is an absence of standardization of concepts, scales, methods, assumptions, parameters in the development of indices for identification of vulnerable areas, which limits comparability across studies and countries.

This problem does not seem to be close to being solved and consequently the urgency is to carry out accurate strategies on vulnerability mapping suitable for comparison ((Nguyen *et al.*, 2016). As a result, consistent methodology, clear description on assumptions and methods for ranking of variables, importance of variables, and variability on that scale, is not usually well defined in literature (Nguyen *et al.*, 2016).

In general, there is a need for coastal assessments that are able to capture the main factors of vulnerability supported by an intense evaluation of metrics (Nguyen et *al.*, 2016; Wamsley *et al.*, 2015). Coastal assessments lack site-specific metrics that reflect description of systems and dynamics. In general, models to predict coastal responses lack predictability capacity, with a few exceptions on cliff shorelines. But even in these cases, erosion processes are poorly understood (Masselink and Russell, 2013).

There is also a necessity to focus on the scale-dependence of parameters either physical or socio-economic (Nguyen *et al.*, 2016). Even though better results are yielded from physical variables, rather than socio-economic, validation is still complicated, and consequently absent in most vulnerability studies (Wolters and Kuenczer, 2015).

Building resilience for expected future impacts will require an active cooperation from natural, social, and engineering sciences to political decision making, stakeholders, Coastal Zone Management and Marine Spatial Planning policies and legislation, and industry. In order that the benefit of vulnerability studies extends into management planning strategies, it is advisable that stakeholders are involved, and their needs are addressed by research (Nguyen *et al.,* 2016). Policy and decision-making objectives should be identified before developing a metric for vulnerability assessment (EEA, 2012; Wimsley *et al.,* 2015).

However most of the coastal assessment studies from literature do not mention any stakeholder group (Masselink and Russell, 2013), indicating that these studies are purely scientifically orientated or the link to decision makers is non-existent. A closer relation across the scientific community, fragmented by cultures and management concepts, would be desirable (Kremer et al., 2013; Metzger & Schröter, 2004).

Additionally, it is important to communicate results in a transparent form to stakeholders, policy makers, local authorities or the general public (Masselink and Russell, 2013). After all, they will benefit from research and adaptation measures accordingly. Better understanding on coastal vulnerability will facilitate that new adaptation techniques can be adjusted to coastal vulnerability (Cooper and Pilkey, 2012; Wong and Losada, 2014; Nicholls, 2015).

Indicator-based vulnerability assessments should be a key component of decision-making in integrated management (Nguyen *et al.*, 2016). Likewise, integrated Coastal Zone Management (ICZM) should issue an effective response through an appropriate adaptation approach in order to reduce vulnerability by minimizing climate-related impacts or enhancing resilience (Nicholls *et al.,* 2007; Wong *et al.,* 2014).

Despite the lack of agreement on future sea-level, research examining different scenarios of sea-level rise and climate change is required at all scales from local to global (Wong *et al.,* 2014; Nicholls, 2014). Coastal management measures should be based on all available information, from mean and high-end sea-level rise scenarios (Renn 2008; Hinkel *et al.,* 2015).

2.9. Chapter summary

Projections on sea-level future changes are subject to a significant number of large uncertainties: ice dynamics, changes in storms, wave climate, but also on the responses of the coastal system. Coastal assessments should consider several scenarios, with a special focus on hotspots.

Climate changes and associated vulnerabilities won't be uniform around the world (IPCC, 2013). Therefore, in order to minimise impacts on humans and ecosystems we need to know how, where, and when to adapt and what to adapt for. Henceforth local and regional vulnerability studies are needed.

Coastal vulnerability indices and rank-based (CVI) methodologies have to be robust to assess relative vulnerability from local and national scales. Indices do not only provide information about potential areas likely to suffer damages regarding future sea-level rise, but also identify local/regional areas most prone to physical changes. CVI development of metrics is extremely important and will not depend not only on what has been identified as important to measure but also on the temporal and spatial scale of the assessment and data availability (Wolters & Kuenzer, 2015). In the lack of standardised international methodology, those methods should be adapted to the context and the purpose of the study, using the best available data (McLaughlin and Cooper, 2010).

SLCs have a critical role in assessments and numerical modelling of physical coastal-system changes (Church *et al.,* 2014). Micro- macroscale controls on coastal system processes and feedbacks affect sea-level movements and vice versa (IPCC, 2007, 2014). However, complex interactions are difficult to identify, quantify and moreover, to incorporate into coastal assessments.

According to Nicholls (2014) integrated assessment are required to accurately assess interacting drivers, including the feedback of adaptation. The key to coping with future impacts of sea-level rise will depend on the magnitude of increase, coastal characteristics, coastal development and adaptation progress. Even with mitigation and adaptation, huge challenges lie ahead (Church *et al.,* 2013) and therefore long-term, planned measurers versus autonomous, should considered (Nicholls, 2014).

Half of the Irish population lives in coastal areas. There is an urgent need in Ireland for estimating and assessing the vulnerability of coastal systems and supporting effective policy responses (McFadden *et al*., 2007a). Despite the evidence of accelerated coastal erosion and coastal change, and ecosystem losses, few studies in Ireland have truly quantified the relationships between observed coastal land loss and the rate of sea-level rise, wind and wave erosion (Mulrennan,1990; 1993; Carter, 1991a; Devoy, 2000, 2008; EUROSION, 2004; Robinson, 2009; OPW, 2010; Coll *et al.*, 2012). EMODnet Project. However suitable, quantitative approaches, especially at high resolution would be extremely valuable if we are to adapt to a warmer world (Devoy, 2000; 2008). Improved knowledge of the physical and socio-economic components would be highly beneficial for flexible adaptation solutions in the coastal zone (Sánchez-Arcilla *et al.,* 2016).

Despite the growing awareness that future events could have catastrophic consequences when assuming no adaptation (Hallegatte *et al*., 2013; Hinkel *et al.*, 2014), only a few countries are actively preparing for it (Stive *et al.*, 2011; Tarrant and Sayers, 2013).

The IPCC (2013) and the European Commission encouraged EU members to identify gaps in knowledge. As years go by, national and regional adaptation strategies and vulnerability assessments are implemented but we are still in need of local accurate vulnerability studies (EC, 2013). The National Climate Change Adaptation Framework (NCCAF) (DECLG; 2012) intends to provide local adaptation strategies for reducing vulnerability to future climate change in Ireland (Adger *et al.,* 2005b). In this regard, the gathering of high-quality information to assess vulnerability at the local level (EPA, 2013) and a wide range of potential impact scenarios would be extremely useful (Gleeson *et al.*, 2013).

Case studies can be seen sometimes as a proof of concept for new methods in data rich areas (Church *et al*., 2006). The Dublin-Wicklow area has been already identified as prone to risk of flooding and erosion (OPW, 2010; Flood, 2012). However, these studies employed simplistic methods and did not take into account the complexity of coastal behaviour or future climate uncertainties. Examining the current physical exposure and future sensitivity to changes in sea-level rise is far more complex than that.

High resolution coastal vulnerability index-based approaches would provide information in a simplified manner, facilitating a rapid assessment and visualization of the system's susceptibility. Quantitative predictions of future storm impacts using local predictions would improve coastal zone adaptation (Wang *et al.,* 2015). This can be used as a guide for planning adaptation and implementation of new ICZM strategies to increase the Irish coast's resilience to sea-level changes.

Under the CoastAdapt project (Interreg programme funded) In Europe some studies have addressed local impact and adaptation strategies and tools in coastal communities engaging local stake holders (Muir *et al.,* 2014). Community's vulnerability to impacts to erosion and flooding was evaluated from site studies, workshops and questionnaires.

At the local/regional scales some practical ICZM have been assessed (eg: Bantry Bay Project). However Regarding implementation of ICZM and climate adaptation in Ireland, there is not a national policy framework for an integrated approach to coastal management (Muir *et al.,* 2014). In other countries Risk and Vulnerability (RAV) assessments were carried out to plan and prepare for local adaptation at municipality scale considering extreme weather, storm surges and socio-economic factors Hammerfest (2010a).

These low-lying, soft rock, sedimentary coasts of Dublin-Wicklow, exhibit a combination of factors for being justified as a potentially vulnerable area, and therefore suitable for testing latest international methodologies. In addition, not only its physical exposure, but socio-economic factors such as high population and concentration of economic assets, makes the location highly sensitive to storm and sea-level rise events. Important structures such as ports are very exposed; therefore future scenarios of inundation would be beneficial for long-term port management and planning (Sierra *et al.*, 2016). However, coastal management should not only provide for better usage of coastal zones but at the same time natural environments should be protected (Jimenez *el at.*, 2017).

Chapter 3: Characteristics of the study area and its environs

3.1. Physical environment

Geology, geomorphology and post-glacial history are essential factors when analysing the characteristics of the coastline. The Irish coast (7400 km long) can be classified as paraglacial (Carter, 1990). It is also highly variable in terms of wave climate and energy, geomorphic development and dynamics (Carter and Orford, 1988).

Documented studies on coastal erosion in Ireland have revealed that most of the Irish coasts are undergoing retreat (Salman *et al.*, 2004). A total of 3,000km of the coast has been classified as 'soft coast', of which over 50% is considered to be at risk from erosion (Devoy, 1990). Approximately 20-30% of this has been categorised as highly vulnerable, mainly southern and eastern coasts and in imminent danger of erosion (DELG, 2001).

The eastern counties of Co. Dublin and Wicklow are susceptible to wave action, tidal and storm surges (Devoy, 2000) and they are predisposed to geomorphological changes from active erosion and deposition processes (McCabe, 1989; EUROSION, 2004; Clark *et al*,. 2004; 2010; Robinson, 2009) and flooding (OPW, 2010; Flood, 2012).

Even though erosion is generally smaller in urban areas due to the existence of coastal defences or naturally resilient areas, potential risk to coastal flooding does exist (OPW, 2010). In fact, according to a Coastal Zone Management report (Martin, 1997), the urbanized soft coast of Dublin is one the three most vulnerable areas of the country to flooding; an important consideration given the concentration population within the Greater Dublin region. It is also an area of major concentration of socio-economic assets, which is a further reason for making it the focus of this research. Figure 3.1 illustrates vulnerable areas in Ireland.

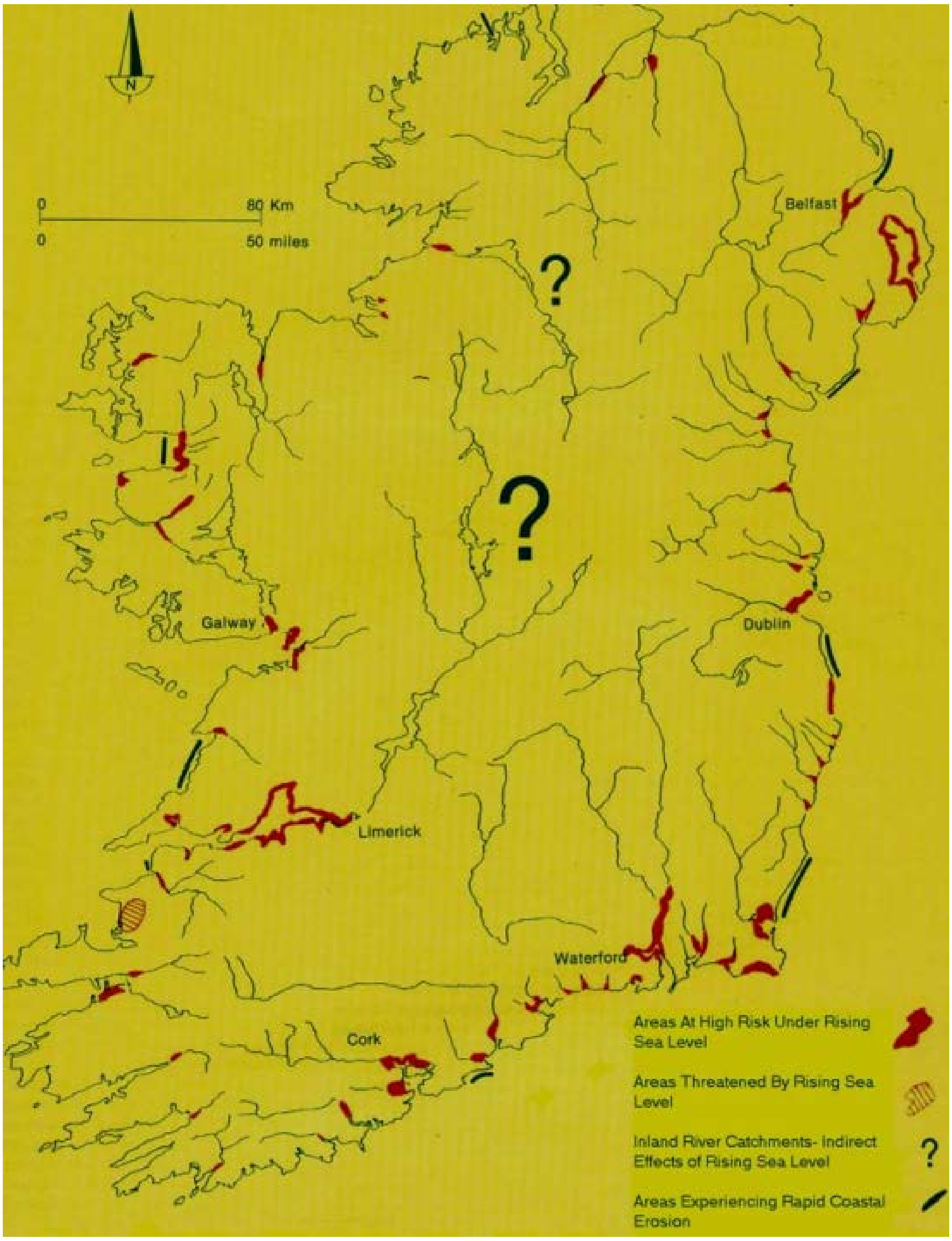


Figure 3.1. Vulnerable areas to relative sea-level and erosion by 2100 by (after Devoy, 1990).

3.1.1. Geological setting

Irish geological context can help to understand the nature of the unconsolidated sediments and their instability towards coastal erosion and sea-level rise.

The current profile of the county Dublin and Wicklow coasts was mainly shaped during the last glaciation between ca. 26kyrs and ca. 17.3kyrs BP (Ballantyne *et al*., 2006).

Three large ice sheets united: the Irish Sea Ice Sheet, the Northern Ice Dome and the Wicklow Mountains Ice Sheet (Hoare, 1975; Synge, 1977). When those ice sheets retreated they left huge amounts of glacial/glaciofluvial sediments behind reaching thickness of 4.5m to 30m in areas such as Dublin Port and Killiney beach (Pellicer, 2008). As consequence, the Dublin-Wicklow areas are largely covered by soft sediments with underlying bedrock, mainly outcropping in areas such as the Howth Peninsula and Wicklow coastal heads (McConnell *et al.,* 1994).

The most common deposits in County Dublin are glacial and glaciofluvial derived from Lower Carboniferous limestone bedrock (brown and black boulder clay). Co. Wicklow’s complex geology is characterised by Pleistocene glacial deposits, mainly boulder clay, covering much of the ice-sculpted bedrock topography (McConnell *et al.,* 1994; McConnell and Philcox, 1994; Farrell *et al.*, 1995).

Coastal systems

The study area encompasses a coastal strip that runs from Portrane to Arklow with an inland buffer of approximately 1-1.7 km covering an area of approximately 188.7 km^2 (see Figure 3.2).

The main coastal systems in the study area include two morphological units: flat coast and cliffs (hard rock and/or soft unconsolidated material). Flat coast sections are composed of sandy and gravelly/shingle beaches, spits and barriers, tombolas (e.g. Howth and Sutton). Flat coasts in the study area can be categorised as sensitive environments represented by low-lying extensions of sandy beaches, sand dunes, plains and spits and large sandy plains in the onshore area (ECOPRO, 1996; Cooper and Pile, 2014). Sandpits are usually semi-parallel to long-shore currents and perpendicularly (N-S) orientated to wave direction (Devoy, 2015a).

In the northern end of the study area (from Howth to Portrane) glacial and fluvial actions have shaped the coast into bays and sandy-muddy estuaries. Large quantities of unconsolidated glacial clays, sands and gravels were swept up and incorporated into coarse-grained storm beach ridges, partly closing the bays and creating estuaries behind them (Mulrennan, 1990). Sheltered areas in north Dublin accumulated low-energy fine sands and muds represented by lagoons, salt marshes, mudflats and sand flats, and also intertidal ridges and runnels in the near shore area

(Carter 1991b; ECOPRO, 1996; Charlton & Orford, 2002). Those areas in north Dublin (eg Portmarnock to Rush) are naturally resilient but vulnerable from being urbanized (Sanchez-Arcilla *et al.,* 2016). North Dublin bay saltmarshes will face inundation whereas sand dune systems like the ones around Bull Island will be replaced by erosion (Brooks *et al*., 2016).

Hard cliffs are represented by headlands alternating with soft, unconsolidated cliffs forming a bay-like coastal profile that provides strongly dissipative morphodynamic regimes (Mulrennan, 1990; 1992). Dublin Bay is formed by Lower Carboniferous Limestone is encloded in between two headlands Cambrian rocks at Howth Head and Silurian Leinster granite in Dalkey Head. Rocky and pebbly shores alternate with fine sands as a result of complex inshore currents and tidal flow impeded by the headlands. Dublin Bay is essentially dominated by large sand banks at both margins extending to Bull Island by means of a large sand dune complex. Rivers discharge into the Irish Sea brings smaller silt and clay sediments to in the intertidal areas, which could mitigate the narrowing of intertidal areas from SLR (Brooks *et al.*, 2016).

Further south, series of outcrops such those at Bray, Greystones, or Wicklow alternate with low, soft unconsolidated of Irish Sea Till derived from limestones and Cambrian sandstones and shale and also with gravels and sandy, gravelly alluvial and glaciofluvial sediments. Shingle and gravelly shores are present in South Dublin and also Co. Wicklow along with sandy beaches/sand-dune systems edged by low rocky cliffs (McConnell and Philcox, 1994). See Plate 3.1 and Plate 3.2.

Beaches will suffer from squeezing in future years (Devoy, 2015b). On barrier coasts will also migrate with higher sea-levels in episodes controlled by sediment accommodation and availability (Masselink and Russell, 2013). Also, estuaries could migrate landward and upward (Rossington and Spearman, 2009), unless sediment is reduced, in which case they will deepen. Natural responses could be reduced with coastal defences (Masselink and Russell, 2013).

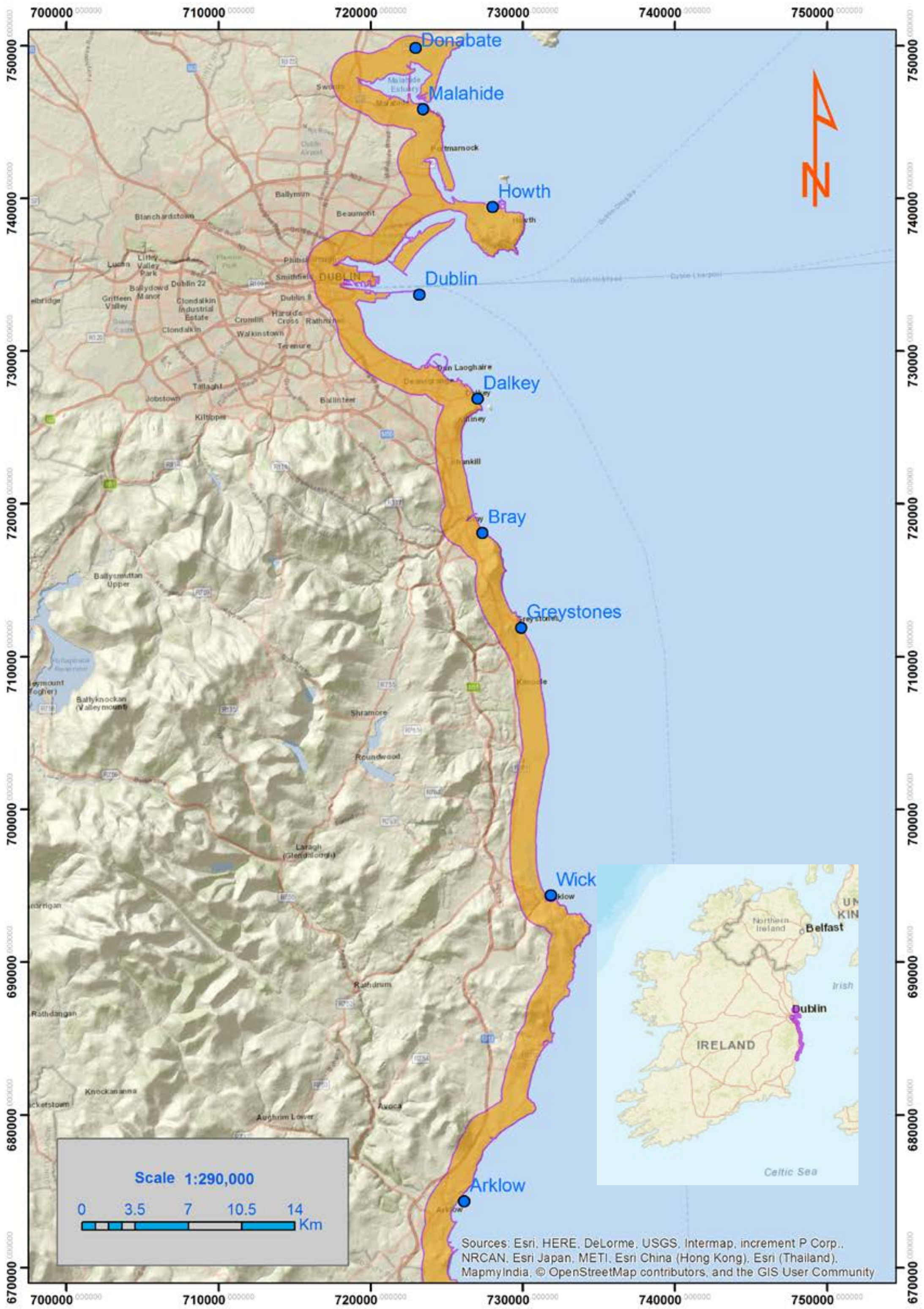


Figure 3.2. Map showing the location of the study area (*Source: Silvia Caloca*).

Plate 3. 1. Views from top left to bottom: sandy beaches in Donabate (North Dublin); low, rocky cliffs at Malahide; lagoon/salt marshes in Portmarnock-Baldoyle; sand-dune systems in Bull Island. View from Howth-Bull Island to Dublin Bay. *Source: Upper left (*Google Earth images @ 2018 Digital Globe)*; others by Silvia Caloca.*

Plate 3. 2. Views from top left to bottom: Shingle and gravelly beaches flanked by soft, till cliffs with gravels (Killiney-Corbawn); Bray Head hard rock; unconsolidated, till and gravel cliffs at Greystones; Gravelly alluvium sediments (Kilcoole-Newcastle); small bay-like showing blown sand in dunes development (South Wicklow). Shingle and gravelly beaches (Bray). Source: two upper right (Google Earth images @ 2018 Digital Globe); *others by Silvia Caloca*.

3.2. Climatic and marine dynamic controls in the study area.

A good knowledge of current and past storm patterns, and their effects, is desirable for coastal assessments (Stone & Orford, 2004).

Ireland is positioned on the path of major North Atlantic storms. This greatly influences wind directions and wave heights in Irish coastal waters which are exposed to strong wave energy and regular low-pressure systems (Füssel 2007; Devoy, 2008; Sweeney *et al.*, 2008;. Consequently, storm surges in the Irish Sea are associated with major Atlantic depressions, usually from a westerly direction (Sweeney, 2000).

Surge strength depends on the speed, intensity and size of the depression as it approaches Ireland (Orford, 1989). The effect of wind on surge levels largely depends on topography, particularly in shallow waters where tide and wave heights get amplified. Gentler gradients, like those in the study area, will influence the impact of future sea-level rise in surges heights (Devoy, 2008; Wang *et al*., 2008). In the shallow-wide Irish continental shelf, wind speed and direction rather than atmospheric pressure, influences storm surge height (McFadden *et al*., 2007a). Hence, in the south Irish Sea, surge height is dominated by the low-pressure effect whereas in the North Irish Sea the wind effect adds ~72% to the height of the surge (Lowe *et al.*, 2001). Extreme surge heights are expected in both the North and South Irish Sea (Flather and Smith, 1998; Lowe *et al.*, 2001; Woodworth *et al.*, 2005) accompanied by changes in 10-50 year return periods (Lowe and Gregory, 2005; Wang *et al*., 2008;). Winter and spring storm wave heights might also increase (Gleeson *et al.*, 2013).

In recent years, exceptionally frequent and intense winter cyclone activity with associated extreme wind speeds, tidal surges and low pressure have caused serious damage on Irish coasts (E-surge, 2014; Met Éireann, 2015; Matthews *et al,*. 2016). The east coast of Ireland was affected by important surge flooding in February 2002 and October 2004. In January 2014 a surge of about one metre coincided with one of the highest spring tides of the year causing intense flooding (Plate 3. 3).

Track of storms and tide conditions could influence flooding potential. In December 1989 the biggest storm surge on record (0.937m) caused by a low pressure system traversing Ireland did not cause much flooding when it hit Dublin fully but at low tide; whereas the 2002 event was a deeper low-system tracking further north and yet it brought intense coastal winds that derived on extreme surge.

Plate 3. 3. Extreme water-levels at the Liffey rivers mouth in Docklands (Co. Dublin) produced by storm-surge that hit Ireland in early January 2014. (*Source: Silvia Caloca)*.

A tide ranging up to 2.2m OD would not cause flooding in Dublin, unless it is combined with a storm surge. This will generate water levels of over 2.5m OD Malin at which the flood warning is activated. This happened in February 2002 when the highest spring tides of the year (1.95m OD) coincided with a surge 0.91m resulting in an extreme water level of ~2.9m OD (the highest on record). See Figure 3.3.

Interestingly enough, sea-level rise on the top of spring tides will not always produce inundation. However, it will have an impact on frequency of extreme events. Thus, 40cm of extra water level from sea-level added to the 2002 event, would convert the 1-100 year event into 1-5year event (Dollard, 2003; IAE, 2007). Sea-level rise will also impact on the 1 in 200-year return period, increasing significant wave heights and raising water levels by at least 0.5m by 2100 (RPS, 2007). Assuming a medium RCP scenario of 0.48m in the future, the 100-year extreme weather occurrence will happen every 1-2 years in Ireland by 2100.

Figure 3. 3. Surge record of 1 in 70yr extreme event that hit Dublin City and Fingal in February 2002. (Met éireann. (2002); Available at http://www.met.ie/climate-ireland/weather-events).

3.2.1. Tidal regimes

Tides are one of the dynamic controls that significantly vary in scale around Ireland. Tidal regimes in the study area range from meso (spring tidal range 2-4 m) but also include microtidal areas in the southern part (<2 m (Carter, 1991a) (Figure 3.4).

Most of the tidal motion at the Irish Sea comes from oscillations of the Atlantic Ocean tidal regime. The structure of co-tidal elevation is virtually the same for both M2 and S2 constituents (lunar and solar forces), supporting the major influence of the amphidromic point (zero tide) on the Irish Sea (Figure 3 5).

Tidal heights refer to Chart Datum (CD) and this datum varies from port to port. However, it is usually set to-or near to-the Lowest Astronomical Tide (LAT) at the nearest port. Mean sea-level at Dublin is 2.46m CD whereas it is 1.30 m CD at Arklow. This small variation in mean sea-level between the two ports is as a result of the influence of land masses and friction inertia, among other factors, and has an effect on tidal movements (ECOPRO, 1996).

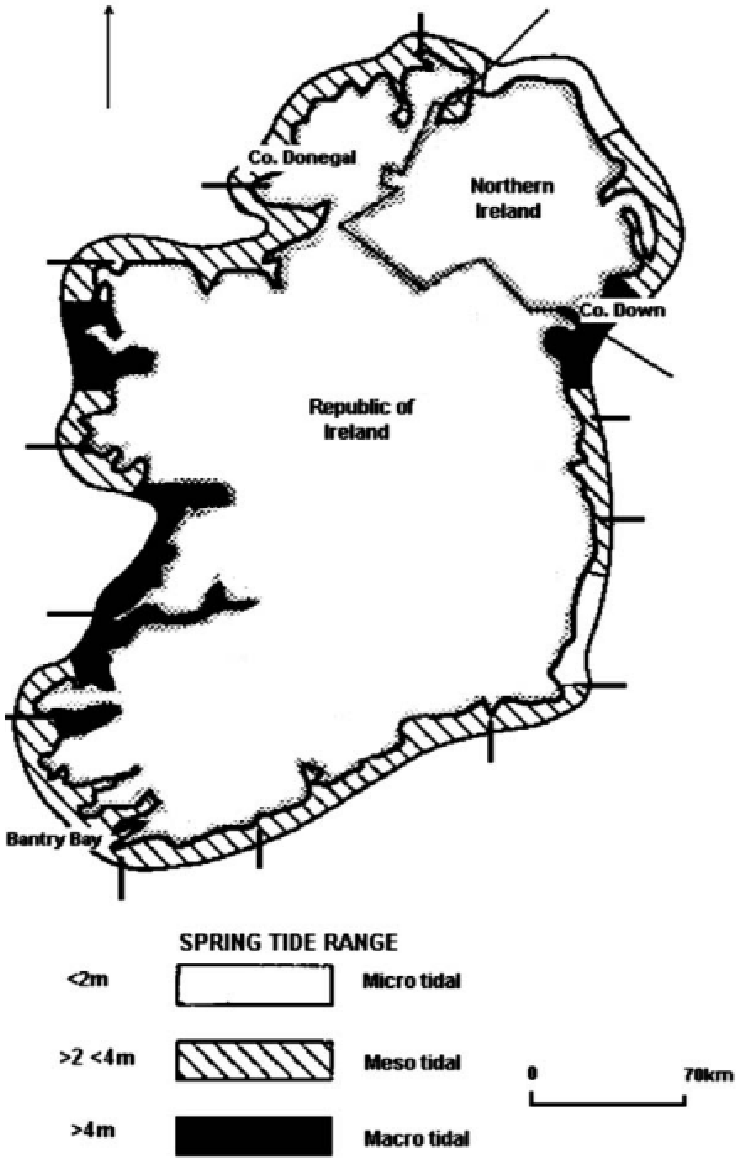


Figure 3. 4. Variation of spring tidal ranges around the Irish coastline (Carter, 1991a).

Maximum tidal range on the east coast is associated with the shelf areas that underlie the potential amplification of shallow waters. Hence, there is a spring tide elevation gradient on the Irish coast from 0.6m at Arklow to 4.5m in Dundalk Bay.

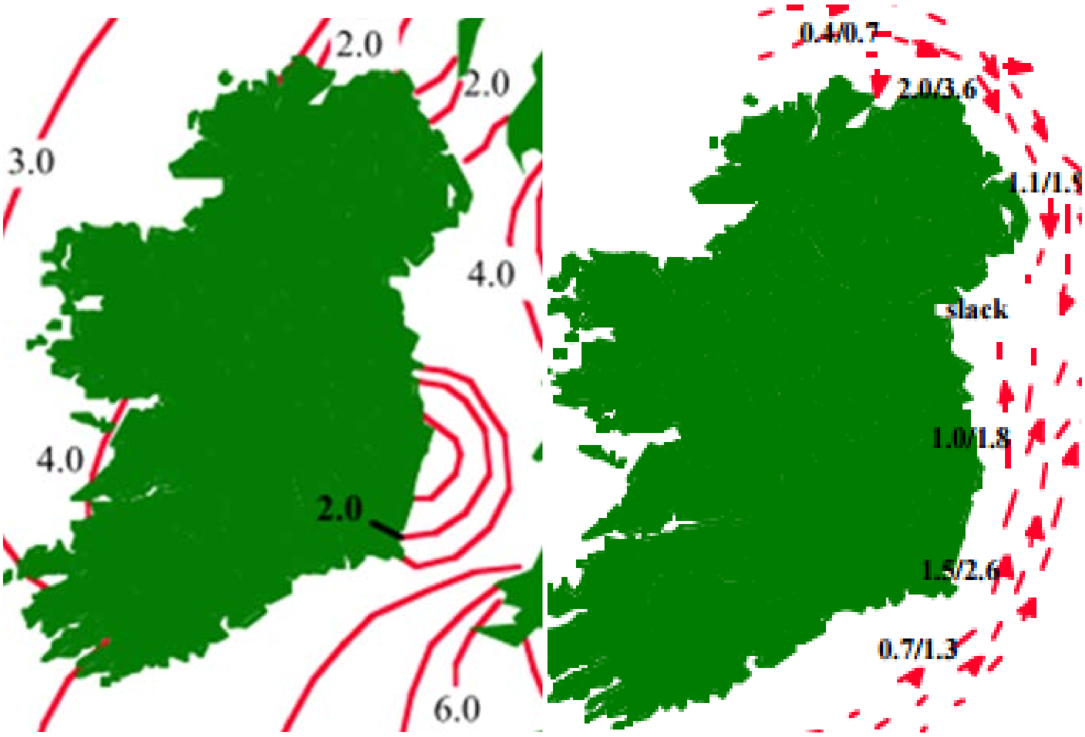


Figure 3. 5. Left. Influence of the amphidromic point on spring tidal range in the Irish Sea. Right. Tidal currents maximum depth averaged flow (m/s). Source ECOPRO (1996).

3.2.2. Exposure to wave climate

Irish Sea coasts only receive about 20% of the wave energy occurring on open Atlantic coasts. While locally-generated sea waves dominate, swell waves entering the Irish Sea through St George's Channel and the North Channel, have an important role (Carter, 1983).

Waves from 90-180 degrees, following the strong south to west air flows are predominant in this area. In the relatively low-energy coasts of the east of Ireland, deep-water Hs waves decrease northwards, and rarely exceed 8-10m during storms. The median (Hs modal) in the Irish Sea region is 1.6-2 m with extreme (1 in 1000) wave heights of 1.9-2m (Orford, 1989; Carter *et al.*, 1993; Gallagher *et al.*, 2014). See Figure 3.6. Future projections indicate that significant wave heights in this area are due to increase (McGrath *et al.*, 2012).

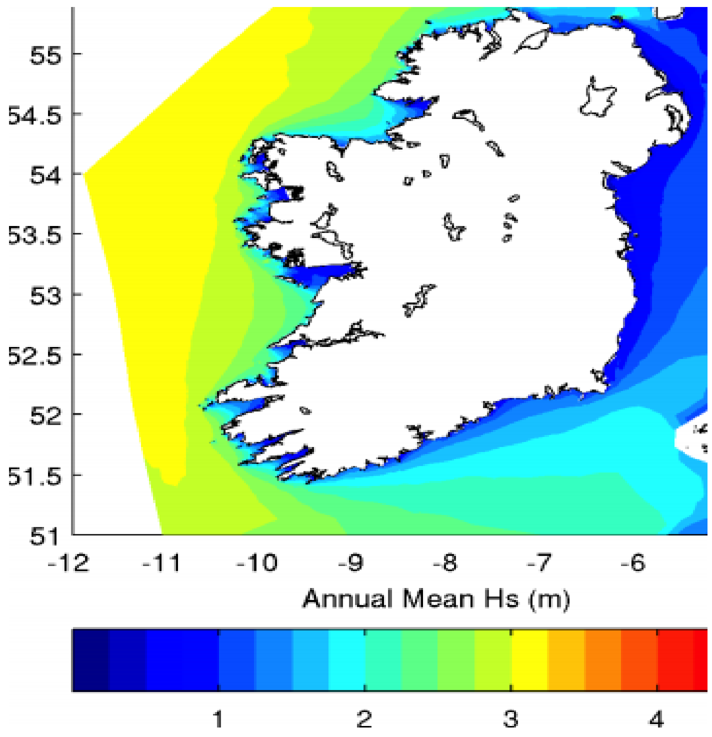


Figure 3. 6. Annual Significant wave Height (Hs) for the period 1979 to 2012 (Gallagher *et al.*, 2014).

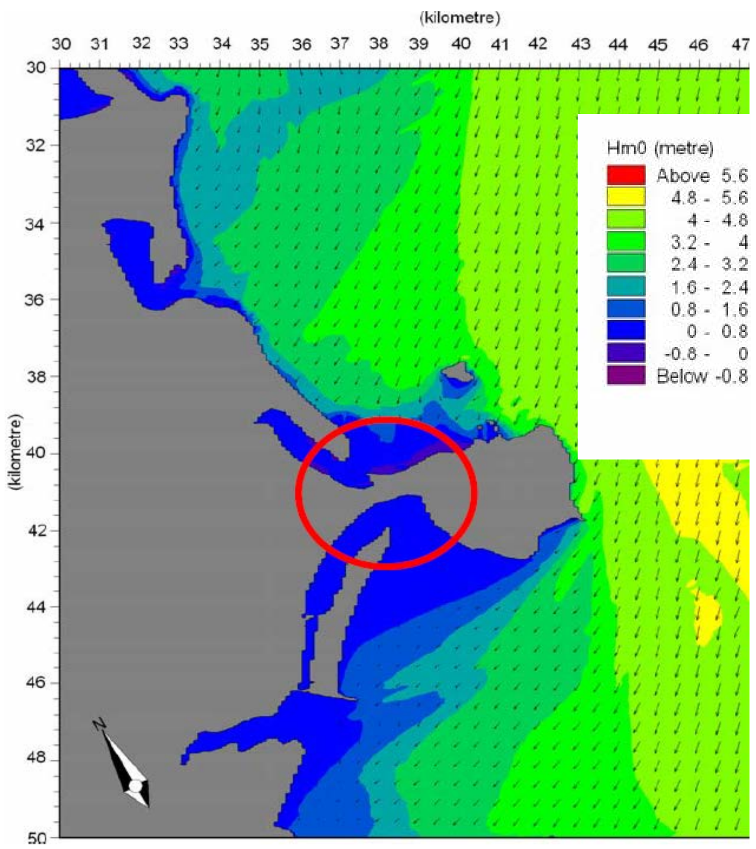


Figure 3. 7. Significant wave heights (Hs) and mean direction from a northerly storm at high tide approaching North Dublin (*OPW, 2010*).

Storm's trajectory and bathymetric controls, such as offshore banks, affect wave trajectories as they approach the coast (Lozano *et al*,. 2004; Regnauld *et al*., 2004). Wave heights and directions from northerly storms can overexpose vulnerable areas such as e.g. Sutton (*OPW*, *2010*) (Figure 3. 7).

3.3. Current relative vulnerability of the study area

3.3.1. Erosion processes

In the study area, eroded sediments generally move alongshore following dynamic processes of erosion and deposition, controlled by sediment supply and waves. Any increased acceleration in coastal retreat under future sea-level rises would result initially in an amplification of this Holocene pattern of coastal morphological development, tending to slow any initially enhanced erosion rates (Devoy, 2000; 2008).

However, coastal erosion varies markedly according to whether coasts are fronted by bedrock or glacial sediment (Carter, 1992) and by the overall energy regime of the coast (Carter and Bartlett, 1990). Cliff and beach sediments are transported offshore into banks which can interfere with wave action According to Carter *et al.* (1987) and Carter and Wilson (1993) there is frequently a deficit of gravelly sediment supply from the offshore-shelf, except from big storms. At the same time, coastal barriers are trapped against hard coast and uplands, and then sediments are reworked and reallocated alongshore, causing coastal squeeze (Pethick, 1993; Pye and Allen, 2000).

Since the late Holocene, sedimentary barriers attached to high hard-rock surfaces are being dissipated, impeding the adjustment of soft sediments required to face future sea-level rise (Salman *et al*., 2004; Devoy, 2008). Steep surfaces restrict onshore movement and adjustment capacity towards sea-level impact, with chances of losing these systems.

Considerable morphological changes in estuary/barrier complexes in North Dublin, mostly related to reclamation of estuaries and man-made structures and disruption of the tidal regime, have been monitored since the 19th century (Mulrennan, 1990; 1993). See Figure 3. 8.

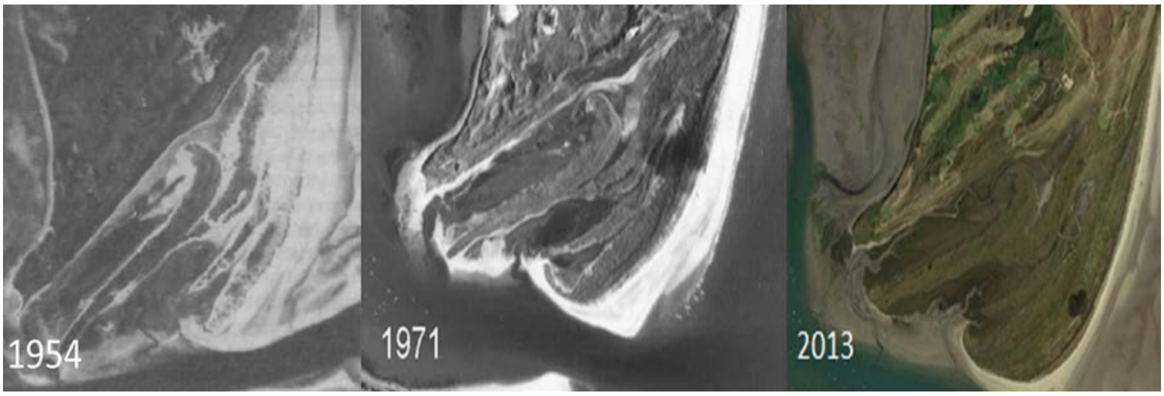


Figure 3. 8. View showing shoreline changes in Donabate- Corballis sand-dune system *(Source: Left, OSI imagery (2013); right: Google Earth images @ 2018 Digital Globe)*.

More recently, evidences of ecosystem losses and accelerated coastal erosion have been detected in the study area (National Coastal Erosion Committee, 1992; EUROSION, 2004; Devoy, 2008; Robinson, 2009; OPW, 2010).

Erosion rates in Ireland vary from 0.5-1 m/year with mean annualised erosion rates of 0.6m for all south East coastal areas. The so-called 'vulnerable soft coast' between County Down and County Wexford, constitutes the most vulnerable along the Eastern Irish coats. This area erodes at 0.2-1.6 m/yr, or greater during stormy years (EUROSION, 2004; Riegel, 2014) and also in sand and dune environments and river mouths and estuaries (Devoy, 2008). Portmarnock Point in north County Dublin presents maximum erosion rates of 0.48m/year (OPW, 2010).

Glacial sediments moderately erode at 0.2–0.5m/yr, normally intensifying to 1–2m/yr, exceeding 3m/yr in hotspots along southern and eastern coasts (Carter and Bartlett, 1990; National Coastal Erosion Committee, 1992; DoE, 2000; EUROSION, 2004; OPW, 2010).

Exposed boulder clay cliffs like those from Killiney to Greystones get easily eroded. Gravels and shingle accumulate from wave energy dissipation and wave refraction, and storm beaches form at their base. Soft unconsolidated cliffed areas from Shanganagh to north Co. Wicklow have been identified as being quite prone to erosion (Robinson, 2009; OPW, 2010). Clastic dykes infilling hydro fractures on cliffs form low spots resilient to wave action, instigating instability and erosion in surrounding areas. Important amounts of sediment are currently being lost from the upper parts of cliffs due to wave action, water percolation and rotational slump processes. In particular, maximum retreats of 0.95-1.2m/yr from 1864 to 2009 were recorded by Robinson (2009). Volumetric material losses of 37-61% were measured between 2005 and 2009 along soft cliffs between Dalkey and Bray.

Rocky coasts respond more slowly than soft coasts to sea-level changes. In terms of erosion, rocky coasts are relatively stable with rates as low as 0.01m-0.1m/yr per century (Devoy, 2008; Masselink and Russell, 2013). High-magnitude, low-frequency events would not always be the main cause of erosion, but rock falls are (Lim *et al.***,** 2010). The relationship between historical rates of sea-level and cliff recession rates is difficult to establish due to the interference of artificial coastal defences. Table 3.1 displays erosion estimates for different cliff types in the study area (ECOPRO, 1996).

Lithology	**Granite**	**Limestone**	**Shales**	**Sandstone**	**Glacial till**
Recession rates (m/year)	0.001	0.001 - 0.01	0.01 - 0.1	0.1 - 1.0	1.0 -10

Table 3. 1. Erosion rates (m/yr) of different cliff types in Ireland (ECOPRO, 1996).

Old estimates based on the Bruun Rule by Carter (1991a) projected annual coastal retreat rates for the East of Ireland as a function of up 30 cm increase in sea-level by 2040 (Table 3. 2).

	Potential coastal recession rates								
	Low SLR (9cm)			**Medium SLR (18cm)**			**High SLR (30cm)**		
East of Ireland	**Shoreline**	2m high cliff	0m high cliff	**Shoreline**	2m high cliff	10m high cliff	**Shoreline**	2m high cliff	10m high cliff
	4.50	3.75	2.25	9.00	7.50	4.50	15.04	12.53	7.5

Table 3. 2. Potential coastal recession rates (m/yr) by 2040 for different sea-level rise based on the Bruun Rule and coastal configuration (after (Carter, 1991a).

3.3.2. Long term past and future relative sea-level rise

After post-glacial rebound, land levels appear stable or sinking gradually in the study area. From tidal trends, sea-level rise is greater than the maximum rate of crustal emergence and is therefore not only explained by isostatic movements. Vertical movement around Dublin is close to zero (0.025mm/yr) (Bradley *et al.*, 2009; Lowe *et al.*, 2009). Satellite observations used for the PanGeo projects suggest that there is no evidence of land movement in Dublin other than localised compressive ground processes (Sheehy and Verbruggen, 2013).

After the last glaciation, there was a fall in relative sea-level, driven by an upwards land rebound. Then, ice retreat paused to give way to a large-scale brief ice re-advance. It was around ~6000 years after the last Glacial Maximum that sea levels began to rise. For the last 6,000yrs, the rate of sea-level rise has remained around 0.45-0.75 mm/yr (Delaney *et al.*, 2012). As will be later discussed in Chapter 5, current trends in sea-level globally and locally, represent a break from those Holocene stable patterns during which global melt water input was practically non-existent (Gehrels and Long, 2008; Brooks *et al.*, 2008; Gehrels, 2010) (Figure 3.6).

Average relative sea-level rise in Ireland ranges from circa 0.5 to 1mm/yr (Devoy 2000a; EUROSION, 2004) although it varies locally. Recent observations around Ireland give 1.7cm/decade since 1916. These will escalate substantially, particularly after the 2050's (Desmond *et al.*, 2009; Sanchez-Arcilla *et al.*, 2016). Satellite data revealed that sea-level in Ireland has risen by up to 6cm since the 90s (Dwyer, 2012). Current estimates from MSL (PMSL, 2015) show nearby trends of 1-2mm/yr.

Future rates of sea-level rise projected for Ireland range between 0.6m (Desmond *et al.*, 2009) or 0.7m by 2100 (Grinsted *et al*., 2015); while other projections for the western Irish coasts show 1.1m for RCP 8.5, within the 90% confidence interval (Sanchez-Arcilla *et al.*, 2016) (Figure 3. 10). This, combined with more frequent intense storms will expose high value urban areas like Clontarf or Sandymount to flooding. Such areas need to be protected (Brooks *et al.*, 2016).

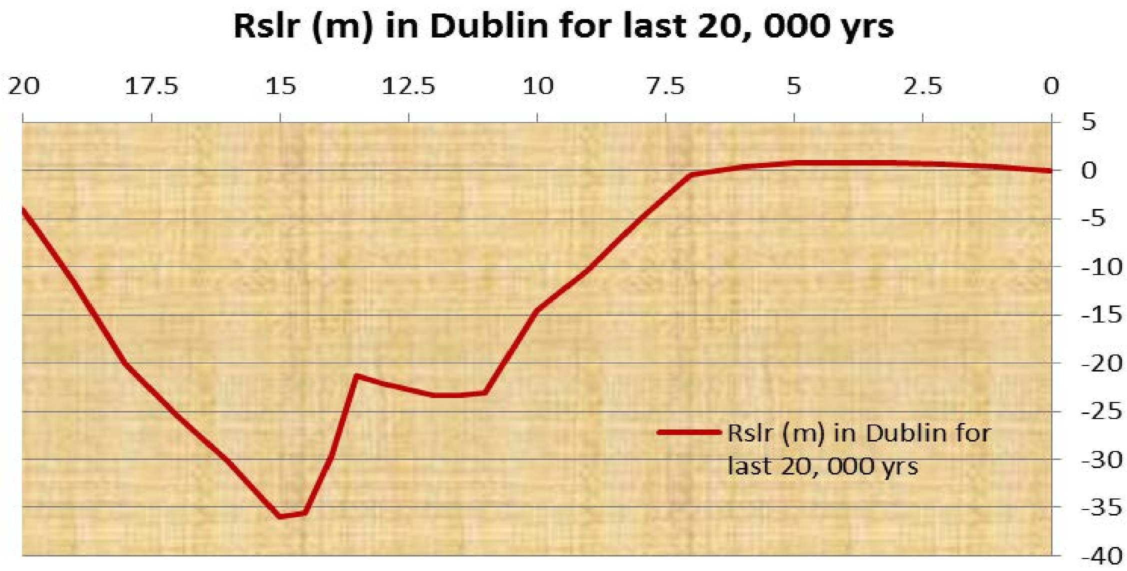


Figure 3. 9. Past relative sea-level rise projected by the glacial isostatic adjustment GIA for Dublin (upper) for the last 7kyrs using 6th polynomial adjustment (Data source: University of Liverpool/ Brooks *et al.*, (2008) modelling).

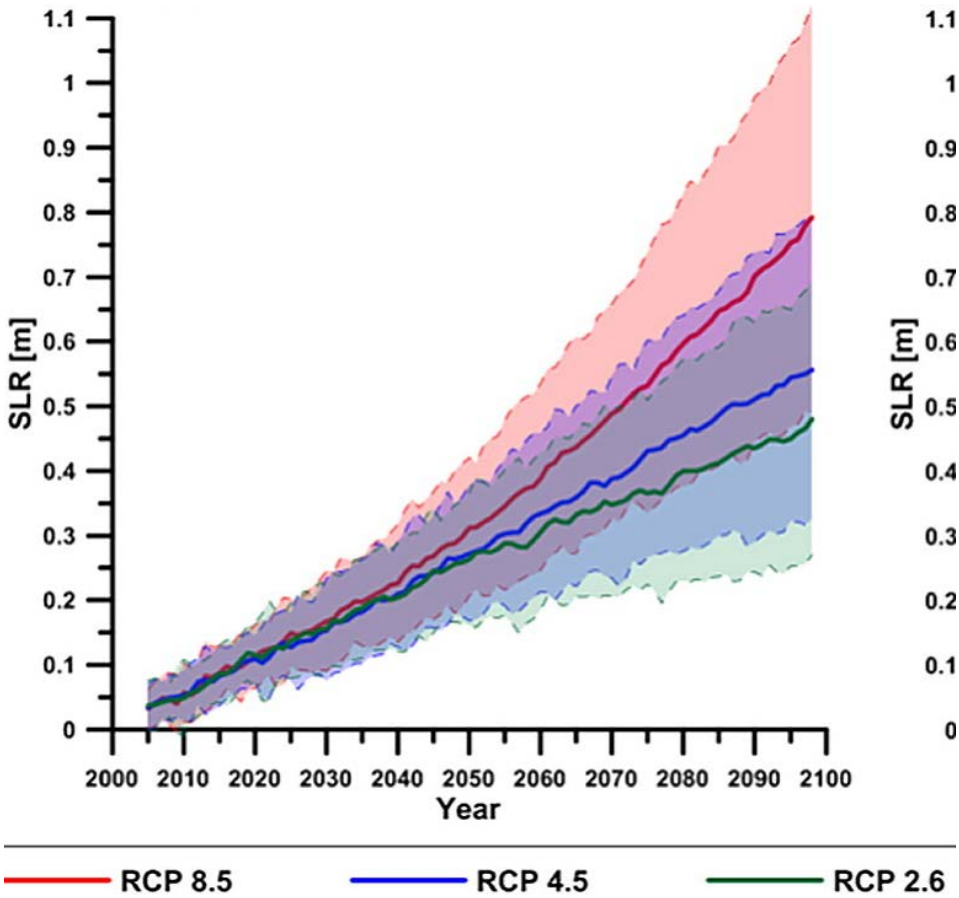


Figure 3. 10. Future SLR projection across the century for the North-Atlantic Ireland coast (Sanchez-Arcilla *et al*., 2016).

3.4. Chapter summary

Coastal erosion and adjustment to the oceanic dynamic controls will shape our coasts differently, increasing the coastal environment's vulnerability to flooding, erosion and impacts of sea-level rise. Global trends are also reflected in Ireland. Climatic changes are presently affecting Irish coasts, threatening future coastal stability. In particular, the unconsolidated, soft and low-lying coast of the study area is highly exposed and already experiencing erosion, flooding and ecosystem losses. Coastal areas and structures need to be protected (Devoy, 2000, 2008; Sanchez-Arcilla *et al*., 2016; EPA, 2018).

Considering that impacts on Irish coasts will be large, Catchment Flood Risk Assessment and Management Studies (CFRAMs) and Integrated Coastal Zone Management should incorporate different climate scenarios (Wilby and Dessai, 2010; Hallegatte, 2013).

Vulnerability analyses were previously carried out in Ireland, mainly in relation to socio-economic scenarios (Carter, 1991a; Devoy, 2008; Flood, 2012; McGloughlin, 2015). Nevertheless, assessing the relative vulnerability of the coast to sea-level rise by means of high resolution, an indexed-based approach has never been attempted before. In this research, successful and robust international methods are tested and applied to the Irish context in order to address how vulnerable the coast is now and how it will be in the future.

Chapter 4: Research methodology

4.1. Introduction

This chapter examines the framework and the three main methods utilised to address the two main goals of the research: the mapping of the current vulnerability of the Dublin-Wicklow area to sea-level rise; and the sensitivity assessment to potential flooding impacts regarding future local scenarios of sea-level rise. Growing demand for vulnerability studies as a component of coastal integrated management vindicates the application of indicator-based vulnerability assessments that enable comparison between sites (Nguyen *et al.,* 2016). The CVI application is one simple and robust method of characterising the vulnerability within a complex environment. It aims to capture and reflect the main aspects of current or future vulnerability which is accomplished by an analysis of indicators and their interactions (Fussel, 2009; Hinkel, 2011).

When analysing dynamic controls that affect a particular coastal area, emphasis should be given to driving factors which might exacerbate their effects. For instance, a high tide coinciding with strong meteorological conditions and wave associated activity, increases water levels, usually resulting in severe damage along the coast (Wang *et al.,* 2008). Estimates of probability of occurrence of storm-surges are extremely valuable for coastal protection in any coastal study (Brown *et al*., 2009). Thus, coastal managers can assess objectively the natural factors that contribute to the evolution of a particular coastal zone, and with aid of local RSL projections, assess how it may evolve in the future.

4.2. Methods I: Current relative coastal vulnerability assessment.

4.2.1. Conceptual vulnerability framework

High resolution coastal vulnerability studies that use multivariate data and adequate site-specific metrics and descriptions to capture the main vulnerability factors, are critical (Bonetti *et al.,* 2012, 2013; Masselink, and Russell, 2013; Nguyen *et al.,* 2016). However, a good metric does not only depend on identification of what is relevant, but also depends on scale (level of detail), purpose, data availability and the specific coastal characteristics (Fussel, 2007; Wamsley *et al*., 2015). Also, metrics should be clear, direct, repeatable, measurable, anticipatory and relevant at that scale (McLaughlin and Cooper, 2010; McKay *et al.,* 2012). A good CVI theoretical framework should also address current hazards or potential future impacts (if possible). It should also include the relevant vulnerability components and coastal processes, the geographical and temporal scope and representativeness, and the main assumptions regarding ranking, links and weighting of variables, and address validation (if possible). All this should be incorporated within the three components: exposure, sensitivity and adaptive capacity (UNFCCC, 2008; Wolters and Kuenczer, 2015; Wamsley *et al.,* 2015; Nguyen *et al.,* 2016).

The CVI index used for this research is a modified version of that employed by US Geological Survey (USGS) for the National Assessment of Coastal Vulnerability to Sea-Level Rise developed by Thieler and Hammer-Klose (1999, 2000a,b) and later applied by Thieler *et al.* (2000); Pendleton *et al.* (2010); Gutierrez *et al*. (2011); Thatcher *et al.* (2013); Gornitz *et al.* (2014).

Variables were adapted to the local scale within the Irish context. However, indicator selection was not restricted by data availability as in previous studies (Bonetti *et al.*, 2010; McLaughlin and Cooper, 2010) which enabled new variables to be generated. As in other studies (Gornitz 1991; Pendleton *et al.*, 2010; Sharples 2006), vulnerability strictly relies on local physical and structural characteristics of the coast and uses its natural ability to adapt to SLR. This CVI allocates different metrics (quantitative and qualitative) to the variables according to their potential role in coastal change. Thus, ranges of vulnerability are based on a coast's potential susceptibility to physical change as sea levels rise. Abuodha and Woodroffe (2006) and Jimenez *et al.* (2009) applied similar methods to determine the relative vulnerability to erosion and inundation at local and regional scales respectively.

The conceptual basis applied to the CVI index used in this research has been primarily based on a previously established theoretical framework (Nicholls *et al*., 2007; Fussel, 2007; Nicholls, 2015; Torresan *et al.,* 2012; IPCC, 2014; Nguyen *et al.,* 2016). Present vulnerability assessment conceptualisation involves the following steps: definition of concepts, the coastal system targeted, the purpose of the study, selection and compilation of indicators of change, classification, normalisation and ranking, and vulnerability map construction. Table 4.1 shows a summary of the conceptual framework adopted for this vulnerability assessment.

Before developing a good metric, it is essential to be aware of the current policy and objectives. Given the lack of studies and future projections, EEA (2012) advised vulnerability assessments to be carried out.

Contact was made with the Office of Public Works (OPW) and Geological Survey of Ireland (GSI) beforehand to inform them of the main purpose and expected outcomes of this research.

Before metrics are applied, the concept of vulnerability and components have to be defined to, not only yield information about what contributes to vulnerability, but also how it is influenced (Fussel, 2007; Abuodja and Woodroffe, 2010; Wimsley *et al.*, 2015). Thus, a vulnerable coastal system was selected on a preliminary basis and components and indicators of change within it were defined.

Sensitivity and adaptive capacity components of the environment, combined with exposure, essentially explain the vulnerability to sea-level rise (Nicholls, 2015). Sensitivity denotes the different characteristics of the system which are susceptible to exposure to shoreline change and flooding, in this case caused by sea-level rise. A preliminary strip of the coast which potentially may be eroded or inundated over the next few years was selected as the targeted natural system. Exposure and sensitivity joint effects will aggravate the negative impact of sea-level rise (Yoo *et al.*, 2014).

Factors	Variables	Vulnerability components	Temporal	Data source/classification and ranking
Climate factor/Hazard	Long sea-level rise trends	Exposure/Direct impacts: Inundation, erosion, saltwater intrusion	current	PMSL data, Dublin port/Own trend calculation
	Extreme events from spring tide-surge+ future	Exposure./Direct impacts: Storm surge, high waves, wind scour, erosion,	future	Extreme WL for AEP (OPW,2010) + own SLR projections & potential flooding maps.
Geological boundary factors	Geomorphology	Sensitivity/ Natural adaptive capacity	current	Own data measurement, classification, ranking and maps
	cliff type	Sensitivity		Own data measurement, classification, ranking and maps
	Coastal slope	Sensitivity		Own data measurement, classification, adapted ranking and maps
	Aspect	Sensitivity		Own data measurement, classification and maps, ranking Sharples (2006)
Coastal forcing (climatic and non-climatic drivers)	Mean sig wave height	Sensitivity	current	Modelled data (Gallagher *et* al., (2014); own classification, ranking & maps
	Relative-sea level rise	Sensitivity		Own data measurement, classification, ranking and maps
	Mean tidal range (non-climatic)	Sensitivity		Own data measurement, classification, ranking and maps
Coastal processes	Shoreline changes	Sensitivity/ Natural adaptive capacity	current/future	Own data measurement, classification, ranking and maps

Table 4.1. Summary of the methodological vulnerability framework adopted in this research.

Next, a set of coastal indicators of change were established and how they relate to the vulnerable situation of this particular system. External indicators are mainly part of exposure (sea-level rise, extreme water levels); whereas internal sensitivity is defined by biophysical natural characteristics and forcing factors interacting at the onshore-see face. Sediment type and long-term shoreline change rates are also relevant to more than one aspect of vulnerability (whether the beach is accretive or erosive). These are indicative of coastal sensitivity but are also an element of the natural adaptive capacity.

Different classifications were applied depending on how the metrics related to the inundation and erosion drivers for every indicator (Fussel, 2007). Several variables at different scales and types of data units contributed to the overall index (McLaughlin and Cooper, 2010). Thus, a standardising system is of particular importance to easily facilitate comparison (Giove *et al.*, 2009; Abuodja and Woodroffe, 2010; Schauser *et al*., 2010). The standardising method was based on ranking scores from 1-5, with five corresponding to the greatest contribution to sea-level rise-related coastal change (Gornitz, 1990; Abuodha and Woodroffe, 2006; Pendelton *et al*., 2010). If ranking is correct and methods are consistent, comparisons will be possible, with other areas (Pendleton *et al.*, 2010; Hinlkel, 2011; Nguyen *et al.*, 2016). The time span considered is limited by data availability and ranges from the 1930s data up to 2017.

4.2.2. Rational for buffering the study area

It is important to specify the geographical area and resolution (De Leon, 2006). In this research, the endangered coastal system is defined by a coastal strip from Donabate to Arklow composed of natural environments and highly populated, urbanised areas. This area corresponds to a high-populated area of important socio-economic value, and consequently, of higher sensitivity to environmental and human exposure.

In coastal vulnerability studies, outlining the coastal zone is a difficult task but a necessary one. First of all, a coastline must be selected. The mean low-water mark (MLWM) has been assigned as the coastal baseline in Ireland (Sea-Fisheries and Maritime Jurisdiction Act, 2006). Because this is difficult to determine, many agencies use the Mean High Water Mark (MHWM) as in this research.

Initially, an examination of relevant datasets and maps for the area was carried out. These included geological, topographical, satellite imagery, all in conjunction with meteorological data. A walkover survey followed. This allowed this research to be placed within a proper context. A preliminary study area contained several sections of an onshore coastal strip from North Co. Dublin to South Dublin, later extended to Arklow (Co. Wicklow). This area encompasses zones from dunes/cliff (including cliff toe, dune vegetation line and/or manmade structures) to the hinterland or backshore, which is the upper limit of the coastal zone that is still affected by marine action. Regarding landward extension, the study area buffer must ensure that the influence of coastal processes on coastal geomorphology is well represented. Quaternary maps suggest that distance buffers must be a minimum of 200m to ensure that the nature of the coast is well captured. However, in order to accurately outline a representative study area, a radius of influence (RICE) from potential erosion and flooding was investigated. Delineating a radius of influence of coastal areas prone to combined erosion and flood (RICE) or independently, has proven to be useful in defining potential areas of vulnerability (Crowell *et al.,* 1999; EUROSION, 2004; Dominguez *et al.,* 2005; Bonetti *et al.,* 2010; Vafeidis *et al.,* 2011).

Inland distance buffers based on current erosion rates and elevation buffers were combined to draw a minimum buffer. A first distance buffer was built by extrapolating coarse erosion rates given by OPW (2010) to 2100 from the current coastline (MHWM). A second buffer containing potential inundated areas by extreme water levels (Annual exceedance probability (AEP) of 1%) was superposed. Finally, a buffer of 1.7km, which is a combination the two previous ones, was generated. This buffer was chosen to be equidistant from coastline for simplicity (See Figure 4. 1).

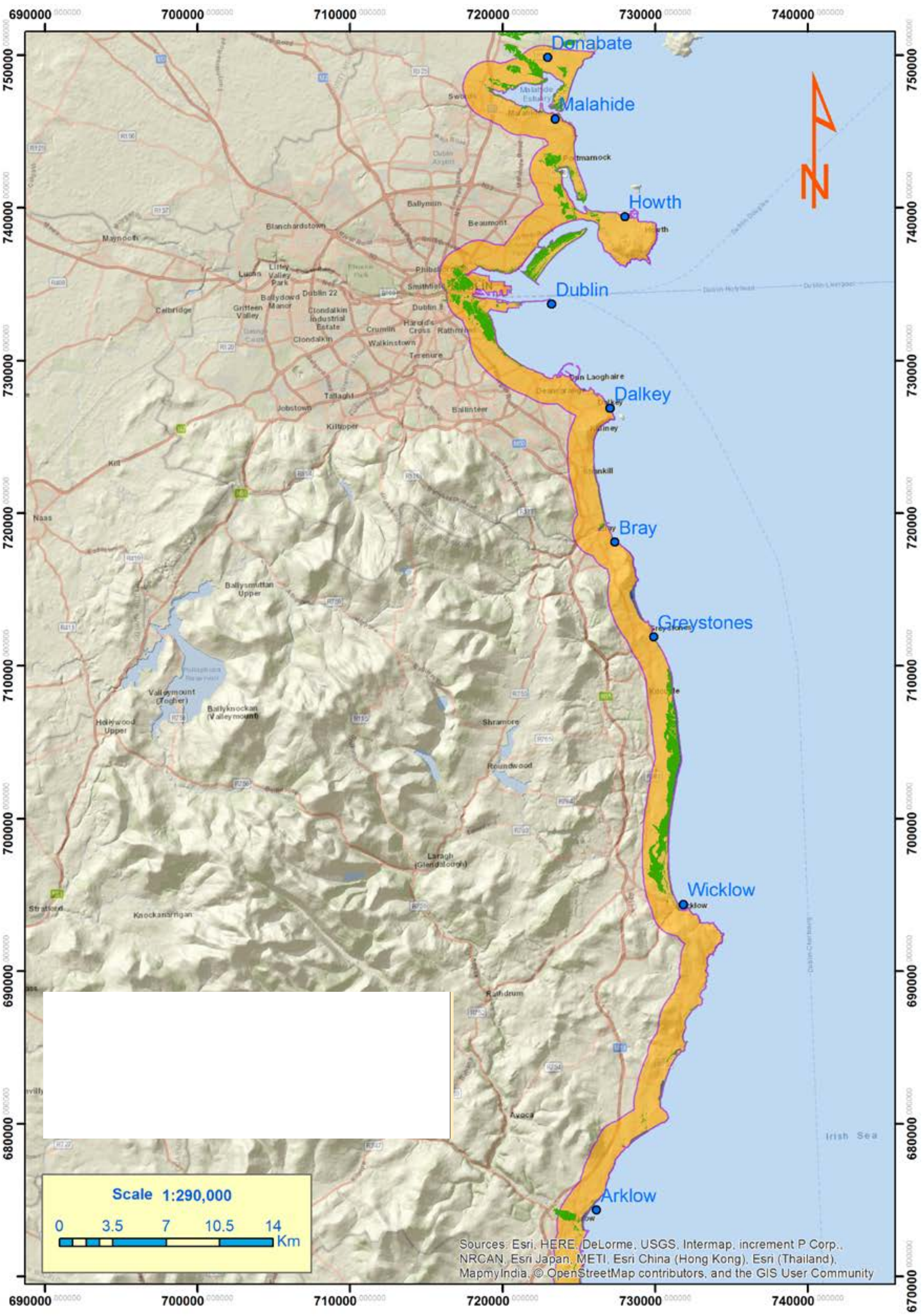


Figure 4. 1. Study area runs from North Dublin to North Wicklow delineated a radius of influence from potential flooding and erosion.(*Source: Silvia Caloca)*.

4.3. Selection of physical indicators of environmental change

When looking at the physical vulnerability of coastal areas to future sea-level rise it is necessary to assess what factors may contribute to it. The first question to investigate is what makes a coastal area susceptible to change. Climate changes are disturbing present and future coastal stability and those changes are reflected by means of coastal indicators. Consequently, prior to any coastal assessment, accurate knowledge of the long-term, global, and regional drivers of environmental change is extremely beneficial (Burkett, 2012).

Identification and assembly of indicators not only constitutes 90% of the entire vulnerability mapping process, but is also a crucial phase for any coastal vulnerability assessment. Consequently, indicators should be chosen wisely (McLaughlin and Cooper, 2010). Those proxy factors of coastal change within each component must be measurable, representative and comparable (IPCC, 2014) and based on known characteristics of the coastal system and compliant to the conceptual framework of vulnerability defined for this research (Balica *et al.*, 2012). It is fundamental that the type, number and geographical span of appropriate indicators involved in the system is properly defined within our framework and is also representative (Birkmann, 2006). Indicators must be able to consistently reflect vulnerability under hazardous conditions. Consequently, the criteria and selection of indicators is crucial in terms of verifying that, under hazardous conditions, areas highly vulnerable are incorporated (and vice versa). Also important is that they reflect sensitivity to changes and are reproducible, readily available, reliable as well as capable of being validated and quality controlled (Hahn, *et al.*, 2003; Balica *et al.*, 2012; Wamsley *et al.*, 2015; Nguyen *et al.*, 2016). The lack of data or standardised procedures from a variety of methods has always been an obstacle (Hinkel 2008; Klein and Hinkel 2009; McLaughlin and Cooper, 2010). Another problem encountered when looking for approaches on assessing coastal vulnerability in the literature is that most of the emphasis is on components and factors but less on detailed guidelines to accommodate methodologies for high resolution studies, gathering data or the process of ranking indicators (De Leon, 2006).

Relevant factors for coastal change and shoreline evolution are typically the same. Thus, a first approach to identify local indicators of coastal change is to look for evidence of erosion and identification of hotspots, and also extreme climate (EUROSION, 2004; Harvey & Woodroffe, 2008). Coastal vulnerability indicators are linked to current regional climate gradients and future projections of climate change specific trends and dynamic controls (EUROSION, 2004; Nicholls *et al., 2*008).

The evolution of a soft coastline is as a result of historical fluctuations in sea-level rise, changing long and short-term weather patterns, action of rivers and human influence (ECOPRO, 1996). Geology, storm activity, oceanographic processes, sediment supply are some of the forcing factors driving coastal changes in response to sea-level (FitzGerald *et al.,* 2008; Williams and Gutierrez, 2009). Climate-induced sea-level rise impacts have also been boosted by human-induced intervention in the form of coastal defences and interference of sediment supply (Nicholls *et al.*, 2008; 2010). Nonetheless, the response to one single stressor is not a straightforward process since complex interactions between physical climate forces, geology and humans occur (Hapke, 2011).

In the context of this study a set of potential indicators of coastal change, each addressing different aspects and components of coastal vulnerability was identified. For the present study, the local and regionally relevant physical variables that strongly influence coastal evolution and determine the spatial variability of the CVI for this area are: shoreline changes, coastal slope, aspect, geomorphology, cliff type (geological boundary factors); and mean tidal range, mean significant wave height and relative sea-level rise (external physical drivers). These are further examined below.

4.3.1. Geological boundary factors

Geomorphology and cliff type

Coastal morphological development is a physical expression of how energy is mitigated. Beach sediment will help to absorb, dissipate and protect coastal areas (Dawson *et al.,* 2009). Whether the coast has sheltered areas, hard rock headlands or barriers, will influence its exposure to wave energy. Effects of future sea-level over the coast will largely depend on the characteristics of its coastal topography and sediments (Sharples, 2006; Dwarakish *et al.,* 2009). Post-glacial processes have incorporated glacial sediments into beaches, dunes and estuaries in the study area. Even though offshore sediment supply is currently limited, glacial sediments such clay and silts will help salt marshes and tidal areas to cope with SLR (Adam, 2002). Great emphasis has been placed on assembling seamless onshore-offshore geomorphological data in the near zone as well as sediment distribution for coastal vulnerability mapping assessments to projected sea-level rise (GEUS, 2013).

Deltas and low-lying plains are extremely sensitive to climate changes in water level downstream and by runoff upstream, exacerbating impacts such as erosion, flooding and anthropogenic degradation (IPCC, 2014). Sea-level rise and storminess will also alter the distribution and balance of sediment in lagoons and estuaries (Pilkey and Young, 2010). Wetlands and sea grass meadows will suffer coastal squeeze if there is no migration possibility. It is expected that sea-level rise might cause dry lands to be inundated and wetlands displaced from intertidal to sub tidal. In general, soft rock substrate is sensitive to erosion, whereas a sedimentary coast would be highly sensitive to both erosion and flooding (Sharples, 2006). Wave overtopping and sediment reworking on shingle and gravelly beaches and coastal man-made defences is also likely, particularly those without the possibility to migrate. However, wave energy changes will be accommodated on sandy beaches with enough sediment. Otherwise they will get excavated unless they retreat inland. Sediment accreted in embayed estuaries or marshes during storms can make them more resilient, depending on transport and sediment supply (Charlton & Orford, 2002; Pethick, 1984).

At small scales, in the short term, using cliff type is more accurate than using solid or drift-geology (McLaughlin and Cooper, 2010). In general, climate change will reduce the resilience of low cliffs as regards impacts, as once the cliffs have retreated, or been damaged, they will not recover their initial stability (Naylor *et al.*, 2010). Cliffs retreat faster with sea-level rise, particularly those with high historical retreat trends (Trenhaile, 2010; Brooks and Spencer, 2014). Storminess and wave energy will also exacerbate erosion processes on both soft and hard cliffs (Naylor *et al.*, 2010; Ashton *et al.*, 2011). All this, combined with high tides and saturated ground from rainfall could quicken geomorphological processes over cliffs, and also increase rock falls (AGUBlogosphere, 2014). Hard cliffs were found to be more sensitive to low-frequency strong events that previously thought (Hansom, 2001). However, compared with soft cliffs, the effects will be minimal (Dawson *et al.,* 2009; Trenhaile, 2011).

The type of cliff and rock strength will determine the degree of erosion. The same factors that affect cliff instability also weaken the cliff, causing falls and slides (Lim *et al.,* 2011). Consequently, in some places, retreat regularly comes in the form of sudden cliff failures and catastrophic events, indicating that erosion on those cliffs can occur fast (Lim *et al*., 2010a; Sistermans and Nieuwenhuis, 2013). For instance, the Holderness erosion hotspot in England currently erodes at 2-6m/yr, mainly during storms and surges. Sea-level effects combined with natural variability will maximise the impacts; for instance, high retreat on soft cliffs in East Anglia (UK) of ~10m/year has been linked to decadal North Atlantic Oscillation (NOA) energy fluctuation (Brooks and Spencer, 2014). Weakening in soft cliffs of south Dublin (Robinson, 2009) and resilience changes in other areas in Ireland have been identified (Jordan, 2016).

In the light of the above, first order mapping should be based on geomorphology and erodibility (Church *et al*., 2006; EUROSION, 2004; Harvey and Woodroffe 2008). Therefore, these two variables have been incorporated in a number of coastal and landslide vulnerability studies (Gornitz, 1990; Gornitz *et al*., 1994; Thieler *et al.,* 2000; McGlauglin, 2001, 2002; Hampton & Griggs, 2004; McFadden *et al,*. 2007a; Hapke & Plant, 2010; McGlauglin and Cooper; 2010; Pendleton *et al.,* 2010; Gutierrez *et al.,* 2011; Ashton *et al.,* 2011; BGS, 2012). For this research, these data were not available and needed to be created.

Coastal topography and slope

Coastal topography and slope is indicative of risk of inundation by flooding and shoreline retreat (Pilkey and David, 1987). Bathymetry and the subtidal substrate slope strongly influence the wave activity and coastline exposure in the near shore zone, and subsequently the physical response of sandy barriers to sea-level rise (Sharples, 2006). Thus, coastal elevation and slope are still valuable indicators for extrapolating future shoreline positions (Gutierrez *et al*., 2011).

Coastlines vulnerability will depend on sediment supply or migration ability. High slope gradients and man-made structures will accelerate squeeze by impeding coastal adjustment (Pethick and Crooks, 2000). Sea-level rises and storms threaten systems that are backed by hard structures or cliffs and even dune systems that can migrate. If sea level rises quickly, systems will not have time for landward migration and barrier islands and wetlands might be seriously affected. This will lead to narrowing beaches and eroding dunes, and consequently, further exposing land to inundation before the next storm strikes (Plant *et al.,* 2010). Low profile land immediately landwards of the mean high-water mark is very vulnerable. Shallow and wide-water inshore zones and continental shelf like this exists in the study area, backed by wide beach systems. These areas favour absorption of wave energy, minimising the impacts of wave-surge over the coast and thus protecting it (Carter, 1991; Carter and Woodroffe, 1994). However, gentler gradients will result in increased storm surge heights and waves and surges driven by winds, making the coast more vulnerable to erosion (ECOPRO, 1996).

Some argue that coastal damage is not proportional to the event's energy. Sometimes high sea levels could be more damaging for coasts than isolated storm events (Betts *et al.,* 2004). In general, low-lying areas might see a real threat from continuous sea-level rises while others will struggle from the combination of sea-level rise and storm surge events (McCarthy *et al.,* 2001). The intertidal slopes provide information on wave energy dissipative gradients and potential storm surge heights while the hinterland zone provides information about semi-stable landforms. Hence good quality, continuous onshore-offshore high-resolution coastal topography data is indispensable for vulnerability and impact assessments (Gornitz, 1990; Gornitz *et al*., 1994; Thieler *et al*., 2000; McLaughlin, 2001; McFadden *et al*,. 2007a; Nageswara Rao *et al.*, 2008; Wang *et al.*, 2008; McLaughlin and Cooper. 2010; Pendleton *et al*., 2010).

