Assessing coastal vulnerability: development of a combined physical and economic index

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List of Acronyms

ABI	Association of British Insurers
AMC	Agricultural Mortgage Corporation
BBC	British Broadcasting Corporation
BGS	British Geological Survey
CIA	Central Intelligence Agency
CVI	Coastal Vulnerability Index
CVI	Climate Vulnerability Index
CCVI	Combined Coastal Vulnerability Index
DARA	No Abbreviation Meaning An independent, international organisation based in Madrid, Spain
DEFRA	Department for Environment, Food and Rural Affairs
DESYCO	DESYCO is a GIS-based Decision support System for Coastal climate change impact assessment
DITTY	Development of an Information Technology Tool for the management of southern European lagoons under the influence of river-basin runoff
EF	Enhanced Fujita
EM-DAT	The International Emergency Disasters Database
EVI	Economic Vulnerability Index
EVI	Environment Vulnerability Index
ECVI	Economic Coastal Vulnerability Index
FVI	Flood Vulnerability Index
EUROSION	A European Initiative for Sustainable Coastal Erosion Management
EPA	Environmental Protection Agency
EA	Environment Agency
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
LVI	Livelihood Vulnerability Index
MLW	Mean Low Water Level
NOAA	National Hurricane Centre
NASA	National Aeronautics and Space Administration

ONS	Office of National Statistics
PCVI	Physical Coastal Vulnerability Index
RRA	Regional Risk Assessment
RSMA	Regional Specialised Meteorological Center
SLR	Sea Level Rise
UKCIP	United Kingdom Climate Impact Programme
SOVI	Social Vulnerability Index
SPSS	Statistical Package for Social Sciences
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
USA	United States of America

Abstract

As a consequence of climate change, global coastal communities are increasingly at risk from sea level rise and increased storm intensities. Therefore, to inform coastal zone management coastal vulnerability assessments with respect to present and predicted climate change scenarios is important. Most of the literature concentrates on physical, and to a lesser extent socio-economic aspects but no comparable studies detailing coastal vulnerability from both physical and economic vulnerability were found. To fill this important research gap, the current study developed a combined coastal vulnerability (physical + economic) index by integrating both a Physical Coastal Vulnerability Index (PCVI) and an Economic Coastal Vulnerability Index (ECVI). All indices were applied to eleven case study sites across the country and based on assessments, the Combined Coastal Vulnerability Index (CCVI) was validated. Subsequently, coastal areas were ranked according to their PCVI, ECVI and CCVI values.

PCVI results showed that Great Yarmouth and Happisburgh have high vulnerability, contrasted against an Aberystwyth frontage that was least vulnerable. ECVI assessments showed that both Great Yarmouth and Skegness have high economic vulnerability while Spurn Head had low economic vulnerability. In total, the economic costs related to case study site vulnerability was assessed at £22.36 billion. Combined coastal vulnerability results showed that Great Yarmouth is highly vulnerable with the highest aggregated score (25) followed by Aberystwyth (21). Llanelli (16) and Lynmouth (16) were least vulnerable with respect to site CCVI.

This research makes a contribution to knowledge, not just for the UK but on a global level. Each location has a unique set of conditions and economic needs, and was found to be functions of physical and economic pressures, e.g. number of properties, coastal erosion and population. Finding the most effective and sustainable solution is important and one that includes knowledge of environmental impact and socio-economic consequences. The three indices (PCVI, ECVI and CCVI) are justified as tools for planners and policy makers for developing management strategies to improve coastal resilience under scenarios of sea-level rise and climate change.

CHAPTER 1 – INTRODUCTION

1. Introduction

1.1 Preface

Coastal regions are vulnerable to extreme weather, such as storms, which incur significant costs to coastal societies. Historically, there are fundamental associations between coastal regions and anthropological settlements (Smit and Pilifosova, 2003; Sing, 2006; Haslett, 2008; Smith, 2013). Coastal populations and infrastructure have increased dramatically resulting in additional stresses due to land use and hydrological changes within low-level catchments (Nicholls *et al*., 2007; Baker, 2012). More than 40% of the world's population lives within 150 kilometres of the coast, and 8 of the 10 largest cities in the world are near the shoreline (Atlas, 2013). Globally, several recent worldwide extreme storm events have caused major human and economic losses in coastal zones, for example, Storm Xynthia (Kolen *et al*., 2010), Hurricane Sandy (Kantamaneni and Phillips, 2013), Typhoon Haiyan (Lagmay *et al*., 2015), and Cyclone Hudhud (Chejarla *et al*., 2016). While in the UK, the 2013-14 storm events caused extensive damage to coastal infrastructure (Huntingford *et al*., 2014; Dawson, 2016; Rangel-Buitrago *et al.,* 2016).

According to Nicholls *et al*. (2007), in excess of 120 million people are exposed to cyclone hazards every year, and 250,000 fatalities were caused by flooding between 1980 and 2000. Globally, floods affect 46 million people every year, and may rise to as many as 60 million a year by 2100 as a consequence of predicted sea level rise (Hoozemans *et al*., 1993). Increased flood events greatly affect socio-economic costs, particularly in populated estuaries, low-lying coastal urban areas, and islands, and these are important communal hotspots of vulnerability (Hinkel *et al*., 2010). The impacts of regional and global climate change, sea level rise, and weather fluctuations, alongside terrestrial processes, are serious threats to all coastal communities (Oliver-Smith, 2009; Zsamboky *et al*., 2011). Therefore, coastal vulnerability assessments are very important when consideration is given to the management and future development of coastal regions not only in the UK but elsewhere across the globe.

1.2 Identified research gaps

Research suggests there is much worldwide physical (Chapter 2) and to a lesser extent, socio-economic coastal vulnerability studies. Despite the socio-economic work of McLaughlin *et al.* (2002) and McLaughlin and Cooper (2010) on the Irish coast, and Denner *et al.*'s (2015) physical vulnerability work on the Welsh coast, very few UK studies have been undertaken.

This includes economic consequences and this was repeated globally because very few studies could be found which detailed both physical and economic vulnerability.

1.2.1 Coastal vulnerability

The UK coastline varies significantly in terms of morphology and human use, the coast being renowned for its distinctive natural beauty and diverse ecosystems. In some areas, there has been intensive tourism growth while, in others, intense industrial expansion. Suffolk and North Norfolk face extensive coastal erosion, with property, and vital natural areas under threat (Cooper and McKenna, 2008). Therefore, the vulnerability of coastal regions, around the United Kingdom with current predictions of sea level rise and climate change is an important factor. England and Wales were profoundly affected by severe storms in 2007, 2012, 2013, and 2014, all of which exacerbated vulnerability in many coastal regions (Slingo *et al*., 2014). Several worldwide studies evaluated coastal vulnerability based on geomorphological and physical perspectives but not from an economic viewpoint (Pethick and Crooks, 2000; Garthe and Hüppop, 2004; Martinez *et al*., 2006; Vittal Hegde and Radhakrishnan Reju, 2007; Abuodha and Woodroffe, 2010; Palmer *et al*., 2011; Balica *et al*., 2012; Gorokhovich *et al*., 2013; Kunte *et al*., 2014). Limited global research has been performed taking into account some socio-economic variables; see for example, Cutter *et al*. (2003), Vincent (2004), Schröter *et al*. (2005), Rygel *et al*. (2006), Hahn *et al*. (2009).

1.3 Aims and objectives

The main aim of this research is the development **of a Combined Physical and Economic Coastal Vulnerability Index**

To achieve this research aim, the following **objectives** have been outlined:

- To identify vulnerable coastal locations across the UK based on review of literature and multiple site visits;
- To assess physical vulnerability by developing and applying a site specific Physical Coastal Vulnerability Index (PCVI) modified from Palmer *et al*.'s (2011) and Denner *et al.'s* (2015) work;
- To estimate economic costs of UK coastal vulnerability at the selected sites by developing and applying an Economic Coastal Vulnerability Index (ECVI);
- To establish a combined Coastal Vulnerability Index (CCVI) from evaluation of site specific PCVI and ECVI indices.

Assessments will provide a useful, easy to use model that can be utilised by coastal managers, policy and decision makers for coastal zone management.

1.4 Scientific rigour and challenges

In developing countries, climate change influences can be catastrophic in terms of human cost but with developed nations, it is more of an economic challenge. However, there are conflicting views on climate change research worldwide. Consequently, this research concentrated on the nexus of climate change, storms, and coastal vulnerability of chosen sites in the UK. Economic data collection and analysis of coastal vulnerability is truly challenging and generally is compiled scientifically. In this respect this study differs in its approach by developing simple models, reducing data input and thereby having a wider appeal.

1.5 Summary

In order to assess current research findings and identify research gaps, literature searches (Chapter 2) began by examining the factors that contribute to coastal vulnerability, followed by an evaluation of current methodological approaches.

CHAPTER 2 – LITERATURE REVIEW

2. Literature Review

2.1 Introduction

A literature review is an objective, via summary and critical scrutiny of relevant, accessible research and non-research literature on the particular topic being studied/investigated (Hart, 1998). There are two main types of literature review; traditional and systematic or methodological. The methodological approach is a rigorous and well-defined method of reviewing the literature regarding particular frameworks in a precise subject area (Parahoo, 2006). Accordingly, the current study divided the literature review into two significant parts as follows (Figure 2.1):

- **2.2 - Topic review**
- **2.3 - Methodological review**

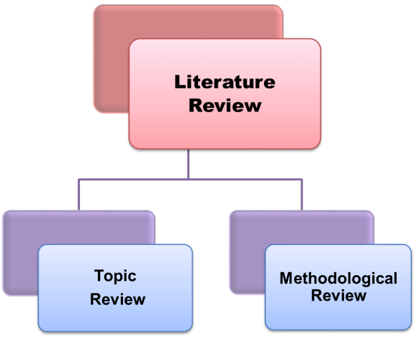


Figure 2.1: Literature review process

2.2 Topic review

Climatologists accept that climate change is an issue that must be addressed, and current climatic scenarios are undoubtedly linked to population growth, global warming, sea level rise, and industrialisation (Hitz and Smith, 2004; Schellnhuber, 2006; Weisse *et al*., 2014). Human-induced or natural climate change can create variations in the occurrence of moderate to severe weather patterns (Meehl *et al*., 2007). Human-induced global warming has significantly contributed to several climatic events that have been observed in the last two centuries (Pachauri *et al*., 2014). Coastal environments are severely affected by these climatic fluctuations (Sutton-Grier *et al*., 2015), and coastal flooding is a growing global concern (McGranahan *et al*., 2007; Kirshen *et al*., 2008). Therefore, this chapter deals with the importance of climate change, global warming, greenhouse gases, sea level rise, and temperature trends related to coastal environmental vulnerability.

2.2.1 Global warming

Global warming is augmented by anthropogenic influence, such as, CO_2 and other emissions alongside weak climate policies and procedures (Cox *et al*., 2000; Walther *et al*., 2002; Lal, 2004; Shine *et al*., 2005; Stern and Treasury, 2006; Leiserowitz, 2006; Houghton, 2009). This has led to increasing climatic change and the formation of unprecedented weather events such as flooding, coastal erosion and storm surges (Adger *et al*., 2005; Bouwer, 2011) evident from recent global storm disasters such as cyclone Hduhud (2014 - India) and hurricane Matthew (2016- US, Canada, Cuba, Jamaica, Colombia) (Chejarla *et al.,* 2016; Camacho et al., 2016).

Increasing worldwide temperatures have been the cause of glacial melt across the world (Hansen *et al*., 2005; Hanna *et al*., 2008), and due to these consequences, storminess has amplified in both frequency and severity (Hanna *et al*., 2008). The warmest year since records began in 1880 was 2015 (NOAA, 2016) and 15 of the 16 warmest years, in the 134-year record, occurred during the 21st century (Table 2.1). Global annual temperature has increased at an average rate of 0.07°C per decade since 1880 and at an average rate of 0.17°C per decade since 1970 (NOAA, 2016). Several factors contribute to global warming, but the main one is an upsurge in greenhouse emissions (Meinshausen *et al*., 2009).

Table 2.1: Sixteen warmest years (1880-2015)
Reproduced from NOAA, 2016

Rank	Year	Anomaly °C
1	2015	0.9
2	2014	0.74
3	2010	0.7
4	2013	0.66
5	2005	0.65
6	1998	0.63
6	2009	0.63
8	2012	0.62
9	2003	0.61
9	2006	0.61
9	2007	0.61
12	2002	0.6
13	2004	0.57
13	2011	0.57
15	2001	0.54
15	2008	0.54

2.2.2 Greenhouse gases

Since the start of the industrial age there has been significant increases in greenhouse gas emissions (CO_2, CH_4, N_2O, fluorinated gasses, hydro fluorocarbons, and sulphur hexafluoride), which entrap the temperature in the atmosphere (Dalal and Allen, 2008; Wiedmann and Minx, 2008) and also generate negative ripples in climate change patterns (Overpeck *et al.*, 1997). The rapid increase in CO_2 concentrations across the globe is mainly due to the combustion of fossil fuels, land use change (Wuebbles and Jain, 2001) and agricultural processes. These actions also cause the high accumulation of CH_4 and N_2O (Motha and Baier, 2005; Conrad, 1996; Wood and Cowie, 2004) gases. However, the impact of rising greenhouse-gas emissions on climate is not evenly felt across the world (Meinshausen *et al.*, 2009) (Figure 2.2).

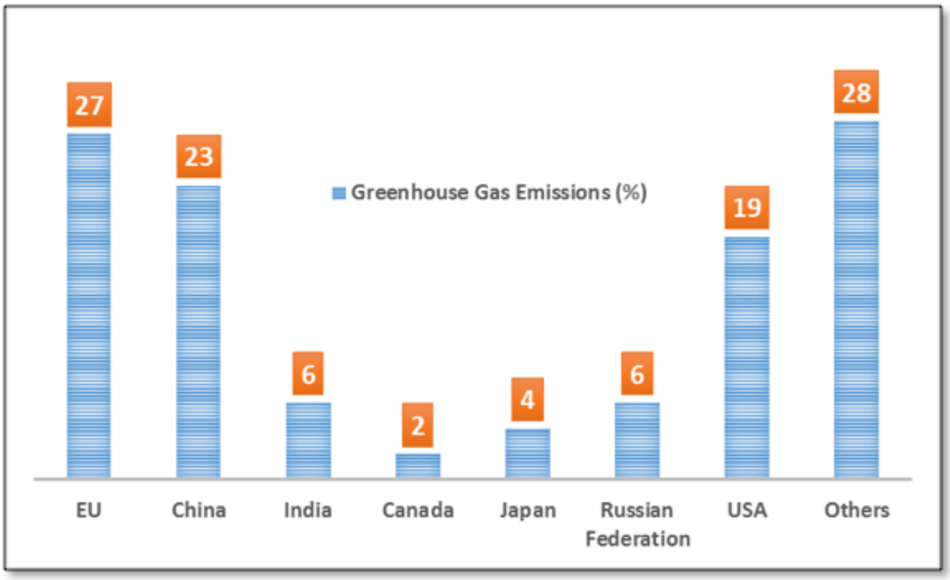


Figure 2.2: Global greenhouse gas emissions (%)

(EU- Excludes Estonia, Latvia and Lithuania)

Reproduced from EPA, 2015

Anthropogenic activities produced 46 billion tonnes of greenhouse gases in 2010, an increase by 35% since 1990 (EPA, 2015; Figure 2.3). Indeed, global emissions of all major greenhouse gases for the period 1990-2010 increased significantly (Figure 2.3) and, CO_2 net emissions rose by 42%, which is important because CO_2 accounts for approximately three-quarters of total global emissions (EPA, 2015). In addition, N_2O and CH_4 emissions increased by 9% and 15% respectively, while fluorinated gases emissions more than doubled (Loáiciga, 2011).

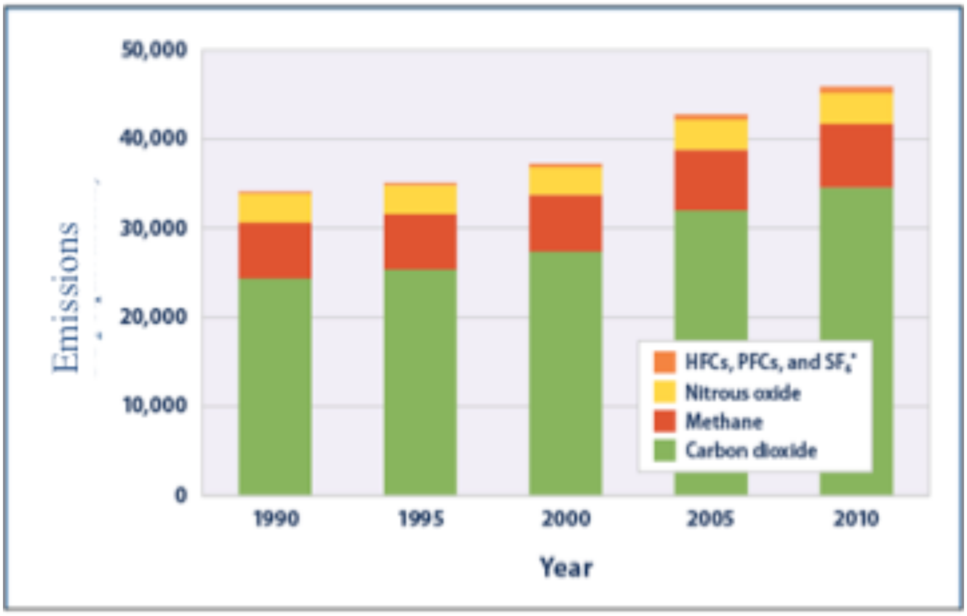


Figure 2.3: Greenhouse gas emissions (1990-2010)

Source: EPA, 2015

2.2.3 Sea level rise (SLR)

In the coming decades SLR is arguably the most harmful effect of increasing global temperatures (El Raey, 2011). The long-term view of increasing sea levels has consequences for both policy and adaptation approaches. Damage costs due to coastal land loss and involuntary migration will be significant as nearly 150 million people living in locations within 1 m of high tides have to move (Anthoff *et al*., 2010; Anthoff and Tol, 2010). Another main consequence of climate change is increased storm incidence and intensity resulting in coastal flooding (Tol, 2002).

Current and predicted future SLR has social and economic implications for those living in low-lying coastal regions (Parmesan and Yohe, 2003; Jevrejeva *et al*., 2008; Nicholls and Cazenave, 2010; Church and White, 2011). There are conflicting estimates of previous SLR for example, Kemp *et al*. (2013) argued that in the last 2000 years sea levels rose by a maximum of 0.6 mm yr^{-1} and Church and White (2011) debated that global sea level had risen by about 1.6 mm yr^{-1} from late 19th century. However, IPCC (2007) suggest that global SLR rates have increased from a relatively constant equilibrium to >3.1 mm yr^{-1} in the last 135 years (Figure 2.4) this is largely due to anthropogenic activities and predictions suggest increases of between 3 and 5 times as much by the end of 21st century. Rahmstorf *et al*. (2007) and Horton *et al*. (2008) suggested that global SLR of between 0.18 m and 0.59 m and Jevrejeva (2012) estimated upper and lower extremes of between 0.57 m and 1.10 m by 2100, would be observed.

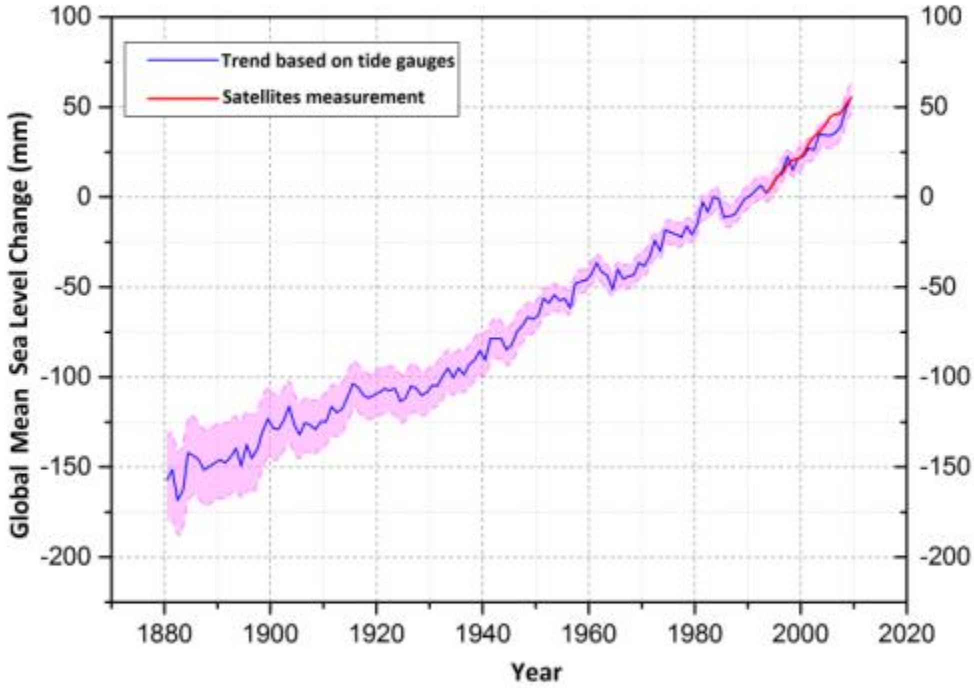


Figure 2.4: SLR trends since 1880

(Produced based on the data of Commonwealth Scientific and Industrial Research Organisation (CSIRO)

2.2.4. Storms - overview

Discussions related to global climate change and the potential of more extreme weather events that may impact on both the coastal population and infrastructure involve both politics and science (O'riordan, 1996). Storms are defined by strong winds, moderate to heavy rain with thunder (Donat *et al*., 2010), differing in origin depending on region and environment from which they originate and are often designated as tropical cyclones, hurricanes, tornadoes, thunderstorms and typhoons (NASA, 2014) (Figure 2.5).

Globally, more than 40,000 thunderstorms occur each day, most occur in the USA, where they can generate tornadoes, severe floods, lightning, cyclones and high winds, etc. (NASA 2014). In November 2013, super typhoon Haiyan, one of the strongest recorded storms struck the Philippines, causing in excess of 5000 fatalities and more than £1billion damage costs (Lin *et al*., 2014; Lum and Margesson, 2014).

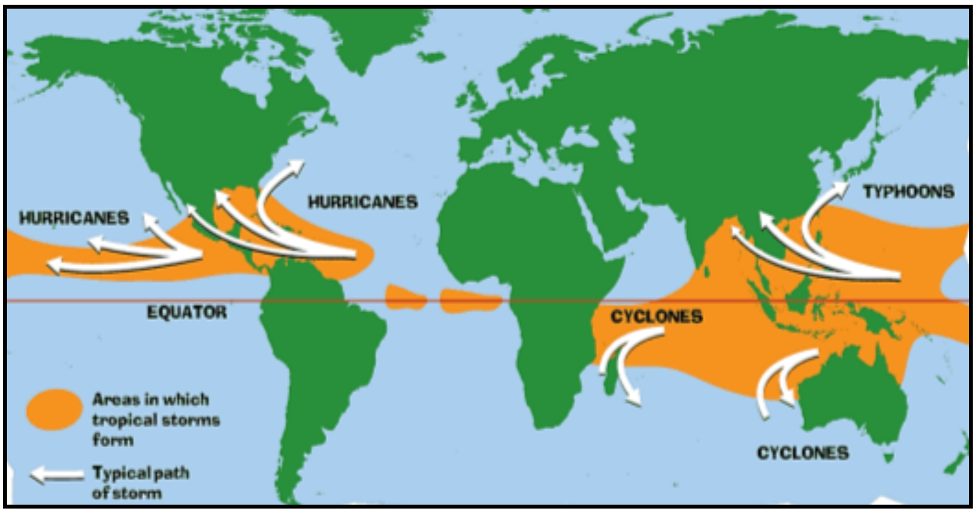


Figure 2.5: Storm classification

Source:NASA, 2014

High intensity hurricanes are more likely to occur in the USA than any other country (Strobl, 2011). However, severe storm events with hurricane force winds are regularly experienced in the UK (Pitt, 2008; Sibley, 2010). For example, a series of powerful winter storms with hurricane force winds occurred between mid-December 2013 and early January 2014 (Slingo *et al*., 2014; Kendon and McCarthy, 2015). Many coastal regions in England and Wales were severely affected by these extreme weather conditions, resulting in several fatalities, approximately 1,700 commercial and residential properties flooded and 160,000 homes suffering power cuts (Huntingford *et al*., 2014; Lewis *et al*., 2015) (Figure 2.6).

Figure 2.6: Storm damage in Aberystwyth - 2014

Source: The Times, 2015

2.2.5 Coastal zones and flood risk

Flooding is a significant natural hazard in many regions across the world. Floods increase the erosion risk and cause concern for the stability of infrastructure and water quality (Dutta *et al*., 2003). Historical records highlight that the frequency and intensity of flooding have increased year by year (Easterling *et. al.,* 2000; Knutson *et al*., 2010). While, predictions highlight that >80% of the global population over the next 50 years will reside in coastal flood risk zones (McGranahan *et al*., 2007; Huq *et al*., 2007; Grimm *et al*., 2008). McGranahan *et al*. (2007) also suggest that many urbanised coastal zones will require improved drainage, flood risk management and flood protection arrangements in many areas. Several factors influence flood occurrence, such as rainfall trends, land and water usage, the characteristics of the drainage basin and most importantly, coastal, estuarine and river management. Flooding has been linked with population increases, urbanisation, and the increase of activities in coastal areas (Meyer and Turner, 1992; Re, 1997; Douben, 2006). Coastal flooding mainly occurs when a storm corresponds with high tides breaching natural and manmade beach protection (Re, 2007). Hurricane-scale weather patterns can occur in the UK, which generate heavy rain and cause coastal flooding (Weisse *et al*., 2014).

2.2.6 Floods and damage costs

Coastal floods are mainly triggered by high water levels due to an amalgamation of tide and storm surges and wave incidents on the coast caused by the effects of wave setup and run-up (Wadey, 2013). Globally between 1994 and 2013, flood events were responsible for 43% of all recorded disasters and affected almost 2.5 bn people, who were living in low-lying coastal areas (Hyndman and Hyndman, 2016; Figure 2.7). In the last two decades, research has shown that storm events are the most expensive in terms of both monetary terms and human loss (EM-DAT, 2014). Between 1980 and 2012, annual global flood losses were > £16 bn, with an average of 5,900 lives lost each year; without resilience procedures, these costs are expected to increase by 430 % by 2080, and possibly by as much as 2,000 % (Jongman *et al*., 2015). If no adaptation measures are implemented to control global warming, Hinkel *et al*. (2014) estimates that the annual global coastal flooding cost may reach £59 billion by 2100. Global coastal flooding events indicate a substantial humanitarian and socioeconomic hazard with more than 20 million people living at or below high tide levels, and 200 million live under storm tide levels (Nicholls and Cazenave, 2010).

Figure 2.7: Southern England floods in 2013

Source: BBC, 2013

2.2.7 Economic loss

Human-induced climate change, though unclear in its particulars, may have adverse effects on the ecology and the economies of the world (Mahlman, 1997). Estimations of annual economic losses caused by climate change are >£490 billion, representing only 1% of the (global domestic product) GDP, while the costs of carbon emissions are >0.7% (DARA, 2012; Table 2.2). According to Stern (2007), the majority of climate change costs comes from global warming and emissions.

Table 2.2: Global climate change costs (£ bn)

Reproduced from DARA, 2012

Sector	Costs in billions 2010 (£)
Climate	454
Carbon	353
World	807

2.2.8 Geology, geography and climate change

The geological record comprises enough evidence highlighting climate fluctuations over millions of years, conserving this evidence in the fossil and sedimentary record (Seinfeld and Pandis, 2012; Crutzen, 2006). Recent technological advances have enabled geologists and geo-researchers to demonstrate how and why climate has transformed in the past, highlighting the importance of separating out natural climatic changes from those influenced by anthropogenic activity. Geography and climate change are heavily interlinked, as geography will determine the variations in climate patterns. To map out the changes, many researchers used the climate classification map, also known as the Wladimir Köppen climate classification map, originally developed by Rudolf Geiger (Rubel and Kottek, 2010; Kottek *et al*., 2006). Climate classification has been extensively used in a wide range of subjects particularly in climate study and in physical geography, agriculture, biology, hydrology, and environmental areas of study.

Furthermore, the nexus of geography and climate change in the UK will be explained in detail in the chapter on physical geography.

2.2.9 Coastlines

Across the globe, there is a relationship between coastal zones and anthropological settlements (Smit and Pilifosova, 2003; Smith, 2013). Coasts have diverse geographical characteristics that influence the generation of trade and other coastal activities, which contributing significantly to the economies of countries. Coastline length also plays an important role in nations' economies. Various countries with the longest coastline are as follows: (Table 2.3).

Table. 2.3: Countries with longest coastline across the globe

Reproduced from CIA, 2012.