Aspect

Topographic factors such as location and orientation of the coast are also responsible for the resistance of the coast towards impacts of sea-level rise (Sharples, 2006; Dwarakish *et al.,* 2009). Aspect will affect the amount of energy spent at that particular location. Shoreline orientation relative to wave climate is a major factor in storm retreat-recovery interactions. However, this variable has only recently been included in some coastal studies (Harris *et al.*, 2000; Mclaughlin, 2001; Mclaughlin *et* *al.*, 2002; Sharples, 2006; Ashton and Murray, 2006a, 2006b; Abuodha and Woodroffe, 2010b; Mclaughlin and Cooper, 2010; Brooks *et al.*, 2016)

In the study area, some coastal segments are more exposed to the action of waves than others. Sheltering and orientation will govern whether the coast will be more exposed to wave significant heights and directions, which are in turn, indicative of storm wave direction approach. Consequently, it will determine whether the coast will change more or less rapidly with sea-level rise (ECOPRO, 2006; Sharples 2006). Consequently, exposure to high wave energy was included on this research.

4.3.2. Physical Drivers of coastal change in response to sea-level rise

The stability of the foreshore is affected by major changes in wave penetration, storm magnitude and frequency, and also is a function of sediment erosion. In coastal vulnerability and impact assessments, dynamic controls that affect a particular coastal environment need to be studied. Hence some of the most important drivers in coastal research studies are:

Rate of relative sea-level rise (RSLR)

Historical rates of relative sea-level rise have always affected sections of the shoreline. Past sea levels have increased the amount of time the coast has been exposed to extreme storm surges and is therefore important in assessing its relative vulnerability to RSL (Zhang *et al.*, 1997). As coasts do respond over time (centuries to millennia) these changes have nothing to do with current SLR trends, present shoreline patterns are better explained in terms of sea-level history. Impacts of sea-level rise are not only determined by the global trends (eustatic), but also regional and local variations and tectonic uplift or subsidence. The combination of sea-level rise and vertical land movements (isostatic changes) at a particular position at the coastline results in relative sea-level rise rate (PSMSL, 2010). See Figure 4.2.

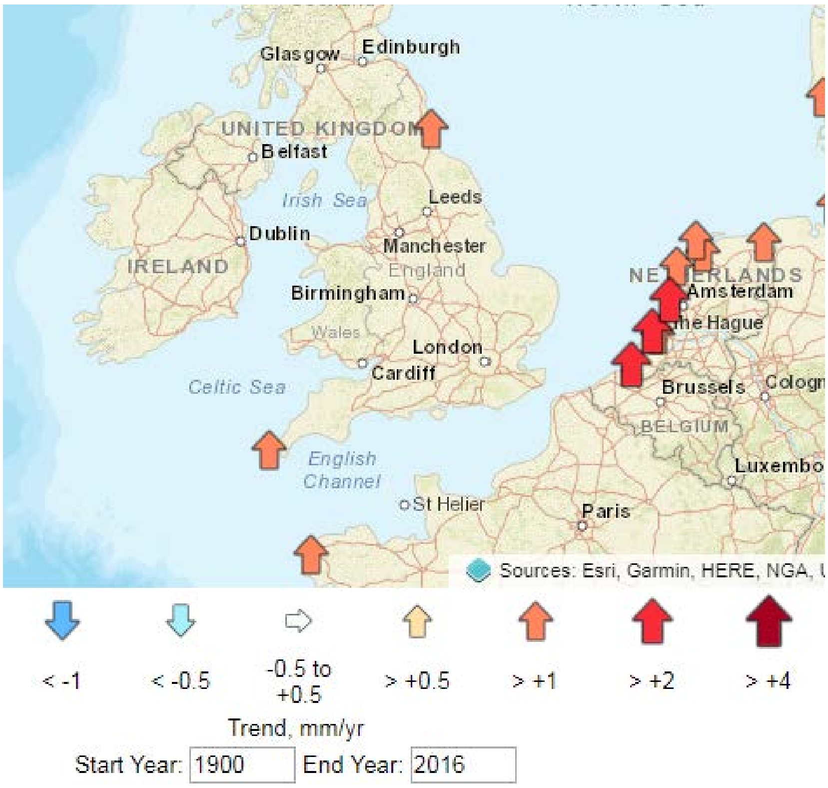


Figure 4. 2 .Relative sea-level in mm/yr from 1900-2016 trends for Europe (not corrected for local subsidence). *Source: Woodworth and Player, 2003; Permanent Service for Mean Sea Level (PSMSL, 2017; 'Tide Gauge Data' (http://www.psmsl. org/products/trends*).

Most relative sea-level changes, locally and regionally, are due to meteorological and oceanographic factors such as oceanic circulation, thermal expansion, wind and atmospheric pressure changes, variations in Earth's gravity and vertical land movements and other minor factors such as river discharge changes (Nicholls *et al.*, 2011). Relative sea-level rise effects will vary spatially causing permanent and/or gradual inundation depending on uplift-subsidence mainly (Carter *et al.*, 2007; Meehl *et al.*, 2007 in IPCC, 2007). The historical record of sea-level change combined with other variables is critical in coastal impact and vulnerability assessments (Gornitz, 1990; Gornitz *et al*., 1994; Thieler *et al*., 2000; Sharples, 2006; Pendleton *et al*., 2010; IPCC, 2014). A suitable relative sea level analysis is extremely valuable for projecting future local sea-level rise scenarios and for driving impact models of future extreme events *(*Warrick, 2009, 2007; Nicholls *et al*., 2011; Yin and Urich, 2013).

Changes in wave climate

Wave climate is of particular interest as the energy imparted to waves by winds in the offshore region is finally dissipated on the coastline and used to transport and distribute sediments. Transport of sediments at the coast mainly occurs during storms by the combinations of waves and tides, storm surges action, and these vary geographically. There are reports that the significant wave height has increased in North Atlantic mid-latitudes (WASA Project, 1995; Woolf *et al*., 2002; IPCC, 2014).

Future wave climate will be more threatening to our coasts. Larger sea-levels increase the average annual/significant wave energies and can result in more significant changes on the coast (Sharples, 2006; Kelm *et al.*, 2004) reshaping tidal basins and estuaries and even producing the rotation of beaches (Pickering *et al*., 2012). Most of the beaches in the study area are so-called drift-aligned systems, so a change in wave climate may greatly affect the shoreline (Orford *et al*., 2002; Alegria- Arzaburu and Masselink, 2010). Small changes in wind patterns will also influence wave climate, and both will adjust coastal sediment and erosion processes (Dawson *et al.*, 2009).

Annual mean significant wave height is an indicator of wave energy, which is indicative of the total average annual swell and storm wave energy received over time and overtopping discharge (Pendleton *et al.*, 2010; Sierra *et al.*, 2016) (Figure 4. 1). Wave direction and long period swell influence erosion rates and can produce damages to coastal structures and major flooding, particularly those with steep shelf or slopes (Semedo *et al.*, 2011; Hoeke *et al.*, 2013). Hence, wave direction has been used as proxy in many coastal vulnerability indices and also in this research (Gornitz, 1990; Gornitz *et al*., 1994; Thieler *et al*., 2000; Mclaughlin, 2001; Sharples, 2006; Dwarakish *et al.*, 2009; Pendleton *et al.*, 2010; Mclaughlin and Cooper, 2010).

$$\mathbf{E = 1/8\ \rho g Hs^2}$$

Equation 4. 1. Energy density proportionality to significant wave height.

where E= energy density, Hs= significant wave height (the highest third of the waves (H1/3)); ρ =water density; and g = acceleration gravity (Pond & Pickard,1983).

Changes in storminess and extreme water levels

Storm-surges are associated with strong or prolonged winds, wave activity controlled by wind stress at the surface and low pressure systems moving at the same speed as the tidal wave in the open sea. The effect of wind on sea-level largely depends on the topography of the area as a storm surge entering shallow water (gentle continental self) also increases in height (Lowe, 2001). Also, a barometric pressure of 1mb below the average will result in an increase of 10mm of sea level (ECOPRO, 1996). Changes in frequency, direction and intensity of storms will expose different parts of the coast and influence its vulnerability, increasing the magnitude and frequency of extreme coastal flooding events (Flather and Smith, 1998; IPCC 2007; 2013). Stronger storm conditions will aggravate coastal morphological impacts, particularly around estuaries, lowering the beach and increasing wave erosion on newly exposed tills and soft cliffs (Devoy, 2000; Church *et al.*, 2006; Wang *et al.*, 2015). Sea-level rise and changes in storm tracks will reshape local bathymetry in European margins (Storch and Weisse, 2008). Recently, changes in mean-sea level rise and storm surge height have been detected in Western Europe instigating flooding and more changes are expected in the future (Nicholls and Cazenave, 2010; EEA, 2012; Weisse et *al.*, 2014; Ferreira *et al.*, 2017).

There is evidence that changes in extreme sea levels are consistent with changes of global mean sea level (GMSL) rather than weather patterns (Marcos *et al.*, 2009; Haigh *et al.*, 2010; Menendez and Woodworth, 2010; Losada *et al.*, 2013) and that they will negatively impact coastal systems (IPCC, 2014). Hydrodynamic models forced by climate models for the Northeast Atlantic showed strong sensitivity to changes in GMSL and RCP’s scenarios (IPCC, 2013; Debenard and Roed, 2008; Wang *et al.*, 2008; Sterl *et al.*, 2009). Consequently, evaluating the exposure of coastal areas to potential extreme water levels exacerbated by sea-level rise, is very important in future coastal vulnerability analysis (Brown and Wolf, 2009; Mendoza & Jiménez, 2009; OPW, 2010; Bosom & Jiménez, 2011; Bonetti *et al.*, 2012).

4.3.3. Non-Climatic drivers

Tides

High tides and waves combined with strong winds have a profound impact on modelling our coastal landscape. Tide raising forces generate a tidal wave of approximately 0.5m in large oceans. However, as it approaches the coast, the shallower water causes the tidal wave to shoal and increase in height. Sometimes it can also reach higher heights due to the existence of the shallow continental shelf and the funnel-shape of the estuary (ECOPRO, 1996). Surges in water level may take a number of days to disappear and for the tide to return to predicted levels. Some authors consider than microtidal regimes pose a higher threat to coastal systems than macro tides as water levels remain higher for longer periods in between high and low-tides (Mclaughlin and Copper, 2010; Pendleton *et al.*, 2010).

In a warmer future, surges might be quite significant when higher water levels coincide with high spring tides. This could increase the risk of lowland coastal flooding and cause drastic changes to coastal geomorphology (Lowe, 2001; Brown *et al.*, 2009). Despite the relatively small size of the study area, tidal regime variability was significant enough to be considered as a relevant indicator for this study, as it has been in large-scaled studies (Gornitz, 1990; Gornitz *et al*., 1994; Thieler *et al*., 2000; McLaughlin, 2001; McLaughlin and Cooper, 2010; Pendleton *et al*., 2010; Gutierrez *et al*., 2011).

4.3.4. Coastal processes: shoreline changes

Despite the fact that sea-level rise has substantial impact on erosion rates at the regional scale, coastal segments are intimately interconnected, so erosion in one site would influence processes such as accretion or flooding in adjacent areas. In the long term, coastal recession is likely to increase with the increasing rate of sea-level rise and changes in wave energy conditions and storm intensity (Masselink and Russell, 2013). Vulnerable barriers, dune systems and coastal vegetation are potentially sensitive to physical hazards related to climate change and sea-level rise. In fact, the factors that are important to coastal change and shoreline evolution are typically the same. Therefore, shoreline changes can be used as a coastal indicator of susceptibility to change, providing appropriated trends are identified (Gornitz, 1990; Gornitz *et al*., 1994, Thieler *et al*., 2000; Pendleton *et al*., 2010). However, coastal erosion is locally influenced by complex processes where, not only relative global and regional sea-level rise intervene, but also by storms, geology and sediment supply. Consequently, raising sea-level over a digital elevation model will not of its own accord determine the new position of the shoreline, as the amount of retreat is subjected to those interactions (Gutierrez *et al.*, 2011; Irish *et al.*, 2010).

4.4. Indicators' compilation, classification and ranking.

4.4.1. Geomorphology

A new coastal geomorphological map was constructed, mapping new coastal units, including the intertidal zones. The map was constructed using all information available from sources that included: the latest 1:50,000 Quaternary maps published by the Geological Survey of Ireland (Pellicer, 2009), OSi Discovery Series map and latest LiDAR at the 1 and 2m grid resolution (OSi, 2009; OPW, 2006). Vegetation correlates with underlying lithology and therefore, Fingal Habitats maps (Doogue *et al.,* 2004) and aerial photographs proved very useful.

Quaternary sediments were converted into coastal forms, polygons reshaped and new features digitised using ArcGIS 10.3 software package. See Figure 4.3. Once the refining mapping phase came to an end, a field investigation followed to corroborate the new mapping, and also to identify erosion hotspots and man-made structures. The final allocated shapefile was topologically cleaned, plotted and reviewed for inconsistencies. In the second phase, geomorphological units were grouped into categories and a classification and ranking scheme were produced.

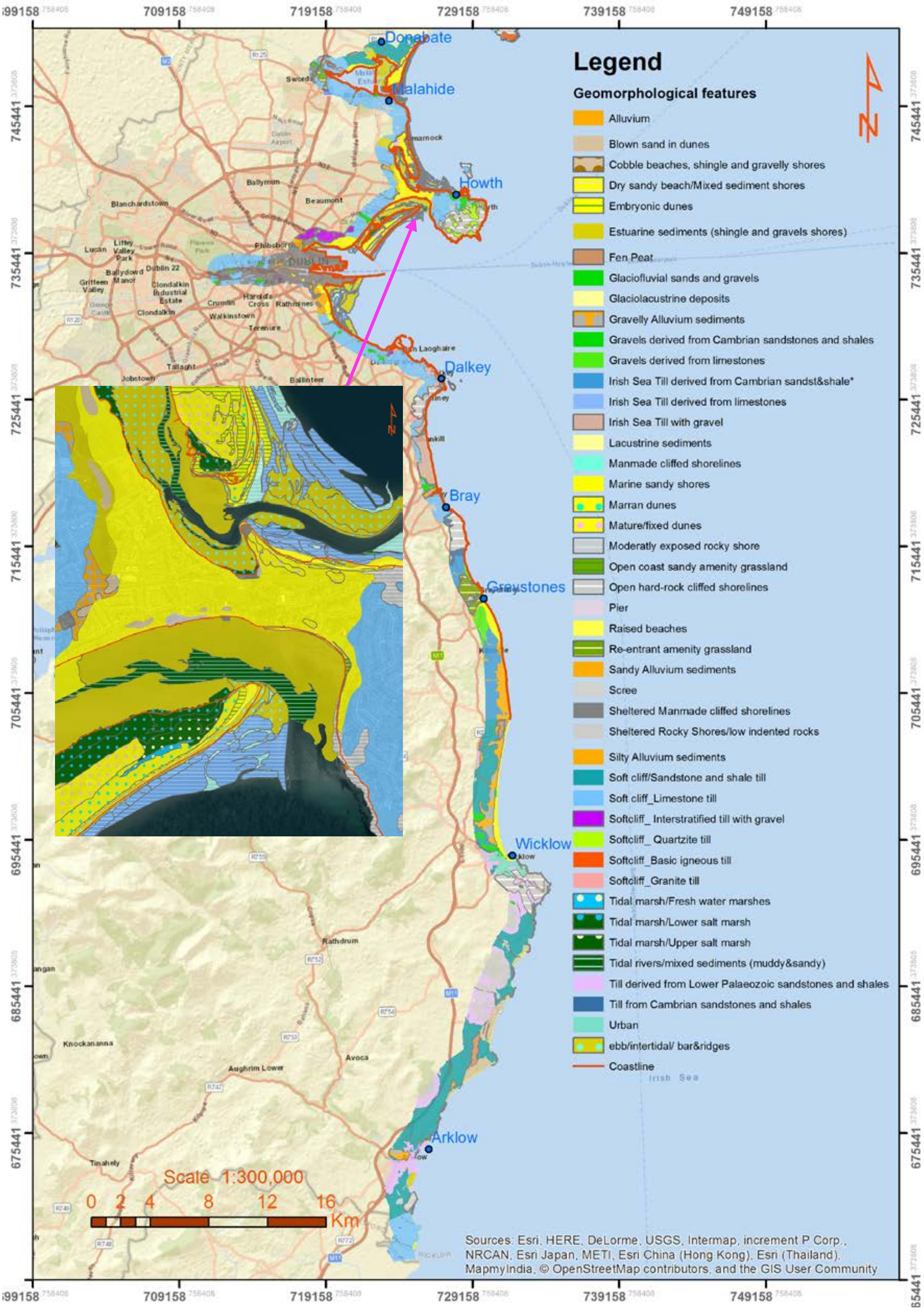


Figure 4. 3. Newly mapped coastal geomorphology features in the study area. Close-up view showing features around Portmarnock strand, Sutton and Bull Island. *(Source: Silvia Caloca)*.

Landforms were mostly classified according to type and erodibility following previous established methodologies (Gornitz *et al.*, 1994; Gornitz & Kanciruk, 1989; McLaughlin, 2000; McLaughlin and Cooper, 2010). In this sense, the final geomorphic vulnerability classification predominantly reflects that of Pendleton *et al.*, (2010). See Table 4. 2.

	1	2	3	4	5
Geomorphology[1]	1 – Very low risk– Rocky, cliffs along coasts, fjords	2 – Low risk– Medium cliffs, indented coasts	3 – Moderate risk– Low cliffs, glacial drift, alluvial plains	4 – High risk– Cobble beaches, estuarine and lagoonal coasts	5 – Very high risk- Barrier beaches, sand beaches, salt marsh, mud flats, deltas, mangroves,

Table 4. 2. Geomorphological classification for CVI calculations (Pendleton *et al.*, 2010).

However, based on the fact that erosional processes will accelerate with sea-level rise, where erosion was happening, viability for inland migration was also considered for features at the frontline. Coastal typologies in the upper intertidal and the backshore were divided into classes according to sediment budget and mobility landform, exposure, and possibility for inland migration (slope implied), reflecting the coastal system's adaptive capacity (Sharples, 2006; Torresan *et al.*, 2008). See Table 4. 3.

Category	Class	Subclass
Open coast sandy shores (OSS)	Backed by low-lying sandy plains	Advancing
	Backed by bedrock	Stable
		Eroding
Open muddy shores (MDS)		
Open clayey-gravel shores (CGS)		
Open slump-prone shores (SPS)		
Sandy barriers and spits (SBR)		
	Sheltered sandy shores	Advancing
	Sheltered muddy shores	Stable
	Sheltered clayey-gravel shores	Eroding
	Sheltered slump-prone shores	
	Sheltered hard-rock cliffed shores	
Open/exposed hard-rock cliffed shores (HCS)		

Table 4. 3. Coastal forms classification by Torressan *et al.*, (2008), adapted from Sharples, (2006).

Final adapted elaborated classification implemented in this research is illustrated in Table 4. 4.

Very low (1)	Low(2)	Moderate (3)	High (4)	Very high (5)
Buff 50m (1)	Buff 50m (1)	Buff 100m (2)	Buff 200m (3)	Buff 200m (3)
Sheltered hard-rock/Manmade cliffed shorelines	Open hard-rock cliffed shorelines /Moderately to highly exposed	Soft unconsolidated cliffs/glacial drift/Alluvium/alluvial plains/ Glaciofluvial/ tills/glaciolacustrine Scree	Cobble beaches, shingleand gravelly shores Raised beaches Estuarine/ lagoon/ re-entrant sandy/soft muddy shores/ open sandy shores backed by bedrock/madeground. Re-entrant amenity grassland /amenity inmediatly backed by bedrock/madeground. **Sheltered** sandy-shores (advancing)/ **muddy shores (stable)/** clayey-gravel shores (eroding).	Sandy shores (Blown sand/sandy beaches/ Barrier beaches/ sand dunes). This category includes: **Open sandy shores** backed by low-lying of unconsolidated sediments or bedrock; **Re-entrant sandy shores** backed by low-lying sandy plains; **Sheltered sandy shores** backed by low-lying of unconsolidated sediments. Salt & fresh marsh, mud flats, deltas/tidal (ebb/intertidal/ bar&ridges), mixed sed shores (muddy&sandy). This category includes **muddy shores** backed by extensive low-lying unconsolidated dominantly muddy. Open coast sandy amenity grassland backed by unconsolidated

Table 4.4. Final geomorphological vulnerability classification based on Sharples (2006); Torresan *et al*., (2008) and Pendleton *et al*., (2010) *(Source: Silvia Caloca)*..

Every coastal feature in the attribute table (total 924) was individually categorised and classified within one of the 46 landform categories under field 'CoastFe4. A dedicated simplified 'StyleCf2' field was also created to colour the maps. Two fields 'Vulclass' and "GEO_R5" display the geomorphological vulnerability rankings. See Table 4. 5.

CoastFe4	StyleCf2	NCliffRank	GEO_R5
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Re-entrant amenity/grassland	Re-entrant amenity grassland	Buff200m (3)	4
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Lower salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Lower salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Lower salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Lower salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Lower salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Upper salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Upper salt marsh	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Fresh water mars	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Fresh water mars	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	ebb/intertidal/ bar&ridges	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	ebb/intertidal/ bar&ridges	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	ebb/intertidal/ bar&ridges	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	ebb/intertidal/ bar&ridges	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	ebb/intertidal/ bar&ridges	Buff200m (3)	5
Salt & fresh marsh, mud flats, deltas/tidal & intertidal	Tidal marsh/Upper salt marsh	Buff200m (3)	5

Table 4. 5. Attribute table displaying the geomorphological classification of 924 individual land forms under CoastFe4' field (after Pendleton *et al.*, (2010; Sharples (2006) and Torresan *et al.*, (2008). (*Source: Silvia Caloca).*

It was decided that cliff type or cliff elevation was not to be included in the geomorphological classification as it has been in other studies (McGlaughlin 2000; Pendleton *et al.*, 2010) but an extra field named 'NCliffrankH' derived from 'CoastFe4' was generated. This field contains distance buffers based on geomorphological characteristics to be used in later cliff categorisation.

4.4.2. Cliff type

Cliff height was used as a suitable proxy combined with simplified landform categories to create a new cliff type. Due to geotechnical and structural processes, soft cliffs get eroded and recede more rapidly, lowering the cliff slope and making them unstable. Low cliffs are more prone to experience failure. Therefore, for the present study, an approach that combines geomorphic units with structural characteristics of the cliff type, slope and elevation was applied (Gornitz *et al., 1994;* Hall et *al.*, 2000; McLaughlin and Cooper, 2010). Landslide classification (BGS, 2012) was primarily used to discriminate and re-map cliff types. This file contained a combination of simplified geomorphology (constructed, granular, anthropogenic, rock and fine sediments) and structural categories (anthropogenic, cliff failure hard rock, cliff failure soft rock, cliffs no failure and low gradient). This was used for a preliminary categorisation of the susceptibility of the cliff. As done in previous studies, a preliminary classification was introduced by dividing every coastal type in the onshore into hard cliffs (low-high), soft unconsolidated coastline (cliffs (low-high) and low gradients)) (ECOPRO, 1996; BGS, 2012). See Table 4. 6.

Onshore zone	**Coastal type**
Rocky sea cliffs	hard coastline
Glacial till / clay cliffs	soft coastline
Dune backed shorelines	soft coastline/low gradient
Manmade structures	combination of hard and soft

Table 4. 6. Preliminary coastline classification into hard/soft (ECOPRO, 1996).

As in recent studies of cliff resilience, (Van Den and Heteren, 2015) distance buffers were combined with cliff heights. The ‘Cliff rank’ field from the geomorphological table helped to differentiate three different elevation transects. Based on erodibility potential a polyline file with perpendicular transects 50, 100 and 200m long from the coastline was generated. This contained estimated cliff heights elevation (maximum and minimum) that was joined to the cliff type point file, so all cliff types had an associated elevation. A vector across the beach profile (break in the slope from base of cliffs) was also determined and used as a criterion in the discrimination of high rocky cliffs.

Man-made structures such as walls were also classified regarding heights. Cliff type information was examined further relative to the latest vegetation line using geomorphological, OSi helicopter oblique images and Google earth images (2016-2017). These images helped to identify anthropogenic areas and also to decide upon elevation categories for final cliff classification i.e.: geomorphology polygons characterised as ‘open hard rock cliff shores’ were selected and compared with the Bedrock map to determine what types of material it contained and what elevations were predominant for that particular type. Finally, cliff types previously divided into hard rocky cliffs, soft unconsolidated and low-gradient sediments (including anthropogenic areas) were further discriminated into high and low.

McLaughlin (2001) and McLaughlin *et al.*, (2002) in Northern Ireland and Pendleton *et al*. (2010) and Gutierrez *et al.* (2011) in the US, ranked shoreline/cliff type and height according to relative resilience to wave attack. Similarly, five categories were created for this research and a vulnerability rank from 1-5 was applied to each category. See final cliff type classification in Table 4. 7.

Cliff types were ranked according to their erodibility and capacity to resist wave action. Higher cliffs are less vulnerable because they are composed of hard rock (Gornitz and Kanciruk, 1989; McLaughlin, 2001; McLaughlin *et al.*, 2002) so they would have a vulnerability of 1-2. Soft cliffs vulnerability classes range from 3-4 whereas low gradient non-consolidated sediments are more exposed to wave attack, storms and extreme tides and therefore they were assigned category 5. It was assumed that engineered anthropogenic walls such as ports and coastal protection walls are resistant and stable. For walls and harbours, there is practically no recession and therefore a very low vulnerability was assumed (Dawson *et al.*, 2009).

Coast type	**Cliff Categories**	**Anthro/ walls/armour**	**Estimated cliff elevation (transect length)**	**Vul ranking**
Hard coast	High solid rocky cliffs	>10 m	>25.5m (Transect 50m)	Very low (1)
	Low solid rocky cliffs	2-10 m	<25.5m (Transect 50m)	Low (2)
Soft coast	High soft unconsolidated gravelly/till cliffs	<2m	>25 m(Transect 100m)	Moderate (3)
	Soft unconsolidated Low boulder clay/Sand and gravel and sandy Alluvium cliffs		<25m (Transect 100m)	High (4)
	Low gradient sand dunes/sandy shingle beaches/sand and gravels		Transect 200m	Very High (5)

Table 4. 7. Cliff type classification and vulnerability ranking. *Source: Silvia Caloca.*

Anthropogenic features were mostly treated as hard rocky cliffs. Anthropogenic areas were sub-divided into walls (high and low) (1-2 vulnerability) and low gradient anthropogenic areas (vulnerability category 3). So they were categorised in between low elevation and hard rock (See Plate 4.1). The Attribute table below shows the classification of the 12,424 polygons of the cliff type file and their ranking in field 'CL_TR5' (See Table 4. 8).

Plate 4. 1 .Example of low gradient anthropogenic area classified as vulnerability category 3 in North Co. Dublin. *Source: Google Earth.*

Newcliffty	CL_TR5	elesoftcli	elehardcli	elevAntro	elev_lowgr	50mCliffEl	100mCliffE
hard rocky cliffs	2	0	24.519631	0	0	24.519631	28.272104
hard rocky cliffs	2	0	24.519631	0	0	24.519631	28.272104
hard rocky cliffs	2	0	24.519631	0	0	24.519631	28.272104
hard rocky cliffs	2	0	17.930139	0	0	17.930139	18.091572
hard rocky cliffs	2	0	17.930139	0	0	17.930139	18.091572
hard rocky cliffs	2	0	17.930139	0	0	17.930139	18.091572
hard rocky cliffs	2	0	14.474443	0	0	14.474443	14.461773
hard rocky cliffs	2	0	14.474443	0	0	14.474443	14.461773
hard rocky cliffs	2	0	22.065852	0	0	22.065852	22.440506
Low Gradient/Granu	5	0	0	0	68.606069	18.327388	29.428801
Low Gradient/Granu	5	0	0	0	68.606069	18.327388	29.428801
Low Gradient/Granu	5	0	0	0	68.606069	18.327388	29.428801
Low Gradient/Granu	5	0	0	0	68.606069	18.327388	29.428801
Low Gradient/Granu	5	0	0	0	65.59994	25.486475	39.816135
Low Gradient/Granu	5	0	0	0	65.59994	25.486475	39.816135
Low Gradient/Granu	5	0	0	0	65.59994	25.486475	39.816135
Low Gradient/Granu	5	0	0	0	65.59994	25.486475	39.816135
Anthro/wall	2	0	0	3.618625	0	3.618625	3.619742
Anthro/wall	2	0	0	3.618625	0	3.618625	3.619742
Anthro/wall	2	0	0	3.618625	0	3.618625	3.619742
Anthro/wall	2	0	0	3.618625	0	3.618625	3.619742
Anthro/wall	2	0	0	3.618625	0	3.618625	3.619742
Anthro/wall	2	0	0	3.618625	0	3.618625	3.619742

0 (0 out of 12424 Selected)

Table 4. 8. Attribute table displaying the cliff type classification and ranking. *Source: Silvia Caloca.*

4.4.3. *Regional coastal slope*

Regional coastal slope was inferred from digital elevation models (DTM). The hinterland coastal slope represents the topographic gradient of the coastal zone extended landwards from the high-water mark (HWM). The coastline was divided into points every 100m and perpendicular transects were generated from these at 50, 100, 150 and 200m. LiDAR (2m resolution) digital terrestrial elevations models (OPW, 2006) were used to calculate the average slope. Orthoimagery and DTM were checked to identify the shortest representative transects that contained the break of slope. Therefore, the 100m transect was used for the calculation of the average slope variable. Slope values were classified and ranked based on the assumption that while steeper offshore gradients absorb less wave energy than gentle (dissipative) gradients, gentler gradients may increase storm surge heights and result in a higher risk of inundation. These characteristics may vary regionally and will determine shoreline responses to sea-level rise. Some classifications separate the hinterland zone into steep slope terrain >20°, gentle slope (6-20°) and flat terrain (0-6°) (Sharples, 2006) while others are based on quintiles distribution of values (Pendleton *et al.*, 2010). Slope classification in this study takes into account both, and divides regional intertidal slope into five categories (Table 4. 9). Next a five-class vulnerability ranking was assigned in the attribute table on field called 'Slope_R5'.

Slope values	**Vulnerability Class**	**Vulnerability ranking**
0°-5°	Very high (5)	5
5°-10°	High (4)	4
10°-20°	Moderate (3)	3
High cliffed coast 20°-30°	Low (2)	2
High cliffed coast >30°	Very low (1)	1

Table 4. 9. Coastal hinterland slope classification and ranking adapted from Sharples (2006).

4.4.4. Aspect

Aspect values were generated by dividing the shoreline into segments and then calculating the segment's orientation. Aspect classification was manually evaluated from the degree of exposure of the shoreline segments towards predominant swell and storm approach directions given by the Mean Sig Wave direction, which in the study area, is approximately SE (N135) (Gallagher *et al.*, 2014). See Figure 4. 4.

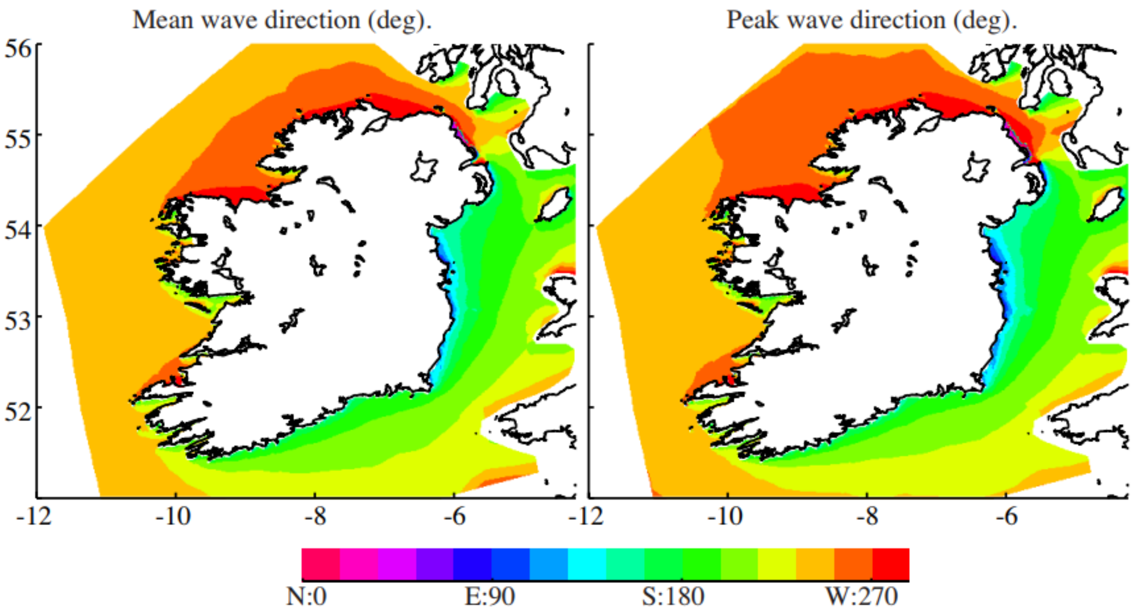


Figure 4. 4. Model diagrams show wave climate directions in Ireland for the period 1979 to 2012 where E: 90° means waves approaching from an Easterly direction (deg). Directions follow meteorological convention: 0◦ waves coming from North, 90◦ waves coming from East. (Gallagher *et al.,* 2014).

Aspect values under a field named 'GRID_CODE', were divided into four categories from greatly exposed, exposed, semi-exposed, sheltered and very sheltered. Fields VulClass5 and 'Asp_R5' showed segments orientation ranges and vulnerability ranking respectively. Segments orientated parallel/semi parallel to wave action were categorised as more vulnerable. See Table 4.10 below.

Vulnerability	**Segment exposure towards main swell & storm direction (N135)**
Very low (1)	Coastline non-exposed to the ocean wave.
Low (2)	Aspect of shoreline segment faces >135º or sheltered from important swell and storm wave approach directions.
Moderate (3)	Aspect of shoreline segment faces between 60º-135º of important swell and storm wave approach directions.
Very high (5)	Aspect of shoreline segment faces within 60º of important swell and storm wave approach directions.

Table 4. 10. Aspect classification of shoreline segments modified after Sharples (2006).

4.4.5. Relative sea-level changes

Values of relative sea-level change data from historical records were derived from monthly Mean Sea Level data (Woodworth and Player, 2003; PSMSL, 2013) and also from Dublin Port tide-gauge paper charts. From these, a trend line showing long-term past relative sea-level data for Dublin was inferred via linear least squares regression. Then a point shapefile with the fixed value 1.96 mm/yr was generated for CVI. As in other studies, given the scale of the present study, this variable was left constant (Abuodha and Woodroffe, 2010b). Consistently with other similar CVI studies (Pendleton *et al.,* 2010), a low (2) vulnerability ranking was assigned to this variable.

4.4.6. Mean Tidal range

From the analysis of tidal data, accurate tidal predictions for at least one year are given from Admiralty charts and Almanac tide tables at hourly intervals for primary ports such as Dublin (North Wall) and secondary ports (i.e: Malahide). If data are sparse as in this case, the alternative to the above is to use a numerical method. VORF and POPREDS models were considered for Mean Spring Tidal Range calculations (over 18.6 years). POLPREDS is an offshore tide and current computation system developed by the Proudman Oceanographic Laboratory (POL).

As displayed in Figure 4.5, tidal range gridded data were output by subtracting the low tide level from the high tide Mean High Water Springs- Mean Low Water Springs (MHWS-MLWS) for every cell within the study area.

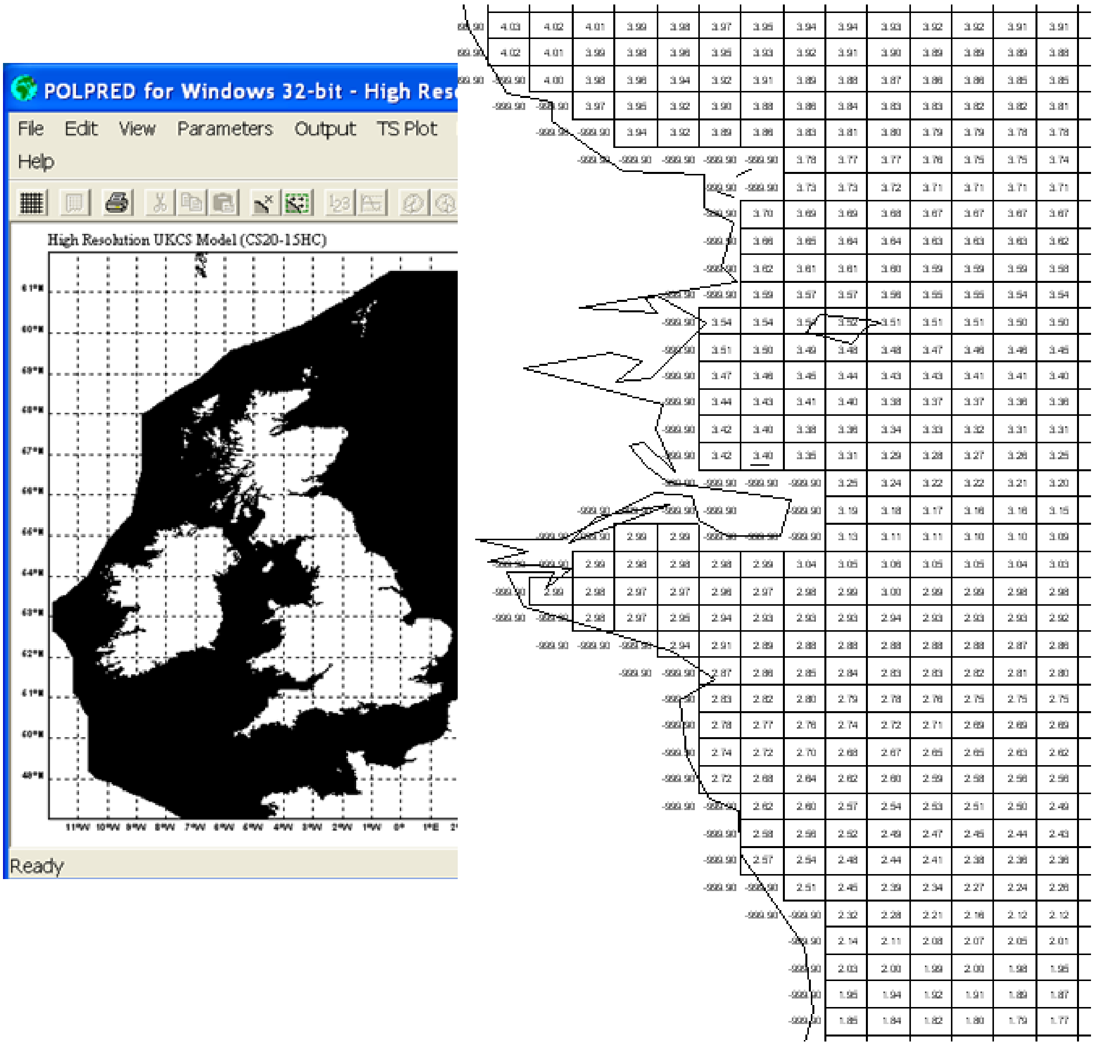


Figure 4. 5. Mean High and Low Water Spring predicted tide generated by POLPREDS (Proudman Oceanographic Laboratory (POL)) in the study area. *Source: Silvia Caloca.*

Despite the fact that the POLPRED model performs quite well offshore, its accuracy begins to break down closer to the coast as weather, morphology and associated interactions begin to have an influence. Tidal regime measurements, closer to the coast, provide more information regarding near shore bathymetry. Consequently, for this research, contour lines outlining tidal regime were acquired from VORF calculations. Mean tidal regimes were calculated from Mean High Water Springs (MHWS) and Mean Low Water Springs (MLWS) and outputs generated from VORF software. As illustrated in Figure 4.6, this consists of a vertical offshore reference frame that allows the conversion between vertical heights/depths from different DATUM.

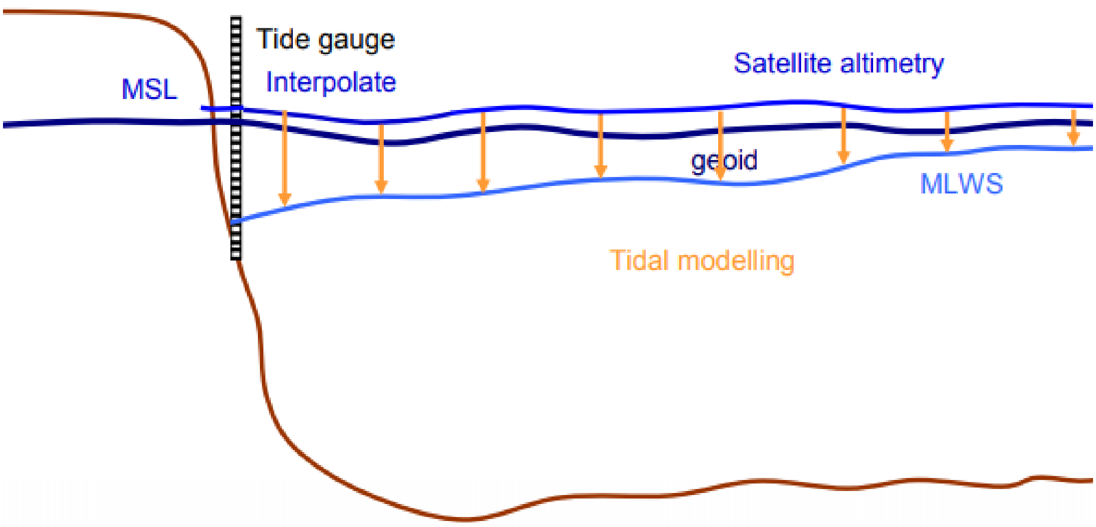


Figure 4. 6. VORF model used for calculating depths between different vertical Datum. *(Source:VORF Manual V8.15 (Available at following web URL): https://www.ths.org.uk/documents/ths.org.uk/).*

Despite the fact that tidal currents are defined by neap and spring tides, only spring tides were considered in this research. MHWS and MLWS values were used instead of Lowest and Highest Astronomical Tide (LAT/HAT) extreme ranges as they are more common and suitable for vulnerability analysis. Tidal ranges were converted from Geographical coordinates to Cartesian using the Irish Transverse Mercator (ITM) system and downloaded into ArcGIS. For visualization purposes, contour lines of a tidal regime were generated. Finally, values were classified according using quantiles and ranked for vulnerability after assuming that micro tidal ranges would pose higher risks (Thieler and Hammar-Klose 1999; Pendleton *et al.*, 2010; Gutierrez *et al.*, 2011). This criteria for ranking vulnerability disregarded assumptions of macrotidal regimes being high-risk on the basis that strong tidal currents are associated with large tide ranges. In this research, it is considered that micro tidal ranges are most vulnerable because in a microtidal environment, water levels are high for longer periods, meaning that it is more probable that high waves occur at high tide, increasing the risk of inundation or erosion from storms.

4.4.7. Mean annual significant wave height (m)

High-resolution 3-hourly directional spectra outputs of mean significant wave height (Hs) and wave direction were hindcast for Irish coasts extracted from the WAVEWATCH III model (Roland, 2008; Tolman, 2009) for the period 2000-2013. Model simulations were based on three different nested grids at a fine resolution from offshore to near shore. An unstructured grid at the finest resolution was driven by wave directional spectra from ERA-Interim Global Wave re-analysis (ECMWF) as the forcing boundary data (see Figure 4.7). High resolution digital elevation models (MBES and LiDAR INFOMAR) at a 2-80m resolution were used. Outputs were used to generate a significant wave height (Hs) contoured map around the study area. Finally, five vulnerability data classes were produced, based on significant wave height gradient. The closer that wave data is to shore, the more valuable they are in providing information regarding vulnerability. Waves heights measured in the near shore, as done for this research, provide information regarding near shore bathymetry, rendering slope metrics less important than they would be if only offshore waves were available (McLaughlin and Cooper, 2010). A wave heights ranking was elaborated from natural breaks. This ranking considered that coasts receiving higher waves, and consequently a greater amount of average annual wave energy, will change most rapidly in response to sea-level rise, other factors being equal.

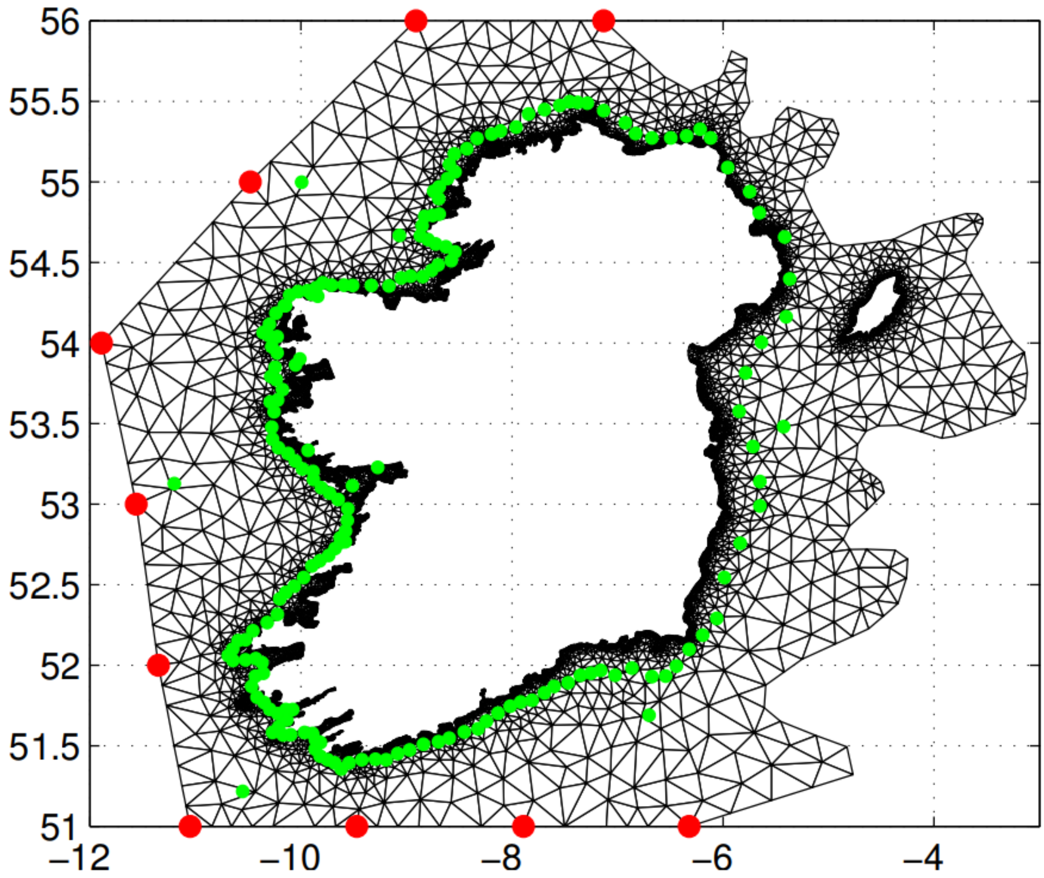


Figure 4. 7. Wave model grid showing 20,235 nodes; unstructured high resolution model shows in red ERA-interim wave model grid points (in red) used for boundary and 3-hourly directional point wave outputs (in green) (Gallagher *et al.*, 2014).

4.4.8. Shoreline changes analysis

The desk study primarily involved compilation of erosion information following EUROSION (2004) guidelines. Recent changes in erosion/accretion were examined demonstrating that this is a valid indicator for coastal vulnerability analysis. Particularly important were those areas where erosion is currently present but not 20 years ago. A close examination of shoreline evolution trend status and identification of areas undergoing changes was carried out and comparison with historical and recent imagery was made. Evidence of past shoreline instability (from CORINE Coastal erosion database since 1985) and more recently (EUROSION database, 2004) or recent coarse shoreline rate data from OPW (2010) were explored (See Figure 4. 8).

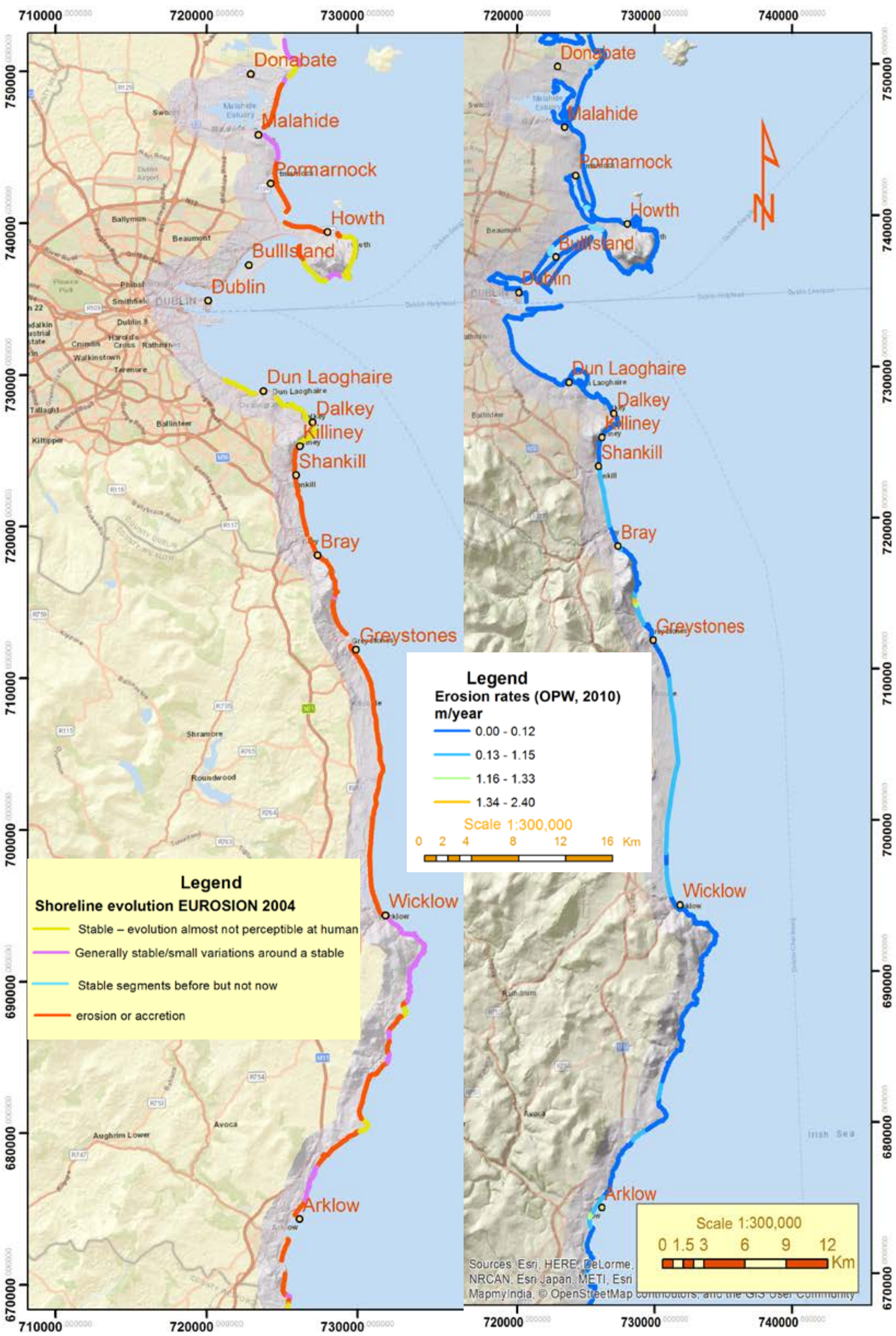


Figure 4. 8. Left. Erosion risk maps drawn using OPW (2010) data. Right. Erosion/accretion maps created using data from EUROSION Project (Salman *et al.*, 2004b). (*Source maps: Silvia Caloca).*

Changes in shoreline evolution, given by the total percentage of erosion or accretion, were investigated. Unstable (erosion or accretion) to stable trends from EUROSION data (2004) were looked at by means of the Coastal Erosion Layer (CEEUBG100KV2) and evolution trends attribute layer (CEEVV2). Changes in the high water mark at the Corballis Barrier and Broad meadow Estuary are also evidenced from historical OSi maps (See Figure 4. 9).

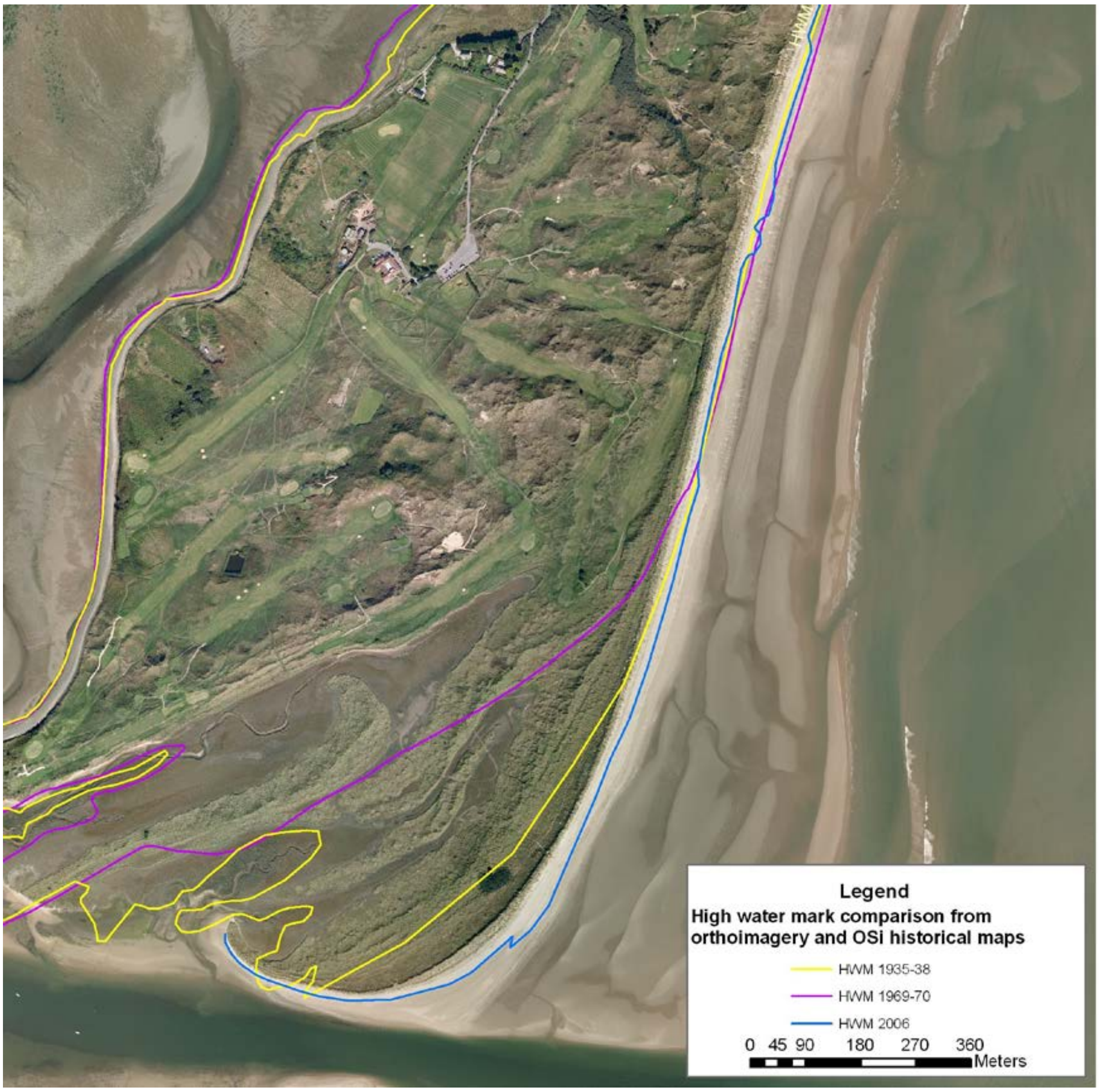


Figure 4. 9. Long-term shoreline changes evidenced from HWM change of position in Corballis Barrier and Broad meadow Estuary. (*Source: Silvia Caloca).*

Next a field survey reconnaissance followed to assess the state of the coast, to locate man-made structures, condition of dune's vegetation, storms' water marks and evidence of long-shore movement. Deposition of finer material in spit development at the beach edges could indicate erosion in narrower and coarser grained sediment up-drift areas. All this was accompanied by field RTK surveys to gather high resolution recent vegetation line data (See Plate 4.2).

Comparing the position of the coastline at various times in the past gives a comprehensive view of the evolution of the coast. To detect the historical changes in the coastline, the recent position of the vegetation line was accurately mapped using available historical imagery. Time series of vegetation lines were digitised from satellite (Google Earth), stereo photographs (OSi, Air Corps), and aerial datasets (OPW; OSi) available in ArcGIS for several years (1952, 1971, 1995, 2000, 2005, 2006, 2008, 2009, 2011, 2013, 2015, 2016 and 2017).

Plate 4. 2. Global positioning System survey carried out by the author using a Trimble VRS equipment (*Source: Silvia Caloca*).

In addition, an extra vegetation line in 2011 was compiled between July-October 2011 by fieldwork by means of a Global positioning System survey using a Trimble VRS differential GPS. This method is more accurate than digitizing over an ortho-photograph. See Plate 4.2.

GPS readings were taken when there was coverage of 5 to 8 satellite and data were stored automatically. At times, the receiver discards the initialization because the RMS is too high. This might be due to too much pole movement, bad environmental conditions or incorrect initializations and measurements that trespass the established tolerances. Corrections were made instantaneously, and readings got downloaded from the control unit once the survey ended. Data was transferred from the controller by connecting the controller to a PC that uses the *Microsoft ActiveSync* technology. Automatic collection at a fixed time of 1 sec was decided to be the most appropriate; although the continuity of data acquisition and accuracy significantly depended on reception. Consequently, large amounts of data were assembled along the coastline defined by the vegetation line at an accuracy level oscillating between 0.009-0.015 m vertically and 0.009-0.012 m horizontally. The root mean square (RMS) error ranged between 0.15-0.30m.

Compatibility of data and their reference systems were assessed. Non-georeferenced OSi 1:30,000 stereo-photographs (1971) were georeferenced from OPW (2006) aerial photographs. During the process, control points were chosen with special care in order to minimise distortions, especially along the coast. Some of the data were compiled in National Irish Grid (IG) projection and then converted to Irish Transverse Mercator (ITM). The projection transformation equation was accurately selected.

In terms of coverage, when comparing this study with previous OPW (2010) data it was noticed, resolution issues aside, in general, the data collected by OPW disregarded accretion and are sparsely distributed (Figure 4.10). Regarding data acquisition accuracy, OPW used two lines for erosion calculations; whereas in this study, up to 12 vegetation lines were employed for calculations, depending on the area (See Plate 4.3).

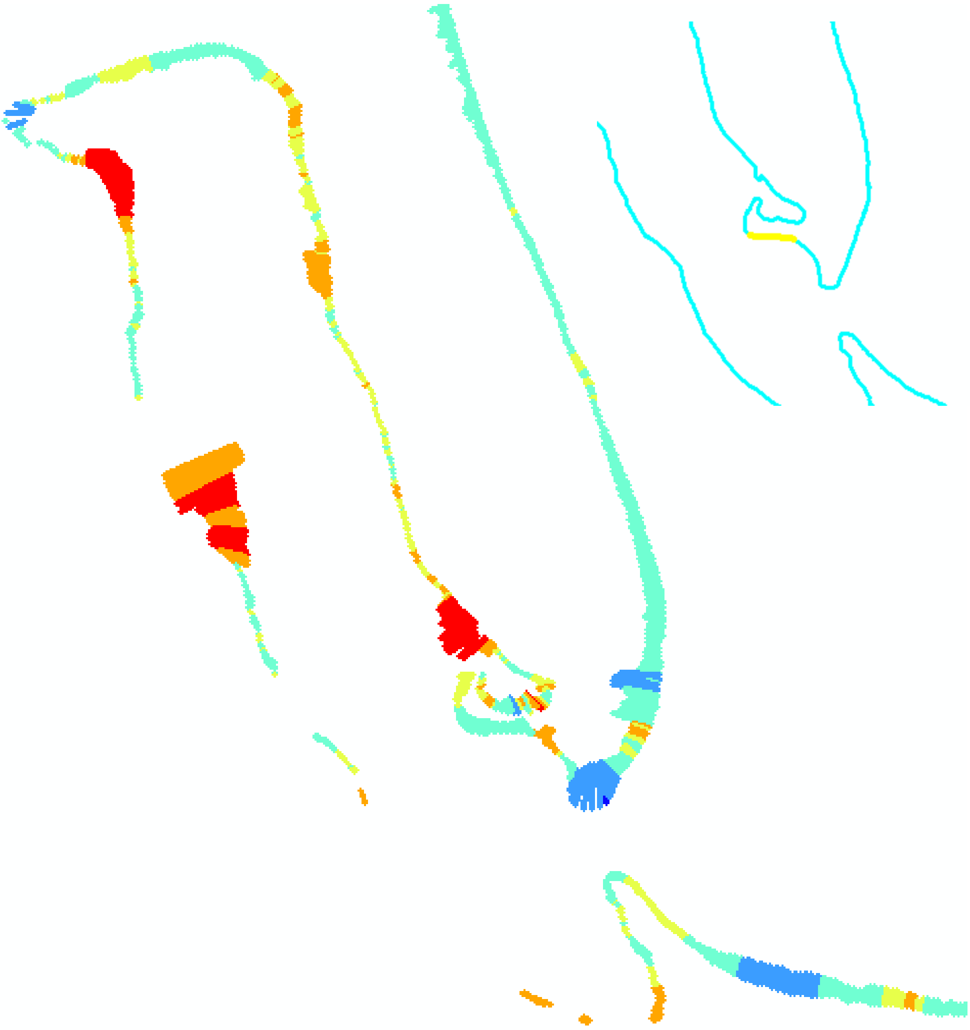


Figure 4. 10. Maps showing erosion data collected by OPW (2010) in North Co. Dublin natural areas (upper right) versus data coverage on this research represented by erosion and accretion transects (down left). (*Source: Silvia Caloca).*

One important limitation from previous studies in the area (OPW, 2010) was not specifying where coastal defences were introduced since the images were taken. To amend this, a review of cliff classification, geomorphological maps and OSi Aerial Oblique Imagery Survey and Google Earth latest imagery was performed to detect anomalies in the shoreline.

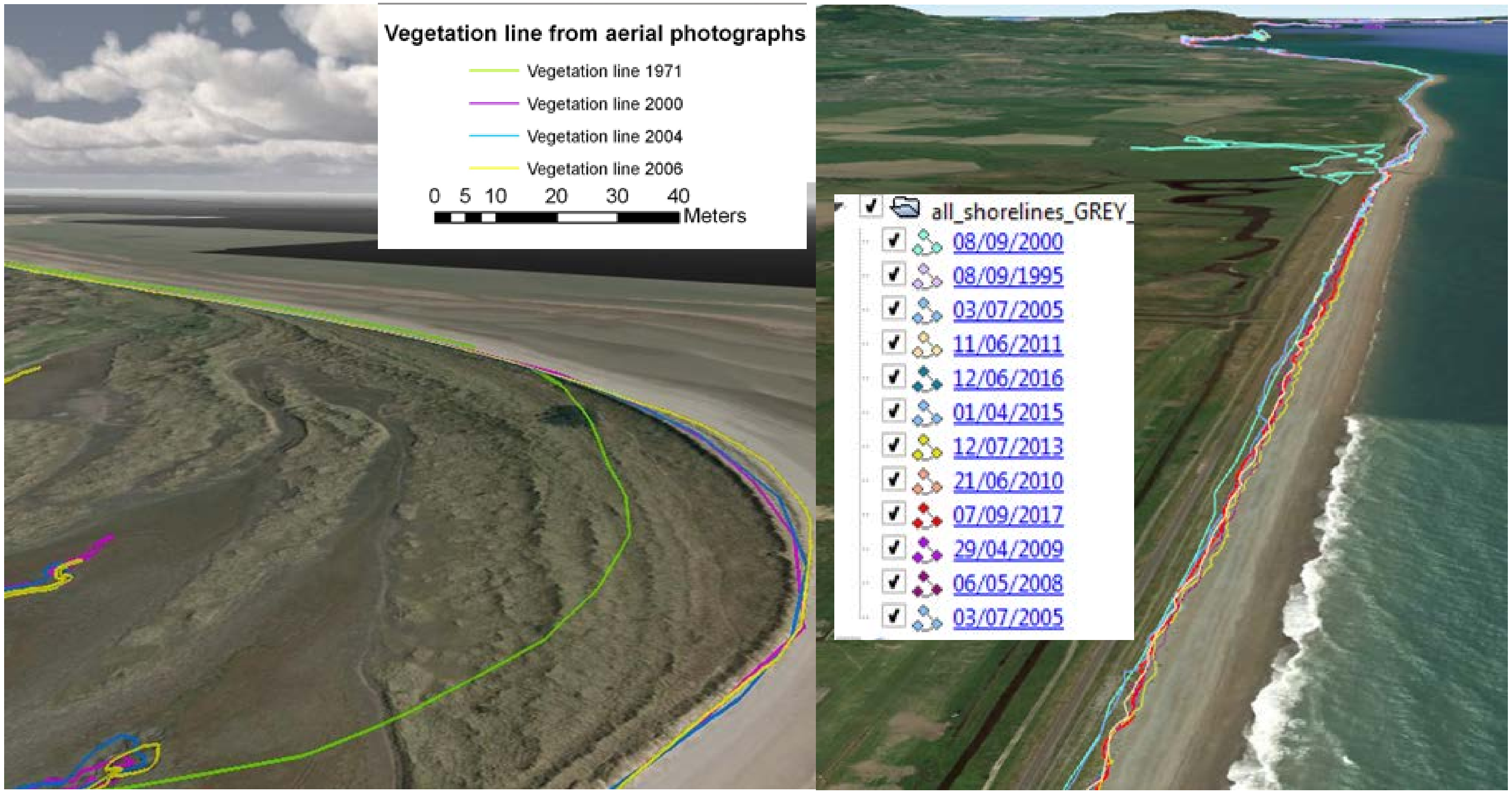


Plate 4. 3. Left. Aerial view showing vegetation lines digitized at the Corballis Barrier (N Dublin). Right. Vegetation lines in south Kilcoole (Co. Wicklow).(*Source: Silvia Caloca).*

Previous GIS-based studies evaluated temporal and spatial shoreline movement of cliff tops related to NAO oscillations in the UK (Brooks *et al.*, 2014; 2016). When compiling vegetation lines in this study, the same criteria and tools were used to standardise digitizing procedures. Digitising criteria adopted was digitising from where vegetation was noticeable and clearly identified from the aerial/satellite photographs involved. Initially anthropogenic areas were not digitised except areas where a wall existed, and considerable accreting vegetation flourished on the seaside. See Plate 4. 4

Plate 4. 4. Vegetation line withing an accreting area in North Wicklow. (*Source: Silvia Caloca).*

Ideally, the cliff base line would have been used but sometimes only the cliff top was available from images. The rational for using cliff top edge rather than base is that it seems more obvious and identifiable on aerial photography (Brook and Spencer, 2014). However, that was not the case on walkover field mapping. Sometimes decisions were just based on vegetation coverage, as illustrated in Plate 4.5. Either criteria from base or top, vegetation lines were consistently digitised for all coastal segments.

Plate 4. 5. Images showing vegetation lines being digitised (red/white) on top/base cliffs. (*Source: digitized over* Google Earth images @ 2018 Digital Globe) *by the author).*

Once the vegetation lines were compiled, the next step was quality control of the data and calculation of uncertainties required for calculations during the compilation phase. Errors in positioning can be introduced from digitising or geo-referencing from various data sources such as aerial photographs or orthophotographs. These types of errors must be accounted for, and yet few studies do so. Previous studies in the area by the Office of Public Works (OPW, 2010) identified geo-referencing, ortho-imagery rectification and misinterpretation of underlying geology as the main sources of inaccuracy when calculating future annual rates. They also highlighted the relevance of the current state of the coastline (ie: protecting walls) and resolution. For instance, in Robinson's survey, the old historical 1864 cliff line was used as a baseline for comparison to 2009. This introduces systematic errors during the conversion process.

Similarly, GPS errors during acquisition are inevitable. For aerial photograph and orthophotographs, some authors introduced 'tidal fluctuation errors' and 'seasonal errors'. In this case, tidal fluctuations did not apply, since for this research, the shoreline was measured using the vegetation line rather than using the Low Water Mark (LWM) (Vitousek *et al.,* 2009). Seasonal errors, accounting for differences in beach profiles associated with cyclic processes of accretion or erosion, were not considered either due to the scarcity of photographs. Distortions caused by camera tilt and topographical features were removed during the process of ortho-rectification of OSi images. The error (RMS) values indicative of inaccuracies, were sometimes omitted due to a lack of information from the source. The errors dealt with in this research are positional and measurement uncertainty. The first relates to the position of the vegetation line when the aerial or orthophotographs were collected and the second with direct measurements. Thus, for every shoreline, the total error is given by the following formula. See Equation 4.2 and summary in Table I.1 (Appendix I).

$$E_{sp} = +/- \sqrt{E_g^{\,2} + E_d^{\,2} + E_p^{\,2} + E_l^{\,2}};$$

Equation 4. 2. Total error uncertainties for WLR.

; where (**E_g**) and (**E_d**) are the geo-referencing or digitizing errors respectively; (**E_p**) the pixel size; (**E_l**) is the GPS/LiDAR the positioning error (Hapke and Reid, 2007).

The next phase involved calculating erosion and accretion rates for different coastal units. These calculations were performed using the new Digital Shoreline Analysis System (DSAS), a dedicated GIS-based extension tool developed in recent years by the US Geological Survey (Himmelstoss, *et al.*, 2009; Thieler *et al.*, 2009).

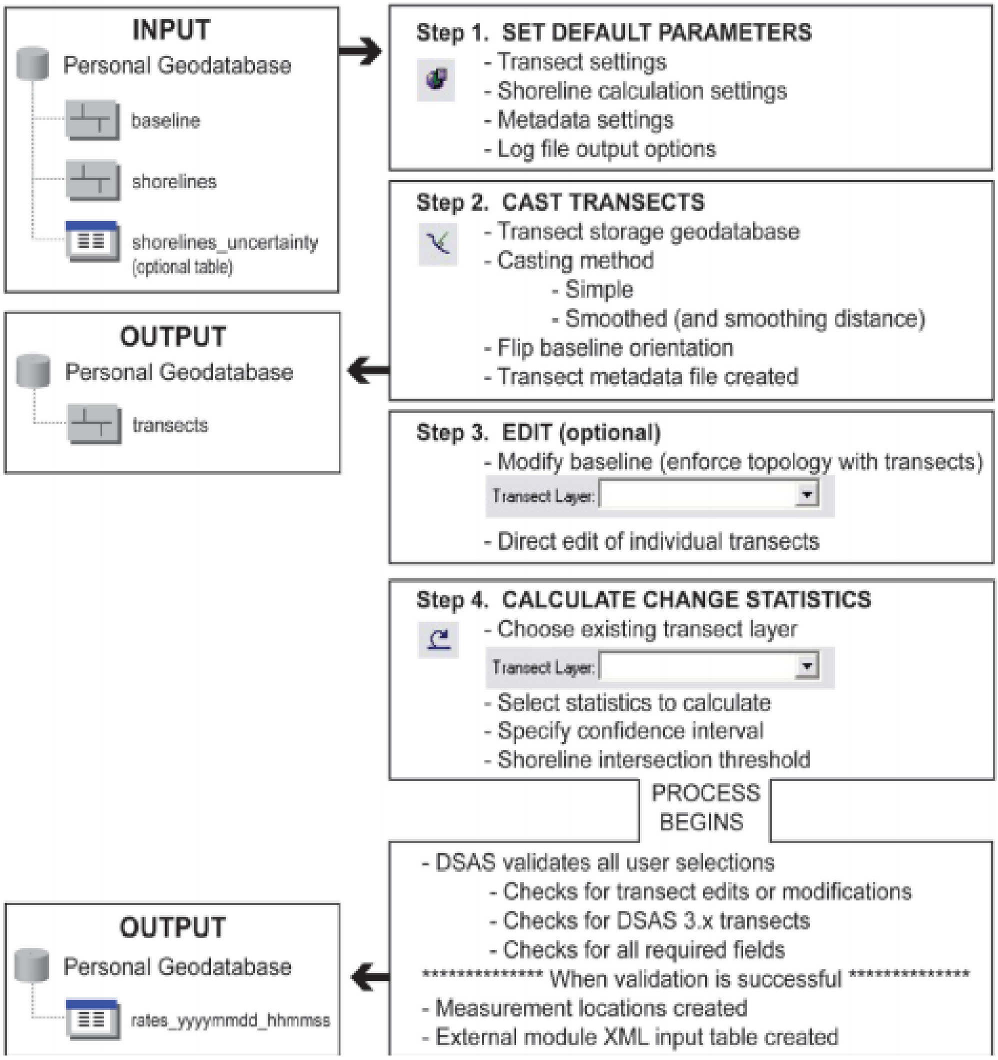


Figure 4. 11. Diagram showing DASS Workflow for shoreline changes calculation (DASS 4.0 manual).

This method provided a measurement of the long-term rate of shoreline change at every point of the coast and, hence has been applied to shoreline analysis in many studies (Thieler *et al.*, 2005; Brooks and Spencer 2010; Brooks *et al.*, 2012, Bonetti *et al.*, 2010). Digitised shorelines and baselines were merged and embedded into an ArcGIS file geodatabase. Figure 4.11 illustrates DASS workflow. The weighted linear regression method (WLR) was applied for statistical shoreline calculations. WLR is more accurate than the 'End Point Rate' (ER) method as it assigns weights and accounts for temporal changes (See Figure 4.12 and Equation 4.3). In EPR, distance is divided by the span of time elapsed between two shoreline positions whereas the rest of the information from other shorelines is overlooked, and error uncertainties are not considered. However, ER values were also calculated for comparison during the quality control phase.

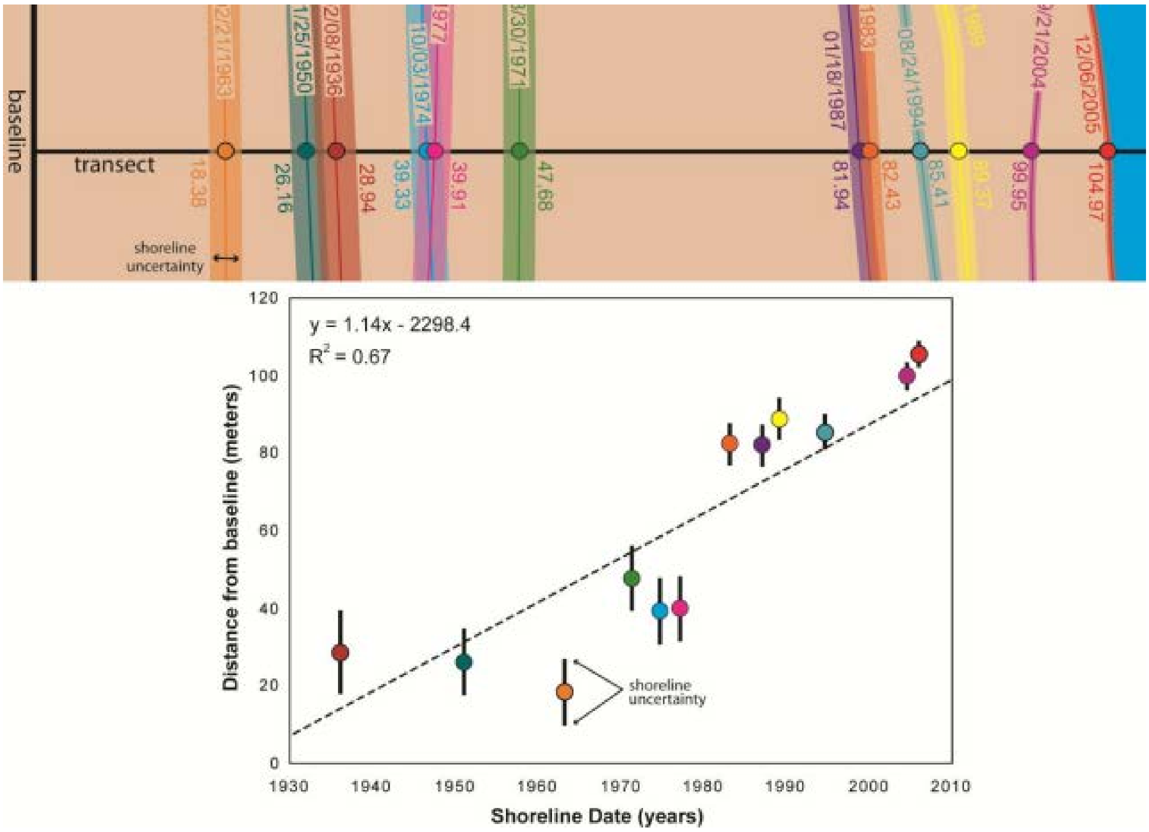


Figure 4. 12. Weighted linear regression (WLR) method applied to shoreline calculations (DSAS 4.0 manual)

$$w = 1/(e2)$$

Equation 4. 3 .Weighted uncertainties calculations for WLR.

;where ‘w’ is weight and ‘e’ are the uncertainty values for that particular shoreline (Genz and others, 2007).

During the shoreline changes calculation process, MHWM was used as a baseline. Compulsory fields were added: shoreline and baseline files, together with corresponding uncertainty values and attribute tables and baseline positions were examined. A minimum of four lines are needed for WLR calculations. The onshore/offshore combined option was found to be not accurate enough. Therefore, coastal segments were grouped using different WLR thresholds and baseline locations, and after they were manually edited and joined. Then, transect parameters were entered, and perpendicular transects generated and clipped (See Figure 4. 13).