**Taken from Masselink and Russell, 2013.*

Rank	Country	Coastline (km)
1	Canada	202,080
2	Indonesia	54,716
3	Greenland (Denmark)	44,087
4	Russia	37,653
5	Philippines	36,289
6	Japan	29,751
7	Australia	25,760
8	Norway	25,148
9	United States	19,924
10	United Kingdom	17,381*
10	New Zealand	15,134

The average population density in coastal areas is more than 80 persons per square kilometre, which is double the global average population density (Creel, 2003;). Due to high anthropogenic use, particularly in recent times, coastlines were adversely affected in the Europe (Carter, 2013). According to UNEP (2013a & b), coastal populations living near to the shoreline around the world suffer from the highest coastal erosion especially in the Europe (Figures 2.8 and 2.9). Figure 2. 8 highlights that the UK coast has mostly altered and it is a one of the shoreline degrading countries in the world. Collectively, rapid population growth and economic and technological development are having a significant effect on coastlines and surrounding areas. However, not all human activities will cause environmental damage, but they are main factors. The physical background chapter explores the coastlines of the UK in-depth and with various examples.

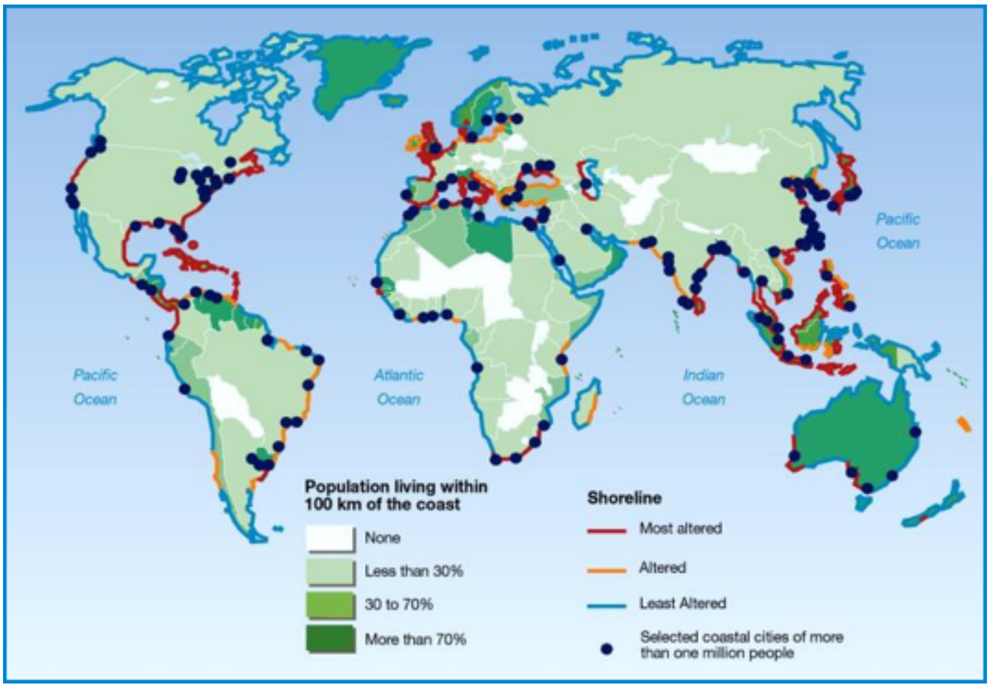


Figure 2.8: Coastal population and shoreline degrading trends across the globe

Source: UNEP, 2013a

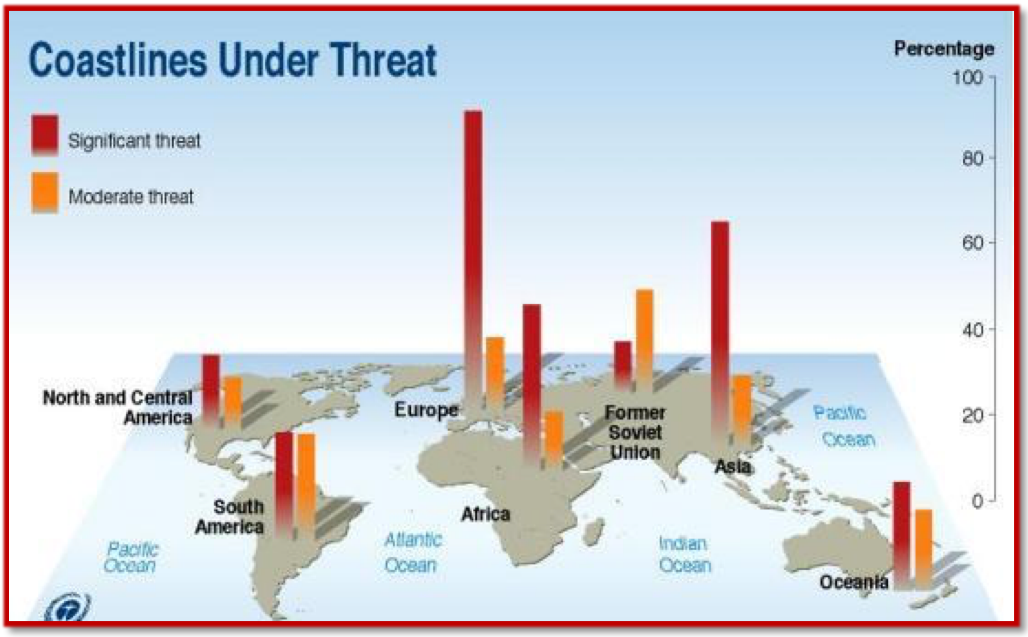


Figure 2.9: Shoreline degradation across the globe

Source: UNEP, 2013b

2.3 Methodological review

2.3.1. Coastal vulnerability

The term vulnerability originated in the field of geography to determine potential risk from naturally occurring hazards. Vulnerability assessments have now become commonplace in the fields of physical and economic geography, environmental science and in related research areas, such as, climate change impacts, sustainability, ecology, public health, livelihood, food security and land usage, and the respective fields define vulnerability in diverse terms (Adger, 2006). The third assessment report of the IPCC (McCarthy, 2001) defined vulnerability as "*the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change*". Historically, much of literature on the topic of human and geographical vulnerability exists but relatively few detail coastal vulnerability; and studies that detail coastal vulnerability in terms of economic cost are extremely sparse (Kantamaneni and Phillips, 2016). The threat to the coastlines occurs where comprehensive growth on the land near the sea is affected by shape and biophysical features (Carter, 2013). Newton *et al*. (2012) introduced a syndrome method of coastal vulnerability assessment that emerged from concerns related to the impacts of climate variations on coastal zones, suggesting that multi-stressors impact the global coastal systems in several ways (Table 2.4). Overall, the concept of vulnerability is multidimensional and it depends on the area and source of hazards (Kantamaneni, 2016a & Kantamaneni2016b).

Table 2.4: Synergetic multi stressors of coastal zone

Reproduced from Newton et al., 2012

Syndrome	Stress
Sediment	From sediment trapping by damming of rivers and the physical disruption of the coastal dynamics by coastal engineering, as well as subsidence
Water	Such as the over-extraction of water from coastal aquifers, decreased river-flow and ageing of water at the river-mouth from damming
Eutrophication	From agriculture, animal rearing, processing of organic matter and sewage
Coastal land-	Such as the destruction of coastal forest, mangroves, salt marshes and wetlands
Coastal urbanisation	In a flood, prone, low-lying coastal zone, on marginal land, as well as coastal megacities
Biodiversity	From stressing or over exploitation of biotic resources, introduction of invasive species, changes in the food web and regime change

2.3.2 Aspects of vulnerability

The concept of coastal vulnerability varies depending on the researcher and environment each defining vulnerability in different ways. Some researchers related vulnerability to natural hazards and the environment (Blaikie *et al*., 2014); others define vulnerability in relation to climate change as well as coastal susceptibility (Adger, 1999; Kelly and Adger, 2000). Klein and Nicholls (1999) developed a framework, which included both natural and socio-economic structures commonly found in coastal environments (Figure 2.10). The main fundamentals of this agenda include the variation between autonomous adaptation and planned adaptation, as well as the substantial effect of the socio-economic system on the natural system. There are diverse opinions on the definition of vulnerability across the globe, as it has a multi-dimensional aspect. However vulnerability related with coasts is simply a measure of the intensity to which anthropological or natural system is unable to cope with adverse effects. Vulnerability can be related with natural hazards, anthropogenic hazards, social hazards or a combination of all three. In this context, a working definition (for the current study) for the vulnerability is as follows:

"Identification of intensity of risk from various hazards, in this case, from coastal impacts, such as, flooding, erosion, storm surge etc. in both physical and economic perspectives.

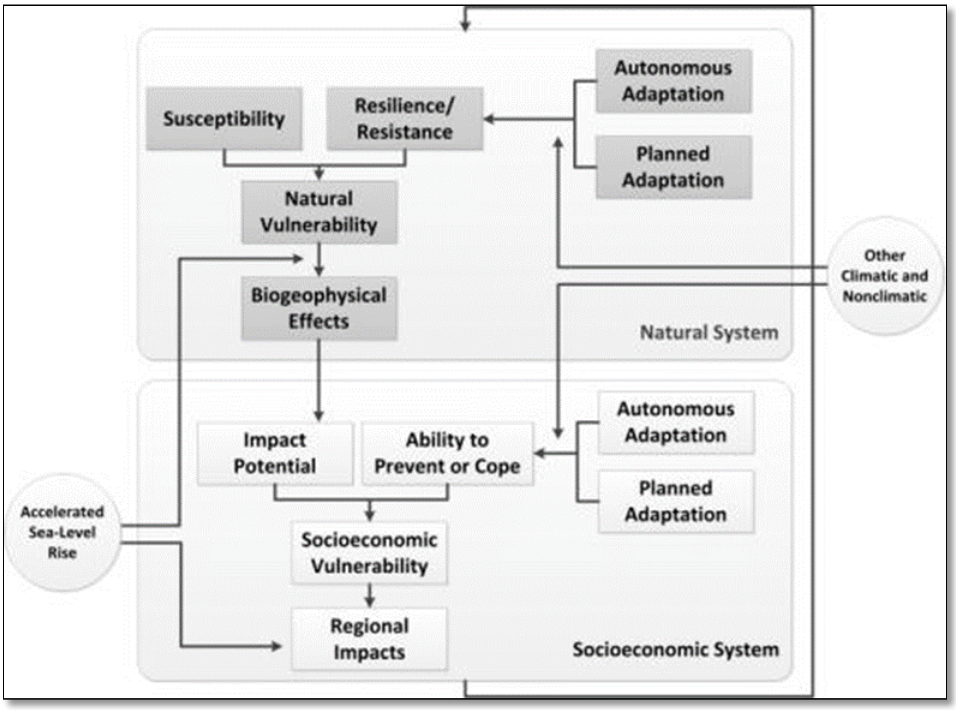


Figure 2.10: Coastal vulnerability framework

Reproduced from Klein and Nicholls, 1999

Based on this working definition, the current study evaluates combined coastal vulnerability of the UK at selected sites, which will be explained in detail in forthcoming chapters.

2.3.3 Coastal vulnerability index and procedures

Even though several methodologies have been used to estimate coastal vulnerability, most are categorised by four basic approaches as described by Ramieri *et al*. (2011), which are explained in detail in following sections.

1 Index-based methods
2 Indicator-based approaches
3 GIS-based decision support systems
4 Dynamic computer models

The Cabinet Office-UK (2012) evaluated risk assessment under the NRA (National Risk Assessment) programme in three categories such as natural events (disasters), major accidents and malicious attacks. This report (4th Chapter) explored that risk assessments for both hazards and threats have been assessed by the public participation surveys. The definition given in section 2.3.3 suggests that the both physical and economic components need to be assessed and this forms the main aim of the current research project. To achieve the aim physical vulnerability will be assessed using an indicator methodology originally developed by Palmer *et al.* (2011) refined for Welsh coast by Denner *et al.* (2015). They now follows a detailed review of the most current methodological approaches used in worldwide coastal vulnerability assessments.

2.3.4 Index-based methods

Index-based methods evaluate coastal vulnerability using a unit-less single-magnitude index scale, measured by quantitative or semi-quantitative assessments and an amalgamation of diverse variables (Pethick and Crooks, 2000). With these methods, the final results dictate the overall vulnerability score based on a combination of all values but they do not provide any indication of how each index value contributes to the overall score (Balica *et al*., 2012). A clear description of accepted procedures is therefore vital to reinforce appropriate usage of index-based methods. A drawback when used on coastal systems is an inability to evaluate socio-economic features such as the number of people affected, quantification of infrastructure damaged, and costs (Gornitz *et al*., 1993; Cooper and McLaughlin, 1998; McLaughlin and Cooper, 2010). These limitations were addressed by using the original CVI's linked with other appropriate indicators, e.g. producing combined indices capable of representing coastal system complexities. However, this involves a large increase in the numbers of indices and complicate the methodology. Alternatively, it is possible to transform the original method of CVI by, for example, taking erosion into account separately and then integrating it with another CVI, for example storms, and then considering socio-economic structures within each of the considered CVIs.

CVI has been used to evaluate coastal vulnerability at European levels, but these tend to be more challenging to apply to the various complex geographical zones (see, for example, Capobianco *et al*., 1999; Sullivan and Meigh, 2005; Garthe and Hüppop, 2004). At regional levels Mendoza and Jimènez (2008) established an approach to evaluate coastal vulnerability at regional scales, which included the effects of storms alongside socio-economic factors, using 42 Catalan coast beaches as a case study.

The initial or first stage deals with the identification of primary variables demonstrating important procedures inducing the coastal vulnerability and the coastal evolution in general aspects (Gornitz, 1991). The number of main variables can be altered slightly depending on geographical and environmental settings but generally a CVI will contain 6 or 7 variables. A second stage then deals with the quantification of relevant variables. Even though several methods may be accessible for this step, quantification is normally grounded on the description of semi-quantitative scores according to a 1-5 scale (Gornitz, 1990). Where 1 specifies a low influence and 5 designates high. Finally, primary variables are combined into a single index. Gornitz *et al.* (1997) offered and tested (in terms of sensitivity analysis) formulations that considered seven key variables for the derivation of the final CVI (Figure 2.11).

Product mean:	$CVI_1 = \frac{(x_1 * x_2 * x_3 * x_4 * \ldots x_n)}{n}$,
Modified product mean:	$CVI_2 = \frac{[x_1 * x_2 * \frac{1}{2}(x_3 + x_4) * x_5 * \frac{1}{2}(x_6 + x_7)]}{n - 2}$,
Average sum of squares:	$CVI_3 = \frac{(x_1^2 + x_2^2 + x_3^2 + x_4^2 + \ldots x_n^2)}{n}$,
Modified product mean (2):	$CVI_4 = \frac{(x_1 * x_2 * x_3 * x_4 * \ldots x_n)}{5^{(n-4)}}$,
Square root of product mean:	$CVI_5 = [\, CVI_1 \,]^{1/2}$, and
Sum of products:	$CVI_6 = 4x_1 + 4x_2 + 2(x_3 + x_4) + 4x_5 + 2(x_6 + x_7)$.
Where: n =variables present	x_1=mean elevation
x_2=local subsidence trend	x_3=geology
x_4=geomorphology	x_5=mean shoreline displacement
x_6=maximum wave height	x_7=mean tidal range.

Figure 2.11: Diverse formulations of CVI

Source: Gornitz et al., 1997

2.3.5 Indicator-based indices

An indicator or set of indicators can be described as an intrinsic and distinctive measure that quantitatively estimates the situation of a structure. An indicator is a sign that précises the data related to a specific phenomenon (Gallopin, 1997). Indicators are simple numerals that indicate the certainty, such as the population rate and the GDP per capita. Certain indicators, such as, population are useful for growth assessment in coastal risk management studies, coastal defence procedures, and coastal risk management organisational procedures (Balica *et al.*, 2012). Balica *et al.* (2012) developed a Coastal City Flood Vulnerability Index based upon exposure, susceptibility and resilience to coastal flooding. It is applied to nine cities (Calcutta, Casablanca, Dhaka, Manila, Buenos Aires, Osaka, Marseille, Shanghai and Rotterdam) across the world, each with diverse kinds of exposure.

Developing and using indicators is not a new concept as economic indicators were developed during the 1940s (Hartmuth, 1998). Indicators offer knowledge regarding structures' elevations, places, densities of population, usages of land, nearness to the coast, and proximity to return periods of various coastal vulnerability events, as well as the responsiveness and preparedness of communal and physical structures (Hinkel, 2011). Researchers have established several vulnerability indicators within a social-ecological system (SES) context (Abson *et al*., 2012; Brooks *et al*., 2005; Mamauag *et al*., 2013; Eakin and Luers, 2006). However, identification of social and natural structures that are inherently attached should be considered for a more holistic method for the assessment of vulnerability (Eakin and Luers, 2006; Kasperson *et al*., 2005; Folke *et al*., 2002).

An indicator Coastal Vulnerability Index is a popular tool to measure the intensity of exposure of communities to hazards (Giljum and Polzin, 2009). The index comprises several qualitative and quantitative indicators, which are interlinked with the formula. Each indicator helps describe the vulnerability of various structures (Balica *et al*., 2012). In those frameworks, indicator-based methods assess the vulnerability of coastal areas based on a set of elements (indicators) that describe vital coastal factors such as coastal drivers, forces, condition, effects, reactions, sensitivity, exposure, hazard, and destruction (Carapuco *et al*., 2016; Tan and Chadbourne, 2015; Giljum and Polzin, 2009). These elements are in some cases pooled into a final indicator. The primary and most vital step in the indicator-based evaluation of vulnerability is a selection of various indicators as well as the number of indicators to be used. Most researchers restrict the number of indicators to between four and ten. The Canadian Council of Ministers of the Environment (2013) considered one hundred indicators, but by a process of elimination narrowed the indicator used in the study to the 12 most important factors.

Furthermore, Houghton *et al*., (2001) categorised the vulnerability indicators into two types: the first type relates to the direct impact on nature and the second relates to the direct impact on people. The first type is constructed on hypothetical conceptions and the second one on numerical perceptions. When this methodology is applied to certain places or events, it is essential to consider two significant factors. The first, encompasses indicators dealing regional capabilities and vulnerabilities, including environmental, ecological, social, and economic procedures along with space and event time. The second one deals with monetary factors, population growth, commercial and residential properties, and climate change patterns (Houghton *et al.*, 2001). The indicator set comprised nine sensitivity indicators (Smeets *et al.*, 1999) that are showed in Table 2.5:

Table 2.5: Sensitivity indicators

Reproduced from Smeets et al., 1999

Number	Indicator
1	Relative sea level rise
2	Shoreline evolution trend status
3	Shoreline changes from stability to erosion or accretion
4	Highest water level
5	Coastal urbanisation (in the 10 km land strip)
6	Reduction of river sediment supply
7	Geological coastal type
8	Elevation
9	Engineered frontage

2.3.6 GIS-based decision support systems

Geographical Information System (GIS)-based methodologies are useful to evaluate the physical condition of a particular system and the development of vulnerability maps. GIS have been approved by users/researchers looking to acquire further information about the physical geography through the computers to transmute vast databases into thematic maps. With the addition of GIS-based models, decision-makers can begin employing the data in a true planning atmosphere (Faber *et al.*, 1997). However, the coastal environment GIS-DSS (geographical information system – decision support system) contains two types: the DITTY DSS – development of information technology tool (Agnetis *et al.*, 2006) and DESYCO-DSS – DEcision support SYstem for COastal climate change impact assessment (Montanari *et al.*, 2014). While Geographical Information System (GIS) tools probably strengthen the spatial application of various CVI indices, GIS can be utilised to improve the spatial data linked to CVI variables and develop various scales of maps highlighting their spatial dissemination (De León and Carlos, 2006). GIS also allows the overlay of CVI outcomes with other spatial data (e.g. layers representing coastal protection procedures, density of population, urbanisation indices, and ecological values). Therefore, GIS supports the combined analysis, which is vital in the evaluation of coastal vulnerability studies, and accordingly in coastal zone assessments. GIS is most valuable for developing quality spatial resolution pictures, which are essential in describing parts of huge geographical regions that are at greater risk and need to be protected (Lillesand *et al*., 2014). Contemporary GIS software permits for this multi-scale and multi-criteria analysis to be carried out both interactively and programmatically in order to test a model via a scripting interface.

2.3.6.1 Development of information technology tool for the management of Southern European lagoon (DITTY-DSS)

This is one of the GIS-based methods for coastal vulnerability evaluation. Mainly it was developed to attain sustainable and rational application of resources in the southern European lagoons by taking into account main anthropogenic effects (Agnetis *et al*., 2006). The DITTY project was produced and tested in five sites for the supervision of coastal lagoons.

2.3.6.2 Decision support system for coastal climate change adaptation (DESYCO)

DESYCO is a GIS-based Decision Support System (DSS) intended for the integrated assessment of multiple impacts of climate change on vulnerable coastal systems (e.g. river deltas, beaches, estuaries and lagoons, wetlands, agricultural and urban areas) (Zanuttigh *et al*., 2014). It implements a Regional Risk Assessment (RRA) procedure, based on Multi-Criteria Decision Analysis (MCDA), to recognise and rank the zones at risk in the considered area. DESYCO is an open source software that accommodates a number of data input files, such as, csv, txt, shape or raster files concerning both climate change hazard circumstances, e.g., global and regional climate projections; high resolution hydrodynamics; hydrological and biogeochemical simulations and physical circumstances related to a specific site, e.g. ecological and socio-economic features of the studied area e.g. geomorphology, coastal topography, occurrence and distribution of vegetation cover, location of synthetic defence (Zanuttigh *et al*., 2014). In the initial stages of development, DESYCO comprised vulnerability indicators and indices for the appraisal of impacts of climate change in coastal zones. Indeed, indicators or indices can be selected from data connected to fields such as ecology, geomorphology, and socio-economics.

2.3.7 Methods based on dynamic computer models

Sector models enable detailed quantitative analyses of coastal processes or specific coastal systems. They are capable of assessing non-linear effects and consider interactions between different processes. They are most useful for addressing specific key factors of coastal vulnerability, in particular at the local and regional scale.

Integrated assessment models can evaluate the vulnerability of coastal systems to multiple climate change impacts. They can include the cross-sector analysis of interaction among different impacts and the synergetic effects of changes in climate and in other key variables affecting the coastal system (such as socio-economic development and adaptation measures). The ability of a fully integrated assessment of coastal vulnerability, also considering dynamic interactions between sectors and/or processes, makes integrated assessment models very useful in supporting policy and decision-making at various scales. However, given the complex nature of such models, their implementation can require significant expertise. In some cases (e.g. RegIS and DESYCO) further effort from the research community is still needed to up-scale the applicability of integrated assessment models to the European scale.

Computer simulations are the main tools used for analysing and mapping susceptibility and risks of coastal systems to climate change. Accessible methods for these procedures are based on dynamic computer modelling and according to Ramieri *et al*. (2011), these fall into two main groups' sector models and integrated assessment models.

- Sector models focus on the examination of coastal vulnerability linked to a specific coastal system. However, these do not directly deal with the appraisal of coastal vulnerability to several climate change impacts (Cicin-Sain and Belfiore, 2005).
- Integrated assessment models appraise the capabilities of coastal vulnerability systems against multiple climate change impacts, including cross-sector examinations of the collaboration among diverse effects and considering variations in other aspects disturbing the coastal system.

Examples of integrated assessment models include FUND, DIVA, SimCLIM, and RegIS (Hinkel and Klein, 2009; Nicholls and Tol, 2006; McLeod *et al*., 2010). The choice of an appraisal technique in a specific situation is also dependent on the accessibility of relevant data. Although several other methods have been developed for coastal vulnerability assessment, most researchers use index- and indicator-based methods and/or integrated models.

2.3.8. Coastal vulnerability frameworks

The seminal work of Gornitz and Kanciruk (1989) created the first coastal vulnerability index, followed by several researchers who established similar methodologies but with different variables depending on physical, environmental and socio-economic circumstances (Shaw *et al*., 1998; Boruff *et al*., 2005; Doukakis, 2005; Pethick and Crooks, 2000; Vittal Hegde and Radhakrishnan Reju, 2007; and Palmer *et al*., 2011). Coastal vulnerability index variables generally measure vulnerability in terms of physical changes, influenced by erosion and sea level rise, the CVI highlighting areas with different levels of impact. The classification of CVI is dependent on the comparative contributions and collaboration of six variables:

a	Geomorphology
b	Shoreline erosion/accretion rate
c	Coastal slope
d	Relative sea-level rise rate,
e	Mean wave height
f	Mean tide range

CVI values range between 0.0 and 1.00: i.e. low values 0.0 to 0.25, and very high values 0.75 – 1.00; each calculated figure falls into the relevant quartile, and each coastal region is then characterised accordingly. CVI is designated (calculated) as the square root of the product of the rank variables divided by total number of variables, as follows:

$$CVI=\sqrt{(a*b*c*d*e*f)/6}$$

This methodology has been successfully applied at many coastal locations around the world, most with differing physical parameters (Pethick and Crooks, 2000; Hegde and Radhakrishnan Reju, 2007; Garthe and Hüppop, 2004; McLaughlin and Cooper, 2010). Alternatively, some CVI evaluations can be performed to appraise the amount of loss that could result from a hazardous incident of a given severity, comprising destruction of infrastructure, disruption of monetary activities, and effects on livelihoods (Blaikie *et al*., 2014; Langston, 2008; Turner *et al*., 1996; McLaughlin and Cooper, 2010; Pendleton *et.al.,* 2010).

In the last two decades, researchers have developed a wide range of vulnerability index parameters that vary depending on the area of research. The following an examination of the most popular indices.

2.3.9 Social vulnerability index

Cutter *et al*. (2003) developed the Social Vulnerability Index (SoVI) by scrutinising the relationship between spatial patterns of social vulnerability and environmental hazards at the sub-local level (county) in the United States. This index identifies potential social burdens (e.g. Flanagan *et al,'s* (2011) social vulnerability index for disaster management) and for this reason, it was initially used by the construction industry. Firstly, the SoVI was calculated for several accumulations and with a subdivision of the distinctive variables to define the impact of scalar and variable changes in index construction; secondly, to test the sensitivity of the algorithm to changes in construction and to determine if that sensitivity was constant in different geographic circumstances or not.

2.3.10 Economic vulnerability index

The United Nations Development, Policy, and Analysing Division (DESA) developed the Economic Vulnerability Index (EVI). It evaluates the structural vulnerability of countries to economic and environmental risk. However, several versions of the EVI index have been produced in recent years and applied to diverse geographical zones (Briguglio, 1995; Briguglio and Galea, 2003; Guillaumont, 2009). The EVI comprises eight socio-economic indicators, which are assembled into several sub-groups (Figure 2.12). The primary aim of EVI is to be applicable at least to developed countries.

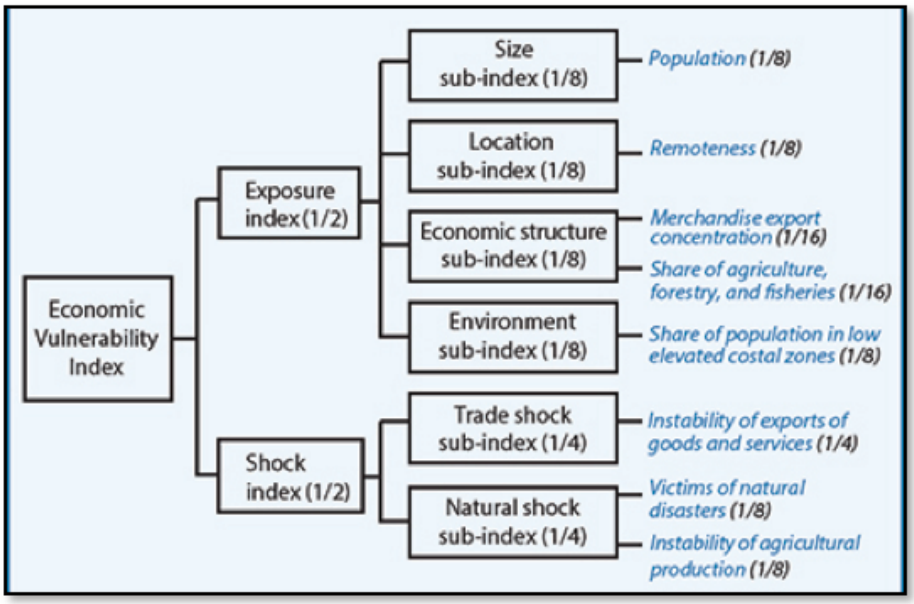


Figure 2.12: Structure o Structure of ECVI

Source: DESA, 2014

2.3.11 Flood vulnerability index

Balica *et al*. (2012) developed Flood Vulnerability Index, which is also called as City Coastal Flood Vulnerability Index (CCFVI; equation 1). The CCFVI model was constructed based on exposure (E) susceptibility (S) and resilience (R) factors and applied to 9 cities around the world, each with different levels of exposure. The index gives a number from 0 to 1, representing relatively low or high coastal flood vulnerability, which displays which cities are in maximum need of additional, more detailed investigation for the needs of decision-makers. With the help of this index, it can be established which cities are greatly vulnerable to coastal flooding with regard to the system's components, i.e. socio-economic, hydro-geological, and politico-administrative. The vulnerability index gives a number from 0 to 1, demonstrating comparatively lower or higher coastal flood vulnerability, which displays which cities are most in need of further and more comprehensive examinations for decision-makers. Once the establishment of flood vulnerability index is finished, it is used to scrutinize the climate change impacts on the vulnerability of these cities over a longer period.

$$FVI = \frac{E \times S}{R}$$

2.3.12 Livelihood vulnerability index

Hahn *et al*. (2009) established the Livelihood Vulnerability Index (LVI), which is used to estimate climate change vulnerability. Primarily, this was applied to Mabote and Moma Districts of Mozambique. Accordingly, researchers surveyed 200 households in each district to collect data on livelihoods, water security, socio-demographics, social networks, health, food, natural disasters, and climate variability. Data was analysed by using a composite index and differential vulnerabilities.

2.3.13 Climate vulnerability index

Sullivan and Meigh (2005) developed the Climate Vulnerability Index (CVI), and it contains a descriptive range of social and physical structures. The CVI emphasises primarily water-related subjects, but it is also relevant to vulnerability issues. The objective of this index is to validate the possibility for construction vulnerability valuations by the CVI. It is also extendable to large areas and contains six key components, and the range is between 0 and 100.

2.3.14 Environmental vulnerability index

The Environmental Vulnerability Index (EVI) is an amalgamation framework for understanding the environmental vulnerability of various countries, which was developed by Kaly and Commission (1999) with the support of the South Pacific Applied Geoscience Commission. The EVI consists of 50 indicators, which are called smart indicators and are used to assess the vulnerability of the environment. These indicators represent the degradation and risk for the environment. EVI contains 5 groups: extremely vulnerable (1), highly vulnerable (2), vulnerable (3), at risk (4) and resilient (5). However, this index is only applied to limited small-island countries.

2.3.15 Multi-scale coastal vulnerability index

McLaughlin and Cooper (2010) established a multi-scale CVI for assessing erosion impacts. It is also applicable to other climate change influenced impacts. The index assimilates three sub-indices:

Coastal characteristic sub-index	Defining the resilience and coastal susceptibility to erosion
Coastal forcing sub-index	Describing the forcing variables subsidising to wave-induced erosion
Socio-economic sub-index	Defining targets potentially at risk

The calculation of every sub-index is constructed on the source of several variables, and its definite identification (number and typology), which depends on the measured application scale. Figure 2.13 demonstrates the variables applied to obtain the three sub-indices in Northern Ireland at the national level (McLaughlin and Cooper, 2002; McLaughlin and Cooper, 2010). The same authors applied the CVI index (and the sub-indices) at the regional and local levels also. However, for these cases, a variety of variables were used.

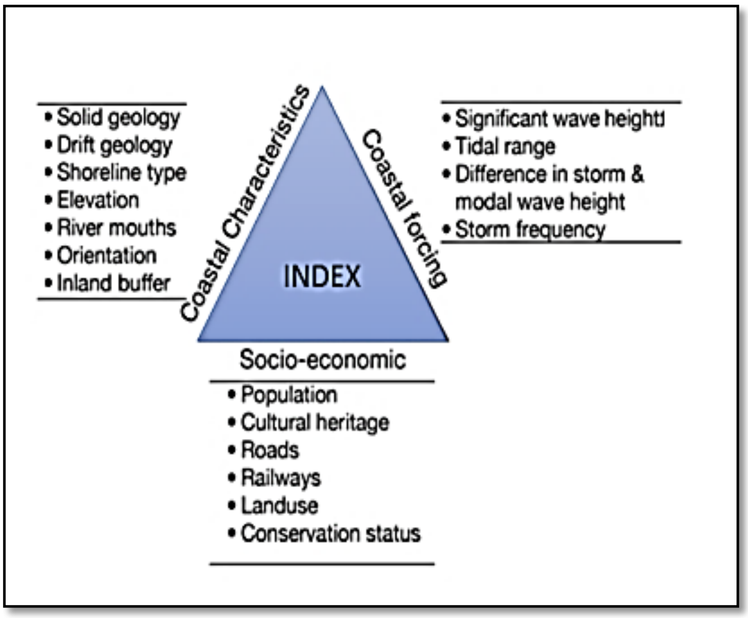


Figure. 2.13: Variables of CVI

Source: Modified from McLaughlin and Cooper, 2010

The recognised variables are further classified according to a 1-5 scale based upon Gornitz (1990) methodology in order to assess the achievements of the coastal vulnerability system, assigning it values from 1 (lowest value) to 5 (highest value).

Table 2.6 demonstrates the matrix used to categorise the three sub-indices variables in McLaughlin and Cooper (2010). The 1-5 scale permits the arithmetic amalgamation of different variables. Sub-indices are computed with the sum of the values of the relative variables; the figure obtained is further standardised to the range of 0-100.

The nationwide applications of this study, which was conducted in Northern Ireland, are measured and shown in Table 2.6

The sub-indices use the subsequent formulations:

Coastal classification (CC) sub-index = (sum of CC var.) – 7]/28} x 100

Coastal forcing (CF) sub-index = {[(sum of CF var.) – 4]/16} x 100

Socio-economic (SE) sub-index = {[(sum of SE var.) – 6]/24} x 100

The final CVI index is calculated as the average of the values of the three sub-indices:

CVI = (CC sub-index + CF sub-index + SE sub-index) / 3

CVI values can be envisioned as a colour-coded vulnerability map. This CVI index is simple and easy to calculate and can be applied easily to several spatial scales. Consequently, supportive multi-scale analysis is vital for coastal planning and management (McLaughlin and Copper, 2010). In addition to the explanation of physical components, the CVI also assimilates socio-economic components. This element does not always significantly impact the whole index score.

Table. 2.6 Matrix for the Variable Ranking and Calculation of 3 Sub-Indexes for the Northern Ireland

Reproduced from McLaughlin and Cooper, 2010

Sub-Index	**Variable**	**1**	**2**	**3**	**4**	**5**
CC	Shoreline Type	High Cliff (>40m)	Medium Cliff (20-20m)	Low Cliff (10-20m)	Shingle Ridge/Bar	Sand Beach
	Rivers	Absent				Present
	Solid Geology	Plutonic, volcanic, high–medium grade metamorphics	Low-grade metamorphics, sandstone and conglomerate well cemented	Most sedimentary rocks	Coarse and/or poorly sorted unconsolidated sediments	Fine unconsolidated sediment, volcanic ash
	Drift Geology	Bedrock, urban	Till/boulder, clay		Raised beach, deposits	Alluvium, blown sand, peat, glacial sands and gravels, glacial outwash sands, recent marine
	Elevation	>30	20-30	10-20	5-10	<5
	Orientation	Not relevant, e.g. sea Loughs		Easterly		Northerly
	Inland Buffer	500-1000 m inland				0-500 m inland
CF	Significant Wave hieght	0-0.74 N 0-0.24 E	0.74-1.49 N 0.24-0.48 E	1.49-2.23 N 0.48-0.72 E	2.23-2.98 N 0.72-0.96 E	>2.98 N > 0.96 E
	Tidal range	>5	3,5-5	2-3,5	1-2	<1
	Difference in model and storm waves	<0.10 N <0.10 S	0.10-1.70 N 0.10-0.25 S	1.70-3.30 N 0.25-0.40 S	3.30-4.90 N 0.40-0.55 S	>4.9 N >0.55 S
	Frequency of onshore storms	0-2.8	2.8-5.6	5.6-8.4	8.4-11.2	>11.2
SE	Settlement	No settlement	Village	Small town	Large town	City
	Cultural Heritage	Absent				Present
	Roads	Absent		A-class		Motorway, dual, carriageway
	Railways	Absent				Present
	Land use	Water bodies, marsh/bog and moor, sparsely vegetated areas, bare rocks	Natural grasslands, coastal areas	Forest	Agriculture	Urban and industrial Infrastructure
	Conservation designation	Absent		International		National

2.4. Advantages and disadvantages of the coastal vulnerability methodologies

Indicators and index-based methods are simple tools to implement. However, their use and application at various capacities fundamentally depend on the availability and quality of data. Modifications of the approaches may also be required in order to address appropriate features in certain areas. Indicators or index-based methods are valuable techniques for supporting the identification of significant vulnerable coastal zones and systems but are not beneficial for a more comprehensive quantifiable appraisal of coastal vulnerability (Harrison *et al*., 2013). However, the simple methodological procedures make CVI index methods valuable for communication purposes. On the whole, indicator methods are quite useful to evaluate coastal vulnerability in greater scales, mostly in economic aspects (Eg: Balica *et al.,* 2012). Index methods are useful for an assessment of vulnerability and coastal risk in both small (Eg: Kumar *et al.,* 2010; Denner *et al.,* 2015) and larger scales (Thieler and Klose, 1999; Romieu *et al.,* 2010) within physical aspects.

2.5. Damage costs impact on the economy

Global natural disasters significantly impact coastal economies. Geographical variations can decrease the global economy at various magnitudes (Lumsdaine and Prasad, 2003). The world's economy is interlinked with climate change, extreme weather variations, and other climate-related factors (Stern, 2007). Hurricane Sandy caused £57 billion damages and reduced the GDP in the USA in 2012 by 0.2% (Kantamaneni and Phillips, 2013). Moreover, the recent flood, as well as extreme weather events in Britain, significantly affected the nation's GDP growth rate (Kantamaneni and Phillips, 2013).

Samuel Henry Prince, a father of disaster studies in the social sciences, offered a systematic description of the Canada Halifax Harbour explosion in 1917 (Prince, 1920). Since then, several scientists have focused their interest on natural disasters. However, chronological records and statistics regarding extreme weather events in the natural environment revealed that the frequency of disasters increased during the 21st century (Seneviratne *et al*., 2012). However, in the late 20th century, occurrences of natural disasters doubled, and economic damage costs far exceeded estimations (Re, 2007). In well-developed countries, such as the US and the UK, natural disasters cause high levels of physical damage and fewer fatalities, but in the developing world, the loss of human life is greater. From 1974 to 2003, two million people died, and more than 180 million people became homeless due to natural disasters (Guha-Sapir *et al*., 2004).

Accordingly, this research focuses on the evaluation of coastal vulnerability of the UK (in selected sites), which is associated with extreme weather events such as floods and coastal erosion and properties within the physical and economic perspectives. Consequently, detailed information on the aforementioned issues will be quoted in subsequent chapters with complete statistics and figures.

2.6. Summary

The literature review analysed and explored existing research related to coastal vulnerability and assessment frameworks such as index and indicator methods, climate change, storms (floods and hurricanes), and their costs and economic consequences. Most research has concentrated on various geomorphological variables/parameters. However, there are no standardised, combined CVI methods to measure the physical and economic impact of coastal vulnerability at all levels. These research gaps are strongly associated with vulnerability aspects but to address these at a regional level and more precise information would need to be collected. While, this chapter reviewed current literature concentrating on coastal vulnerability aspects worldwide, Chapter 3 focuses on the physical and economic geography of the UK.

CHAPTER 3 – PHYSICAL AND ECONOMIC GEOGRAPHY

3. Physical and Economic Geography

3.1 Introduction

The literature review (Chapter 2) dealt with various issues of climate change, coastal vulnerability and economic consequences and the current research thinking with regard to the evaluation of coastline vulnerability on a global scale. This chapter reviews current literature detailing the geography, seal level rise, winds, temperature trends, coastal erosion, floods, environmental forcing and coastal vulnerability of the UK.

3.2 Geography

The UK with its moderately temperate climate (Easterling *et al*., 2000), is an Island nation located in Western Europe and made up of four countries, Wales, England, Scotland and Northern Ireland (Figure 3.1). The total area of the UK is 243,610 km^2 comprising of 241,930 km^2 land and 1,680 km^2 of water, with a population of *circa* 63 million (The World Bank, 2014). Bounded by four bodies of water, the English Channel, the North Sea, Irish Sea and Atlantic Ocean (Mackinder, 1907), UK coastline measured 17,381 km in length (Masselink and Russell, 2013). The UK coast is one of the diverse coasts in the Europe and hugely developed with massive urbanisation and industrialisation especially at Southeast (Ballinger, 2002). Most of the infrastructure located near to the coast is severely affected by coastal erosion and flooding (Phillips and Jones, 2006) in some coastal regions. Recent climate change variations increase the risk of flooding and extreme weather events (Easterling *et al*., 2000).

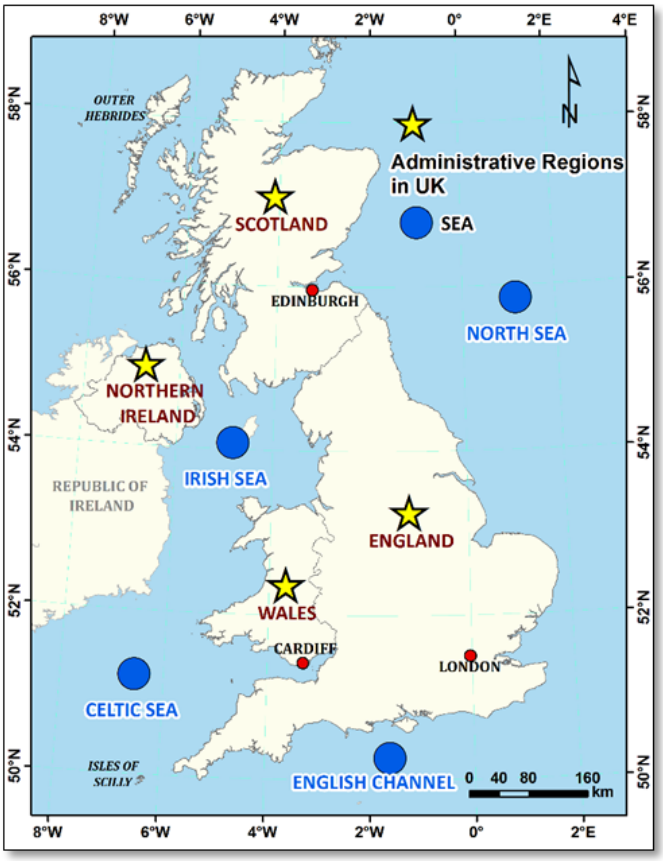


Figure 3.1: The UK with Sea Boundaries

3.3 Sea level rise

Global warming and rising sea levels are the strongest reasons for the local sea-level rise (LSL) (French, 1993; Gornitz *et al*., 1994). It creates dangerous scenarios for the population as well as properties, particularly in coastal areas in the form of coastal floods, erosion and storm surges (Nicholls, 2007). Globally, sea levels have risen almost 20 cm since the mid-19th century (Douglas, 2001), these trends are in line with other research results (Antunes and Taborda (2009) and the UK climate projections (UKCP09). These global trends influence the UK especially along the Norfolk and Suffolk coastlines in southeast England, where records show a historic rising trend (Doody, 2004a; Pye and Blot, 2006; Brooks and Spencer, 2012). In recent decades, sea levels have risen by *circa* 2 mm yr^{-1} at Lowestoft, *circa* 1.2 mm at Newlyn (Cannell *et al*., 2004) and in a recent comprehensive review of tide gauge data for the Bristol Channel and Severn Estuary by Phillips and Crisp (2010) concluded that there had been a detectible rise in mean sea levels and indicated a rise in the order of 30cm by 2050, and a rising trend of 2.4mm/yr^{-1}.

Meanwhile, the rise in local sea level creates increased risk at many locations around the UK (Table 3.1) and this is of concern considering that more than 40% of energy and manufacturing industries and in excess of 50% of fertile agricultural land are located close (within 10 km) to the coast (Nicholls and Small, 2002).

Table. 3.1: Current and predicted SLR at various locations around the UK

Reproduced from UKCIP (December 2010)

	London			**Cardiff**			**Edinburgh**			**Belfast**		
	High	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**	**High**	**Med**	**Low**
2000	3.5	3.0	2.5	3.5	2.9	2.5	2.2	1.6	1.2	2.3	1.7	1.3
2010	7.3	6.2	5.3	7.3	6.2	5.3	4.7	3.5	2.6	4.9	3.8	2.8
2020	11.5	9.7	8.2	11.5	9.7	8.2	7.5	5.7	4.3	7.8	6.0	4.6
2030	16.0	13.5	11.4	15.9	13.4	11.4	10.7	8.2	6.1	11.1	8.6	6.6
2040	20.8	17.5	14.8	20.8	17.5	14.8	14.2	10.9	8.2	14.7	11.4	8.7
2050	25.8	21.8	18.4	25.9	21.8	18.4	18.0	13.9	10.5	18.6	14.5	11.1
2060	31.4	26.3	22.2	31.4	26.3	22.2	22.1	17.1	13.0	22.9	17.8	13.7
2070	37.2	31.2	26.3	37.1	31.1	26.3	26.6	20.6	15.7	27.4	21.4	16.5
2080	43.3	36.3	30.5	43.3	36.2	30.5	31.4	24.4	18.6	32.3	25.3	19.6
2090	49.7	41.6	35.0	49.7	41.6	35.0	36.5	28.4	21.8	37.6	29.4	22.8
2095	53.1	44.4	37.3	53.1	44.4	37.3	39.2	30.5	23.4	40.3	31.6	24.5

The range of sea level rise around the UK (before land movements are included) is estimated to be between 12 and 76 cm for the period 1990–2095. Taking vertical land movement into consideration provides larger sea level rise predictions relative to the land in more southern regions of the UK, where land is collapsing, and somewhat lower upsurges in relative sea level for northern regions (Figure 3.2).

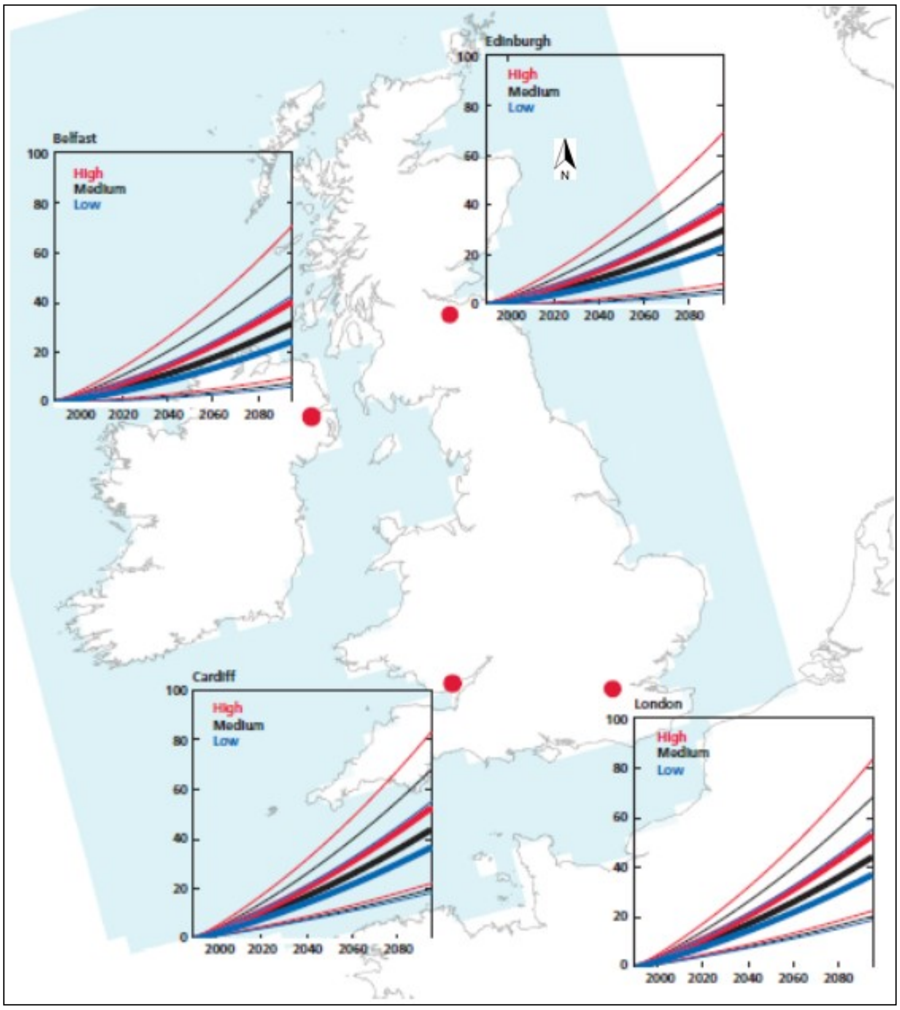


Figure 3.2: Map of UK sea level rise (2000-2080)

Source*: UKCIP, 2010*

3.4 Storms

Frequency and intensity of storms are predicted to increase with the potential to cause significant damage to coastal infrastructure and cause potential economic loss (Benson and Clay, 2004; Nicholls and Kebede, 2011; Slingo *et al*., 2014). Over the last 60 years, major storm events around the UK have increased (in the terms of damage and intensity) (Allan *et al*., 2009). However, Rangel-Buitrago *et al.*'s (2016) work on the Bristol Channel showed that the increasing storminess in the late 20th Century reported by Allan *et al*. (2009) -(such as Port Talbot) did not as expected continue into the first decades of the 21st century. However, Smith (2013) has predicted that storms and associated coastal and river flooding, along with hurricane winds, will be the greatest threat to the UK in the 21st century. Indeed, December 2013 and January 2014 were the third wettest months since 1910, and December 2013 was the windiest month since 1969 with average wind speed of almost 60 knots (31

ms^{-1}) (Met Office, 2014; Huntingford *et al*., 2014). Table 3.2 produced from data supplied by the Meteorological Office highlights that 2000 and 2012 were amongst the wettest on record For example between 1981 and 2010 the average yearly rainfall was around 1100 mm, in 2012 the total rainfall was 1,330.7mm (Met Office, 2014).

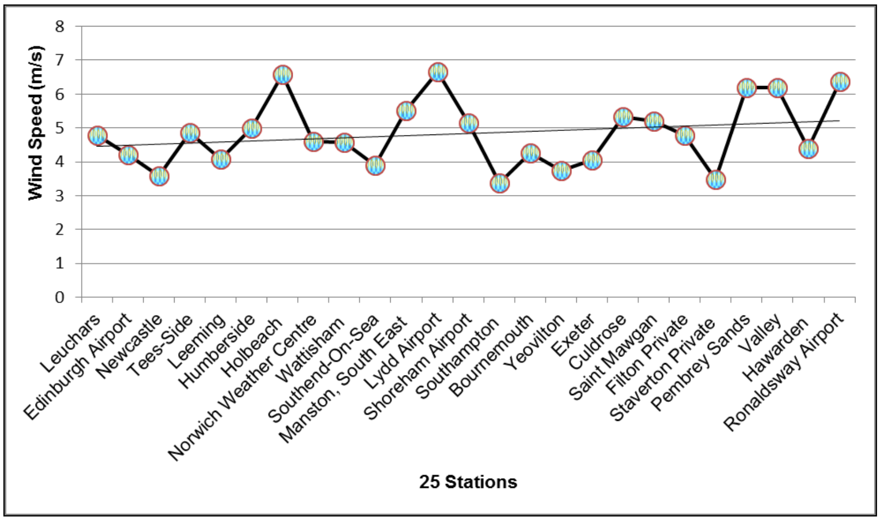
Table 3.2: UK'S Top Five Wettest Years
Data supplied by Met Office (2014)

Year	Rainfall (mm)
2000	1337.3 mm
2012	1330.7 mm
1954	1309.1 mm
2008	1295.0 mm
2002	1283.7 mm

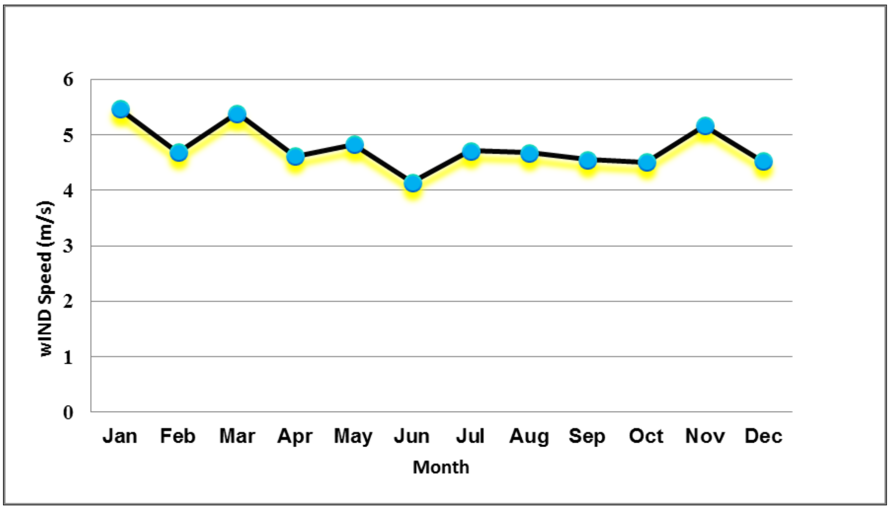
3.5 Winds

As previously discussed hurricane scale winds were recorded in December 2013, subjecting the country to an unusually energetic sequence of storms with the highest recorded winds between the 4th and 5th December. Storm surges coupled with high tides caused significant damage around the UK's coastline comparable to the 1953 flood events along the eastern English coastline (Slingo *et al*., 2014; Met Office, 2014). However, many weather warnings from the Environment Agency and Met Office, as well as coastal defence structures, reduce the intensity of economic damage.

Furthermore, average wind speed for the period between 2000 and 2014 for the UK (25 locations) was 4.84 ms^{-1}, with the highest recorded at Lydd airport (6.6 ms^{-1}), and lowest > 3.3 ms^{-1}recorded at Southampton (Kantamaneni, 2015; Figures 3.3a and 3.3b). However, the highest wind speeds occur in January (5.4 ms^{-1}) and the lowest in June (4.1 ms^{-1}). The average wind speed is showing an increasing trend, and it rose from 0.1 $ms^{-1}$to 3.5 $ms^{-1}$for the aforementioned period (Kantamaneni, 2015).



(a)



(b)

Figure 3.3: a) Wind speed at 25 stations and b) Average wind speed as per month (2000-2014)

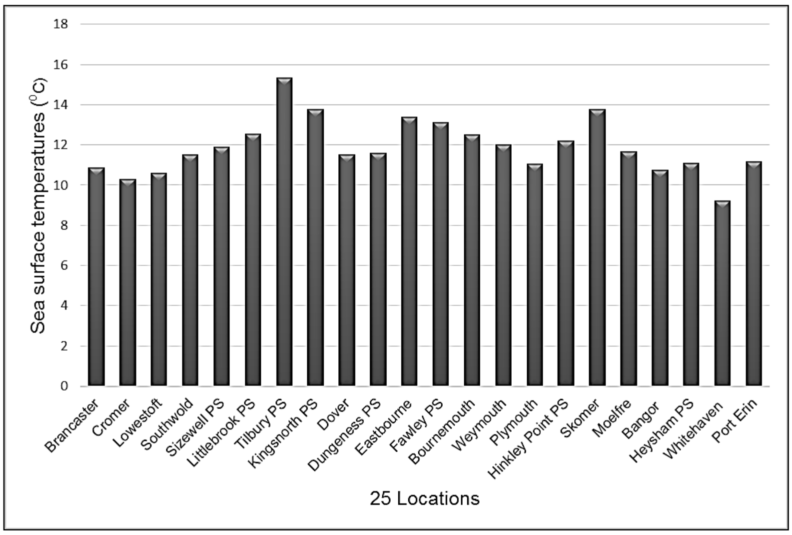
As previously mentioned, much of the damage caused by the 2013/14 storms was associated to storm surges (Huntingford *et al*., 2014). For example, In the Bristol Channel (Avonmouth) tide heights in excess of 15m were recorded (Met Office, 2014).

3.6 Temperature

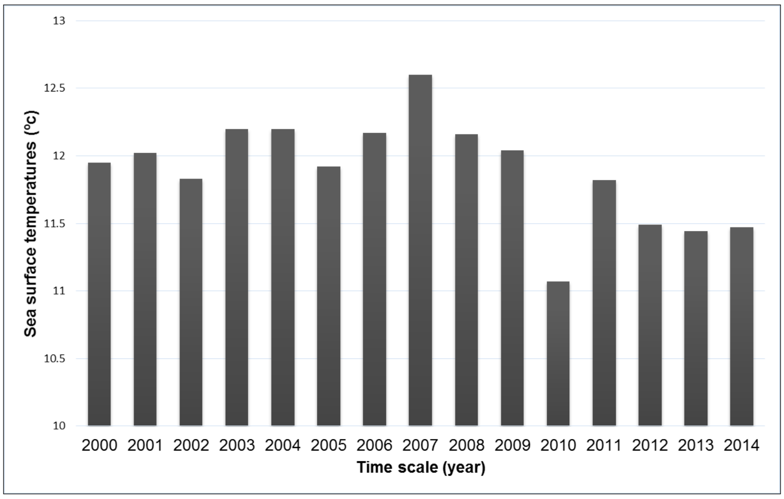
The global climate is being affected by rising human-induced emissions of greenhouse gases into the atmosphere (Moss *et al*., 2010), and the United Kingdom is not exempt from those impacts. Greenhouse gases in particular, CO_2 emissions, are the primary reason for rapid and recent climate change scenarios (Hulme *et al*., 2002; Boykoff, 2007; Johnson *et al*., 2009). CO_2 emissions, derived mainly from fossil-fuel combustion, increased by more than 40% from 1990 to 2008, and since the last century, while the earth has warmed by *circa* 0.7°C, average UK temperatures have increased by 1°C from the mid-1970s (Jenkins and Newborough, 2007). More than 2,000 deaths were recorded in England and Wales during the 2003 August heat wave (Johnson *et al*., 2005). Accelerated temperature change is expected to become more severe in the future due to human-induced climate forcing (Mitchell *et al*., 2006).