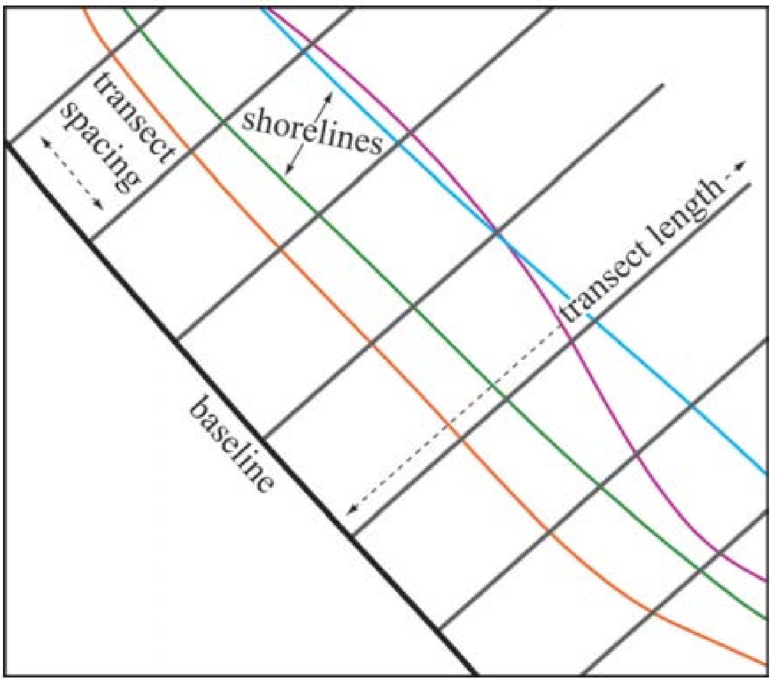


Figure 4. 13. Diagram showing transect position perpendicular to shoreline (DASS 4.0 manual).

Once transects were calculated, quality control was performed. Coastal segments were divided into segments with similar characteristics so that baselines were either located on the seaside or landwards, as appropriate (See Figure 4.14).

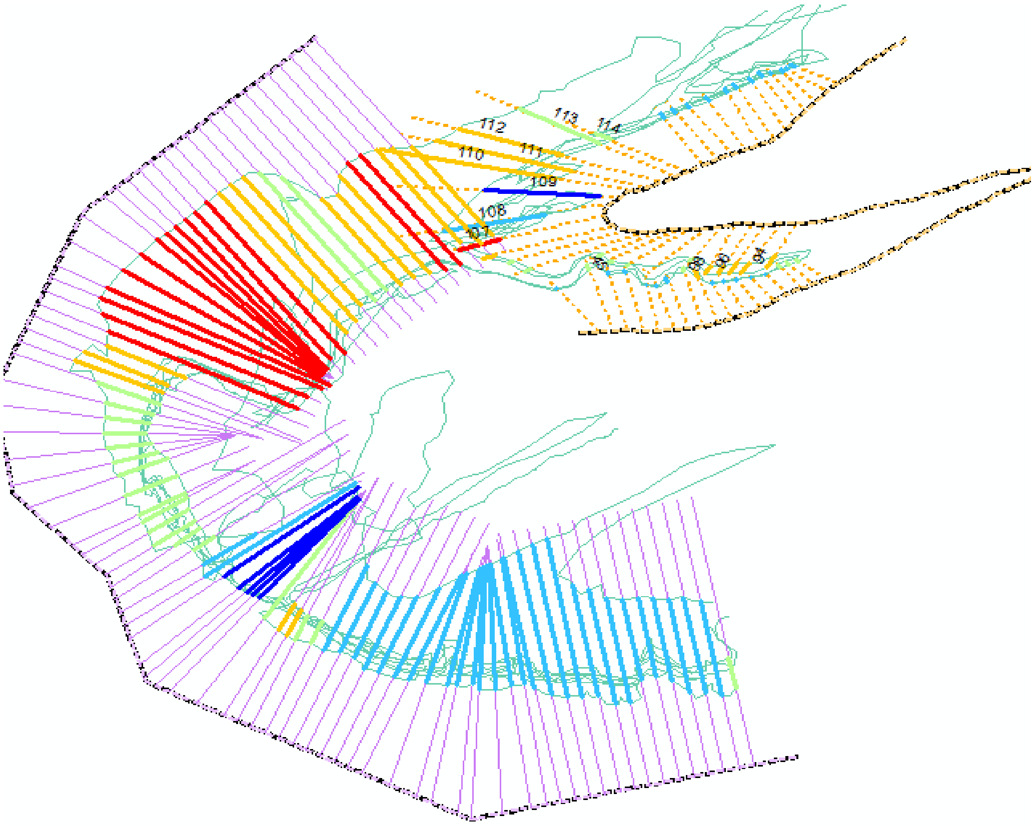


Figure 4. 14. Baseline positions (dashed lines) over transects situated landwards or seaside from vegetationshorelines (*Source: Silvia Caloca).*

Shoreline change values were either taken from one side or the other, avoiding overlapping transects. However, if two sections with transects with different parameters overlapped, transect built up from a higher number of shorelines, in general prevailed. Sometimes, using fewer shorelines (i.e.: leaving 1971 shoreline out) would totally change the output from erosion to accretion. In these cases, the worst-case scenario was considered. Nonetheless, this criterion had its exceptions. For instance, results created from a greater number of lines made the WLR increase accretion. In this case using more lines prevailed over the worst-case scenario, providing that accretion was the overall trend.

Finally, a review of anomalous data was carried out. Calculations in non-anthropogenic areas with fewer lines (less than 4) were directly discarded to minimise errors. In general, most of the anthropogenic coastal areas were avoided during the digitizing phase and therefore lines were not even recorded in the first place. Either way a post-digitising review of current anthropogenic coastal areas was carried out, based on the latest cliff classification and newest Google maps imagery. Values (-3 m to +3m/year) were checked against individual vegetation lines and historical data. Exceptionally high values were left in areas with an established erosion history. High values from -3 to -6m/yr were located in low lying areas such as salt marshes in Bull Island and Portmarnock-Sutton (see Figure 4. 15).

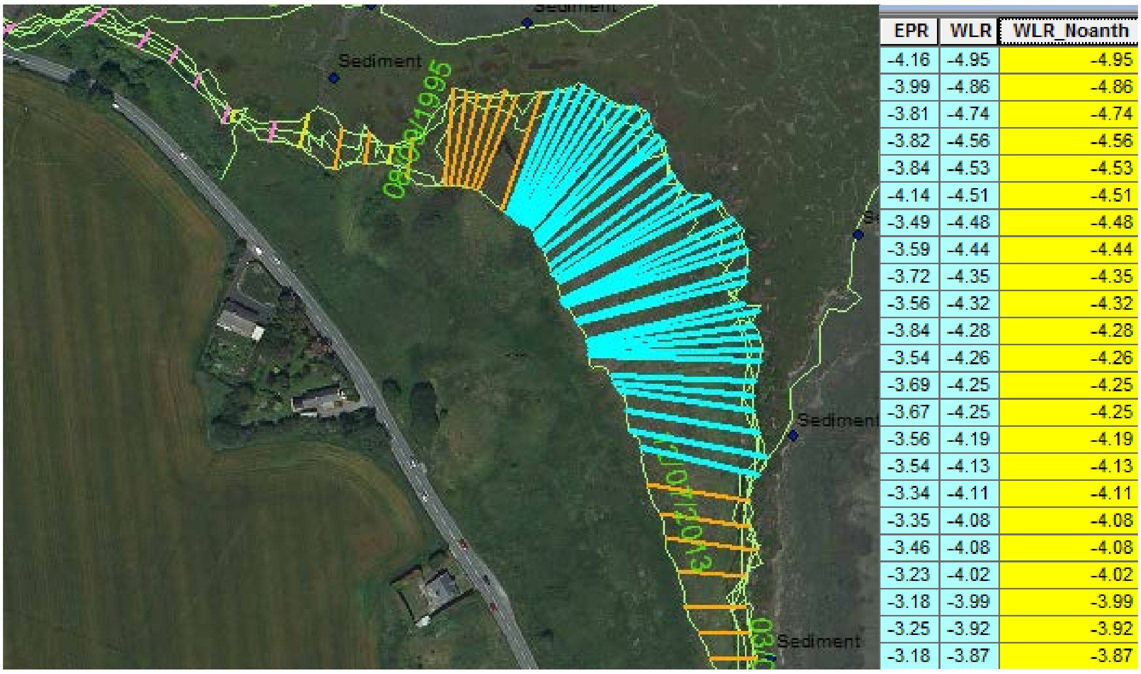


Figure 4. 15. High erosion values were spotted in salt marshes Portmarnock-Sutton. *Source: Silvia Caloca.*

With respect to accretion values, anomalously, high rates of 6-12.9m/yr were also investigated. It was noticed that some outliers occurred by the wall in the southern part of Bull Island. Those were probably generated from digitising errors over man-made structures in one of the vegetation lines. Accordingly, those values were removed. High accretion was also observed in Sandymount industrial zones. In this case some of the high values came out from digitizing but some were reasonable considering the effects of the wall. Next, the study area was also examined to differentiate rocky, sedimentary (with and without coastal defences) categories, by draping shoreline values over the latest cliff file (See Figure 4. 16).

Figure 4. 16. Shoreline transects falling within man-made structures identified in cliff point file (highlighted in blue) were reclassified (WRL=0).(*Source: Silvia Caloca).*

Recession for cliffs protected by walls or man-made structures is null (Dawson *et al.*, 2009). Consequently, a new field called 'WLR_NoAnt' was added to the attribute table and WLR values falling within man-made structures were reclassified WLR=0.

Areas where WLR =-1 were also double checked against vegetation lines to differentiate true ‘-1’values from errors. Two extra fields were added: 'Classifv1'= C where values existed and UC=no data. Finally, a shoreline classification was produced and vulnerability rankings were assigned A separate vulnerability ranking was produced under the field ‘Nbks_SCR5’ based on established practice (Pendleton *et al.*, 2010; Gutierrez, *et al.*, 2011) and on modified natural breaks. See Table 4. 11.

Vulnerability ranking/Shoreline rates	Shoreline changes m/yr (Pendelton *et al.*, 2010 & Gutierrez, *et al.*, 2011).	Shoreline changes m/yr customised from natural breaks
1	>2m/yr	>2
2	1 to 2m	0.2-2
3	-1 to 1m	-0.2 to 0.2
4	-2 to -1	-1 to -0.2
5	<-2m	-3.68-1

Table 4. 11 .Shoreline changes classification and vulnerability ranking.

Despite the fact that initially anthropogenic areas were avoided, it was necessary to assign values to every point along the coast, in order to apply CVI. Hence gaps were filled in with extrapolated values and non-recorded anthropogenic areas were also completed with WLR=0 (vulnerability ranking=3) to avoid zero ranking values for CVI calculations.

4.5. Volumetric analysis: case study

Soft cliffs are prone to respond rapidly to environmental patterns (e.g. changes in storminess or inter-decadal variation) and consequently they are perfect systems upon which to quantity coastal response (Trenhaile, 2011; Brook and Spencer, 2014). Short-term, erosion changes evidenced by volumetric differences were calculated by subtracting elevation (z values) from co-georeferenced pairs of DTMs with the same cell size and extent. The net change per unit area (1 sq m) was calculated for every two grids subjected to availability using methods previously used (Robinson ,20009; Woolard and Colby 2002; Mitasova *et al*,. 2009; Brook and Spencer, 2014).

Two LiDAR datasets were used:

- OPW LiDAR Digital elevation grid model (Office of Public Works, 2006). Ground Point Cloud is 2m spacing and the DTM has an accuracy of less than a 1m horizontally (x, y) and less than 0.25m vertically (z). Elevation data are in Irish Grid projection and shown in meters relative to OD Malin.

- LiDAR Digital elevation grid Model Geological Survey of Ireland (GSI, 2017) Terrestial LiDAR. Accuracy vertical 0.01 m; Horizontal 20cm.

A vertical error model of 0.35cm was applied, so shoreline changes with elevation differences above ±0.35 m were considered as net gains or losses.

4.6. Application of Coastal vulnerability index (CVI)

Once the most representative indicators of coastal change were compiled, classified and ranked, a Coastal Vulnerability Index (CVI) was created. CVI yields data that can be interpreted as relative vulnerability where the effects of sea-level rise are potentially the greatest. Using ArcGIS, the coast was divided into equidistant points and a CVI was applied to each by using the square root of the overall product of the ranked variables divided by the total number of variables. See Equation 4. 4. Results were displayed for every indicator and then added up into single contoured CVI vulnerability maps using different combinations of variables. As in previous studies, final CVI values were divided into quartile ranges (Abuodha, and Woodroffe, 2006; 2010b; Pendleton *et al.*, 2010) and ranked, for simplicity, within 3 categories. High pixel values would indicate high vulnerability to effects of sea-level rise and low pixel values, which would represent low vulnerability.

$$\mathbf{CVI= (a*b*c*d*e*f*g*h /n)^{1/2}}$$

Equation 4. 4 .Coastal vulnerability index applied for this research (Thieler and Hammer-Klose, 1999, 2000a,b).

;where CVI where ‘a, b, c, d, e, f, g and h’ are the variables and ‘n’ is the number of them.

However, it may not be necessary to use all the available variables since many can be highly intercorrelated. Assessments should employ as few comparable metrics as possible, avoiding some processes being overrepresented but including all the relevant vulnerability factors (Birkmann ,2006; Preston *et al.,* 2008; McLaughlin and Cooper, 2010). Despite the fact that only a few studies carry perform weighted analysis, it is recommended (Torres *et al.,* 2000; Wang *et al.,* 2011; Li *et al.,* 2012; Wolters and Kuenzer , 2015). See Figure 4.17.

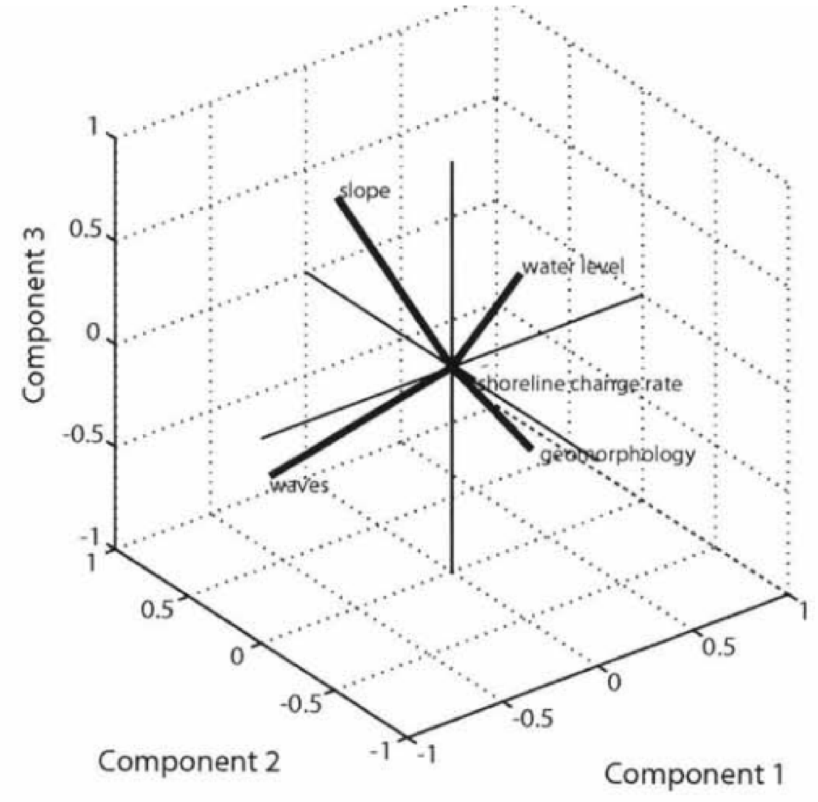


Figure 4.17. Diagram showing an example of bi-plot for three principal components using similar variables (Pendleton *et al*., 2010; Gutierrez *et al.*, 2011).

Consequently, Principal Components Analysis (PCA) was also used here as in some studies to reduce the number of independent variables (Boruff *et al.,* 2005; Pendleton *et al.,* 2010). Then, after the more relevant indicators were shortlisted, CVI map analysis could be placed into the appropriate context. The relationship between variables was explored by means of the covariance matrix. The outputs from the PCA were used to prioritise variables that were employed in producing the definitive CVI.

This allowed testing to be carried out omitting some variables (Abuodha and Woodroffe, 2010b).

4.7. Methods II: Local Sea-level scenarios

Some of the physical impacts caused by changes in relative-sea level that would significantly benefit from relative sea-level scenario generation are: inundation, flood and storm damage (sea-surge and backwater effect (river)); long-term wetland loss and change; morphological changes; saltwater intrusion; and rising water tables obstructing drainage. In assessing impacts to future sea-level rise, local sea-level rise (RSLR) rather than global changes should be used (Nicholls *et al.*, 2014b). As recommended by the United Nations Framework Convention on Climate Change UNFCCC (2014), the SimCLIM software, widely used in North America, New Zealand and Australia for creating local sea-level rise scenarios used impact modelling (Warrick, et al, 2005; 2009; 2007; Nicholls *et al*,. 2011; Kopp *et al*, .2014. It was also used in this research. Future scenarios of sea-level change were generated using the dedicated Sea Level Scenario Generator tool in order to later investigate the sensitivity of the system to impacts of enhanced sea levels (CLIMsystems Limited, 2013). This analyses sensitivity, risks and impacts in local areas by incorporating global, regional and local components based on results from AR5 (CMIP5) that incorporates thermal expansion or melting components.

Different countries will have different resolutions depending on which model they are using (eg. HADCM3 for UK has relatively high resolution for atmospheric and ocean variables). The SimCLIM sea-level scenario generator can create ensemble patterns for several combinations of GCMs, with median and lower/upper percentiles ranges (Figure 4. 18). Changes in sea-level are expressed as yearly changes (in cm) from 1990 to 2100.

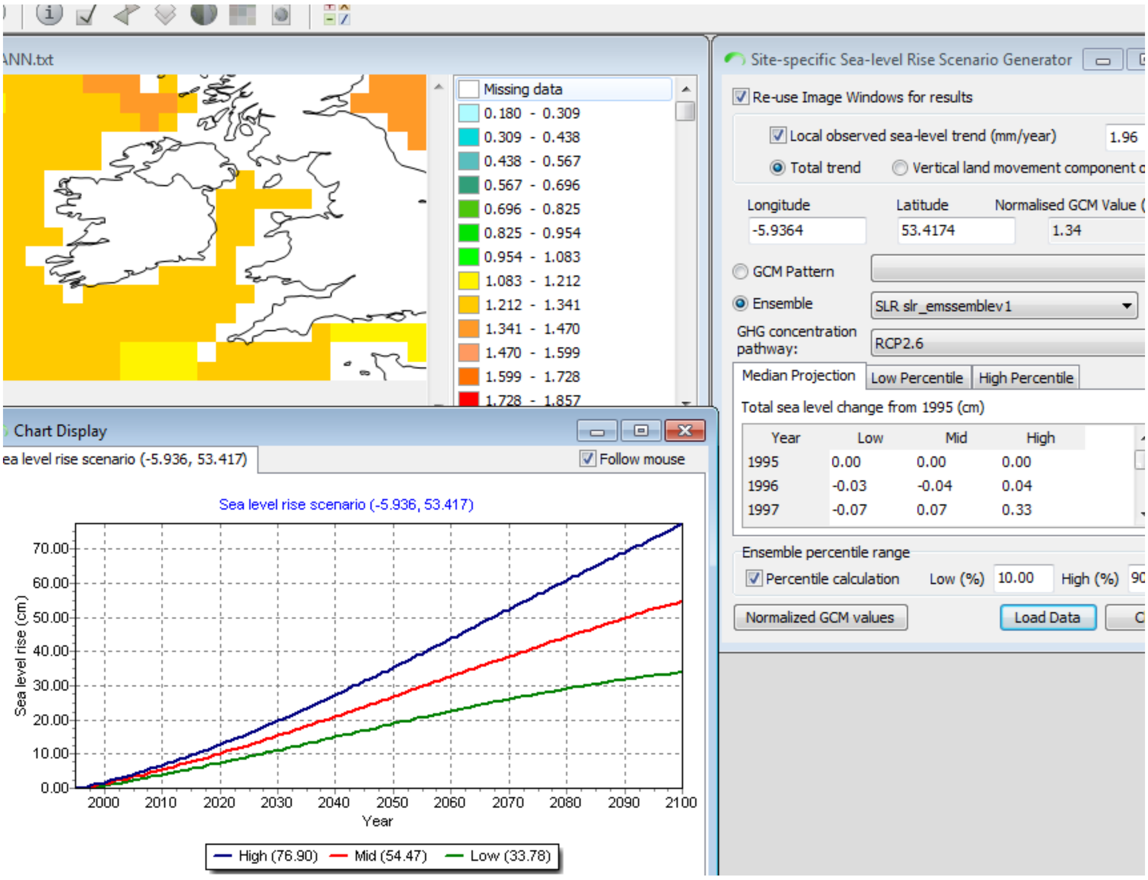


Figure 4. 18. Sea-level generator tool from SimCLIM software. Legend values represent scaling factor of local changes compared to global mean sea-level.

For regional projections, global mean sea level needs to be combined with geographical patterns. SimCLIM applies a pattern scaling method that derives regional spatial patterns of sea-level change from ocean processes generated by coupled Atmospheric Ocean Global Circulation Models (AOGCMs). This is done by using the average spatial pattern of change divided by global-mean value of thermal expansion for any particular period in the future. This is expressed in units of global sea-level change. Then it applies a normalisation consisting of future average spatial pattern/global mean sea-level value for the same period. SimCLIM (2013) includes a global climate model MAGICC (Wigley, 2008) which is forced by the latest CMIP5 climatic data (AR5) and climate sensitivity. AR5 data contain four concentration scenarios. MAGGIC estimates projections by 2100 above 1990's levels assuming different patterns of sensitivity and melting scenarios.

Pattern-scaling is only applied to the thermal expansion side of the total change; other sea-level contributions such as melting from ice caps are also included, but affected by huge uncertainties (Yin *et al.,* 2013).

Subsidence rates in the study area are assumed to continue in future as at present. SimCLIM software gives the option to directly enter the rate of vertical land movement, if known. If the vertical land movement trend is not known, the user can input the overall (unadjusted) recent sea-level trend, in mm/year (for example, as estimated from tide-gauge data). For the present research, it was decided to use only century-scale past relative sea-level trends calculated from high resolution monthly mean sea-level records (1938 to 2012) from (PSMSL) and Dublin Port. This observed sea-level trend does not differentiate between climate change related sea-level and changes from local land movements, and it is important therefore that double counting should be avoided. Therefore, land movement trends should be calculated, in order to know the exact contribution from the local non-climatic to relative sea-level change for the future. In order to estimate the relative sea-level rise, SimCLIM adjusts the locally observed trend by subtracting the observed global trend of 1.8mm/yr. Basically, the non-climatic trend is obtained and added to regional projections to obtain local projections (See Equation 4. 5).

$$OBS_{ncc} = OBS_L - OBS_g \text{ [GCM x TE + (1-TE)]}$$

Equation 4. 5 .SimCLIM Method to calculate the non-climate-change local trend in sea-level (mm/yr) caused by vertical land movement (SimCLIM, 2013).

Where OBS_{ncc} is the non-climate-related trend; OBS_L is the local observed trend from tide gauge data (mm/yr); OBS_g observed global-mean sea-level trend = (1.8mm/yr, ± 0.3 mm yr^{-1} (Nerem *et al.*, 2006; Church *et al.*, 2013); [GCM x TE + (1-TE)] is the GCM normalised scale pattern for thermal expansion.

Thus, relative sea- level values from model simulations were interpolated to generate projections at a 0.5°x 0.5°. Modelled relative sea-level rise ranking is going to reflect primarily regional to local isostatic or tectonic effects. Three resulting outputs of future sea-level change are produced. One of the limitations of SimCLIM is uncertainty in downscaled projections which depend on using the best available data for that particular location. Although in the Irish case, grids outputs are slightly coarse, this model still represents the only one available for calculating local sea-level projections for this area.

4.8. Methods III: Future coastal vulnerability assessment: Sensitivity analysis for future scenarios.

4.8.1. Potential future flooding impacts

Storm surges represent a challenge to our coasts with or without climate change (Storsh *et al*., 2015). Assessments at all scales have been carried out on inundation and storm impacts (Nicholls *et al.,* 2008). A measurement of coastal susceptibility would highly benefit from an analysis of de-trended (for relative sea level) historical hourly recorded positive surges (observed-predicted tidal levels) measured at different tide gauges across the study area. However, where recorded sea level data are not of a sufficient length of time to carry out extreme value analysis, joint probability analysis of tide and surge data can provide estimates of extreme sea levels (ECOPRO, 1996; Brown and Wolf, 2009; OPW, 2010). In order to analyse sea-level rise impacts of coastal areas, diverse methodologies have been used ranging from inundation mapping (Strauss *et al.,* 2012) to elaborate numerical models (Lorenzo-Trueba and Ashton, 2014). Since numerical models were not an option for this research, flood mapping was derived by analysing several scenarios of damage related to the probability of an adverse effect, added to adverse effects of rising sea-levels, as done in other studies (Bonetti *et al.*, 2010; Salecker *et al.,* 2011; Perini *et al.,* 2016). Some authors advise a combination of vulnerability and risk/hazard indices (Ferreira *et al*., 2017).

Coastal management should consider all available information. There is a high probability (~0-33 %) of projections falling within the upper ends of SLR scenarios (Church *et al.,* 2013). While multiple-scenarios broad and facilitate the range of options for adaptation for policy-makers, for impact and vulnerability studies it is advisable that highly sensitive places should plan for the worst sea-level rise scenarios. This means using high-end sea-level rise scenarios without adaptation (Allen Consulting Group, 2005; Renn 2008; Dasgupta 2009, Jevrejeva *et al.*, 2014; Hinkel *et al.*, 2015; Sierra *et al.*, 2016). As a result, risk probabilistic approaches for estimating future potential coastal changes in order to anticipate potential scenarios of flooding and erosion, are strongly advisable (Dawson *et al.*, 2009). Exposure of coastal areas to storms was assessed by identifying the presence of significant areas of low-lying land immediately landwards of the mean high water mark or likely to do so as a result of a projected future sea-level rise.

Impacts under the extreme scenario (RCP 8.5) high-end scenarios of sea-level rise by 2100 (with very low probability of occurrence 5 %) were used for this research. As in previous studies, in order to visualise the vulnerability of the area to future impacts, several maps representing the vulnerability to sea level rise inundation for each event would be produced (Preston *et al.*, 2008; Sayers *et al.*, 2017). Flood hazard (extent and depth) maps for extremes AEP were produced in Greater Dublin area as part of the Irish Coastal Protection Strategy Study (ICPSS) by OPW (2010) to assess current level of hazard. One limitation of this study was that these hazard maps neither accounted for climate change impacts (from future climate changes, sea-level changes, storms variability or erosion rates, and consequently shoreline positions), and although land movement ranges from + 0.1 to - 0.2 mm/year (South East Coast), OPW models not yet been adjusted for isostatic rebound either.

For this study, predicted extreme levels for 0.5, and less extreme 1 and 2% annual exceedance probability (AEP) events combined with tide-surge modelling were provided by OPW (2010). Extreme water levels are referenced to OD Malin (which is the Mean Sea Level at Portmore Pier, Malin Head, County Donegal, between 1960 and 1969).

Annual exceedance probabilities are expressed as odds of an event per year or return periods. Return periods do not exclude that two extreme events can happen almost at the same time. For instance, 1% probability (1:100) assumes floods happening approximately once in 100 years (See Figure 4. 19).

Annual Exceedance Probability (%)	Odds of Occurrence in any Given Year	Return Period (yrs)
50	2 : 1	2
20	5 : 1	5
10	10 : 1	10
5	20 : 1	20
2	50 : 1	50
1	100 : 1	100
0.5	200 : 1	200
0.2	500 : 1	500
0.1	1000 : 1	1000

Figure 4. 19. Annual exceedance probabilities represented on event per year and return periods (OPW, 2010).

For this research, the water levels were not assumed to be constant in the future. As opposed to OPW (2010) studies, this research takes into account potential impacts or effects from future local sea-level rise and land movement adjustments. As changes will happen gradually, high resolution topographic data are crucial. A digital terrain model was used to define the extent of the predicted floodplain. Thus, potential areas for future flooding were created by overlapping extreme water levels with future sea-level projections to predict flooding extent. Using this approach of inundating the area by rising water levels, rather than analysing secondary interactions was considered. This research does not take into like terrain roughness or migration from wetlands or estuaries and other morphological processes during a storm (beach and dune erosion) for which numerical modelling would be necessary.

Water level point data were converted to a grid (2m) and masked to the same extent as the LiDAR dataset, and data for each return period (0.5%, 0.1% and 1% AEP events) was subtracted from the LiDAR elevation values. Areas were reclassified leaving only negative resultant values indicative of potential flooding areas from a particular exceedance probability. For the same exceedance, these areas were converted into polygons and then were assigned a risk range for different future sea-level scenarios.

4.8.2. Coastal Impact models using SimCLIM

Future shoreline movement in a low gradient sand environment was calculated for different scenarios using the SimCLIM impact model dedicated tool (Figure 4 .20). The model uses the Brunn Rule method and allows for different combinations of site parameters.

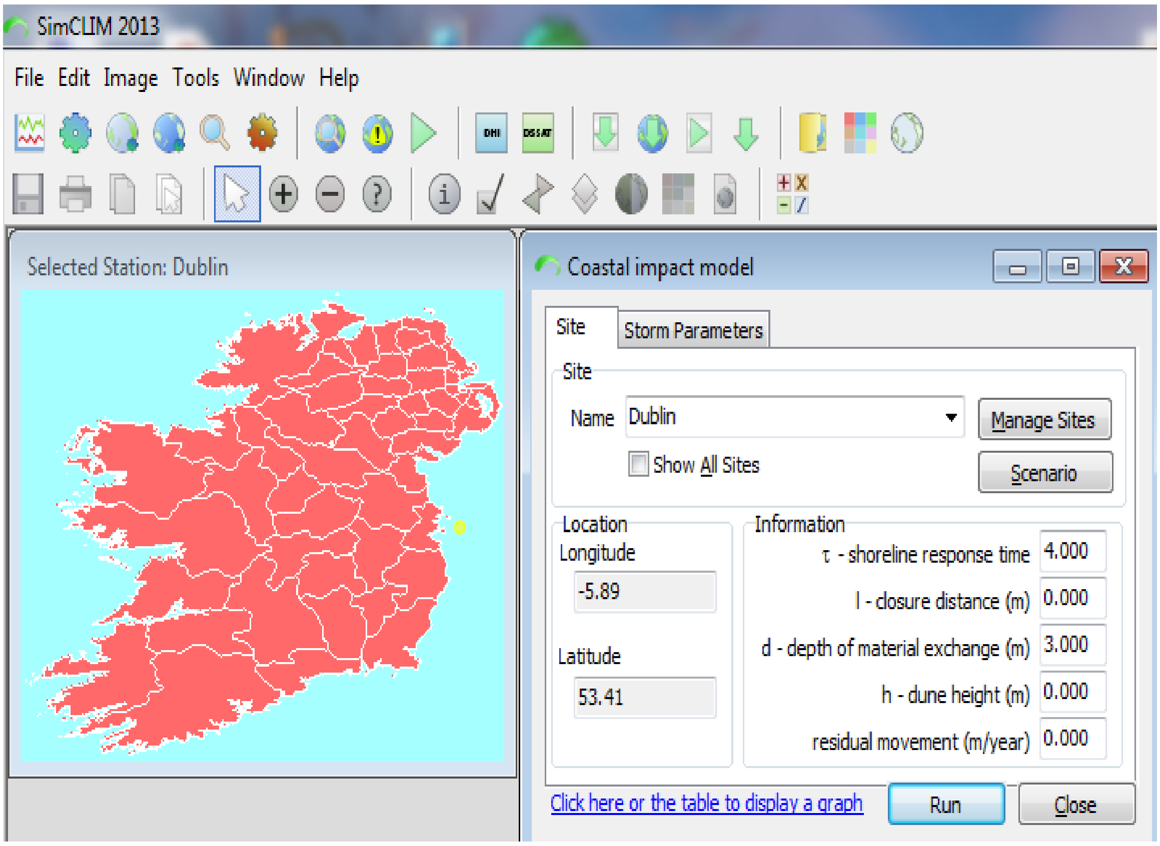


Figure 4. 20. SimCLIM impact model scenario tool used to project shoreline changes in low-gradient sedimentary environments within the study area (SimCLIM, 2013).

4.9. Chapter summary

Data compilation and processing, classification and ranking in combination with the application of robust methods and metrics, constitute the key to coastal vulnerability studies. CVI methods were applied in this research to characterise the vulnerability and to simplify the complex environment in this particular area, revealing information that can be used for coastal management. The first step towards understanding shoreline response to water-level changes is analysing and quantifying the physical indicators or variables that contribute to its coastal evolution. That is: the characteristics of its shoreline that makes it susceptible to change now and over the next century based on its physical response to sea level rise. In this study, the most relevant variables representing diverse structural characteristics and coastal processes that will have affect the coastal sensitivity to sea-level rise were identified and compiled: shoreline changes, relative sea-level rise, tidal range, annual mean wave height, geomorphology, cliff type, aspect and coastal slope. Values were divided into ranges, classified, and ranked based on their contribution to vulnerability. Several coastal vulnerability indices (CVI) were produced in which levels of vulnerability were estimated through the analysis and combination of previously assessed local indicators and illustrated by means of 2D thematic maps.

Future vulnerability to inundation and erosion were also examined by means of SimCLIM (2013) tools. Scenarios of inundations from extremes were recreated using the Sea-Level Scenario Generator tool. This tool has the capacity to incorporate changes of climate from global to local scale and was used to generate future local projections of sea-level change. These projections were combined with historical extreme water levels to anticipate future potential impacts necessary for coastal protection.

Chapters 6, 7 and 8 show the results derived from methods described above.

Chapter 5: Future relative sea-level scenarios for the Dublin area

5.1. Permanent Mean sea-level (PSMSL)

Long-term monthly mean sea-level data provided by the Permanent Service for Mean Sea Level (PSMSL, 2013) and Dublin Port from 1938 to 2012 were used to calculate the relative sea-level trends specifically for the study area. Initially, sea level measurements were converted to a Revised Local Reference (RLR); a common datum defined at 7000mm below the sea-level was applied to avoid operating with RLR negative values during the time series analysis (Figure 5.1). Data quality control was applied to historic data to ensure datum continuity throughout the series. For this reason, metric data were not used for secular trend analysis of sea level as long-term datum control was not guaranteed throughout the dataset (Woodworth and Player, 2003; PSMSL, 2013). Until 2001, Dublin mean sea-level data were referred to Lowest Astronomical Tide (L.A.T) whereas between 2002 and 2012 data were referred to Chart Datum.

In order to include latest data provided by Dublin Port (2009 to 2012), an additional constant value of 4.577m was added to monthly measurements to refer to RLR (1987). Plotting changes in mean sea-level values alone do not show any evident trends (Figure 5.2). The value of a trend line as a suitable estimate for future change depends on the length of the time series, which in this case is long enough. A trend line fitted via linear least-squares regression which assigns a value of relative sea-level rate from the slope regression coefficient was used for calculating trends from previous mean monthly sea-level data. There are some differences in the sea-level rise before ~1980 (small rise continues) and afterwards i.e. 1980-2000 (upward and downward trends of large magnitudes). The rate of change of relative sea-level shows a rising secular trend before the 1960s followed by a decrease after the 1980s to rapidly rise again since late 1987 into the early 1990’s and then strong increases since the 2000s.

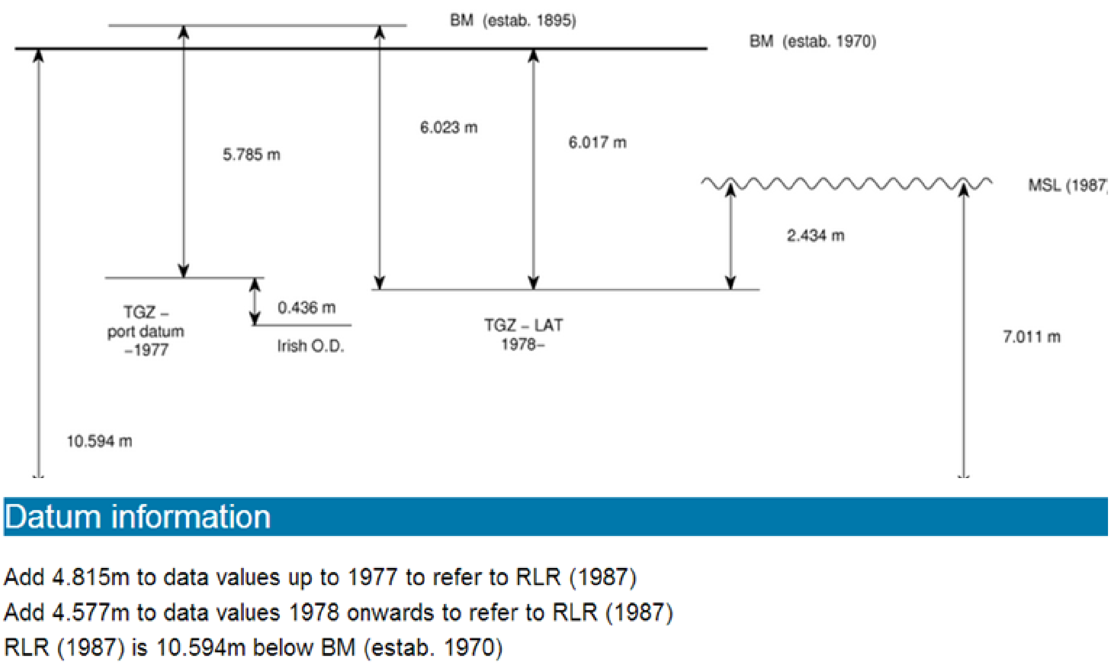


Figure 5.1. Diagram showing the Revised Local Reference (RLR) for Dublin Station (*Source: Woodworth and Player, 2003; PSMSL, 2013*).

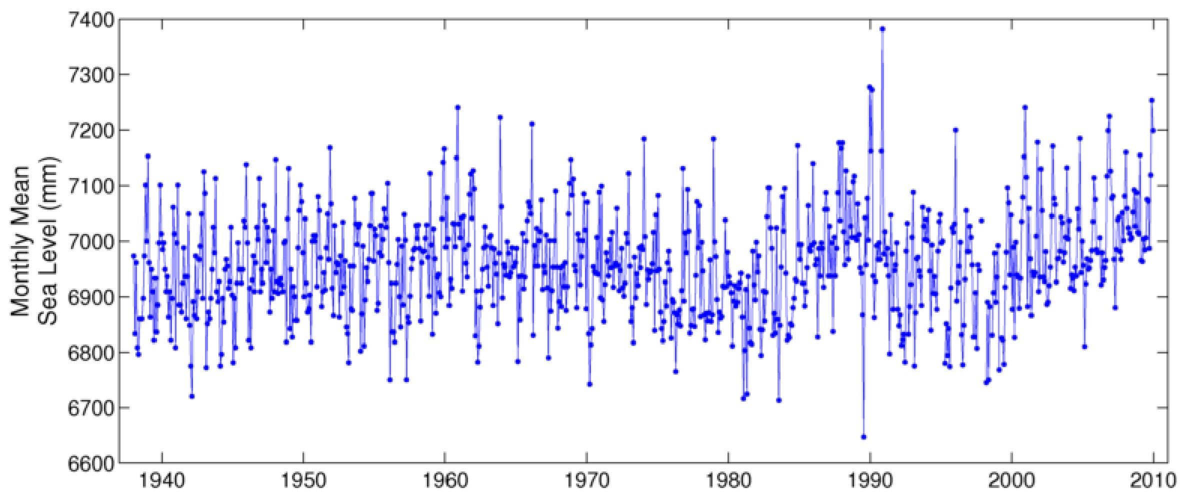


Figure 5.2. Relative mean monthly sea-level changes (mm/yr) at Dublin obtained from historical records retrieved on the 2013-01-29 from Dublin tide gauge data (*Source: Woodworth and Player, 2003; PSMSL, 2012*).

One way to get a better impression of the change of sea-level rate and how stable it might be is by looking at the recursive fit (see Figure 5.3). Thus the analysis started halfway through the time-series (~1960s) in order to obtain a slope estimate. Beyond this point, the rate progresses by repeatedly adding new monthly values for successive years and re-calculates estimates.

This allows us to put local trends into context and avoid being too reliant on a single regression line.

Figure 5.4 shows the trend for each year with respect to the previous 44 years. On this graph, the absence of any trends during 1990-2000's is more evident than in the preceding graphs. The rate of change has rapidly increased and this is quite evident from the graphs below. By adding the 2009-2012 data from Dublin Port, the continuation of the upward trend is confirmed, but also the trend rapidly escalates from 1.45 to 1.96mm/yr. These values are in agreement with other estimates of sea-level trends in Europe (PMSL, 2013).

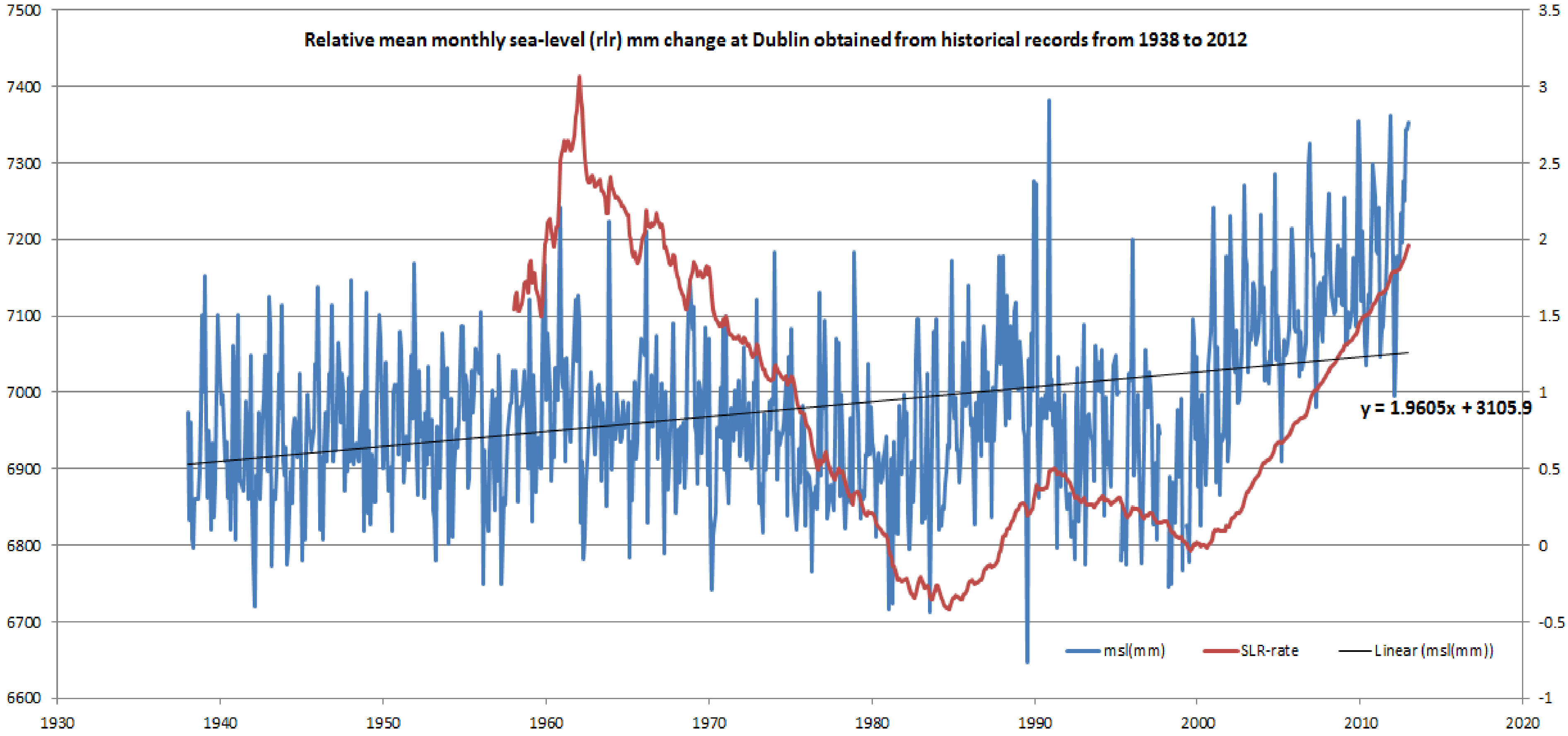


Figure 5.3. Relative mean monthly sea-level change (mm) at Dublin obtained from historical records from 1938 to 2012 is shown in blue. The red line represents recursive fit for sea-level rise-rate trends since 1958. *Data source: (retrieved 2013-03-20, Woodworth and Player, 2003; PSMSL, 2012).*

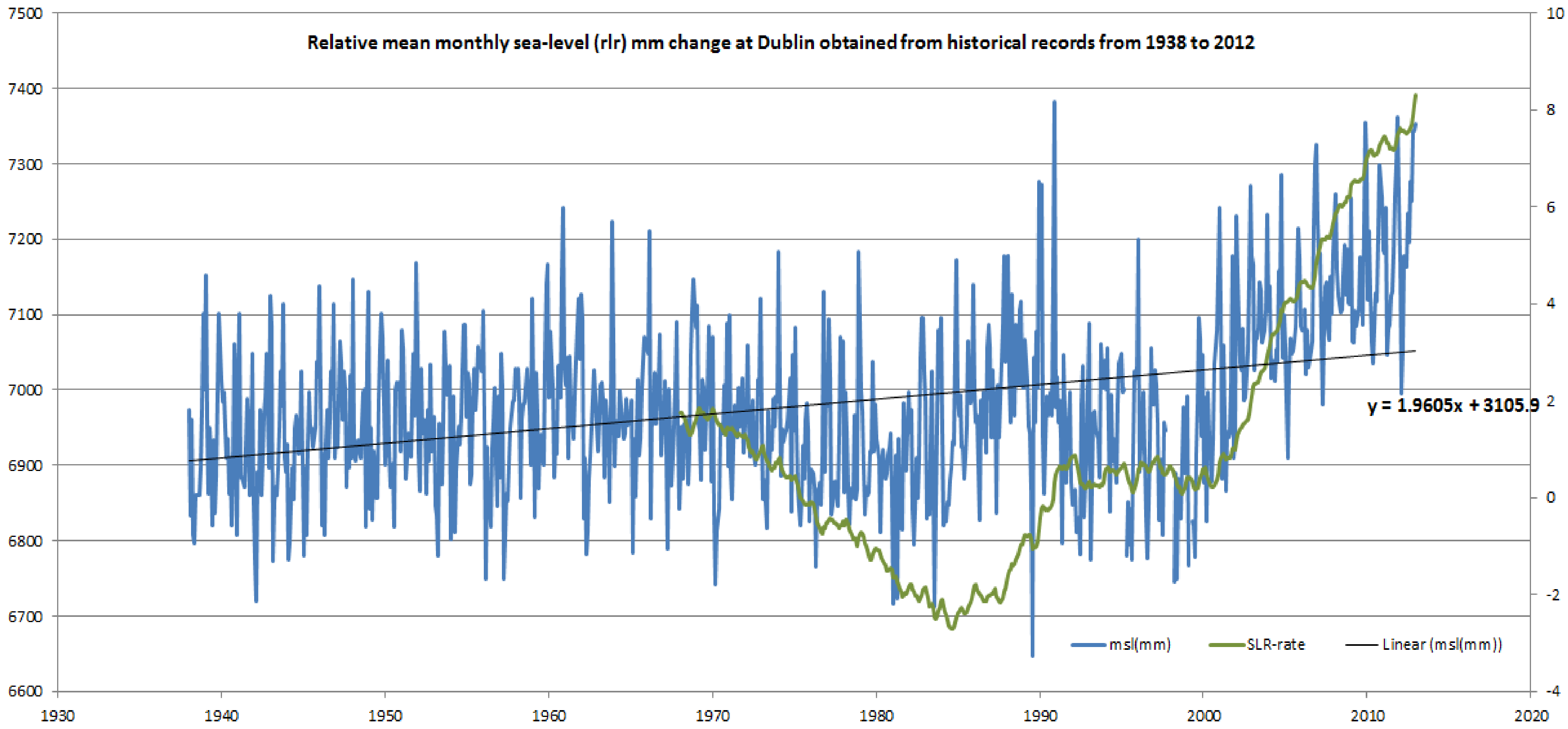


Figure 5.4. Relative mean monthly sea-level change (mm) at Dublin obtained from historical records from 1938 to 2012 is shown in blue and sea-level rise-rate trends since the 70's in green. (*Data source: retrieved 2013-03-20, Woodworth and Player, 2003; PSMSL, 2012).*

5.2. Sensitivity analysis: Modelling future site-specific scenarios of sea-level rise.

Regionally to locally-varying, time-dependent scenarios of future relative sea-level rise have been modelled by SimCLIM (2013) forced by RCP scenarios for the end of the century from 1995 (baseline range 1986-2005). The use of individual models, or even assigning more weight to the most regionally sensitive GCMs would not guarantee better results. Hence, an ensemble model for all 24 available GCMs and four different RCPs (2.6, 4.5, 6.0 and 8.5) were run to generate future sea-level estimates (Figure 5.5). The model produced three local estimates of the recent greenhouse gas related trend component using low, mid and high scenarios of sensitivity for 1990-2100 (estimates of global-mean sea-level trend of 1.0, 1.5 and 2.0 mm/yr respectively). The model outputs include central estimates and also low-probability upper and lower limits based on the 5^{th} and 95^{th} percentiles. These are crucial for coastal flooding and vulnerability scenarios.

A cell of interest was identified around the Dublin area, and then the option to normalize GCM pattern values was activated. The associated scaling factor represents the portion of sea-level change at that particular cell in relation to global values (i.e.: ‘1’ means sea-level at this location equals global trend).

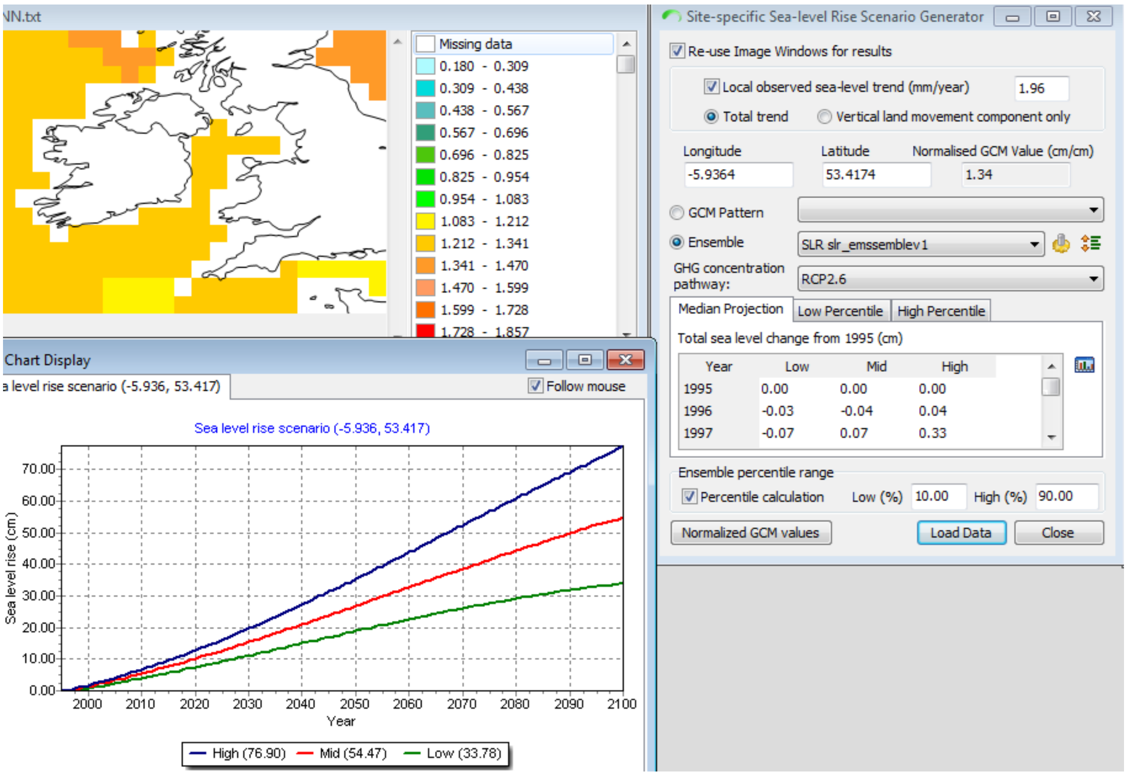


Figure 5.5. SimCLIM local median projections of relative sea-level at Dublin using a 24- ensemble model run for different RCP.8.5 scenarios. (*Source: Silvia Caloca).*

In this case, the vertical movement value is unknown. Therefore, in order to transform these values into relative sea-level rise for Dublin, an overall mean sea-level local trend of 1.96mm/yr, previously obtained from Dublin Port tide-gauge (1938-2012) was entered under 'local observed sea-level trend (mm/yr)' while the 'total trend' option is activated. Then the software subtracts an estimate of the climate change related portion of that trend from the local trend. After this, the model adds the resulting non-climatic trend to the regional component in order to avoid double-counting for the climate-related influences, which would definitely overinflate future sea-level calculations. Future estimates of sea-level rise were modelled using the 24-ensemble run for several simulations using different RCP scenarios and sensitivities (See Figure 5.6). The likely ranges are displayed as thick solid lines bounded in green for RCP 2.6, purple for RCP 4.5, blue for RCP 6.0 and red for RCP 8.5. Uncertainty ranges for a high percentile (95^{th}) and low percentile (5^{th}) are also displayed by broken solid dashed and dotted lines respectively.

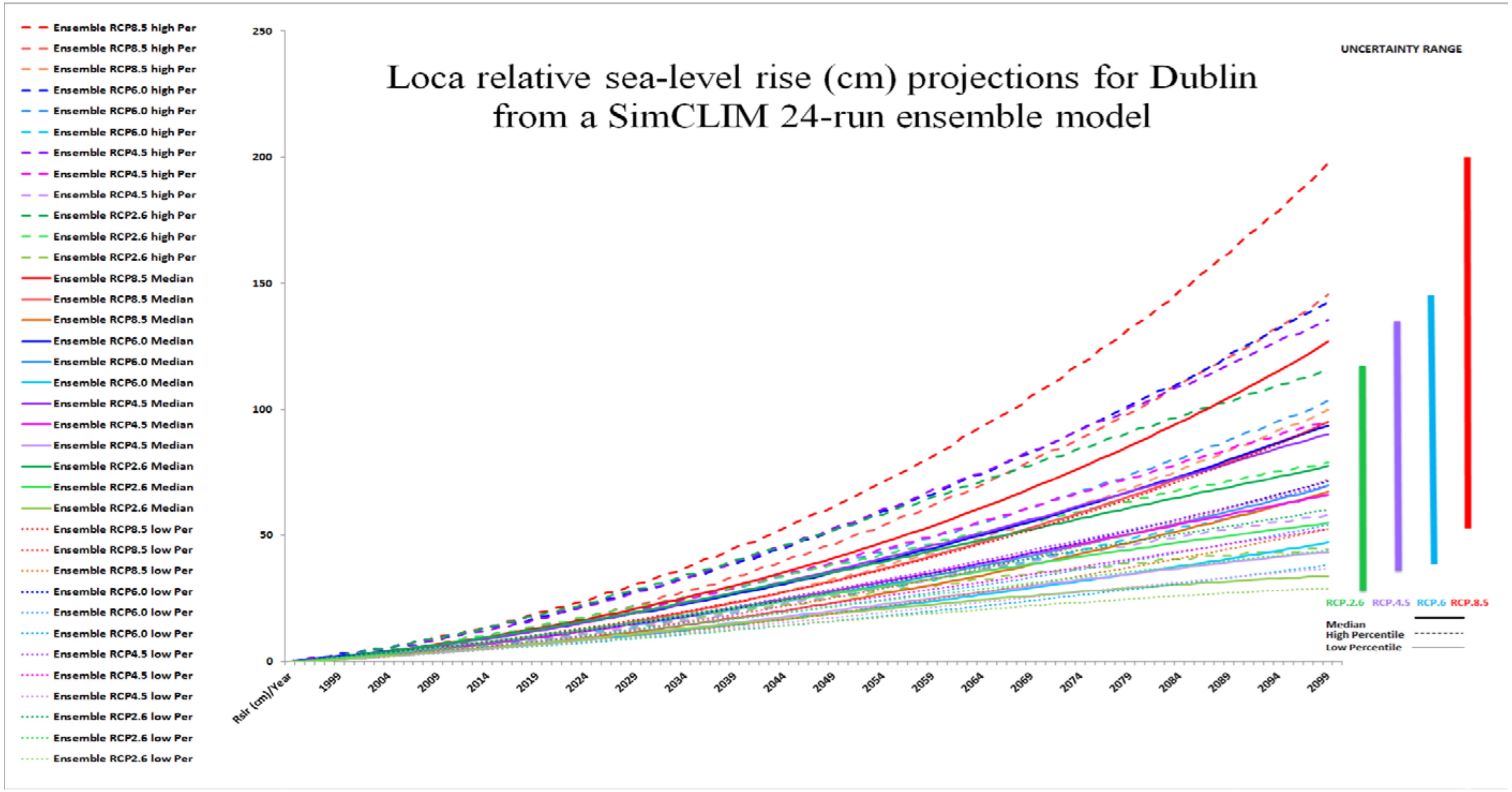


Figure 5.6. Future yearly estimates (cm) of local relative sea-level rise above 1995 (baseline range 1986-2005) for the Dublin area by 2100 calculated for the low, medium and high sensitive emissions scenarios and 2.6, 4.5, 6.0 and 8.5 RPC's for a 24-ensemble model run. Sea-level rise lines are Heavy=median (likely or 67% probability range), dashed=high (95th) percentile; dotted= low (5th) percentile. (*Source: Silvia Caloca).*

RCP's	Sensitivity	Uncertainty range (cm)		Central estimate-median (cm)	Year
		5th percentile	95th percentile		
RCP 2.6 scenarios (AR5) for a 24-ensemble run	High	21.51	40.24	27.35	**2040**
	Medium	17.05	29.72	21	
RCP 4.5 scenarios (AR5) for a 24-ensemble run	High	21.79	39.33	27.26	
	Medium	17.56	28.79	21.06	
RCP 6.0 scenarios (AR5) for a 24-ensemble run	High	21.06	38.57	26.52	
	Medium	16.73	29.51	20.71	
RCP 8.5 scenarios (AR5) for a 24-ensemble run	High	23.5	44.83	**30.15**	
	Medium	18.6	33.9	23.37	
RCP 2.6 scenarios (AR5) for a 24-ensemble run	High	34.23	65.34	43.93	**2060**
	Medium	26.38	46.5	32.65	
RCP 4.5 scenarios (AR5) for a 24-ensemble run	High	36.1	68.03	46.06	
	Medium	28.65	49.22	35.06	
RCP 6.0 scenarios (AR5) for a 24-ensemble run	High	35.03	66.22	44.76	
	Medium	27.34	48.89	34.06	
RCP 8.5 scenarios (AR5) for a 24-ensemble run	High	41.27	81.34	**53.77**	
	Medium	32.75	61.86	41.83	
RCP 2.6 scenarios (AR5) for a 24-ensemble run	High	47.34	90.85	60.91	**2080**
	Medium	35.61	63.18	44.21	
RCP 4.5 scenarios (AR5) for a 24-ensemble run	High	52.31	101.15	67.53	
	Medium	40.51	72.94	50.62	
RCP 6.0 scenarios (AR5) for a 24-ensemble run	High	51.79	101.7	67.35	
	Medium	39.77	73.88	50.4	
RCP 8.5 scenarios (AR5) for a 24-ensemble run	High	64.55	132.19	85.64	
	Medium	50.53	98.5	65.48	
RCP 2.6 scenarios (AR5) for a 24-ensemble run	High	60.09	115.98	77.52	**2100**
	Medium	44.06	79.08	54.98	
RCP 4.5 scenarios (AR5) for a 24-ensemble run	High	69.63	135.38	90.13	
	Medium	52.69	95.72	66.1	
RCP 6.0 scenarios (AR5) for a 24-ensemble run	High	71.38	103.58	93.57	
	Medium	54.4	103.58	69.74	
RCP 8.5 scenarios (AR5) for a 24-ensemble run	High	94.92	197.7	126.96	
	Medium	72.29	145.43	95.09	

Table 5.1. Central estimates (likely range) and uncertainty ranges (cm) for 90th- 10th and 5th-95th percentiles of relative sea-level changes (cm) with respect to 1995 (1986-2005) levels projected for coming decades (2040, 2060, 2080 and 2100) for the Dublin area. *(Source: Silvia Caloca).*

Likely ranges vary from 30-127cm for (RCP 8.5), 26-94cm (RCP 6.0), 27-90 (RCP 4.5) and 21-77cm (RCP 2.6). The extreme ranges of uncertainty are bounded by 21cm for RCP 2.6 and 198cm for RCP 8.5. Similarly, Table 5.1 shows outputs of local relative sea-level estimates (cm) for coming decades 2040, 2060, 2080 and 2100 above 1995 levels for medium and high sensitivity.

5.3. Chapter summary

Annual local sea-level projections were generated for the Dublin area using the SimCLIM Sea-level Scenario generator tool for various RCP scenarios and low, mid and high sensitivities of temperature and eustatic sea-level. Central estimates and $5^{th}/95^{th}$ percentile confidence intervals were generated using an ensemble model run of 24 GCMs.

Likely sea level rises ranged from 127cm for (RCP 8.5), 94cm (RCP 6.0) and 78cm (RCP 2.6) by the end of the 21st century. Worst case scenarios (95th percentile) from high sensitivity RCP 8.5 scenarios projected extreme increases of 198cm by the end of the century. Although plausible, this is considered unlikely (<5%). However, for coastal impact and vulnerability assessments, the extreme ranges are highly relevant.

Chapter 6: Assessment of current coastal vulnerability

This second chapter on results embraces a comprehensive vulnerability assessment to identify vulnerable coastal areas to impacts of sea-level rise. It begins by showing results on compilation, processing and variable analysis. Several maps revealed the relative vulnerability of individual indicators and finally, a series of coastal vulnerability index (CVI) maps were produced to determine the overall vulnerability.

6.1. Indicators description

6.1.1. Geomorphology

Vulnerability ranks based on new refined geomorphological map are displayed in Figure 6.1. This shows areas of very high vulnerability (sandy-shores and saltmarshes) in north Dublin (Donabate, Portmarnock, Bull Island), Sandymount, south Greystones and North Arklow. Areas of high vulnerability appear near Wicklow town and are characterised by open coast sandy shores backed by bedrock or man-made structures, but also are evident in alluvial sediments and estuaries and lagoons, re-entrant amenity grasslands and raised beaches. Moderate vulnerability values are more commonly distributed and mainly correspond to gravelly alluvial sediments and plains, glaciolacustrine, glaciofluvial sands and gravels, tills, cobble beaches, shingle and gravelly shores. Open hard-rock cliffed shorelines and moderately, exposed rocky shores like those in the Howth peninsula and Bray, Dalkey, Wicklow headlands show low vulnerability. Lastly, areas formed by sheltered hard-rock and man-made and urbanised areas such as Dublin piers, show very low vulnerability.

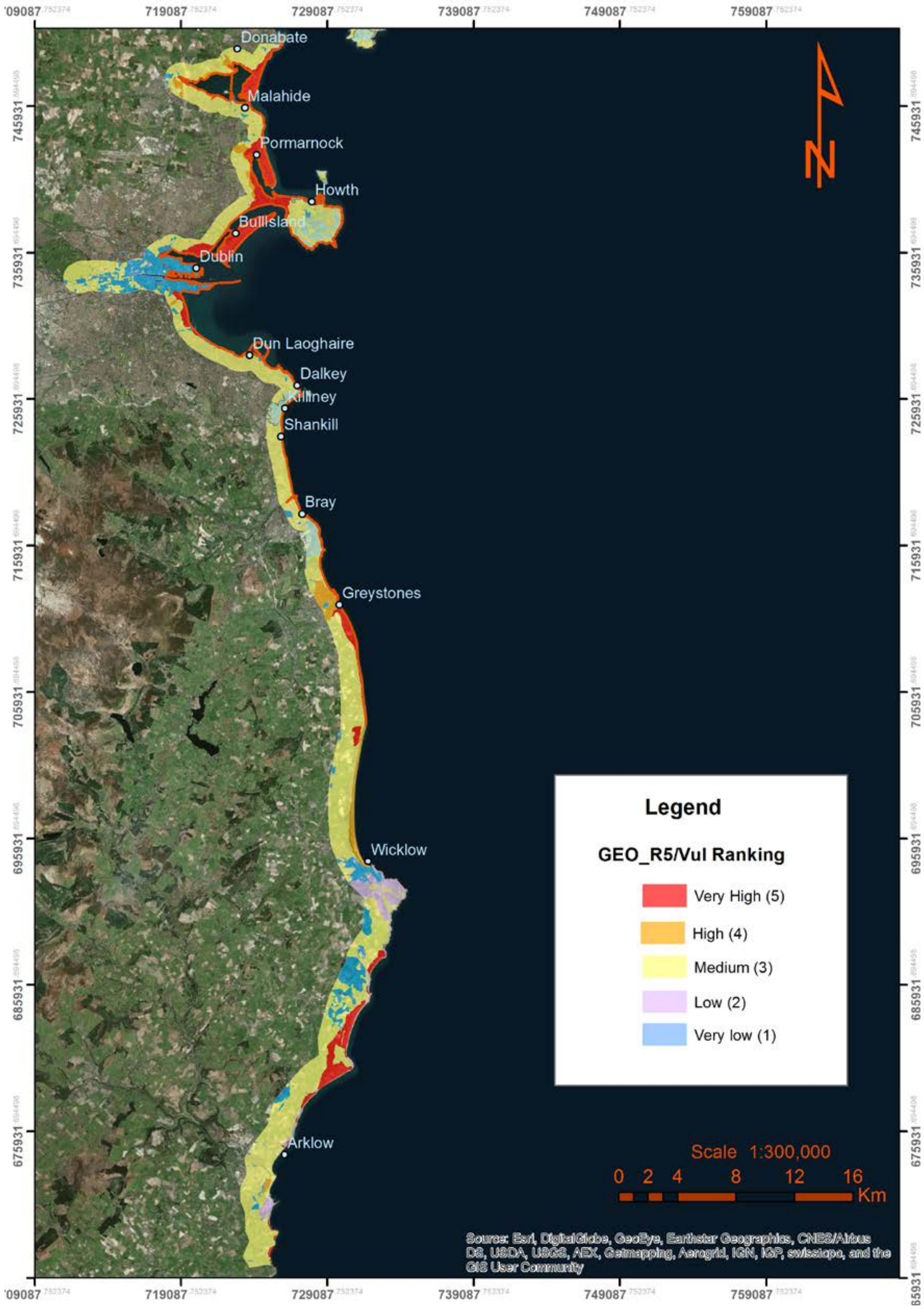


Figure 6. 1. Map showing the relative vulnerability ranking (from very low to very high vulnerability) of the geomorphological variable in the study area. (*Source: Silvia Caloca*).

6.1.2. Cliff type

Results from cliff type classification are displayed in Figure 6.2. Hard rocky cliffs would have a vulnerability of 1 or 2, depending on elevation. High hard rocky cliffs are composed of moderately to highly exposed hard-rock (those in Killiney Head and Howth/Bray Head are made of granites, greywacke and quartzite with elevations >25.5m; vulnerability=1). Low hard rocky cliffs are exemplified by those at Malahide and Portmarnock made of limestones and siltstones (<25.5m; vulnerability=2).

Soft unconsolidated cliffs predominate in South Dublin and Wicklow. Moderate to very steep soft clayey/gravelly or colluvial shores with more boulders than sand and gravels are classed as vulnerability= 3. Low profile soft, clayey – gravelly cliffs like those around Shankill are made of sandy alluvial deposits plus sand and gravels and are classed as vulnerability=4.

Low gradient non-consolidated cliffs (sand dunes/aeolian/marine sand) predominate in the northern end of the study area but also long sandy dune beaches in coastal areas around Wicklow. Those are assigned vulnerability class 5.

6.1.3. Coastal slope

Two steep average slope categories were produced (>30° and 20-30°) and were found at Howth and Bray Head. Moderate slopes are scattered around the area such as at Donabate dune systems, Howth and Dalkey Heads, and south Wicklow down to Arklow. High and very high can be found in low lying areas (0-5°; 5-10°) mainly concentrated in the Northern end, between Greystones and Wicklow and from Wicklow to Arklow. See Figure 6.3.

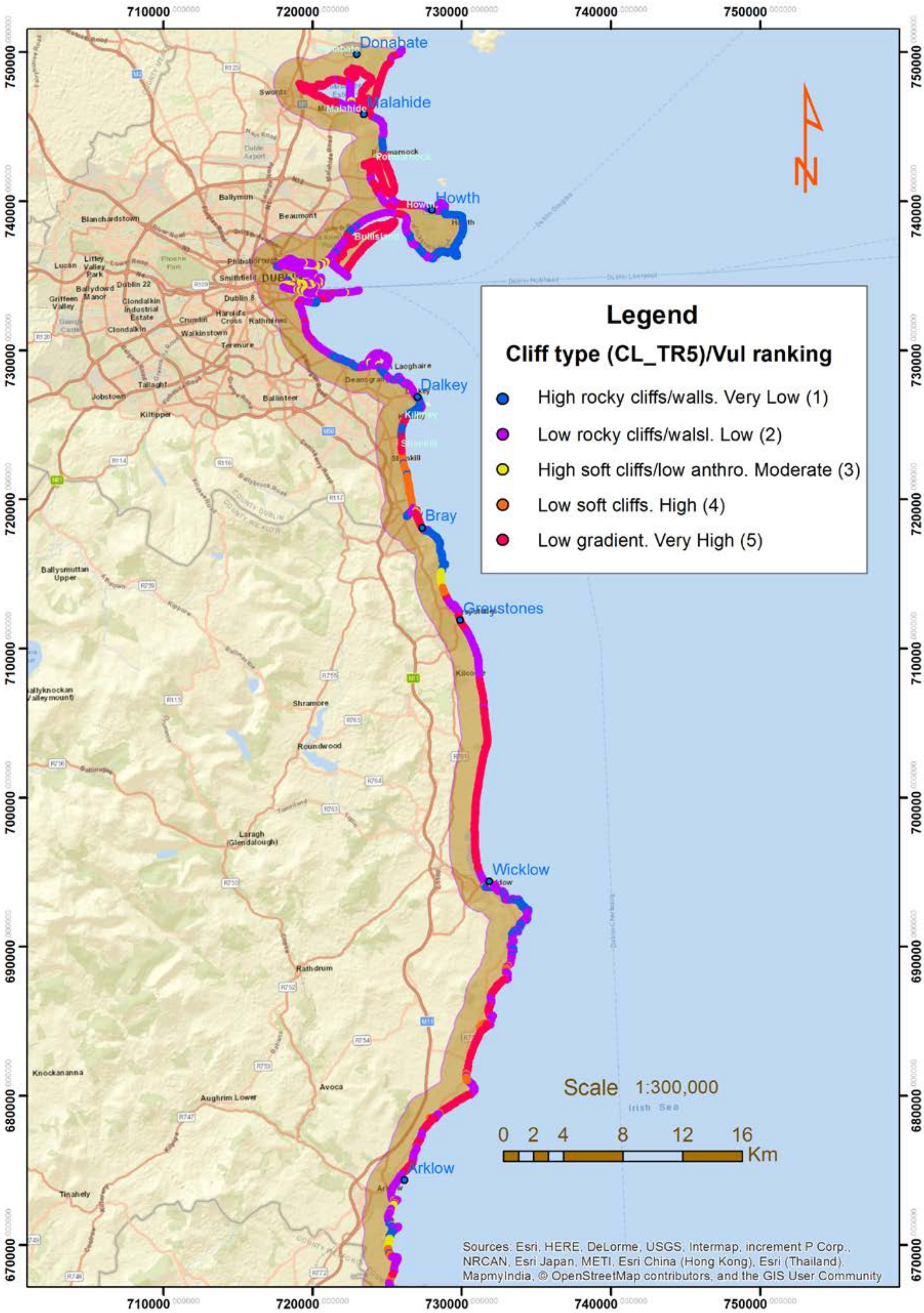


Figure 6. 2. Map showing the relative vulnerability ranking (from very low to very high vulnerability) of the cliff type variable in the study area. (*Source: Silvia Caloca)*.

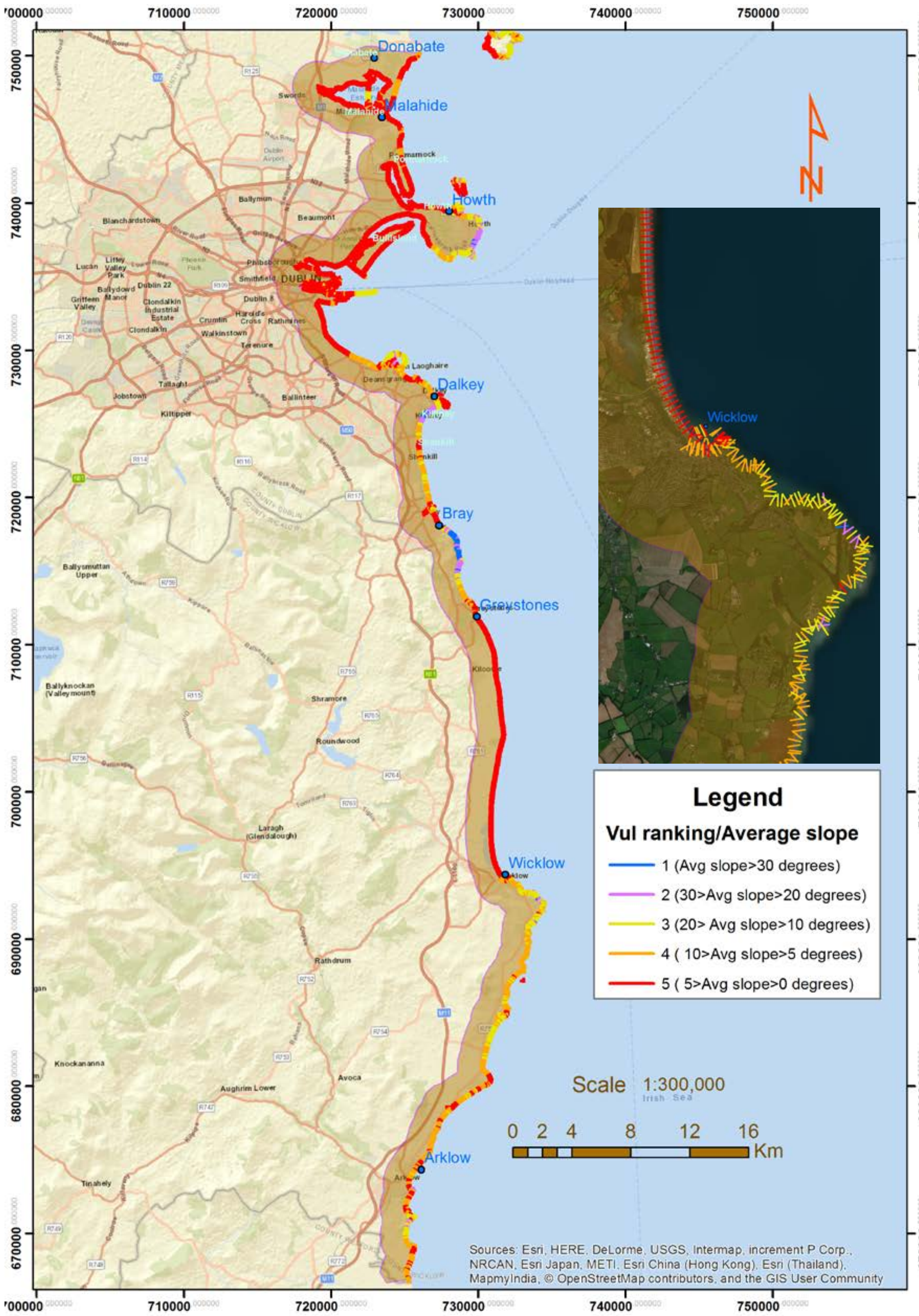


Figure 6. 3. Map showing average slope and value distribution in the study area associated ranking. *(Source: Silvia Caloca).*

6.1.4. Aspect

Concentrations of very exposed segments are characteristic of areas from Wicklow and Arklow in the south part of the area. In the northern part, some appear along sandy environments of Bull Island and Donabate strand. Long beach and soft cliffed areas from Dalkey to Wicklow are classified as exposed and semi-exposed (Figure 6.4).

6.1.5. Relative sea-level rise (mm/yr)

The rate of change was calculated from the slope of the recursive fitting curve from which a total trend of relative sea-level rate of 1.96mm/yr was estimated (Chapter 5). Then a point shapefile with the fixed value 1.96mm/yr was generated for CVI.