Average sea surface temperatures (SST) recorded at 25 locations between 2000 and 2014 around the UK is 11.8^{0}C; the highest temperature was 12.6^{0}C, which was recorded in 2007, and the lowest was 11^{0}C, which was recorded in 2010 (Figure 3.4a & b; Kantamaneni, 2015). It is quite evident that there are increasing SST trends in UK. Overall, in fifteen years, regional sea surface temperatures rose from 0.1^{0}C to 0.7^{0}C (Kantamaneni, 2015). However, the trends of 2013 and 2014 are unclear, currently, because of lack of an incomplete dataset. Between 2000 and 2014 SST's varied at the 25 recording locations around the UK. The highest temperature recorded was 15.3^{0}C in Tilbury PS, and the lowest was 9.2^{0}C, recorded at Whitehaven (Figure 3.4a).

Figure 3.4b shows the average annual sea level temperature recorded at the 25 locations around the UK for the period between 2000 and 2014. Despite predicted increases and in line with Rangel –Buitrago *et al.*'s (2016) storm work, SST's rose from the beginning of the century until 2007 and then a lowering trend was observed until the end of the assessment period.



(a)



(b)

Figure 3.4: a) Average sea surface temperature trends for the period of 2000-2014 at 25 locations around the UK and b) Annual average sea level temperatures

Source: Kantamaneni, 2016

3.7 Developed coastlines and coastal vulnerability indices

In the UK, more than 50% of the population live and work near the coastline (Dorling and Thomas, 2004; McGranahan *et al.*, 2007). Every year, the UK's coasts, particularly attract tourists from all over the world, crucial to many regional economies and contributing generate up the national economy (Gormsen, 1997; Davenport and Davenport, 2006). Ninety percentage of trade commutes through seaports (Warwick University, 2010), and maritime industries and service sectors contribute more than £17 billion annually to the UK's economy, with the figure expected to rise to as much as £25 billion by 2020 (Marine Industries Leadership Council, 2010). The maritime service sector contributed *circa* 1% to the national GDP and £2.7 billion in tax revenue in 2011 (Economics, 2013). Continuous occupation and rapid population growth within UK coastal areas have aggravated current risks of coastal flooding and erosion (Dodman, 2009; Figure 3.5). Furthermore, nearly 3008 km are currently undergoing erosion, (Doody, 2004b; 2013). Engineering structures protect an additional 3185 km of the coastline, and recent research reveals that the rate and pace of erosion across the UK are moderate (EUROSION, 2004; Masselink and Russell, 2011).

Figure 3.5: Developed Coastline (Aberystwyth)

3.7.1. Coastal vulnerability indices

As mentioned in Chapter 2 (Section 2.3), there are many existing methodologies across the globe to evaluate coastal vulnerability, but not in the UK. However, very few studies (McLaughlin and Cooper, 2010; Denner *et al.,* 2015) focused on physical aspects of coastal susceptibility at regional scales (Northern Ireland and Llanelli). In those frameworks, the multi scale coastal vulnerability index was important and it was explained elaborately in Section 2.13.5.

3.8 History of floods in the UK

Floods are part of the UK's coastal environment, and it is accepted that it is not technically possible or economically feasible to protect all assets from flooding (Johnson *et al*., 2007). Prolonged time series data can play a vital role in understanding flood intensity in multiple dimensions (Kochel and Baker, 1982; Merz *et al*., 2010). However, the majority of universal flood records are no older than 50 years (Macklin, 2006). Human loss on a large scale is uncommon in the United Kingdom, but previously, significant events have occurred. Thousands of deaths were recorded during the Bristol Channel floods (30th of January 1607) and Great storm of Britain (26th November 1703). These two events cumulatively accounted for >15,000 deaths (BBC, 2003; 2007). However, detailed recording of UK flood damage costs only commenced in 2007 and the Environment Agency now holds an extensive freely available database detailing both sustained damage and economic costs for England.

However, Environment Agencies and other government organisations such as Natural Resource Wales, record the data regarding storms and other related events that occur across the country. They also map the flood risk areas as shown in Figure 3.6.

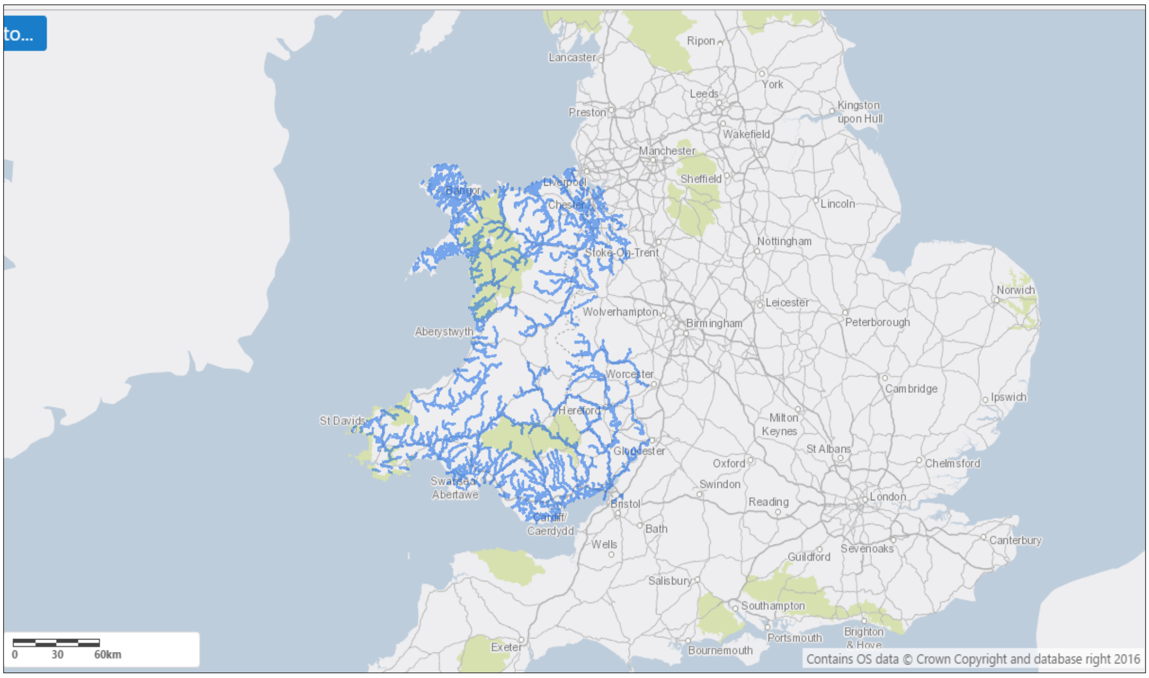


Figure. 3.6: Flood risk map –Wales

Source: Natural Resource Wales, 2016

As an example, in 1952, a natural disaster/flood struck the small coastal town of Lynmouth (Devon, England) and destroyed 100 buildings (Figure 3.7) 28 bridges, and additional commercial properties (Dobbie and Wolf, 1953). In 1953, North Sea floods struck England and Scotland and caused damage to 1,600 km of coastline and 24,000 residential properties (Met Office, 2015) while in April 1998, heavy rain struck the Midlands, causing heavy flooding with approximately 4,200 houses and business affected and costing £350 million (McEwen *et al*., 2002). Moreover, in autumn 2000, major floods affected England and Wales and caused £1 billion of damage with approximately 10,000 houses damaged, railway links washed away, and highways and power supplies cut off (Marsh and Dale, 2002; Pall *et al*., 2011; Alexander and Jones, 2000). In 2007, heavy summer rain caused extensive flooding in parts of England, particularly south and East Yorkshire, Worcestershire, Gloucestershire, and Oxfordshire. Significantly, there was unprecedented flooding of assets and infrastructure in some areas, and the resulting disruption, economic loss, and social anguish turned the summer 2007 floods into a nationwide catastrophe. Estimates, prepared shortly after the floods, indicated total losses at *circa* £4 billion, of which insured losses were thought to be approximately £3 billion (Environment Agency, 2010). During recent storm events, particularly during the winter of 2013 and 2014, much of the UK experienced recurrent powerful rainfall and flooding events, and this had a significant impact on property, transport and coastal protection structures in coastal regions, such as, Dawlish, Aberystwyth and Llanelli (Huntingford *et al.,* 2015; Denner *et al.,* 2015). Due to rapid climate changes, the UK has suffered from unprecedented flooding events, especially in recent decades (Steynor *et al.,* 2012; Kantamaneni and Phillips, 2016).

Figure 3.7: Lynmouth Floods in 1952

Source: BBC, 2010

3.9 Coastal erosion

Coastal erosion characteristically results in the inland retreat of the shoreline. This can increase the coastal flooding risk and result in loss of land and damage to buildings and infrastructure. Unexpected coastal erosion incidents may risk the lives of people. Rates of coastal erosion and deposition at international (Figure 2.8 and Figure 2.9), national, and regional (Figure 3.8) scales. According to BGS (2014), 113,000 residential and 9,000 commercial properties have been at risk of erosion across England and Wales. However, coastal erosion mostly occurs in coastal lowland areas and along soft sediment coastlines such as the East Anglian coast (Great Yarmouth), east Yorkshire (Spurn Head), and the Thames Estuary (French, 2004; Van der Wal, 2004). According to Muir *et al*. (2013) and BGS (2014), Benbecula and Happisburgh are highly vulnerable to sea level rise, coastal flooding and erosion. The magnitude of coastal erosion depends on the state of coastal defences. Though some areas have strong coastal defences (in the case of Aberystwyth), they face frequent coastal damage from the impacts of storms at sea (Kantamaneni, 2016a). Due to the low height of coastal defences, Dawlish is facing high erosion rates due to frequent flooding (Dawson *et al.,* 2016; Kantamaneni and Phillips, 2016). Three major 2004 studies conducted by Foresight Future Flooding, EUROSION, and Future Coast explored flooding and erosion problems in the UK (Thorne *et al.,* 2007).

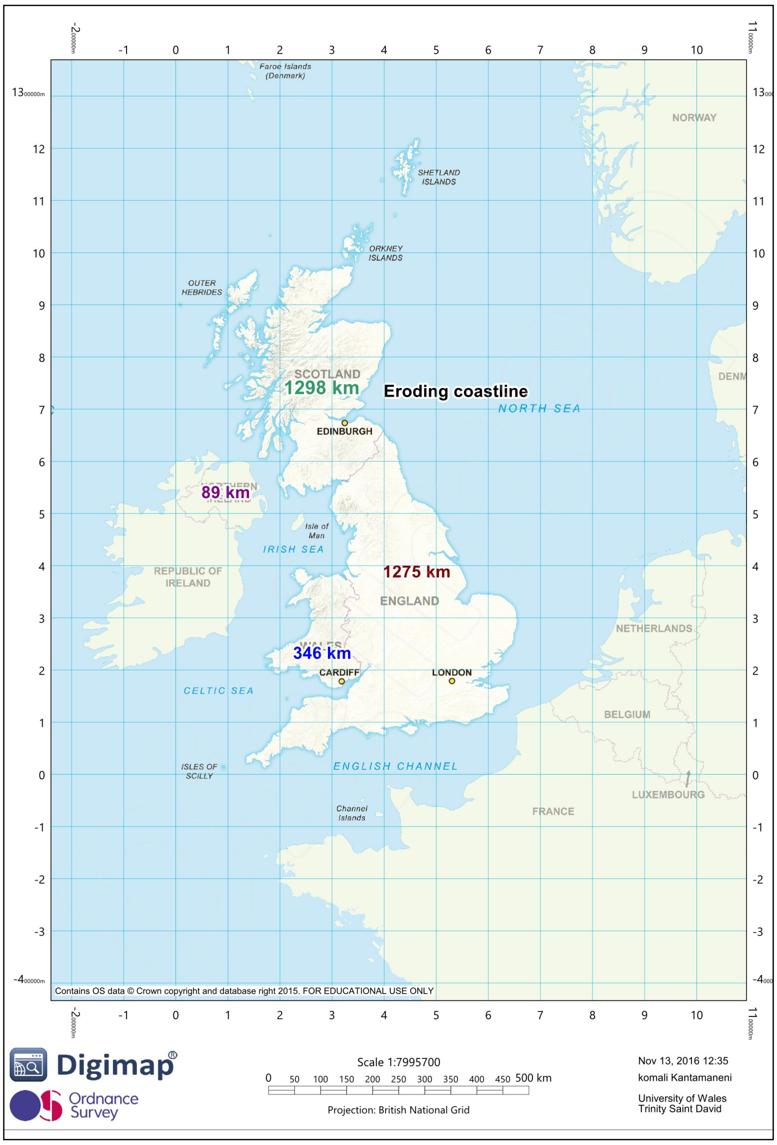


Figure 3.8: Map of coastal erosion in the UK

Source: Reproduced from Masselink and Russell, 2011

A great amount of the coastline of the UK is currently suffering from erosion (17%), and of the 3,700-km coastline of England and Wales 28% is experiencing erosion greater than >10 cm yr^{-1}. Coastal Erosion Risk Mapping project (Rogers *et al.,* 2008) has explored that 42% of the coast of England and Wales is at risk from erosion, of which 82% is unprotected. Coastal erosion impacts were clearly identified on tidal flats, cliffs, salt marshes, and beaches. The most significant risks from coastal erosion were flooding, rock falls, loss of land, and damage to commercial and residential infrastructure. Coastal properties across the country amounting to some 1,026,000 housing assets, 74,000 commercial assets, and some 432,000 hectares of farming land with a principal cost of more than £132 billion are potentially at risk from coastal flooding; altogether, this is equivalent to £10.48 billion that is converted for inflation on £7.7 billion between 2001 and 2013 (Penning-Rowsell *et al*., 2014). Therefore, coastal communities who are living in coastal vulnerability zones are at high risk of flooding and erosion in the UK, especially in England.

3.10 Economic loss

UK flood damage costs have increased significantly influenced by a series of flooding events between 2007 and 2013 and were the caused significant economic damage in England and Wales and to a lesser extent Northern Ireland and Scotland (Met Office, 2014). However, the most significant example in history is the 18th-century (1703) hurricane, which caused damage costs of more than £20 billion (calculated according to current inflation rates) and 8000 fatalities (Derham, 1704). The Lynmouth Flood (1952), which caused 34 deaths, also brought about a huge economic loss in England (Dobbie and Wolf, 1953). However, most of the economic loss came from flooding events, and, accordingly, Table 3.3 reveals monetary loss trends since 1990.

Table 3.3: Top ten Natural Disasters and Damage Costs in the UK (1990 - 2014)

Source: Modified from - EM-DAT, 2014

Disaster	**Date**	**Damage (£)**
Flood	11-Oct-2000	3, 861,471
Flood	25-Jun-2007	2,814,292
Flood	20-Jul-2007	2,814,292
Storm	25-Jan-1990	2,225,254
Flood	21-Nov-2012	1,047,178
Storm	15-Oct-1987	1,024,271
Storm	28-Oct-2000	981,730
Storm	18-Jan-2007	785,384
Storm	25-Feb-1990	589,038
Storm	5-Jan-1991	589,038

3.11 National (UK) GDP and impact of destruction costs on GDP

The United Kingdom is the world's sixth-largest economy with a 2014 GDP of £2.1 trillion (The World Bank, 2016). It also has world-famous beaches, contributing to the national economy in the form of tourism (Vaz *et al*., 2009). However, the UK is increasingly vulnerable to impacts of coastal erosion, flash and surface flooding, storm surges and extremes in weather compared to recent memory (Wilby and Keenan, 2012). Severe weather conditions and adaptation costs have impacted the national GDP considerably in the 21st century (Turner *et al*., 1996; McCarthy, 2001; Kantamaneni, 2015). For example, 2007's summer floods turned into a nationwide catastrophe. The cost of this event was highlighted by a negative impact on the 2007 national GDP, significantly affecting local economies. In recent times, more weather events such as floods are creating serious destruction to infrastructure directly (Kantamaneni, 2016a) and to business indirectly causing slight albeit significant economic fluctuations (Dawson *et al*., 2016).

3.12 Summary

This chapter concentrated on geographical and environmental drivers that influence coastal vulnerability risk issues related to the UK. Accordingly, this chapter identified that there is no combined coastal vulnerability index (CVI) for the evaluation of United Kingdom coastal vulnerability in both physical and economic terms. In order to improve expertise in this important area identified research gaps needed to be filled. Therefore, a CVI methodology has been developed that considers both physical and economic variables. This methodology will be discussed in detail in Chapter 4.

CHAPTER 4 - METHODOLOGY

4. Methodology

4.1 Introduction

The literature review identified that extensive research had been carried out with respect to natural disasters and coastal vulnerability procedures. The physical and economic background chapter also identified that research was needed to identify both physical and economic coastal vulnerability in the UK. Based on previous work done, there was an obvious need to better understand the available methods (indicators, index, GIS and model based methods) that can be operatively and concretely applied for assessing coastal vulnerability. Therefore, this chapter sets out methodological approaches and procedures to evaluate combined coastal vulnerability (physical and economic) of selected UK sites. Firstly, PCVI was developed and then applied to a number of case study areas and consequently an ECVI was developed and applied to the same case sites. As a result, a CCVI was developed based on PCVI and ECVI results.

Therefore, this chapter describes the development of a conceptual framework as well as the application procedures required to evaluate coastal vulnerability. Basic CVI concepts of Denner *et al*. (2015) and Palmer *et al.* (2011) have been adapted to the current study for an evaluation of PCVI. This methodology was modified based on the case study site characteristics. As a result of adding two new physical parameters (distance of built structures and coastal defences) to those defined by Palmer *et al.* (2011) and Denner *et al.* (2015) the selected areas were measured differently (Section 4.5.1). Furthermore, an Economic Coastal Vulnerability Index (ECVI) model was created by utilising newly developed economic parameters in order to appraise such vulnerability. Subsequently, the PCVI results were compared and contrasted with ECVI results and subsequently CCVI was developed. Along with these evaluations, ArcGIS vulnerability maps were also generated for an easy comparison of these indices.

4.2 Desk study

Before establishing the fieldwork, a desk study was undertaken to gather storm and coastal economics data for the UK. This information was obtained under special access for researchers from following organisations.

- NASA
- EEA
- NOAA

- Met Office
- Environment Agency
- British Geological Survey
- World Disaster Data
- ABI – Association of British Insurers
- ONS – Office of National Statistics
- Ordnance Survey Maps
- British Museum photographs
- Devon County Council Photographs
- Act of Freedom of Information
- Local Authorities
- Insurance Companies/NGO

4.2.1 Parametric tests associated with the desk study

Data analysis begins with an attempt to find associations between variables and regression analysis. Regression analysis is a basic tool (Douglas and Crowell, 2000) and these type methods are useful when considering one of the variables, such as, time as a function of the other. Davis (2005) as determined from:

$$y = (c + mx) + \varepsilon)$$

Where y is the independent variable; c is a constant; mx, regression coefficients; and x_1, x_2, and x_n are dependant variables; and ε is the error between model and actual results (Field, 2009). Variables c and m are calculated from the following:

$$m = \frac{\sum xy \quad \frac{-\sum x \sum y}{n}}{\sum x^2 \quad \frac{-(\sum x)^2}{n}}$$

$$c = \frac{y}{n} \; -m \; \frac{x}{n}$$

Proportional dataset variability is explained by the statistical model determined from the coefficient of determination, which is simply the square of the sample Pearson correlation moment coefficients. Pearson's product moment correlation coefficient (r) determined from:

$$\text{Correlation Coefficient } (r_{calc}) = \frac{n\sum xy - \sum x \sum y}{\sqrt{(n\sum x^2 - (\sum x)^2)(n\sum y^2 - (\sum y)^2)}}$$

Where, n is the number of data pairs, x and y are data points on each axis (Wheater and Cook, 2000).

The significance of the regression line is given by the following formulae:

$$SS_{total} = \sum y^2 - \frac{(\sum y)^2}{n}$$

$$SS_{regression} = \frac{\sum xy - \frac{(\sum x \sum y)^2}{n}}{\sum x^2 - \frac{(\sum x)^2}{n}}$$

$$SS_{residual} = SS_{total} - SS_{regression}$$

The statistical programme SPSS (21st version) was used to analyse the gathered desktop study data and ECVI values. ArcGIS (10.3 version) was also utilised to develop coastal vulnerability maps.

4.3. Methodological approaches for coastal vulnerability indices

In terms of its economic value, both the literature review and physical background (Chapters 2 and 3 respectively) highlighted the need to investigate UK coastal vulnerability, mainly because of its diverse characteristics in terms of both the built and natural environments. However, Chapter 2 also identified that no single vulnerability assessment methodology existed that enabled evaluation of cost in relation to flood, storm-surge and other natural mechanisms related to climate change. Furthermore, in the UK, there is no specific government organisation that evaluates economic storm data; this leads to ambiguity in the study of economic coastal vulnerability. This research identified that the vulnerability effects need to be evaluated in a systematic order and that new frameworks should be developed to achieve best results.

4.4 Site selection

The main aim of this research is a development of combined coastal vulnerability (physical and economic) and an important objective was the identification of suitable case study sites (Section 1.3). Published work (literature), recent events and multiple site visits were used to identify the most suitable sites all with varying physical and economic characteristics. Zsamboky *et al.* (2011) explored that Great Yarmouth, Skegness, Llanelli and Benbecula were particularly vulnerable based on coastal erosion, SLR and frequent flooding events (section 3.9). They also identified that Lincolnshire, Yorkshire and East Anglian coastlines were highly vulnerable. Happisburgh on the East Anglian coast has been the subject of televised debate and research carried out by Poulton *et al.* (2006) calculated coastal erosion rates of circa 9 m yr^{-1}. However, this is partially caused by SLR and postglacial rebound as identified in Section 3.3: they suggested that tourism contributes significantly to the village economy, is being threatened by receding cliff line. The highly dynamic coastline between Holderness and Spurn head is particularly liable to erosion (BGS, 2014). The winter storms between December 2013 and January 2014 have identified both Dawlish and Aberystwyth situated close to the coastline are vulnerable see for example Dawson *et al*. (2015) and Kantamaneni (2016b) (section 3.9). The British Geological Survey (2014) has identified Hallsands and Happisburgh as vulnerable to rapid coastal erosion (section 3.9). While, Neath Port Talbot County Borough Council (2013) state that the steel and associated industries located in Port Talbot are vulnerable to both erosion and flood impact. Increased coastal erosion rates (Section 3.9) mainly caused by increasing environmental forcing conditions may have a catastrophic effect on heavily industrialised coastal areas, such as, Port Talbot Steelworks, may lead to economic costs that that would have an effect on National GDP (Section 3.11). Whereas the touristic Town of Aberystwyth is heavily reliant on sea defence resilience and any breakdown would lead to local economic loss (Section 3.9). Similarly, Lynmouth tourism is threatened by flood potential from two rivers (section 3.8) and coastal erosion (Environment Agency, 2012). As can be seen it is generally accepted (within the literature) factors that influence physical and economic vulnerability were explored and variables derived for eleven case study sites. Seven in England, three in Wales and one in Scotland, each with differing geographic and geological characteristics and varying environmental forcing exposure (Table 4.1 and Figure 4.1). Based on the analysis, there are many vulnerability hotspots across the UK, but these selected case study locations are in need of immediate consideration and accordingly those study sites were selected for an evaluation.

Table 4.1: Coastal vulnerability sites

England	Wales	Scotland
• Spurn Head • Hallsands ▪ Lynmouth • Happisburgh • Dawlish • Great Yarmouth • Skegness	• Aberystwyth • Port Talbot • Llanelli	• Benbecula Island

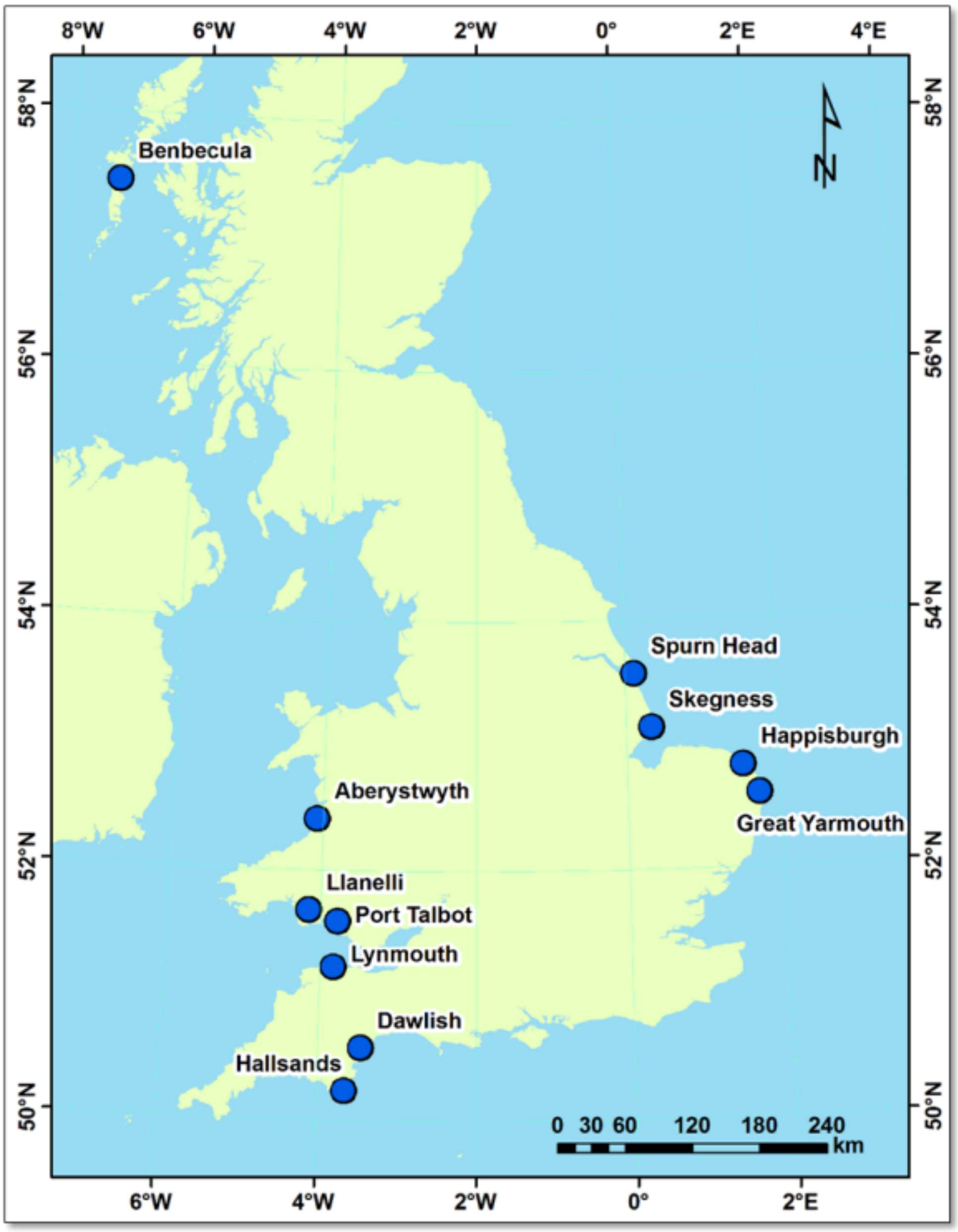


Figure 4.1: Map of coastal vulnerability sites

4.4.1 Description of selected sites

I. Spurn Head

Spurn Head comprises (geomorphological) sand and shingle spit covered by dunes, together with an area of till and alluvium to the north (May and Hansom, 2003), which originally formed around the end of the 16th century (Sistermans and Nieuwenhuis, 2013; Figure 4.2). The spit extends 5.5.km south-westwards across the Humber estuary and rises only a few meters above sea level (May and Hansom, 2003). To the north low till cliffs are being eroded at rates (Section 3.9) in excess of 2.5 m yr^{-1} and this in turn feeds sediment to the spit. Macro tidal tides with a tidal range of 6m influence sediment deposition along the frontal lobe of the spit that can erode at rates of between 1m and 2 m yr^{-1} (Quinn *et al*., 2009). However, erosion rates have varied over time and exact estimations are difficult. The erosion occurs mostly during storm surges and there is documented evidence that the spit has been breached on several occasions (Sistermans and Nieuwenhuis, 2013). With predicted sea level rise increasing storm risk (Section 3.3) and consequential increasing flows from the Humber River, Spurn Head was identified as potentially vulnerable and in need of assessment.

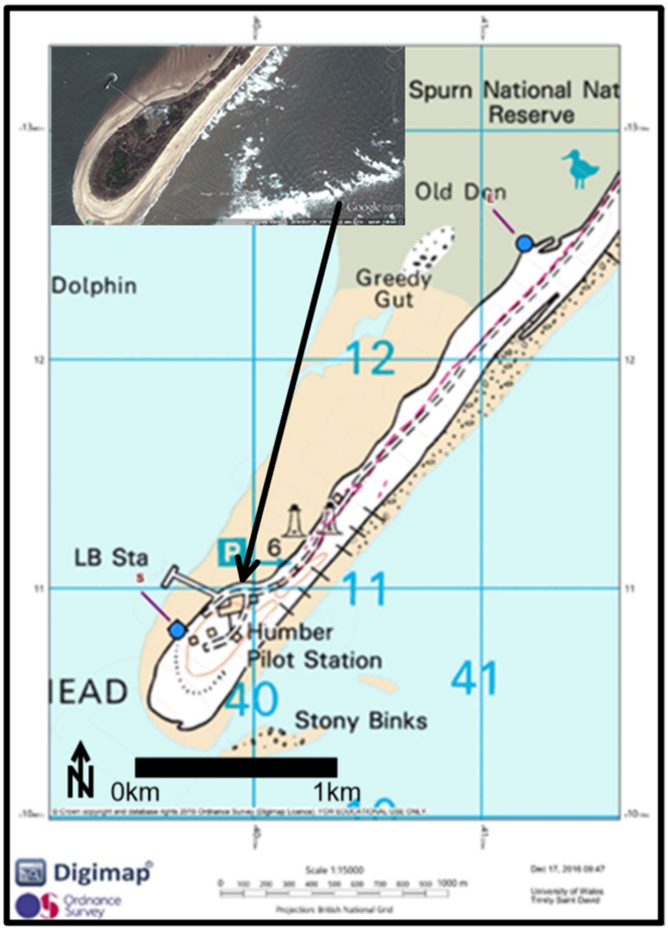


Figure 4.2: Spurn Head coastline and measuring points

II. Hallsands

A combination of gravel extraction, focused wave energy and high wave and tide conditions have resulted in rapid coastal erosion making this region as one of the highly-eroded sites in the UK (Section 3.9). The surrounding cliffs comprise mica-schist and quartz-schist that formed a raised platform the foundation of the hamlet of Hallsands, schists possess many structural features that weaken the cliffs, and the sea has exploited these weaknesses (May and Hansom, 2003). In February 2014, storms damaged coastal defences (Figure 4.3) by violent waves and high tides, which left the village nearly, vanished though shoreline management has been protecting the coastline for years. However, it is not strong enough to protect Hallsands shoreline from chronic waves and intense storm strikes. Because of these reasons Hallsands considered as one of the vulnerable sites in the UK and accordingly people are not showing interest to reside in this region. However, they want to construct only holiday homes. Surprisingly, the market for properties at this is also high given it has a significant coastal risk.

Figure 4.3: Hallsands coastline and measuring points

III. Lynmouth

Strong northwesterly winds coinciding with high tides can cause damage to residential and commercial properties (Figure 4.4) since 1952; severe coastal flooding events often destruct this region (Section 3.8) (Scrase and Sheate, 2005) due to exuberated climatic change scenarios (Kantamaneni and Phillips, 2016). While, floodwater also poses a significant threat to low-level properties and population; flood risk for this site comes from river, surface water and tidal flooding. Land use and management variations, together with urban development in the catchment, sea level rise (which will be rise 500 mm by 2100) will also affect the frequency and magnitude of flooding in this region (Environment Agency, 2012). Lynmouth is one of the economic zones (market town) in Devon Council area and it has relatively sluggish population growth i.e. 3.5% since 1991 when to compare with other counties. Due to its commercial activities, Lynmouth has good fiscal value though it has a small population (Devon City Council, 2007). The south west coast of England is exposed to an energetic wave regime emanating from the Atlantic Ocean. These waves are heavily diffracted by headlands and focus the energy within in the many embayed beaches along this coastline. Between October 2013 and April 2014 the south west coast experienced 22 extreme storms (Masselink *et al.,* 2015). Even though Lynmouth has a high coastal elevation, it was significantly vulnerable to coastal flooding and erosion as a consequence of spring tidal range storm and surge conditions, that essentially restricted river flows from entering the sea.

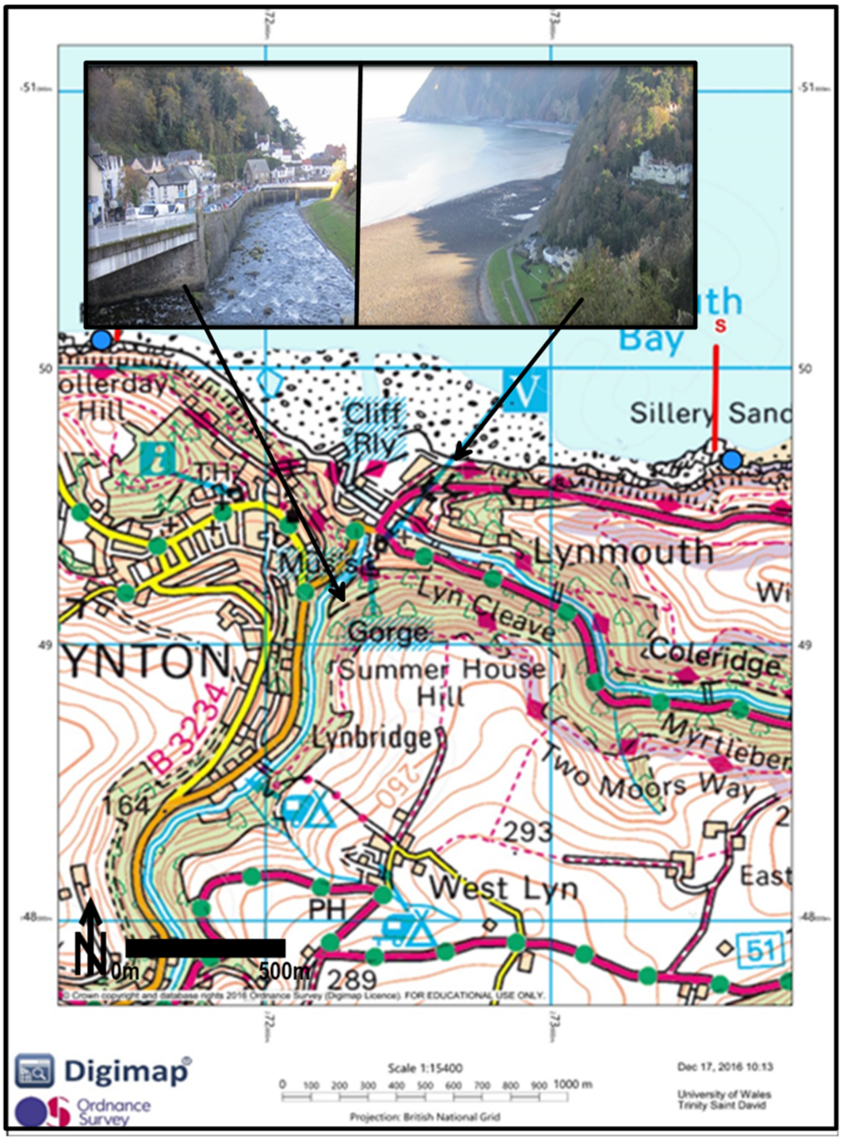


Figure 4.4:–Lynmouth coastline and measuring points

IV. Happisburgh

Happisburgh cliffs range in height from 6 m to 10 m, comprised of a sequence of several glacial tills, separated by beds of stratified silt, clay and sand, marine deposits underneath the modern beach material are periodically exposed to storms (Hart, 1999; Lee *et al*., 2004). Coastal flooding and erosion are significant risks at Happisburgh (Section 3.9) and in recent years the coastline has retreated by as much as 260 metres. Storm waves erode the glacial till at the base of the cliffs causing collapse and rapid erosion (BGS, 2014). Aerial photographic evidence given in Figure 4.5 shows coastal changes between 1999 (left panel) and 2014 (right panel) highlighting the previously mentioned erosion trend. While, the 2006 aerial photograph shows the coastal protection measures that reduced erosion rates. The coastline is exposed to a variety of wave directions and is especially vulnerable to storms generated from the north as there is no fetch limitation in this direction (Thomalla and Vincent, 2003). Because of these reasons Happisburgh is considered to be to be one of the highly vulnerable coastal sites in the UK. Even though Happisburgh is highly vulnerable to coastal erosion surprisingly property prices remain high (Kantamaneni, 2016b).

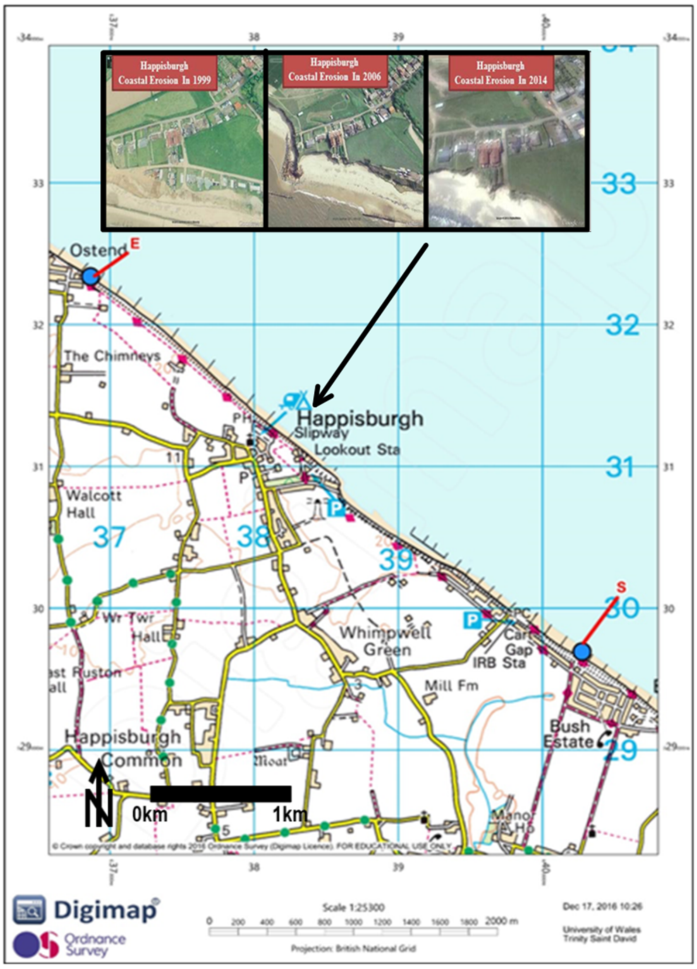


Figure 4.5: Happisburgh coastline and measuring points

V. Dawlish

Recent, winter storms and storm surges have caused a great deal infrastructure damage along the Dawlish coastline. This was particularly apparent during the 2013/12 winter storms, when sea was breached, properties damaged (Section 3.8) and a 6 km stretch of railway line was so severely damaged that train services were disrupted for more than two months (Dawson *et al.*, 2016). However, the track between Dawlish and Teignmouth has been vulnerable to frequent closure during high waves and storm events since it was built. Dawlish is also one of the rapidly growing regions in Devon particularly along the coastline (Figure

4.6).

Figure 4.6: Dawlish coastline and measuring points

VI. Great Yarmouth

Great Yarmouth is a low-lying coastal town (Figure 4.7) constructed on a spit, comprising of varying proportions of sand and gravel. The region has a history of coastal flooding, not helped by the fact that the river Yare separates the spit from the mainland at its western end (Nicholas, 2007). Great Yarmouth is one of the flood prone (coastal and fluvial) areas in the England as evidenced since 1953 (Kelman, 2003; Dawson *et al*., 2009). (Section 3.8 and 3.9) Three hundred million years ago, Great Yarmouth coast/beach was physically formed and widely covered with glacial drift deposits (Norfolk Heritage Explorer, 2015). Landslides and erosion are common problems in this region. Though it has coastal erosion and storm risk, population and property growth has been high over the last three decades. Economically it is one of fastest growing economies in England, consisting of several large industries such as energy, electronics and offshore gas, which contribute significantly to the GDP of national and local economies. This industrialisation, contributes to a high population growth in the area 7.6% since 2001, a figure that is predicted to double by 2021 (Great Yarmouth Council, 2014).

Figure 4.7: Great Yarmouth coastline and measuring points

VII. Skegness

Skegness has been subject to erosion and general retreat for several centuries (Dugdale and Vere, 1993; Figure 4.8). The key climate risks for Skegness are frequent and unprecedented flooding events, fluctuations in weather patterns and increased occurrence of summer precipitation. In recent decades, additional sea defences were constructed to protect vital infrastructure from erosion. While, the high water table and low-lying landscape of this region, in conjunction with the increased risk associated with sea level rise, post glacial rebound (Subduction) and storm surges, intensify the area's physical vulnerability to the effects of climate change (Section 3.9) (Zsamboky *et al*., 2011).

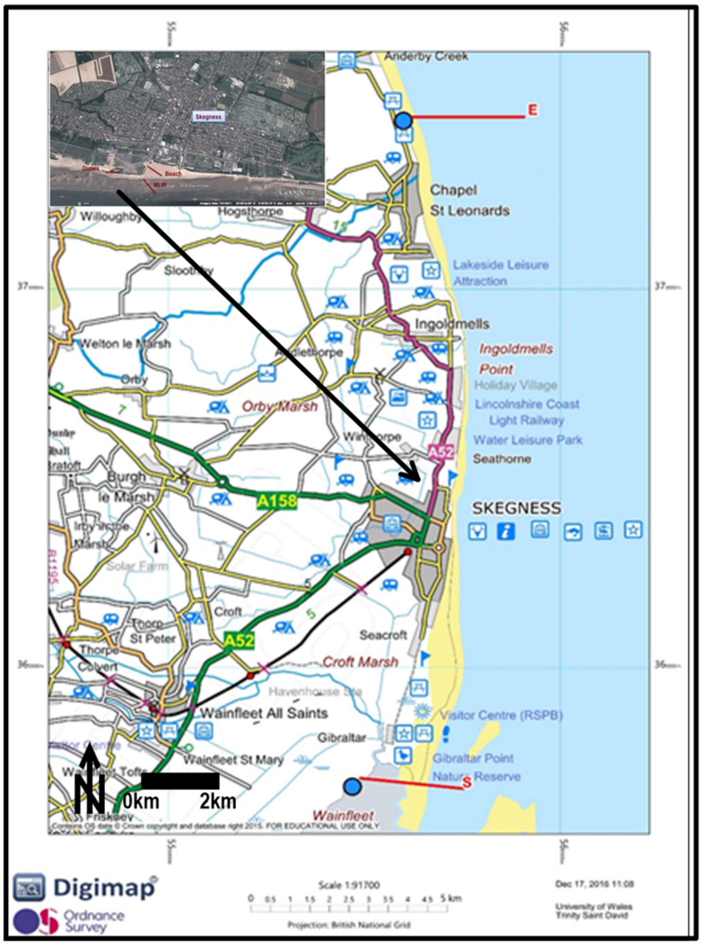


Figure 4.8: Skegness coastline and measuring points

VIII. Benbecula

Benbecula is extremely exposed to North Atlantic Ocean winter storms and waves particularly in winter months (Dawson *et al*., 2007; Wolf and Woolf, 2006). Accordingly, high waves and coastal erosion are the most significant problems in this region (Section 3.9), and it is a highly eroding site due to the rapid disintegration of coastline into the sea (Kantamaneni and Phillips, 2016). These situations also affect transport system (ferry service) enormously particularly in the winter period, which is the main way to reach this site. Due to these reasons, population have been in decline decrease rate is very high since 1991, i.e., 32%. Cumulatively, these reasons make Benbecula a highly vulnerable and isolated area in the UK (Figure 4.9).

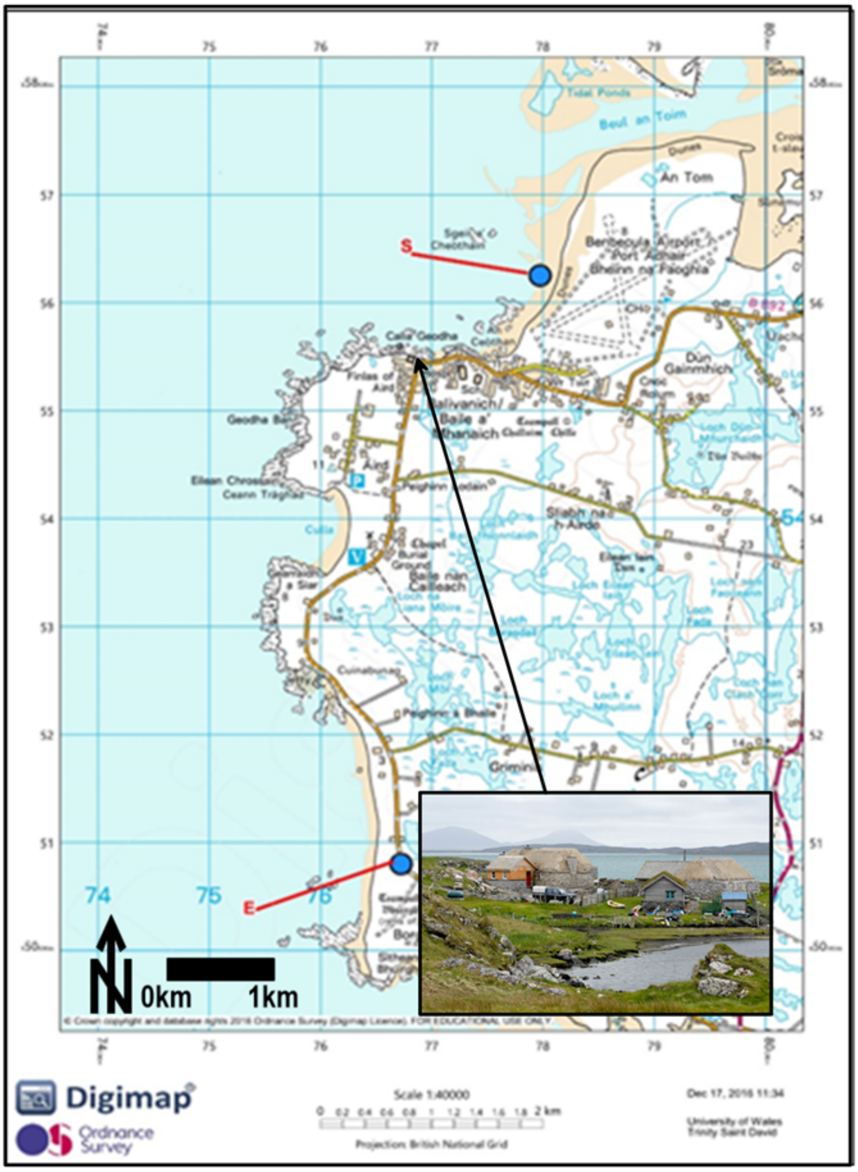


Figure 4.9: Benbecula coastline and measuring points

IX. Aberystwyth

Aberystwyth is the main touristic spot and administrative region of the west coast of Wales; though it has a small coastline (>2km) (Aberystwyth Guide, 2015), it has a high socio-economic value due to the town's tourism, education, and retail sectors. Population growth is very rapid i.e. 23% since 1970 (Ceredigion County Council, 2006). Currently, properties in Aberystwyth have high market value (Kantamaneni, 2016b). Frequent storm strikes are not unusual phenomena in Aberystwyth; starting several decades ago, repeated storms ravaged this region and damaged infrastructure (Section 3.8 and Section 3.9) costing several million (Figure 4.10) as evidenced in 1927, 2008, 2013 and 2014 (major events). In particular, 2014 storms damaged *circa* 2 km of railway track between Aberystwyth and Machynlleth severely, and nearly two weeks were needed for repairs. In addition, the widespread destruction of the seawall and walking path and the flooding of more than ten houses occurred. Future climatic conditions and levels of damage due to various coastal hazards will worsen the situation if strict adaptation and coastal defence procedures are not implemented in the near future (Slingo *et al*. 2014).

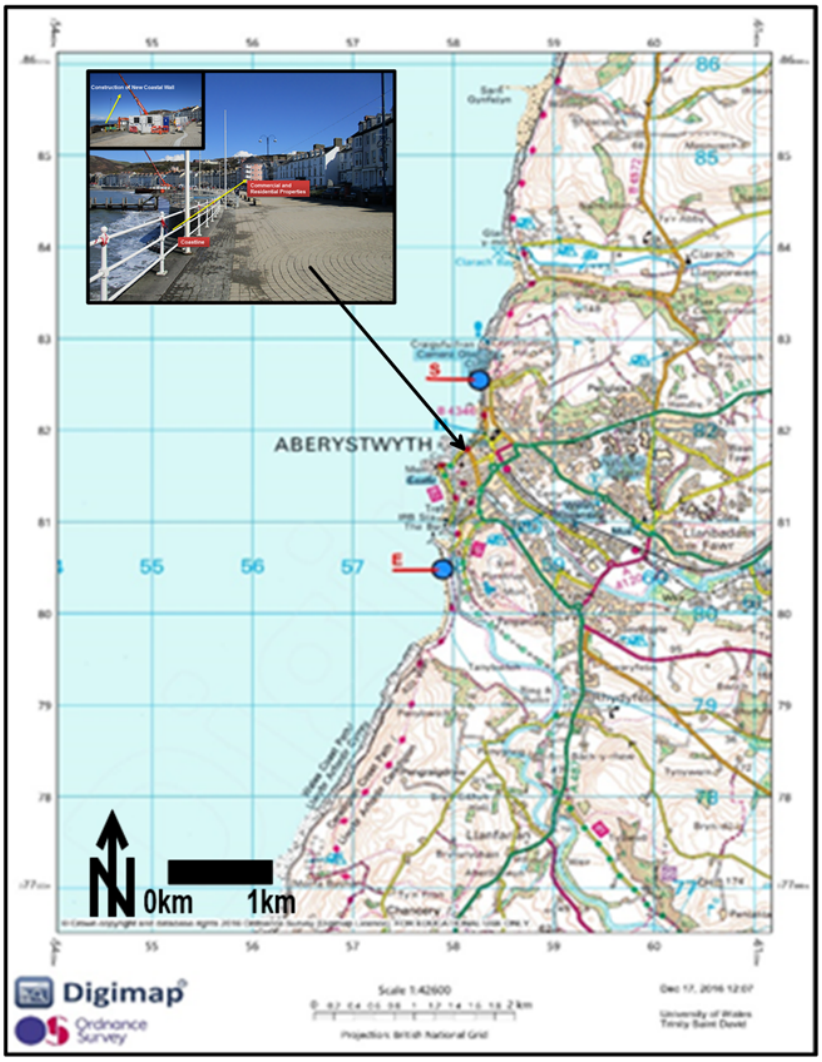


Figure 4.10: Aberystwyth coastline and measuring points

X. Port Talbot

The Port Talbot coastline is backed either by natural dune systems or retaining structures but many of the commercial and residential properties built in this relatively low lying area are at risk of flooding (Figure 4.11). Strong winds and tides generated in the Bristol Channel contribute to a high-energy wave environment (Section 3.4) (Allan *et al*., 2009). Prevailing winds emanate from the southwest and the macro tidal environment has a spring tidal range 7.5 m (Phillips and Crisp, 2010), and storm waves >5.5 m with periods >8.5 s are not uncommon in this region (Thomas *et al*., 2015). Historically linked to the coal, steel and fishing industries, the current industrial activity is centered on Port Talbot steelworks. Port Talbot Harbour promontory with associated dredged channels, interrupt longshore sediment drift, along with freshwater inputs from the rivers, Neath, Afan and Kenfig that flow into Swansea Bay (Thomas *et al*., 2015). While, due to the economic downturn in this region; growth rate was not positive between 2008 and 2011, but now it has constant growth from industrial side. Population growth rate has steadily increased since 2001, at 4% (ONS, 2012). Due to the industrialisation, this area has high economic value.

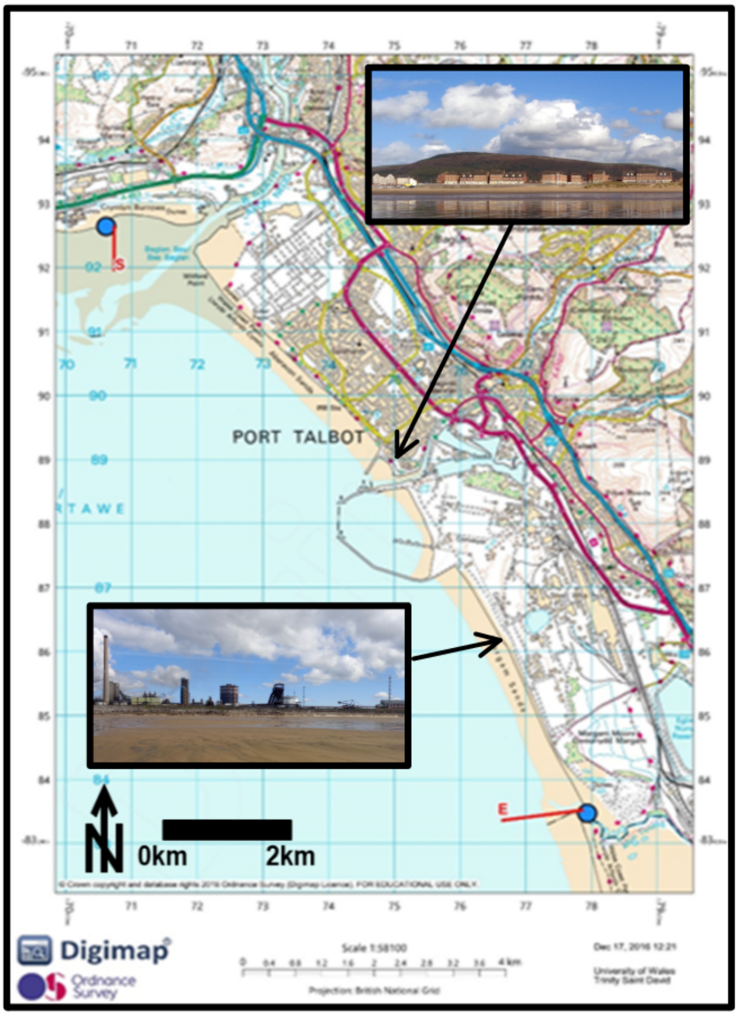


Figure 4.11: Port Talbot coastline and measuring points

XI. Llanelli

The decline of the coal and steel industries led to economic decline and disadvantage in the Llanelli area (Zsamboky *et al*., 2011). To stimulate the local economy the Local Authority in conjunction with other interested stakeholders developed a regeneration strategy focusing on the tourist sector (CCC, 2007). The transformation of the former site of the Llanelli Steel Works into Sandy Water Park was the catalyst for the Millennium Coastal Park. The park attracts a million visitors annually and was hailed as an example of successful sustainable design and construction (Figure. 4.12; Holmes, 2003; Phillips *et al*., 2009). However, recent storm events severely damaged the coastal path, rail infrastructure and impacted on several newly constructed dwellings (Section 3.8) (Denner *et al*., 2015). It is acknowledged that continuous flooding in the area resulted from an increase in impervious surfaces resulting from new developments and an increased sewage base load by housing stock expansion resulting from the coinciding of high tides with heavy rainfall (CCC, 2007).

Figure 4.12: Llanelli coastline and measuring points

4.5 PCVI Data

Statistical data regarding beach and dune width were obtained by direct measurement within a GIS (Mapinfo® 15) and from Ordnance survey maps obtained via Digimap®. Distance of vegetation and built structures behind the back beach, coastal slope and rocky outcrop were obtained from Google Earth/NASA maps. Detailed description regarding physical parameters was given for each of the case study sites in Chapter 5.

4.5.1 Physical parameters and measurement

Aligning with Denner *et al.'s* (2015) work on the Welsh coast, seven physical parameters were used to estimate physical vulnerability (Section 4.1). These were Beach width, dune width, distance of vegetation behind the back beach, distance of built structures behind the back beach, coastal slope, rocky outcrop and coastal defences. Accordingly in this research, transect lines were drawn perpendicular to the coast at 0.5 km spacing. In line with Denner *et al*. (2015) the back beach was used as a proxy baseline, measurements extended to a line drawn 0.5 km inland approximately parallel to the baseline and as far as mean low water in a seaward direction (Figure 4.15). Subsequently, detailed measurements based upon each parameter were recorded along each transect.

Table 4.2 details physical thresholds for each parameter based upon the methodologies adopted by Palmer *et al*. (2011), and refined by Denner *et al*. (2015) and assigned a ranking score between 1 and 4. Individual measurements were then compared and contrasted with Table 4.3 and assigned a ranking score between extremely low (1), low (2), moderate (3) high (4) to assess vulnerability quantitatively. With rankings applied, these values were then summed for each location to provide a relative CVI score using Comparative PCVI = $P_a + P_b + Pc + P_d + P_e + P_f + P_g$, where "$P_a$ ***to*** P_g" are the respective ranking score for each parameter (equation 1; section 4.3.2). The PCVI value would range between a minimum value of 7 and a maximum of 28. These scores were compared with Table 4.3 in order to categorise the level of physical vulnerability for each location.