6.1.6. Mean tidal range (m)

Resulting tidal ranges modelled in VORF are illustrated in (Figure 6.4).VORF usually produces better results than POLPRED when compared to actual tide observations on the ground and allow us to generate values at selected points to better capture tidal variability along the coastal study area. Data closer to onshore would be more accurate for this assessment as measurements provide more information regarding near shore bathymetry. The difference in spring ranges at a particular point is minor and would not affect the final tidal ranges classification (see Table 6.1).

POLPRED				VORF (LAT)		
MHWS	MLWS	Spring Range (m)		MHWS	MLWS	Spring Range (m)
2.94	0.5	2.44		4.034	0.780	3.254

Table 6.1. Difference in tidal regimes generated by VORF and POLPREDS at Dun Laoghaire Port ((53.297039, -6.131404); Ellipsoid Height (m) = 60.056)). (*Source: Silvia Caloca*).

It is evident that the tidal range around Arklow is lower than Dublin which is further away from the amphidromic point. Tidal ranges increase southwards from Larne and northwards from Wicklow.

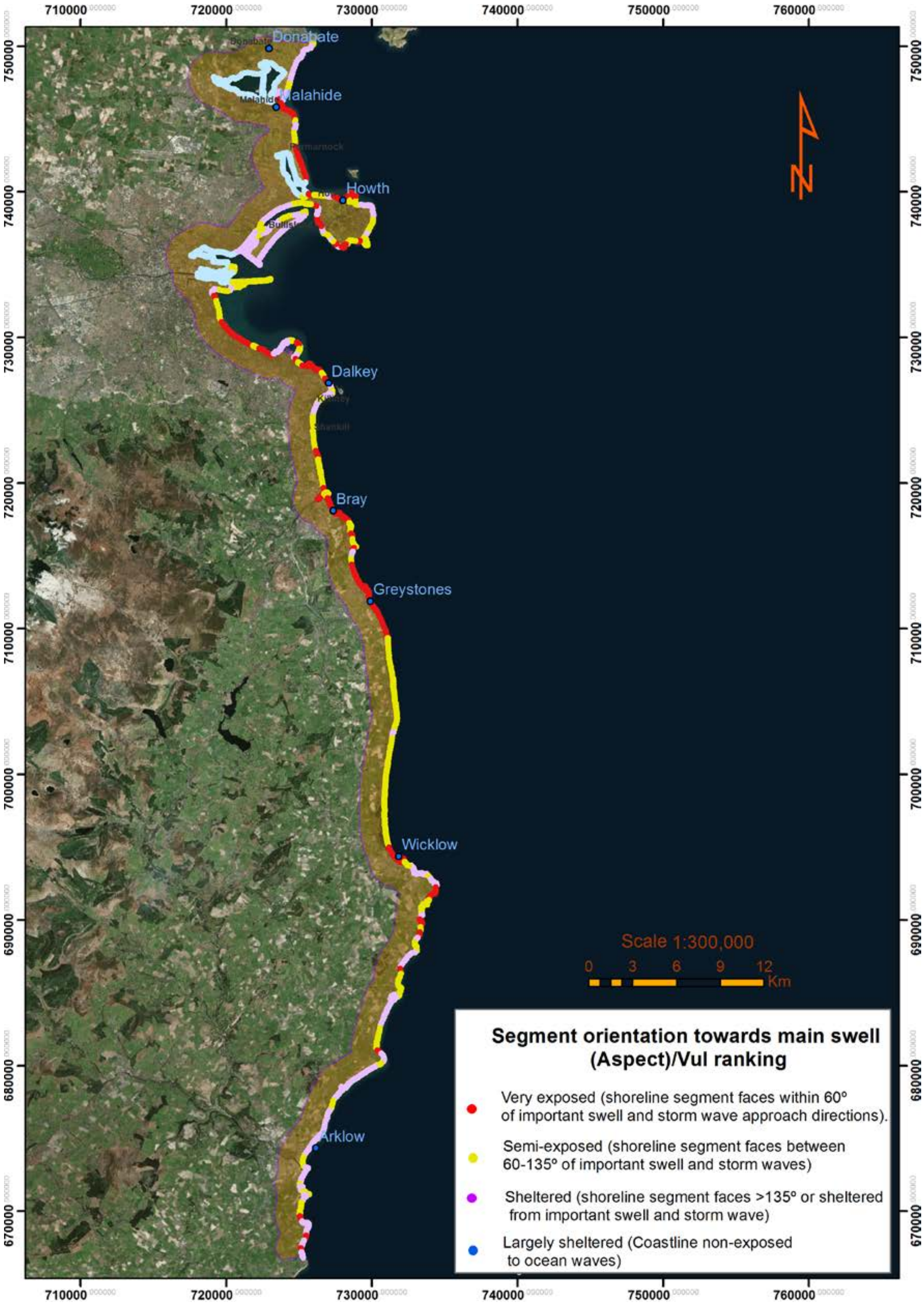


Figure 6. 4. Orientation of coastal segments towards the main swell action in the area (N135º), and vulnerability ranking. *(Source: Silvia Caloca).*

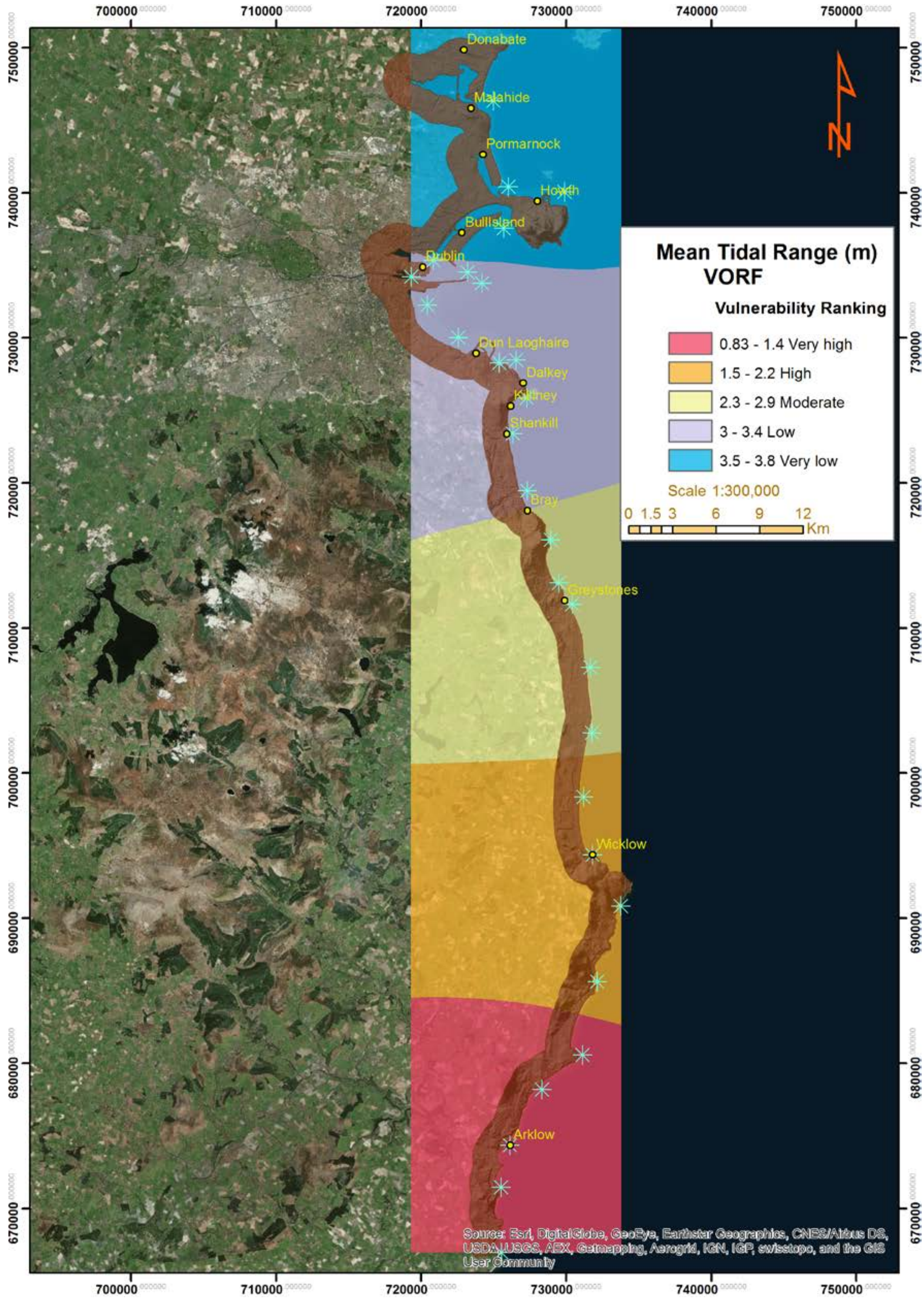


Figure 6. 5. Variations of Mean predicted spring tidal ranges modelled by VORF. *(Source: Silvia Caloca).*

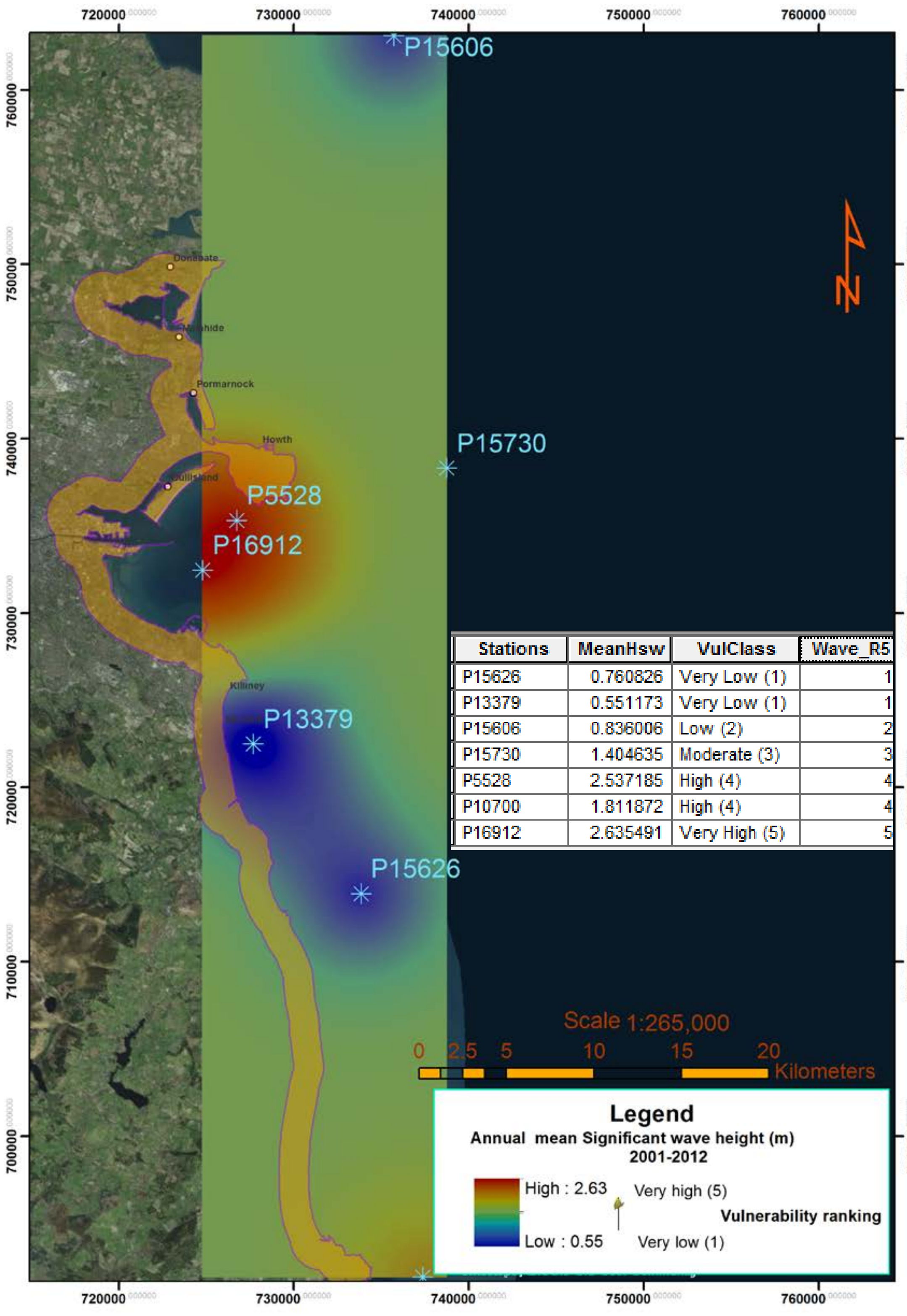
6.1.7. Mean annual wave height (m)

Vulnerability ranking was based on quantile distribution of mean annual significant wave heights (Hs). Modelled outputs of annual mean significant wave heights data from 2000-2012 are illustrated in Figure 6.7. Highest values of 2.53 -2.63m occurred around Dublin Bay, whereas lowest values 0.76-0.55m are concentrated around Dalkey and Greystones in south Dublin. In the rest of the areas, wave height values range from 1.40 to 1.81m.

6.1.8. Shoreline changes (m/yr)

Shoreline changes recorded from vegetation lines between 1952 and 2017 vary between 5.8m to -3.8m/yr within the study area (Figure 6.9). Negative values represent areas with erosion whereas positive values appear in accreting areas. Very low vulnerable areas (of shoreline change 2-5.8m/yr) coincide with highly accreting sandy environments like those in south Bull Island. Very high vulnerable areas are characteristic of eroding, low-lying sandy environments in North Dublin or soft unconsolidated zones (cliffs or low gradient) in the southern end (Figure 6.8).

Moderate values ranging between -0.2-0.2m/yr are scattered across the area but they predominate around Dublin given the high concentration of coastal defences or man-made structures such as harbours. These would have been associated with WLR=0 values. In other areas, values close to zero represent low gradient stable areas or hard rocky areas (i.e. Howth and Bray). Low and high vulnerable zones are observed all along the area. Low vulnerable zones correspond to accreting areas situated at the edges of sandy, dune strands like those in Portmarnock or Bull Island. They can also be found in south Dublin. Moderate to high vulnerability also occurs in southern areas around Wicklow. High vulnerable areas can be observed between Wicklow and Arklow.



Stations	MeanHsw	VulClass	Wave_R5
P15626	0.760826	Very Low (1)	1
P13379	0.551173	Very Low (1)	1
P15606	0.836006	Low (2)	2
P15730	1.404635	Moderate (3)	3
P5528	2.537185	High (4)	4
P10700	1.811872	High (4)	4
P16912	2.635491	Very High (5)	5

Figure 6. 6. Distribution of annual mean significant wave heights in the study area (Hs). *(Source: Silvia Caloca).*

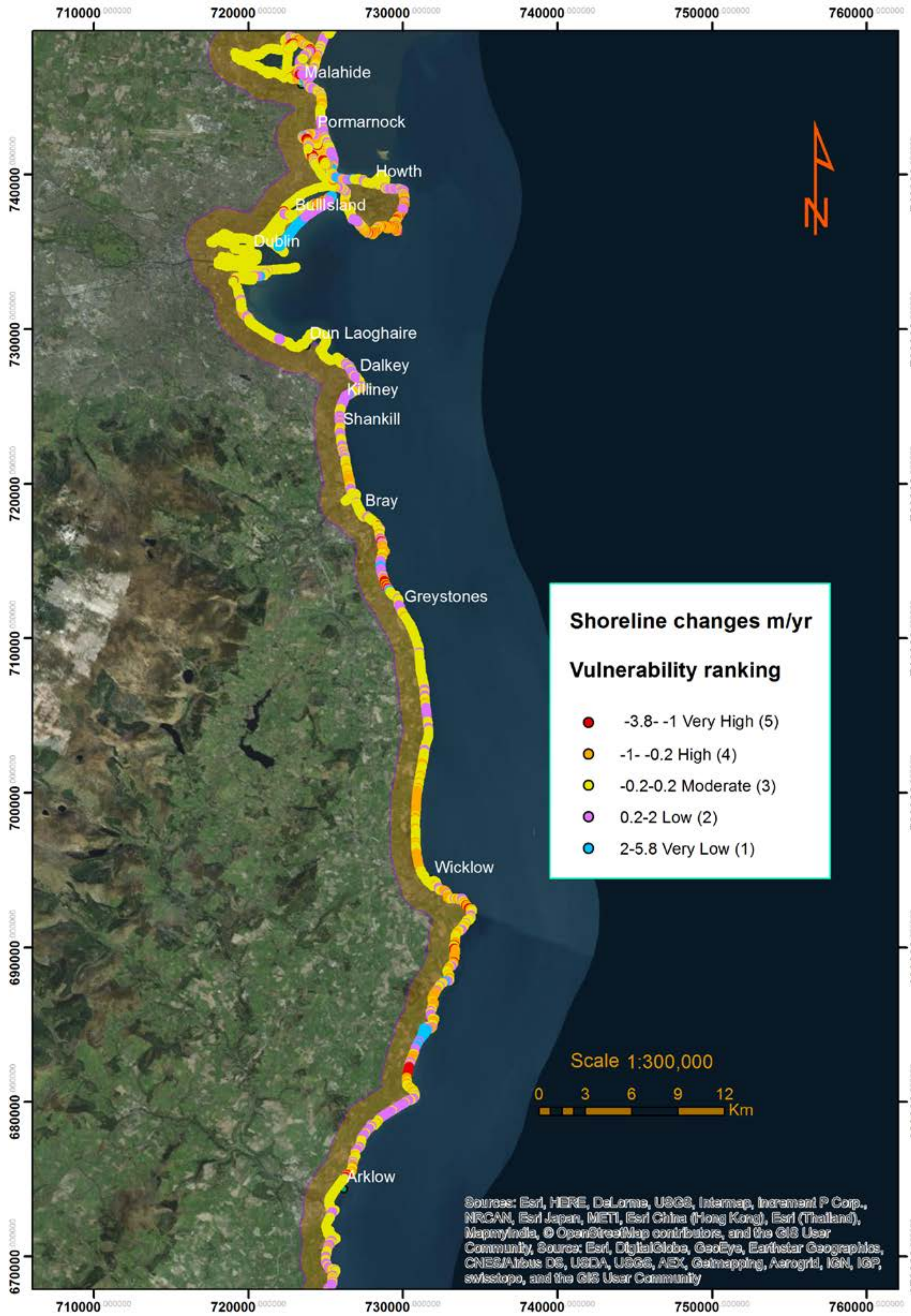


Figure 6. 7. Distribution of long-term shoreline changes. (*Source: Silvia Caloca).*

6.1.9. Volumetric analysis in Corbawn (South Dublin): Case study

The case study was run in Corbawn, formed of soft, unconsolidated cliffs in the South of Dublin. The site has an area of 21,727m².Volumetric analyses were calculated using two LiDAR datasets collected in 2006 (OPW) and 2017 (GSI, 2017). See Plate 6.1.

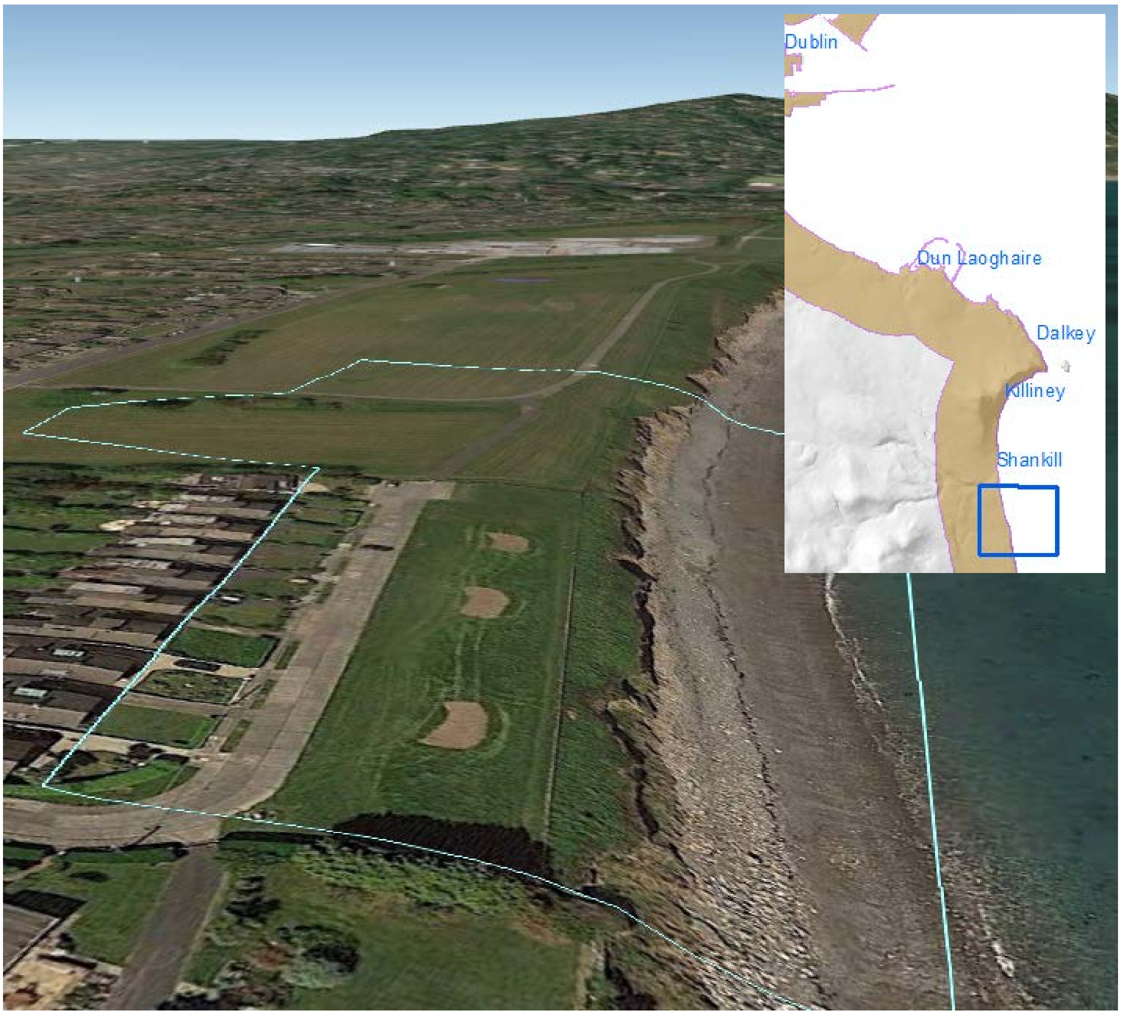


Plate 6.1. Aerial view of the case are in Corbawn (South Dublin) where Terrestrial LiDAR (vertical 0.01 m; horizontal 20cm) was collected by the GSI (2017)*(Source: Silvia Caloca).*

Results indicate that erosion takes place largely along the beach, from the foreshore to the backshore, while accretion occurs primarily in high ground above the cliffs in the NW of the study area. The areas further onshore remain largely unchanged.

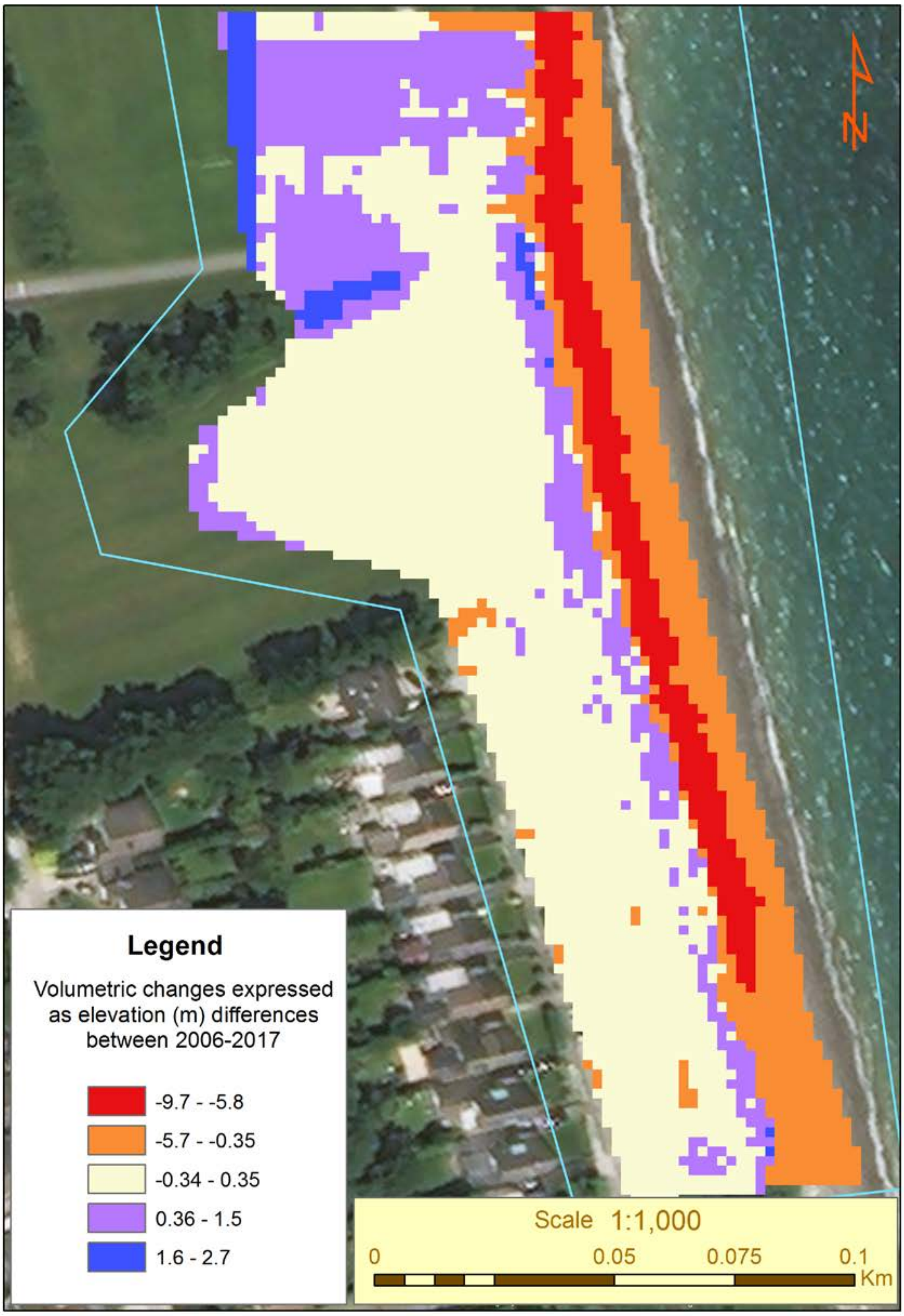


Figure 6. 8. Volumetric changes in Corbawn between 2006 and 2017 expressed in z (m). (Source: Silvia Caloca).

The surface change value, equivalent to the percentage of the area that has suffered erosion within that period is 27.1% from the total in 2006. The average depth difference in the eroded areas is -4.15m, while the total eroded is approximately 18,400m³. The average volumetric loss rate (z) is approximately 0.37m/year. Vertical differences between these datasets are illustrated in Figure 6.8.

6.2. Application of the coastal vulnerability index (CVI)

6.2.1. CVI using six variables

A coastal vulnerability index map (CVI 6) was produced using the following variables: regional coastal slope, geomorphology, mean tidal range, relative sea-level rise, wave height and shoreline change. A frequency distribution of the values shows a histogram positively skewed towards the low CVI values (Figure 6.9).

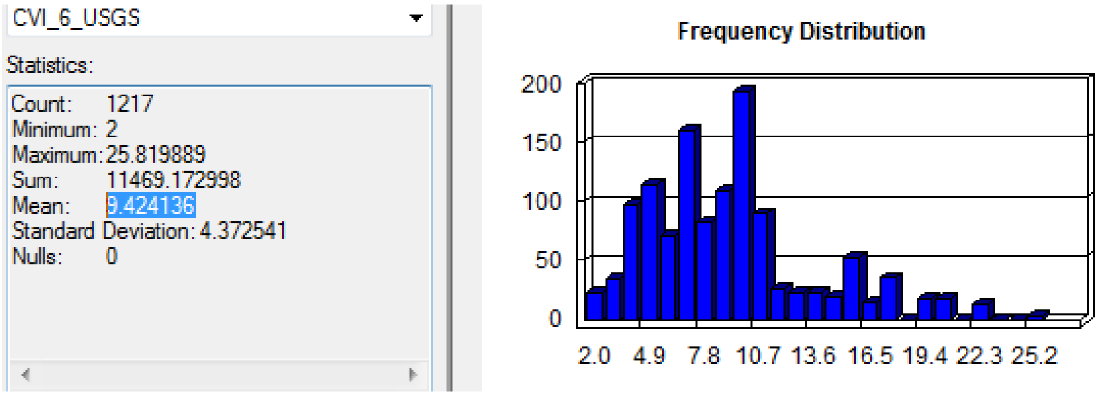


Figure 6. 9. Histogram shows the frequency distribution of CVI6 values. *(Source: Silvia Caloca).*

As it can be seen in Figure 6.10, the study area was subdivided into four distinctive sub-zones from south to north. CVI 6 values range from 2 to circa 26 with a mean of 9.42. CVI 6 values are predominantly high in the southern part as far as Greystones with very few short intervals of moderate values.

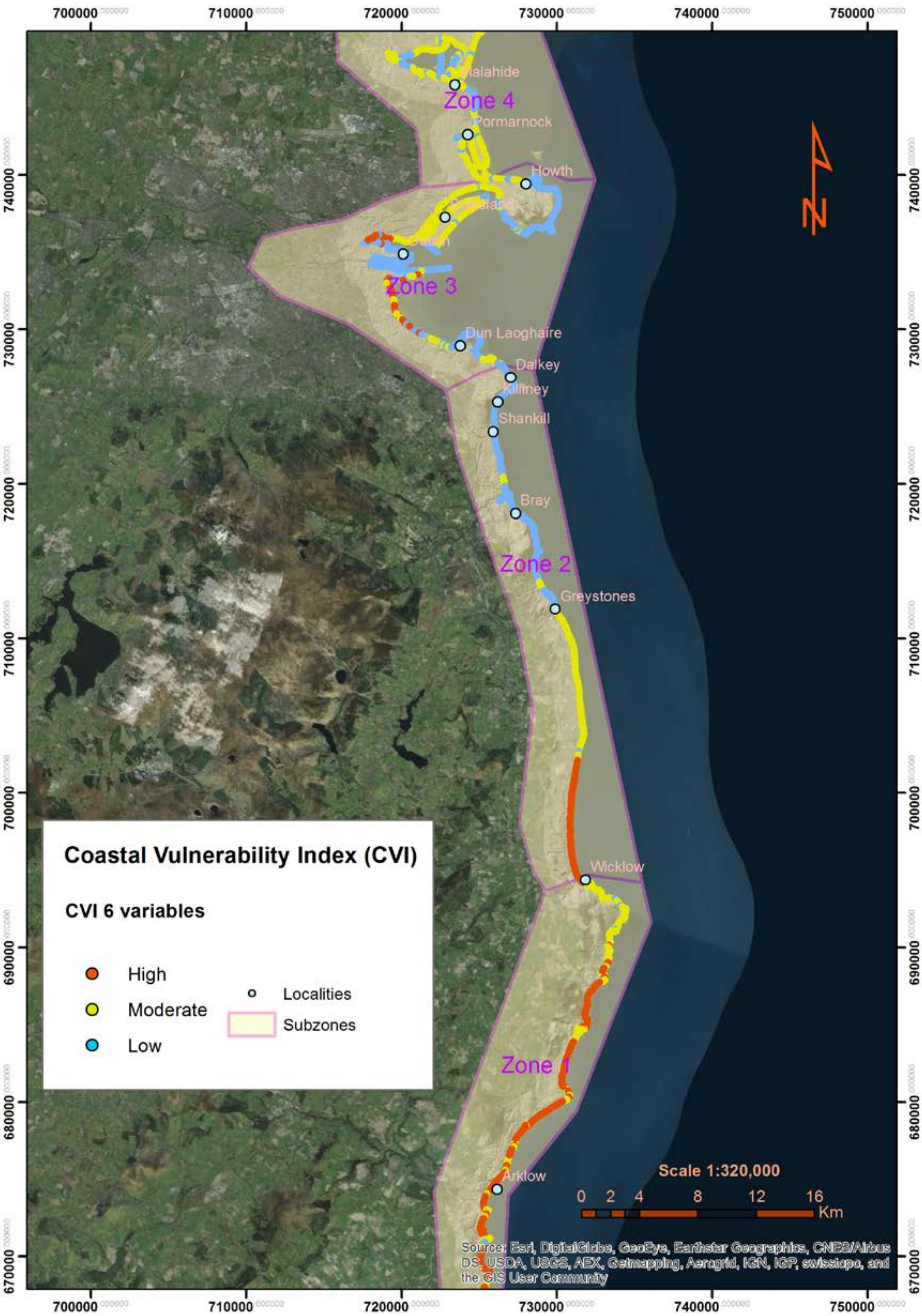


Figure 6.10. Coastal vulnerability map using 6 variables showing from high to low vulnerability ranking. *(Source: Silvia Caloca).*

From Greystones to Dún Laoghaire, CVI values are generally low, interrupted in a few places by moderate values. Values within a strip from north of Dún Laoghaire and to south of the Dublin South Wall, CVI values are predominantly high; however moderate and low CVI values are often present. North Dublin (Bull Island) shows moderate CVI values whereas Howth peninsula contains rather low CVI values. North of Howth peninsula patches of moderate CVI are evident, interrupted by intervals of low CVIs.

Box plots in Figure 6.11 and Figure 6.12 display the distribution of CVI 6 values for the four zones.

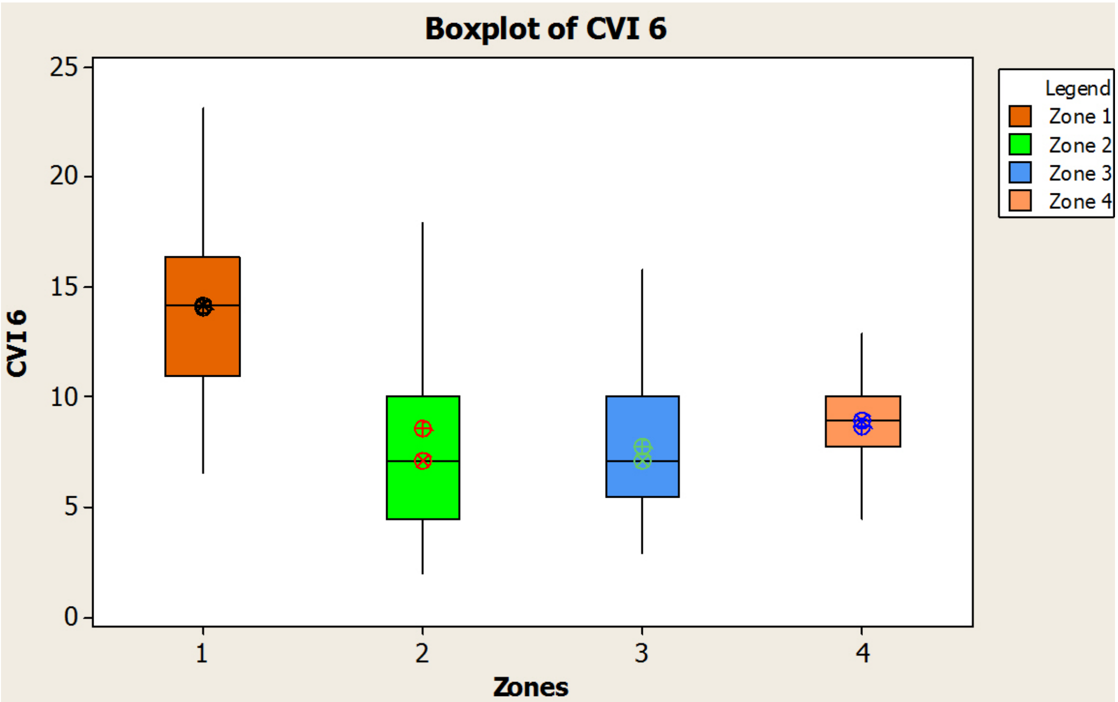


Figure 6.11. Boxplot showing CVI 6 values (using 6 variables) for all zones; ⊗ is the median and ⊕ is the mean. The coloured box represents the inner quartiles for each zone. (Source: Silvia Caloca).

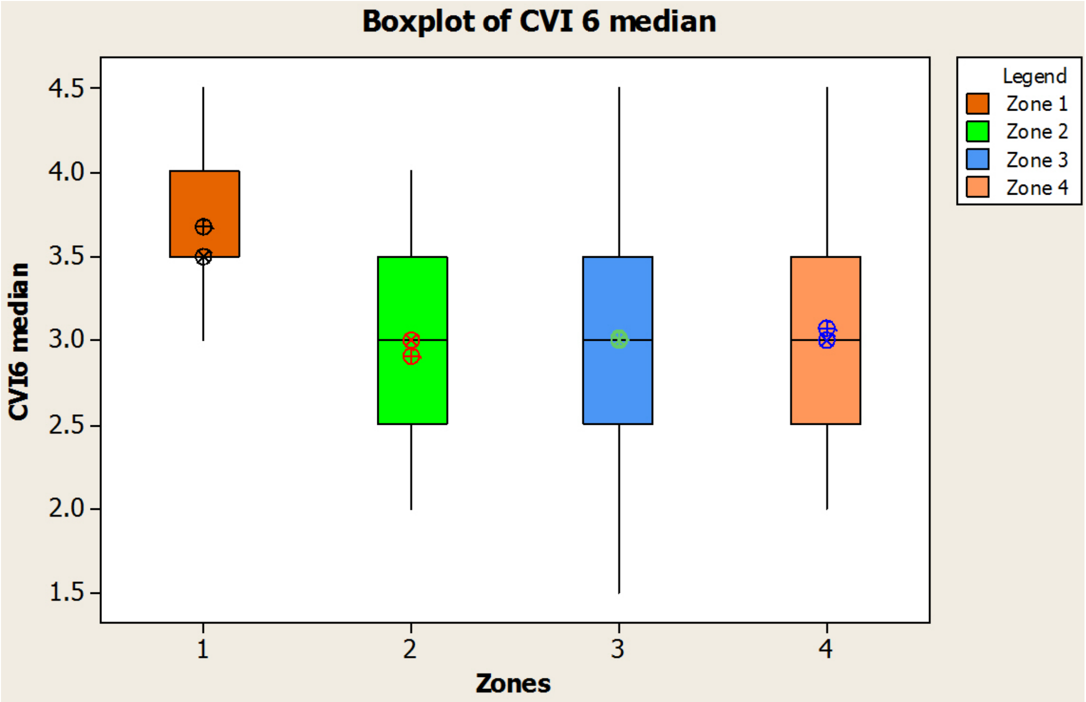


Figure 6.12. Boxplot showing median CVI 6 values and the range of ranked variables used to determine the index; ⊗ is the median and ⊕ is the mean. The coloured box represents the inner quartiles for each zone. (Source: Silvia Caloca).

Zone 1

Zone 1 corresponds to the shoreline from Arklow to Wicklow Head (Figure 6.10). This is the longest zone with 255 data points evaluated. In general, this shows high CVI values with a mean of 14.1. Most of the values, Q1-Q3 lie between 10.95-16.33. The interquartile range (IQR) is 5.37. The northern part, around Wicklow Head, shows moderate CVI values (mean 10.60) compared to the southern part (mean 15.55). See (Figure 6.11 and Figure 6.12).

Zone 2

This zone runs from Wicklow Head to Dalkey Head. It is slightly orientated NW-SE but quite linear with exceptions in Killiney Bay and Bray to Greystones Head with virtually no bedrock outcropping from Greystones to Wicklow

This area shows moderate CVI values in general. However, differences can be observed at regional level. The mean value is 8.58. Most of the values, Q1-Q3, fall between 4.47-10. The interquartile range is 5.52 (Figure 6.11 and Figure 6.12).

Three sections can be differentiated based on their CVI 6 values. The southern part: very high CVI values (mean 18). The middle part is characterised by moderate values (mean 8.97) and the northern part by very low values (mean 4.98) (Figure 6.10).

Zone 3

Zone 3 encompasses Dublin Bay enclosed by the Howth peninsula and Dalkey Head. This area is characterised predominantly by moderate values (Figure 6.10). However, local and regional variability is high with a mean of 7.77. Most of the values, Q1-Q3, are between 5.48-10. The interquartile range is 4.52 (Figure 6.11 and Figure 6.12).

Four parts can be differentiated based on their CVI 6 values. Urban areas are characterised by man-made structures and very low CVI values (mean 6.2). The southern part of Dublin Bay part shows moderate to high CVI values (mean 11.13). The northern part of Dublin Bay (Bull Island) shows moderate values (mean 9.29). Howth peninsula presents low CVI values (mean 5.38).

Zone 4

This area runs from Howth to Donabate and is formed of long beach strands with estuaries alternating with tills and low bedrock outcrops. The most northern part of the study area is characterised by moderate values and low variability and has a mean of 8.63. Most of the values, Q1-Q3 range between 7.75-8.94 (IQR 2.25) Figure 6.11 and Figure 6.12).

Two main types of coastline can be differentiated based on their CVI 6 values: man-made parts: moderate to low CVI values (mean 7.2); and engineered coastline moderate values (mean 9.3). See Figure 6.10.

6.2.2. *CVI 8 using eight variables*

A coastal vulnerability index map was constructed (CVI 8) using the variables employed in CVI 6 plus aspect and cliff type. CVI 8 values range from 3 to 90 with a mean of 22.15. The variables are positively skewed towards low values (Figure 6.13)

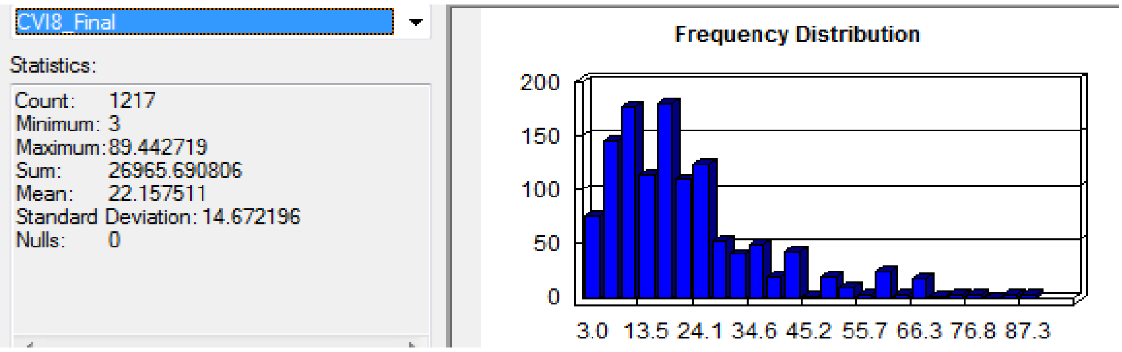


Figure 6.13. Histogram shows the frequency distribution of CVI8 values and basic statistics. *(Source: Silvia Caloca).*

An overview from south to north shows that CVI values are predominantly high in the southern part from Arklow to just before Greystones (Figure 6.14). There are a few occurrences of moderate and low CVIs, particularly around Wicklow Head. From north of Greystones to as far as Dún Laoghaire, CVI values are generally low with a few moderate values in places.

From north of Dún Laoghaire, along Dublin Bay as far the Howth peninsula, CVI values are low to moderate. North Dublin (Bull Island) contains moderate CVI values whereas the Howth peninsula has low CVI values. Areas from Howth northwards show moderate CVIs alternating with low CVIs values. A zonal description of the CVI values is detailed below with the aid of the CVI boxplots.

Figure 6.15 shows the range of values for every zone whereas Figure 6.16 shows median values for all variables that were used as a proxy for total vulnerability to coastal change.

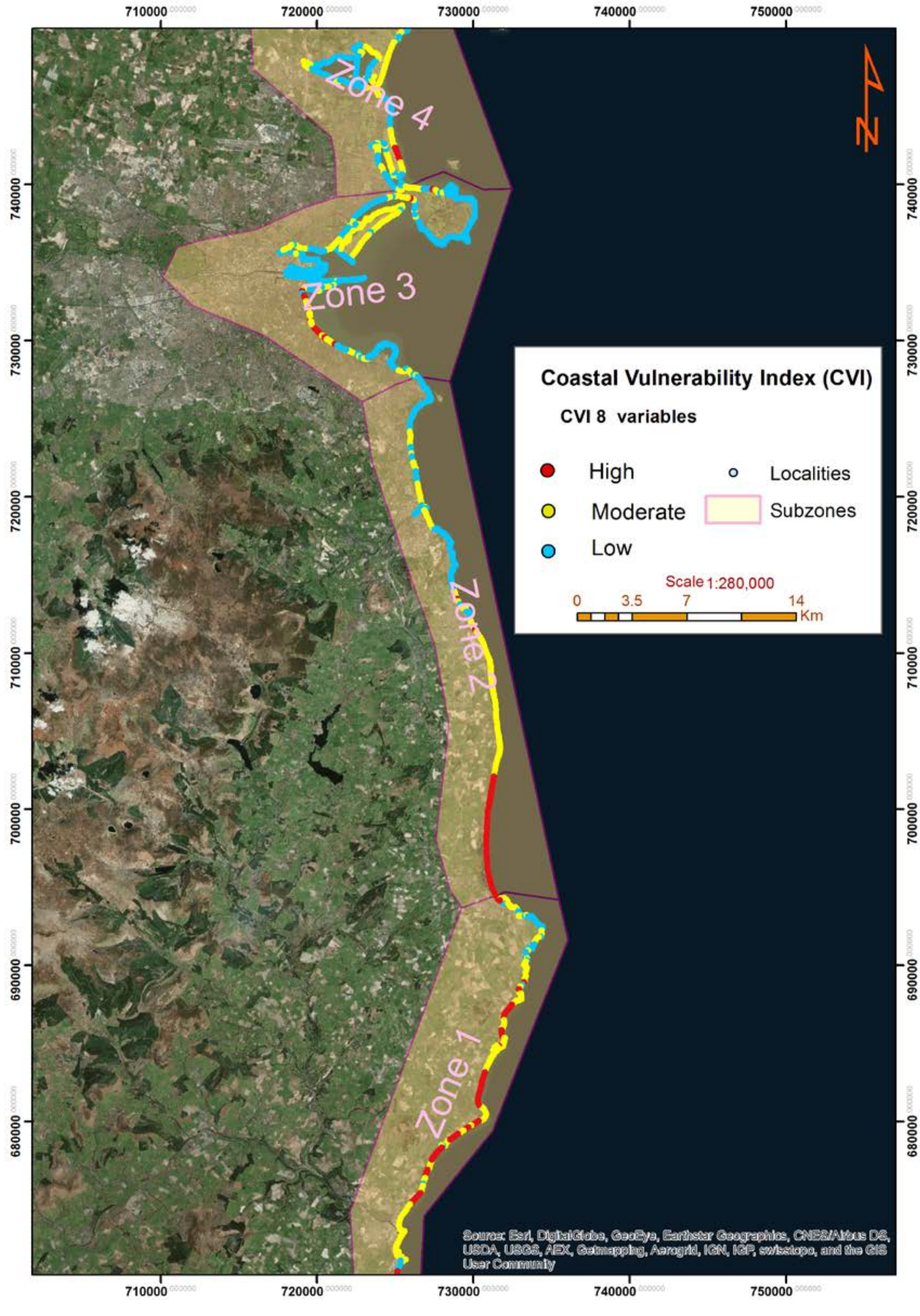


Figure 6. 14. Coastal vulnerability index using 8 variables showing from high to low vulnerability ranking. *(Source: Silvia Caloca).*

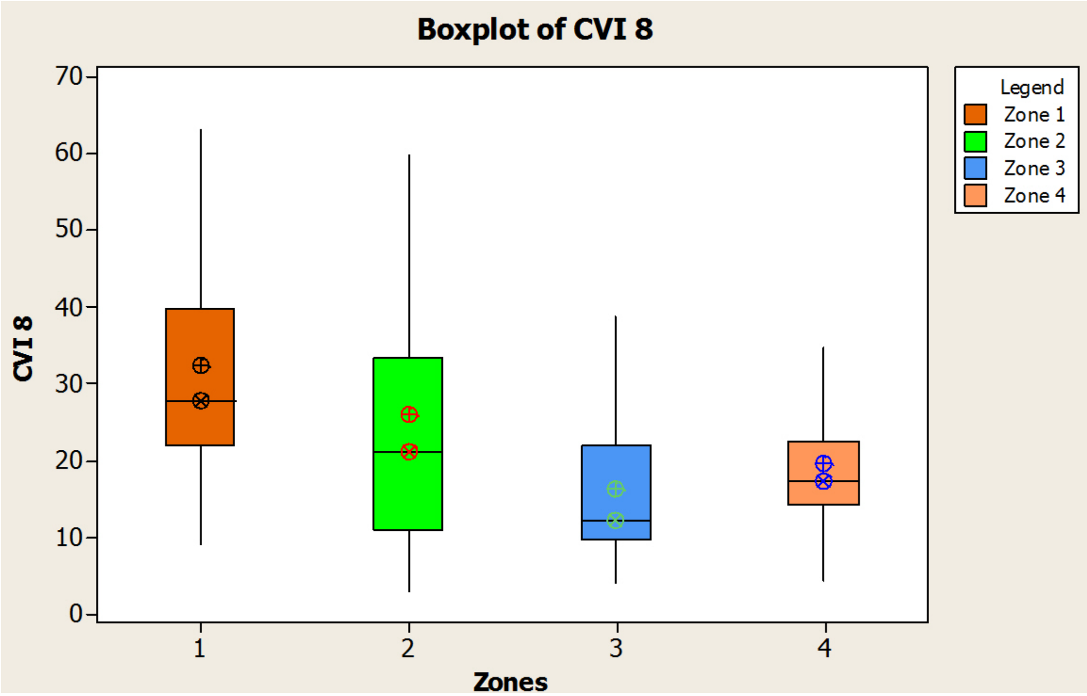


Figure 6. 15. Boxplot showing CVI values (using 8 variables) for all zones; ⊗ is the median and ⊕ is the mean. The coloured box represents the inner quartiles for each zone. *(Source: Silvia Caloca).*

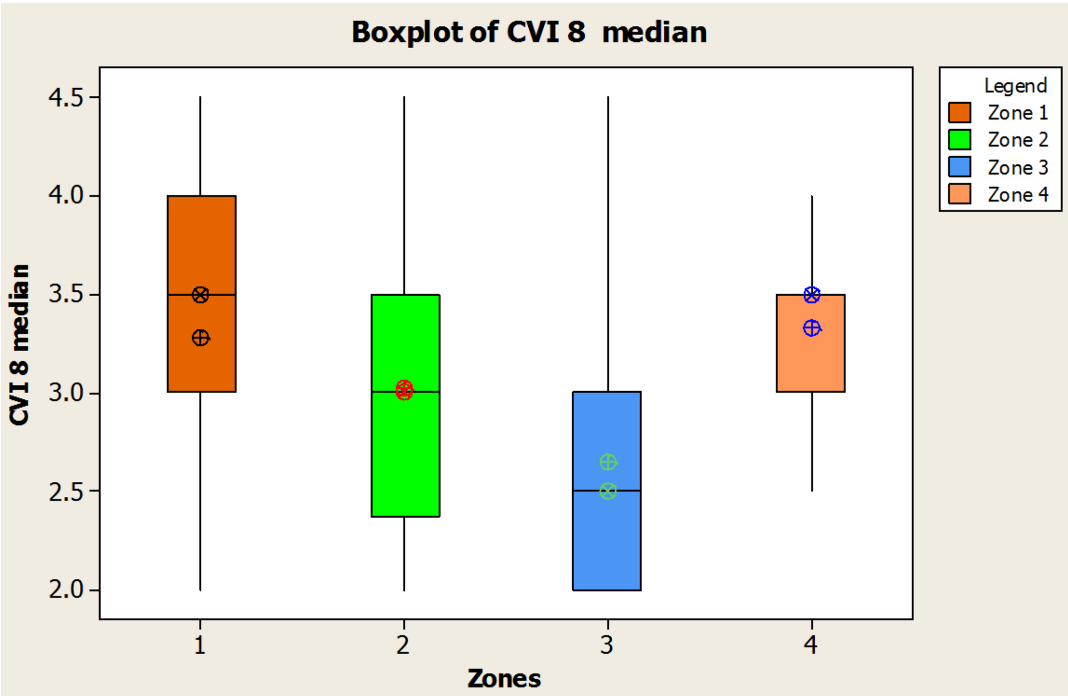


Figure 6. 16. Boxplot showing median CVI 8 values and the range of ranked variables used to determine the index; ⊗ is the median and ⊕ is the mean. The coloured box represents the inner quartiles. *(Source: Silvia Caloca).*

Zone 1

This is the longest zone with 255 data points evaluated. CVI values are predominantly high in this region. The mean CVI is 32.3. The interquartile range (IQR) is 18.1. The median of the 8 ranked variables is 3.5, a moderate to high vulnerability index. In the northern part around Wicklow Head, CVI values are on average less than the rest of the area. Some local variability, generally associated with moderate CVI values for a few hundred meters, can be observed in the southern end around the Arklow region (Figure 6.14).

Zone 2

In general, this area shows moderate CVI values (Figure 6.14). However, large scale regional variability can be observed. The mean CVI is 25.97. The interquartile range (IQR) is 22.59. The median of the 8 ranked variables is 3,a moderate vulnerability index. Three geographical sections can be identified from south to north based on their CVI values: a southern part with very high CVI values (mean: 61.33); a middle part, a short interval between Kilcoole and Greystones, characterised by moderate values (mean: 27.6); and a northern part containing very low values (mean: 14.42).

Zone 3

This area is characterised predominantly by moderate values and variability. The mean CVI is 16.23 and the interquartile range (IQR) is 12.42. Four areas can be differentiated based on their CVI values: (1) Urban areas characterised by man-made structures where CVI values are very low (mean: 10.4); (2) the southern part of Dublin Bay characterised by moderate to high CVI (mean: 27.36; (3) the northern part of Dublin Bay (Bull Island) characterised by moderate values (mean: 23.7); (4) a northern part, along the Howth peninsula, represented by low CVI values (mean: 11.36).

Zone 4

The northern part of the study area is characterised by moderate values and low variability. The CVI mean is 19.6. The interquartile range (IQR) is 8.22. Two distinct types of coastline are noticeable: (1) non-exposed coastline, including the Baldoyle area and inner part of Malahide, with very low values and a mean of 16.2 and (2) exposed coastline with moderate values with a mean of 23.9.

Plate 6.2 below illustrates a 3D aerial view of the CVI calculated in the study area to better visualise where the vulnerable areas are located.

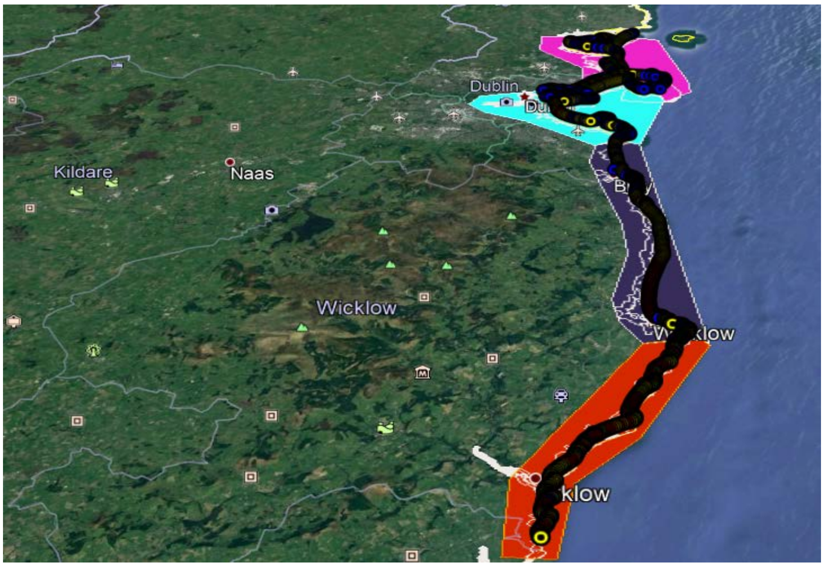


Plate 6. 2. This video shows an aerial view of the most vulnerable areas from CVI analysis https://youtu.be/hOq7ND7ygd4 . *(Source: Silvia Caloca).*

6.2.3. Description of variable values by zone

Description below explains the influence of main variables by zone is described and represented on box-plot diagrams showing median CVI (8 variables) and the range of ranked variables used to determine the index per zone.

Zone 1 is overall characterised by high vulnerability, is primarily influenced by large tidal ranges, high waves and relatively low costal slopes (Figure 6.17).

Zone 2 is generally characterised by moderate vulnerability, is primarily influenced by high variability in the onshore coastal physical variables such as Slope, Geomorphology and Cliff type, coupled with lower variability intermediate tidal ranges and Aspect (Figure 6.18).

Zone 3 shows relatively low vulnerability, is primarily influenced by low tidal range and low rankings in cliff types and Aspect. High rankings in Slope and Waves are also present in short segments along the coastline Figure 6.19.

Zone 4 is represented by moderate vulnerability, which is primarily influenced by very low variability in five of the ranked variables. Geomorphology has high vulnerability ranking and moderate variability, while Aspect has generally low values and moderate variability (Figure 6.20).

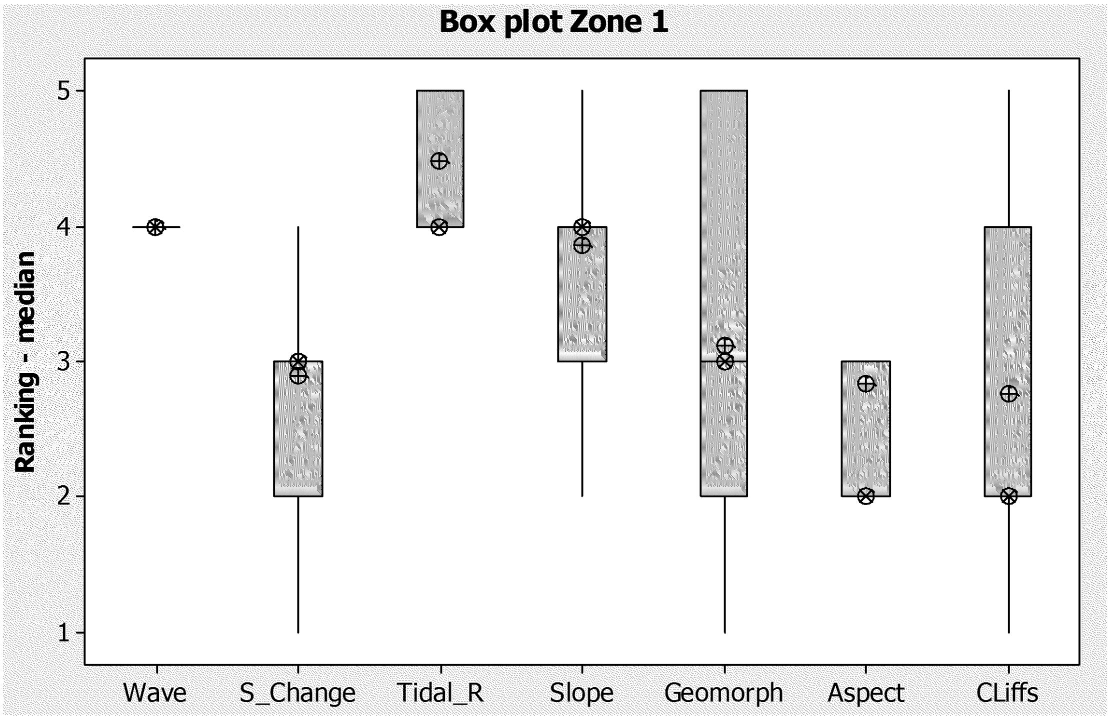


Figure 6.17. Box plot showing statistics on variables values in zone1; ⊗ is the median and ⊕ is the mean. The shaded box represents the inner quartiles for each zone. *(Source: Silvia Caloca)*

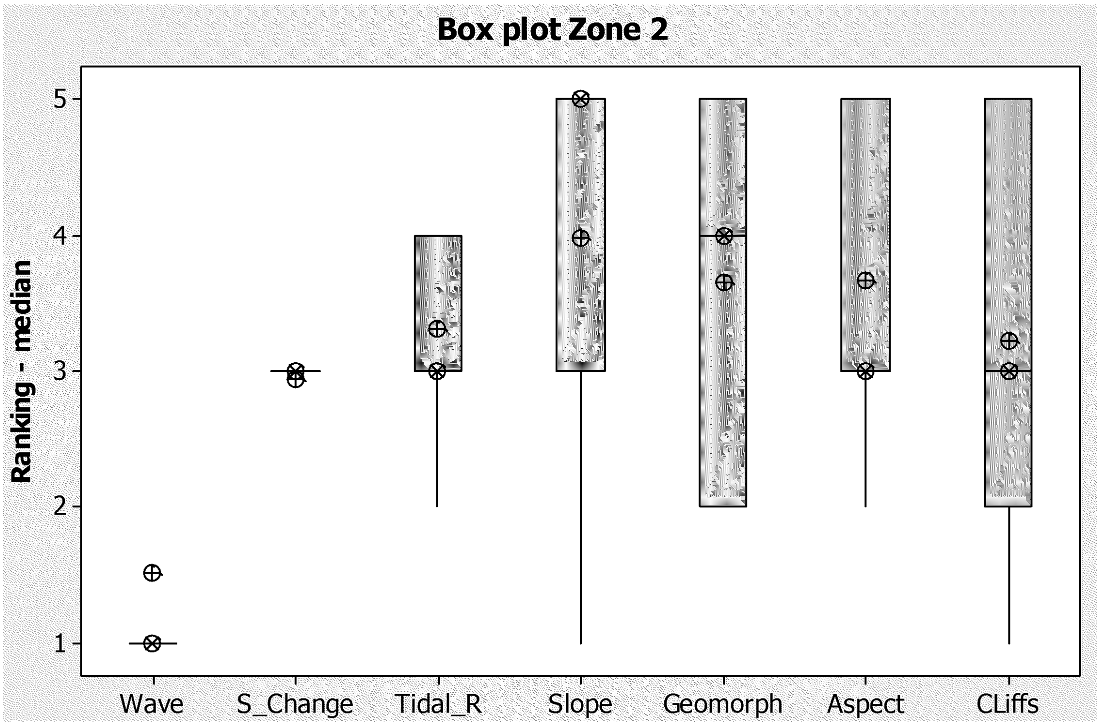


Figure 6.18. Box plot showing statistics on variables in zone 2; ⊗ is the median and ⊕ is the mean. The shaded box represents the inner quartiles for each zone. *(Source: Silvia Caloca).*

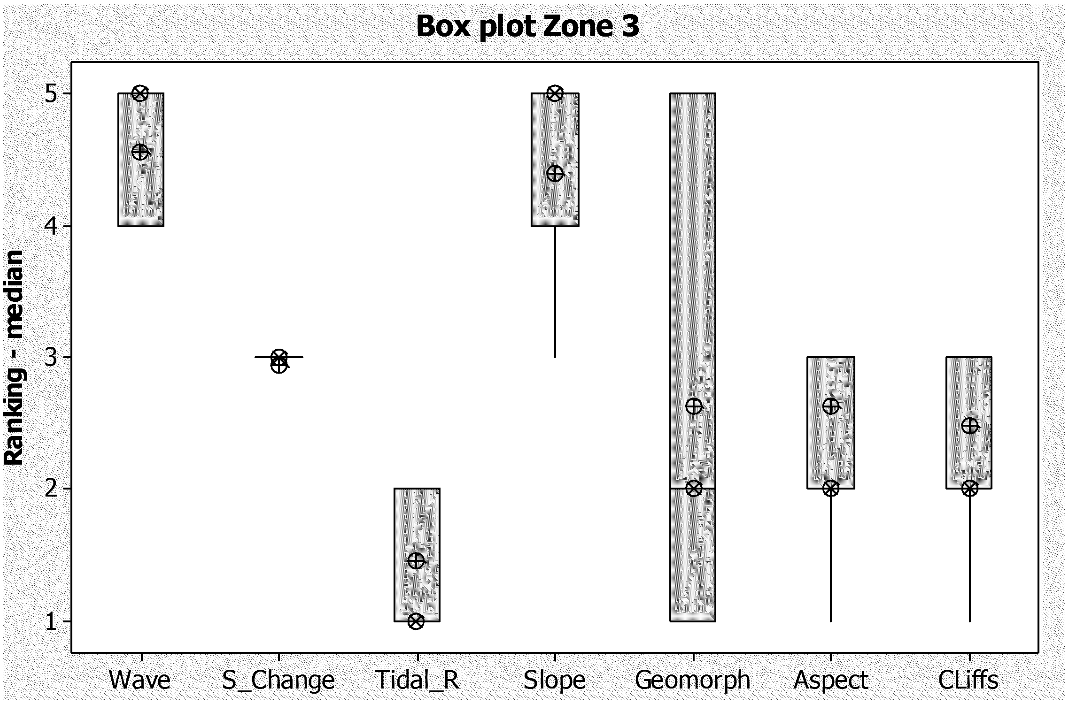


Figure 6.19. Box plot showing statistics on variables in zone 3; ⊗ is the median and ⊕ is the mean. The shaded box represents the inner quartiles for each zone. *(Source: Silvia Caloca).*

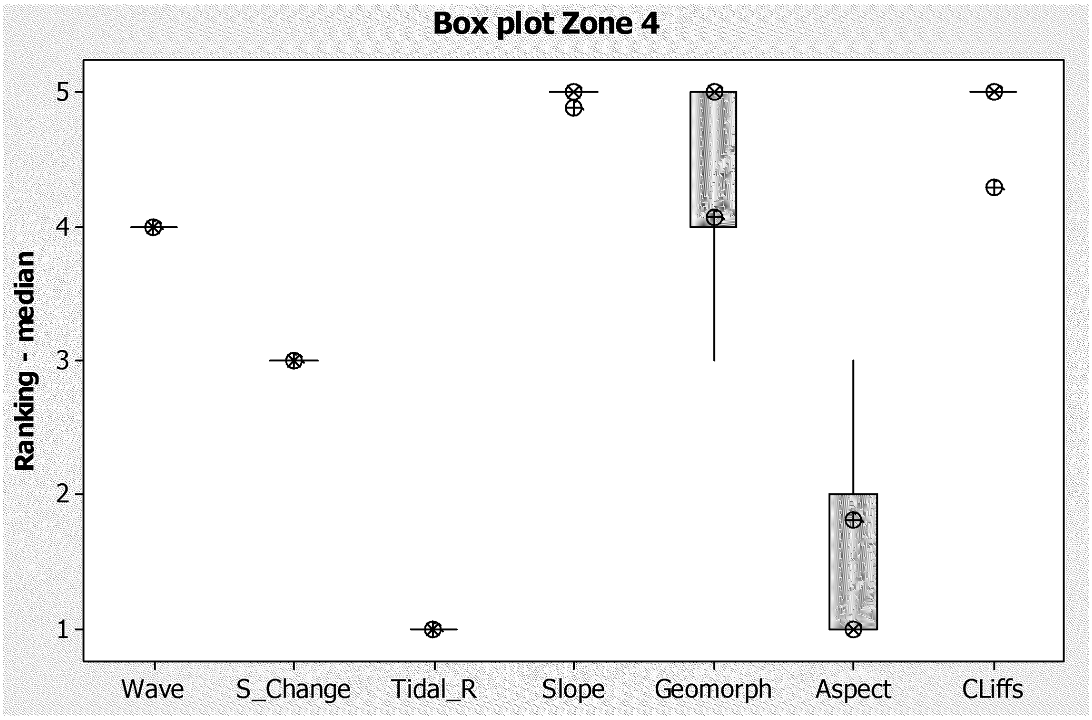


Figure 6.20. Box plot showing statistics on variables in zone 4; ⊗ is the median and ⊕ is the mean. The shaded box represents the inner quartiles for each zone. *(Source: Silvia Caloca).*

6.3. Principal Component Analysis (PCA).

In order to measure the degree of linear relationship between each pair of ranked variables, the Pearson's correlation coefficient matrix was calculated and examined. The results (Table 6.2) show that overall the linear correlation between the variables is weak (r<|0.35|) except for slope (slp_R5) versus cliff type (CL_TR5) (r=0.44) and geomorphology (GEO_R5) vs cliffs (CL_TR5) (r=0.65).

	Wave_R5	Shoreline	TR5_Quant2	slp_R5	GEO_R5
Shoreline change	0.044				
TR5_Quant2	-0.285	-0.045			
slp_R5	0.246	-0.077	-0.272		
GEO_R5	-0.204	-0.165	-0.011	0.343	
CL_TR5	-0.040	-0.182	-0.088	**0.440**	**0.645**
Aspect	-0.328	-0.000	0.212	-0.202	-0.080

Table 6. 2. Pearson's linear correlation matrix for 7 variables (relative sea-level rise is not included because it is constant). *(Source: Silvia Caloca)*

The relationship among the various components and indicators was further assessed by means of PCA. The main applications of factor analytic techniques are: (1) to detect structure in the relationships between variables, that is to classify variables (2) to reduce the number of variables.

A principal component analysis summary of the covariance matrix of coastal variables, including eigenvalues, percentage of variance, and coefficients of the principal component, was carried out. Seven variables were included (as one is constant) and seven principal components were calculated. The following variables were examined: mean significant wave height (WAVE_R5); shoreline change (SC_R5); Mean tidal range (TR5_Quant2); regional coastal slope (slp_R5); geomorphology (GEO_R5); cliff type (CL_TR5); aspect or orientation towards main swell (ASP_R5).

	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Eigenvalue	4.4862	2.929	1.577	1.063	0.805	0.562	0.479
Proportion	0.377	0.246	0.132	0.089	0.068	0.047	0.040
Cumulative (%)	37.7	62.3	75.5	84.5	91.2	96.0	100.0

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7
Wave_R5	0.016	0.535	-0.170	**0.696**	-0.288	0.342	0.024
Shoreline	0.066	0.042	0.015	-0.051	-0.050	-0.072	**0.992**
TR5_Quant2	0.132	**-0.589**	**-0.727**	0.302	-0.052	-0.108	0.033
slp_R5	-0.254	0.166	0.089	0.335	-0.005	**-0.887**	-0.039
GEO_R5	-0.644	-0.284	0.112	-0.081	**-0.687**	0.115	0.023
CL_TR5	**-0.671**	-0.054	-0.077	0.191	0.660	0.238	0.109
Aspect	0.219	-0.504	0.645	0.517	0.065	0.101	0.034

Table 6.3. Principal component analysis summary of the covariance matrix of coastal variables for PCA-8. Top: eigenvalues and proportions. Bottom: loadings for each principal component, where Wave_R5 is mean significant wave height; Shoreline: shoreline change; TR5_Quant2 mean significant tidal range; GEO_R5: geomorphology; CL_TR5: cliff type; Aspect. *(Source: Silvia Caloca)*

The first six principal components (PC) explain circa 96% of the total variance among the variables for the entire study area, the first five 91%, the first four 84% of the total variance, the first three 75% and the first two 62%. Slope has high loading on principal component six. Shoreline change does not have loadings greater than 0.72 in the first 6 principal components. See Table 6.3. The first principal component (PC1) accounts for 38% of the total variability and identifies coasts where cliffs (-0.67) and geomorphology (-0.64) variables are equally predominant (high or low). The second (PC2) accounts for 25% and identifies coasts where the major loadings come from two oceanographic driven variables: high tidal range (-0.59) and low wave height (0.54) (or vice versa). The third (PC3) accounts for 13% and identifies high tidal range coasts (0.73) and low aspect coast (0.65) (or vice versa). PC1 shows the high loadings of cliff type and geomorphology; and PC2 shows wave and tidal range acting in opposite directions (Figure 6.21). The decay in the eigenvalues towards the highest principal components (i.e. PC7) is typical in PCA and shows the importance of each individual PC in explaining the variability. In this case it shows that PC7 plays only a minimal role in the overall model (Figure 6.22).

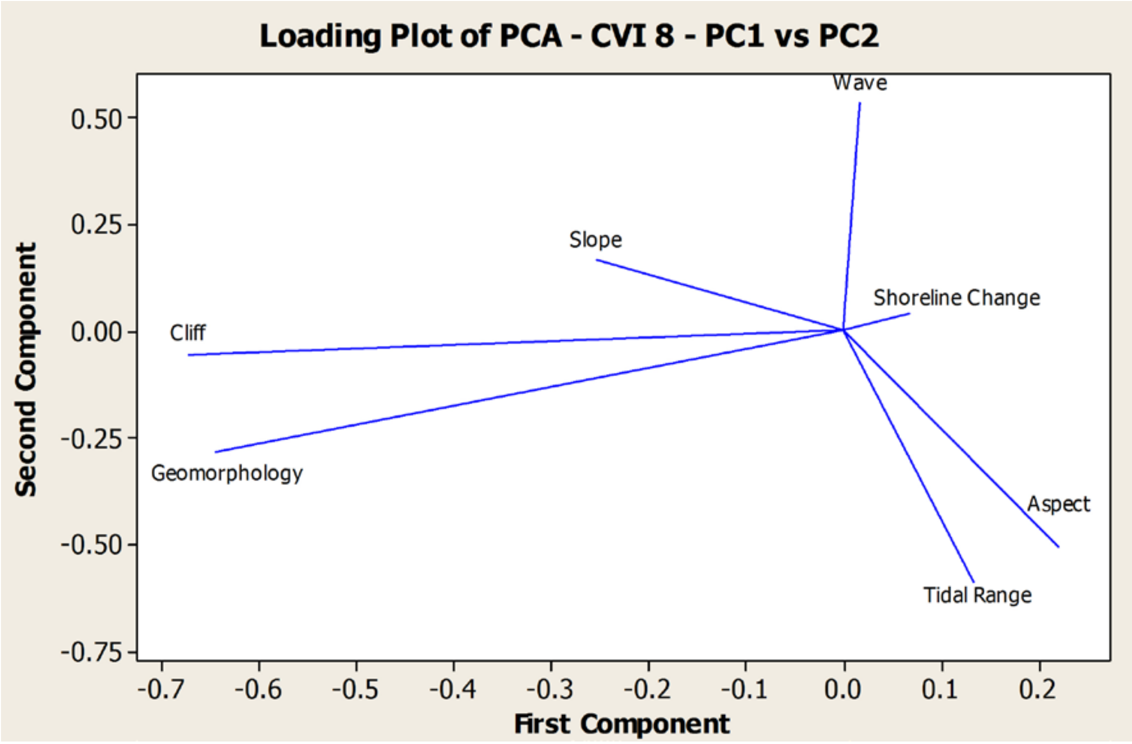


Figure 6.21. Graph displaying the loading plot of variables for principal components PC1 and PC2. *(Source: Silvia Caloca).*

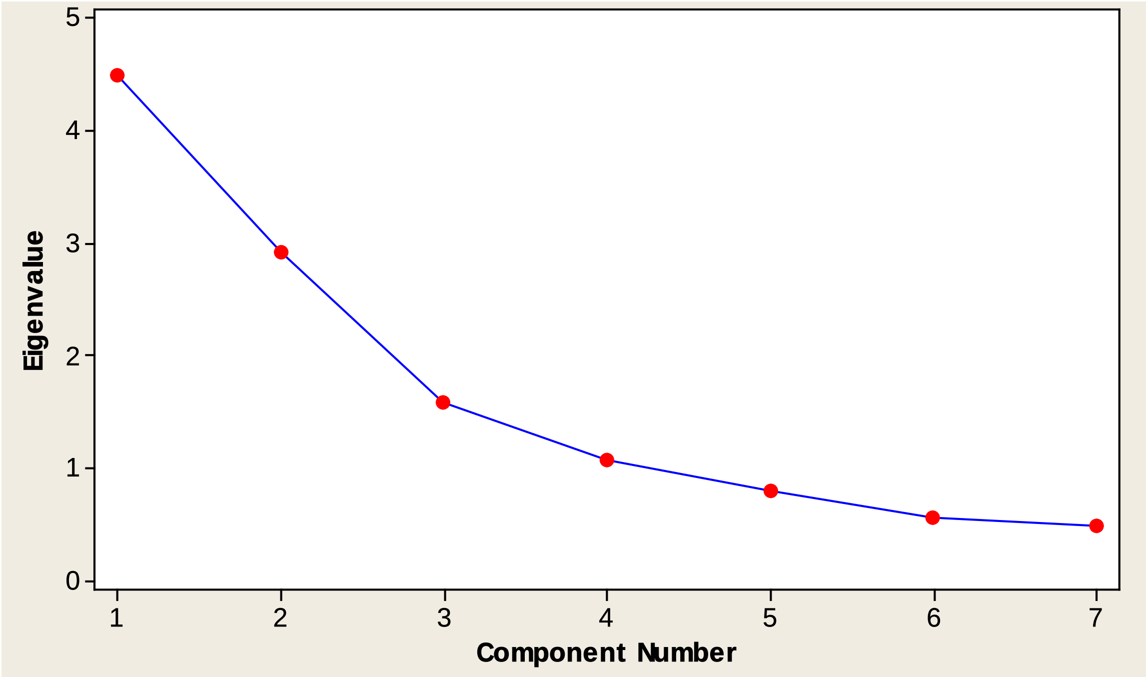


Figure 6.22. Screen plot showing the decay of eigenvalues versus the principal components. *(Source: Silvia Caloca)*

6.3.1. Comparison between CVI maps

PCA results show that all the variables have influence in the CVI 6 calculation, although the first 4 principal components account for 94% of the variability, while PC5 only accounts for 6% and it is largely correlated to shoreline change variable (r=0.993). Similarly, PCA analysis for CVI 8 show that the first 6 principal components account for 96% of the variability, while PC7 only contributes to 4% of the total variability, mainly from shoreline contribution (r=0.992).

The linear correlation between CVI 8 and CVI 6 indices is also strong (r: 0.85 R^2:0.73). However, it is significantly less correlated than CVI 8 and CVI 7 (r: 0.96 R^2:0.92). This relationship (CVI 6/CVI 8) is reflected in the scatter plot of the two normalized CVI (Figure 6.23) and also on the coastline profile graph of the normalised values for the entire coastline, which displays significant variations in localised segments (Figure 6.24).

The statistical analysis, as a result of comparing CVI 8 and CVI 6 in previous figures above suggests that the two extra variables calculated (cliff and aspect) carry significant influence in the coastal vulnerability index; cliff is an onshore variable, while aspect incorporates an oceanographic component.

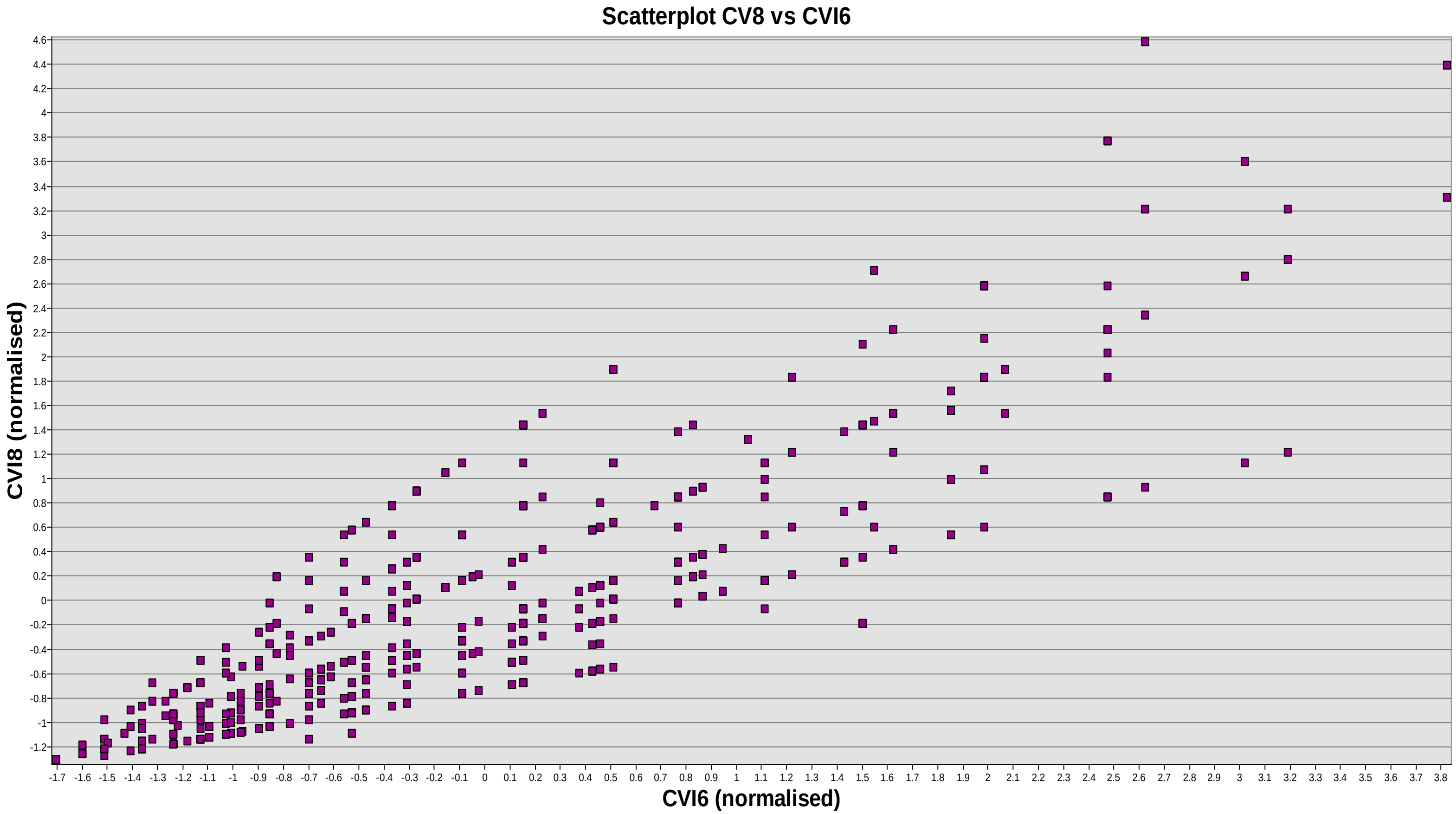


Figure 6.23. Scatterplot showing correlation of the two normalized indices CVI 8 versus CVI 6. *(Source: Silvia Caloca).*

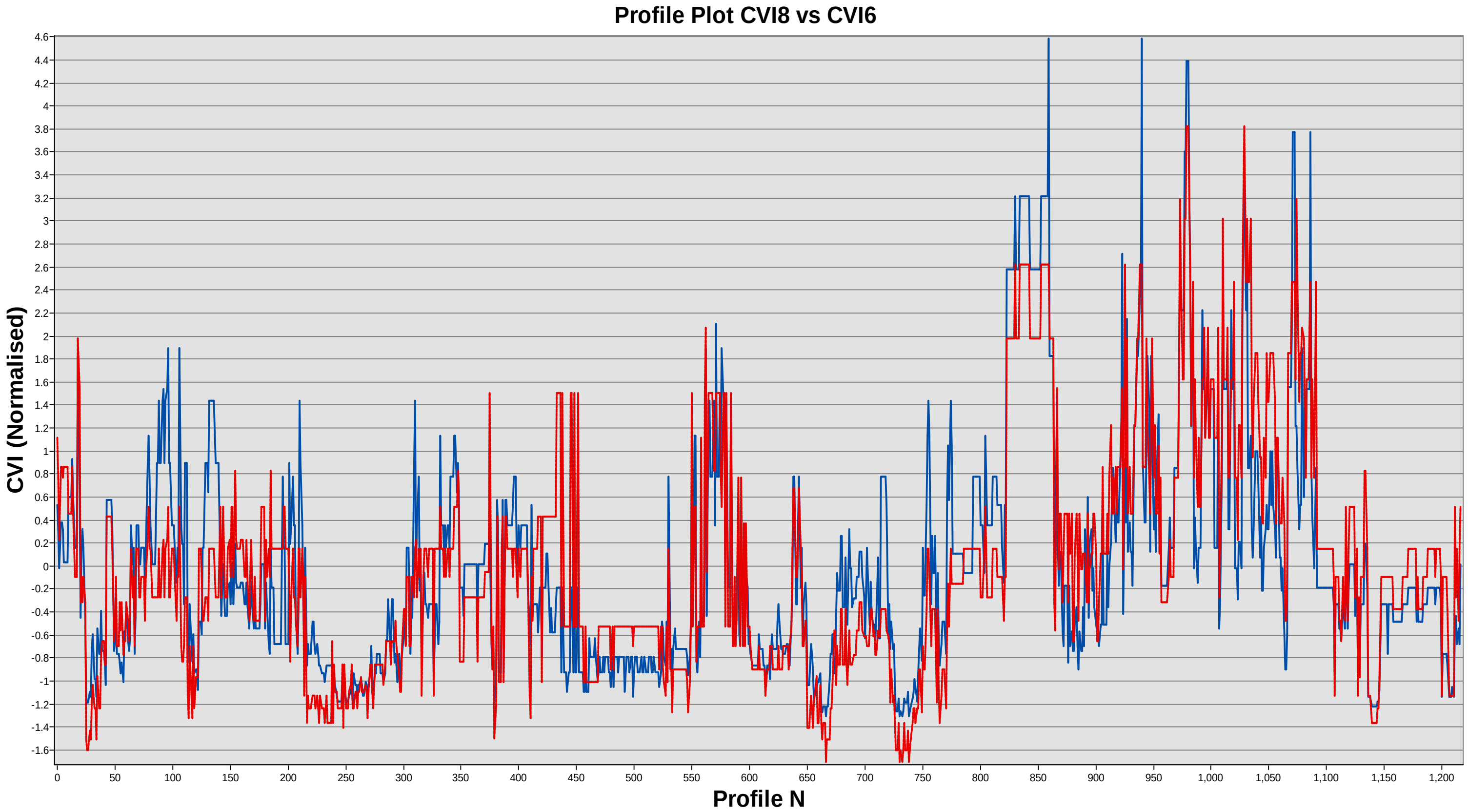


Figure 6.24. Coastline profile showing CVI 8 (blue) and CVI 6 (red) normalised values for the entire area from south (left) to north (right). *(Source: Silvia Caloca).*

6.4. Validation

Recent shoreline changes calculated from vegetation lines between 2015 and 2017 were used to validate CVI 8 results in soft, unconsolidated areas around Brittas Bay and Three-Mile Water in Co. Wicklow.

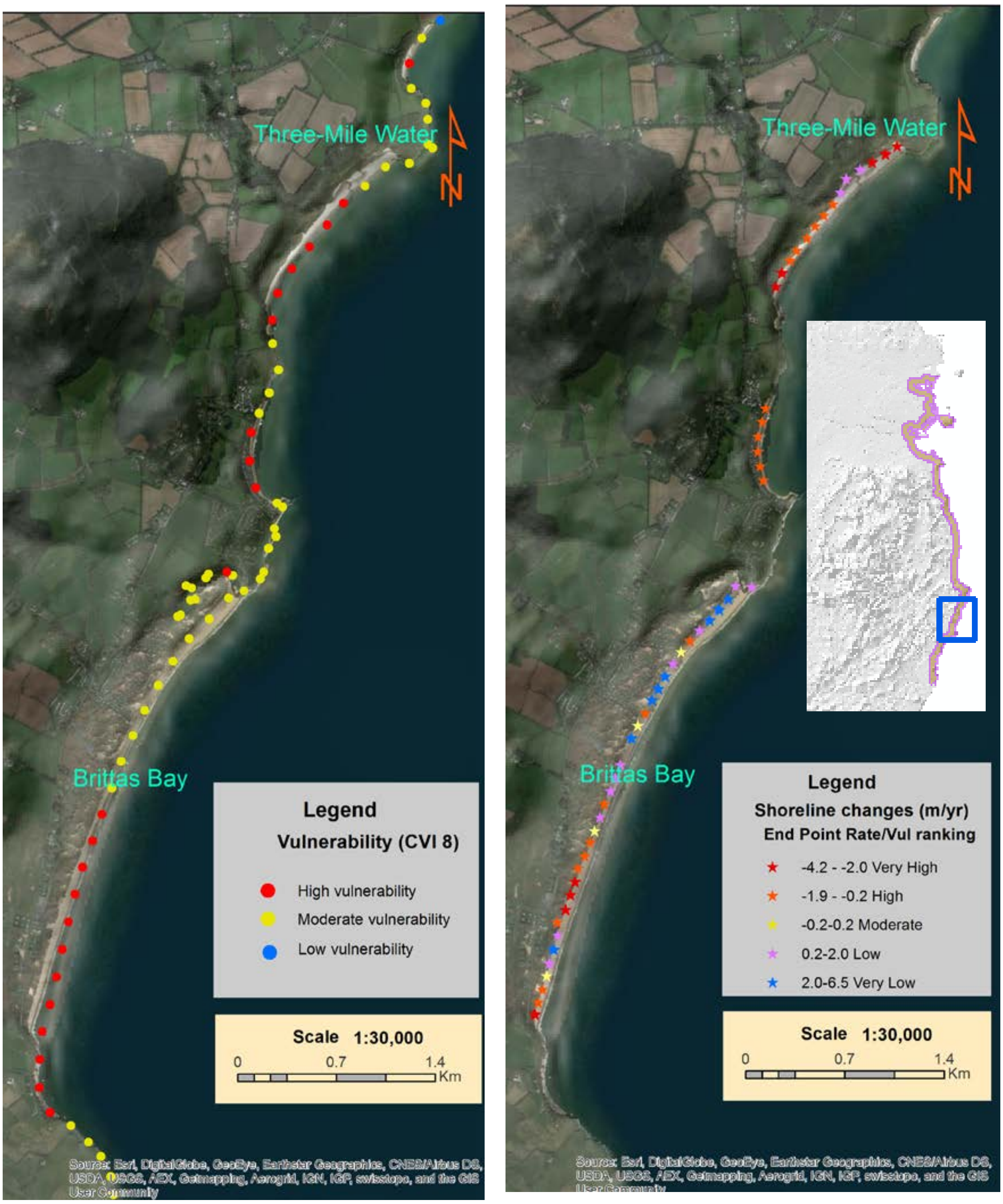


Figure 6. 25. High CVI values validated against recent shoreline changes (2015-2017) zone 1.

Shoreline changes rates were performed over an in independent ant recent period using the End Point Rate (EPR) method. These method was used (as opposed to WLR used in CVI 8) suitable for calculating rates of change using two vegetation lines.

As it can be appreciated in Figure 6.25 high vulnerability areas are correlated to areas experiencing larger shoreline changes (high to very high).

6.5. Chapter summary

The main areas of vulnerability to impacts of sea-level rise were identified. A combination of all relevant coastal indicators into a single CVI resulted in a series of susceptibility maps that highlighted where the sea-level related changes will most likely happen.

Results are displayed by means of thematic maps from the nine variables, evidencing areas of vulnerability expressed by ranking from very low to very high. Two vulnerability indices were calculated using the most relevant six and eight variables (CVI 6 and CVI 8). Based on this the study area was subdivided into four distinctive sub-zones.

Dimensionality and relationship among the various components and indicators was further assessed by means of PCA. The first six principal components largely account for most of the total variance. Principal Component 7 accounts for a minimal part of the total variance. The first Principal Component has major contributions from Cliff Type and Geomorphology, while the second Principal Component from Wave and Tidal Range.

A validation test was performed on CVI 8 against recent shoreline changes. This validation show high correlation in soft, unconsolidated areas of Britta's Bay and The Three-Mile Water in Co. Wicklow.

Chapter 7: Assessment of impacts of climate change and sea-level change

7.1. Sensitivity analysis of future impacts of sea-level rise on storm surges

Extreme water levels for 59 points across the study area, obtained from joint probability analysis of tide and surge data of the top 79 extreme events in North Dublin (1969-2004) and 56 events in South Dublin (1959 to 2000) (ICPSS, 2010), were used to explore future potential inundation scenarios. Local relative sea-level projections were added to account for the climate component on water level heights.

To detect small gradual changes, a high resolution LiDAR digital elevation model at 1-2m (horizontal) and 0.25m (vertical), was used as a base to recreate potential scenarios of inundation for 2040, 2060, 2080 and 2100. Uncertainty of +/- 330mm on extreme water levels was applied due accuracies in water levels calculation (+/- 180mm error) plus digital terrain model (+/- 150mm) by OPW (2010).

Coastal areas prone to inundation are identified for the 1-in 50-year (2%AEP), 1-in-100 years (1% AEP) and the 1-in-200 year (0.5% AEP) extreme events. Maximum extreme water levels from tide-surge combined with local sea-level projections resulted in water depths 5.67m (1% AEP) and 5.58m (2% AEP) OD Malin by 2100. See all flooding maps for the different AEP displayed in Appendix II.

Worst case scenarios are illustrated below in Figures 7.1, 7.2 and 7.3 for 0.5% exceedance probability events by 2100. An extreme water level of 5.76m is evident. This is the most extreme, though the least frequent, scenario. Flood extent maps show vulnerable areas around Portrane to Malahide, from Five Mile Point to Wicklow and around Arklow.

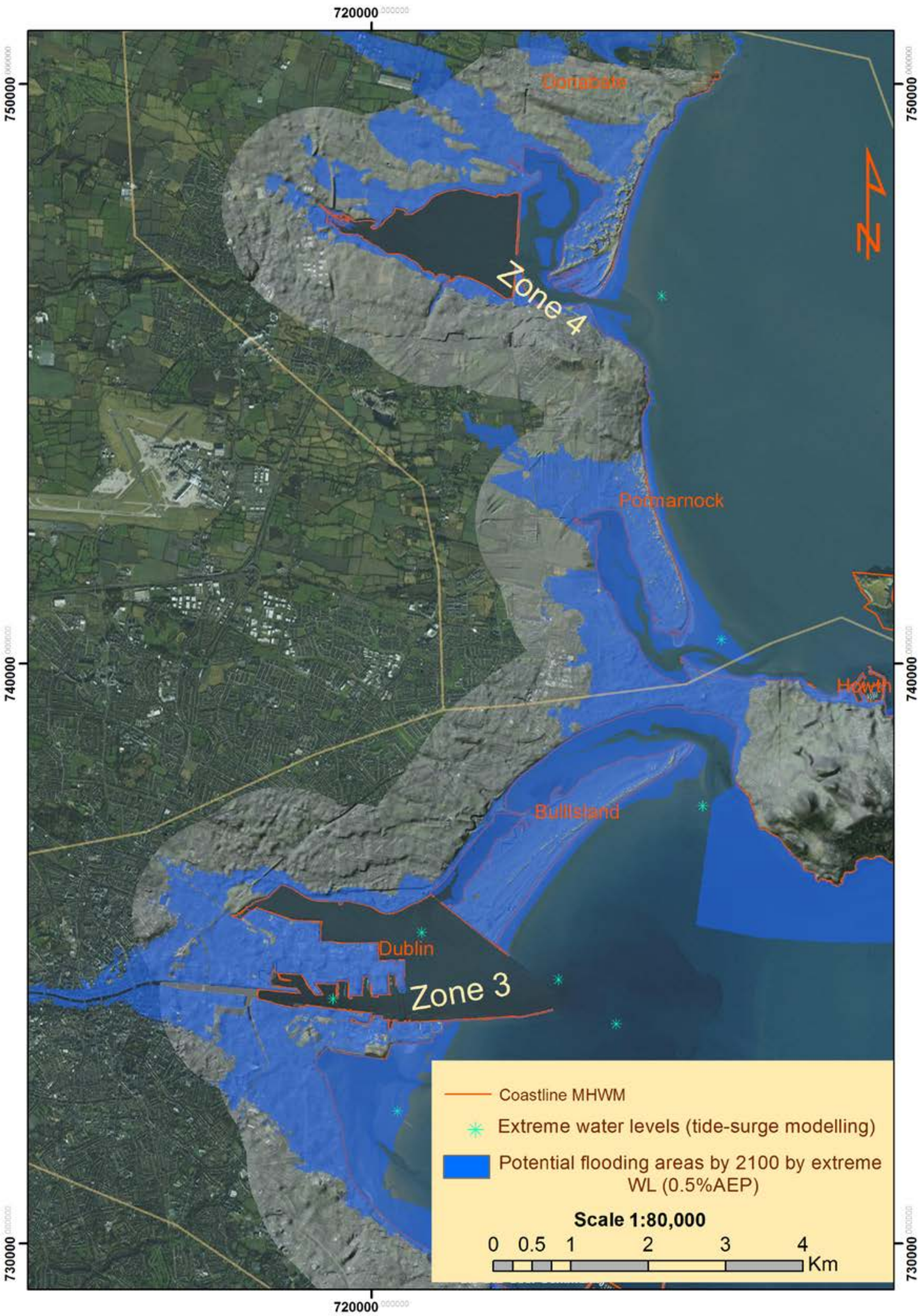


Figure 7.1. Close up showing inundated areas from Portrane to Dublin by 2100 and extreme water levels (0.5%AEP) event. *(Source: Silvia Caloca).*

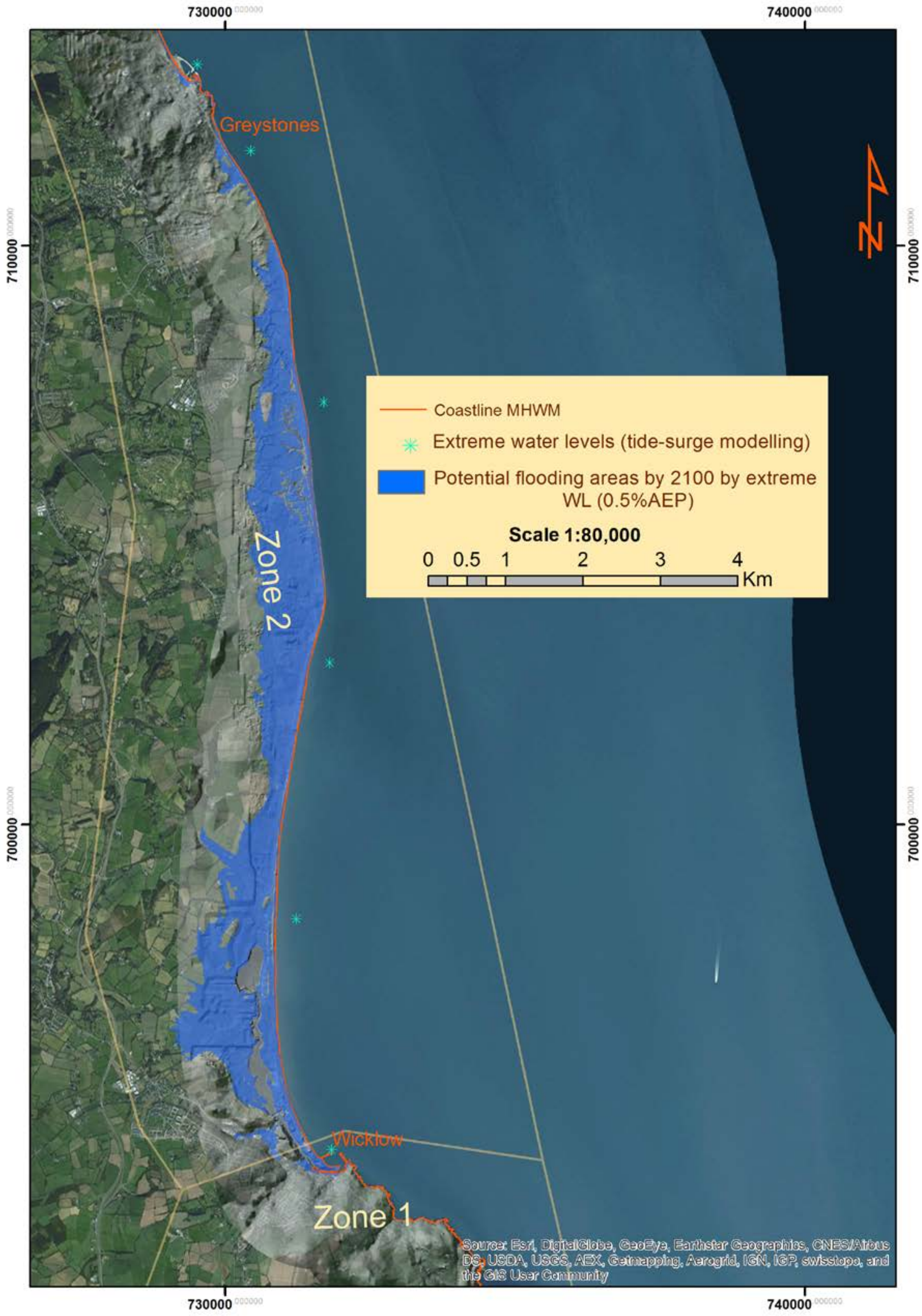


Figure 7.2. Close up showing inundated areas from the Five Mile Point to Wicklow by 2100 and 0.5% (AEP) event. *(Source: Silvia Caloca)*.

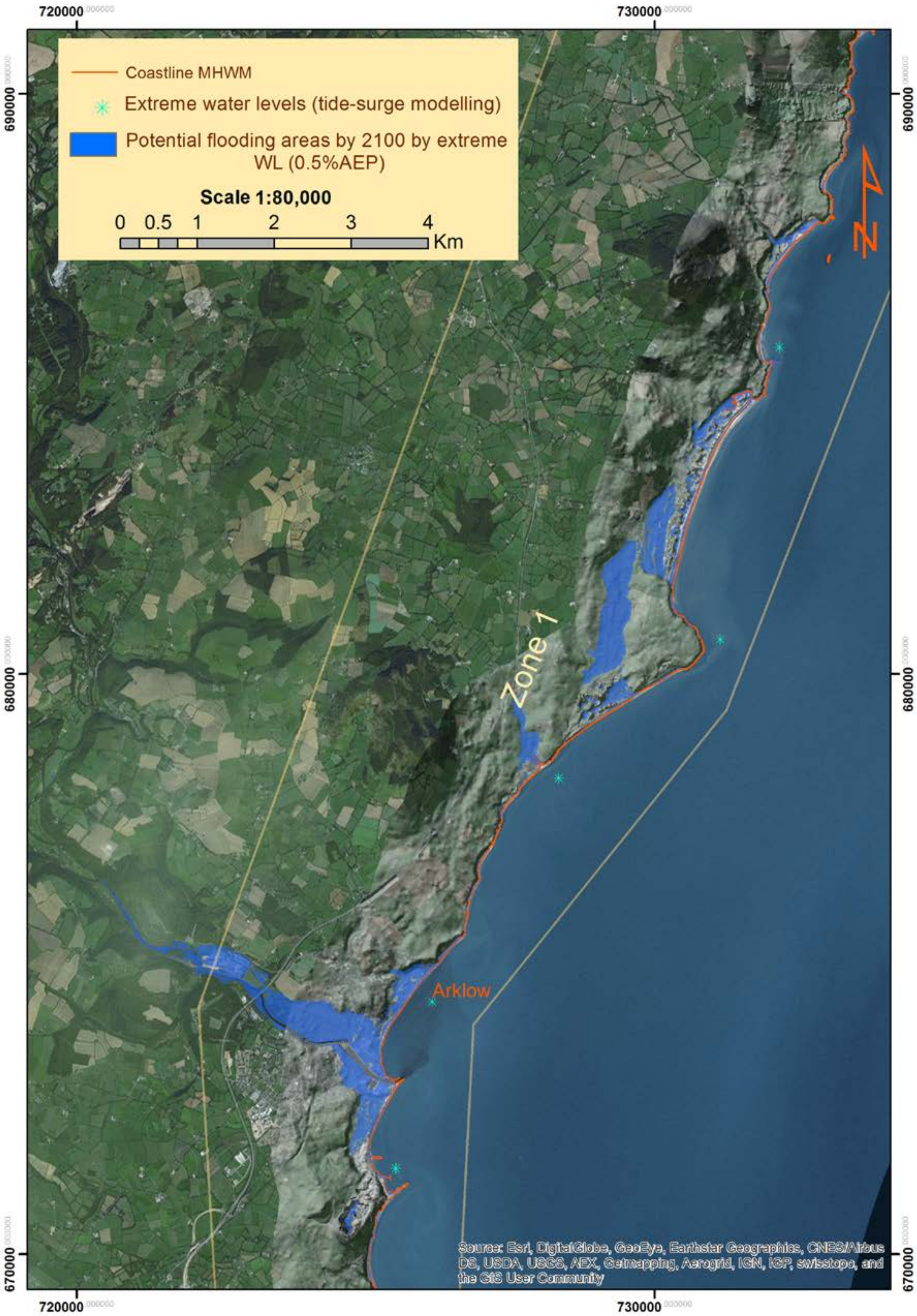


Figure 7.3**.** Close up showing inundated areas around Arklow by 2100 and 0.5% (AEP) event. *(Source: Silvia Caloca)*.

7.2. Coastal impact models

Several high sensitivity scenarios of coastal behaviour towards future sea-level rise were built for the Dublin area using the latest SimCLIM coastal impact model. Scenario 1 was produced using a shoreline response time (τ) =1 year; closure distance l=5km; depth of material exchange (d) =10m; dune height (B) =5m residual shoreline movement 25cm/year for baseline run assuming no sea-level rise (Figure 7.4). Shoreline movement by 2050 is expected to be 13.8m, 26.2m by 2100.

Similarly, a second scenario was run using same parameters but different closure distance l=2km and depth of material exchange d=5m. As it can be appreciated in Figure 7.5 shoreline is projected to change by 2050 by 13.4m while 24.9m are expected by 2100.

Next, 95^{th} percentile etimates of sea-level rise were applied for both scenarios using 1.96mm/yr total trend of sea-level rise for 28 ensemble run model RCP8.5.

Results from Figure 7.6 show shoreline movements of -169.6m for a sea-level rise of 54.9cm by 2050 while -513.78m are given by 2100 for 95^{th} percentile estimates of sea-level rise of 161.6cm. Similarly Figure 7.7 shows shoreline movements of -124.7 m for a sea-level rise of 69.6cm by 2050 while -402.6m are given by 2100 for a 95^{th} estimates of sea-level rise of 214.4cm.

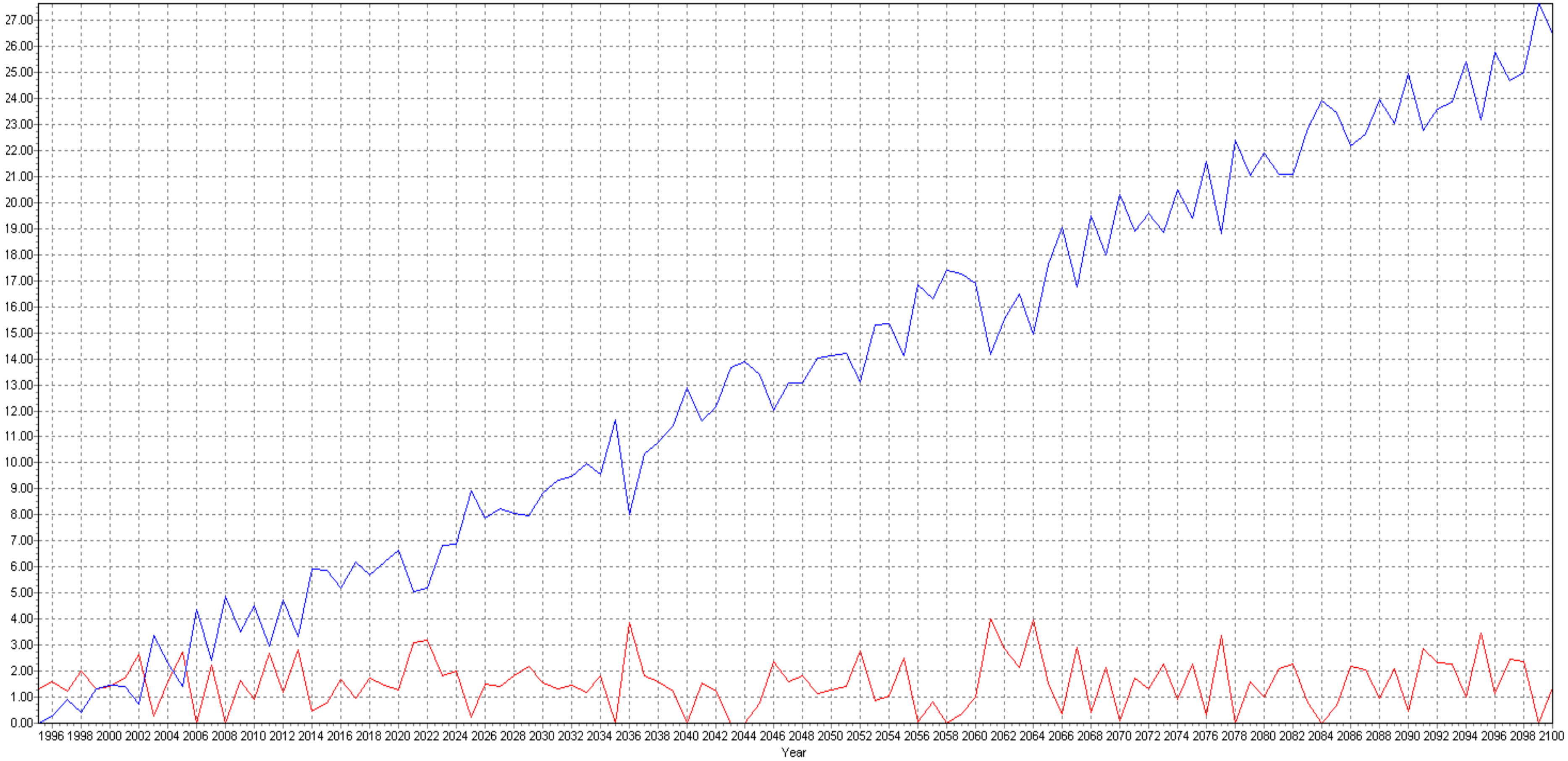


Figure 7.4. Scenario 1 showing estimated fluctuations in storm erosion (m/year; in red) and total shoreline changes (m, in blue) using τ=1, L5km, h=10m. B=5m residual 25cm parameters, for a high sensitivity baseline run (HADGEM2-CC) without adding sea-level rise. *(Source: Silvia Caloca).*

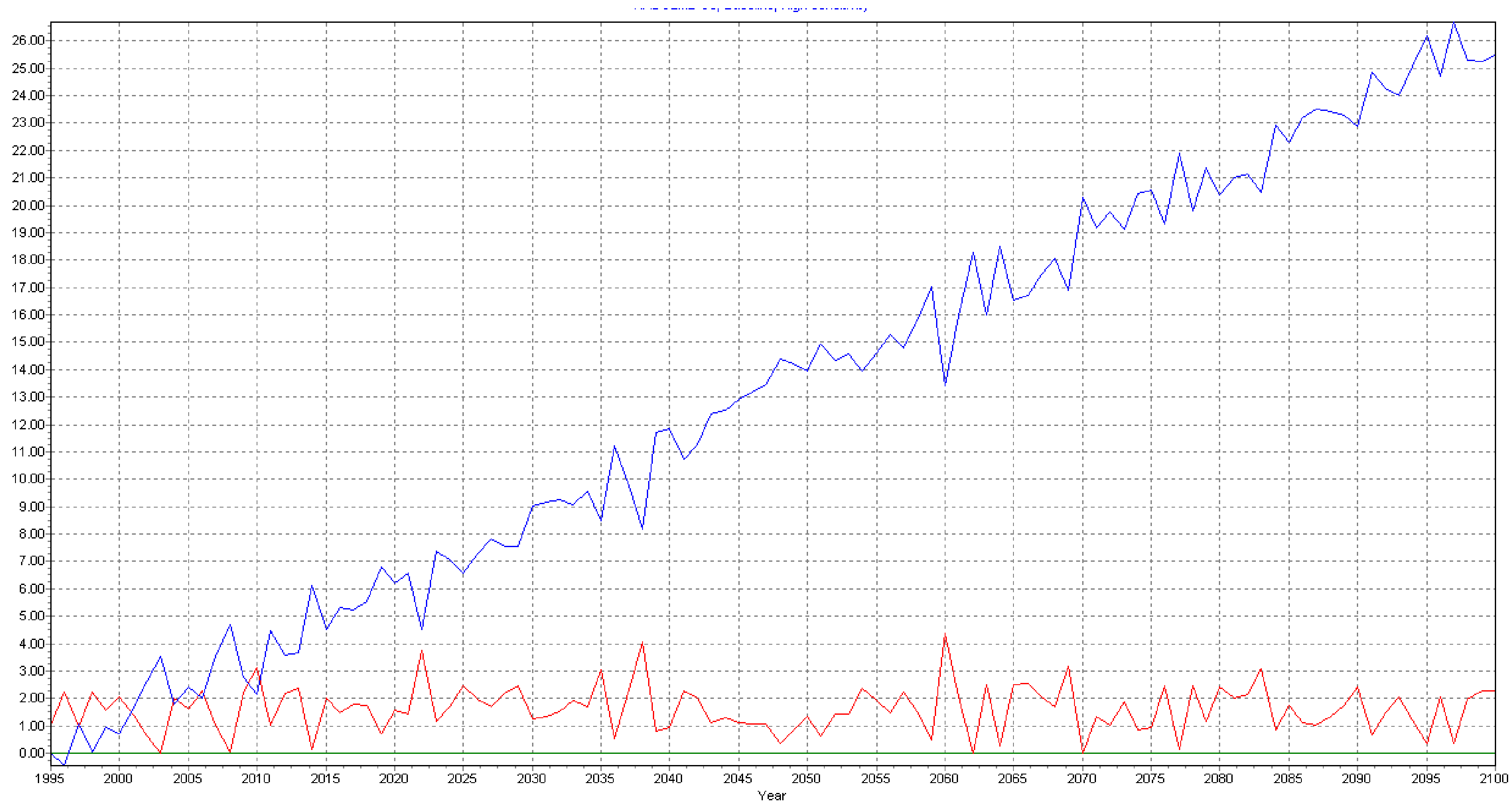


Figure 7.5**.** Scenario 2 showing estimated fluctuations in storm erosion (m/year; in red) and total shoreline changes (m, in blue) using τ=1, L= 2km , h=5m. B=5m, residual 25cm parameters, for a high sensitivity baseline run (HADGEM2-CC) without sea-level rise. *(Source: Silvia Caloca).*

Figure 7.6. Future shoreline change (m) estimates (in blue) and estimated fluctuations in storm erosion (m/year; in red) using $\tau 1$, L=5km, h=10m, B=5m, residual 25cm parameters, for 95th percentile, high sensitivity RCP 8.5 scenarios and a local sea-level trends projections (in green) from a 28-ensemble model run. *(Source: Silvia Caloca)*.

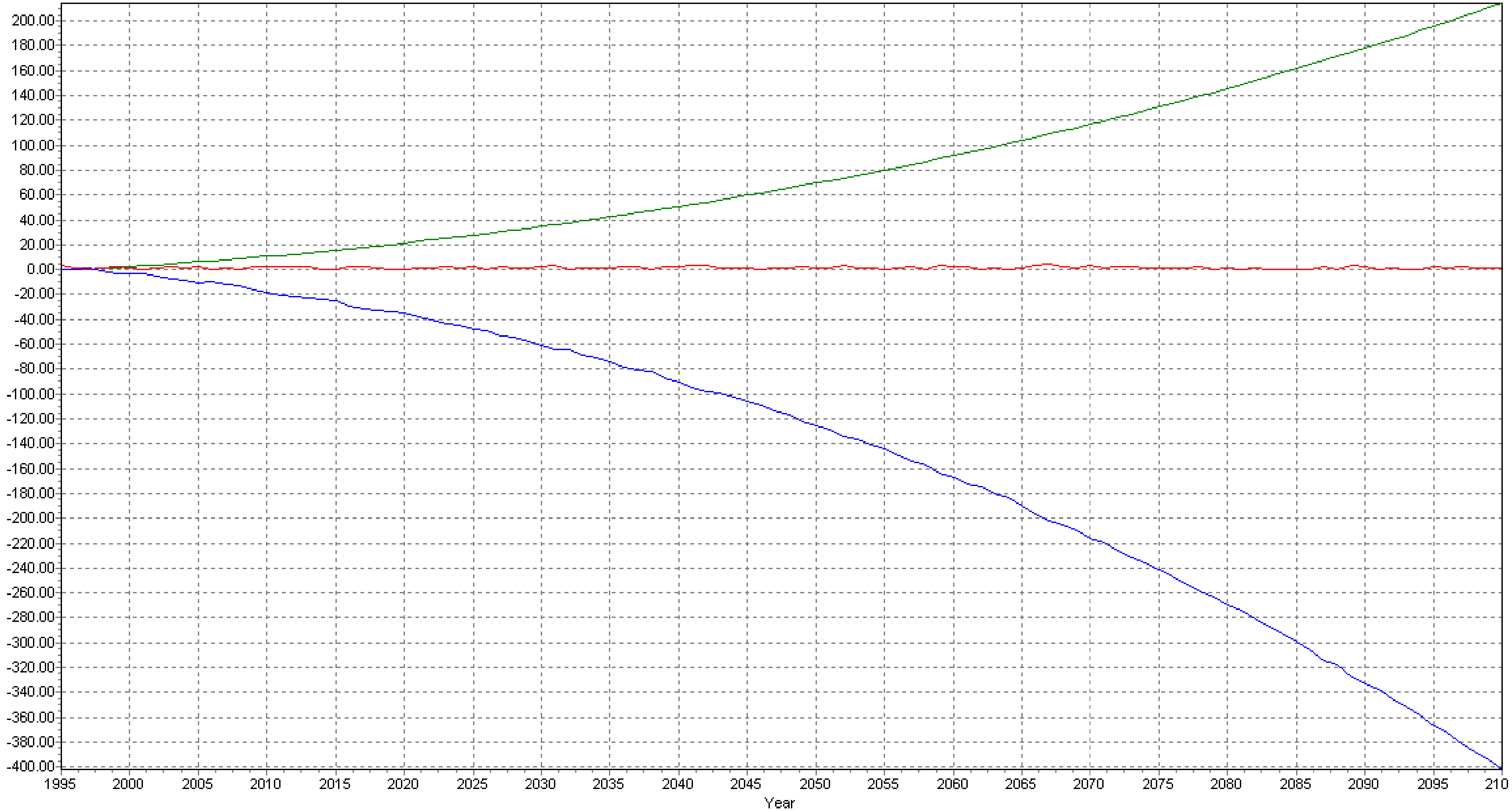


Figure 7.7**.** Shoreline change (m) and fluctuations in storm erosion (m/year; in red) for $\tau 1$, L=2km, h=5m, B=5m, residual 25cm for 95th percentile, high sensitivity, RCP 8.5 scenarios and sea-level rise projections (in green) from a 28-ensemble model run. *(Source: Silvia Caloca).*

7.3. Identification of hotspots

Hotspots were identified overlapping CVI and potential areas of inundation from extreme events (1, 2 and 0.5 % AEP).

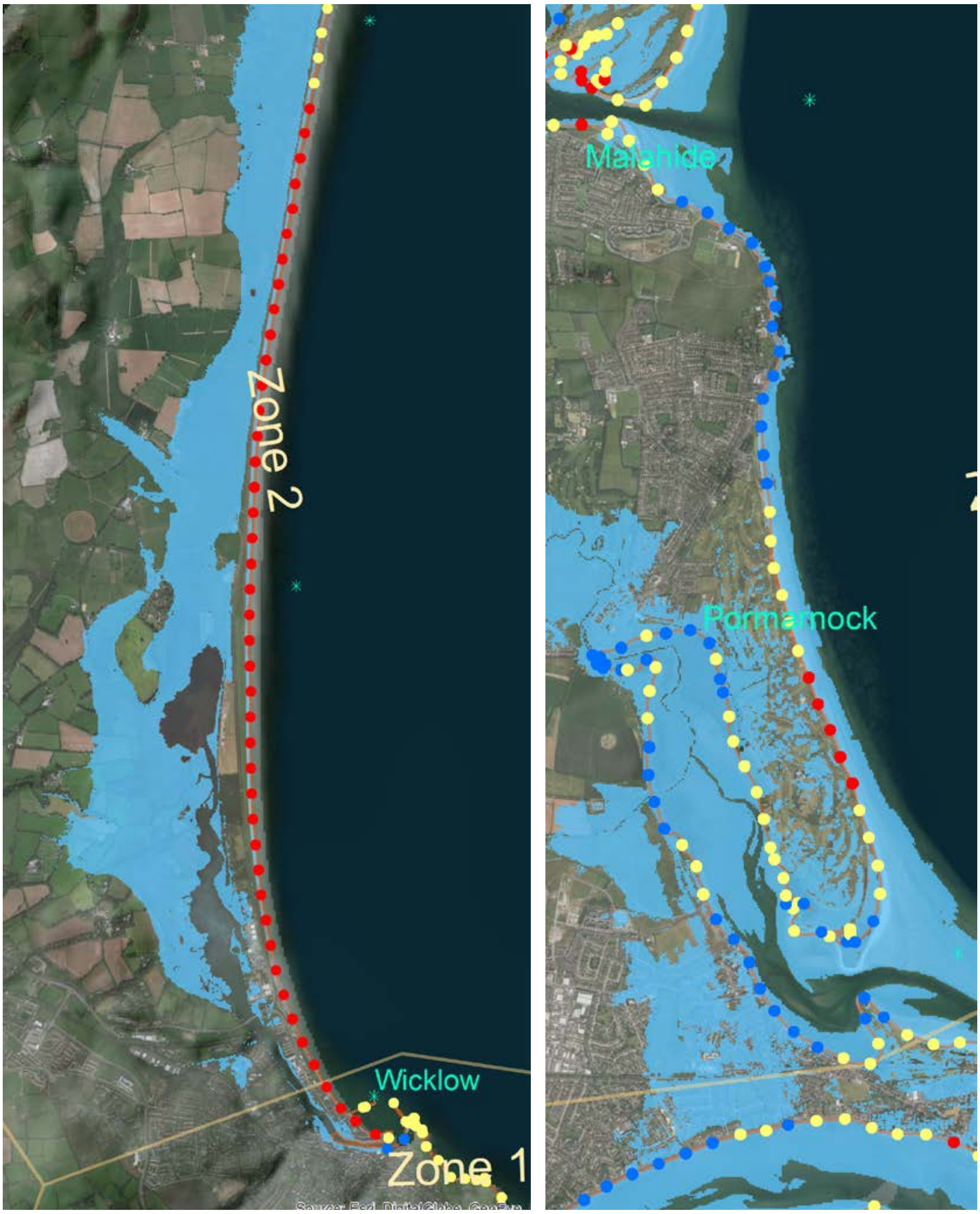


Figure 7. 8. Hotspots identified from CVI most vulnerable areas and potential flooding from 0.5% (AEP) extreme events, in Zone 2 (left) and Zone 4 (right).

Coastal areas in Zone 2, running from the Five Mile Point to Wicklow town and around Portmarnock-Sutton in Zone 4 (North Dublin), constitute vulnerable spots from both CVI and all future extreme flooding examined.

7.4. Chapter summary

In order to investigate the sensitivity of the system to impacts of enhanced sea levels, exposure to storms was evaluated by identifying vulnerable areas to potential flooding impacts based on local relative sea-level rise and return periods of probable extreme water events. Similarly, long-term shoreline probable changes associated with local sea-level projections were also determined using the SimCLIM coastal model.

Worst case flooding scenario is exemplified by a 0.5% exceedance probability events with maximum water levels of 5.76m OD Malin, particularly affecting soft, low-lying areas in North Dublin, near Wicklow and Arklow.

Regarding shoreline movement in low-gradient environment, uncertainty levels from two scenarios show retreats ranging from 124 to 169m by 2050 and 402 to 513m by 2100.

Hotspots were identified in North Dublin and Wicklow by overlapping CVI and potential areas of inundation from extreme events (1, 2 and 0.5 % AEP).

Chapter 8: Discussion

8.1. Introduction

The first indication of vulnerability came from the shoreline classification process, based on the examination of the variables, and the subsequent ranking assigned to each coastal point. In general, the areas found to be less vulnerable were those characterised by high relief, sheltered from the influence of the main oceanic processes and formed by rock outcrops or anthropogenic structures.

8.2. Summary of key findings of results

Thematic index-based maps were constructed to identify current vulnerable areas to impacts of sea-level rise using six and eight variables. Overall CVI shows that high values are predominant in the southern areas from Arklow to Greystones, with a few moderate and low occurrences around Wicklow Head. From Greystones to Dún Laoghaire, CVI values are low in general, with a few moderate values. From there northwards CVI values are low to moderate along Dublin Bay as far the Howth peninsula. North Dublin (Bull Island) has moderate CVI values, whereas low values are found in the Howth peninsula. Heading north from Howth peninsula, moderate CVIs alternate with low values.

Regarding the contribution of variables to the CVI, PCA analysis for CVI 6 using five variables (as relative sea-level rise was considered a constant) showed that all the variables have influence in the CVI calculation. However, PCA analysis for CVI 6 showed that PC5 only accounted for 6% of the total variability and that it is largely correlated (almost exclusively) to the shoreline change variable (Pearson’s coefficient r=0.993). Similarly, PCA analysis for CVI 8 incorporated 7 variables (relative sea-level rise is constant) and also showed that all the variables have influence in the CVI calculation. CVI 8 showed that the first six principal components largely account for most of the total variance. The first principal component showed major contributions from cliff type and geomorphology, while the second principal component emphasised wave and tidal range, acting in opposite direction. The third component identifies high tidal range coasts and low aspect coasts (or vice versa). Slope has high loading on principal component six which only contributes 5% to the total variability. Shoreline change does not have loadings greater than 0.72% in the first six principal components. Similarly, for CVI 6, PC 7 is largely correlated to shoreline change (r=0.992), and only accounts for a small contribution.

CVI maps indicate that highly vulnerable areas are mainly influenced by small tidal ranges (high ranking), high waves and relatively low coastal slopes and were located from Arklow to Wicklow (zone 1). Moderate vulnerability was found from Wicklow to Dalkey (zone 2) and in North Dublin (zone 4). Zone 2 showed high variability in slope, geomorphology and cliff type, coupled with lower variability in intermediate tidal range and aspect. Zone 4 was represented by very low variability in five of the ranked variables. Geomorphology has high and moderate vulnerability, while aspect has generally low vulnerability values and moderate variability. Low vulnerability was found around Dublin Bay (zone 3), characterised by low ranking in tidal range, cliff types and aspect variables. High vulnerability rankings, coming from high rankings on slope and waves also occurred, and can be found distributed in short segments along the coastline.

Additionally, volumetric analyses were performed to complement shoreline change analysis. The site in Corbawn, located in the southern sector, showed clear indications of erosion within the two intervals examined: The average volumetric loss rate (z) is approximately 0.37m/year from 2006 to 2017. The percentage of the area that has suffered erosion is 27.1% from the total, with a total volume eroded of approximately 18,400m^3.

Local relative sea-level projections for Dublin for 2040, 2060, 2080 and 2100 (when compared to a 1995 baseline) were produced for three RCPs and low, mid and high sensitivity scenarios for the 5th to 95th percentile confidence intervals. The most likely median sea-level projections vary from 127cm for (RCP 8.5), 94 (RCP 6.0) to 78cm (RCP 2.6) by 2100. The worst-case scenario estimates 198cm was given by the 95th percentile for high sensitivity RCP 8.5.

These projections were used for future sensitivity analysis. First, potential impacts were calculated combining local sea-level projections and return periods of tide-surge extreme events to construct inundation maps for 2040, 2060, 2080 and 2100. Extreme water levels reached maximum elevations of 5.76m (0.5% AEP) and 5.67m and 5.58m (1% and 2% AEP by 2100 OD Malin. Once coastal current and future susceptibility was evaluated, hotspots were targeted.

Second, future shoreline movement was investigated along unprotected sandy environments in the North of Dublin ender local future sea-level rise scenarios. Results indicate maximum retreats of 125m to 170m by 2050 and 402-514m by 2100, using the worst-case scenario.

8.3. CVI Methodological issues discussion

8.3.1. Vulnerability framework

Vulnerability concepts and selection of indicators were identified as crucial. Robustness and consistency of methods, accuracy of data, are essential for coastal vulnerability assessments. Only a few of the CVI methodologies reviewed described how to adapt other methods to their local study characteristics or how specific metrics would be developed. Even fewer utilized independent ranking methods or performed weights analysis on variables (Torres *et al.,* 2000; Li *et al.,* 2012). Assigning weight is a tedious and difficult process that is not included in many studies due to the lack of knowledge about indicators and/or theoretical vulnerability framework. However, this was widely achieved in this research as evidenced in Chapter 4, which examined the complexity involved.

Despite the fact that socioeconomic factors are very relevant for local studies, many studies do not include those (Torresan *et al.*, 2012). This is because multi-component studies are more complex and, therefore very infrequent compared to single-component, single-process studies due to lack of data or expertise (McLaughlin *et al.*, 2002, 2010). Secondly, there also is little consensus in literature on socio-economic variables compared with biophysical indicators. This is due to the lack of data, heterogeneity, and scales issues. It is also not clear which variables best represent the capacity of that community to cope with changes (Nguyen *et al.*, 2016).

At a national scale level, inclusion of the human component would have been more relevant. Comparing the CVI map produced in this study with a CEVI (coastal economic vulnerability index) map that included socioeconomic variables such as land use, location of main residential and commercial buildings and valuable infrastructure, might have been useful. This might have enabled a better prioritization of community activities and use of resources for implementing policies to direct new development away from the most vulnerable areas. The highest vulnerability rankings would have come from coastal segments that combined high physical vulnerability and a concentration of economically valuable infrastructure, mainly around Dublin. The lowest vulnerability rankings would have come as result of low population density and low urban development combined with lower physical vulnerability. In this research low populated areas are mainly concentrated in Co. Wicklow and north of Dublin, precisely where the CVI shows high values.

In this research, vulnerability strictly relies on local physical characteristics and socioeconomic factors were not aggregated to the final CVI. In this sense some might consider it as a merely susceptibility measurement (Bonetti *et al.*, 2012; Abuodha and Woodroffe, 2010b). However, the study area was intentionally selected over a small highly, urbanized and populated region of a great economic value namely Greater Dublin, later expanded to Arklow. Consequently, human factors were not initially included in the original framework design, but their value was always indirectly implied.

While omitted in many studies, the natural capacity of the system was accounted for in this research by the classification and ranking of geomorphological and shoreline type variables. Regarding geomorphological classification, where beach zones are formed by cohesive or sandy material this is a surrogate for natural adaptive capacity. For example, after a storm, sandy sediments displaced offshore return rapidly. Also, the natural ability of an ecosystem to migrate inland was explicitly included into the ranking. In shorelines, wherever accretion is taking place, it means the shoreline is somehow naturally adjusting to changes.

8.3.2. Uncertainties and limitations of using CVI

Vulnerability assessments will be accompanied by many uncertainties but will throw light on the operation of the complete coastal system. This will enable vulnerable areas to be identified.

The choice of methods used will also influence results. Heterogeneity of data, pre-processing and conversion processes introduces uncertainty during the indicators compilation process (Preston *et al.,* 2008). Uncertainties arising from methodologies will be also constrained by the scope of the project concerned, data availability and expertise levels.

One must be careful about over-interpreting the results. On the one hand, during the indicators selection phase, giving semi-quantitative or qualitative values helps to avoid questions of accuracy. However, this approach might inhibit policymakers from using it for adaptation purposes due to the absence of a more quantitative approach. On the other hand, relying upon quantitative scenarios can lead to misconceptions regarding uncertainties and accuracy as they can generate a false sense of security.

Simplicity of results was also one of the aims of this research. CVI thematic maps presented here are easier to interpret than multiple vulnerability layers as recently done in other vulnerability studies (BGS, 2017). Despite this, the coastal vulnerability methods applied here should not be considered only as a simplistic approach.

A range of skills are required on CVI assessments that involve a great deal of cross-sectoral resources or expertise only available to large projects. Many decisions, such as the choice of techniques, depended on the availability, technology and appropriate expertise. In many previous assessments, authors signalled time requirements and data availability as one of the main constraints (McLaughlin *et al.,* 2002; McLaughlin and Cooper, 2010; Ferreira et *al.,* 2017). This was not an impediment in this research, since most of the variables were specifically created for the purpose of this research.

Integrating results from different data sources, modelling activities and approaches, for very high resolution vulnerability has its risks. One of the weaknesses is that index creation involves a very long process in which subjective decisions and assumptions are made throughout relation to indicators compilation, classification and ranking. As it was shown in chapter 4, methods implementation and data assembly were complex, intricate and time consuming. Underlying assumptions, particularly during classification and ranking, and the accuracy of data, are some of the weaknesses. However, if the vulnerability concept is well defined, and methods and metrics are well constrained, as in this research, evaluation and interpretation is relatively straightforward.

Variables were derived using different measurement scales in this research. There was no need to standardise the values as a consistent ranking was applied.

Another limitation is that any CVI method yields results that cannot be directly compared with specific physical effects. Also, results are not directly comparable to other areas elsewhere. However, as McLaughlin and Cooper (2010) suggested, high resolution data can easily be adapted to a wider context, not the other way around. This point is discussed below in section 8.3.3.

8.3.3. Spatial and temporal issues

Regional coastal vulnerability index assessments do not provide absolute predictions about impacts of sea-level rise; that is they do not tell us when changes will happen, they do highlight the areas more prone to experience those changes. Thus, the CVI is quite a static restricted to the period over which data availability exists. However, it still constitutes a robust method for prioritizing decisions and provides a basis for predicting future shoreline changes.

Validity can be an issue as variables change temporally and spatially. In this regard, CVI assesses current conditions and therefore would more than likely underestimate future vulnerability to RSLR If future predictions were included in the CVI, then the validity of the vulnerability map would be extended in time (as done in the sensitivity assessment to potential future flooding in chapter 7).

Sometimes, some variables do not contribute to CVI spatial variability at that scale. In this case, different future projections of sea-level rise were not included at sub scale resolution as this variable was considered constant given the size of the study area.

For a larger study area, RSLR would have more variability, providing a higher contribution to the index.

In relation to what controls erosion at a local level, some variables can also become obsolete. Some metrics might not be relevant at one scale but valuable at another. For example, McLaughlin and Cooper (2010) considered coastal orientation and tidal range very relevant at national scales, while they were discarded at local level. One of the peculiarities for spatially expanding the study area southwards was to gain variability in tidal range.

The most important variables in determining the spatial variability of the CVI for this area are geomorphology and cliff type. In other studies, landform class is not available and therefore, was not used. On this research it was not available either, but it was created for that purpose.

If a smaller scale and/or a wider area are considered, classification, ranges and rankings of some variables would need to be adapted. In this case most of the variables were compiled specifically for this study and results are not transferable to other areas without modification.

8.3.4. Compilation of variables

Compilation, classification and ranking of coastal indicators proved to be a challenging process for all the variables involved. It is a time consuming and laborious process to gather, classify and assemble all data from diverse sources. Quality control on the compilation and post-classification of the variables was essential in deriving the accuracy of the final coastal vulnerability index-based maps.

Long-term shoreline change analysis

Shoreline change analysis is a tricky process that has to be examined within a particular context. Defining shoreline position and, moreover, interpreting shoreline changes was challenging. To determine the vegetation line is not always straightforward due to local patterns, re-vegetation and barrier movement after storms, or when substantial rework from accretion of erosion in fore dunes take place.

Shoreline changes calculated in this research match closely when compared against latest OPW (2010) annual rate calculations in some areas. In others the results from this study are generally larger than the OPW projections.

Shoreline change values range from +5.8m to -3.8m/yr. Very low vulnerability areas coincide with highly accreting sandy environments, while very high vulnerability areas are typical of eroding, low-lying sandy environments or soft unconsolidated zones. Moderate values (-0.2-0.2m/yr) are scattered throughout the area but they predominate around coastal defences in Dublin and stable or hard-rock areas. Low and high vulnerability zones are observed throughout the area. Low vulnerability zones generally correspond to accreting areas situated at the edges of sand dune environments.

The effect of coastal defences was considered after vegetation lines were checked against recent satellite imagery. Future coastal defences planned in the area were not considered and so the worst-case scenario was assumed for these areas. There is generally little threat from erosion in the larger urbanised areas.

Unconsolidated till cliffs in South Dublin gave erosion rates of 0.65m/yr between Shanganagh and Bray and 2.41 m/yr near Greystones. These results are slightly higher than those of 0.50 or 1.22 m/yr rates calculated by OPW and Robinson (2009). This is explicable in terms of the higher resolution and data quality used in this research. Erosion rates on this research show maximum erosion ~3m/yr around south Wicklow-Arklow in agreement with former studies (Carter and Bartlett, 1990) ECOPRO (1996) whereas OPW data shows max around 1.3m /yr.

Soft, unconsolidated cliff's rapid response to environmental changes makes them perfect systems to assess short-term and/or long-term changes. In this sense, volumetric change calculations represent an alternative for measuring spatio/temporal cliff changes. This is especially so in hotspots, providing that LiDAR series are available. In this research a LIDAR dataset was available for 2017 in Corbawn at a vertical accuracy of 0.01m (South Dublin). This made possible a comparison between 2006-2017 to assess not only the percentage of area changed but also the volume eroded and the average volumetric loss rate.

The comparison in the Corbawn area between the shoreline change (calculated using DSAS tool) and the average volumetric rate is complex but interrelated. DSAS measures direct shoreline movements from the coastline on the horizontal scale, while the volumetric change rate is estimated from the difference in height (z). It is also worth noticing that final volumetric estimates can be sensitive to actions other than erosion such as redistribution of material to adjacent areas and/or human intervention. Also, the time-span between the two is slightly different. Nevertheless, the results complement each other pointing both at erosion patterns in similar magnitudes of scale. Shoreline change was extracted from End Point averages -0.15m /year on the horizontal scale, while the vertical rate in the volumetric analysis yields to 0.37m/year.

Using only a single period of 10 years it was not sufficient to specify to what degree detected changes responded to long-term SLR or decadal variability. Although results are more accurate comparing LidAR time series, some authors avoided this problem by determining volumes by multiplying cliff heights by the retreat for each DSAS transect, assuming that there is no erosion gradient between the edge and the base (Brook and Spencer, 2014).

Wave data

Newly available significant wave height data from 2000-2012 was used in this research. Wave height was found to be higher in Dublin Bay, probably related to increases in wave height occurring when entering into shallow waters in the confined area of the Bay.

Tidal range

Unlike other coastal vulnerability index-based studies (McLaughlin and Cooper, 2010), tidal ranges showed significant variability, increasing south to north, despite the size of the study area. This influenced considerably the spatial variability of the vulnerability and was one of the factors justifying the extension of the study area from Greystones to Arklow.

Aspect

This variable has not been used in many studies and this research demonstrated its contribution to CVI as being quite relevant. Soft-rock coasts and associated beaches are generally drift-aligned along the main transport direction and this variable was ranked to reflect this.

Relative-sea level rise

A recent GIA model (Bradley *et al*., 2008) of relative sea-level changes for the British Isles for the last 21 kyr for several sites along the Dublin coast was considered initially. Ideally using these data, a contoured map of relative sea-level changes from the study area could have been generated. However, the intention was that the various sets of data would be temporally comparable, and this involves "long-term" sea-level data appropriate for a ~century-scale CVI. Consequently, this data was discarded given the low resolution of the data for trend calculations.

Trend analysis in MSL requires at least 30 years of data to avoid cyclical trends. Initially, estimates of local changes in sea-level at several locations were intended. However, due to the lack of long-term tide gauge datasets within the study area, relative changes were only calculated for Dublin, as long-term (century-scale) monthly data was required. Therefore, Dublin long-term monthly mean values from 1938 to 2012 were used to calculate the specific RSLR trends for the study area.

In addition, it is very unlikely that within the study area, there is any statistically significant spatial variability in century-scale sea-level rates. An exception would be if there is a strong gradient in GIA or other land movement (e.g., due to groundwater extraction causing regional subsidence), which is not the case. As a consequence, a trend of 1.96mm/yr in the relative sea-level rate variable was a constant variable in the area. This should not affect the overall vulnerability calculations as the relatively strong variation in coastal geomorphology, cliffs etc., will be a sufficiently important source of CVI variability. For future studies, other areas should not be assumed to have same subsidence, providing a long-term tide gauge MSL data for local projections is available.

Also, the relative sea-level rise trend of 1.6 mm/yr was classified as low vulnerability (as in Pendleton *et al.*, 2010), which is perhaps a rather conservative value, looking at the accelerating rate of global sea-level changes since the 1990s. This would not have an impact on CVI outcomes as this value was left as a constant. Nevertheless, if having a RSLR gradient over a wider area, it would spatially influence the CVI.

*8.3.5. PCA multivariate analysis***.**

There is a deficiency in literature on the application and analysis of importance of variables. This is extremely important to elucidate which coastal physical indicators most contribute to CVI and why.

The PCA analysis was instrumental in identifying the contribution of variables to the vulnerability at every point in the study area. Some authors claimed that measuring the relative importance of indicators through weighting methods could introduce biased results (Abuodha and Woodroffe, 2010b, Wamsley *et al.,* 2015). However, in this study it was considered that subjectivity plays a role in the overall process. That is why expert judgement and robust methods are required. Weights were not applied in this research but alternatively a statistical PCA was used to identify relevant variables.

Based on the PCA results for the two CVI datasets, shoreline change is not significant, particularly in CVI8. These results agree with those of Pendleton *et al.,* (2010) and Abuodha and Woodroffe (2010b). Their suggestion was that shoreline change could be removed from the CVI calculation. Assuming that shoreline change does not have a strong influence on the CVI, variable dimensionality could have been reduced to seven with only a minimum loss of information.

However, shoreline's contribution to CVI 6 is as low as slope in CVI 8. The slope in CVI 6 shows a higher contribution than that in CVI 8. Therefore, not only the number but also the combination of variables seems to have an effect on CVI. Variables such as geomorphology and cliff type are already largely ranked based on erodibility and show significant weights on CVI. Therefore, the fact that shoreline does not show relevance on CVI does not mean erosion processes are not relevant for future sea-level rises. Shoreline changes relevance could be perhaps explained by their variability within the study area. However, the effects of the rest of the variables upon future shoreline changes remain to be analysed.

PCA results highlight the large influence of the coastal physical indicators in the CVI variability along the coast. PC1 is largely the sum of Geomorphology, Cliff and to a lesser extent Slope. These results suggest that the calculations and the rankings allocation of these variables can have a significant impact on the CVI. This is particularly relevant to Slope, as this variable is scale dependant.

CVI ranges are a relative measure. They also are dependent on the number of variables employed. A derived index, such as the CVI, is generally used to further stretch the differences amongst the ranked values. Furthermore, the median values of the ranked variables provide a measure closer to the original individual variable rankings. Based on this, it can be concluded that zones 1 and 4 show more vulnerability, followed by zones 2 and 3, an area clearly urbanised. In general, PC8 shows that the more relevant variables are cliff type, tidal range, aspect and wave height, followed by geomorphology and slope. Two extra variables added in this research included in CVI 8 (cliff and aspect) carry significant influence in the coastal vulnerability index. Cliff is an onshore variable, while aspect incorporates an oceanographic component.

The statistical analysis, as a result of comparing CVI 8 and CVI 6 suggests that the two extra variables calculated (cliff and aspect) carry significant influence in the coastal vulnerability index. PCA throws light on how to reduce dimensionality of the overall CVI mapping only to seven most relevant variables (geomorphology, cliff type, tidal, range, wave height, aspect, and slope). This would be useful if methodology is to be replicated at the same scale, in other areas.

8.3.6. Validation of CVI results

Shoreline change could be considered to be a good indicator of current coastal susceptibility. CVI was compared to recent shoreline changes. The validity of the CVI was tested against observed recent shoreline changes within the 2015-2017 time frame in natural, soft, unconsolidated areas, mainly dune systems in Co. Wicklow. The chosen period constitutes an independent and relatively storm free period, not included in previous CVI 8 calculation for this area.

When an area is under the influence of storms, complex erosion and accretion, strong spatial and temporal variations impeding dominant trends might be obscured. In these cases the validation of the CVI cannot only rely on this variable, but also depends on the relative ranking of all variables.

8.3.7. CVI approach for CZM

A coastal vulnerability index is useful in prioritising decisions. Despite the fact that CVI reflects current conditions it identifies areas most likely to be affected by future sea-level rise. However it might underestimate future vulnerability to sea-level rises.

The coastal vulnerability index presented here is quite robust. The resulting vulnerability databases for the study area are large, medium scale, and high resolution. This also provides a comprehensive selection of indices that can be used at national scale, and serve as guidance to other national agencies worldwide. While the outcome from the USGS was carried out at km-scale spacing, on this study was conducted at a resolution of 200m. Consequently, the outcome might be more suitable for county/regional planning. The addition of new variables (cliff type and aspect) not included in other large index-based methodologies at national scale, or tidal range, also provided more reliable CVI results.

In general, global scale methods cannot be applied directly to local areas. Consequently local methods were adapted for this research. A greater level of detail was required at high spatial resolution to distinguish between areas of vulnerability. Expanding CVI to larger areas would also add information on some variables, gaining perspective. However, metrics are scale dependent, so some variables might not be significant at one scale but become valuable at another.

Generally, results cannot be easily compared across scales directly or sometimes from different variables from components at the same scale. It can be difficult to compare this study to other vulnerability studies where similar CVI methods have not been employed. However easy comparison can be made to wider areas (even abroad) providing similar CVI metrics was used. Strong metrics applied for this research makes it suitable for comparison with other studies.

Expansion to a generalised, national-scale approach could be useful for assessment that involves better distribution EU funds, to prioritise resources in vulnerable areas. However if possible it would be better start operating at a high resolution scale, and then extend to lower resolutions by generalising data.

ICZM provides a useful tool in regional strategic planning. Coastal zone management policies should address vulnerability assessments of SLR impacts at national and local level. This should be related to European ICZM initiatives.

Some steps have been taken at the local/regional scales to implement some practical ICZM strategies in Ireland and Europe (Hammerfest, 2010a; Muir *et al.*, 2014). Knowing where the areas of greater vulnerability are before introducing local measures is crucial.

8.4. Sea-level projections and uncertainties

Past secular sea-level trends for Dublin Bay were used to generate future projections in Chapter 5 and also for assessing future flooding and estimated shoreline movement in Chapter 7.

This approach incorporating sea-level projections in this work offers a more innovative and comprehensive strategy by taking into account a range of local, regional and global factors affecting coastal vulnerability at a local scale.

The SimCLIM model enabled site-specific estimations of sea-level rise for the Dublin area and a quantification of uncertainty. New regionally to locally-varying, time-dependent high resolution scenarios of future relative sea-level rise were generated for this area for likely and high-end scenarios.

SimCLIM enabled the local subsidence component to be extracted from the total trend calculated in chapter 5 and takes this into account. Local sea-level rise projections from previous SimCLIM versions were based on AR4 data, without considering entire climate-cycle feedbacks and effects from ice sheet flow that could not be included with confidence. SimCLIM projections are based on more recent knowledge, that incorporates more processes and feedbacks included in AR5, and are usually of a higher spatial resolution than earlier models.

Despite these uncertainties, high-end estimates of 197.7 cm by 2100 in this research, from the improbable but yet possible, worst-case scenario is higher than previous projections for Ireland ~1.1m for Ireland (Arcilla *et al.*, 2016). However they are in agreement with other European high-end estimates for the RCP 8.5 scenarios of 184cm (median)/292cm (95% quantiles) (Le Bars *et al.*, 2017); 270cm from the H++ scenario in UK (Ranger *et al.*, 2013); 250cm for the (80%-95% quantiles) (Kopp *et al.*, 2014, Sweet *et al.*, 2017); 180cm by Jevrejeva *et al.* (2014); 190cm (Lowe *et al.*, 2009); 2m (NOAA, 2012).

If a wider area is considered high-resolution gridded outputs could provide a gradient of projections of sea-level along the coast. This will be valuable, providing long-term tide-gauge data is available and RSLR is spatially-variable at the scale of the research.

Currently the latest version of SimCLIM (2013) employed in this research uses a database based on the latest IPCC/AR5 assessment data which provides the low, mid and high estimates of global-mean sea-level trend of 1.0, 1.5 and 2.0 mm/yr respectively. However, those trends might be still conservative considering the latest rate of sea-level rise of 3.4mm/ year from 1993 to the present.

Low emission sensitivity scenarios were disregarded on this research as according to latest research the 2^{o}C global temperature limit will be exceeded by 2040 (Hawkins, 2016).

Regarding model predictions, even though there is high confidence in model robustness, there is some behaviour that, given the nature of the physical systems, are unpredictable.

When modelling local projections, assumptions were made regarding the continuity of these current local trends in future years. Since trends will probably follow a nonlinear path, they are unlikely to remain as has been observed in recent years. Future sea levels will depend on local factors such as groundwater depletion; regional trends will be influenced by ice sheet melt in Greenland or Antarctica. Uncertainties will also exist regarding future emissions, policy responses, climate sensitivity to radiative forcing, feedbacks, climate variability, etc.

One of the limitations when using SimCLIM v3.6 (2013) physical-process model is that uncertainty in projections using different RCPs does not account for the entire range of possibilities. Downscaling approaches from AR5 GCMs to the local also introduces errors resulting from the local responses of climate variables that together with land movements introduce uncertainties, particularly when analysing impacts.

In general, projections will also be sensitive to the choice of GCM. Nevertheless, an ensemble-based approach is preferable when generating local relative sea-level change scenarios. However, there is no such a thing as a single best sea-level scenario, but rather a range of uncertainties. In addition, the fact that a model simulates current climate more accurately does not mean that it will perform the same for future projections.

Also, trends for different RCPS's tend to diverge from the 2050's creating larger uncertainties, especially on impacts. However, this should not be used as an excuse for inaction.

In the long term, sedimentary coasts will adjust to sea-level rise by retreating. Rising sea levels will be accompanied by other coastal processes, apart from submergence, such as wetland loss and change, erosion, and direct and indirect human impacts. The complexity of local factors involved has been already discussed in chapter 2. These local factors make it difficult to extrapolate climate change-related shoreline changes.

Despite the relevance assigned to SLR projections for coastal vulnerability assessments, they constitute only one of a number of contributory factors to assessing coastal vulnerability. SLR contributes to feedbacks associated to coastal processes (eg: sediment flux and sedimentary infilling of coastal-accommodation), which are responses connected to human interactions, and therefore will affect the effectiveness of SLR in driving coastal retreat. Sometimes human activity overcomes natural processes. In general, is difficult to quantify contributors to SLRs, and feedbacks involved needed for validation of model output.

Future rates of sea-level change as the main factor of coastal change, should not diminish the importance of other significant forcing factors such as of variability in storminess. Some authors (Nicholls, 2015) recommend that adaptation should be analysed in a context that includes complex interaction between driver and feedbacks. This interaction might aggravate impacts, in response to future sea-level rise and associated storminess. Despite this, this interaction has been addressed in the present study. However, the feedback contribution remains difficult to evaluate.

8.5. Future vulnerability assessment

For coastal impact and vulnerability assessments, low probability, high impact, events are most significant. Consequently, worst case scenarios of sea-level change were used to analyse potential impacts from extreme inundation and shoreline change. This scenario is the most appropriated for assessing impacts and adaptation (Nicholls *et al*., 2013; Hinkel *et al.*, 2015).

Damage from flooding and extreme weather using estimates of future sea-level rise and increase on storm surges have been used in some Europen countries to address local impact and adaptation strategies and tools in coastal communities (Oor et al., 2012).

Given the random nature of extreme tide-surge events, their future behaviour can only be characterised in terms of a probability of occurrence. Several potential flood depths for different annual exceedance probabilities (AEP) were investigated (0.5, 1 and 2%). The 0.5 and 1 % events are more extreme but less probable than 2%. However, those events could become more frequent, with only a small additional sea-level rise, and therefore the next 50 years is a relevant time frame. That is why flooding by 2% AEP was also explored in this research. Sensitive areas to future flooding such as those near the Wicklow, Sutton and Bull Island in Dublin Bay can be considered as hotspots when compared with CVI vulnerability areas.

The state of the coastal defences that might be affected by any increase in the frequency of extreme events, and the evaluation of potential defence failures was not considered. This information was not available and, in any case, is an engineering issue. However, the height of the defences was implicit in the digital elevation model used. Scenarios of inundation were constructed disregarding the interaction between water and topography/sediment type. Potential flooding areas were generated simply by rising extreme water levels over digital elevation models. Also, the mean sea-level rise can affect the distribution of the surge at specific locations. For this research a fixed value of relative sea-level rise was considered for the entire area.

Potential flooding extents for the same events considered in this research have been previously validated for this area (OPW, 2010) not including future sea level rise scenarios. OPW models not yet been adjusted for isostatic rebound either.

Extreme water levels were used in this study, but sea level projections were also incorporated in this study. Regarding future scenarios of inundation rising the sea by certain amount does not mean all the areas below certain elevation will be inundated. The reason is the intricate physical processes that intervene on RSLR impacts (storm impacts, barrier island migration, wetland accretion, shoreline erosion). In this regard, field mapping of inundation areas after future major surges will provide useful information for comparison with those areas identified in this research.

As it was mentioned above there is uncertainty on the effects of climate change on future storms behaviour and probability of occurrence of extreme events. Future changes in wind direction and strength, will also affect the magnitude of the storm-surges, and modify return periods in the area. Extreme water levels were based on tide-surge modelling from the Irish Coastal Protection Strategy Study (ICPSS) by OPW (2010). More updated information in future storminess would have been desirable.

Change in storm climatology in this area (eg: more frequent and intense Easterly circulations) will impact on vulnerability. However, any increase in dry spells in between storms will facilitate aeolian sediment transport and will help the coast to readjust. In this sense monitoring shoreline changes in between and after storms over annual and decadal periods, would certainly add knowledge to understanding shoreline response to storminess, natural decadal variability and coast recovery time.

Similarly, future shoreline projections are driven by complex interactions and processes subject to climate uncertainties. Present shoreline patterns are better explained in terms of sea-level history. As coasts take time to respond (centuries to millennia) these changes have nothing to do with recent SLR trends, and therefore estimates might be conservative.

Despite uncertainties, the SimCLIM simulation tool recreates shoreline responses to sea-level rise. Regarding future research on this field, one step forward would be introducing probabilistic methods involving the application of Bayesian network (BN) techniques, from physical parameters previously compiled for CVI, to assess the long-term erosion patterns as a response to future sea-level scenarios. Unfortunate these resources were not available for this research.

8.6. Identification of hotspots

This research attempted to identify coastal areas that are potentially more vulnerable to more frequent tidal flooding from higher storm surges and rising relative sea level, and erosion, that received high CVI values. High resolution indexed-based vulnerability maps identified the main vulnerable areas through an analysis of interactions between driving forcing factors, geological boundary conditions and coastal processes' response. The combination of high-risk environment identified by means of the CVI (High), and detailed assessment of future impacts of sea-level rise (from extreme water levels from 0.5, 1 and 2% AEP events, resulted in the identification of hotspots.

The most vulnerable areas (CVI 8) were located in the southern part of the study area (zone 1) primarily due to a combination of factors such as relatively low coastal slopes (flooding hotspots), strong waves and low tidal regime. See Figure 6.14, Figure 7.1. Figure 7.2 and Figure 7.3.