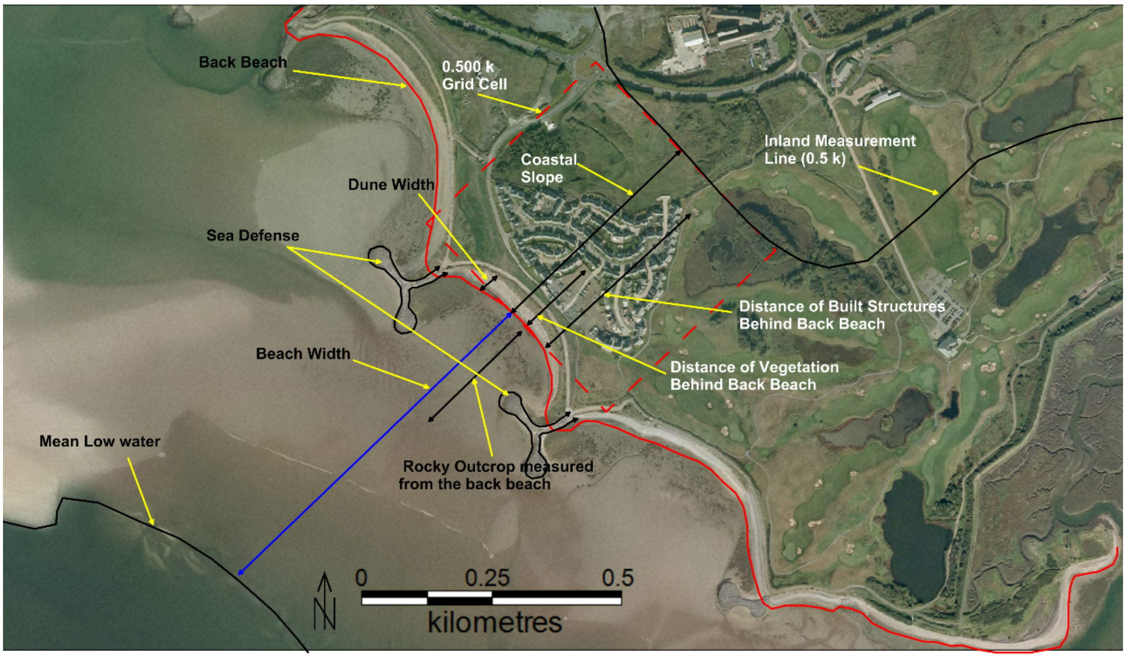


Figure 4.13: Transect line and 0.5 km coastal cell

Table 4.2: Physical parameter ratings of the level of vulnerability

	Physical Vulnerability Values			
Physical Parameter	**Extremely Low (1)**	**Low (2)**	**Moderate (3)**	**High (4)**
Beach width (P_a)	> 150m	100 –150m	50m – 100m	< 50m
Dune width (P_b)	> 150m	50 –150m	25m – 50m	< 25m
Coastal slope (P_c)	> 12%	12% – 8%	8% -- 4%	< 4%
Distance of vegetation behind the back beach (P_d)	> 600m	200m –600m	100m – 200m	< 100m
Distance of built structures behind the back beach (P_e)	>600m	200m –600m	100m – 200m	< 100m
Rocky outcrop (P_f)	> 50%	20% –50%	10% – 20%	< 10%
Sea defences (P_g)	> 50%	20% –50%	10% – 20%	< 10%

Table 4.3: Vulnerability level ratings (PCVI)

Total Relative Vulnerability Score	Range of Vulnerability
<12	**Very Low**
12-15	Low
16-18	Moderate
19 -23	High
24-28	Very High

4.6 Economic coastal Vulnerability

Economic coastal vulnerability was designed by the author and applied to the selected case study site locations (sections 4.1 and 4.4).

Three basic methodologies were adapted for the establishment of proposed ECVI, as follows:

I. Indicator based approach (Balica *et al*., 2012)
II. Indicator based approach (Palmer *et al*., 2011)
III. Geographical Information System

4.6.1 Indicator based approach -1

Balica *et al.* (2012) developed a flood vulnerability index based on three factors: susceptibility, exposure and resilience to coastal flooding. Originally applied to nine of the most vulnerable coastal cities, the methodology concentrated on three system components: hydro-geological, socio-economic and politico-administrative. They subsequently developed a group of indicators, interlinked with each system component. Each vulnerability factor (exposure, susceptibility and resilience) characterised a set of essential indicators based on the features of a coastal system. The dimensionless indicator index utilised a numerical system with numbers ranging from 0 to 1 to establish low or high coastal flood vulnerability. This highlighted those cities that were most at risk and suggested that further comprehensive examination would be required both for decision- and policymakers. Their indicator selection process was applied to the selection of ECVI parameters in this research.

4.6.2 Indicator based approach -2

Palmer *et.al.* (2011) developed a coastal vulnerability index (CVI) for the KwaZulu-Natal (KZN) coast, South Africa. This approach examined the relative coastal vulnerability of the KZN coast to erosion and severe weather incidents. This CVI was established based on remote sensing data from which a set of physical parameters was developed into indicators of vulnerability. The CVI scores were used to classify the coast into five classes, based on its relative degree of vulnerability, and these values ranged from very low to very high and highlighted what proportion of coast falls within each class. The final vulnerability scores were obtained using equation 1 below. This formula concept has been taken and utilised in this research.

$$\text{Relative CVI} = a + b + c + d + e + f + g \qquad \text{(equation 1)}$$

4.6.3 GIS approach

This method is interlinked with an assessment of coastal vulnerability to estimate risk, identify vulnerable regions as well as the development of vulnerability maps for the considered coastline used in the research.

4.7 ECVI data

Statistical data (2013-2015) regarding population (2015), commercial and residential properties (2015) were obtained from the Office for National Statistics (ONS), together with county and District councils of England, Wales and Scotland. Property data related to the chosen case studies i.e. Llanelli, Happisburgh, Skegness and Benbecula was obtained from the UK government under the freedom of information Act. Flood data was obtained from Meteorological Office, Environment Agencies and Local Authorities (2013-2015). Coastal erosion data was collected from British Geological Survey and United Kingdom Climate Impact Predictions and Local Authorities 2013-2015). Estimated values of both commercial and residential properties and land values were obtained from Her Majesties Revenue Office for England, Wales and Scotland, Association of British Insurers (ABI) and the Agricultural Mortgage Corporation (AMC) (2013-2015).

Population data were obtained from various Local Authorities and District Councils. Aberystwyth, Port Talbot, Llanelli, Devon, Lynton, and Lynmouth, and Hallsands provided the most up-to-date and detailed information. As general overview, ONS statistics are quite useful. However, for small-scale estimations (measurements below 5 km), Local Authorities data is very helpful and frequently up to date. In addition, this study utilised the data which obtained from multiple observations at various coastal locations across the United Kingdom between 2013 and 2015. This work used the data of rateable properties but did not take into consideration data for heritage properties such as churches and museums, or for large infrastructures such as bridges, roads, and railways. This is as a result of challenges with regard to data paucity, time limitations and requirement for selected parameters to be common to all chosen site locations. The current study already analysed several types of infrastructure such as properties, population, the economic value of the specific site, etc. While transportation and other large infrastructures are important for an economic consideration, these should be evaluated separately. If too many things are evaluated in one study, it leads to ambiguity, and the aim may not be addressed appropriately. However, this is an area that needs further investigation in the future.

4.7.1. Selection of economic parameters

For this study, economic parameters have been obtained using Balica *et al.*'s (2012) indicator-based methodology (Section 2.3.5; Section 4.1). Similar to their approach, 20 initial parameters were chosen, and after the analysis, the initial parameters were reduced to 12. Further following trend analysis, parameters were reduced to 6 of the most significant (Table 4.4). A detailed analysis of economic parameter choice is given in Chapter 5- section 5.5.

Table 4.4: Economic parameters

Number	Economic Parameters	Designated Code
1	Commercial Properties	a
2	Residential Properties	b
3	Economic Value of Site	c
4	Population	d
5	Coastal Erosion	e
6	Flood Event Impact	f

4.7.2 ECVI technical description

Using the 2014 aerial photograph, a transect baseline was drawn across the frontage (i.e. parallel to the coast) on each of the identified coastal vulnerability sites and 1km grid square (or cell) was drawn inland from the baseline (Figure 4.14). Subsequently, detailed measurements based upon each parameter were recorded within each identified cell. Detailed measures were offered in Chapter 8 in sub section 8.2.

Figure 4.14: 1 km coastal cells on Transect line

Data was collected from various aforementioned organisations (mentioned in earlier paragraphs) regarding the number of properties (2015), cost economic value of the location and current market prices, population, and flood impact. These economic values were then used to construct Table 4.5 detailing economic thresholds for each parameter and assign a ranking score between 1 and 5. The individual cell measurements were then compared and contrasted with Table 4.6 and assigned a ranking score between extremely low (1), low (2), moderate (3) high (4) and extremely high (5) to assess vulnerability quantitatively. With rankings applied, these values were then summed for each location to provide a relative CVI score using Comparative ECVI = a + b +c +d +e + f, where "***a to f***" are the respective ranking score for each parameter (equation 1; section 4.3.2). The ECVI value would range between a minimum value of 6 and a maximum of 30. These scores were utilised (Table 4.5 and Table 4.6) to categorise the level of economic vulnerability for each location.

Table 4.5: Rating economic coastal vulnerability parameters (m- millions; bn- billions) (Rates are for the period of 2013-2015)

Economic Parameter	Economic Threshold				
	1 Extremely Low £	2 Low £	3 Moderate £	4 High £	5 Extremely High £
Commercial Properties	<2 m	2 – 10m	>10 – 30m	>30 - 70m	>70 m
Residential Properties	<30 m	30 – 80m	>80 – 130m	>130 – 180 m	>180m
Economic Value of Site	<10 m	10 – 50m	>50 – 100m	>100 – 150 m	>150m
Population	<500	500- 2,000	>2,000– 5,000	>5,000 – 10,000	>10,000
Coastal Erosion	<0.3m	0.3 – 2.5m	2.6 – 5m	>5 – 9m	>9 m
Flood (event) Impact	<3m	3- 9m	>9 – 15m	>15 – 35m	>35m

Table 4.6: ECVI relative ranking

Total Relative Vulnerability Score	Range of Vulnerability
<12	**Extremely Low**
12-15	Low
16-18	Moderate
19-22	High
23-30	Extremely high

4.7.3 Economic parameters threshold

Economic parameters threshold was achieved by the analysis of statistical information obtained from various government organisations such as Local Authorities, Office of National Statistics (ONS), Environment Agency, the Met Office, BGS, and others for the period 2013-2015. Each of the selected economic parameters is specific and contributes similarly (equally) towards the economic coastal vulnerability measurement. Accordingly, they are equally weighted on a measurement scale (1-5). However, the threshold for these parameters is allocated based on an analysis of the data, which was obtained from different organisations (above mentioned) and then compared with current international/national market rates, particularly for residential and commercial properties. Global property values reached £153 trillion in 2015, and residential property value is £113 trillions (tn). There are 2.5 bn households in the world, and the average residential house price is £35,055. According to international trade market value, total residential housing stock in the UK has been valued at £6.17 tn. However, the local organisation's value for UK properties is 6.01 tn, which is lower than the international market value (Savills World Research, 2016). In these circumstances, the research found that there was no considerable difference between international market rates and the UK organisation's data (rates) for residential and commercial properties for the 11 selected sites, but a considerable difference was identified for other UK locations such as London, Southampton, Birmingham, and Winchester. Therefore, all property rates for the 11 sites for 2013-2015 were analysed based upon data provided with thanks from the respective local authorities. This data was used to develop an economic 1-5 scale given in Table 4.5.

Estimated commercial and residential property costs per km-2 was calculated using equations 1 and 2. Where, the cost of commercial properties (cp) was estimated by comparing the average commercial property valuation (cpv) within each cell, with the actual number measured (mcp). Similarly, the cost of residential properties (rp) was estimated by comparing the average residential property valuation (cpv) within each cell, with the actual number measured (mrp).

$$cp = cpv \times mcp \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(equation 1)}$$

$$rp = rpv \times mrp \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(equation 2)}$$

Population was the only non-economic parameter used in the analysis, with data provided by the Local Authority that consisted of overall population density (tpd), total number of residential homes (trh) and the number of unoccupied residential homes (turh). From this data, both the number of residents/residential home (nrrh) and percentage occupancy (po) was calculated using the following formulae.

$$n_{rrh} = \frac{t_{pd}}{t_{rh} - t_{urh}} \quad \text{....................(3)}$$

$$P_o = \frac{t_{urh}}{t_{rh}} \text{X100} \quad \text{..............(4)}$$

Google Earth and Ordnance Survey maps were used to estimate the total number of residential properties (p_{kms}) within each 1 km square.

$$\text{Population km}^{-1} = p_{kms} \text{ x (1) x (2)......(5)}$$

For the remaining parameters, for example coastal erosion, flood damage impact, and economic value of each site, Local Authorities and Met Office data were analysed and compared. Literature searches (sections 3.3, 3.8, 3.9, 3.10 and 4.4) identified flood impact and coastal erosion as important factors in the analysis of coastal vulnerability. Therefore, data on flood impact and/or coastal erosion for the last decade was assessed for all selected sites.

4.8 Comparison of PCVI and ECVI

To assess a locations combined physical and economic vulnerability, computed scores for each location were averaged, summated and then divided by two, giving a value between 1 and 29 (equation below)

$$CCVI = \frac{(Average\ PCVI + Average\ ECVI)}{2}$$

For example, Spurn head combined Physical vulnerability score was 132 obtained from 6 cells, while; an overall score of 22 was obtained from 2 cells.

$$CCVI = \frac{(132/6 + 22/2)}{2}$$

$$CCVI = \frac{(22+11)}{2} = 16$$

Therefore, a vulnerability score of 16 would suggest that the coastal location is at moderate risk and in this case, the management response would suggest that further studies be carried out before any long-term proposals are formulated.

4.9 Summary

The literature review and physical background sections identified the research gaps as well as the necessity of development of new methods to evaluate combined coastal vulnerability (physical and economic) of the UK. Accordingly, this chapter described the selection of coastal vulnerability hotspots across the UK along with the process of the methodological approaches as follows:

I. Evaluation of combined coastal vulnerability of the UK by development and application of PCVI, ECVI and then subsequently further development of CCVI based on PCVI and ECVI results.

An evaluation of recent temporal trends, which have influenced the choice of physical and economic parameters, alongside detailed descriptions of parameter selection process is given in Chapter 5.

CHAPTER 5 - DATA EVALUATION AND PARAMETER SELECTION

5. Data evaluation and parameter selection

5.1 Introduction

Having dealt with the methodological frameworks for estimating physical and economic vulnerability (Chapter 4) and it is now necessary to explore the analysis of physical and economic parameters. It is also pertinent to address sea level rise, population trends, and perception, which are interlinked with the selection of economic parameters.

5.2 Precipitation

Temporal precipitation and time series produced from seasonal data shows a clear positive trend indicative of a temporal annual increase in rainfall during autumn, spring (Figure 5. 1a) and winter months (Figure 5. 1b). This was contrasted against a negative trend indicative of a temporal reduction in rainfall during summer months (Figure 5. 1b). A regression model was constructed using annual rainfall data for the UK, showed that positive correlation existed as given by the equation $y = 0.6015x - 83.434$ (Figure 5.1c). Even though the model coefficient of determination (R^2) explained less than 1% of the data variation, it suggested that between 1910 and 2016 a statistically significant linear trend existed ($p<0.01$), suggesting that there was an increase in UK rainfall through time of *circa* 1mm yr^{-1}.

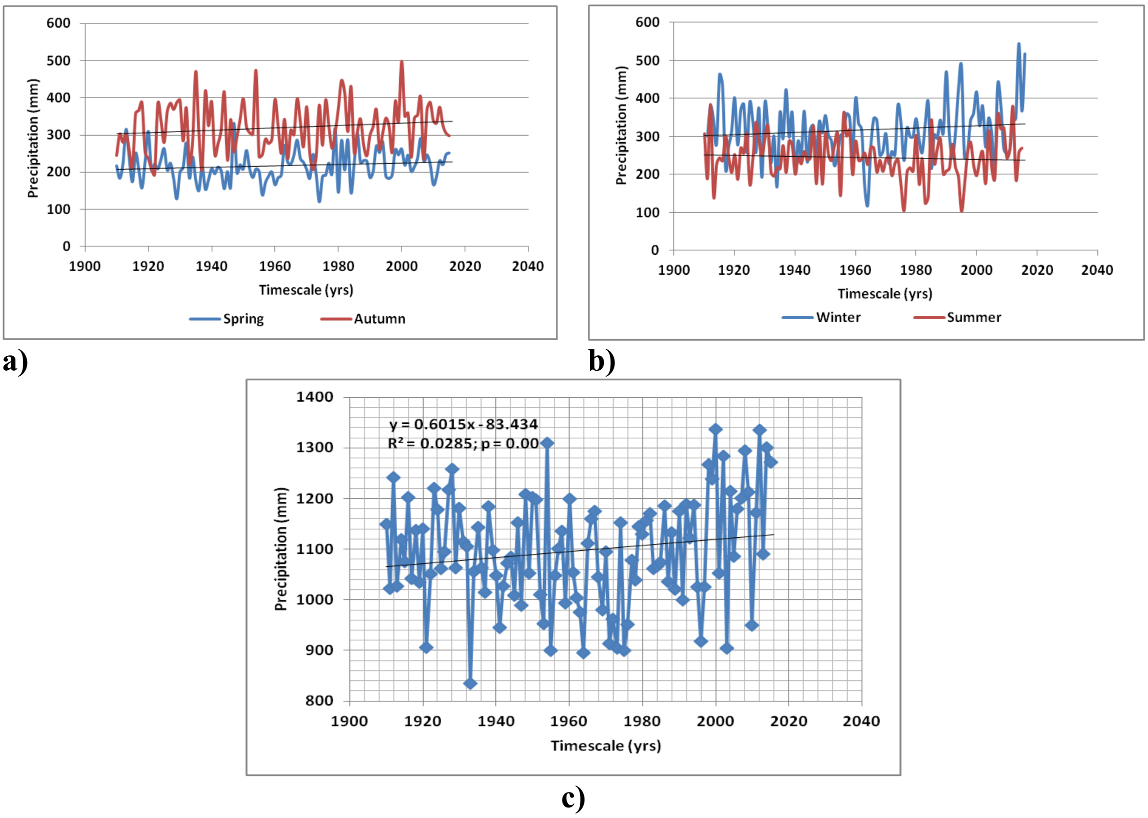


Figure 5.1: Annual average precipitation rates for the UK in-between 1910-2016 a) Spring and Autumn values, b) Summer and winter values and c) overall average values.

5.3 Population

Annual population data for the UK was obtained from the Office for National Statistics for the period between 1972 and 2014. A regression model constructed from temporal changes showed high positive correlation indicating a consistent increasing trend, given by the regression equation y = 11707x – 2E+07. The regression model coefficient of determination (R^2 = 79%) showed that a significant percentage of data variation was explained by the passage of time (p=0.00) (Figure 5.2). The UK population is projected to increase by 9.7 million over the next 25 years from an estimated 64.6 million in mid-2014 to 74.3 million in mid-2039 (ONS, 2014).

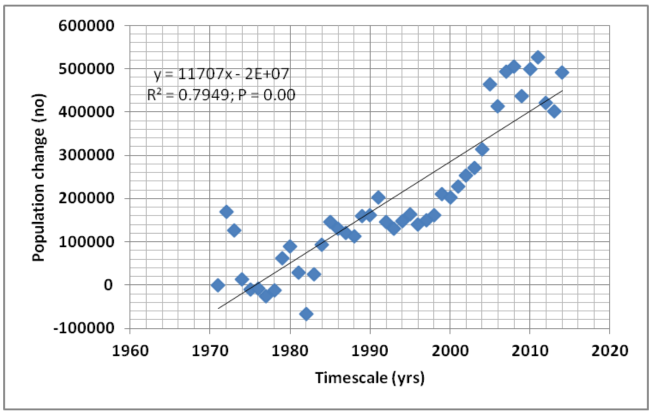


Figure 5.2: Temporal Changes in the UK population from 1972 - 2014

5.4 Sea level change

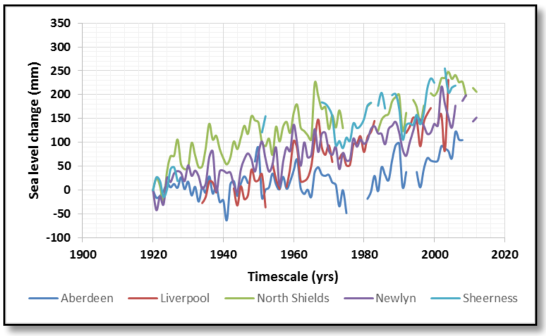
Sea level change data (data obtained from the National Oceanographic Centre) was analysed based upon the five longest sea level records in the UK i.e. Aberdeen (1862-2011), Liverpool (1858-2011), North Shields (1896-2011), Sheerness (1834-2006) and Newlyn (1916-2011). These data are representative of annual mean values of sea level in these areas but when overall averaged values are computed the results are representative of general sea level fluctuations experienced by the UK. Prior to 1920 data was sparse and as a consequence analysis used data from 1920 to 2014.

Figure 5.3a shows time series of sea level variation from 1920 to 2014, Recently, North Shields and Sheerness have experienced the greatest rises in sea level, compared to 1920. An increase of *circa* 190 mm compared with 1920 was seen at both these sites since 1998. Until the mid-1980s, sea levels in Aberdeen had remained relatively stable when compared to the 1920. However, every year since 1985, sea levels have been higher. On average, in the past two decades sea levels are more than 50 mm higher than the baseline (National Oceanography Centre, 2014). Sea levels have been higher than 1920 by more than 100 mm between 2006 and 2008, with a 55 mm increase from 2005 to 2006 alone.

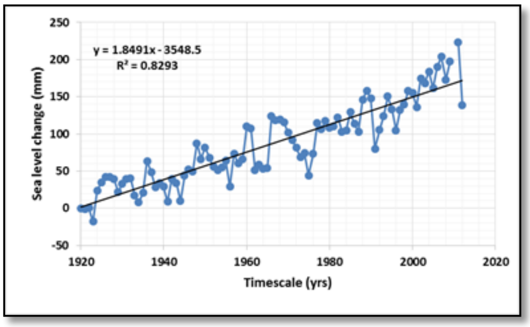
Sea levels in Liverpool and Newlyn have also increased significantly in the past few decades. Sea levels have regularly been more than 100 mm higher than 1920 levels at both these sites since the 1980s. In 2011 Liverpool observed the largest rise in sea level since 1920 of all five sites i.e. 312 mm increase from 1920 level (National Oceanography Centre, 2014).

A regression model constructed using annual average sea level variation between the four ports, highlighted a positive correlation suggesting that sea levels had risen between 1920 and 2014 (Figure 5.3b). This was given by the regression equation $y = 1.8419x - 3548.5$.

The coefficient of determination showed that over three quarters of sea level variation was explained by the passage of time (R2 = 83%) and was indicative of a steady sea level rise of almost 2mm yr $^{-1}$, these results concur with Phillips *et al*. (2013).



a)



b)

Figure 5.3: Sea level changes between 1920 and 2014, a) time series showing sea level variation at four UK ports and b) time series showing overall average change

5.5. Selection of Parameters

For the initial analysis, this research utilised 20 economic parameters (Table 5.1; Figure 5.4), similar to Balica *et al*. (2012) as economic parameters. Prior to finalisation of these parameters a series of steps were involved. Initially, 20 parameters were selected based on various factors such as sea level rise, temperatures trends, and population trends.

Based on this analysis results, the parameter numbers were reduced. A reduction of the parameters for an evaluation of the economic coastal vulnerability at regional scale (UK) is necessary. Some parameters (20) are not potentially relevant in the case of the eleven identified case study areas of the UK (Example: coastal discharges and unpopulated zones), so to simplify the methodological process, they are reduced to 12 and further reduced and restricted to 6, based on the suitability and potentiality of the parameters (Figure 5.4). Parameter reduction is not a new procedure in coastal vulnerability assessment studies, and several researchers have already implemented this technique successfully. Balica *et al*. (2012) initially considered 71 indicators and then reduced their number to 12, and the Canadian Council of Ministries of Environment (2003) selected nearly 100 indicators, which were reduced to 12 as well.

Table 5.1 Economic parameters with working definitions

Number	Economic Parameter	Definition
1	Population in coastal vulnerability zones	People who are living near to coastline including low-lying, and estuarine areas.
2	High growth of civilisation alongside of coasts	Population growth rate alongside the coasts
3	Marine industry growth Ports business, warships, sea and river defences etc.)	Marine industry growth alongside the coasts
4	Infrastructure (Properties roads, etc.)	Types of infrastructure in coastal zones (Did not include Transport)
5	Urbanised area	Based on population number and growth rate in urbanised areas
6	Urban growth	Based on urban population growth rate
7	Land use	Use of land for variety of reasons (Eg: Infrastructure development)
8	Economic value of site	Economic value of particular areas near to coastline
9	Precipitation	Precipitation trends in various regions
10	Coastal discharges	Discharges of waste water and other materials into coastal waters (excludes nuclear waste)
11	Flood impact	How much of flood impact on coastal areas
12	Drainage system	Quality of drainage system in coastal areas
13	Frequency of floods	Frequency period of flooding events and flood strikes in coastal areas
14	Storm insurance	Claimed insurances in a particular period and in a particular area especially in coastal areas
15	Damage costs	Storm damage costs in coastal areas
16	Coastal erosion	Coastal erosion impact in coastal areas
17	Return period of storms	Frequency period of various storms in coastal areas particularly in coastal areas
18	Coastal defences	Coastal defence structures and viability of those structures
19	Preparedness and awareness	% of storm awareness and preparedness
20	Unpopulated zones	Coastal zones without inhabitants or very few number of people

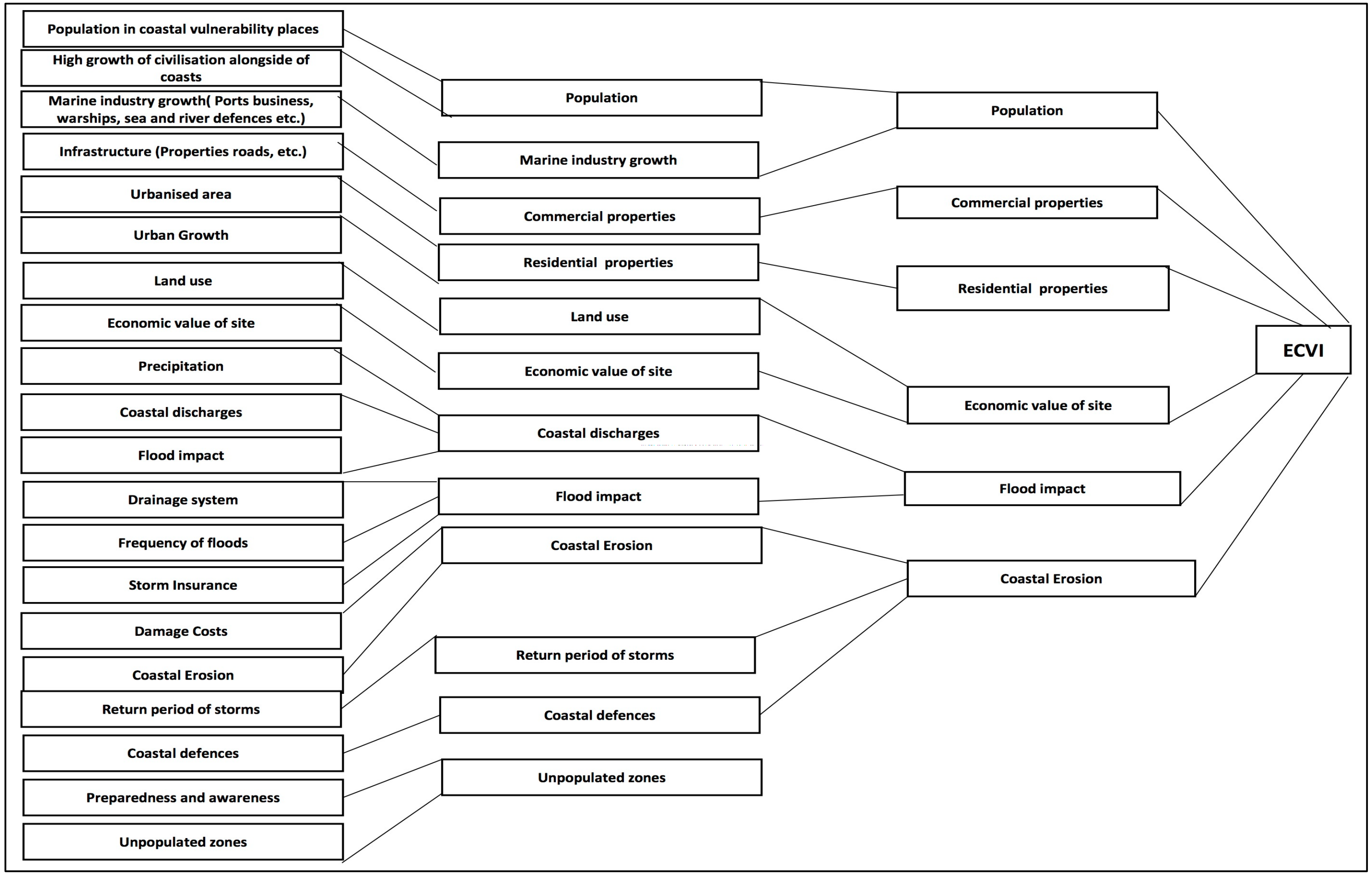


Figure 5.4: Process model showing the reduction of economic coastal vulnerability parameters

5.6 Economic parameters description

a. Commercial properties

Commercial properties are important in coastal vulnerability studies and several researchers have used this parameter in their vulnerability assessment studies in various forms (Balica *et al*., 2012; Gilbert and Vellinga, 1990). Meanwhile, many coastal properties are damaged by several storm events across the UK as evidenced in 2006, 2008, 2010, 2012, 2013, 2014 and 2015 (Kantamaneni and Phillips, 2016; Kantamaneni, 2016a; Kantamaneni, 2016b). This damage showed a significant impact on local economics (Kantamaneni and Phillips, 2016). Accordingly, commercial properties were selected as one of the significant parameters for this study. NASA-Google Earth Pro maps (2014 & 2015) and Google Earth Explorer were used to identify the commercial buildings at selected sites. Economic statistics and an accurate number of commercial properties of a particular zone were obtained from UK's Office of National Statistics (ONS) and Local Authorities (2015). Figure 5.5 shows a typical measurement taken from the coast to a commercial property in Port Talbot.

Figure 5.5: Commercial property distance measurement from coast

b. Residential properties

Several previous studies have been highlighted that residential properties are a vital parameter in the assessment of coastal vulnerability; see, for example, Gilbert and Vellinga (1990). As a significant number of residential properties are vulnerable in some UK coastal regions, this research considered residential properties as one of the potential evaluation parameters. NASA-Google Earth Pro, Google Street maps and ordnance survey maps (2014 & 2015) were used to identify the number of properties. However, the statistics of properties, the economic value, and the numbers were obtained from insurance companies, the Office of National Statistics (ONS), and Met Office organisations. This type of measurement reflects coastal settlement vulnerability and Figure 5.6 shows typical measurements that were taken from the coast to the line of residential properties.

Figure 5.6: Residential properties distance measurement from the coast at Dawlish

c. Economic value of site

The economic value of sites (Figure 5.7) in particular coastal zones is used as a significant parameter in evaluating coastal vulnerability in the modern era. However, it is a challenging task to estimate land and site value based on current circumstances and market fluctuations (Fausold and Lilieholm, 1999). ONS, insurance companies, housing agencies, and Local Authorities data are utilised for the economic valuation of a particular place. Not only that but also considered various factors like intensity of exposure to flood frequency, coastal erosion, tourist zone, industrial area, and pollution. Subsequently, ECVI values are offered.

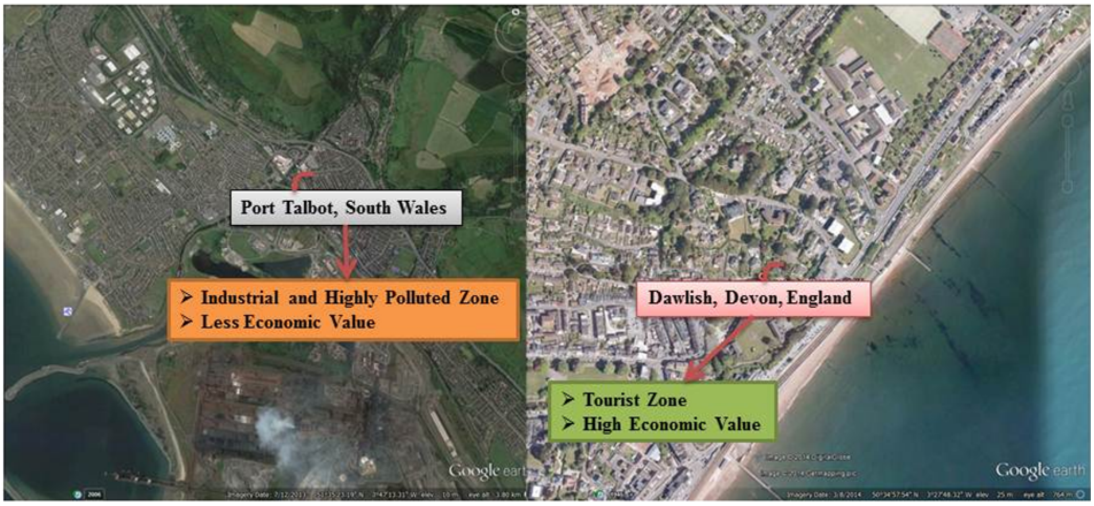


Figure 5.7: Assessment of economic value of site

d. Population

This parameter is also an important element in ECVI assessment (Figure 5.8). Several researchers have used this parameter in their coastal vulnerability studies such as Vittal Hegde and Radhakrishnan Reju (2007) and Kantamaneni (2016). Several large swathes of coastal communities are exposed to coastal hazards every year across the UK in particular at coastal regions (Kantamaneni and Phillips, 2016). Therefore, population is selected as a significant parameter. However, this study measured the population in terms of thousands (non-economic) rather than in monetary terms because it is unusual to offer economic consequences to the population[1] (with the exception of Kantamaneni, 2016a). Therefore, this type of measurement reflects the vulnerability of coastal settlements as well as coastal zones in the United Kingdom. Google Earth NASA maps are used for the estimation of populations in selected sites. However, accurate population statistics were also obtained from Local Authorities for particular areas.

[1] It is rather difficult to offer the same economic figure to the 11 coastal area people under the cost of life. Accordingly, I did not provide any economic consequences to the population of 11 identified (selected) areas of the UK.

Figure 5.8: High and low density of population in different coastal areas of the UK

e. Coastal erosion

This parameter is also an impact factor in the assessment of coastal vulnerability (Boruff *et al*., 2005). Coastal erosion is one of the biggest problems in some coastal regions of the UK and is particularly high in England, where several kilometres of coastline have already disintegrated into the sea (Thorne *et al*., 2007). Accordingly, this study selected coastal erosion as a significant parameter. NASA Google Earth Pro, Ordnance Survey satellite images, and Orthophotographs are used. Infrastructure damage due to coastal erosion was also evaluated in economic terms with data of damage statistics obtained from insurance companies (private and public), the Office of National Statistics (ONS), the Met Office, and the British Geological Survey.

f. Flood impact

The literature review highlighted that flood events play a significant role in coastal change coupled with a rising global and regional sea level, they are likely to become of increasing significance in coastal erosion. Especially, coastal floods are the greatest threat to the coastal communities of the various places of England (Figure 5.9), Wales, and Scotland (Kantamaneni and Phillips, 2016). However, the geographical arrangement of coastal settlements across the United Kingdom is uneven. Besides, the heavy infrastructure established alongside the shoreline plays an important role in the building of the national economy. Therefore, additional considerations are necessary when evaluating the probability of moving settlements and infrastructure inland. For this reason, it was important to include this parameter (flood economic impact) into the index, in spite of not being a conventional economic coastal vulnerability parameter. Both the Met Office and Insurance companies provided these records. From historical information, it was possible to define where the most flood events had affected major coastal areas.

Figure 5.9: Coastal properties in Dawlish after math of 2014 flood incident

5.7 Physical vulnerability index (PCVI)

5.7.1 Physical parameters

Denner *et al.*'s (2015) seminal UK work on the Welsh coast, seven physical parameters were used to estimate physical vulnerability (section 4.6.1). There follows a detailed description of the measurement principles for each parameter.

a. Beach width

Sandy beaches are extremely efficient absorbers of wave energy and, therefore, dissipate erosive energy: the wider the beach, the less vulnerable is the shoreline to the erosive power of waves (Carter and Woodroffe, 1994; Jiminez *et al.,* 2008). Beach width was measured from the back beach (Figure 5.10) coordinates to the mean low water level MLW mark using GIS spatial datasets. Owing to variations in tidal range and the presence in some locations of deep-water channels running adjacent to the shoreline for (example Llanelli) the MLW mark differs greatly. Digimaps that comprises the Ordnance Survey maps and spatial data were used for measurement of this parameter.

b. Dune width

Dunes are a fundamental part of the shoreline, acting as a natural barrier and the greater the width, the greater the protection Pye and Blott (2006). Dune systems are prevalent at some case study locations and therefore despite its limited usefulness across the entire study area the parameter was still considered. Dune width was measured (5.11) as the distance between a pre-determined back beach coordinate and the nearest built environment structure, or fully vegetated area, using GIS spatial databases. Digimaps that comprises the Ordnance Survey maps and spatial data were often used for measurement of this parameter.

c. Coastal slope

Determination of coastal slope provides an indication of relative vulnerability to inundation and the rapidity of shoreline retreat because low-sloping coastal regions should retreat faster than steeper regions (Pilkey, 1987). Therefore, coastal slope is very important parameter in physical vulnerability estimation studies and accordingly, for this study, a distance of 500m was established to back side of beach. Google Earth's Pro (elevation profile) was used to measure this physical parameter as shown in Figure 5.12.

Figure 5.10: An Ordnance Survey Map showing the measurement of beach width from back beach to MLW

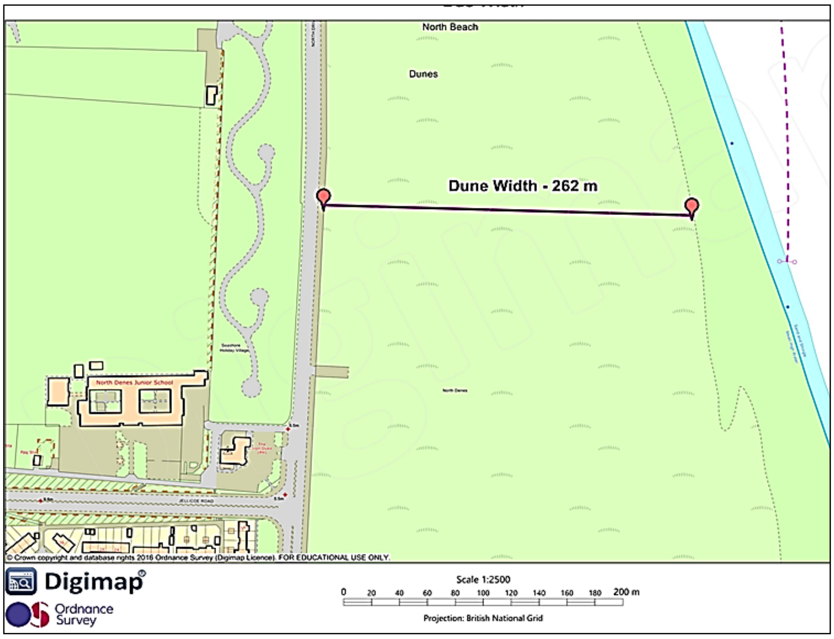


Figure 5.11: An Ordnance Survey Map showing the measurement of dune width

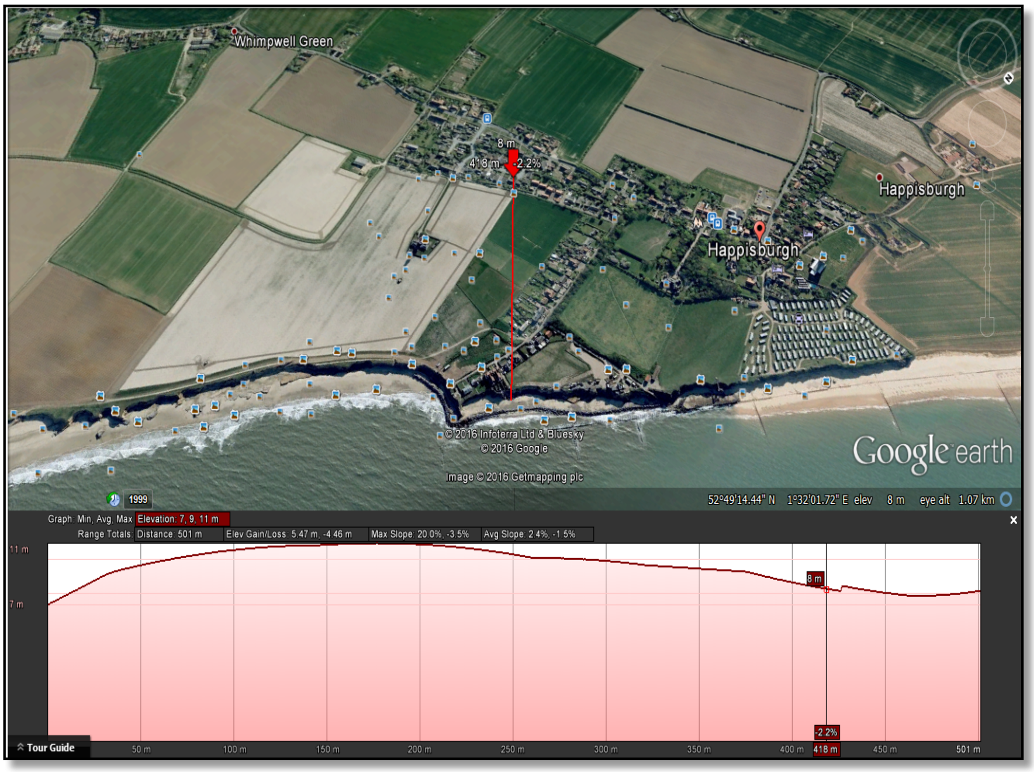


Figure 5.12: an aerial photograph and section through (inset) showing coastal slope measurement from the back-beach elevation and highest and lowest elevation points are depicted in red

d. Distance of vegetation behind the back beach

For this study, a distance of 500 m was chosen to measure the distance of vegetation behind the back beach (Figure 5.13). In areas where foliage did not extend beyond built structures, vegetation was measured to that point. Built structures such as paths, roads, and railways were measured for width and deducted from the total vegetation if there was significant vegetation expanse beyond these structures. Digimaps that comprises the Ordnance Survey maps and spatial data were used for measurement of this parameter.

e. Distance of built structures behind the back beach

For this study, a distance of 500m was also chosen to measure the distance of built structures (Figure 5.14) such as paths, roads, railways, private and commercial buildings behind the back beach. In areas where foliage was encountered, the vegetation was measured and the total vegetation deducted from the built structure expanse.

Figure 5.13: An aerial photograph showing the measurement of back beach vegetation to 500m inland distance line

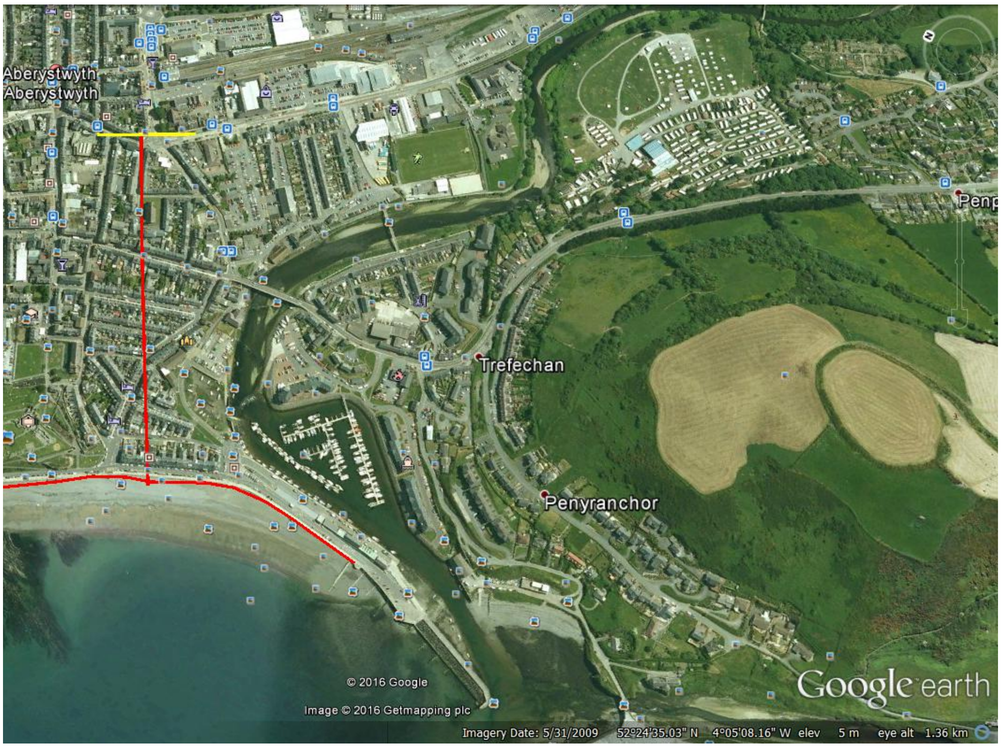


Figure 5.14: An aerial photograph showing the measurement of built structures behind the back beach

f. Percentage of rocky outcrop

The coastal landform least vulnerable to sea level rise and impacts of coastal erosion are rocky coasts (Gornitz *et al.,* 1991). Therefore, the width of these structures within individually surveyed cells was measured and included as the percentage of rocky outcrop (Figure 5.15) along the transect line between MSL and back beach coordinates and all measurements were calculated using a combination of GIS and Orthophotographs.

g. Sea defences

Sea Defences are protection structures, which are constructed along the shoreline. These structures comprise a variety of material such as rock revetment, solid wall, timber, natural, rock. Coastal defences protect the shoreline, properties and people from coastal erosion, flooding. Therefore, sea defence was selected as one of the significant parameters for this study. Figure 5.16 shows typical measurements and these were based upon percentage shoreline coverage within each cell.

Figure 5.15: Rocky outcrop

Figure 5.16: Sea defence structures

5.8. Accuracy of NASA- Google Earth Maps and Data

There are two kinds of accuracy regarding google maps. One is the positional accuracy and the other is image accuracy (resolution of the images).

Undoubtedly, Google Earth has become the ultimate source of spatial data and information for private and public decision-support systems for social interactions. Respect to the imagery accuracy, it is very accurate (with very high resolution). Most land areas are covered in satellite imagery with a resolution of about 15 m per pixel. This base imagery is 30m multispectral Landsat which is pan sharpened with the 15m Landsat imagery. Quality is improved in most population centers with the areas covered by aircraft imagery (orthophotography) with several pixels per meter. While oceans are generally, covered at a much lower resolution (NASA-EOSDIS, 2016). In an investigation, the researchers compared virtually traced positions against high-precision (<1 m) field measurements along three stratigraphic unconformity sub-sections in the Big Bend region to determine current positional accuracy for the Google Earth terrain model. A horizontal position accuracy of 2.64 m RMSE was determined for the Google Earth terrain model with mean offset distance being 6.95 m. (Benker *et al.,* 2011).

With more than 200 million users since its release in June 2005, Google Earth is recognised for its potential to significantly improve the visualisation and dissemination of scientific data. Some experts have recently begun using this cost-free imagery source (Potere, 2008) for their scientific research. It is common to use NASA's Google Earth maps (in various scales) and data to evaluate socioeconomic vulnerability in scientific research, evidenced by a research paper by Pulighe *et al.* (2016), Physical coastal vulnerability studies have also benefited from the use of google maps (see for example Palmer *et al.,* 2011 and Denner *et al.,* 2015).

The work of Douglas *et al.* (1998) demonstrated that combined errors inherent with early aerial photographs could be of the order of 7.5-8.9 m. Root Mean Square Error (RMSE), which is the most commonly used measure of accuracy. It is the squared differences between data set co-ordinate values, and co-ordinates from an independent more accurate source for identical points. Corrections should be kept as low as possible (Moore, 2000). Mohammed *et al.* (2013) using Google earth free source of data, evaluated both horizontal and vertical accuracy by comparing measured Google Earth coordinates with dGPS receiver coordinates. Root Mean Square Error (RMSE) was computed for horizontal coordinates and was found to be 1.59m. For height measurement RMSE was computed to be 1.7m. This compares favourably with other coastal research studies (see for example Thomas *et al.,* 2010; Thomas *et al.,* 2011, Thomas *et al.,* 2014; Alharbi 2015). Even though, there was no scope to identify the error using control surveys at this stage, the work of Mohammed *et al.* (2013) suggests that achieved RMSE values are suitable to determine coastal change. However, it is recognised that control surveys along cell boundaries and at transect locations would enhance results and is recommended for any future work. To further enhance research accuracy, both Google imagery and Street maps were compared and to reduce the potential for human error, only one analyst was used for quantification.

However, economic parameter information (how many properties in a particular area) was gathered from Local Authorities and other reliable organisations. Based on that information, NASA's Google Earth maps were used to measure per-square-km resolution at selected sites (how many properties per square km at identified sites) to evaluate vulnerability for the current study.

5.9 Summary

This chapter described the sea level rise, population trends, and perception, which are interlinked with the selection of economic parameters and then finalised the six economic parameters with appropriate examples. Meanwhile, this section also explored the seven physical parameters using appropriate aerial photographs and Ordnance survey maps within a GIS environment. The next chapter (chapter 6) will appraise the measurements of physical parameters applied to the 11 case studies.

CHAPTER 6 - PCVI

6. Physical coastal vulnerability index (PCVI)

6.1 Introduction

Chapter 1 (section 1.1) identified that climate change and particularly SLR will have worldwide effects on low lying and heavily populated coastal areas and provided study aims and objectives. Literature searches (sections 2.3, 3 and 3.4) highlighted the severity and drivers that influence coastal change and discussed current thinking in in terms of risk evaluation and determination of coastal vulnerability extend. These underpinned the selection of case study sites and suitable methodologies (Chapters 4 and 5) to assess both the physical and economic vulnerability of each case study site. The following chapter assesses physical vulnerability aspects.

For the assessment coastal vulnerability the aim is to make use of characteristics and classify potential impacts of climate change on different coastal sections (Bagdanaviciute *et al*., 2015). Originally, CVI methods took into account factors related to the local hydrodynamic regime (tidal amplitude, wave climate etc.) and geomorphology (slope, sediment type etc.).

Firstly, this chapter analyses the susceptibility of each chosen coastal location and then combines results to identify overall vulnerability. Measurements were taken in accordance with the procedures described (PCVI methodology) in section 4.5.1 for each chosen case study location, by subdividing each shoreline frontage into 0.5 km cells. In total, 158 cells along 79 km of coastline were identified (Table 6.1). Three locations in Wales measured *circa* 27.5 km of coastline (55 cells), seven English locations measured 44 (88 cells) km and one Scottish region measured *circa* 8 (15 cells) km. Coastal cell measurements at particular specific locations have been evaluated based on council statistics (2013-2015) and 2015 NASA Google earth maps. In particular, lateral boundary information obtained from 11 Local Authorities (eg: Aberystwyth, Great Yarmouth, etc).

Table 6.1: Assessed coastal locations and number of coastal cells

Site Name	Shoreline Measurement Number/Cells	Area
Spurn Head	6	**England** 44 km measured (0.5 km cells – 88)
Hallsands	8	
Lynmouth	4	
Happisburgh	8	
Dawlish	11	
Great Yarmouth	28	
Skegness	23	
Benbecula	15	**Scotland** 7.5 km measured (0.5 km cells – 15)
Aberystwyth	5	**Wales** 27.5 km measured (0.5 km cells – 55)
Llanelli	26	
Port Talbot	24	

6.2 Spurn Head

The beach width showed significant variations ranging from 630 m within cell 1 to 109 m in cell 5. Sixty-six percentage recorded beach widths in excess of 250 metres, influencing an overall average beach width of 315 metres (Figure 6.1a). Dunes were recorded in five of the six identified cells and widths varied between 63 m (cell 6) and 13 m (cell 4; Figure 6.1b). The overall average dune width was 34 metres. The sand and shingle spit of Spurn Head is a narrow feature, which widens at its distal end and for this reason only one cell recorded a coastal slope in accordance with the methodology. The coastal slope close to the distal end was 2.5%. Distance of vegetation behind the back beach also showed significant variation ranging from 97 m in cell 3 (i.e. close to the distal end) to 34 m in cell 4, with an overall average width of 59 m (Figure 6.1c).

The distance of built structures behind the back beach is influenced by the erosive nature both the Humber Estuary flows on the western side of the spit and by a reduction in long shore sediment input on the eastern side (section 4.4.1). Only three cells recorded structures behind the back beach (cells 2, 3 and 4 respectively) all with a similar distance of around 3 m (Figure 6.1d). It was not surprising that rocky outcrops were absent from this spit feature and no sea defence structures had been constructed within the area of study.

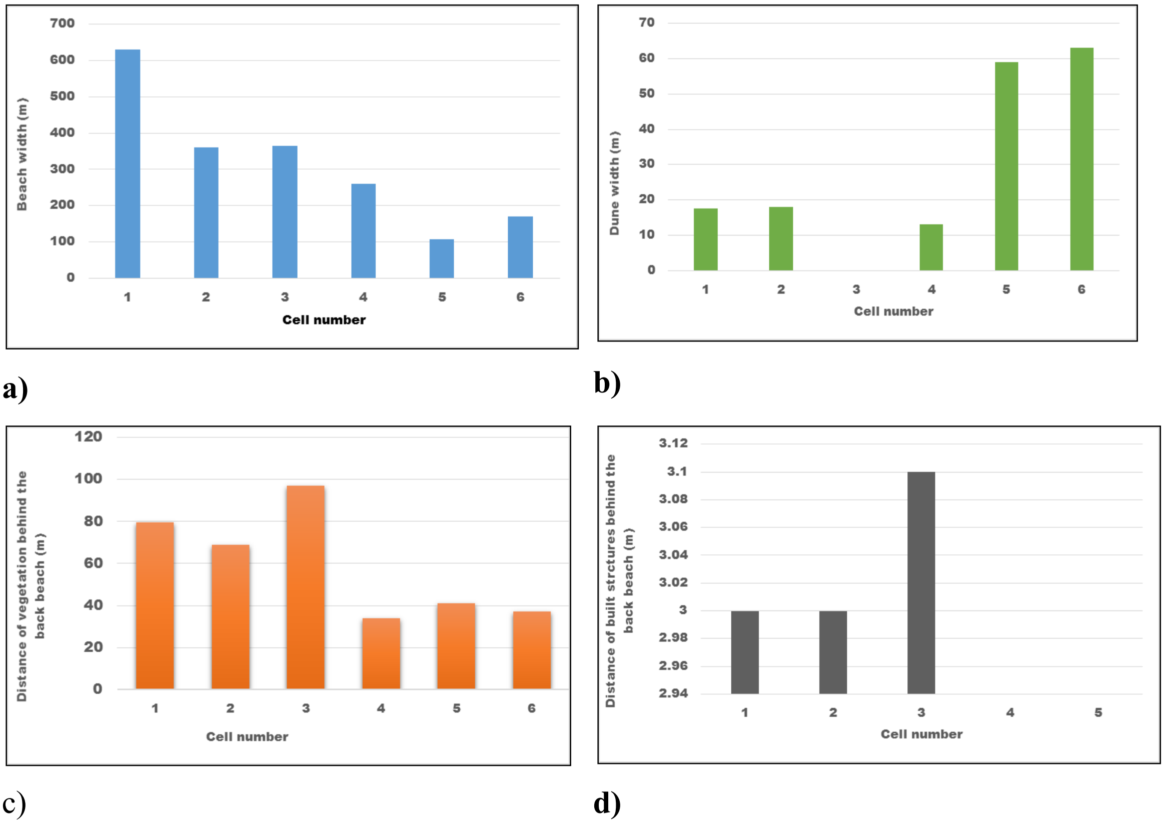


Figure 6.1: Graphical representations of Spurn Head

6.3 Hallsands

With the exception of cell 1 (76 m) beach width at Hallsands ranged between *circa* 20 m and *circa* 27 m. The average overall beach width of around 30 m was influenced by cell 1 results and 80% of cells recorded lower than average values (Figure 6.2a). Dune width was recorded in one cell (cell 4; 10m). For coastal slope values, there is a significant difference existed between maximum (19.8% in cell 6) and minimum (2.4% in cell 8) coastal slope values. The average coastal slope was 11.9% and similar to beach width results, 80% of cells recorded higher than the average values (Figure 6.2b). A clear difference was observed in measured distance values of vegetation behind the back beach. The average was 462 m between a maximum of 496 m recorded in 3 cells (2, 5 and 6 respectively) and minimum of 340 m, recorded in the eighth cell. More than 60% of cells recorded higher than average values (Figure 6.2c).