Moderate vulnerability was found in zone 2. This arises from high variability in the onshore coastal physical variables and low variability in tidal influence and aspect influence. From boxplots (Figure 6.18), aspect is higher in zone 2 compared to zone 1, and this elevates the CVI in this zone. This highly vulnerable area within zone 2, running from the Five Mile Point to Wicklow town, shows low tidal ranges (high ranking), low slopes and semi-exposed, to highly exposed, aspect. Also this area shows medium to high erosion rates and high potential flooding from all the AEP events, particularly for the 0.5% (AEP) event. Therefore, the area should definitely be identified as a hotspot (See Figure 7.3).

Low vulnerability was found in zone 3 around Dublin Bay, characterised by high tidal range and low (to moderate) rankings in cliff types (mostly anthropogenic) and aspect variables. High rankings occasionally came from low slopes and high waves.

Zone 4 shows moderate variability arising from high ranks in geomorphology, intermediate and low from aspect, and very low variability from the rest of the variables. In relation to this, the area around Pormarnock and Sutton-Howth over the tombolo constitutes an extremely vulnerable spot from both CVI and future flooding. Even though it shows moderate ranking, geomorphology has a large load given by marine deposits (beach sands). Aspect will also be important to consider, particularly for northerly storms. Also, slope is very relevant, although would not have a heavy weight in the CVI for this area. The area around Howth tombolo is almost at sea-level and then, very prone to inundation and storms, and consequently a hotspot.

8.7. Stakeholder involvement

A dialogue between science and stakeholders is important part of the results. This is to clarify the purpose of the study, the scale of investigation, which scenarios will be most helpful to them. In this sense other expert opinions and stakeholder involvement was very relevant, and yet most of the studies in the literature omit it (Schauser *et al.,* 2010; Masselink and Russell, 2013). This indicates that either those studies are purely scientifically orientated or the dialogue has never been established.

Stakeholders should be informed by the best and most updated science. In this research, this part was successfully accomplished; purpose and expected outcomes were beforehand discussed with management at the Geological Survey of Ireland (GSI) and Office of Public Works (OPW). Consequently, feedback on results should be communicated, as it is ultimately stakeholders (and policy makers) that would allocate resources and coordinate investment, where is most needed.

Similarly, as done in the United States (USGS), one of the largest Irish mapping agencies, the Geological Survey of Ireland (GSI) will develop national vulnerability maps based on the high-resolution indexed-based assessments presented in this research. GSI projects will accommodate funding to future monitoring, data gathering and resourced towards a national mapping approach.

8.8. Adaptation

Autonomous adaptation processes (as opposed to planned) are generally not successful. Therefore, an approach is needed requiring a deep knowledge of the system, the drivers and the processes involved. Knowledge is also needed regarding future SLR projections and potential impacts. These are widely covered in this research. Adaptation should not only focus on socio-economic and human factors but also on natural ecosystems.

Although much will be learned in practice, local information is very much in need for adaptation studies (Wong *et al.*, 2014; Nicholls, 2015). Understanding the coastal system and processes is very important for adaptation, and this can be done from CVI analysis. Much emphasis has been given on literature to adaptation. However, this cannot be done unless vulnerable areas are identified.

It is also better developing a long term strategy based on potential impacts. Currently this is not usually the approach employed. Vulnerability and potential impacts maps produced in this research would be highly beneficial for exploring multiple-scenarios that facilitate a range of options for adaptation. As demonstrated in this research it is sensible to plan for the most likely scenarios, but also to be aware of some potential events that are uncertain and could have unpredictable consequences. In this sense it is advisable that highly sensitive places should deal with high magnitude low probability events that could have major impacts on coasts**.**

From the results of this work, adaptation recommendations would focus on measures that mainly ensure safety in the short-term (2020-2060). However, it is recommended that the management strategy should be flexible and based on monitoring of the most vulnerable areas. Considering long-term options is advisable, providing new information is updated through an adequate conceptual scheme for decision-making under new scenarios.

Current approaches based on hold-the-line, are questionable and not feasible in the long-term. Many recent studies have advocated a managed realignment policy, mainly for the long term (20–50 and 50–100 years). This also involves long-term management options which consider wider area processes and monitoring (Nicholls *et al.*, 2011; 2013; Park *et al.*, 2012).

Based on deeper understanding of vulnerable areas gained from this work, a range of innovative approaches can be envisaged. Rather than employing one single approach, it would make more sense to use customised options for different locations. These would include a mixture of planned retreat measures (e.g. recreational areas) or soft/hard barriers (beach nourishment/berm/dune construction) to enhance resilience towards storms.

Hard-engineered, high cost defences will be needed to protect major infrastructures, and protect, monitor and regulate natural systems (Brooks et *al.*, 2016).

As it was clear in this study, impacts from extreme flooding are particularly relevant in urban areas and big cities. As it can be appreciated from Figures 7.1, 7.2 and 7.3, extreme flooding Dublin areas, could affect port operability and possibly cause serious management problems, particularly, under unlikely scenarios. Therefore, upper tails, low probability SLR scenarios examined in this research are particularly relevant for the long-term port management and planning. For instance, higher depths of inundation for projections for 2080–2100 from the 200-year return period (AEP 0.5) of 5.1-5.76m OD Malin should be taken into account for coastal infrastructure design in sensitive areas. Similarly, planning for accommodating probable coastal retreat of 402m to 514m by 2100 in low-gradient areas in North Dublin would also be desirable.

Highly populated built up areas will continue to expand in the Greater Dublin Region; so these areas will need protection. Architecturally, Dublin is a low-rise city. Adaptation should aim to encourage high density developments rather than spread low rise housing behind areas at risks which minimise the possibilities for planned retreat.

In order to deal with future flooding uncertainties, different adaptation measures have been proposed for the long-term under 1-5m flooding scenarios in London (Ranger *et al*., 2013). This work could be considered as a follow up work using results outlined in Chapter 5 and 7, instead of using random thresholds.

Artificial coastal protection must be approached within a specific context as it interferes with natural adaptive capacity, affecting longshore transport, and disrupting erosion patterns rather than stopping them. Implementing policies to deal with coastal defences based on results from this research should be done with caution. Hard measures in one area might be successful in stopping or at least slowing down the erosion locally but it could also increase erosion in areas downstream. Also, sea-level rise can result in progradation in neighbouring areas protecting it from flooding from erosion. As coastal defences impede the natural retreat of estuaries with sea-level rise, estuarine areas of the northern part of the area, managed realignment to allow salt marsh and intertidal mudflats to develop landward might work better.

Future coastal erosion could lead not only to loss of land, but detection of natural or artificial defences that will worsen coastal flooding. Increases in the return frequency of extreme events could make defences fail earlier, disrupting current erosion patterns.

In this research, the location of the coastal defences for shoreline calculations was considered, although the state, quality or durability of them in the long term, was not. Knowledge of the coastal defences at risk would be interesting where defences need updating. Further development in vulnerable areas need to be avoided.

8.9. Summary

The information from this study can be used for Integrated Coastal Zone Management (ICZM) to develop long-term strategic adaptation plans in order to increase capacity to future SLR as it been advised. Coastal managers could this information to allocate available resources on different areas: ecosystem reestablishment, beach nourishment, and infrastructure protection, identifying long-term planning to enhance resiliency in vulnerable areas. Most importantly, the study provides a CVI map-based approach at high resolution which is lacking in many comparable works. This has been demonstrated as being robust enough to identify areas of high vulnerability based on several characteristics of the coastal environment in eastern Ireland.

In order to address issues related to adaptation, there is a risk that stakeholders and policy makers might over or under rely on CVI information. Uncertainties about future climate and associated vulnerability are large. Unknown thresholds, unpredictable interactions and non-linear or abrupt changes of the system will aggravate impacts. However, this cascade of uncertainty cannot be an impediment for investing and tackling adaptation. To target adaptation, multi-scenarios need to be assessed and priority levels identified so that measures can be implemented.

Some of the advantages of applying an index-based approach versus non-index methodologies are: clarity of results; flexibility in the index selection and weighting; and the ability to include non-physical factors. Some of the disadvantages are the high degree of expertise and resources required to produce and assemble large amounts of high resolution data.

New coastal protection management strategies aiming to prepare for current and future impacts must be oriented to protect the most vulnerable areas from impacts of future extreme water levels. The National Climate Change Adaptation Framework (NCCAF) (DECLG, 2012) provides direction for local administrations for adaptation and to reduce vulnerability. And yet there is not national plan or policies in Ireland for adapting coastal management to impacts and effects of climate change regarding its physical coastal vulnerability. This is perhaps because the information is not there yet in the first place. That is precisely what this research assessment intends, by investigating resilience to future challenges, while being compliant to key national development priorities.

Decision makers in Ireland should base regulations on new, high-quality local assessments that explore current and future climate change impacts instead of relying on out-of-date information. Therefore the national ICZM strategy should include local to regional coastal vulnerability maps and impact assessments, and accommodate up to date information.

Chapter 9: Conclusions

9.1. Concluding remarks

The main purpose of this research was to identify and quantify the susceptibility of the area to the adverse effects of sea-level rise. Novel methods were adapted to the local context to explore the relationships between drivers, (e.g: sea level rise), geological boundary conditions and the coast's responses. Hence the study offers a profound understanding of the coastal evolution in this area.

The study characterised the coastline in terms of vulnerability. To achieve this it employed a robust methodology, adapted to the Irish context, but capable of being extended to a national scale. Finally it identified compiled and analysed the most relevant coastal indicators for the study area concerned and explored their inter-relationships in coastal hotspots.

Using an indexed-based vulnerability approach to identify vulnerable areas to future sea-level rise provided several beneficial outcomes.

1. The approach provides an easy visual representation of sensitive areas, enabling coastal managers to prioritize or concentrate efforts on adaptation. The main areas of vulnerability were identified by both CVI and analysis using individual variables.

2. PCA analysis implied that dimensionality could be easily reduced. This would reduce the amount of time for indicators compilation, accounting for 90% of the overall workload. At this scale, analysis shows CVI mapping can be successfully performed using only the following variables: cliff type, geomorphology, tidal range, aspect, wave height and coastal slope. Even though in this research shoreline change does not have significant weight in the CVI, it constitutes a unique, high-resolution dataset for Ireland, which is extremely useful for impact risk assessments and as a tool for validation.

3. Innovative international approaches were capable of being applied to the study area with a few modifications. Compiling and adding aspect and cliff type, as separate from geomorphology, clarified the relations between geological variables in the CVI. Both have significant influence on CVI, and therefore their incorporation was fully justified.

4. The CVI presented here can be adapted to other scales. The high resolution and strong metrics employed within a robust conceptual framework provides considerable utility for long term decision making. The successful implementation was dependent on the level of expertise available for data compilation and quality control and this would be an essential requirement for the use of the technique at other scales.

5. Although this vulnerability assessment is unique to the study area, the approach taken in terms of indicator selection and weighting is easily adapted to a high resolution study at a smaller scale. It also possesses the capacity to include additional non-physical factors.

Quantifying uncertainty by analysing sea-level scenarios and return periods of surge events in vulnerable areas provided useful information on potential flooding impacts. A likely sea level scenario for the area for 2100 ranges between 78 and 127cm. High-end estimates represented the. The worst-case scenario of 198cm by the end of the century is plausible, although considered unlikely at present. These estimates are still subject to a degree of uncertainty, meaning that local estimates might still be conservative, could dramatically impact sensitive areas. The results of this research would highly benefit vulnerability assessments, since they highlight areas (hotspots) most prone to physical changes, and which might require careful monitoring.

Recognising that some future climate changes are unavoidable, adaptation is now inevitable and must start immediately. Accordingly, a national ICZM strategy should include adaption strategies available to local government based on local to regional coastal vulnerable assessments, such as those presented in this research. The outcomes of this work should enable stakeholders and policy makers to identify key climatic threats and impacts of concern. It will enable them to explore targeted flexible multiple-scenarios adaptation options for short and long-term scenarios to minimise future risks to ecosystems and the main coastal infrastructures. Avoiding developing assets in vulnerable locations is advisable. Planned retreat measures (managed realignment) or soft/hard barriers (beach nourishment/berm/dune construction) could be used to enhance resilience in natural areas (eg: North Dublin dunes); Hard-engineered reinforcement in highly populated built up areas under the long-term flood scenarios should be considered.

Estimating current vulnerability to sea-level rise and quantifying sea-level rise impacts would be not possible without a profound knowledge of the physical characteristics and responses from a multi-stressor environment. Identifying and defining the contribution of different components and indicators of change to spatial patterns of vulnerability is basic if we are to reduce future the vulnerability of this particular area.

9.2. Recommendations on future research

- Monitoring short and long-term responses in soft cliffs (shoreline and volumetric changes) and in other vulnerable areas.

- Regarding future research, one strategy worth considering would be introducing probabilistic methods involving the application of Bayesian network (BN) techniques, from physical parameters previously compiled for CVI, to assess the long-term erosion patterns as a response to future sea-level scenarios.

- These CVI approaches, if extended to wider areas, would also benefit from incorporating socio-economic factors into a Coastal Economic Vulnerability Index (CEVI). Thus, economic variables could overlap different scenarios of inundation outlined in chapter 7 from local projections (chapter 5) representing the land typologies with sensitive structures (hospitals, schools, water and electricity networks, railways, residential assets) at risk of future impacts.

Bibliography

Abraham. (2013). A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change. *Reviews of Geophysics*, 51(3), 450–483.

Abuodha, P. A. and Woodroffe, C. D. (2006). International assessments of the vulnerability of the coastal zone to climate change, including an Australian perspective. Australian Greenhouse Office, *Department of the Environment and Heritage*, September 2006, 75p.

Abuodha, P. A. and Woodroffe, C. D.(2007). Assessing vulnerability of coasts to climate change: a review of approaches and their application to the Australian coast. In: Woodroffe CD, Bruce E, Puotinen M,Furness RA (eds) GIS for the coastal zone: a selection of papers from CoastGIS 2006. Australian *National Centre for Ocean Resources and Security University of Wollongong*, Wollongong, p 458.

Abuodha, P. A. and Woodroffe, C. D. (2010). Assessing vulnerability to sea-level rise using a coastal sensitivity index: A case study from southeast Australia. Journal of Coastal Conservation, 14 (3), pp. 189-205.

Abuodha, P., Woodroffe, C.D. (2010a). Vulnerability assessment. In: Green, D.R. (Ed.), Coastal Zone Management. Thomas Telford Ltd, London, pp. 262e290.

Abuodha, P.,Woodroffe, C.D. (2010b). Assessing vulnerability to sea-level rise using a coastal sensitivity index: a case study from southeast Australia. J. Coast. Conserv.14, 189e205.

Adam, P. (2002) Saltmarshes in a time of change. Env. Cons., 29, 39–61.

Adger,W.N., Brooks, N., Bentham, G., Agnew, M., Eriksen, S. (2004). New Indicators of Vulnerability and Adaptive Capacity. Tyndall Centre for Climate Change Research.

Adger,W.N., Brooks, N., Bentham, G., Agnew, M., Eriksen, S. (2004). New Indicators of Vulnerability and Adaptive Capacity. Tyndall Centre for Climate Change Research.

Adger, W. N.(2006).Vulnerability. Global Environmental Change .16:268–281.

Adger, W.N. and Vincent, K. (2005). Uncertainty in adaptive capacity, C.R. Geo-science 337:399–410.

Adger, W. N., Arnell, N. W. and Tompkins, E. L. (2005b). 'Successful adaptation to climate change across scales.' Global Environmental Change 15(2): 77–86.

AGUBlogosphere (2014). (Available at following web URL: http://blogs.agu.org/landslideblog/2014/01/04/hastings-rockfall/. (2014).

Alexander, D. (2000). Confronting Catastrophe. Terra, Hertfordshire.

Allen Consulting Group. (2005). Climate change risk and vulnerability: Promoting an efficient adaptation response in Australia. Australian Greenhouse Office.

Angell, E.,and Stokke, K. B. (2014). Vulnerability and adaptive capacity in Hammerfest, Norway. Ocean & coastal management, 94, 56-65.

Anthoff, D., R.J. Nicholls, and R.S.J. Tol. (2010). The economic impact of substantial sea-level rise. Mitigation and Adaptation Strategies for Global Change 15:321–335. DOI 10.1007/s11027-010-9220-7.

Ashton, A.D. and Murray, A.B. (2006a). High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. J. Geophys. Res. Earth Surf. 111 (F4). http://dx.doi.org/10.1029/2005JF000422.

Ashton, A.D. and Murray, A.B. (2006b). High-angle wave instability and emergent shoreline shapes: 2. Wave climate analysis and comparisons to nature. J. Geophys. Res. Earth Surf. 111 (F4). http://dx.doi.org/10.1029/2005JF000423.

Arnell, N. W., Lowe, J. A., Brown, S., Gosling, S. N., Gottschalk, P., Hinkel, J,and Rose, G. A. (2013). A global assessment of the effects of climate policy on the impacts of climate change.Nature Climate Change,3(5), 512.

Ashton, A. D., Walkden, M. J., and Dickson, M. E. (2011). Equilibrium responses of cliffed coasts to changes in the rate of sea level rise. Marine Geology, 284(1-4), 217-229.

Bacon, S. and Carter, D.J.T. (1991). Wave climate changes in the North Atlantic and North Sea. *International Journal of Climatology*, 11, pp. 545-558.

Ballantyne, C. K., McCarroll, D., & Stone, J. O. (2006). Vertical dimensions and age of the Wicklow Mountains ice dome, Eastern Ireland, and implications for the extent of the last Irish ice sheet. *Quaternary Science Reviews*, 25(17-18), 2048-2058.

Balica, S. F. and Wright, N.G. (2009). A network of knowledge on applying an indicator-based methodology for minimizing flood vulnerability. *Hydrol Process* 23(20):2983–2986.

Balica, S.F., Wright, N.G., and Van der Meulen, F. (2012). A flood vulnerability index for coastalcities and its use in assessing climate change impacts. Natural Hazards. 1 - 33 . ISSN 0921-030X https://doi.org/10.1007/s11069-012-0234-1.

Baxter, J. M., Buckley, P. J., and Wallace, C. J. (2010). Marine Climate Change Impacts Annual Report Card 2010–2011. MCCIP: Lowestoft, UK, 12.

Benassai, G., Di Paola, G., Aucelli, P.P.C., 2015. Coastal risk assessment of a microtidal littoral plain in response to sea level rise. Ocean Coast. Manag. 104, 22e35. Press, Cambridge, UK, pp. 315e356.

Betts, N. L., Orford, J. D., White, D. and Graham, C. J., 2004. Storminess and surges in the South-Western Approaches of the eastern North Atlantic: the synoptic climatology of recent extreme coastal storms. *Marine Geology*, 210: 227-246.

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J. M., Gulev, S., and Shum, C. K. (2007). Observations: Oceanic climate change and sea level, in Climate Change 2007: The Physical Science Basis: Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., pp. 385–432, *Cambridge Univ. Press*, New York.

Bindschadler, R. A., Nowicki, S., Abe-Ouchi, A., Aschwanden, A., Choi, H., Fastook, J., ... & Jackson, C. (2013). Ice-sheet model sensitivities to environmental forcing and their use in projecting future sea level (the SeaRISE project).Journal of Glaciology,59(214), 195-224.

Birkmann, J.(2007). Risk and vulnerability indicators at different scales: applicability, usefulness and policy implications. Environ. Hazards 7, 20e31.

Birkmann, J. (2006). Indicators and criteria for measuring vulnerability: theoretical bases and requirements. In: Birkmann, J. (Ed.), Measuring Vulnerability to Natural Hazards: towards Disaster Resilient Societies. United Nations University Press, New Delhi, India.

Bijlsma, L; O'Callahan, J., Hillen, R., Misdorp, R., Mieremet, B., Ries, K., and Spradley, J.R. (eds.), 1992. Global ClimateChange and the Rising Challenge of the Sea. Report of the CoastalZone Management Subgroup, Response Strategies Working Groupof the Intergovernmental Panel on Climate Change. The Hague,Netherlands: Ministry of Transport, Public Works and WaterManagement, 45p.

BGS (2013). BGS Landslides vulnerability and hazards report/Data. Available at following web URL: http://www.bgs.ac.uk/products/html.

BGS (2017). BGS coastal vulnerability map at the 1:50,000 scale for England and Wales. http://www.bgs.ac.uk/products/geohazards/coastalVulnerability.html.

Birkmann, J. (2006). "Measuring Vulnerability to Promote Disaster-Resilient Societies: Conceptual Frameworks and Definitions." In 'Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies' by J. Birkmann (Ed), United Nations University Press.

Bjarnadottir, S., Li, Y., and Stewart, M. G. (2011). A probabilistic-based framework for impact and adaptation assessment of climate change on hurricane damage risks and costs. Structural Safety, 33(3), 173-185.

Boateng, I. (2012). GIS assessment of coastal vulnerability to climate change and coastal adaption planning in Vietnam. Journal of Coastal Conservation 16: 25–36.

Bollmann, M., Bosch, T., Colijn, F., Ebinghaus, R., Froese, R., Guessow, K.,.and Weinberger, F. (2010). World ocean review 2010: living with the oceans.

Bonetti, J.; Klein, A. H. F., Muler, M.; De Luca, C. B.; Silva, G. V.; Toldo JR., E. E. and M. González. 2012. Spatial and numerical methodologies on coastal erosion and flooding risk assessment. In: Finkl, C. (Editor) Coastal Hazards. Chapter 16. Coastal Research Library Series. Springer, Dordrecht, p. 423-442. ISBN: 978-94-007-5233-7.

Boruff, B.J.; Emrich, C., and Cutter, S.L. (2005). Erosion hazard vulnerability of US coastal counties. Journal of Coastal Research, 21(5), 932–942.

Bosello, F., Nicholls, R.J., Richards, J., Roson, R. and R. S. J. T. (2012). Economic impacts of climate change in Europe: sea-level rise. Climatic Change. *Climatic Change*, *112*, 63–81.

Bosom García, E.,and Jiménez Quintana, J. A.(2011). Probabilistic coastal vulnerability assessment to storms at regional scale: application to Catalan beaches (NW Mediterranean).

Boruff, B.J.; Emrich, C., and Cutter, S.L. (2005). Erosion hazard vulnerability of U.S. coastal counties. Journal of Coasta.l Research, 21(5), 932–942.

Burke *et al.* (2001). Coastal populations and shoreline degradation. World Research Institute, Washington DC, 2001; Paul Harrison, Fred Pearce, AAAS Atlas of Population and Environment 2001, American Association for the Advancement of Science, University of California Press, Berkley.

Burkett, V., and M. D. (2012). Coastal Impacts, Adaptation and Vulnerabilities: A Technical Input to the 2013 National Climate Assessment. Island Press, 216pp.

Bradley, S. L., Milne, G. A., Teferle, F. N., Bingley, R. M., & Orliac, E. J. (2009). Glacial isostatic adjustment of the British Isles: new constraints from GPS measurements of crustal motion. Geophysical Journal International, 178(1), 14-22.

Broadleaf Capital International (2006). Climate Change Impacts & Risk Management. A Guide for Business and Government. Published by the Australian Greenhouse Office, in the Department of the Environment and Heritage. ISBN: 1 921120 56 8.

Brooks, N.; Adger, W.N., and Kelly, P.M. (2005). The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Global EnvironmentalChange, 15, 151–163.

Brooks, A. J., Bradley, S. L., Edwards, R. J., Milne, G. A., Horton, B.,and Shennan, I. (2008). Postglacial relative sea-level observations from Ireland and their role in glacial rebound modelling. Journal of Quaternary Science, 23(2), 175-192.

Brooks, S.M. and Spencer, T. (2012). Shoreline retreat and sediment release in response to accelerating sea-level rise: measuring and modelling cliff line dynamics on the Suffolk Coast, UK. Glob. Planet. Change, 80-81, 165-179.

Brooks, S. M., and Spencer, T. (2014). Importance of decadal scale variability in shoreline response: examples from soft rock cliffs, East Anglian coast, UK. *Journal of coastal conservation*, 18(5), 581-593.

Brooks, P.R., Nairn, R., Harris, M., Jeffrey, D., Crowe, T.P. (2016). Dublin Port and Dublin Bay: Reconnecting with nature and people. *Regional Studies in Marine Science*, *8*, 234-25. http://dx.doi.org/10.1016/j.rsma.2016.03.007.

Brooks, S. M., Spencer, T., McIvor, A., and Möller, I. (2016). Reconstructing and understanding the impacts of storms and surges, southern North Sea. Earth Surface Processes and Landforms, 41(6), 855-864. http://dx.doi.org/10.1002/esp.3905.

Brooks, S. M., Spencer, T., and Christie, E. K. (2017). Storm impacts and shoreline recovery: Mechanisms and controls in the southern North Sea. *Geomorphology*, *283*, 48-60.

Brown, J. M., and Wolf, J. (2009). Coupled wave and surge modelling for the eastern Irish Sea and implications for model wind-stress. Continental Shelf Research, 29(10), 1329-1342.

Brown, S., Barton, M.E. and Nicholls, R.J. (2011).Coastal retreat and/or advance adjacent to defences in England and Wales. J. Coast. Cons., 15, 659-670.

Brown, J. M., Souza, A. J., and Wolf, J. (2010). Surge modelling in the eastern Irish Sea: present and future storm impact. Ocean Dynamics, 60(2), 227-236.

Brown, J. M., Souza, A. J., and Wolf, J. (2010). An investigation of recent decadal-scale storm events in the eastern Irish Sea. Journal of Geophysical Research: Oceans, 115(C5).

Bromwich, D. H., Nicolas, J. P., Monaghan, A. J., Lazzara, M. A., Keller, L. M., Weidner, G. A., and Wilson, A. B. (2013). Central West Antarctica among the most rapidly warming regions on Earth. Nature Geoscience, 6(139-145). doi:doi:10.1038/ngeo1671.

Bruun, P. (1962). Sea-level rise as a cause of shore erosion. Proceedings of the American Society of Civil Engineers. Journal of the Waterways and Harbors Division, 88: 117–130.

Bruun, P. (1983). Review of conditions for use of the Bruun Rule of erosion. Coastal Engineering 7, 77 – 89.

Bryan, B., Harvey, N., Belperio, A. and Bourman, B. (2001), Distributed process modelling for regional assessment of coastal vulnerability to sea-level rise. Environmental Modelling and Assessment, vol 6, pp 57-65.

Charlton, R. and Orford, J., (2002). Managing fluvial and coastal environments. Colourpoint Books (28 Feb.2002).

Caloca-Casado, S and Sweeney, J. (2010). Identification of physical indicators of coastal vulnerability to impacts of climate change and sea level rise in the Dublin area. INFOMAR funded project. Collaboration with the Irish Climate Research and Analysis Units (ICARUS) Department of Geography, National University of Ireland, Maynooth. December 2010.

Carter, R.W.G. (1991a). Sea-level changes. In: Mc Williams, B.E.(ed.), Climate Change: Studies on the Implications for Ireland. Dublin, Ireland: Department of the Environment, pp. 125–171.

Carter, R.W.G. (1991b). Effects of climate change on the coastline of Ireland. Unpublished report to the Irish Government as part of the ―Climate Change and its impact on Ireland‖ programme.

Carter, R.W.G. (1992). Climate Change - Studies on the Implications for Ireland. Dept. of the Environment, Rep. ofIrl..

Carter, R.W.G. (1992). Sea level changes, past, present and future. In Applications of Quaternary research, ed. J.M. Gray, Quaternary proceedings, vol. 2, pp.

Carter, R.W.G. (1993). Age origin and significance of the raised gravel barrier at Church Bay, Rathlin Island, Co. Antrim. Irish Geography 26, 141–6.

Carter, R.W.G. and Balsillie.J.H. (1983). On the amount of wave energy transmitted over nearshore sand bars. Earth. Surf. Proc. Landforms. 8: 213-222.

Carter, R. W. G., Johnston, T. W., McKenna, J., and Orford, J. D. (1987). Sea-level, sediment supply and coastal changes: examples from the coast of Ireland. *Progress in Oceanography*, *18*(1-4), 79-101Carter, D.J.T. and Draper, L. (1988). Has the north-east Atlantic become rougher? Nature, 332, pp. 494.Carter, D.J.T. & Draper, L. (1988). Has the north-east Atlantic become rougher? Nature, 332, pp. 494.

Carter, R.W.G. and Bartlett, D.J. (1990). Coastal erosion in Northern Ireland – Part 1: Sand beaches, dunes and river mouths. Irish Geography, 23, 1-16.

Carter, R.W.G. and Wilson, P. (1993). Aeolian processes and deposits in north-west Ireland. In: PYE, K. (ed.), The Dynamics and Environmental Context of Aeolian Sedimentary Systems. London: Geological Society of London, Special Publication 72, pp. 173–190.

Carter, R.W.G. and Woodroffe C. D. (1994). Coastal Evolution: Late Quaternary Shoreline Morphodynamics.Cambridge, United Kingdom: Cambridge University Press. 517. p.

Carter, T. R., Hulme, M., and Lal, M. (2007).General guidelines on the use of scenario data for climate impact and adaptation assessment.

Cazenave, A., and Cozannet, G.L. (2013). Sea-Level rise and its impacts. Earth's Future. 2, 2 (15-34). https:/doi.org/10.1002/2013EF000188.

Coast of Ireland Aerial Oblique Imagery Survey, 2003 (available at following web URL):

www.coastalhelicopterview.ie/imf5104/imf.jsp?site=Helicopter.

Chambers, R. (1989). Vulnerability. Editorial introduction. In: IDS Bulletin. , Sussex, 20(2), 17.

Church, J. A., Gregory, J. M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M. T., ... and Woodworth, P. L. (2001). Changes in sea level. In , in: JT Houghton, Y. Ding, DJ Griggs, M. Noguer, PJ Van der Linden, X. Dai, K. Maskell, and CA Johnson (eds.): Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel (pp. 639-694).

Church, J. A., and W. N. J. (2006). A 20th century acceleration in global sea-level rise. Geophys. Res. Lett, (33, L01602). doi:10.1029/2005GL024826.

Church, J. A., Woodroffe, C.,and Schneider, J. (2006). Assessing and mapping Australia's coastal vulnerability to climate change: Expert Technical Workshop.Australian Greenhouse Office, Department of the Environment and Heritage, 2006.

Church, J. A., Aarup, T., Wilson, W. S., and Woodworth, P. L. (2007). Sea-level rise and vulnerable coastal populations. Tudor Rose, 177–179. Retrieved from http://startinternational.org/library/archive/files/sealevelrise_churchetal07_5cbf169066.pdf

Church, J. A., White, N. J., Aarup, T., Wilson, W. S., Woodworth, P. L., Domingues, C. M., ..and Lambeck, K. (2008). Understanding global sea levels: past, present and future. Sustainability Science, 3(1), 9-22.

Church. J. A., W. N. . and D. C. (2010). Understanding sea level changes over the last half century and its implications for the future. Geophysical Research Abstracts . Vol. 12, EGU2010-15017, 2010EGU General Assembly 2010 © Author(s) 2010.

Church, J.A., Woodworth, P.L., Aarup, T., Wilson, W.S. (Eds.). (2010). Understanding Sea-level Rise and Variability. Wiley-Blackwell, Hoboken, NJ, USA, 428 pp.

Church, J. A. and W. N. J. (2011). Sea-level rise from the late 19th to the early 21st Century. Surveys in Geophysics. doi:10.1007/s10712-011-9119-1.

Church, J. A., White, N. J., Konikow, L. F., Domingues, C. M., Cogley, J. G., Rignot, E., Gregory, J. M., van den Broeke, M. R., Monaghan, A. J., and Velicogna, I. (2011). Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. Geophysical Research Letters, 38(L18601). doi:doi:10.1029/2011GL048794.

Church, J. A., *et al*. (2013a). Sea level change Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change ed T F Stocker, D Qin, G-K Plattner, M Tignor, S K Allen, J Boschung, A Nauels, Y Xia, V Bex and P M Midgley (Cambridge: Cambridge University Press).

Church, J.A., Clark, P.U., et al., 2014. Sea Level Change. Contribution in Working Group I to the IPCC Fifth Assessment Report on, Climate Change 2014: The Physical Science Basis. The Working Group I (WGI) contribution to the IPCC Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2013: Stockholm, Sweden. doi:doi:10.1017/CBO9781107415324.

Church, J. A., *et al*. (2013b). Sea-level rise by 2100 Science 342 1445 Cogley J G 2009 Geodetic and direct mass-balance measurements: comparison and joint analysis Ann. Glaciol. 50 96–100.

Church, J. A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S.,Levermann, A., Merrifield. M.A, Milne, G.A., Nerem, R.S. (2013) Sea level change. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of working Group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, New York NY.

Church, J. A., D. Monselesan, J. M. Gregory, and B. M….(2013). Evaluating the ability of process based models to project sea-level change. *Environ. Res. Lett*, *8*(015051).

CoastAdapt, 2014. CoastAdapt: The Sea as Our Neighbour. European Union, Northern Periphery Programme (2007 e 2013). http://coastadapt.org.

COCOADAPT, (2015). Sweeney, J., Bourke, D., Coll, J., Flood, S., Gormally, M., Hall, J., McGloughlin, J., Murphy, C., Salmon, N., Sheehy-Skeffington, M., Smyth, D. (2015) COCOADAPT: Co-ordination, Communication and Adaptation for Climate Change in Ireland: An Integrated Approach. : Environmental Protection Agency.

Clark, P. U., McCabe, A. M., Mix, A. C., and Weaver, A. J. (2004). Rapid rise of sea level 19,000 years ago and its global implications. *Science*, *304*(5674), 1141-1144.

Cronin, T. M. (2011). Was pre–twentieth century sea level stable?. Eos, Transactions American Geophysical Union, 92(49), 455-456.

Crooks. S (2004). The effect of sea-level rise on coastal geomorphology. Ibis 146:18–20

CSIRO and NASA Goddard Space Flight Centre (2015).http://climate.nasa.gov/vital-signs/sea-level/. (2014). No Title. Retrieved from http://climate.nasa.gov/vital-signs/sea-level.

Coll, J., and Sweeney, J. (2015) Current and future vulnerabilities to Climate Change in Ireland. : EPA (2015).

Collins, M., An, S.I., Cai, W.J., Ganachaud, A., Guilyardi, E., Jin, F.F., Jochum, M., Lengaigne, M., Power, S., Timmermann, A., Vecchi, G. & Wittenberg, A. (2010). The impact of global warming on the tropical Pacific ocean and El Nino. Nature Geoscience, 3(6), pp. 391-397.

Cooper, J.A.G., Cummins, V. (Eds.), 2009. Coastal Management in Northwest Europe. Elsevier, Amsterdam, 869 pp.

Cutter, S.L.; Boruff, B.J., and Shirley, W.L. (2003). Social vulnerability to environmental hazards. *Social Science Quarterly*, 84(2), 242–261.

CZM (1992). IPCC CZMS, 1992. Global Climate Change and the Rising Challenge of the Sea. Report of the Coastal Zone Management Subgroup. IPCC Response Strategies Working Group, Rijkswaterstaat, The Hague. Appendix C.

Dasgupta, S., B. Meisner L C., Wheeler, D., and Yan, J. (2009): The impact of sea level rise on developing countries: a comparative analysis. Climatic Change 93(3-4), 379-388.

Dasgupta, S., B. Murray ,L, S., and Wheeler, D. (2011). Exposure of developing countries to sea-level rise and storm surges. Climatic Change, 106, 567-579.

DASS 4.0 manual. Thieler, E.R, Himmelstoss E.A, Zichichi J.L., and Miller, T.L (2005). Digital Shoreline Analysis System (DSAS). An ArcGISc extension for calculating shoreline change. US Geological Survey Open-File Report 2005–1304.

Dawson, R. J., Dickson, M. E., Nicholls, R. J., Hall, J. W., Walkden, M. J., Stansby, P. K., ...and Watkinson, A. R. (2009). Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Climatic Change, 95(1-2), 249-288).

Debernard, J.B. and Røed, L.P. (2008).Future wind, wave and storm surge climate in the Northern Seas: a revisit. Tellus A 60(3): 427-438.

DECLG (2012). National Climate Change Adaptation Framework: Building Resilience to Climate Change. Dublin, Department of the Environment, Community and Local Government. Departemetn of the Environment. December 2012.

DoE (2000). National Climate Change Strategy. Department of the Environment Dublin. © Government of Ireland 2000.Dublin, Ireland:, pp. 125–171.

DEH (2000). Department of the Environment and Local Government. Annual report. © Government of Ireland 2001 ISBN PN 10428 Annual Report 2000.

DEFRA(2002). Futurecoast (2002) *Final Project Report*, DEFRA, http:// www.defra.gov.uk/environ/fcd/futurecoast.htm.

De Groot, A.V., de Vries, S., Keijsers, J.G.S., Riksen, M.J.P.M., Ye, Q., Poortinga, A., Arens, S.M., Bochev-Van der Burgh, L.M., Wijnberg, K.M., Schretlen, J.L., van Thiel, J.S.M., de Vries, J.,2012. Measuring and modelling coastal dune development in the Netherlands. In: Proceedings of NCK-Days 2012: Crossing Borders in Coastal Research. Enschede, The Netherlands. http:// dx.doi.org/10.3990/2.17

De Leon, J. C. V. (2006). Vulnerability: A conceptual and methodological review. United National University, Institute for Environment and Human Security.

DELG, 2001. Local Government Act 2001. Department of Housing, Planing and Local Goverenment.

Dollard, B (2003), Enterprise Ireland Coastal Zone Management Network (CZMNet) INTERREG Network Project Progress Report. 2003.

Doukakis, E. (2005). Coastal vulnerability and risk parameters. *European Water*, *11*(12), 3-7.

Dwarakish, G. S., Vinay, S. A., Natesan, U., Asano, T., Kakinuma, T., Venkataramana, K., ... and Babita, M. K. (2009). Coastal vulnerability assessment of the future sea level rise in Udupi coastal zone of Karnataka state, west coast of India. Ocean & Coastal Management, 52(9), 467-478.

De Sherbinin, A., Schiller, A., & Pulsipher, A. (2007). The vulnerability of global cities to climate hazards. Environ. Urban, 19(1), 39–64.

Devoy, R. J. N. (1990). Sea-level changes and Ireland. Technology Ireland, 22(5), 24-30.

Devoy, R. J. N. (2000). Implications of accelerated sea-level rise for Ireland. In: De La Vega -Leinert, A.C., Nicholls, R.J., and Tol ,R.S.J. (eds.), European Vulnerability and Adaptation to Impacts of Accelerated Sea-Level Rise. Proceedings of SURVAS Expert Workshop, ZMK, University of Hamburg. Flood Hazard Research Centre, Middlesex University, United Kingdom, pp. 33–46.

Devoy, R. J. N; De Groot, T.A.M.; Jelgersma, S.; Marson, I.; Nicholls, R.J.; Paskoff, R., and Plag, H.P. (2000a). Sea-level changes and coastal processes: recommendations. In: Smith, D., Raper, S., Zerbini,, S., and Sánchez-Arcilla, A. (eds.), Sea Level Change and Coastal Processes: Implications for Europe. Brussels, Belgium: European Commission, pp. 1–8.

Devoy, R. J. N. (2008). Coastal vulnerability and the implications of sea-level rise for Ireland. Journal of Coastal Research, 24(2), 352–341. doi:ISSN 0749-0208.

Devoy, R. J. (2015a). Sea-level rise: causes, impacts, and scenarios for change. In Coastal and Marine Hazards, Risks, and Disasters (pp. 197-241). http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

Devoy, R. J. (2015b). The development and management of the Dingle Bay Spit-Barriers of southwest Ireland. In *Sand and Gravel Spits* (pp. 139-180). Springer, Cham.

Desmond, M., O'Brien, P. and McGovern, F. 2009. A summary of the state of knowledge on climate change 1135 impacts for Ireland. CCRP Report No. 1. Wexford, Environmental Protection Agency.

Dickens, G. R. (1999). Blast in the past. Nature, 401, 752–5.

Dixon, T. H., Amelung, F., Ferretti, A., Novali, F., Rocca, F., Dokka, R., ... & Whitman, D. (2006). Space geodesy: Subsidence and flooding in New Orleans. *Nature*, *441*(7093), 587–588.

Dong, P. and Guzzetti, F. (2005). Frequency-size statistics of coastal soft-cliff erosion. J. Waterway Port Coast. Ocean Eng., 131, 37-42.

Downing, T. E., Butterfield, R., Cohen, S., Huq, S., Moss, R., Rahman, A., Sokona, Y., and Stephen, L.: (2001). Climate Change Vulnerability: Linking Impacts and Adaptation. Report to the Governing Council of the United Nations Programme. United Nations Environmental Programme, Nairobi, Kenya.

Dwyer, N. (2012). The status of Ireland's climate, 2012. *Climate change research programme*.

Dwyer, N and Devoy, R *in,* Dwyer, N. (2012). The status of Ireland's climate, 2012. *Climate change research programme (EPA).*

ECOPRO (1996). Environmental Code of Practise. ISBN: 07076 - 3744 – 9.Government of Ireland 1996. Published by the stationary office18.

Eakin, H., and Luers, A. L. (2006). Assessing the Vulnerability of Social-Environmental Systems. Annual Review of Environment and Resources, 31(1):365– 394, 2006. doi: 10.1146/annurev.energy.30.050504.144352.

Elliott, S. J., Ku, E. M., and Lineton, B. (2007). A state space model for cochlear mechanics, J. Acoust. Soc. Am. 122, 2759-2771.

Emanuel, K. (2005). Increasing destructiveness of tropical cyclones over the past 30 years. Nature, 436(7051), 686–688.

EC (2013). European Comission. An EU Strategy on adaptation to climate change. Communication from the commission to the European Parliament, The council, The European economic and social committee and the committee of the regions. EU Comission. 216 final. Retrieved from http://ies.jrc.ec.europa.eu/news/440/154/Launch-of-the-EU-Strategy-on-adaptation-to-climate-change.html

Eriksen, S. and P. Kelly. (2007). Developing Credible Vulnerability Indicators for Climate Adaptation Policy Assessment. Mitigation and Adaptation Strategies for Global Change, 12(4):495–524, May 2007. URL http://dx.doi.org/10.1007/s11027-006-3460-6.

eSurge. (2013). E storm surge data access-eSuerge Web Portal. (available at following web URL:http://www.storm-surge.info/data-access.

European Environmental Agency (EEA). (2006). The changing faces of Europe's coastal areas. Luxembourg: Office for Official Publications of the European Communities. ISBN 92-9167-842-2. ISSN 1725-9177 © EEA. No 6/2006. Copenhagen. Retrieved from http://www.vliz.be/projects/SAIL/eea_report_6_2006.pdf

European Environment Agency (EEA). (2011). Methods for Assessing CoastalVulnerability to Climate Change. Bologna, Italy: European Environment Agency, ETC/CCA Technical Paper 1/2011.

European Environmental Agency (EEA). (2012). Climate change, impacts and vulnerability in Europe 2012. An indicator-based report. EEA Report No 12/2012. Retrieved from http://www.heritagecouncil.ie/fileadmin/user_upload/Publications/Marine/Climate_change_-_impacts_and_vulnerability_in_Europe_2012_Summary.pdf.

EPA (2018). Bruen, M., & Dzakpasu, M. WARNDIS Project Final Report: A Review of Climate Change-related Hazards and Natural Disaster Vulnerabilities and of Agencies Involved in Warning and Disaster Management.

Environmental Protection Agency (EPA). (2013). National Adaptive Capacity AssessmentClimate Change Research Programme (CCRP) 2007-2013. Report Series No. 17.

Environmental Protection Agency (EPA). (2003). Climate Change: Scenarios and Impacts for Ireland. RTDI programma 2000-2006.

EUROSION. (2004). Living with coastal erosion in Europe: Sediment and Space for Sustainability PART III – Methodology for assessing regional indicators. 20 May 2004. Retrieved from http://www.eurosion.org/reports-online/part3.pdf.

Falaleeva, M., O'Mahony, C., Gray, S., Desmond, M., Gault, J., & Cummins, V. (2011). Towards climate adaptation and coastal governance in Ireland: Integrated architecture for effective management?. Marine Policy, 35(6), 784-793.

Farrell E. R., Coxon, P., Doff D. H. ,Priedhomme, L. (1995). The genesis of brown boulder clay of Dublin.Quarterly Journal of Engineering Geology, 28.

Field, C. B. (Ed.). (2012). Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change. Cambridge University Press.

FitzGerald, D. M., Fenster, M. S., Argow, B. A., and Buynevich, I. V. (2008). Coastal impacts due to sea-level rise. Annu. Rev. Earth Planet. Sci., 36, 601-647.

Flather, R. A., and Smith, J. A. (1998). First estimates of changes in extreme storm surge elevations due to the doubling of CO2. The Global Atmosphere and Ocean System, 6(2), 193-208.

Flax LK, Jackson RW, Stein DN (2002) Community vulnerability assessment tool methodology. Nat Hazards Rev 34(163):1527–6988. doi:10.1061/(ASCE).

Flood, S. (2012). Climate Change and Potential Economic Impacts in Ireland: The Case for Adaptation (Doctoral dissertation, National University of Ireland Maynooth).

Füssel, H. M., and Klein, R. J. (2006). Climate change vulnerability assessments: an evolution of conceptual thinking. Climatic change, 75(3), 301-329.

Füssel, H. M. (2007). Adaptation planning for climate change: concepts, assessment approaches, and key lessons. Sustainability Science 2(2): 265–275.

Füssel, H.M. (2007). Vulnerability: a generally applicable conceptual framework for climate change research. Glob. Environ. Change 17, 155e167.

Füssel, H.M.(2010). Review and Quantitative Analysis of Indices of Climate Change Exposure, Adaptive Capacity, Sensitivity, and Impacts. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/9193 License: CC BY 3.0 IGO.

Gallagher, S., Tiron, R. and Dias, F. (2014). A long-term nearshore wave hindcast for Ireland: Atlantic and Irish Sea coasts (1979–2012). Ocean Dynamics, 64(8), pp.1163–1180. DOI: 10.1007/s10236-014-0728-3.

Gallagher S., Tiron R., Whelan E., Gleeson E., Dias F., McGrath R. (2016). The nearshore wind and wave energy potential of Ireland: a high resolution assessment of availability and accessibility. Renew Energy 2016; 88:494-516.

Gehrels, W.R., and Long, A.J. (2008). 'Sea level is not level: The case for a new approach to predicting UK sea-level rise' Geography Compass, vol 93, no. 1, pp. 11-16.

Gehrels,W. R. (2010). Sea-level changes since the Last Glacial Maximum: an appraisal of the IPCC Fourth Assessment Report. *Journal of Quaternary Science*, *25*(1), 26-38.

Geographic, N. (2013). Rising seas-Map. If all ice melted. (available at following web URL http://ngm.nationalgeographic.com).

Gesch, D.B.; Gutierrez, B.T., and Gill, S.K. (2009). Coastal elevations. In: Titus, J.G. (coordinating lead author);Anderson, K.E.; Cahoon, D.R.; Gesch, D.B.; Gill, S.K.; Gutierrez, B.T.; Thieler, E.R., and Williams, S.J. (leadauthors), Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington, D.C.: U.S. Environmental Protection Agency, pp. 25–42.

Ge Y, Dou W, Gu Z et al (2013). Assessment of social vulnerability to natural hazards in the Yangtze River Delta, China. Stoch Env ResRisk A 27:1899–1908. doi:10.1007/s00477-013-0725-y.

Gibson, P. J., Caloca-Casado, S and Jiménez-Martín, D. (2012). Integrated Coastal Mapping of Dublin Bay Geomorphology based on geophysical data, satellite inferred bathymetry and 3D integration with INFOMAR datasets. INFOMAR funded project .Collaboration with the Irish Climate Research and Analysis Units (ICARUS) Department of Geography, National University of Ireland, Maynooth. (Available at following web URL:http://infomar.ie/documents/Research/INF-11-07-GIB.pdf).

Giove, S., Brancia, A., Satterstrom, F. K., and Linkov, I (2009).: Decision Support Systems and Environment: Role of MCDA, edited by: Marcomini A., Suter G. W., and Critto A., Decision Support Systems for Risk-Based Management of Contaminated Sites, Springer Science Business Media, LLC 2009, 53–73, 2009.

Gleeson, E., McGrath, R., and Treanor, M. (2013). Ireland’s climate: the road ahead. Met Éireann, Dublin.

Google Earth images @ 2018 Digital Globe.

Gornitz, V. (1990). Vulnerability of the East Coast, U.S.A. to future sea level rise. Journal of Coastal Research, Special Issue No. 9, pp. 201-237.

Gornitz, V. (1991). Global coastal hazards from future sea level rise. Palaeogeography, Palaeoclimatology, Palaeoecology, 89, pp. 379-398.

Gornitz, V., and White, T.W. (1992). A coastal hazards database for the U.S. West Coast: ORNL/CDIAC-81, NDP-043C, Oak Ridge National Laboratory, Oak Ridge, Tenn.

Gornitz, V. M., Daniels, R. C., White, T. W., and Birdwell, K. R. (1994). The development of a coastal risk assessment database: Vulnerability to sea-level rise.

Gornitz, V. (2013). *Rising seas: Past, present, future*. Columbia University Press.

Green, C. and L. McFadden (2007). Coastal vulnerability as discourse about meanings and values. Journal of Risk Research 10(8): 1027–1045.

Grinsted, A., Jevrejeva, S., Riva, R.E.M., Dahl-Jensen, D. (2015). Sea level rise projections for northern Europe 1234 under RCP8.5. Climate Research 64, 15-23.

GSI (2017). Terrestrial LiDAR (vertical 0.01 m; horizontal 20cm) collected by the GSI (2017).

Gulev, S.K., and Grigorieva,V. (2006). Variability of the winter wind waves and swell in the North Atlantic and North Pacific as revealed by the voluntary observing ship data, Journal of Climate, 19, pp. 5667-5685.

Gutierrez, B. T., Williams, S. J., and Thieler, E. R. (2007). Potential for shoreline changes due to sea-level rise along the US mid-Atlantic region. US Geological Survey.

Gutierrez, B.T., Williams, S.J., and Thieler, E.R. (2009). Ocean coasts. In, Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. J.G. Titus (coordinating lead author), K.E. Anderson, D.R. Cahoon, D.B. Gesch, S.K. Gill, B.T. Gutierrez, E.R. Thieler, and S.J. Williams (lead authors). U.S. Environmental Protection Agency, Washington DC, pp. 43-56.

Gutierrez, B. T., Plant, N. G., & Thieler, E. R. (2011). A Bayesian network to predict coastal vulnerability to sea level rise. Journal of Geophysical Research: Earth Surface, 116(F2).

Gutierrez, B. T., Plant, N. G., Thieler, E. R., and Turecek, A. (2015). Using a Bayesian network to predict barrier island geomorphologic characteristics. *Journal of Geophysical Research: Earth Surface*, *120*(12), 2452-2475.

Hahn, H. (2003). Indicators and Other Instruments for Local Risk Management for Communities and Local Governments. Document Prepared as Part of the Documents Related to the Project: Local Risk Management for Communities and Local Governments. The German Technical Cooperation Agency, GTZ, for IADB.

Haigh, I., Nicholls, R., and Wells, N., 2010: Assessing changes in extreme sea levels: Application to the English Channel, 1900–2006. Continental Shelf Research, 30(9), 1042-1055.

Hallegatte, S. (2009) Strategies to adapt to an uncertain climate change, Global Environmental Change 19, 240- 247.

Hallegatte, S., Green, C., Nicholls, R. J., and Corfee-Morlot, J. (2013). Future flood losses in major coastal cities. *Nature Climate Change*, *3*(9), 802–806.

Hampton, M.A. and Griggs, G.B. (Eds.). (2004). Formation, Evolution, and Stability of Coastal Cliffs — Status and Trends. The U.S. Climate Change Science Program References 282 Geological Survey professional paper 1693. U.S. Geological Survey, Reston, VA, 123 pp.

Hansen, J. e*t al.* (2005b). Earth's Energy Imbalance: Confirmation and Implications. *Science*, *308*(b 5727), 1431–1435. doi: DOI: 10.1126/science.1110252.

Hansen, J. et al. (2007). Climate change and trace gases. *Phil. Trans. R. Soc. A*, *365*, 1925–1954. doi:doi:10.1098/rsta.2007.2052.

Hansen, J., Ruedy, R., Glascoe, J., Sato, M. (2012). GISS analysis of surface temperature change. Geophysical Research: Atmospheres, 104(2156–2202, Wiley).

Hansom, J.D. (2001). Coastal sensitivity to environmental change: a view from the beach. CATENA, 42(2-4), pp. 291-305. doi:10.1016/S0341-8162(00)00142-9.

Hanson, S., Nicholls, R., Ranger, N., Hallegatte, S., Corfee-Morlot, J., Herweijer, C., and Chateau, J. (2011). A global ranking of port cities with high exposure to climate extremes. Climatic Change, 104(1), 89–111. http://doi.org/DOI 10.1007/s10584-010-9977-4.

Hammerfest kommune, 2010a. Risiko- og sårbarhetsanalyse Hammerfest kommune. 2010.

Harvey, N. (2006). Rates and impacts of global sea-level change. Nova Science Publishers. 2006

Harvey, N., and Nicholls, R. (2008). Global sea-level rise and coastal vulnerability. Sustainability Science, 3(1), 5-7.

Harvey, N., and Woodroffe, C. D. (2008). Australian approaches to coastal vulnerability assessment. Sustain Sci (2008) 3:67–87. DOI 10.1007/s11625-008-0041-5.

Hapke, C.,and Plant, N. (2010). Predicting coastal cliff erosion using a Bayesian probabilistic model. Marine Geology, 278, pp. 140-149.

Hapke, C. J. (2011). National assessment of shoreline change: Historical shoreline change along the New England and Mid-Atlantic coasts.

Hay, J.E. (2009). Institutional and Policy Analysis of Disaster Risk Reduction and Climate Change Adaptation in Pacific Island Countries. United Nations International System for Disaster Reduction (UNISDR) and the United Nations Development Programme (UNDP), Suva, Fiji.

Hinkel, J. (2005). DIVA: an iterative method for building modular integrated models. *Advances in Geosciences*, *4*, 45-50.

Hinkel, J., (2008). Transdisciplinary knowledge integration. Cases from integrated assessment and vulnerability assessment. Ph.D. thesis, Wageningen University, Wageningen, The Netherlands.

Hinkel, J., and Klein, R. J. (2007). Integrating knowledge for assessing coastal vulnerability to climate change. *McFadden et al.(eds)*.

Hinkel, J. (2011). Indicators of vulnerability and adaptive capacity: Towards a clarification of the science–policy interface. Global Environmental Change, 21, pp. 198-208.

Hinkel, J., and Klein, R. J. (2009). Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. Global Environmental Change, 19(3), 384-395.

Hinkel, J. and R.J.T. Klein. (2009). The DINAS-COAST project: Developing a tool for the dynamic and interactive assessment of coastal vulnerability. Global Environmental Change, 19(3), 384-395.

Hinkel, J., Nicholls, R. J., Tol, R. S., Wang, Z. B., Hamilton, J. M., Boot, G., ... and Klein, R. J. (2013). A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. Global and Planetary change, 111, 150-158.

Hinkel, J., D.P. van Vuuren, R.J. Nicholls, and R.J.T. Klein (2013). The effects of mitigation and adaptation on coastal impacts in the 21st century. Climatic Change, 117, 17:783–794.

Hinkel, J., Lincke, D., Vafeidis, A. T., Perrette, M., Nicholls, R. J., Tol, R. S.,and Levermann, A. (2014). Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences*, *111*(9), 3292-3297.

Hinkel, J., Jaeger, C., Nicholls, R. J., Lowe, J., Renn, O., & Peijun, S. (2015). Sea-level rise scenarios and coastal risk management. *Nature Climate Change*, *5*(3), 188.

Hoare, P. G. 1975. The pattern of glaciation in county Dublin. Proceedings of the Royal Irish Academy 75B, 207–224.

Hoeke, R. K., McInnes, K. L., Kruger, J. C., McNaught, R. J., Hunter, J. R., & Smithers, S. G. (2013). Widespread inundation of Pacific islands triggered by distant-source wind-waves. *Global and Planetary Change*, *108*, 128-138.

Horn, D. P. (2015). Storm surge warning, mitigation, and adaptation. *In Coastal and Marine Hazards, Risks, and Disasters* (pp.153-180). http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

Houser, C., (2009) Synchronization of transport and supply in beach–dune interaction. Prog. Phys. Geogr. 33, 733–746.

IAE (2007). Ireland at risk: Water. The impact of climate change on the water environment. © *The Irish Academy of Engineering*, September 2007 ISBN No.: 1898 012 938.

IPCC (2001). Climate change 2001: the scientific basis. Contribution of Working Group 1 to the Third Assessment Report of the Intergovernmental Panel on Climate Change, edited by JT Houghton, Y. Ding, DJ Griggs, M. Noguer, PJ van der Linden, X. Dai, K. Maskell and CA Johnson (eds). Cambridge University Press, Cambridge, UK, and New York, USA, 2001. No. of pages: 881. Price£ 34.95, US $49.95, ISBN 0-521-01495-6 (paperback). ISBN 0-521-80767-0 (hardback). International Journal of Climatology, 22(9), 1144-1144.

IPCC. (2007). Climate Change 2007 : Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change (Vol. 4). Cambridge University Press. In Climate Change 2007.

IPCC. (2013a). Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. : Stockholm, Sweden. http://doi.org/doi:10.1017/CBO9781107415324.

IPCC. (2013b). Climate Change 2013: The Physical Science Basis. The Working Group I (WGI) contribution to the IPCC Fifth Assessment Report of the Intergovernmental Panel on Climate Change 2013: Stockholm, Sweden. doi:doi:10.1017/CBO9781107415324.

IPCC.(2014a) [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K. L. E., Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L. L. W., & (eds.)]. (2014). IPCC, 2014a: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

Irish, J.L, A.E. Frey, J.D. Rosati, F. Olivera, L.M. Dunkin, J.M. Kaihatu, C.M. Ferreira and B.L. Edge. 2010): Potential implications of global warming and barrier island degradation on future hurricane inundation, property damages, and population impacted. Ocean and Coastal Management, 53: 645-657.

ISDR, I. S. for D. R. (2004). Living with Risk. A Global Review of Disaster Reduction Initiatives. Retrieved from http://www.unisdr.org/.

Japan meteorological agency (2014). (Available at following web URL: http://www.jma.go.jp/jma/indexe.html.

Jennings, E., and Jeffrey, D. W. (2005). The Link between biogeochemical nitrogen cycling and intertidal green 1281 macroalgae in Dublin Bay. In Wilson, J.G. (Ed) The intertidal ecosystem: the value of Ireland's shores.

Jevrejeva, S., Moore, J. C., and A. G. (n.d.) 2012. Sea level projections to AD2500 with a new generation of climate change scenarios. Global and Planetary Change, (80-81), 14–20,. doi:doi:10.1016/j.gloplacha.2011.09.006

Jevrejeva, A Grinsted, J. C. M. (2014). Upper limit for sea level projections by 2100. Environmental Research Letters, 9 (10), 104008. doi:http://dx.doi.org/10.1088/1748-9326/9/10/104008.

Jiménez, J. A., P. Ciavola, Y. Balouin, C. Armaroli, E. Bosom and M. Gervais (2009). Geomorphic coastal vulnerability to storms in microtidal fetch-limited environments: application to NW Mediterranean and N Adriatic Seas. Journal of Coastal Research, 2(56), 1641-1645.

Jiménez, J. A., Valdemoro, H. I., Bosom, E., Sánchez-Arcilla, A., & Nicholls, R. J. (2017). Impacts of sea-level rise-induced erosion on the Catalan coast. *Regional environmental change*, *17*(2), 593-603.

Jonkman, S. N., Hillen, M. M., Nicholls, R. J., Kanning, W., & van Ledden, M. (2013). Costs of adapting coastal defences to sea-level rise—new estimates and their implications. Journal of Coastal Research, 29(5), 1212-1226.

Jordan, C. (2016). Resilience Mapping of Irish Coast - Pilot. Coastal and Marine Processes Session, Conference of Irish Geographers, Dublin, Ireland.

Joughin, I., B. E. Smith, and D. M. Holland, 2010. (2010). Sensitivity of 21st century sea level to ocean-induced thinning of Pine Island Glacier, Antarctica. Geophysical Research Letters, 37(L20502). doi:doi:10.1029/2010GL044819.

Jouzel, J., V. Masson-Delmotte, O. Cattani, G. Dreyfus, S. Falourd, G. Hoffmann, B. Minster, J. Nouet, J. M. Barnola, J. Chappellaz, H. Fischer, J. C. Gallet, S. Johnson, M. Leuenberger, L. Loulergue, D. Luethi, H. Oerter, F. Parrenin, G. Raisbeck, D. Ray, and E. W. W. (2007). Orbital and millennial Antarctic climate variability over the past 800,000 years. Science, 317(5839), 793–797.

Khazendar, A., Borstad, C. P., Scheuchl, B., Rignot, E., & Seroussi, H. (2015). The evolving instability of the remnant Larsen B Ice Shelf and its tributary glaciers. *Earth and Planetary Science Letters*, *419*, 199-210.

Kirshen, P., Watson, C., Douglas, E., Gontz, A., Lee, J., and Tian, Y. (2008). Coastal flooding in the Northeastern United States due to climate change. Mitigation and Adaptation Strategies for Global Change, 13(5-6), pp. 437-451.

Katsman, C. A., A. Sterl, J. J. Beersma, H. W. van den Brink, W. Hazeleger, R. E. Kopp, D. Kroon, J. Kwadijk, R. Lammersen, J. Lowe, M. Oppenheimer, H. - P. Plag, J. Ridley, H. von Storch, D. G. Vaughan, P. Vellinga, L. L. A. Vermeersen, R. S. W. Wal, and R. W. (2011). Exploring high-end scenarios for local sea level rise to develop flood protection strategies for a low-lying delta - the Netherlands as an example. Climatic Change, 109, 617–645. doi:doi:10.1007/s10584-011-0037-5.

Kebede, A.S. and Nicholls R.J. (2012). Exposure and vulnerability to climate extremes: population and asset exposure to coastal flooding in Dar es Salaam, Tanzania. Regional Environmental Change 12:81–94.

Kemp, A. C., B. P. Horton, J. P. Donnelly, M. E. Mann, M. (2011). Vermeer, and S. Rahmstorf, 2011: Klein, R. J., and Hinkel, J. (2009). Global Assessment of Coastal Vulnerability to Sea-Level Rise: Experience from DINAS-COAST. Assessing Vulnerability to Global Environmental Change: Making Research Useful for Adaptatin Decision Making and Policy, 79-96.

Kewei Lyu, Xuebin Zhang, John A. Church, A. B. A. S. and J. H. (2014). Time of emergence for regional sea-level change. Nature Climate Change, 4(1006-1010). doi:doi:10.1038/nclimate2397.

Khazendar, A., Borstad, C. P., Scheuchl, B., Rignot, E., and Seroussi, H. (2015). The evolving instability of the remnant Larsen B Ice Shelf and its tributary glaciers. Earth and Planetary Science Letters, 419, 199-210.

Klein, R.J.T., Aston, J., Buckley, E.N., Capobianco, M., Mizutani, N., Nicholls, R.J., Nunn, P.D., Ragoonaden, S., (2000). Coastal adaptation. In: Metz, B., Davidson, O.R., Martens, J.W., Van Rooijen, S.N.M., Van Wie McGrory, L.L. (Eds.), IPCC Special Report on Methodological and Technological Issues in Technology Transfer. Cambridge University Press, Cambridge, UK.

Knutson, T. R., McBride, J. L., Chan, J., Emanuel, K., Holland, G., Landsea, C., ..and Sugi, M. (2010). Tropical cyclones and climate change. Nature Geoscience, 3(3), 157–163.

Kremer, H., Nicholls, R., Ratter, B., Weisse, R. (2013). Interdisciplinary research and perspectives on current and future storm surges. Nat. Hazards 66, 1293e1294.

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. and Tebaldi, C. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth’s Future, 1, 383–406. doi:doi: 10.1002/2014EF000239.

Koks, E. E., de Moel, H., Aerts, J. C., & Bouwer, L. M. (2014). Effect of spatial adaptation measures on flood risk: study of coastal floods in Belgium. *Regional environmental change*, *14*(1), 413-425.

Lambeck *et al.,* 2002. Glacial rebound of the British Isles—I. Preliminary model results. Geophysical Journal International, 115(3), 941–959.

Landerer, F, N. (2013). Rising seas-Map: Uneven impacts of sea-level rise. National geographic. (available at following web URL: http://ngm.nationalgeographic.com. (n.d.)).

Lazarus, E. D. (2014). Threshold effects of hazard mitigation in coastal human-environmental systems. Earth Surface Dynamics, 2(1), 35.

Leahy, T. (2009). Flood Risk Management in Dublin A strategic overview. Dublin City Council.

Le Bars, D., Drijfhout, S., and de Vries, H. (2017). A high-end sea level rise probabilistic projection including rapid Antarctic ice sheet mass loss. Environmental Research Letters, 12(4), 044013.

Lee, E.M. (2008) Coastal cliff behaviour: observations on relationship between beach levels and recession rates. Geomorph 101:558–571

Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., ...and Zweng, M. M. (2012). World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. Geophysical Research Letters, 39(10).

Lewis, S. E., Brodie, J. E., McCulloch, M. T., Mallela, J., Jupiter, S. D., Williams, H. S. and Matson, E. G. (2012). An assessment of an environmental gradient using coral geochemical records, Whitsunday Islands, Great Barrier Reef, Australia. *Marine pollution bulletin*, *65*(4-9), 306-319.

Lim, M., Rosser, N. J., Allison, R. J. & Petley, D. N. (2010a) Erosional processes in the hard rock coastal cliffs at Staithes, North Yorkshire. Geomorphology, 114, 12-21.

Lim, M., Rosser, N.J., Petley, D. N., Norman, E., Barlow, J. & Brain, M. (2010b). Characterising coastal cliff erosional environments: Microclimate-rock interactions. In: WILLIAMS, A. L., PINCHES, G. M., CHIN, C. Y., MCMORRAN, T. J. & MASSEY, C. I., (eds.) Geologically Active. Auckland, New Zealand, CRC Press.

Lim, M., Rosser, N.J., Petley, D. N., and Keen M. (2011) Quantifying the Controls and Influence of Tide and Wave Impacts on Coastal Rock Cliff Erosion. Journal of Coastal Research, 27, 46-56.

Linham, M.M. and Nicholls, R.J. (2012). Adapting technologies for coastal erosion and flooding: a review. Maritime Eng., 165, 95-111.

Linkov, I.; Eisenberg, D.A.; Bates, M.E.; Chang, D.; Convertino, M.;Allen, J.H.; Flynn, S.E., and Seager, T.P. (2013). Measurable resilience for actionable policy.

Losada, I.J, Reguero, B.G., Mendez F.J, Castanedo, S., Abascal, A.J., Minguez, R. (2013): Long-term Changes in Sea-level Components in Latin America and the Caribbean. Global and Planetary Change, 104:34-50.

Lorenzo-Trueba, J., and Ashton, A.D. (2014), Rollover, drowning, and discontinuous retreat: Distinct modes of barrier response to sea-level rise arising from a simple morphodynamic model, J. Geophys. Res. Earth Surface, 119, 779–801, doi:10.1002/2013JF002941.

Lowe, J. A., Gregory, J. M., and Flather, R. A. (2001). Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. *Climate dynamics*, *18*(3-4), 179-188.

Lowe, J. A., and Gregory, J. M. (2005). The effects of climate change on storm surges around the United Kingdom. Philosophical Transactions of the Royal Society of London A: *Mathematical, Physical and Engineering Sciences*, *363*(1831), 1313-1328.

Lowe, J.A.., Gregory, J.M., and Flather, R.A. (2001): Changes in the occurrence of storm surges around the United Kingdom under a future climate scenario using a dynamic storm surge model driven by the Hadley Centre climate models. Clim. Dyn., 18, 179-188.

Lowe, J. A., and Gregory, J. M. (2005). The effects of climate change on storm surges around the United Kingdom. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 363(1831), 1313-1328.

Lowe, J.A., Woodworth, P.L., Knutson, T., McDonald,R.E., McInnes, K.L., Woth, K., von Storch, H., Wolf,J., Swail, V., Bernier, N.B., Gulev, S., Horsburgh, K.J.,Unnikrishnan, A.S., Hunter, J.R. and Weisse, R. (2010).Past and future changes in extreme sea levels and waves. In Church, J.A., Woodworth, P.L., Aarup, T. andWilson, W.S. (eds), Understanding Sea Level Rise and Variability. Wiley-Blackwell, Oxford, pp. 326–375.

Lozano, I., and Devoy, R. J. N. (2000). Storm activity along the Atlantic coastlines of Europe: a case study of the last four decades and a CO2 x2 experiment (ECHAM4 T106). In Geophysical Research Abstracts (Vol. 2).

Lozano, I., and Devoy, R. J. N. (2000). Storm activity along the Atlantic coastlines of Europe: a case study of the last four decades and a CO2 x2 experiment (ECHAM4 T106). In Geophysical Research Abstracts (Vol. 2).

Lüthi, D., *et al*. (2008). EPICA Dome C Ice Core 800KYr Carbon Dioxide Data.

Lyu, K., Zhang, X., Church, J. A., Slangen, A. B., and Hu, J. (2014). Time of emergence for regional sea-level change. *Nature Climate Change*, *4*(11), 1006.

Mackey, P., and Russell, M. (2011). Climate Change scenarios, sea level rise for Ca Mau, Kien Giang—Climate change impact and adaptation study in the Mekong Delta. Asian Development Bank, TA.

Maguire, T (2010). Dublin Flood Initiative Coastal flood forecasting. Flood risk management summit. Croke Park, 2010.

Mahapatra, M., Ratheesh, R., & Rajawat, A. S.(2013). Sea level rise and coastal vulnerability assessment: a review. International Journal of Geology, Earth & Environmental Sciences ISSN: 2277, 2081.

McGrath, T., Nolan, G., McGovern, E. (2012) Chemical characteristics of water masses in the Rockall Trough. *Deep Sea Research Part I: Oceanographic Research Papers*, Vol. 61, pp. 57–73.

McCarthy, J. J. (Ed.). (2001). IPCC Climate Change 2001: Impacts, Adaptation, and Vulnerability:

contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Matthews, T., Mullan, D., Wilby, R. L., Broderick, C., & Murphy, C. (2016). Past and future climate change in the context of memorable seasonal extremes. *Climate Risk Management*, *11*, 37-52.

Martin, B. S. (1997). Coastal Zone Management: A Draft Policy for Ireland. Discussion Document. Deaprtment of the Marine and Natural Resources.

Marzeion, B., A. H. Jarosch, and M. Hofer. (2012). Past and future sea-level change from the surface mass balance of glaciers. The Cryosphere Discussions, 6, 3177–3241. doi:doi:10.5194/tcd-6-3177-2012.

Marcos, M., M. N. Tsimplis, and A. G. P. Shaw. (2009). Sea level extremes in southern Europe. Journal of Geophysical Research-Oceans, 114 (C01007).

Martin, B.,S. (1997), Coastal Zone Management – A Draft Policy for Ireland, Departments of the Environment and Local Government, Marine and Natural Resources and Arts, Heritage, Gaeltacht and the Islands.

Masselink, G., and Russell, P. (2013). Impacts of climate change on coastal erosion. *MCCIP Science Review*, *2013*, 71-86.

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M., Conley, D. (2015). The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. Earth Surf. Process. Landf. 41, 378–391.

Mercer, J. H. (1978). West Antarctic ice sheet and CO2 greenhouse effect: a threat of disaster. *Nature*, *271*(5643), 321.

McCabe, A. M., and Dardis, G. F. (1989). A geological view of drumlins in Ireland. *Quaternary Science Reviews*, *8*(2), 169-177.

McConnell, B., and Philcox ,M.E. (1994). Geology of Kildare - Wicklow: A Geological Description, with accompanying Bedrock Geology 1:100,000 scale map, Sheet 16.

McConnell, B., Philcox, M. E., Sleeman, A. G., Stanley, G., Flegg, A. M., Daly, E. P., Warren, W. P. (1994). A Geological Description to Accompany the BedrockGeology 1:100,000 Map Series, Sheet 16, Kildare – Wicklow. GeologicalSurvey of Ireland, Dublin, 69 pp. þ 1:100,000 scale Bedrock Geology Map sheet 16.

McCrath, R., Lynch, I?, Dunne, S., Hanafin, j., Nishimura, E., Nolan, I, Venkata J.R., Semmler, T.. Sweeney C., and Wang, S. (2008). Ireland in a Warmer World. Scientific Predictions of the Irish Climate in the Twenty-First Century Final report of C41, Dublin.

McFadden, L., Nicholls, R. J., and Penning-Roswell, E. (2007a). Managing coastal vulnerability. Elsevier, Amsterdam,pp. 261.

McGloughlin, J. S., and Sweeney, J. (2012). Governance and climate change: Making the transition to an adapted Ireland.

McGloughlin, J.S. and Sweeney, J. (2013) Governance and Climate Change: Making the Transition to an Adapted Ireland (2007-CCRP-2.6 COCOADAPT). Environmental Protection Agency: Wexford,57pp.

McGloughlin, J. S. (2015). Climate change governance: enhancing local authorities' adaptive capacity (Doctoral dissertation, National University of Ireland Maynooth).

McKay, S.K.; Linkov, I.; Fischenich, J.C.; Miller, S.J., and Valverde, Jr., L.J. (2012). Ecosystem Restoration Objectives and Metrics. U.S. Army Engineer Research & Development Center Technical NoteERDC TN-EMRRP-EBA-16, 19p.

McLaughlin, S. (2001). Assessment and Development of a Coastal Vulnerability Index for Northern Ireland Employing GIS Techniques. , University of Ulster, Coleraine.

Mclaughlin, S., Mckenna, J., and Cooper, J. A. G. (2002). Socio-economic data in coastal vulnerability indices : constraints and opportunities. Journal of Coastal Research, 497(36).

McLaughlin, S., and Cooper, J. A. G. (2010). A multi-scale coastal vulnerability index: A tool for coastal managers?. *Environmental Hazards*, 9(3), 233-248.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and C. Z. (2007). .“Global Climate Projections.” In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (Eds.), Cambridge University Press, New York (2007).

Meehl, G. A., Covey, C., Taylor, K. E., Delworth, T., Stouffer, R. J., Latif, M., & Mitchell, J. F. (2007). The WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of the American Meteorological Society, 88(9), 1383-1394.

Mendoza, E. T., and Jiménez, J. A. (2009). Regional vulnerability analysis of Catalan beaches to storms. Proceedings of the ICE-Maritime Engineering,162(3), 127-135.

Menendez, M. and Woodworth , P.L. (2010): Changes in extreme high water levels based on a quasi-global tidegauge dataset. Journal of Geophysical Research, 115, C10011.

Mercer, J.H.(1978). West Antarctic ice sheet and CO2 greenhouse effect: a threat for disaster. Nature 271.5643 (1978):321.

Met éireann. (2002). Exceptional weather events. Retrieved from http://www.met.ie/climate-ireland/weather-events/Feb2002_Floods.pdf.

Met éireann. (2015). Exceptional weather events. Available at following web URL: http://www.met.ie/climate-ireland.

MetOffice. (2013). UK Met Office (2013). The recent pause in global warming (1): What do observations of the climate system tell us? UK Met Office Report, July 2013. Retrieved http://www.metoffice.gov.uk/media/pdf/e/f/Paper1_Observing_changes_in_the_climate_system.PDF deleted from chapter 1.

MetOffice. (2014). 2014: A year of record-breaking temperatures? Retrieved from http://www.metoffice.gov.uk/media/pdf/e/c/synopsis_paper_global_climate_2014_Dec.pdf; http://www.metoffice.gov.uk/research/news/2014-temperatures.

Miller, T.L., Morton, R.A., and Sallenger, A.H. (2005). National Assessment of Shoreline Change: A GIS Compilation of Vector Shorelines and Associated Change Data for the U.S. Southeast Atlantic Coast: U.S. Geological Survey, Open-File Report 2005-1326, St. Petersburg, FL.

Moore J C, Grinsted A, Zwinger T and Jevrejeva S (2013). Semi-empirical and process-based global sea level projections Rev. Geophys. 51 484–522.

Montreuil, A-L. and Bullard, J.E. (2012) A 150-year record of coastline dynamics within a sediment cell: Eastern England. Geomorphology, doi:10.1016/j.geomorph.2012.08.008.

Morice, C.P., Kennedy, J.J., Rayner, N.A. and Jones, P. D. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 dataset. Journal of Geophysical Research, 117. http://doi.org/doi:10.1029/2011JD017187.

Moss, R.H., Brenkert, A.L., Malone, E.L. (2001). Vulnerability to climate change: quantitative approach,” Report prepared for the US Department of Energy.NASA/GISS. (2015). World of Change: Global Temperatures. Retrieved from http://data.giss.nasa.gov/gistemp/.

MOVE (2008). MOVE Report Summary. MOVE (Methods for the improvement of vulnerability assessment in Europe). ID: 211590. Universita Degli Studi di Firenze. Italy.

Mulrennan, M. E. (1990). The Geomorphic Development of the Barrier-Beach Complexes of the North County Dublin Coastline. Unpubl. Ph.D. thesis. University College Dublin, 2 vols.

Mulrennan, M. E. (1992). Ridge and runnel beach morphodynamics: an example from the central east coast of Ireland. *Journal of Coastal Research*, 906-918.

Mulrennan, M. E. (1993). Changes since the Nineteenth Century to the Estuary-Barrier Complexesof North County Dublin. Irish Geography, 26: 1, 1-13.

Muir, D., Cooper, J. A. G., & Petursdottir, G. (2014). (2014). Challenges and opportunities in climate change adaptation for communities in Europe's northern periphery. (2014): 1-8.

National Aeronautics and Space Administration (NASA) (2017). Satellite sea level observations.NASA Goddard Space Flight Centre. (Data available at following web UR: https://climate.nasa.gov/vital-signs/sea-level).

National coastal erosion committee, 1992. Coastal Management.- A case for action.

National Oceanic and Atmospheric Administration (NOAA). (2012). Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Technical Report OAR CPO-1. Climate Program Office (CPO). Climate Program Office Silver Spring, MD December 2012. Retrieved from http://cpo.noaa.gov/sites/cpo/Reports/2012/NOAA_SLR_r3.pdf.

Naylor, L.A., Stephenson, W.J., Trenhaile, A.S. (2010): Rock coast geomorphology: Recent advances and future research directions. Geomorphology, 114 (1-2), pp. 3-11.

Nerem, R.S., Leuliette, E., and Cazenave, A.(2006). Present-day change: A review. External Geophysics, Climate and Environment. C.R Geoscience 338 (2006) 1077-1083.

Neumann, B., Vafeidis, A. T., Zimmermann, J., AND Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding-a global assessment. PloS one, 10(3), e0118571.

Nguyen, T. T., Bonetti, J., Rogers, K., & Woodroffe, C. D. (2016). Indicator-based assessment of climate-change impacts on coasts: A review of concepts, methodological approaches and vulnerability indices. *Ocean & Coastal Management*, *123*, 18-43.

Nicholls, R.J. and Mimura, N., 1998. Regional issues raised by sea-level rise and their policy implications. Climatic Research, 11, 5–18.

Nicholls, R. J., and de la Vega-Leinert, A. C. (2000). Synthesis and upscaling of sea-level rise vulnerability assessment studies (SURVAS): SURVAS methodology. Flood Hazard Research Centre, Middlesex University, USA.

Nicholls, R. J., and Klein, R. J. (2005). Climate change and coastal management on Europe's coast. In Managing European Coasts (pp. 199-226). Springer, Berlin, Heidelberg.

Nicholls, R. J., and Tol, R. S. (2006). Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 364(1841), 1073-1095.

Nicholls, R. J. et al. (2007). In IPCC Climate Change (2007): Impacts, Adaptation and Vulnerability (eds Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J. & Hanson, C. E.) 315–356 (Cambridge Univ. Press, 2007).

Nicholls, R. J., Wong, P. P., Burkett, V. R., Codignotto, J. O., Hay, J. E.,. McLean, R. Ragoonaden, F, S., and Woodroffe, C. D. (2007), Coastal systems and low-lying areas, in Climate Change 2007: Impacts, Adaptation and Vulnerability: Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by M. L. Parry et al., pp. 315–356, Cambridge Univ. Press, Cambridge, U. K.

Nicholls, R.J., Wong, P.P., Burkett, V.R., Woodroffe, C.D., Hay, J.E. (2008a). Climate change and coastal vulnerability assessment: scenarios for integrated assessment', Sustainability Science 3(1), 89–102.DOI 10.1007/s11625-008-0050-4.

Nicholls, R.J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Chateau, J., Muir-Wood, R. (2008b). Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes: Exposure Estimates", OECD Environment Working Papers, No. 1, OECD Publishing. http://dx.doi.org/10.1787/011766488208.

Nicholls, R. J., and Cazenave, A. (2010), Sea-level rise and its impact on coastal zones. *Science,* 328(5985), 1517–1520, doi:10.1126/science .1185782.

Nicholls, R.J., N. Marinova, J.A. Lowe, S. Brown, P. Vellinga, D. de Gusmao, J. Hinkel y R.S.J. Tol, (2011). Sea-level rise and its possible impacts given a 'beyond 4ºC world' in the twenty-first century. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 369 (1934), 161-181.

Nicholls, R. J. et al. (2013). WIREs Clim. Change http://dx.doi.org/10.1002/wcc.253 (2013).

Nicholls, R.J., Stive, M.J.F., Tol, R.S.J., 2014a. Coping with coastal change. In: Masselink, G.,Gehrels, R. (Eds.), Coastal Environments and Global Change. Wiley, Chichester, UK.Nicholls, R.J., Hanson, S.E., Lowe, J.A., Warrick, R.A., Lu, X., Long, A.J., 2014b. Sea-level scenarios for evaluating coastal impacts. Wiley Interdiscip. Rev.: Clim. Change 5 (1),129 e150.

Nicholls, R. J., Hanson, S. E., Lowe, J. A., Warrick, R. A., Lu, X., and Long, A. J. (2014). Sea- level scenarios for evaluating coastal impacts. Wiley Interdisciplinary Reviews: Climate Change, 5(1), 129-150.

Nicholls (2015). Adapting to Sea-Level Rise, in Shroder, J.F., Ellis, J.T, and Sherman, D.J.(2015). Coastal and Marine Hazards, Risks, and Disasters (pp. 243-270). http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

Nick, F. M., Vieli, A., Andersen, M. L., Joughin, I., Payne, A., Edwards, T. L., .and Van de Wal, R. S. (2013). Future sea-level rise from Greenland's main outlet glaciers in a warming climate. Nature, 497 (7448), 235.

NOAA (2012). National Oceanic and Atmospheric Administration Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Technical Report OAR CPO-1. Climate Program Office (CPO). Climate Program Office Silver Spring, MD December 2012.

NOAA (2014). National Climatic Data Center, State of the Climate: Global Analysis for December 2014. Available at following web URL: http://www.ncdc.noaa.gov/sotc/global/2014/12.

NOAA/ ESRL (2015). Available at following web URL:www.esrl.noaa.gov/gmd/ccgg/trends/

NOAA (2017). NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published August 2017, retrieved on September 11, 2017 Available at following web URL:http://www.noaa.gov/.

Nordhaus, W. (2007). A Review of the Stern Review on the Economics of Climate Change. Journal of Economic Literature. 176-183.

Oort, B. V., Hovelsrud, G. K., Dannevig, H., & Rybråten, S. (2012). NORADAPT-Community Adaptation and Vulnerability in Norway. CICERO Report. 2012.

OPW (2006). Terrestrial LiDAR (vertical 0.25 m; horizontal 2m grid resolution) collected by the OPW (2006).

OPW (2010). Irish Coastal Protection Strategy Study Phase 3 - North East Coast Work Packages 2, 3 & 4A - Technical Report IBE0071/June 2010.

OPW (2010) Catchment Flood Risk Assessment and Management (CFRAM) flood maps. (Available at following web URL:https://www.floodinfo.ie/).

OSi (2009). Terrestrial LiDAR (vertical 0.25 m; horizontal 1m grid resolution) collected by the OSi (2009).

OSI imagery (2013). Ordnance Survey of Ireland. Stereophotographs and ortoimagery (GSI digital licence agreement).

Oppenheimer, M. (1998). Global warming and the stability of the West Antarctic Ice Sheet. Nature, 393(6683), 325.

Orford, J.D. (1989). A review of tides, currents and waves in ihe Irish Sea. in. Sweeney. J.C. (ed.) The Irish Sea: A Resource at Risk. Geographical Society of Ireland. Special Publications No 3. 18-46.

Orford, J.D., Forbes, D.L. and Jennings, S.C. (2002). Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. Geomorphology, 48, 51-85.

Orford, J., Jennings, S. and Pethick, J.S. (2003). Extreme storm effect on gravel-dominated barriers. Coast. Dyn., ASCE, paper on CD-ROM.

Parris, A., P. Bromirski, V. Burkett, D. Cayan, M. Culver, J. Hall, R. Horton, K. Knuuti, R. Moss, J. Obeysekera, A. Sallenger, and J. W. (2012). Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Tech Memo OAR CPO-1. 37 pp., National Oceanic and Atmospheric Administration, Silver Spring. NOAA Tech Memo OAR CPO-1. 37 pp., National Oceanic and Atmospheric Administration, Silver Spring, MD.

Palutikof, J. P., Rissik, D., Webb, S., Tonmoy, F. N., Boulter, S. L., Leitch, A. M.,.and Campbell, M. J. (2018). CoastAdapt: an adaptation decision support framework for Australia's coastal managers.Climatic Change, 1-17.

Pellicer, X. M. (2008). Quaternary Geology of County Dublin: a description to accompany the Quaternary Geology Map of County Dublin. Unpublished report. Geological Survey of Ireland.

Pelling, M. (2003). The Vulnerability of Cities. Natural Disasters and Social Resilience. Earthscan Publications, London.

Pendleton, E.A., Williams, S.J., and Thieler, E.R. (2004a). Coastal vulnerability assessment of Assateague Island National Seashore (ASIS) to sea-level rise: U.S. Geological Survey Open-File Report 2004-1020. Available at http://pubs.usgs.gov/of/2004/1020/.

Pendleton, E.A., Williams, S.J., and Thieler, E.R. (2004b). Coastal vulnerability assessment of Fire Island National Seashore (FIIS) to sea-level rise: U.S. Geological Survey Open-File Report 03-439. Available at http://pubs.usgs.gov/of/2003/of03-439/.

Pendleton, E. A., Thieler, E. R., & Williams, S. J. (2005). Coastal vulnerability assessment of Channel Islands National Park (CHIS) to sea-level rise. US Geological Survey.

Pendleton, E.A.; Thieler, E.R., and Williams, S.J., (2005a). Coastal Vulnerability Assessment of National Park of American Samoa to Sea-Level Rise. U.S. Geological Survey Open-File Report 2005-1055.

Pendleton, E. A., Thieler, E. R., & Williams, S. J. (2005b). Coastal vulnerability assessment of golden gate national recreation area to sea-level rise. US Geological Survey.

Pendleton, E. A., Thieler, E. R., & Williams, S. J. (2010). Importance of coastal change variables in determining vulnerability to sea-and lake-level change. Journal of Coastal Research, 176-183.

Pendleton, E. A., Barras, J. A., Williams, S. J., & Twichell, D. C. (2010).Coastal vulnerability assessment of the Northern Gulf of Mexico to sea-level rise and coastal change (No. 2010-1146). US Geological Survey.

Peters, G., Marland, G., Le Quere, M., Boden T., Canadell, J.,& Raupach M. (2011). Rapid Growth in CO2 emissions after the 2008-2009 global financial crisis. Nature Climate Change, doi:10.1038/nclimate1332.

Pfeffer, W.T., Harper, J.T., O'Neel, S. (008).'Kinematic constraints on glacier contributions to 21st century sea-level rise', Science 321, 1340–1343.

Perini, L., Calabrese, L., Salerno, G., Ciavola, P., & Armaroli, C. (2016). Evaluation of coastal vulnerability to flooding: comparison of two different methodologies adopted by the Emilia-Romagna region (Italy). Natural Hazards and Earth System Sciences, 16(1), 181.

Pethick, J. S. (1984). An introduction to coastal geomorphology. Dept. of Geography, Univ. of Hull.

Pethick, J. (1993). Shoreline adjustments and coastal management: physical and biological processes under accelerated sea-level rise. Geographical Journal, 162-168.

Pethick, J.S. (1998). Coastal Chadwick, A.J., Karunarathna, H., Gehrels, W.R., O'Brien, D. and Dales, D. (2005) A new analysis of the Slapton barrier beach system, UK. Maritime Engineering, 158, 147-161.

Pethick, J. S., and Crooks, S. (2000). Development of a coastal vulnerability index: a geomorphological perspective. Environmental conservation, 27(4), 359-367.Pfeffer, W. T., Harper, J. T., & O'Neel, S. (2008). Kinematic constraints on glacier contributions to 21st-century sea-level rise. Science, 321(5894), 1340–1343.

Pickering, M.D., Wells, N.C., Horsburgh, K.J. and Green, J.A.M. (2012).The impact of future sea-level rise on the European Shelf tides. *Continental Shelf Res*., 35, 1-15.

Pilkey, O.H., Davis, T.W., 1987. An analysis of coastal recession models: North Carolina coast. In: Nummedal, D., Pilkey, O.H., Howard, J.D. (Eds.), Sea-Level Fluctuation and Coastal Evolution. Society of Economic Paleontologists and Mineralogists, pp. 59 – 68.

Pilkey, O.H., Young, R.S., Riggs, S.R., Smith, A.W.S., Wu, H., and Pilkey, W.D., 1993, The concept of a shoreface profile of equilibrium: a critical review: Journal of Coastal Research, v. 9, p. 255-278.

Pilkey, O. H., and Young, R. (2010). *The rising sea*. Island Press.

Plant, N. G., Stockdon, H. F., Sallenger, A. H., Turco, M. J., East, J. W., Taylor, A. A., & Shaffer, W. A. (2010). Forecasting hurricane impact on coastal topography. *Eos, Transactions American Geophysical Union*, *91*(7), 65-66.

Polsky, C.; Schröter, D.; Patt, A; Gaffin, S.; Martello, M.L; Neff, R.; Pulsipher, A.; Selin, H. (2003). Assessing Vulnerabilities to the Effects of Global Change: An Eight-Step Approach. (Research a.).

Proudman Ocean Laboratory (available at following web URL: http://www.pol.ac.uk/appl/polpred.html).

Pond, S. and Pickard, G.L. (1983) Introductory dynamical oceanography. 2nd Edition,Pergamon Press, Oxford.

Preston, B. L., Abbs, D., Beveridge, B., Brooke, C., Gorddard, R., Hunt, G., ... & Withycombe, G. (2007). Spatial approaches for assessing vulnerability and consequences in climate change assessments. In MODSIM 2007 (Conference: Christchurch, New Zealand.

Preston, B.L., Smith, T., Brooke, C., Gorddard, R., Measham, T., Withycombe, G., McInnes, K., Abbs, D., Beveridge, B., and Morrison, C. (2008) Mapping Climate Change Vulnerability in the Sydney Coastal Councils Group. Prepared for the Sydney Coastal Councils Group by the CSIRO Climate Adaptation Flagship, Canberra.

Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., van den Broeke, M. R., Vaughan, D. G., & Padman, L. (2012). Corrected ICESat altimetry data, surface mass balance, and firn elevation change on Antarctic ice shelves. http://dx.doi.org/10.1594/PANGAEA.775984.

PMSL (2009). Permanent Service for Mean Sea Level (PSMSL); 'Tide Gauge Data' (Available at following web URL : http://www.psmsl. org/products/trend).

PSMSL (2010). Permanent Service for Mean Sea Level (PSMSL); 'Tide Gauge Data' (http://www.psmsl. org/products/trend (Available at following web URL: http://www.psmsl.org/data/obtaining/psmsl.hel.

PSMSL (2015). Permanent Service for Mean Sea Level (PSMSL); 'Tide Gauge Data' (http://www.psmsl. org/products/trend (Available at following web URL: http://www.psmsl.org/data/obtaining/psmsl.hel.

Pye, K.; Allen, J.R.L. (Ed.) (2000). Coastal and estuarine environments: sedimentology, geomorphology and geoarchaeology. Geological Society Special Publication, 175. The Geological Society: London. ISBN 1-86239-070-3. 435 pp.

Rahmstorf, S. (2007). A semi-empirical approach to projecting future sea-level rise. Science, 315(5810), 368-370.

Rahmstorf, S. (2010), A new view on sea level rise, Nat. Rep. Clim. Change, 4, 44–45, doi:10.1038/ climate.2010.29.

Rahmstorf, S., Perrette, M., & Vermeer, M. (2012). Testing the robustness of semi-empirical sea level projections. Climate Dynamics, 39(3-4), 861-875.

Raji, O., Niazi, S., Snoussi, M., Dezileau, L., & Khouakhi, A. (2013). Vulnerability assessment of a lagoon to sea level rise and storm events: Nador lagoon (NE Morocco). Journal of Coastal Research, 65(sp1), 802-807.

Ranger N, Reeder T and Lowe J (2013). Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 project EURO J. Dec. Proc. 1 233–62.

Renn, O. (2008). Risk Governance: Coping with Uncertainty in a Complex World.

Regnauld, H., Pirazzoli, P. A., Morvan, G., & Ruz, M. (2004). Impacts of storms and evolution of the coastline in western France. *Marine Geology*, *210*(1-4), 325-337.

Robinson, A. (2009). An investigation of coastal erosion retreat boundaries of the East Coast of Ireland between 1864 and 2009 and development of a volumetric change detection methodology to model the spatial extents of two surface grids using LiDAR and RTK GPS data sets. Department of Geography (NUIM).

Robinson, A., R. and Calov, A. G. (2012). Multistability and critical thresholds of the Greenland ice sheet. Nature Climate Change, 2, 429–432. doi:doi:10.1038/nclimate1449.

Ribot, J. C. (1995). 'The causal structure of vulnerability: Its application to climate impact analysis', GeoJournal 35, 119–122.

Rodríguez, I., Montoya, I., Sánchez, M. J., & Carreño, F. (2009). Geographic information systems applied to integrated coastal zone management. *Geomorphology*, *107*(1-2), 100-105.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard (2008). Recent Antarctic ice mass loss from radar interferometry and regional climate modeling, Nat. Geosci., 1, 106–110, doi:10.1038/ ngeo102. Schaefer, J.

Rignot E., J. L. 1, 2,*, J. Mouginot1, M. Morlighem1, H. S. andB. S. (2014). Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011. Geophysical Research Letters, 41(10), 3502–3509. doi:DOI: 10.1002/2014GL060140.

Rossington, K. and Spearman, J. (2009) Past and future evolution in the Thames Estuary. Ocean Dynamics, 59, 709-718.

RPS Consulting Engineers (2010). Final Technical Report "ICPSS, Phase2, Work Packages 2, 3 & 4A, Strategic Assessment of Coastal Flooding and Erosion Extents – South East Coast - Dalkey Island to Carnsore Point Pilot Area" 8.

Rotzoll, K., & Fletcher, C. H. (2012). Assessment of groundwater inundation as a consequence of sea-level rise. Nature Climate Change, 3(5), 477–481.

Rotzoll, K., & Fletcher, C. H. (2013). Assessment of groundwater inundation as a consequence of sea-level rise. Nature Climate Change, 3(5), 477-481).

Ruggiero, P., Komar, P. D., and Allan, J. C. (2010b). "Increasing wave heights and extreme-value projections: The wave climate of the U.S. Pacific Northwest." Coastal Eng., 57(5), 539–552.

Salecker, D., Gruhn, A., Schlamkow C., and Fröhle, P.(2014).: Statisticalanalysis of hydrodynamic impacts for risk assessment of coastalareas, J. Coastal Res., SI 64, 1906–1910, 2011.Sierra JP, Casas-Prat M (2014) Analysis of potential impacts oncoastal areas due to changes in wave conditions. Clim Change 124:861–876. doi:10.1007/s10584-014-1120-5.

Salman, A. · Lombardo, S. · Doody, P. (2004). Living with coastal erosion in Europe: Sediment and Space for Sustainability. Eurosion project reports. PART 1. Major findings and policy Recomendations of the EUROSION porject. Service contract B4-3301/2001/329175/MAR/B3 "Coastal erosion – Evaluation of the need for action" Directorate General Environment. © 2004 EUCC. Retrieved from http://www.eurosion.org/reports-online/part1.pdf.

Sallenger, A.S., Wright, C.W. & Lillycrop, J. (2007). Coastal change impacts during Hurricane Katrina: an overview. In, Coastal Sediments 07. Kraus, N.C. and Rosati, J.D. (Eds.). America Society of Civil Engineers, Reston, VA, pp. 888-896.

Sallenger JR, Asbury H., Doran, Kara S., et Howd, Peter A. (2012). Hotspot of accelerated sea-level rise on the Atlantic coast of North America. *Nature Climate Change*, 2012, vol. 2, no 12, p. 884.

Sánchez-Arcilla, A., García-León, M., Gracia, V., Devoy, R., Stanica, A., & Gault, J. (2016). Managing coastal environments under climate change: pathways to adaptation. *Science of the total environment*, *572*, 1336-1352.

Sankari, T. S., Chandramouli, A. R., Gokul, K., Surya, S. M., & Saravanavel, J. (2015). Coastal Vulnerability Mapping Using Geospatial Technologies in Cuddalore-Pichavaram Coastal Tract, Tamil Nadu, India. *Aquatic Procedia*, *4*, 412-418.

Sano, M., Gainza, J., Baum, S., Choy, D. L., Neumann, S., & Tomlinson, R. (2015). Coastal vulnerability and progress in climate change adaptation: An Australian case study. Regional Studies in Marine Science, 2, 113-123.

Satta, A., Puddu, M., Venturini, S., & Giupponi, C. (2017). Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. International Journal of Disaster Risk Reduction, 24, 284-296.

Sayers, P. B., Horritt, M., Penning-Rowsell, E., & McKenzie, A. (2015). Climate Change Risk Assessment 2017: Projections of future flood risk in the UK. *Research undertaken by Sayers and Partners on behalf of the Committee on Climate Change. Published by Committee on Climate Change, London*.

Schaeffer, M., Hare, W., Rahmstorf, S., Vermeer, M. (2012). Long-term sea-level rise implied by 1.5° C and 2° C warming levels. Nature Climate Change. doi:10.1038/NCLIMATE158.

Schmidtlein, M., Deutsch, R., Piegorsch, W., and Cutter, S. (2008): A sensitivity analysis of the social vulnerability index, Risk Anal., 28, 1099–1114, 2008.

Schneiderbauer S. and Ehrlich, D. (2004). Risk, Hazard and People's Vulnerability to Natural Hazards: A Review of Definitions, Concepts and Data. Luxembourg: Office for Official Publication of the European Communities.

Semedo, A., K. Sušelj, A. Rutgersson, and A. Sterl. (2011): A global view on the wind sea and swell climate and variability from ERA-40. Journal of Climate, 24(5), 1461-1479.

Seneviratne, S.I., N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, and X. Zhang. (2012). Changes in climate extremes and their impacts on the natural physical environment. In: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, pp. 109-230.

Sharples, C. (2006). Indicative Mapping of Tasmanian Coastal Vulnerability to Climate Change and Sea Level Rise: Explanatory Report. Report to Department of Primary Industries, Water & Environment, Tasmania, 2nd Edition, pl.

Sheehy, M. and Verbruggen, K. (2013) D7.1.25 Geohazard Description for Dublin, Geological Survey of Ireland: Available at http://www.pangeoproject.eu/pdfs/english/dublin/PGGH_dublin_008.pdf

Shaw, J., Taylor, R.B., Solomon, S., Christian, H.A., & Forbes, D.L. (1998). Potential impacts of global sea-level rise on Canadian coasts. The Canadian Geographer, 42(4), pp. 365-379.

Shroder, J. F. Ellis, J.T., AND Sherman, D.J. (2015). *Coastal and Marine Hazards, Risks, and Disasters*. http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

Sierra, J. P., Casanovas, I., Mösso, C., Mestres, M., & Sánchez-Arcilla, A. (2016). Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise. *Regional environmental change*, *16*(5), 1457-1468.

Silva, S. F., Martinho, M., Capitão, R., Reis, T., Fortes, C. J., & Ferreira, J. C. (2017). An index-based method for coastal-flood risk assessment in low-lying areas (Costa de Caparica, Portugal). *Ocean & Coastal Management*, *144*, 90-104.

Silvano, A., Rintoul, S. R., & Herraiz-Borreguero, L. (2016). Ocean-ice shelf interaction in East Antarctica. Oceanography, 29(4), 130-143.

SimCLIM (2013). SimCLIM systems (Available at following web URL:http://www.simclim.com/).

Sistermans, P. and Nieuwenhuis, O. (2013). Holderness Coast (United Kingdom. 1st ed. [ebook] Amersfoort: DHV. Available at: http://databases.euccd.de/files/000164_EUROSION_Holderness_coast.pdf

Slott, J.M., Murray, A.B., Ashton, A.D., & Crowley, T.J. (2006). Coastline responses to changing storm patterns. Geophysical Research Letters, 33, L18404, doi:10.1029/2006GL027445.

Small, C., & Nicholls, R. J. (2003). A global analysis of human settlement in coastal zones. Journal of Coastal Research, 584-599.

Smith, T.M., R.W. Reynolds, Thomas C. Peterson, and J. L. (2008). Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006). Journal of Climate, 21(2283–2293).

Smith, J.M., Cialone, M.A., Wamsley, T.V., & McAlpin, T. (2010). Potential impact of sea level rise on coastal surges in southeast Louisiana. Ocean Engineering, 37(1), pp. 37-47. (Kirshen et al. (2008).

Solomon, S., G. - K. Plattner, R. Knutti, and P. F. (2009). Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences. doi:oi:10.1073/pnas.0812721106.

Sørensen, L. S., Simonsen, S. B., Nielsen, K., Lucas-Picher, P., Spada, G., Adalgeirsdottir, G., ... and Hvidberg, C. S. (2011). Mass balance of the Greenland ice sheet (2003-2008) from ICESat data-the impact of interpolation, sampling and firn density. The Cryosphere, 5(1), 173.

Spencer, T., Brooks, S.M., Möller, I., Evans, B.R. (2014). Where local matters: impacts of a major North Sea storm surge. EOS Trans. Am. Geophys. Union 95:269–270. http:// dx.doi.org/10.1002/2014EO300002.

Steig, E. J., Ding, Q., Battisti, D. S., & Jenkins, A. (2012). Tropical forcing of Circumpolar Deep Water inflow and outlet glacier thinning in the Amundsen Sea Embayment, West Antarctica. *Annals of Glaciology*, *53*(60), 19-28.

Sterl, A., H. Van den Brink, de Vries, H., Haarsma, R., and Van Meijgaard, E.. (2009): An ensemble study of extreme storm surge related water levels in the North Sea in a changing climate. Ocean Science, 5(3), 369-378.

Stockdon, H.F., Holman, R.A., Howd, P.A and Sallenger, A.H. (2006) Empirical parameterization of setup, swash and runup. Coast. Eng., 53, 573-588. De Alegria-Arzaburu, A.R. and Masselink, G. (2010) Storm response and beach rotation on a gravel beach, Slapton Sands, U.K. Marine Geology, 278, 77-99.

Stolper, D., List, J. H., and Thieler, E. R. (2005). Simulating the evolution of coastal morphology and stratigraphy with a new morphologicalbehavior model (GEOMBEST), Mar. Geol., 218, 17–36, doi:10.1016/j.margeo.2005.02.019.

Stone, G. W., & Orford, J. D. (2004). Storms and their significance in coastal morpho-sedimentary dynamics. Marine Geology, 210(1), 1-5.

Storch, V.S.,Jiang, W., and Furmanczyk, K.F.(2015). Storm Surge Case Studies. *In Coastal and Marine Hazards, Risks, and Disasters* (pp.181-196). http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

Strauss, B. H., R. Ziemlinski, J. L. Weiss, and Overpeck J. .. (2012), Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States, Environ. Res. Lett., 7, 021001, doi:10.1088/1748-9326/7/1/014033.

Synge, F. M. (1977). The coasts of Leinster (Ireland). In: Kidson, C., Tooley, M.J. (Eds.), The Quaternary History of the Irish Sea. Geological Journal Special Issue, vol. 7. Seel House Press, Liverpool, pp. 115–131.

s.85(1) of the Sea-Fisheries and Maritime Jurisdiction Act. (2006). For commentary on a similar provision in the Maritime Jurisdiction Act 1959 (repealed by the 2006 Act), see C.R. Symmons, ―Ireland and the Law of the Sea‖ in The Law of the Sea: The European Union and its Member States (T. Treves ed., Martinus Nijhoff Publishers, The Hague/Boston/London, 1997), p. 267.

Sweet, W. V, Kopp, R. E, Weaver, C. P., Obeysekera ,J., Horton, R. M.,Thieler, E. R., and Zervas, C, (201). NOAA Technical Report. 2017. NOS CO -OPS 083: Global and Regional Sea Level RiseScenarios for the United States Tech. rep. Silver Spring,Maryland.

Sweeney, J. (2000). A three-century storm climatology of Dublin. Irish Geography, 33, 1–14. The Irish National Meteorological Service (Met Eireann. 1996). Unpublished. http://www.met.ie/.

Sweeney, K., Fealy, R., McElwain, L., Siggins, L. and Trinies, V.(2008). Changing shades of Green Environmental and cultural Impacts of Climate change in Ireland: The Irish American Climate Change Porject and Rockefeller Family Fund.

Tebaldi, C., Strauss, B. H., & Zervas, C. E. (2012). Modelling sea level rise impacts on storm surges along US coasts. Environmental Research Letters, 7(1), 014032.

Torresan, S., Critto, A., Dalla Valle, Matte.,Harvey, N., Marcomini, A. (2008). Assessing coastal vulnerability to climate change: comparing segmentation at global and regional scales. Sustain Sci (2008) 3:45–65. DOI 10.1007/s11625-008-0045.

Torresan, S., Critto, A., Rizzi, J., and Marcomini, A. (2012). Assessment of coastal vulnerability to climate change hazards at the regional scale: the case study of the North Adriatic Sea. *Natural Hazards and Earth System Sciences*, *12*(7), 2347.

Torresan, S., (2017). Risk-based Assessment of Climate Change Impacts on Coastal Zones: the Case Study of the North Adriatic Sea, 2010. http://edepot.wur.nl/319572.

Townend, I. and Pethick, J.S. (2002). Estuarine flooding and managed retreat. Philos. Transact. A Math. Phys. Eng. Sci., 360, 1477-1495.

Trenhaile, A. S. (2010). The effect of Holocene changes in relative sea level on the morphology of rocky coasts. *Geomorphology, 114*(1-2), 30-41.

Trenhaile, A. S. (2011). Predicting the response of hard and soft rock coasts to changes in sea level and wave height. Climatic Change, 109(3-4), 599-615.

Thatcher, C.A.; Brock J.C., and Pendleton, E.A. (2013). Economic Vulnerability to Sea-Level Rise Along the Northern U.S. Gulf Coast. *In*: Brock, J.C.; Barras, J.A., and Williams, S.J. (eds.), *Understanding and Predicting Change in the Coastal Ecosystems of the Northern Gulf of Mexico*, Journal of Coastal Research, Special Issue No. 63, pp. 234–243, Coconut Creek (Florida), ISSN 0749–0208.

Thieler, E. R., and Danforth, W. W. (1994). Historical shoreline mapping (I): improving techniques and reducing positioning errors. *Journal of Coastal Research*, 549-563.

Thieler, E.R. and Hammar-Klose, E.S. (1999). National assessment of coastal vulnerability to sealevel rise: Preliminary results for the U.S. Atlantic coast. U.S. Geological Survey Open-File Report 99-593, 1 map sheet. Available at http://pubs.usgs.gov/of/of99-593/.

Thieler, E.R., Pilkey, O.H., Young, R.S., Bush, D.M., and Chai, F. (2000), The use of mathematical models to predict beach behavior for coastal engineering: A critical review: Journal of Coastal Research, no. 16, v. 1, p. 48-70.

Thieler, E.R. and Hammar-Klose, E.S. (2000a). National assessment of coastal vulnerability to sealevel rise: Preliminary results for the U.S. Pacific Coast. U.S. Geological Survey Open-File Report 00-178, 1 map sheet. Retrieved from http://pubs.usgs.gov/of/of00-178/. Thieler, E.R. & Hammar-Klose, E.S. (2000b). National assessment of coastal vulnerability to sea-level rise: Preliminary results for the U.S. Gulf of Mexico Coast. U.S. Geological Survey Open-File Report 00-179, 1 map sheet. Retrieved from http://pubs.usgs.gov/of/of00-179/

Thieler, E.R. and Hammar-Klose, E.S. (2000b). National Assessment of Coastal Vulnerability to Future Sea Level Rise: Preliminary Results for the U.S. Gulf of Mexico Coast. U.S. Geological Survey, Open-File Report 00-179, 1 sheet.

Thieler, E.r., Williams, S.J., and Beavers., R. (2002). Vulnerability of U.S national parks to sea-level rise and coastal changes: U. S Geological Survey Fact Sheet FS-095-02, 2 P. (Available at the following url:http:/pubs.usgs.gov/fs/fs095-02/.

Thieler, E.R, Himmelstoss E.A, Zichichi J.L., and Miller, T.L (2005). Digital Shoreline Analysis System (DSAS) version 3.0: An ArcGISc extension for calculating shoreline change. US Geological Survey Open-File Report 2005–1304.

Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., & Ergul, A. (2009). The Digital Shoreline Analysis System (DSAS) version 4.0-an ArcGIS extension for calculating shoreline change (No. 2008-1278). US Geological Survey.

Trenhaile, A, S. (2010). Modelling cochesive day coast evolution and response to climate change. Marine Geology, 277, 11-20.

Tripati, A. K., Roberts, C. D., & Eagle, R. A. (2009). Coupling of CO 2 and Ice Sheet Stability Over Major Climate Transitions of the Last 20 Million Years. Science (Vol. 326). Retrieved from http://www.sciencemag.org/content/326/5958/1394.

Turner, B.L.; Kasperson, R.E.; Matsone, P.A.; McCarthy, J.J.; Corellg, R.W.; Christensene, L; Eckley, N. K., & J.X.; Luers, A.; Martello, M.L.; Polsky, C.; Pulsipher, A.; Schiller, A. (2003). A Framework for Vulnerability Analysis in Sustainability. Science. In: PNAS., 100(14), 8074–8079. Retrieved from www.pnas.org/cgi/doi/10.1073/.

United Nations. (2004). Living with Risk: A Global Review of Disaster Reduction Initiatives. Geneva: United Nations International Strategy for Disaster Reduction, 429p.

UNDP. (2005). Adaptation Policy Frameworks for Climate Change: Developing Strategies, Policies, and Measures. Cambridge University Press, USA. UNEP, 2008. The UNEP 2008 Annual Report.

UKCP09 (2009). UK Climate Projections (Available at following web URL: http://ukclimateprojections.defra.gov.uk/).

USGCRP (U.S. Global Change Research Program). (2011). NCA Report Series, Volume 9: Uses of Vulnerability Assessments for the National Climate Assessment. Washington, U.S. Global Change Research Program, 36 pp.

UNFCC (2008) .Compendium on methods and tools to evaluate impacts, assess vulnerability, and adaptation to climate change (2008). Available at following web URL:http://unfccc.int/adaptation/nairobi_workprogramme/compendium_on_methods_tools/items/2674.php.

United Nations (2004). Living with Risk: A Global Review of Disaster Reduction Initiatives. Geneva: United Nations InternationalStrategy for Disaster Reduction, 429p.

Van der Linden P., and J. F. B. M. (2009). ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project. In Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. 160pp.

Von Storch, H., & Weisse, R. (2008). Regional storm climate and related marine hazards in the Northeast Atlantic. *Climate extremes and society*, 54-73.

Von Storch, H., Jiang, W.,and Furmanczyk, K. K. (2015). Storm surge case studies. *in* Shroder, J.F., Ellis, J.T, and Sherman, D.J.(2015). *Coastal and Marine Hazards, Risks, and Disasters* (pp. 181-196). http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

VORF manual V8.15 (Available at following web URL: https://confluence.qps.nl/qinsy/en/ and https://www.ths.org.uk/documents/ths.org.uk/).

Walkden, M. and Hall, J. (2005). A predictive meso-scale model of the erosion and profile development of soft rock shores. Coast. Eng., 52, 535-563.

Wamsley, T. V., Collier, Z. A., Brodie, K., Dunkin, L. M., Raff, D.,and Rosati, J. D. (2015). Guidance for developing coastal vulnerability metrics. Journal of Coastal Research, 31(6), 1521-1530.

Wang, X. L., Swail, V. R., & Zwiers, F. W. (2006). Climatology and changes of extratropical cyclone activity: Comparison of ERA-40 with NCEP–NCAR reanalysis for 1958–2001. Journal of Climate, 19(13), 3145-3166.

Wang, S., McGrath, R., Hanafin, J., Lynch, P., Semmler, T., & Nolan, P. (2008). The impact of climate change on storm surges over Irish waters. Ocean Modelling, 25(1-2), 83-94.

Wang, X. L., Zwiers, F. W., Swail, V. R., & Feng, Y. (2009). Trends and variability of storminess in the Northeast Atlantic region, 1874–2007. Climate Dynamics, 33(7-8), 1179.

Wang H, Kong Y, Li. H, Li. L, Ren L. (2011a). Evaluation of the redcrowned crane habitat in the Yellow River Delta Nature Reserve. Procedia Environmental Sciences 10:1519–1525. doi:10.1016/j. proenv.2011.09.242.

Wang, P and Briggs, T.M.R (2015). Storm-Induced Morphology Changes along barrier Ilsands and Poststorm recovery.*in* Shroder, J.F., Ellis, J.T, and Sherman, D.J.(2015). *Coastal and Marine Hazards, Risks, and Disasters* (pp. 271-306). http://dx.doi.org/10.1016/B978-0-12-396483-0.00010-8 Copyright © 2015 Elsevier Inc. All rights reserved.

Warrick, R.A. (2007). SimCLIM: Recent Developments of an Integrated Model for Multi-scale, Risk-based Assessments of Climate Change Impacts and Adaptation. Proceedings of the 2007 ANZSEE Conference on Re-inventing Sustainability: A Climate for Change, held 3-6 July 2007, Noosaville, Queensland.

Warrick, R. A. (2009). Using SimCLIM for modelling the impacts of climate extremes in a changing climate: a preliminary case study of household water harvesting in Southeast Queensland.

Watson, C. S., White, N. J., Church, J. A., King, M. A., Burgette, R. J., & Legresy, B. (2015). Unabated global mean sea-level rise over the satellite altimeter era. Nature Climate Change. Nature Climate Change 5, 565–568 (2015) doi:10.1038/nclimate2635.

WASA (1995). Waves and Storms in the North Atlantic) Project.1995. European Commission, DGXI.

Wells (1997), in: Wang et al. (2008). Atmosphere and Ocean: A Physical Introduction. John Wiley and Sons Ltd.

Webster, P. J., Holland, G. J., Curry, J. A., & Chang, H. R. (2005). Changes in tropical cyclone number, duration, and intensity in a warming environment. Science, 309(5742), 1844–1846.

Williams, S.J., Gutierrez, B.T., Titus, J.G., Gill, S.K., Cahoon, D.R., Thieler, E.R., Anderson, K.E., FitzGerald, D., Burkett, V., & Samenow, J. (2009). Sea-level rise and its effects on the coast. In: Coastal Sensitivity to Sea-Level Rise: A Focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. [J.G. Titus (coordinating lead author), K.E. Anderson, D.R. Cahoon, D.B. Gesch, S.K. Gill, B.T. Gutierrez, E.R. Thieler, and S.J. Williams (lead authors)]. U.S. Environmental Protection Agency, Washington DC, pp. 11-24.

Wilby, R.L., Dessai S., (2010) Robust adaptation to climate change, Weather, 65, 180-185.

Brooks, P.R., Nairn, R., Harris, M., Jeffrey, D., Crowe, T.P., Dublin Port and Dublin Bay: Reconnecting with nature and people. Regional Studies in Marine Science (2016), http://dx.doi.org/10.1016/j.rsma.2016.03.007.

White P.; Pelling, M.; Sen, K.; Seddon, D.; Russell, S.; and Few, R. (2005). No Title. Disaster Risk Reduction. A Development Concern. DFID.

WMO. (2013). The Global Climate 2001-2010: a decade of climate extremes. WMO, No. 1103 (pp. 1–119). http://doi.org/978-92-631-1103-6.

Wolters, M. L., and Kuenzer, C. (2015). Vulnerability assessments of coastal river deltas-categorization and review. *Journal of coastal conservation*, *19*(3), 345-368.

Wong, P.P., Losada, I.J., Gattuso, J., Hinkel, J., Khattabi, A., McInnes, K., Saito, Y., Sallenger, A.(2014). Coastal systems and low-lying areas. In: Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change on, Climate Change 2014: Impacts, Adaptation and Vulnerability. Cambridge University Press, Cambridge, United Kingdom.

Woolf, D.K., Challenor, P.G. and Corron, P.D. (2002). The variability and predictability of North Atlantic wave climate. Journal of Geography Research 107, 3145, doi: 10.029/200IJC001124.

Woodworth and Player, 2003; Permanent Service for Mean Sea Level (PSMSL), 2013; 'Tide Gauge Data' (http://www.psmsl. org/products/trends).

Woodworth and Player, 2003; Permanent Service for Mean Sea Level (PSMSL), 2015; 'Tide Gauge Data' (http://www.psmsl. org/products/trend).

Woodworth, P. L., Menéndez, M. , and Gehrels, W. R. (2011): Evidence for century-timescale acceleration in mean sea levels and for recent changes in extreme sea levels. *Surv. Geophys.*, 32, 603–618, doi:10.1007/s10712-011-9112-8.

Woodworth, P. L. (2005). Have there been large recent sea level changes in the Maldive Islands?. Global and Planetary Change, 49(1-2), 1-18.

Wu, L., Cai, W., Zhang, L., Nakamura, H., Timmermann, A., Joyce, T.,.. and Chang, P. (2012). Enhanced warming over the global subtropical western boundary currents. *Nature Climate Change*, *2*(3), 161.

Wu, S.; Yarnal, B., and Fisher, A. (2002). Vulnerability of coastal communities to sea-level rise: a case study of Cape May County, New Jersey, U.S.A. Climate Research, 22, 255–270.

Xia, J., Falconer, R. A., Lin, B., & Tan, G. (2011). Estimation of future coastal flood risk in the Severn Estuary due to a barrage. *Journal of Flood Risk Management*, *4*(3), 247-259.

Yin, J.H. (2005). A consistent poleward shift of the storm tracks in simulations of 21st century climate. Geophysical Research Letters, 32, L18701.

Yin, J., Schlesinger, M. E., and Stouffer, R. J. (2009). Model projections of rapid sea-level rise on the northeast coast of the United States. Nature Geoscience, 2(4), 262.

Yin, J. (2012). Century to multi-century sea level rise projections from CMIP5 models. Geophysical Research Letters, 39(7). doi:doi:10.1029/2012GL052947.

Yin, C., Li, Y., and Urich, P. (2013). SimCLIM 2013 Data Manual. *CLIMsystems Ltd*, *9.*

Yoo, G., Hwang, J. H., and Choi, C. (2011). Development and application of a methodology for vulnerability assessment of climate change in coastal cities. *Ocean & coastal management*, *54*(7), 524-534.

Yoo, G., Kim, A. R., & Hadi, S. (2014). A methodology to assess environmental vulnerability in a coastal city: application to Jakarta, Indonesia. *Ocean & coastal management*, *102*, 169-177.

Zachos J.C, Dickens. G R., and. Z. R. (2008). An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. Nature, 45(279-283). doi:doi:10.1038/nature06588.

Zhang, Y., Wallace, J. M., and Battisti, D. S. (1997). ENSO-like interdecadal variability: 1900–93. Journal of climate, 10(5), 1004-1020.

Zhang, X., F.W. Zwiers, G.C. Hegerl, F.H. Lambert, N.P. Gillett, S. Solomon, P. S. 2007. (2007). Detection of human influence on 20th century precipitation trends. Nature. doi:doi:10.1038/nature06025.

Appendix I: Positional and measurement uncertainties for shoreline changes calculations using WLR methods

.

Measurement Uncertainties (m)	**(Eg) Georeferencing /RMS value/ Error acquisition**	**Ed (digitizing)**	**Ep (Pixel)**	**El (GPS/LiDAR)**	**E_{sp} (year)**
1952Aircorps (1:10,560)	0.58 m	1 m	1 m	N/A	+/-1.60m
1971OSi (1:30,000)	0.97 m. OSi 1:30,000 stereophotographs (1971) where georeferenced using OPW (2006) aerial photographs. In this process control points were chosen with special care in order to minimise distortions, especially along the coast.	2 m	1 m	N/A	+/- 2.39m
1995 OSi (1:40 000)	Unknown (estimated 1-1.5m). The ortho-rectification process removes distortions caused by camera tilt and topographical features to produce a scale accurate image.	1-1.5m (av 1.25m)	1m	N/A	+/- 2.03m
2000 OSi	Unknown (estimated ~0.6-0.7m; avg 0.65m) .The ortho-rectification process removes distortions caused by camera tilt and topographical features to produce a scale accurate image.	1.7m	1 m	N/A	+/- 2.07m
2005 OSi	Unknown (estimated ~0.6-0.7; avg 0.65m). The ortho-rectification process removes distortions caused by camera tilt and topographical features to produce a scale accurate image. Unknown	1m	1m	N/A	+/- 1.55 m

Measurement Uncertainties (m)	(Eg) Georeferencing /RMS value/ Error acquisition	Ed (digitizing)	Ep (Pixel)	El(GPS/LiDAR)	E_{sp} (year)
2006 OPW	Unknown	`0.6-1/2= 0.8 m	0.25 m	N/A	+/-0.83 m
2009 OSi	Unknown (estimated 0.6-0.7; avg 0.65m) .The ortho-rectification process removes distortions caused by camera tilt and topographical features to produce a scale accurate image. Unknown	1-1.5m (av 1.25m)	1m	N/A	+/-1.73 m
31/05/2009 & 29/04/2009 Google	Unknown	0.8m	15-30cm= Avg 22.5 cm	N/A	+/- 0.83m
06/05/2008Google	Unknown	0.8m	15-30cm= Avg 22.5 cm	N/A	+/- 0.83m
21/06/2010 Google	Unknown	0.8m	15-30cm= Avg 22.5 cm	N/A	+/- 0.83m
11/06/2011 ESRI	Unknown	0.8m	15-30cm. Avg 22.5cm	N/A	+/- 0.83m

Measurement Uncertainties (m)	**(Eg)Georeferencing /RMS value/ Error acquisition**	**Ed (digitizing)**	**Ep (Pixel)**	**El (GPS/LiDAR)**	**E_{sp} (year)**
28/10/11(RTK)	Root mean square (RMS) error between 0.15-0.30; avg=0.225 m	N/A	N/A	Accuracy level 0.009-0.015 m vertically and 0.009-0.013	+/- 0.22m
07/12/2013 Google	Unknown	0.8m	15-30cm= Avg 22.5 cm	N/A	+/- 0.83m
01/04/2015 Google	Unknown	0.65m	15cm	N/A	+/- 0.66m
06/02/2016 Google	Unknown	0.65m	15cm	N/A	+/- 0.66m
07/09/2017 Google	Unknown	0.65m	15cm	N/A	0.66m

Table I. 1. Total error uncertainties from positional and measurement to populate the uncertainty field requested for weighted linear regression (WLR) calculations. (*Source: Silvia Caloca).*

Appendix II: Potential flooding areas from extreme water levels by 2040, 2060, 2080 and 2100.

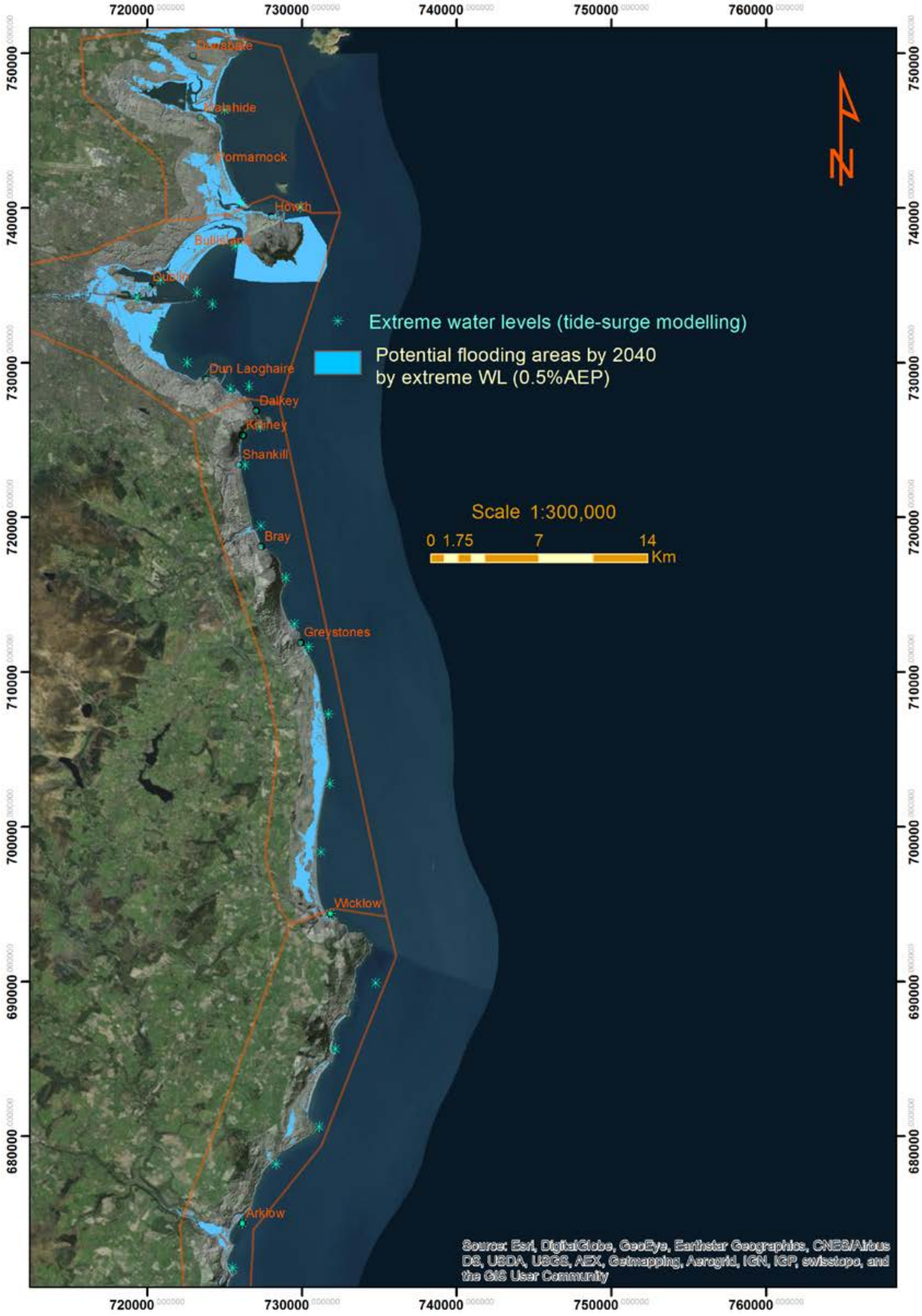


Figure II. 1. Potential flooding areas from extreme water levels (0.5%AEP) by 2040 (*Source: Silvia Caloca*).

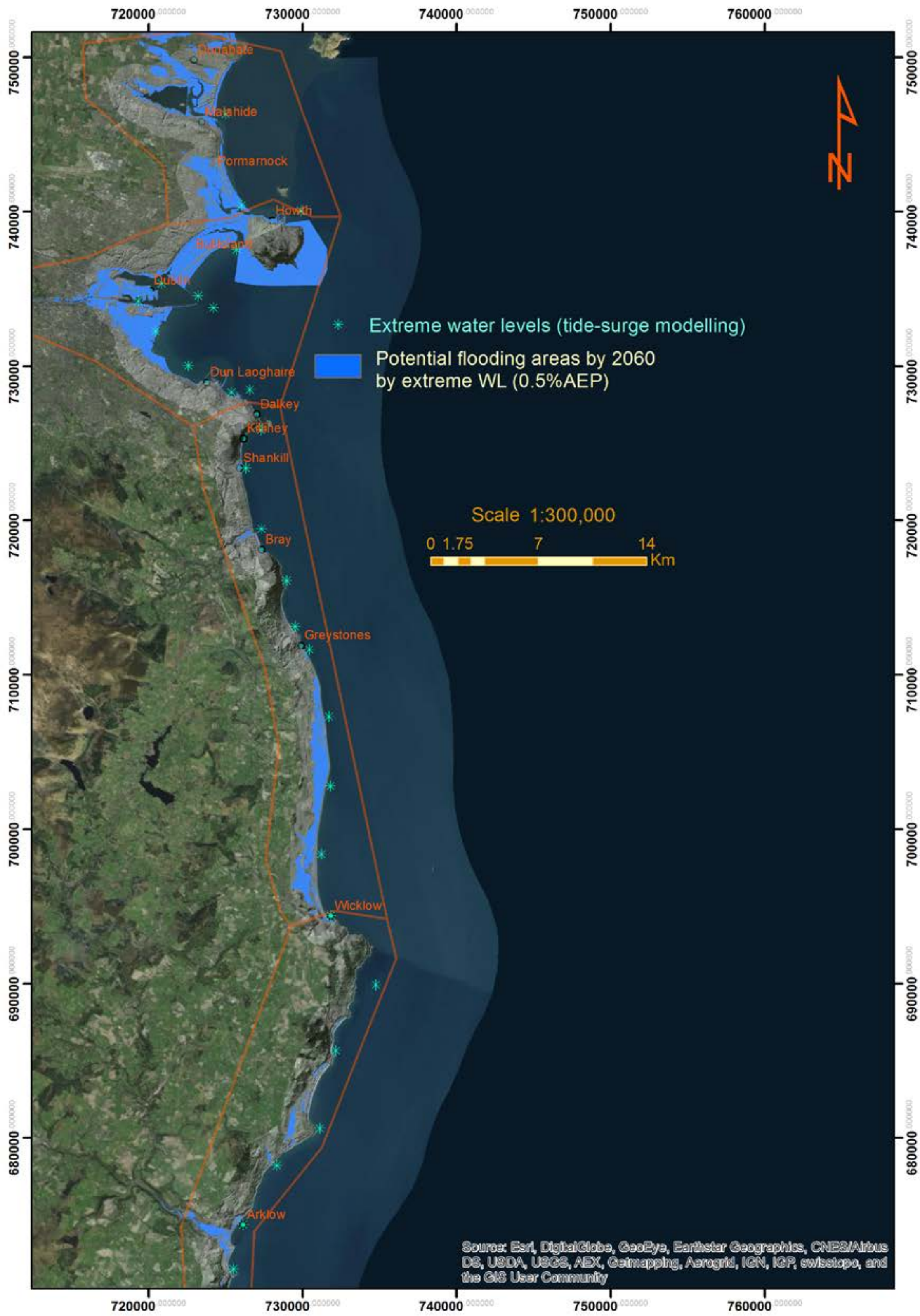


Figure II. 2. Potential flooding areas from extreme water levels (0.5%AEP) by 2060. (*Source: Silvia Caloca*).

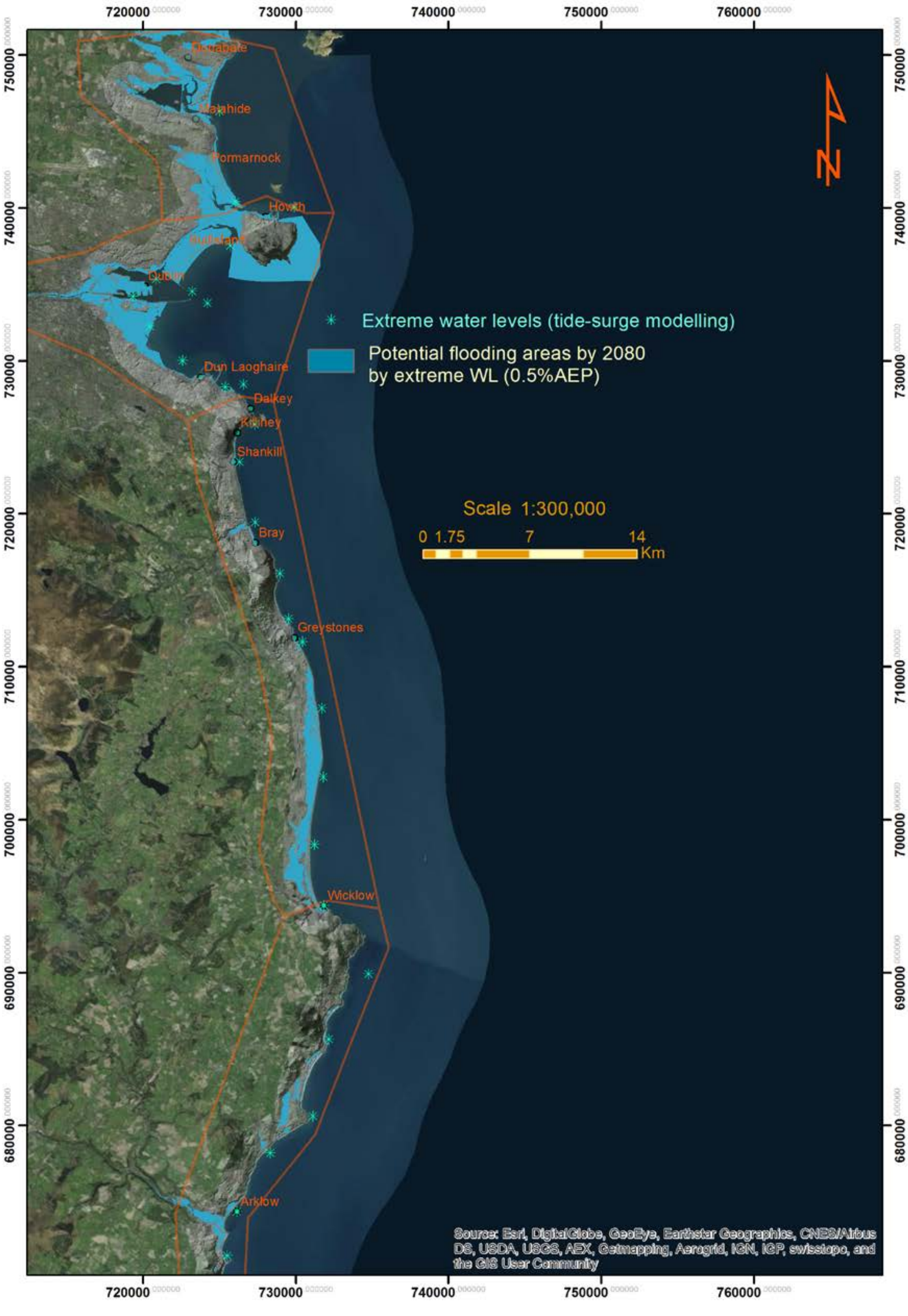


Figure II. 3. Potential flooding areas from extreme water levels (0.5%AEP) by 2080. (*Source: Silvia Caloca*).

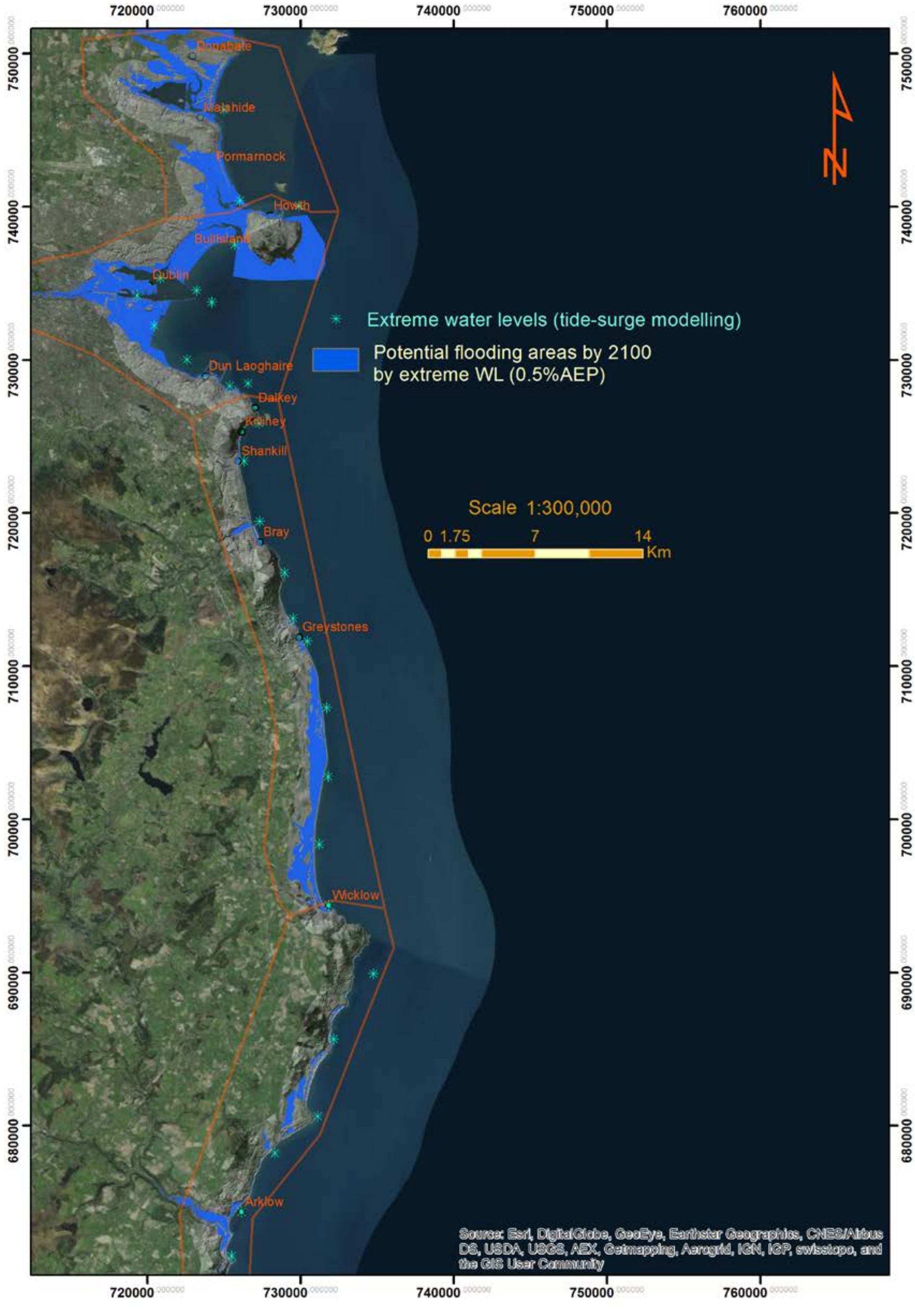


Figure II. 4. Potential flooding areas from extreme water levels (0.5%AEP) by 2100. *(Source: Silvia Caloca).*

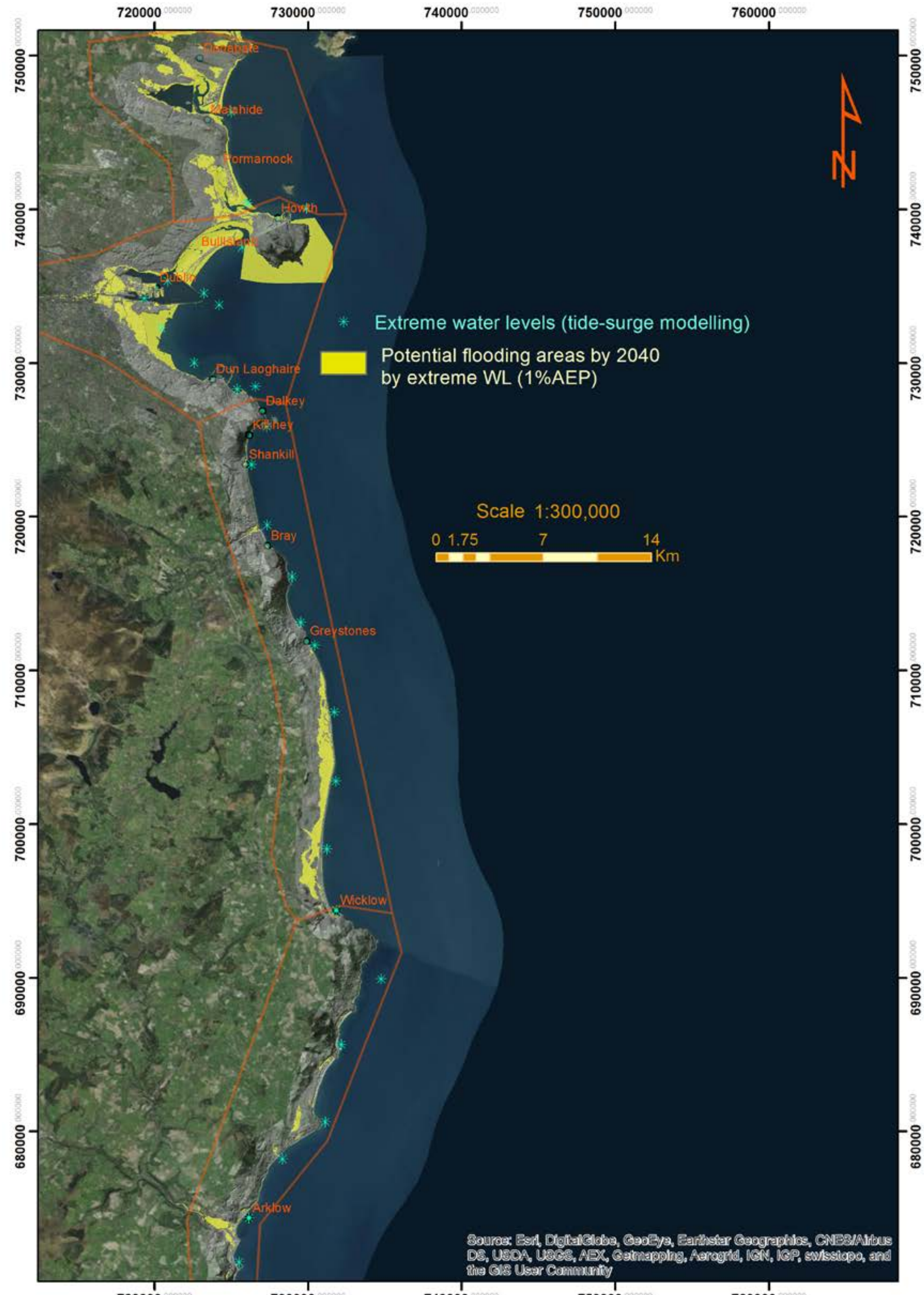


Figure II. 5. Potential flooding areas from extreme water levels (1%AEP) by 2040. *(Source: Silvia Caloca).*

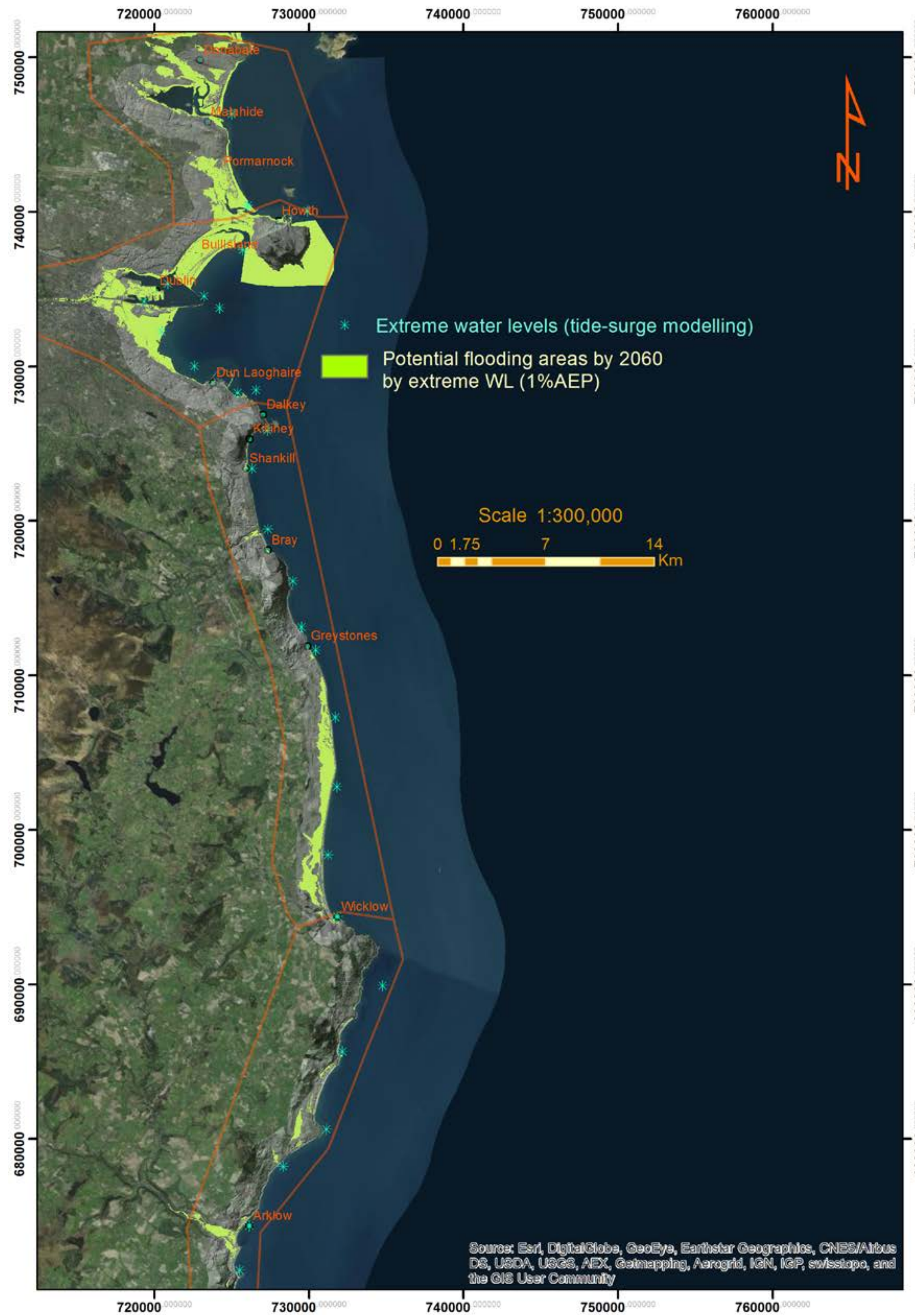


Figure II. 6. Potential flooding areas from extreme water levels (1%AEP) by 2060. *(Source: Silvia Caloca).*

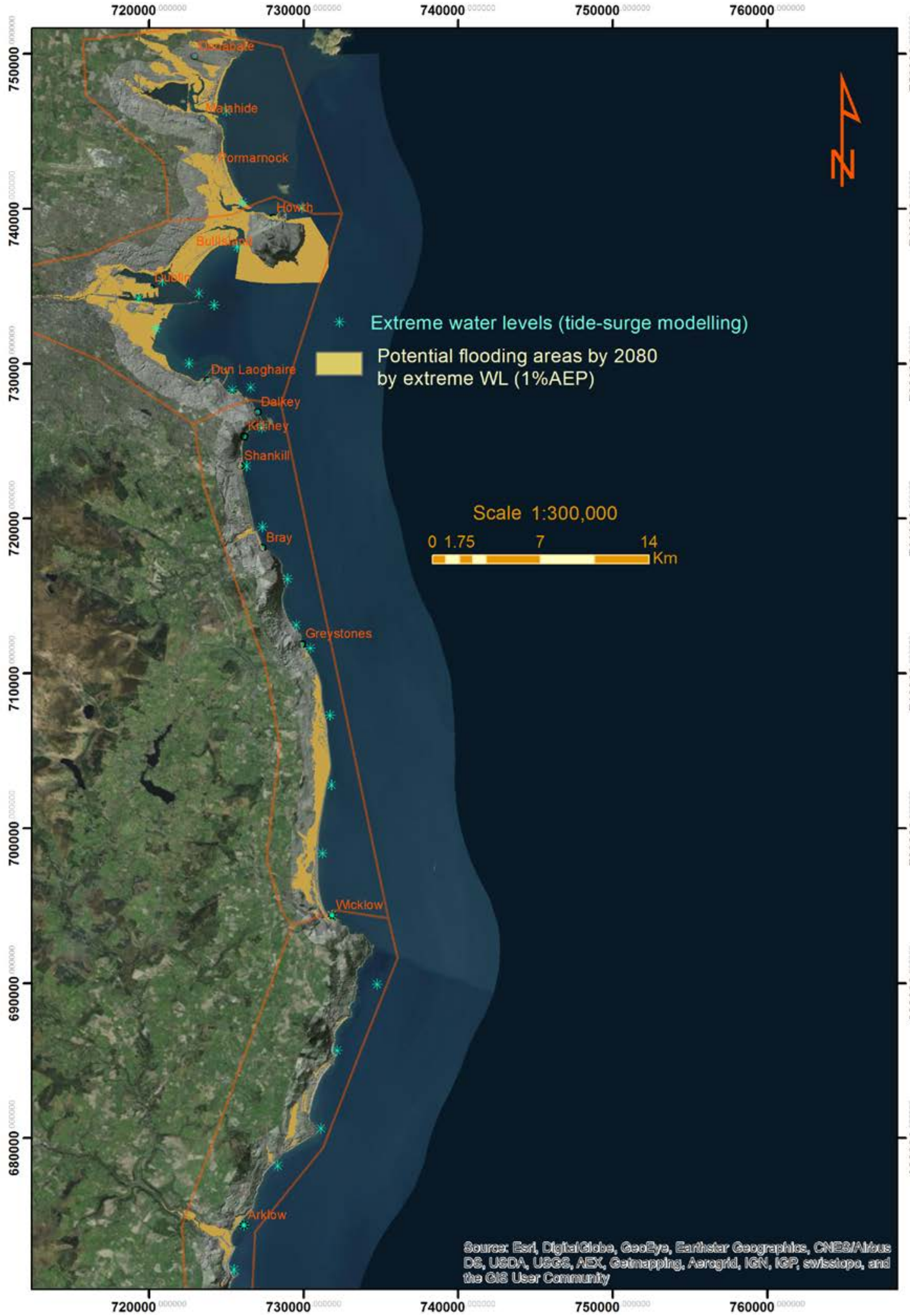


Figure II. 7. Potential flooding areas from extreme water levels (1%AEP) by 2080. *(Source: Silvia Caloca).*

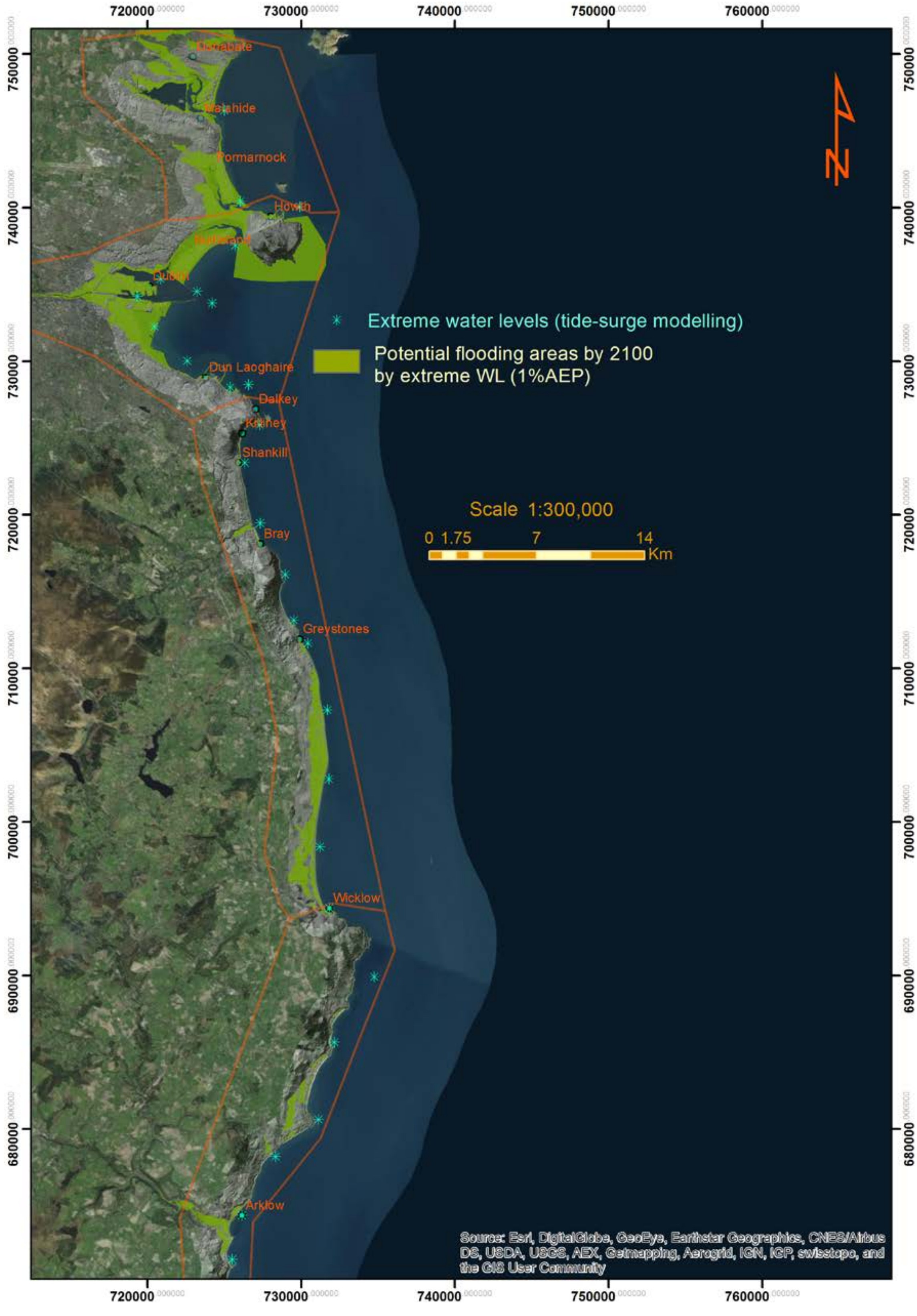


Figure II. 8 Potential flooding areas from extreme water levels (1%AEP) by 2100. *(Source: Silvia Caloca).*

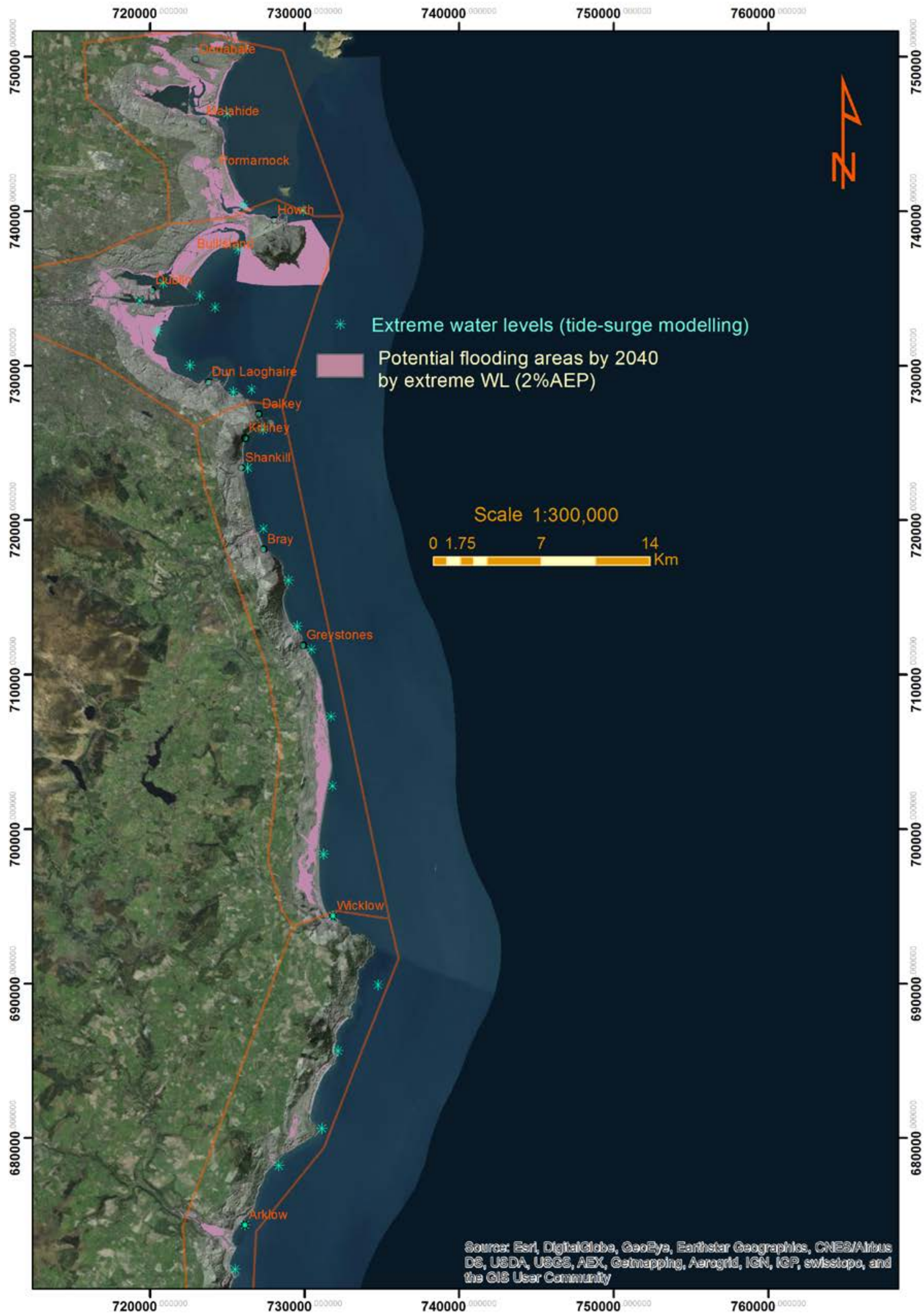


Figure II. 9. Potential flooding areas from extreme water levels (2%AEP) by 2040. *(Source: Silvia Caloca).*

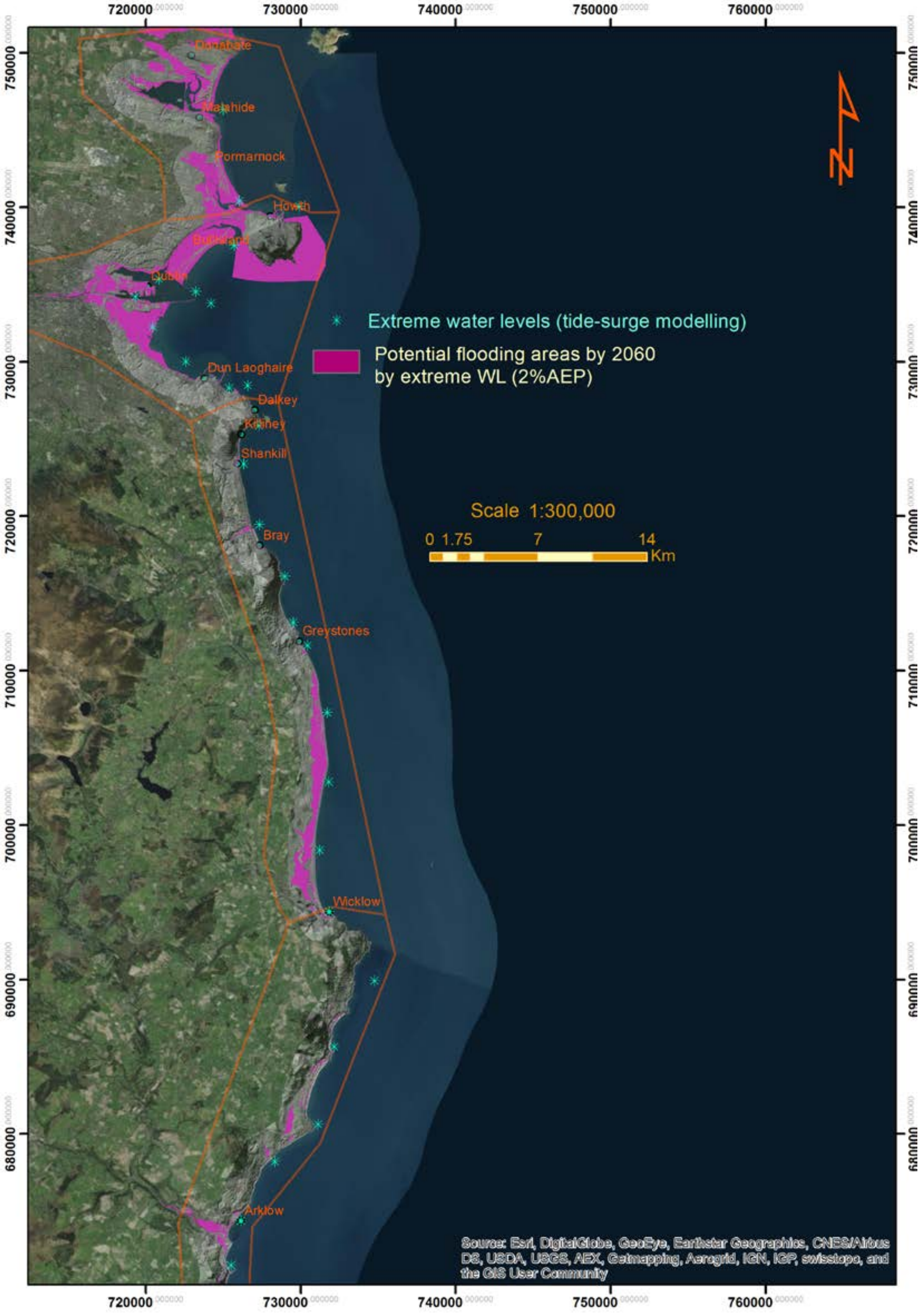


Figure II. 10. Potential flooding areas from extreme water levels (2%AEP) by 2060. *(Source: Silvia Caloca).*

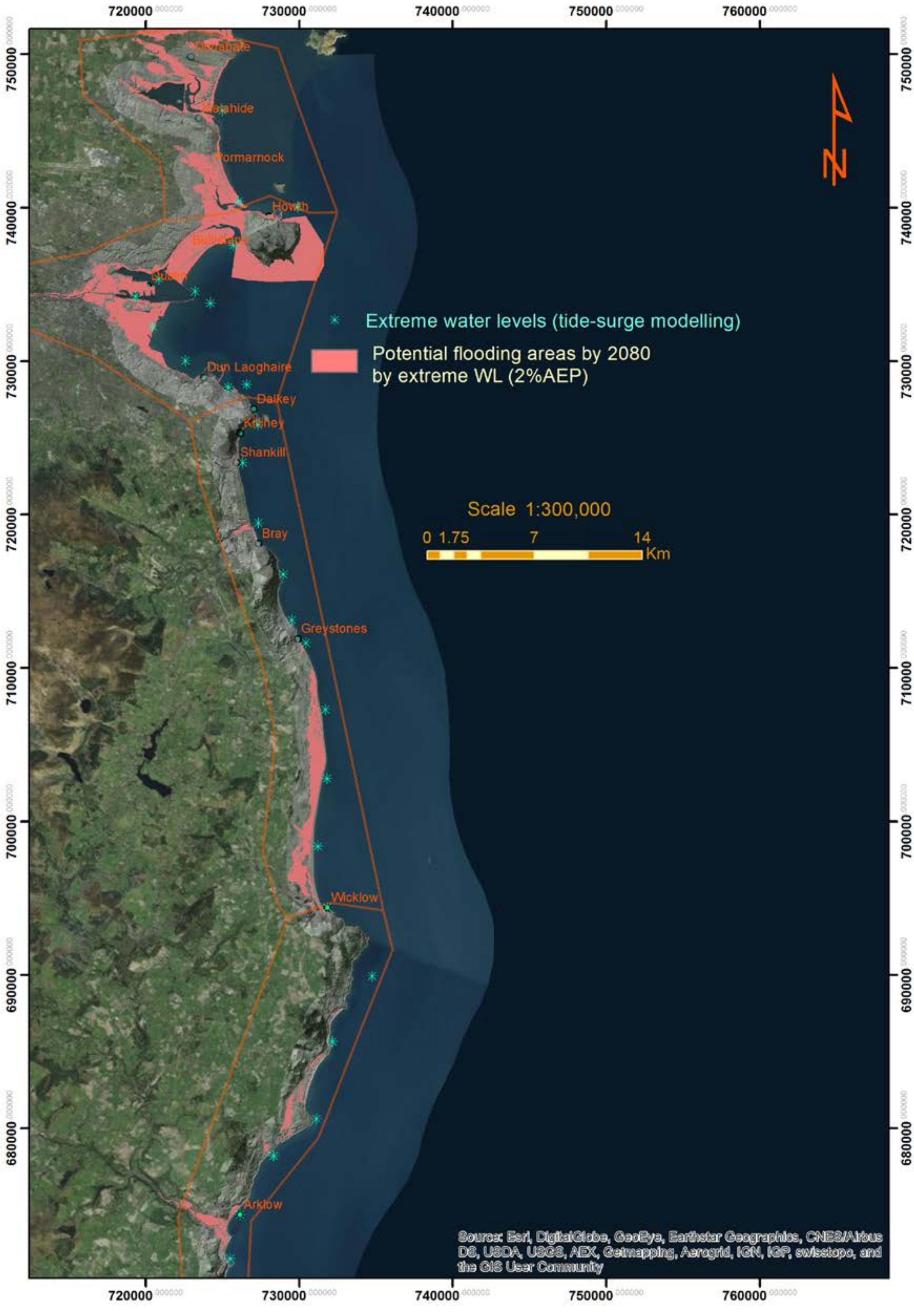


Figure II. 11. Potential flooding areas from extreme water levels (2%AEP) by 2080. *(Source: Silvia Caloca).*

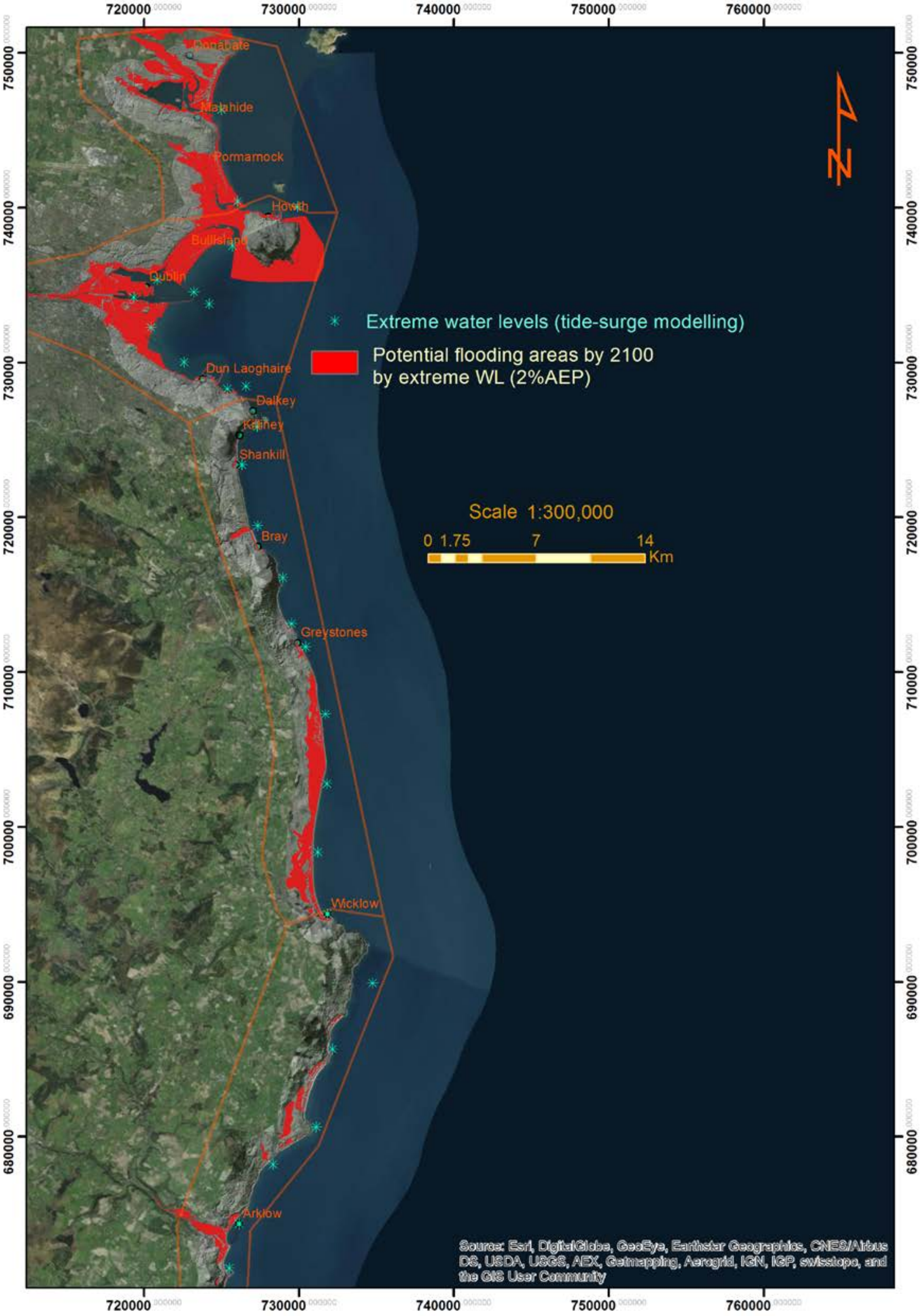


Figure II. 12. Potential flooding areas from extreme water levels (2%AEP) by 2100. *(Source: Silvia Caloca).*

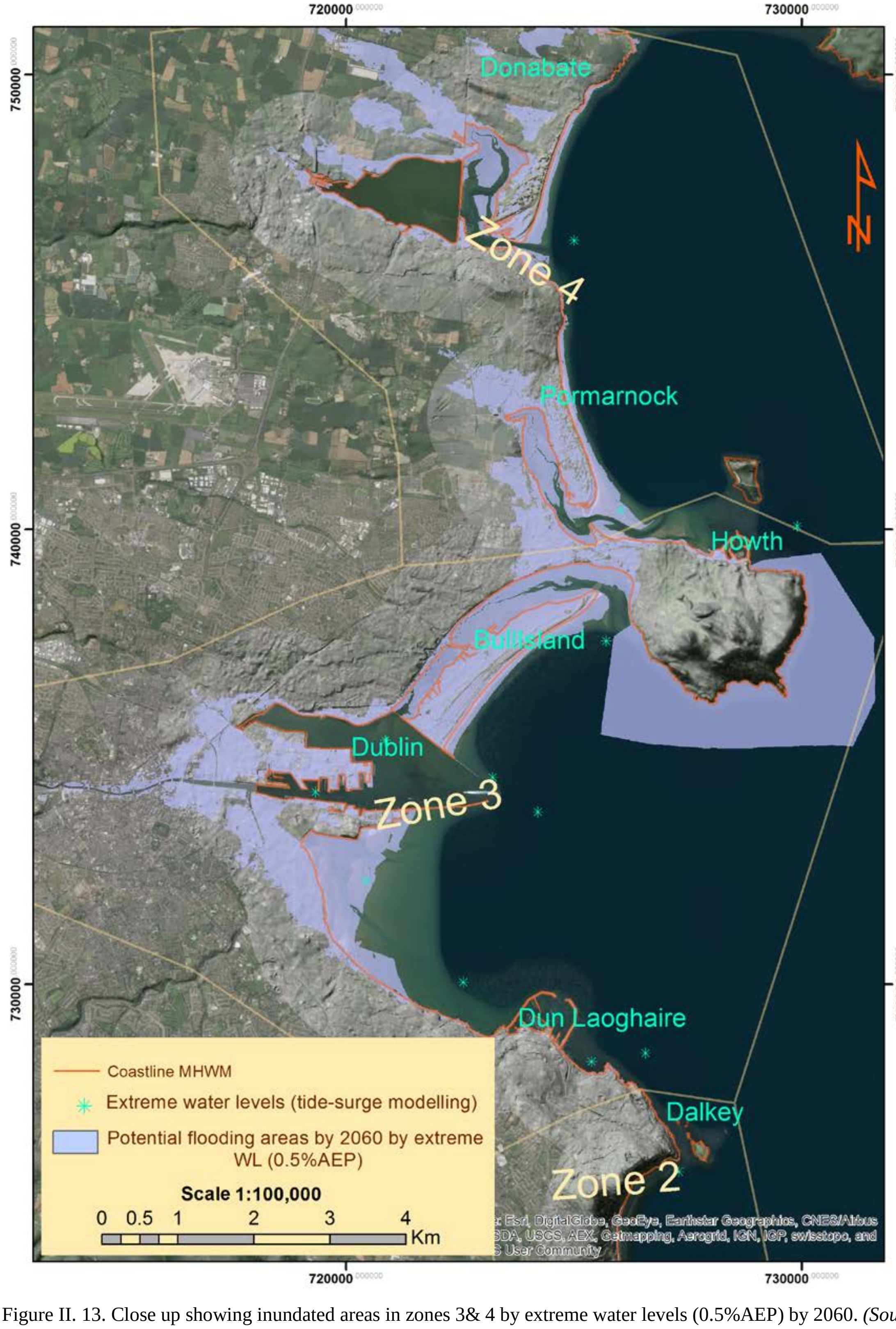


Figure II. 13. Close up showing inundated areas in zones 3& 4 by extreme water levels (0.5%AEP) by 2060. *(Source: Silvia Caloca).*

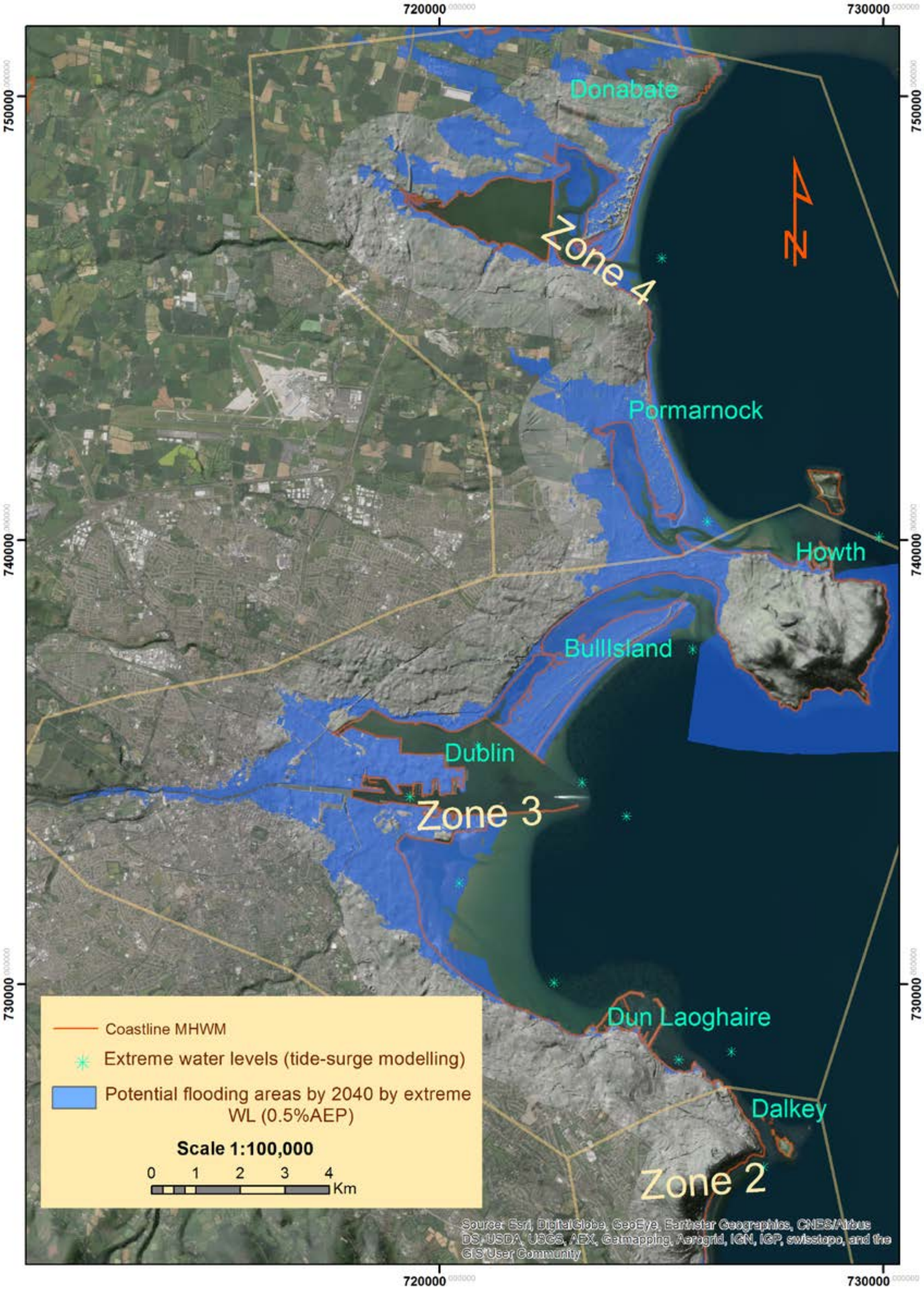


Figure II. 14. Close up showing inundated areas in zones 3& 4 by extreme water levels (0.5%AEP) by 2100. *(Source: Silvia Caloca).*

Figure II. 15. Close up showing inundated areas in zones 3 & 4 by extreme water levels (1%AEP) by 2060. *(Source: Silvia Caloca).*

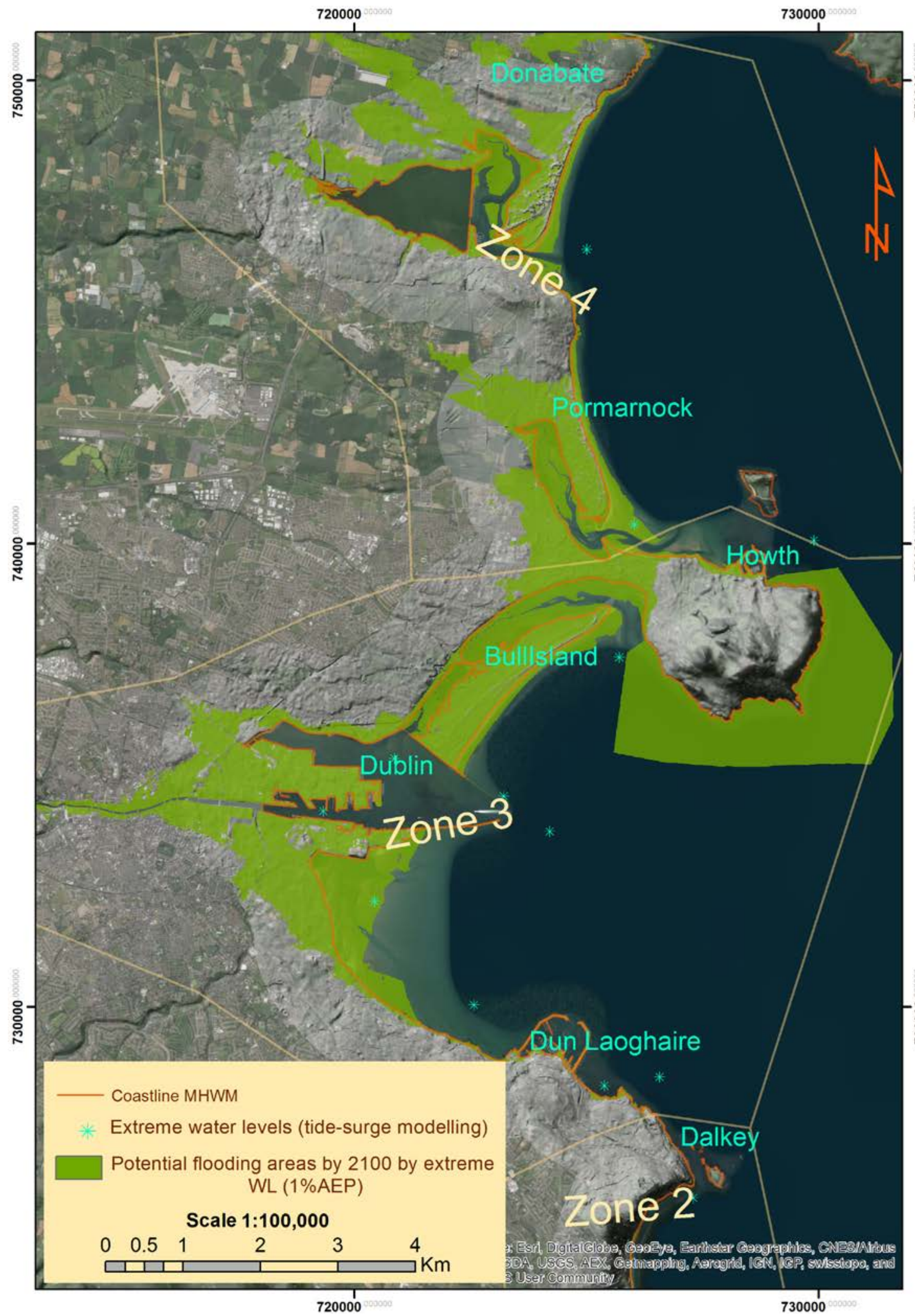


Figure II. 16. Close up showing inundated areas in zones 3 & 4 by extreme water levels (1%AEP) by 2100.

(Source: Silvia Caloca).

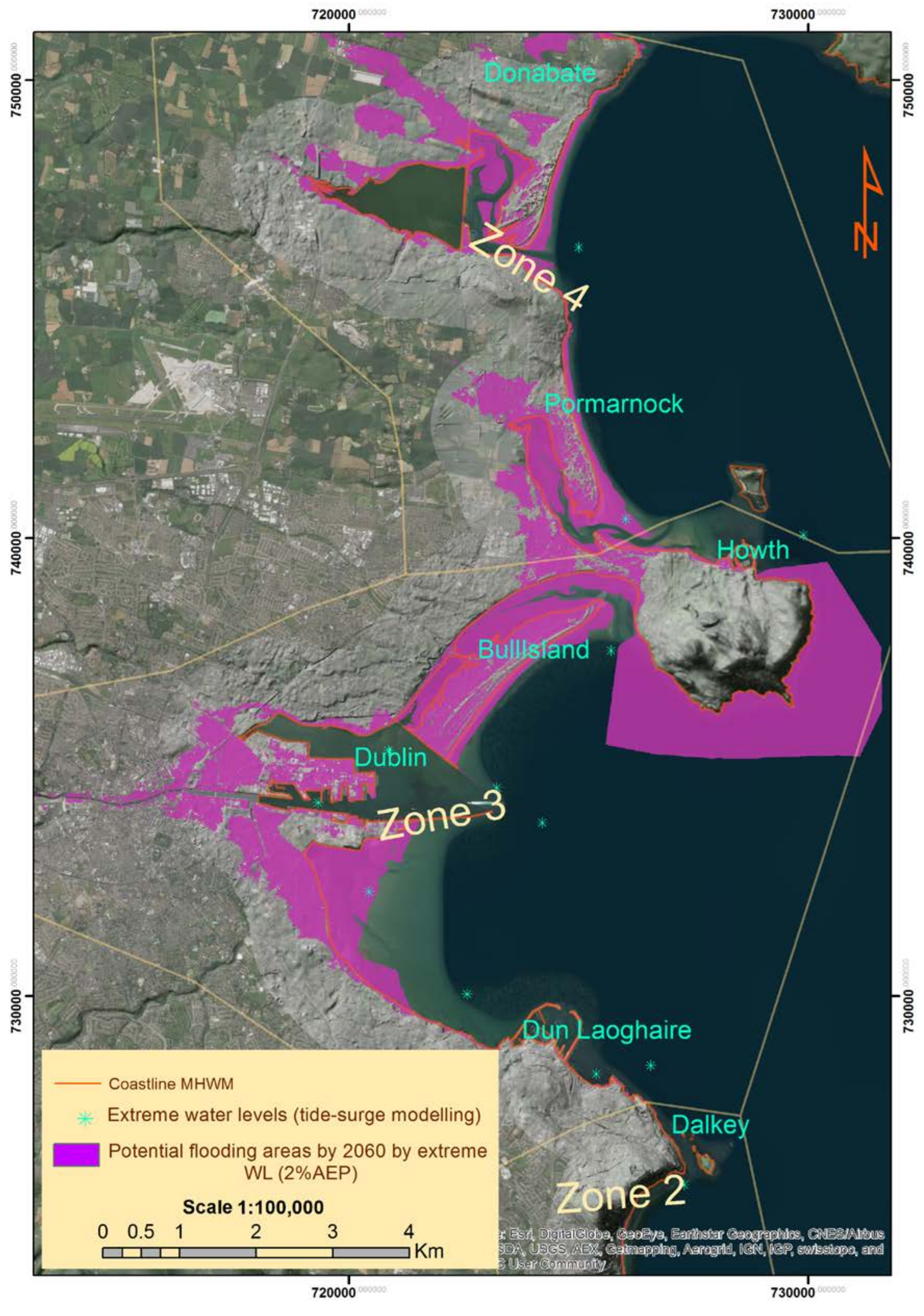


Figure II. 17. Close up showing inundated areas in zones 3 & 4 by extreme water levels (2%AEP) by 2060. *(Source: Silvia Caloca).*

Figure II. 18. Close up showing inundated areas in zones 3& 4 by extreme water levels (2%AEP) by 2100. *(Source: Silvia Caloca).*

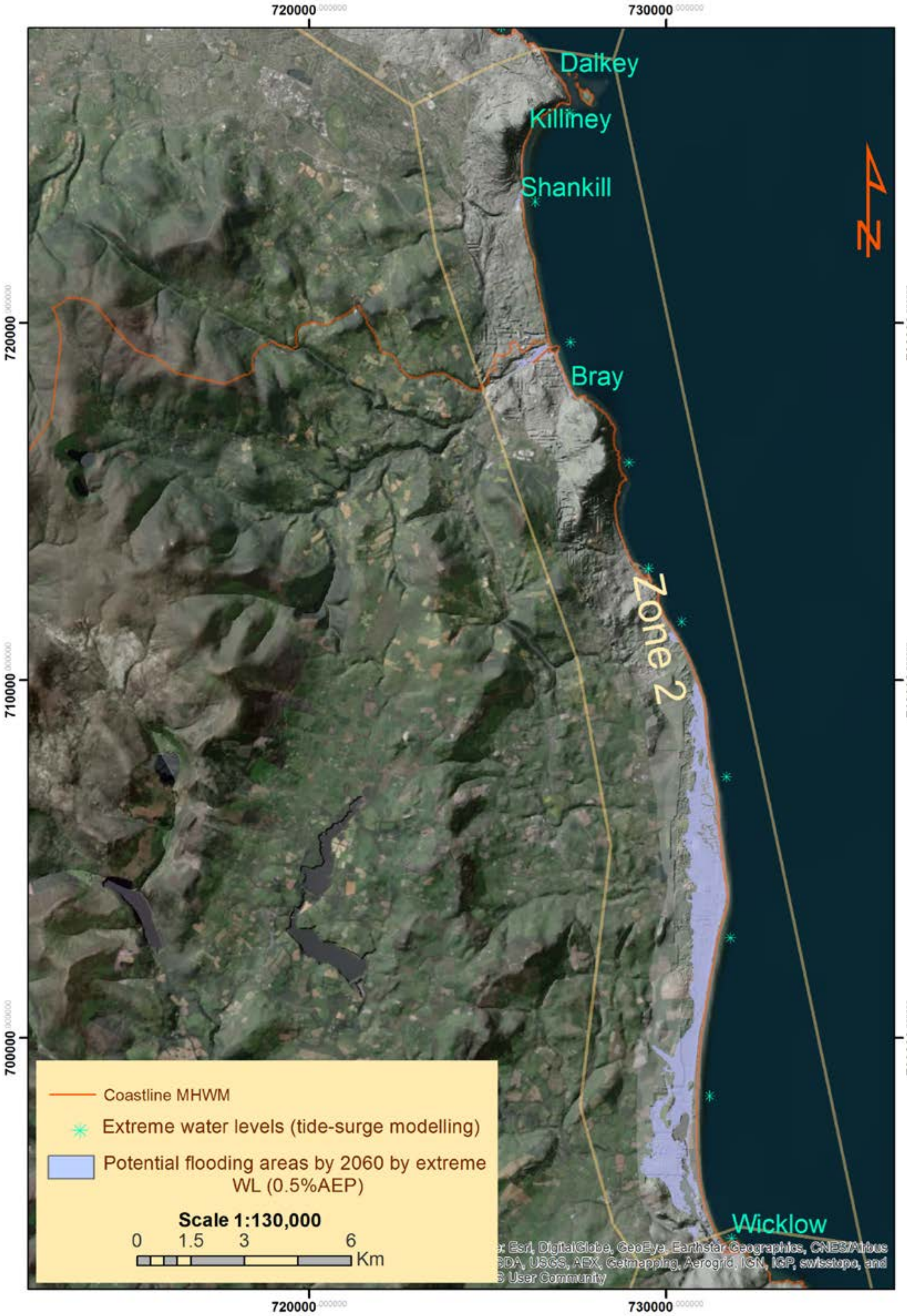


Figure II. 19. Close up showing inundated areas in zone 2 by extreme water levels (0.5%AEP) by 2060.

(Source: Silvia Caloca).

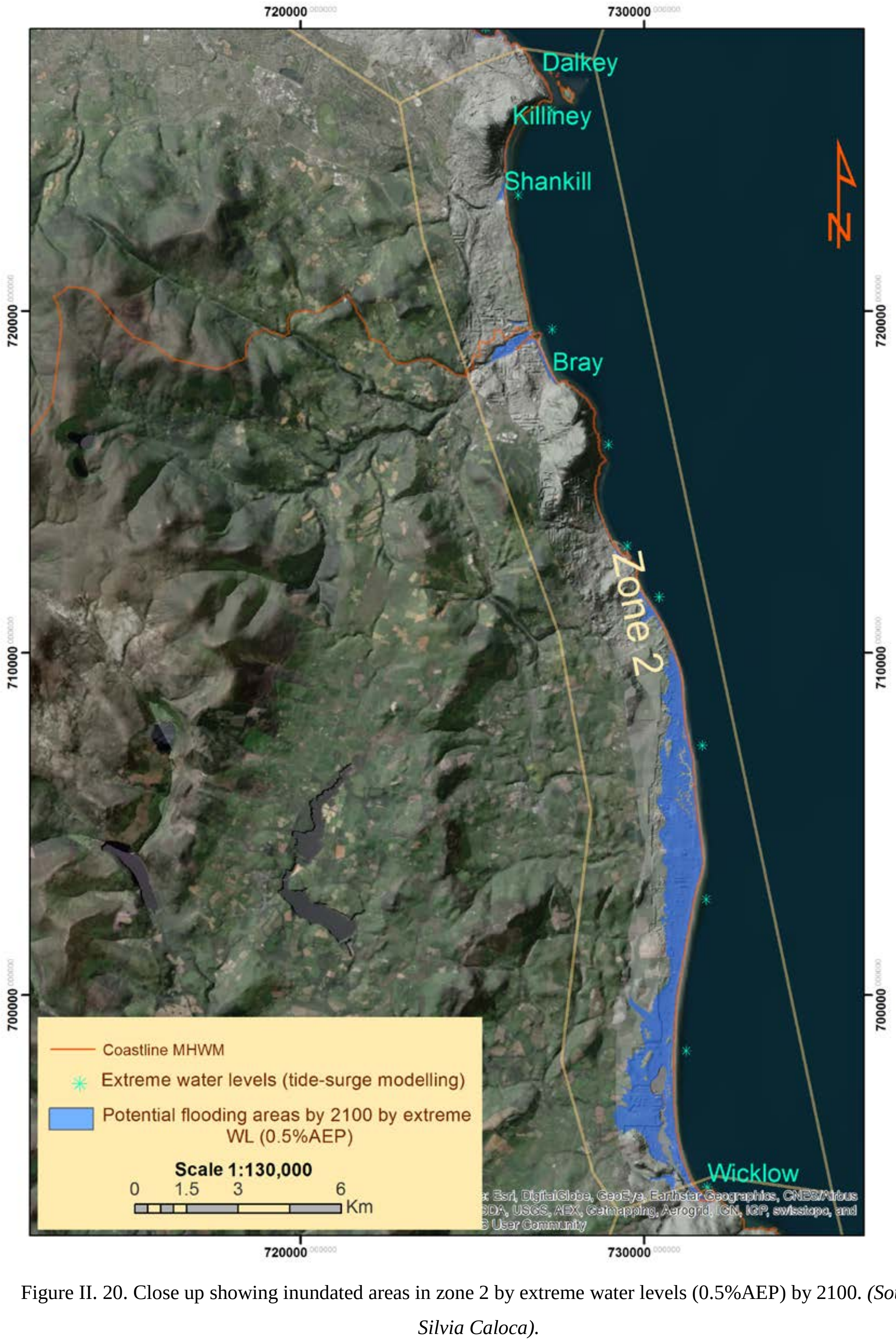


Figure II. 20. Close up showing inundated areas in zone 2 by extreme water levels (0.5%AEP) by 2100. *(Source: Silvia Caloca).*

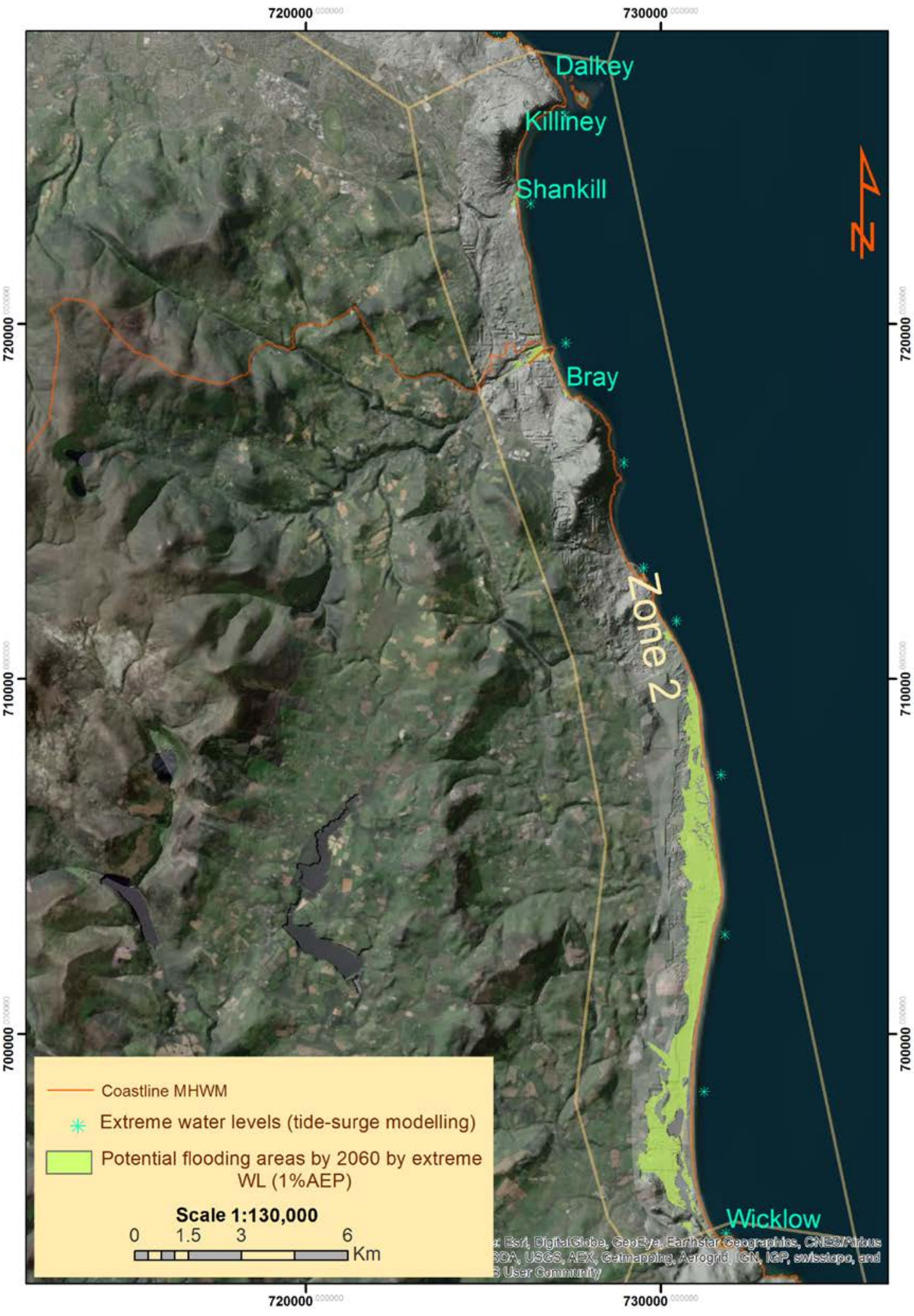


Figure II. 21. Close up showing inundated areas in zone 2 by extreme water levels (1%AEP) by 2060.

(Source: Silvia Caloca).

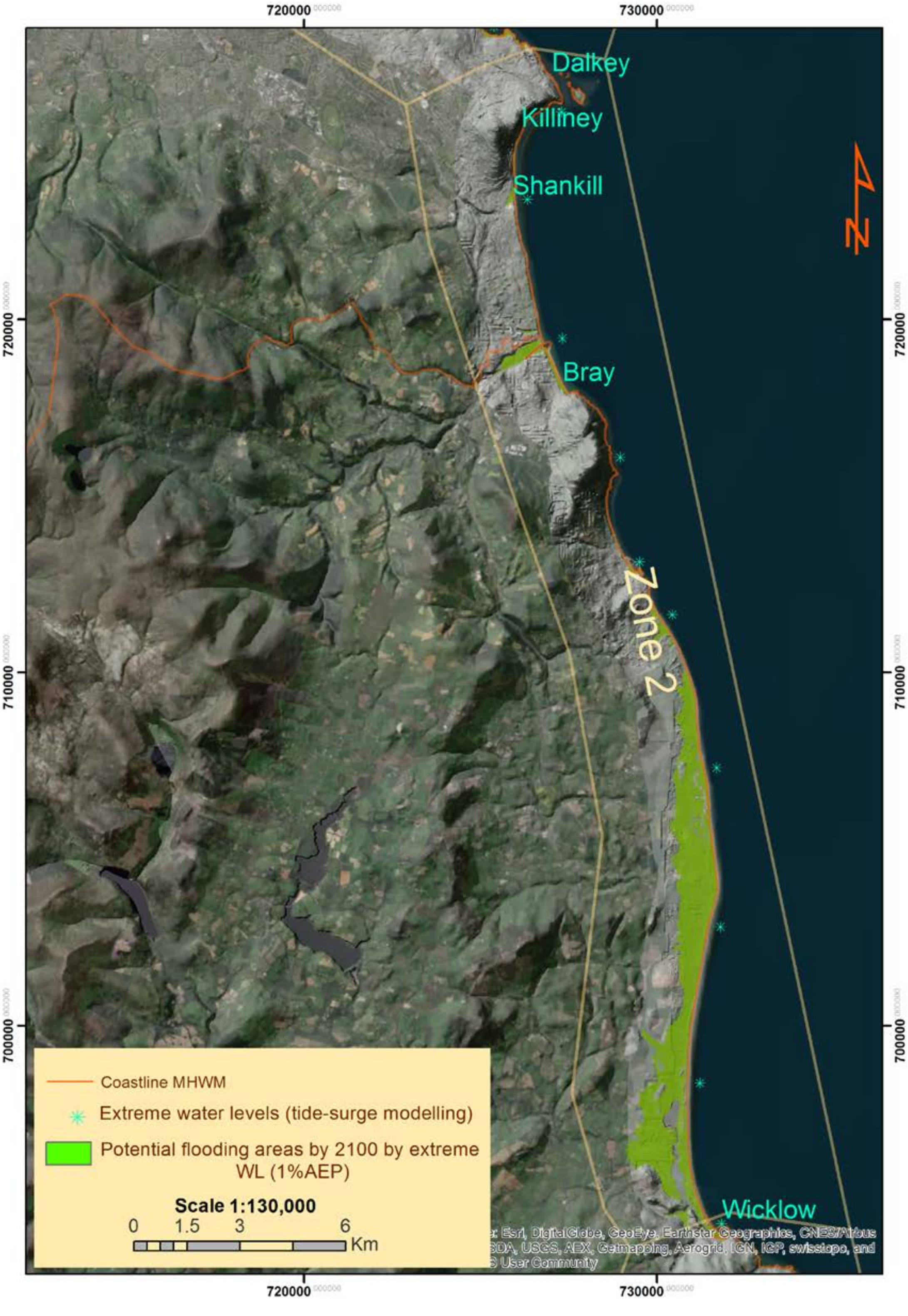


Figure II. 22. Close up showing inundated areas in zone 2 by extreme water levels (1%AEP) by 2100. *(Source: Silvia Caloca).*

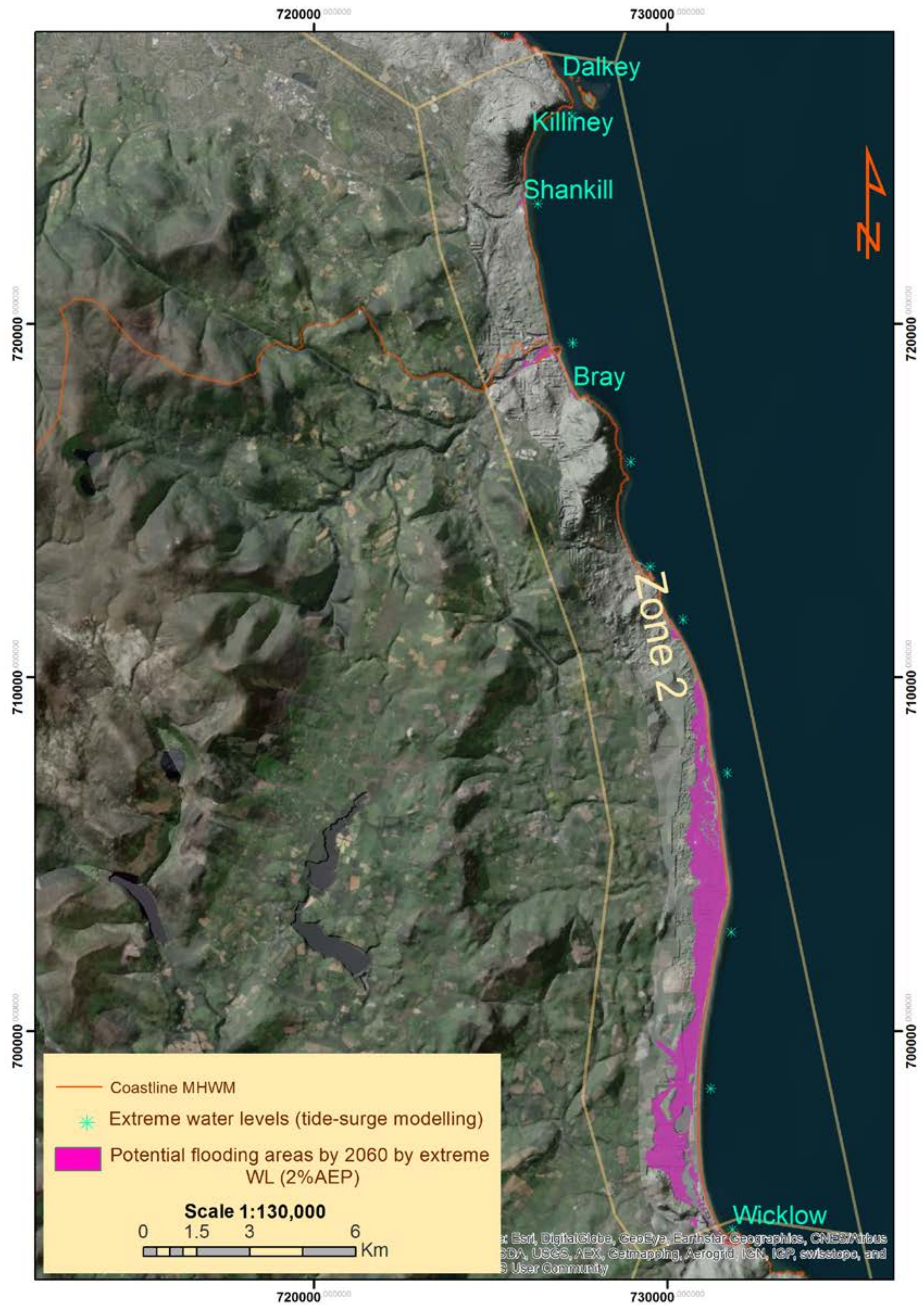


Figure II. 23. Close up showing inundated areas in zone 2 by extreme water levels (2%AEP) by 2060. *(Source: Silvia Caloca).*

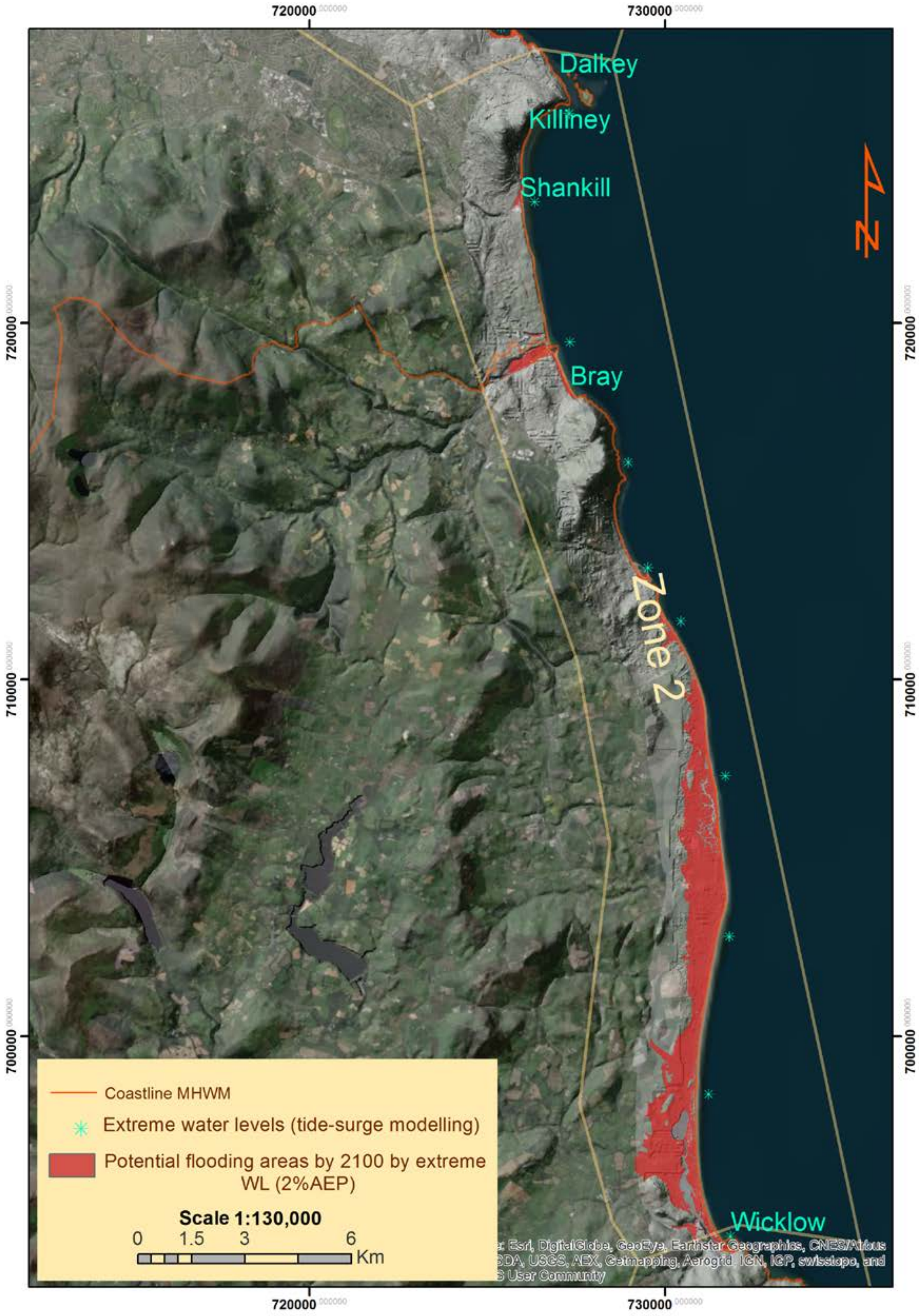


Figure II. 24. Close up showing inundated areas in zone 2 by extreme water levels (2%AEP) by 2100.

(Source: Silvia Caloca).

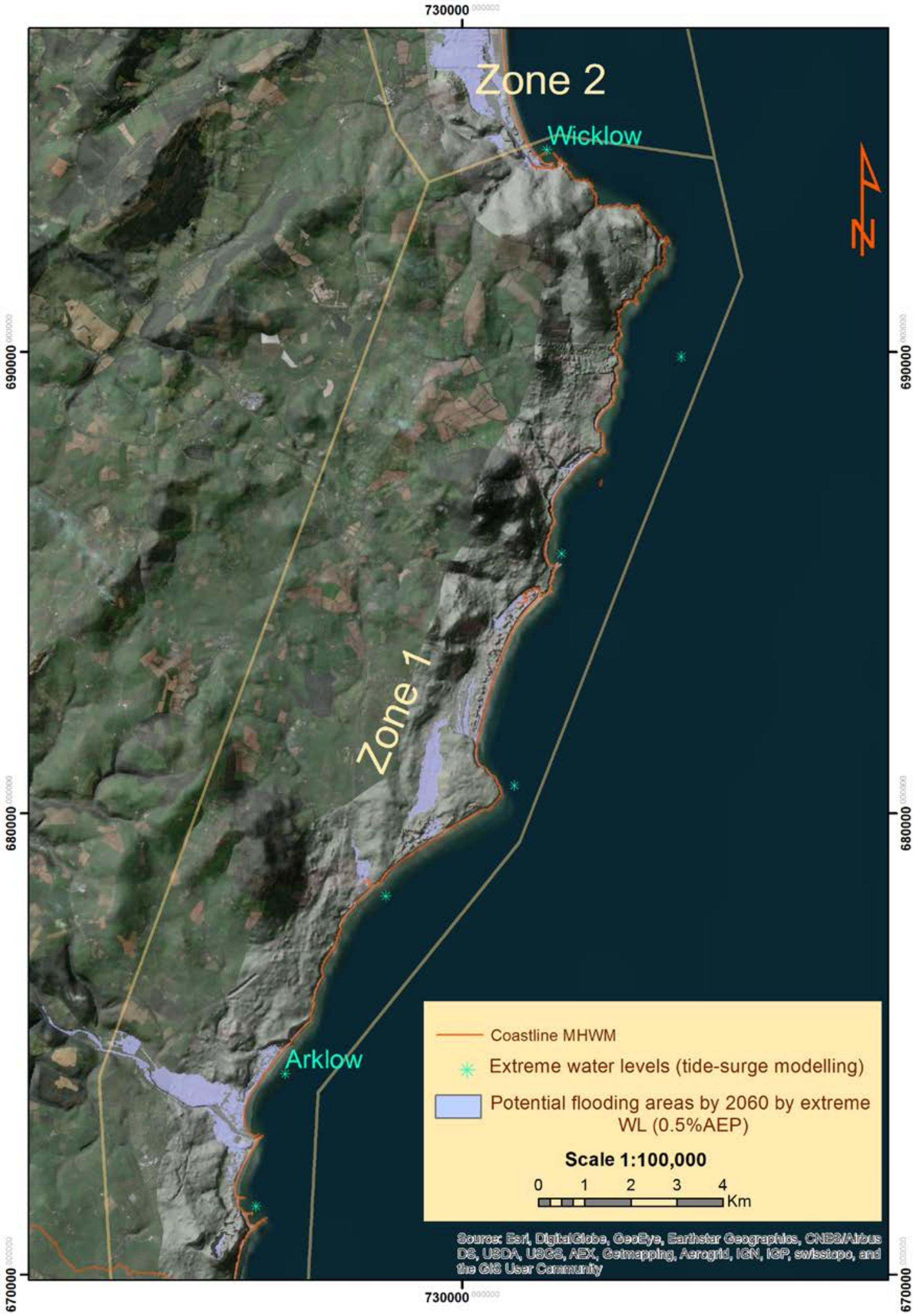


Figure II. 25. Close up showing inundated areas in zone 1 by extreme water levels (0.5%AEP) by 2060.

(Source: Silvia Caloca).

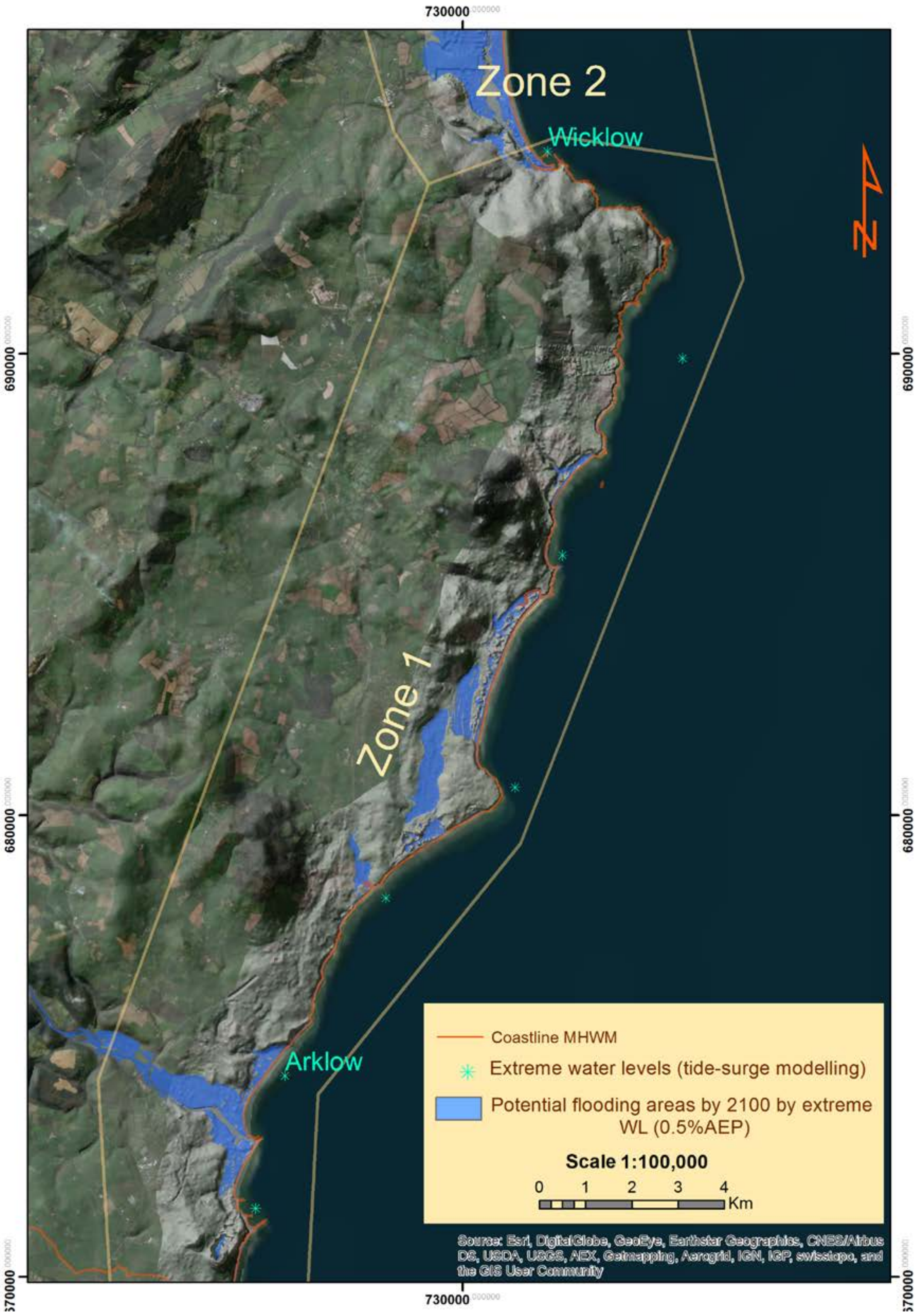


Figure II. 26. Close up showing inundated areas in zone 1 by extreme water levels (0.5%AEP) by 2100.

(Source: Silvia Caloca).

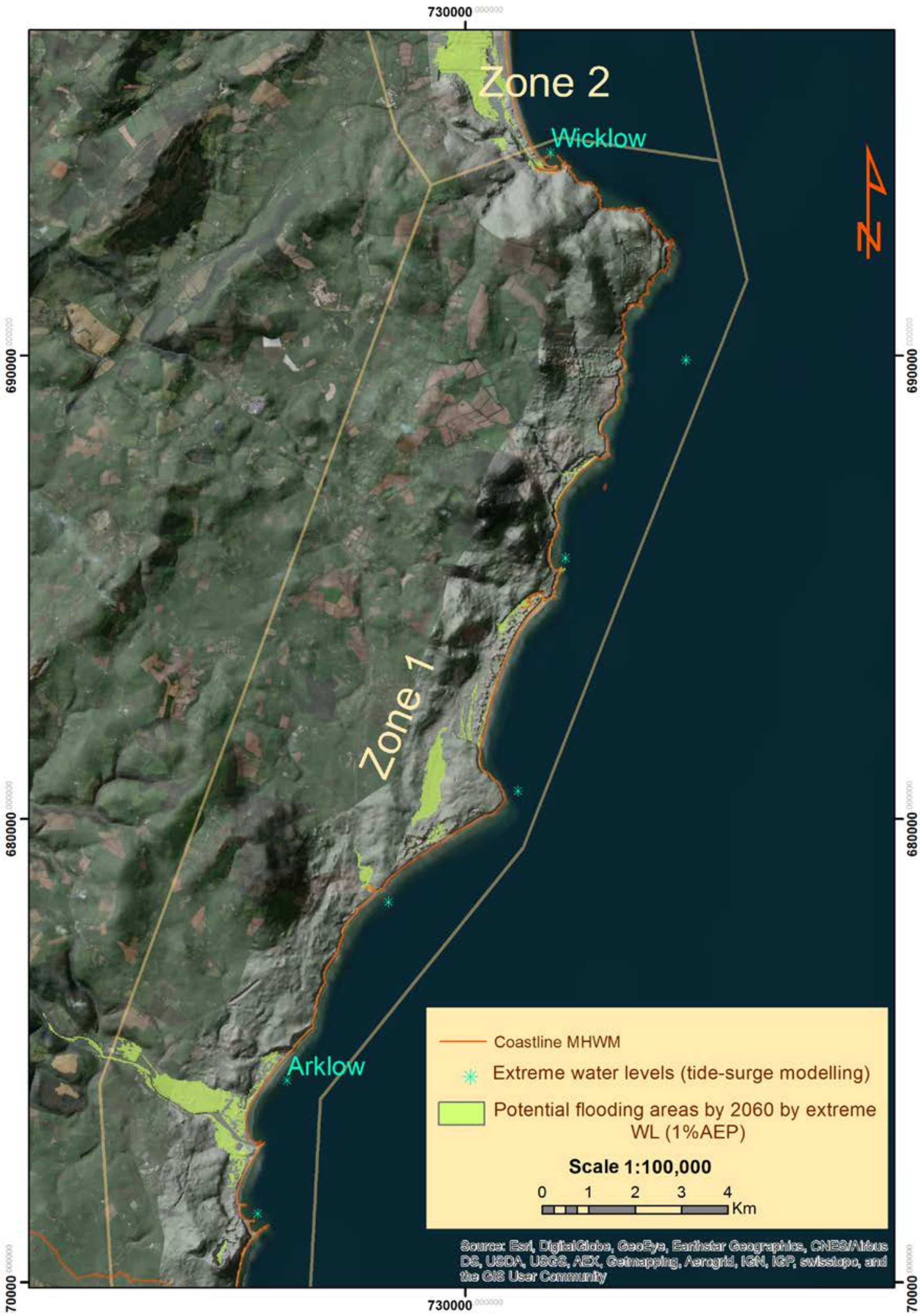


Figure II. 27. Close up showing inundated areas in zone 1 by extreme water levels (1%AEP) by 2060.

(Source: Silvia Caloca).

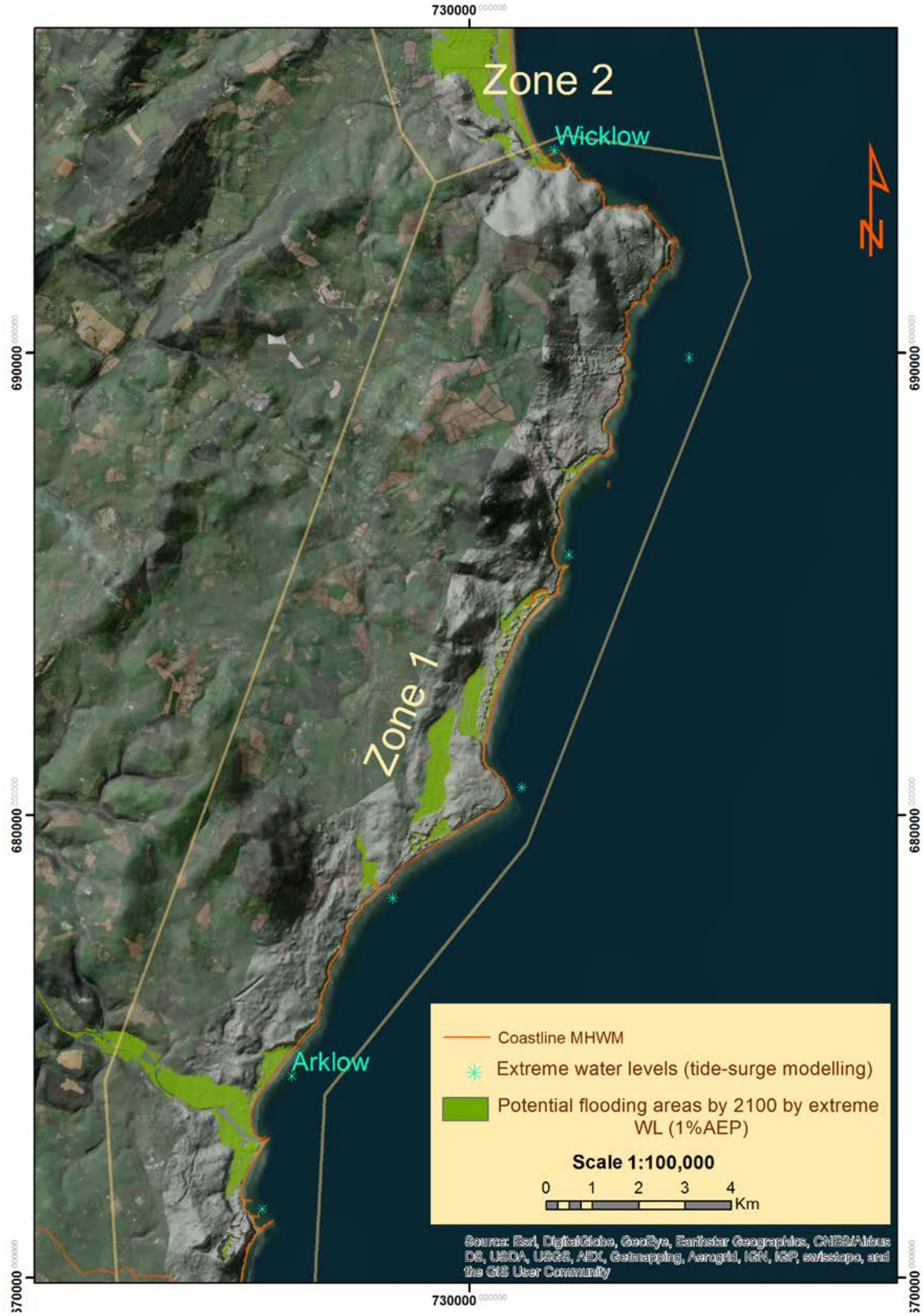


Figure II. 28. Close up showing inundated areas in zone 1 by extreme water levels (1%AEP) by 2100.

(Source: Silvia Caloca).

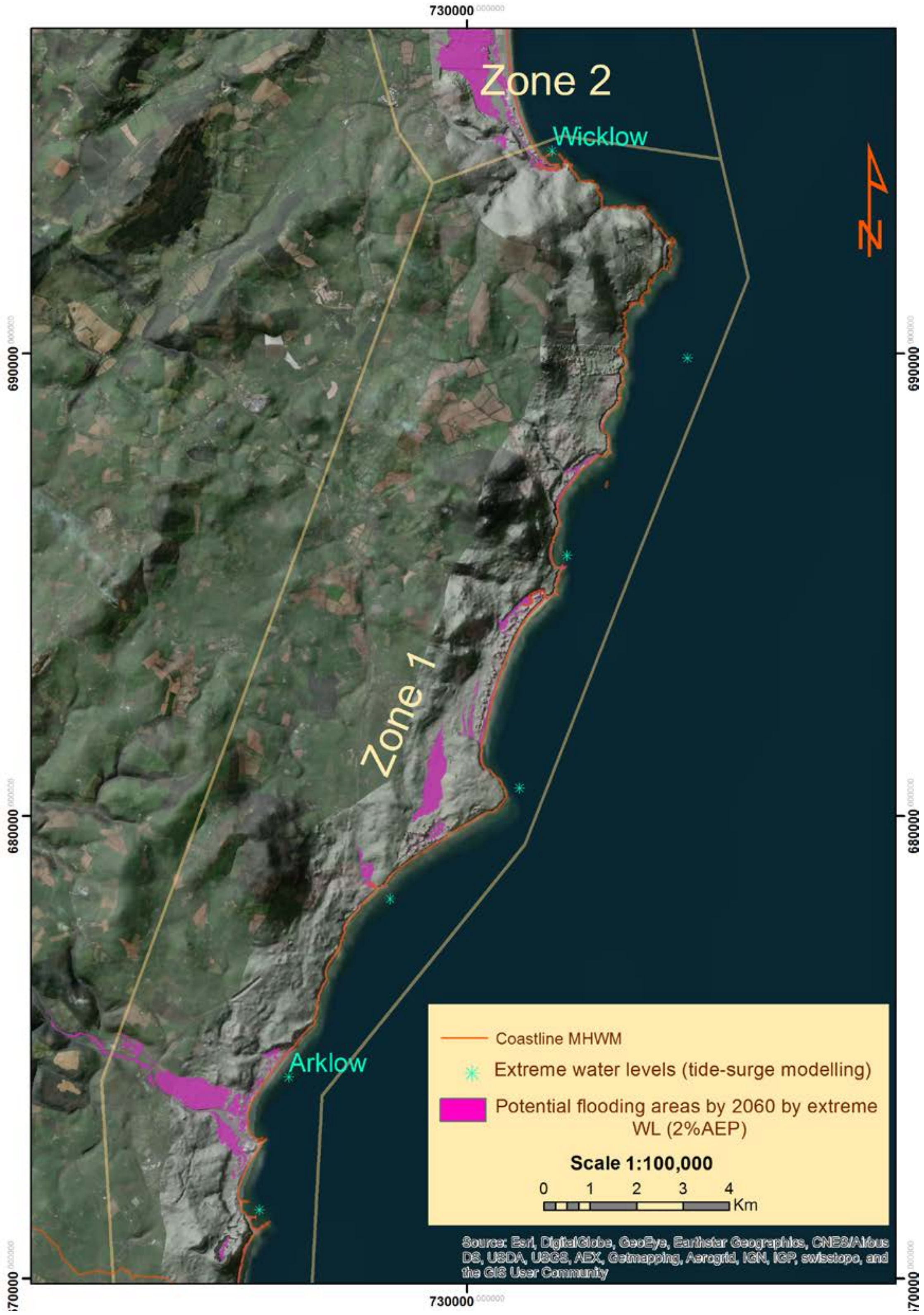


Figure II. 29. Close up showing inundated areas in zone 1 by extreme water levels (2%AEP) by 2060.

(Source: Silvia Caloca).

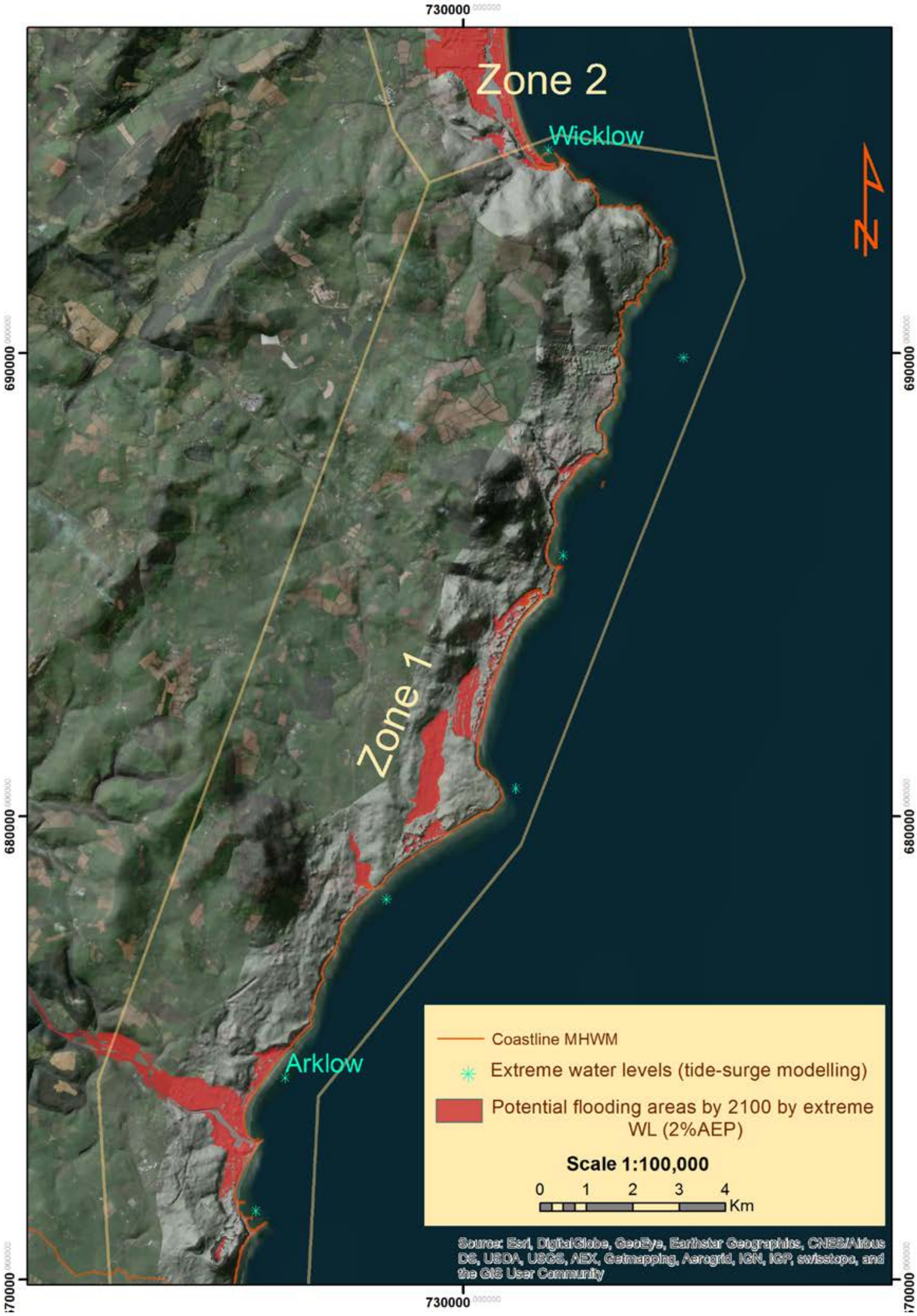


Figure II. 30. Close up showing inundated areas in zone 1 by extreme water levels (2%AEP) by 2100. *(Source: Silvia Caloca).*