When measurements taken of built structures located behind the back beach, the maximum distance was recorded in the eighth cell (160 m), with a minimum recorded of 4 m in 3 cells (2, 5 and 6 respectively). The overall average was 42 m and 25% of cells recorded higher than average values (Figure 6.2d). Rocky outcrops were only recorded in 2 cells, cell 7 (26%) and cell 8 (13%), rocky outcrops were not detected in 75% of the cells (Figure 6.2e). Three cells comprise sea defence structures (4, 7 and 8 respectively) and of these, the average shoreline protection was 59% (Figure 6.2f).

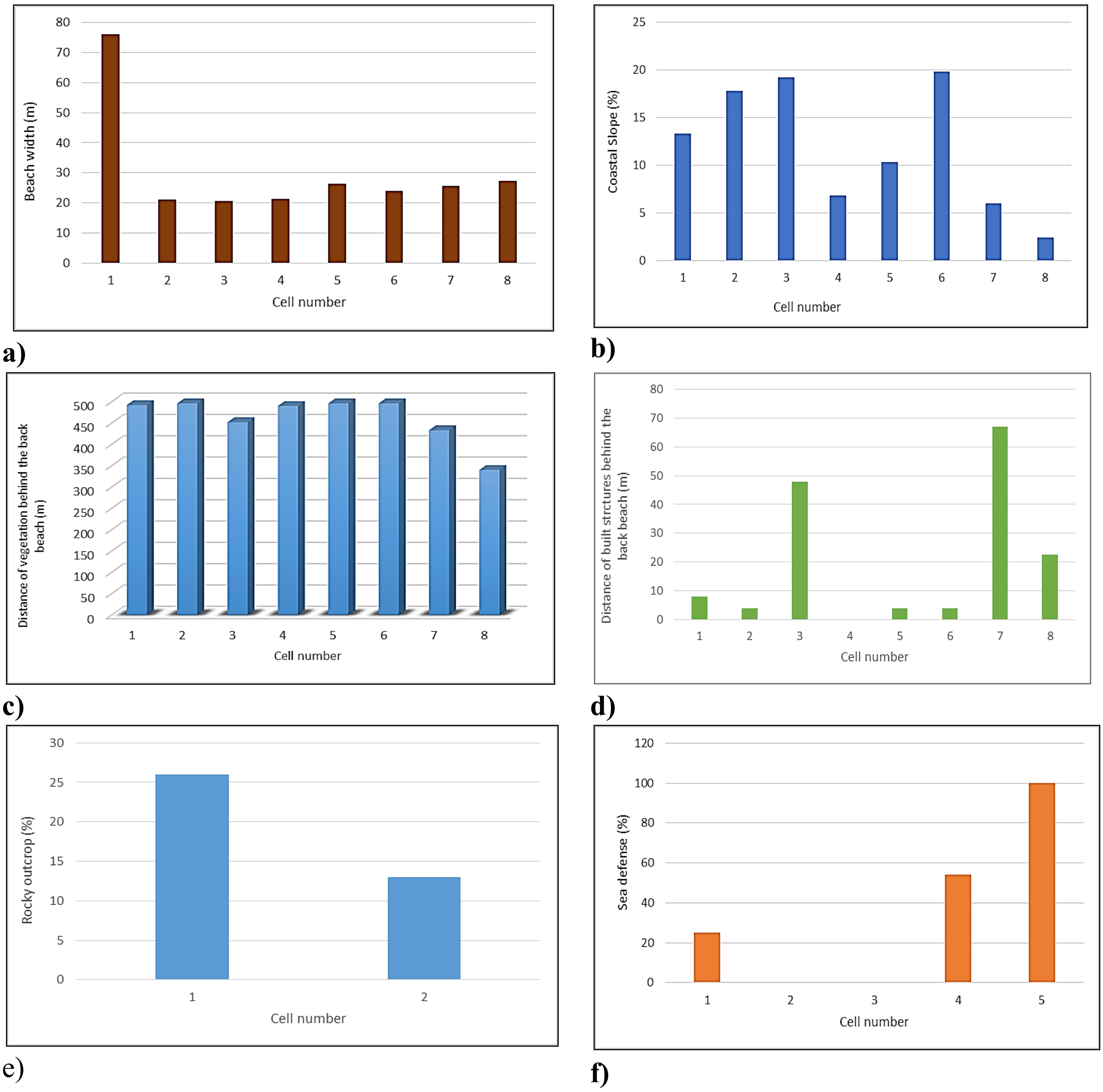


Figure 6.2: Graphical representations of Hallsands

6.4. Lynmouth

The beach width varies significantly between a maximum of 378 m (cell 3) and minimum of 121 m in the fourth cell. The overall average beach width was 209 m and 50% of cells recorded more than average beach width values (Figure 6.3a). The maximum coastal slope recorded was 48% (cell 4) and minimum 21.3% (cell 2), with an overall average of 33.7%

and 50% of cells recorded higher than the average measurements (Figure 6.3b). The maximum recorded distance of vegetation behind the back beach was 500 m (cell 4) and minimum 105 m (Cell 3), 50% of cells recorded more than average value of 331 m (Figure 6.3c). The maximum and minimum recorded for the distance of built structures behind the back beach was 295 m (cell 1) and 39 m (cell 3) respectively (Figure 6.3d) and 50% of cells recorded more than the average of 143m. There were no dunes, rocky outcrops or sea defence structures.

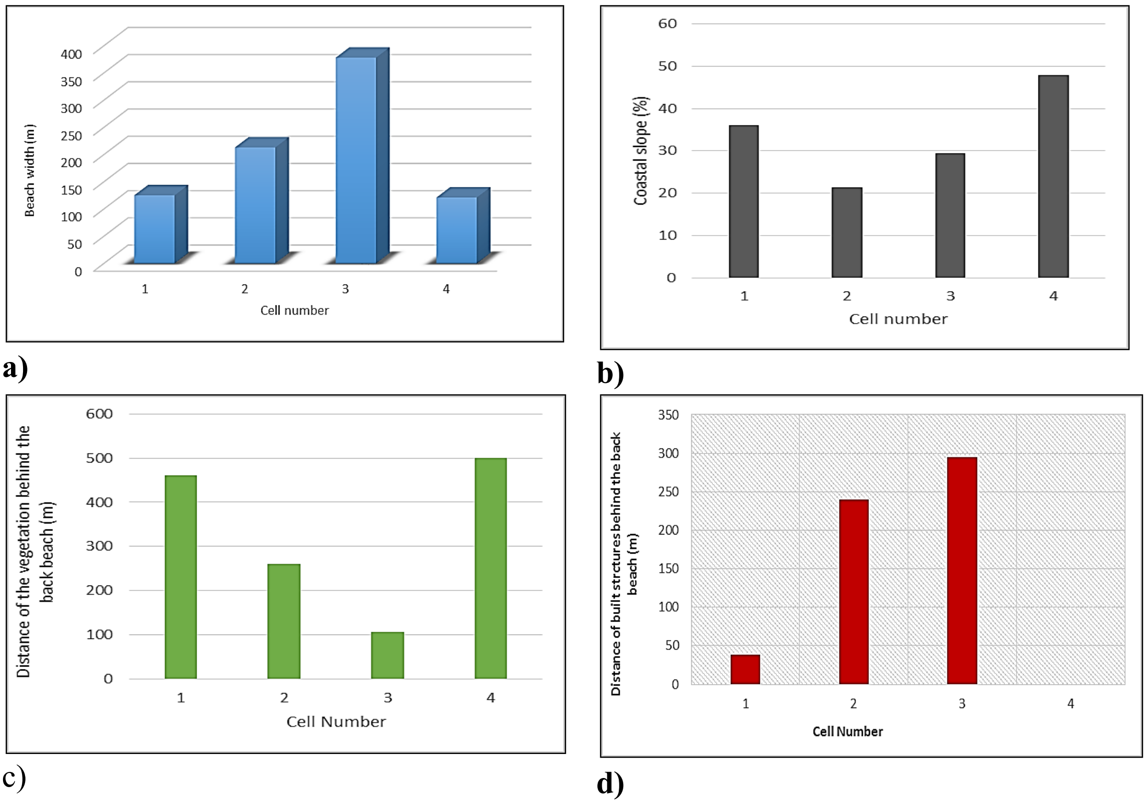


Figure 6.3: Graphical representations of Lynmouth

6.5 Happisburgh

The average beach width between a maximum of 49 m (cell 5) and minimum of 11.3 m (cell 1) measured 36 m with 62% of cells recording higher than average values (Figure 6.4a). Dunes were only recorded in the first and second cells and measurements of 21 m and 33 m recorded. The average coastal slope between the maximum of 3.9% (cell 6) and minimum of 0.6 % (cell 1) was 1.8%, and 62% of cells recorded lower than average values (Figure 6.4b). The overall average distance of vegetation behind the back beach was 281 m between maximum and minimum recorded distances of 477 m and 4 m respectively and 50% of the recorded values were greater than the average (Figure 6.4c). The overall average distance of built structures behind the back beach between the maximum of 477 m recorded in the fifth cell and minimum of 56 m (cell 1) was 166 m and 62% of the distances measured were lower than the average (Figure 6.4d). Only 3 cells contained rocky outcrops recording 79% coverage in the first cell and 11.4% in the sixth cell, giving an overall average of 15.7% (Figure 6.4e). Less than half of the studied cells exhibited any form of sea defence. The overall average of those measured cells was 65%, with a maximum of 100% recorded in the first cell, and minimum in the sixth cell 24% (Figure 6.4f).

6.6 Dawlish

The average beach width was 67.5 m between the maximum of 139 m recorded in the eighth cell and minimum of 21.2 m recorded in the fourth cell. Forty five percent of cells recorded higher than average values (Figure 6.5a). Dune width was only recorded in the last 3 cells and ranged between a maximum of 107 m to a minimum of 79 m (Figure 6.5b). The average coastal slope was 4.2% between a maximum of 11.2% recorded in the second cell and minimum of 1.1 % recorded in the eleventh cell and 45% of cells recorded higher than average values (Figure 6.5c). The average distance of vegetation behind the back beach between a maximum of 464 m in the fifth cell and minimum of 60 m (cell 1) was 232 m, 27% of cells recorded more than average value (Figure 6.5d). The average distance of built structures behind the back beach was 356 m, between the maximum distance of 500 m, recorded in cells 2, 3 and 7, with the minimum recorded in cell 5 was 35 m, recorded at the fifth cell and 36% of cells recorded higher than average values (Figure 6.5e). Rocky outcrops were only recorded in cell 7 (55%), and sea defence structures were recorded in 81% of the cells, all providing 100% coverage (Figure 6.5f).

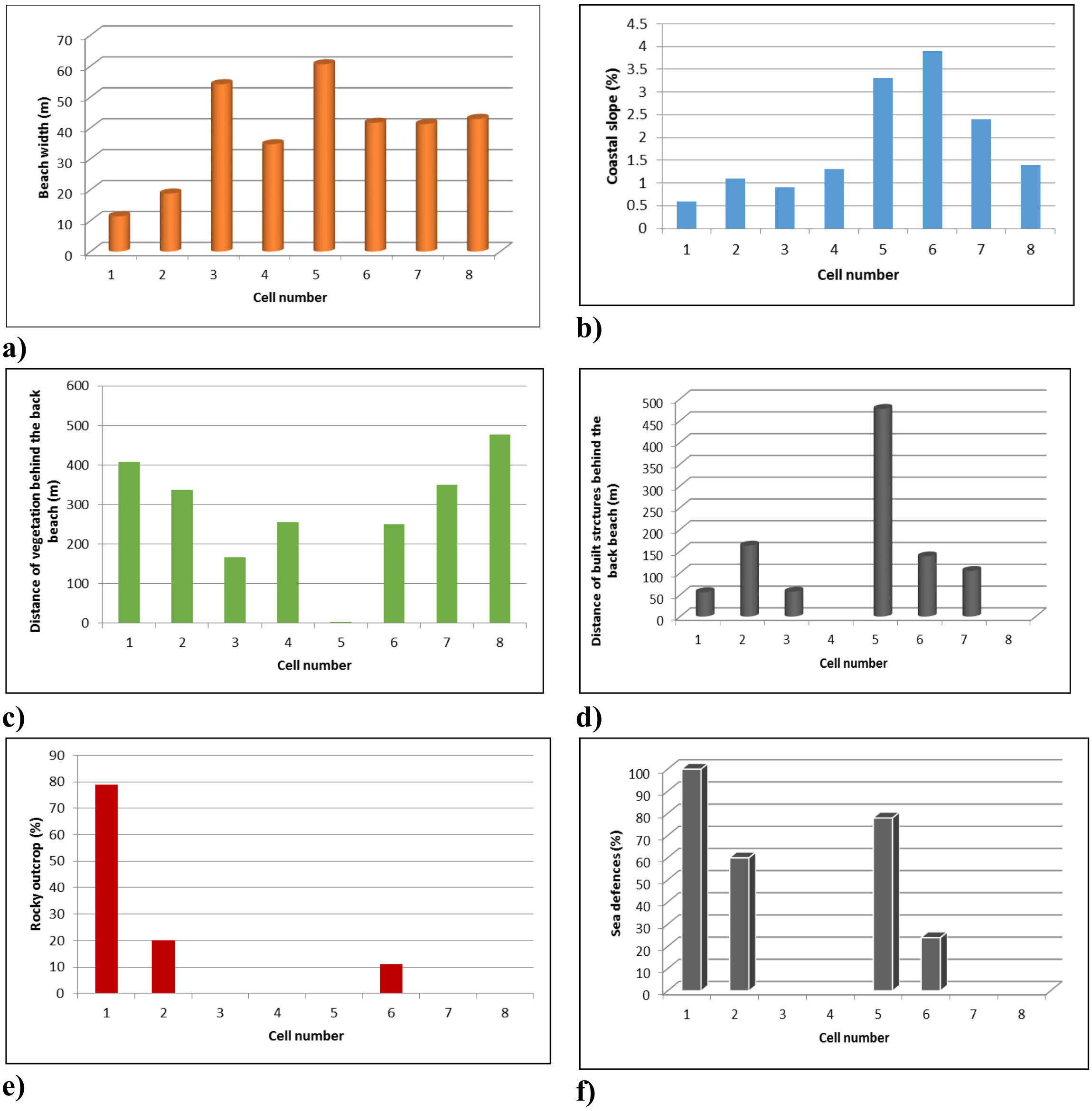


Figure 6.4: Graphical representations of Happisburgh

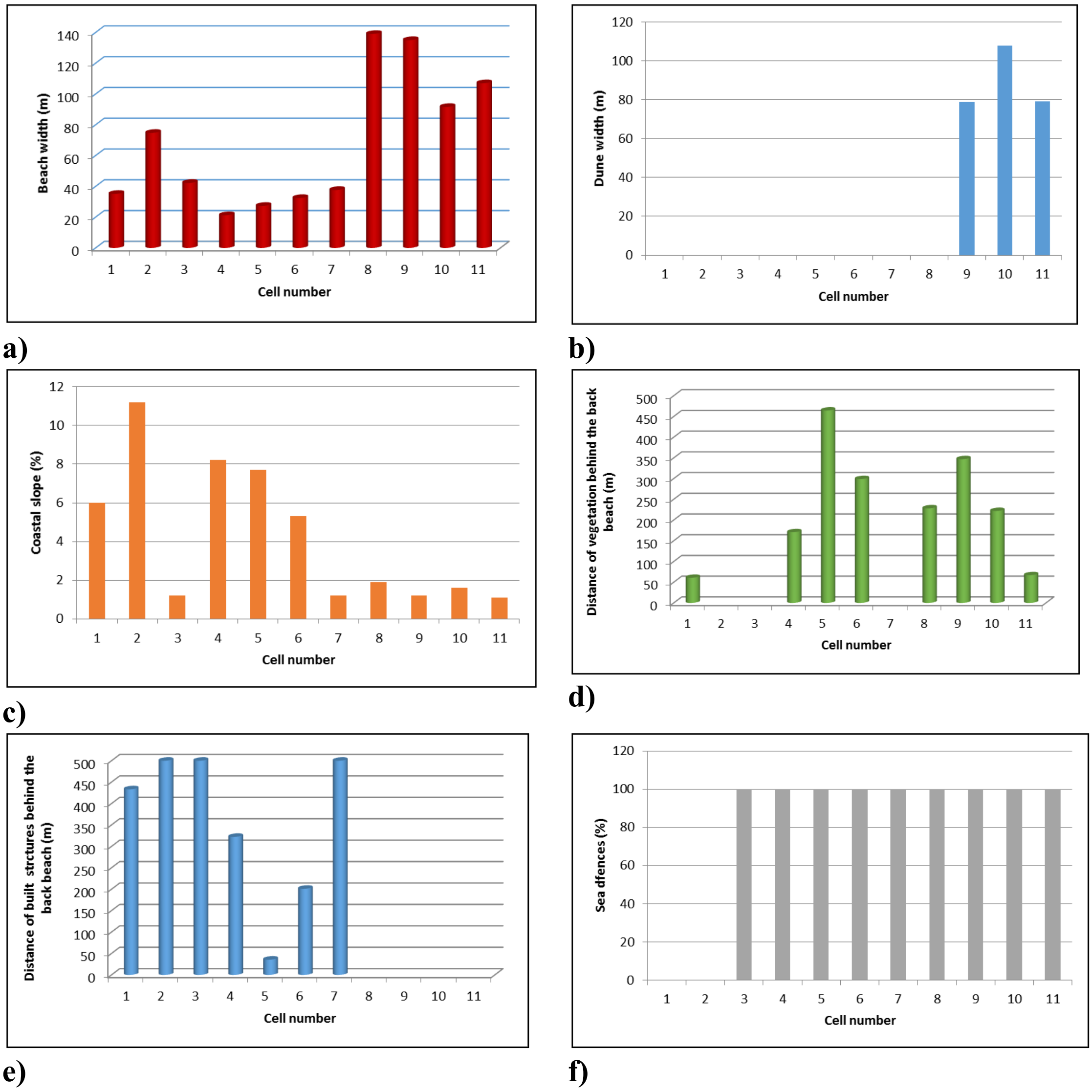


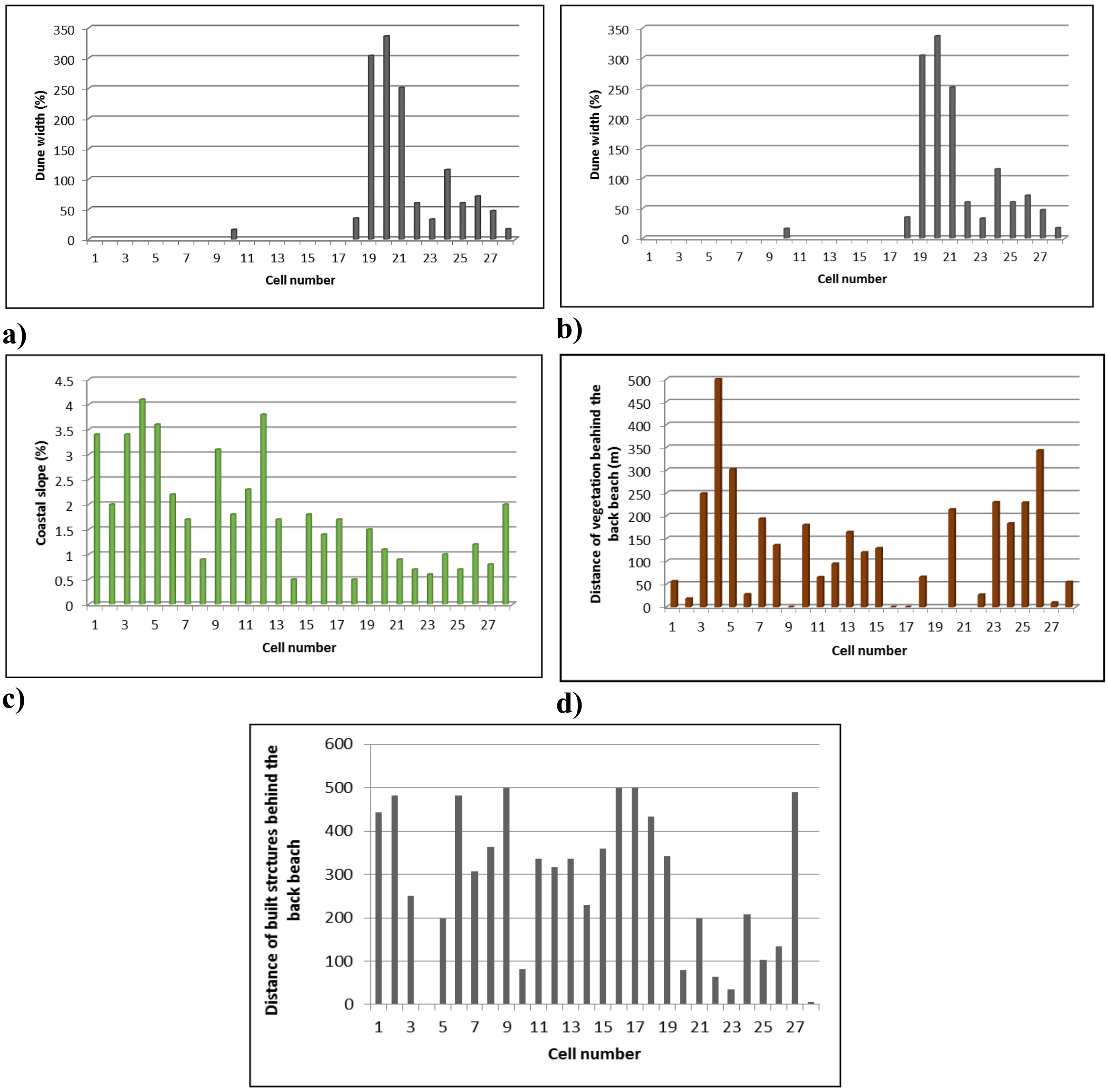
Figure 6.5: Graphical representations of Dawlish

6.7 Great Yarmouth

The average beach width between a maximum of 590 m recorded in the ninth cell and minimum of 1.4 m in the seventh cell was 56 metres and 89% of cells recorded lower than average values (Figure 6.6a). Less than half of the assessed shoreline showed dune morphology and the average of those cells that recorded dune width was 112 metres between the maximum 336 m; cell 12) and minimum (16 m; cell 10) recorded values (Figure 6.6b). The average recorded coastal slope was 1.8%, between a maximum of 4.1% recorded in the fourth cell and minimum of 0.5 % recorded in the fourteenth and eighteenth cells. Fifty-seven percent of cells recorded lower than the average value (Figure 6.6c).

The average distance of vegetation behind the back beach was 141.6 metres, with the maximum distance of 500 m recorded in the fourth cell and minimum in the second cell (10

m) and 39% of cells recorded more than the average distance (Figure 6.6d). The average distance of built structures behind the back beach was 277 m between the maximum (500 m; cell 9) and minimum (5 m; cell 28) recorded distances and 53% of cells recorded higher than average values (Figure 6.6e). There was no rocky outcrops or sea defences recorded.



a) b) c) d) e)

Figure 6.6: Graphical representations of Great Yarmouth

6.8 Skegness

The average beach width between the maximum of 326 m recorded in the ninth cell and minimum of 128 m in the seventeenth cell, was 206 m, with 56% of the cells recording higher than average values (Figure 6.7a). Less than half of the cells contained dune morphology and the average those measured between the maximum (91 m; cell 3) and minimum (9 m; cell 9) was 58.8 m (Figure 6.7b). The average coastal slope was 1.3%, between the maximum of 3.9% recorded in the twenty first cell and minimum of 0.4 % recorded in the first cell. Sixty percent of cells recorded lower than the average value (Figure 6.7c). The maximum distance of vegetation behind the back beach was 390 m (cell 9) and minimum of 6 m (cell 4), with 60% of cells recording lower than the average distance of 121 m (Figure 6.7d).

The average distance of built structures behind the back beach was 329 m, recorded between a maximum distance of 494 m (cell 12) and minimum of 30 m in the first cell and 60% of cells recorded higher than the average values (Figure 6.7e). Rocky outcrop was only recorded in the eighth cell (3.09%) and sea defences were recorded in the seventh and eighth cells (35% and 100% respectively).

6.9 Benbecula

The average beach width was 105.8 m, between the maximum of 255m recorded in the first cell and minimum of 37 m (cell 10) and 53% of cells recorded higher than the average values (Figure 6.8a). Dune width was only recorded in 20% of the cells and the average of those cells was 97.7 m, with the maximum recorded in the first cell of 184 m and minimum 49 m in the twelfth cell (Figure 6.8b). The average recorded coastal slope was 1.1%, between a maximum of 1.9% (cell 2) and minimum of 0.6 % (cell 1) and 53% of cells recorded higher than average values (Figure 6.8c).

The average distance of vegetation behind the back beach was 348 m and 60% of cells recorded more than the average value. The maximum distance of 490 m recorded in the fifteenth cell and minimum the second cell (137 m) (Figure 6.8d). The average distance of built structures behind the back beach was 142 m between the maximum (363 m; cell 2) and minimum (10 m; cell 15) recorded and 60% of cells lower than average values (Figure 6.8e). Rocky outcrops were recorded in less than half the cells the average between the maximum (100% coverage) recorded in six cells and minimum recorded in the third cell (76%), was 96%. There were no sea defence structures present.

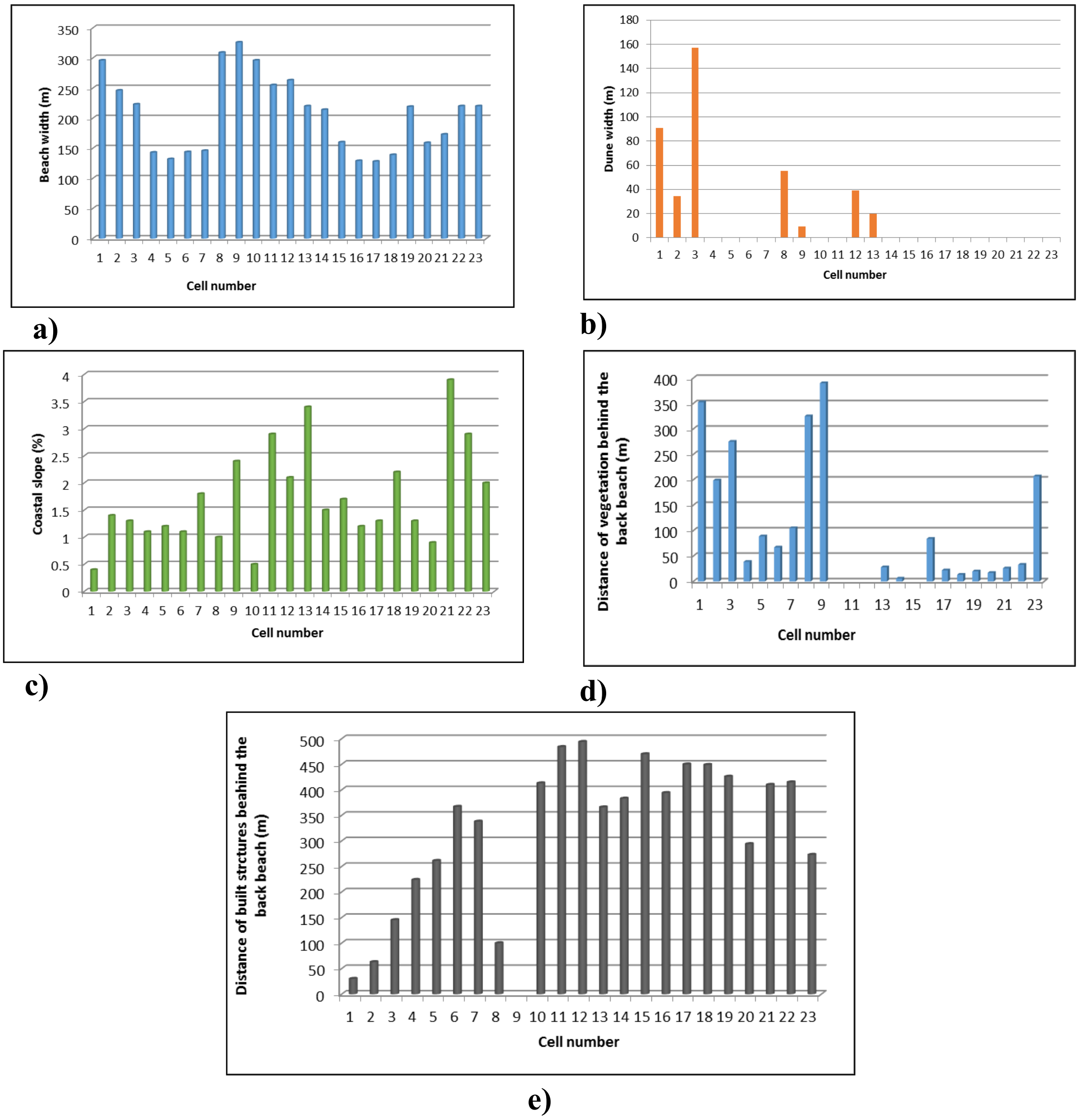


Figure 6.7: Graphical representations of Skegness

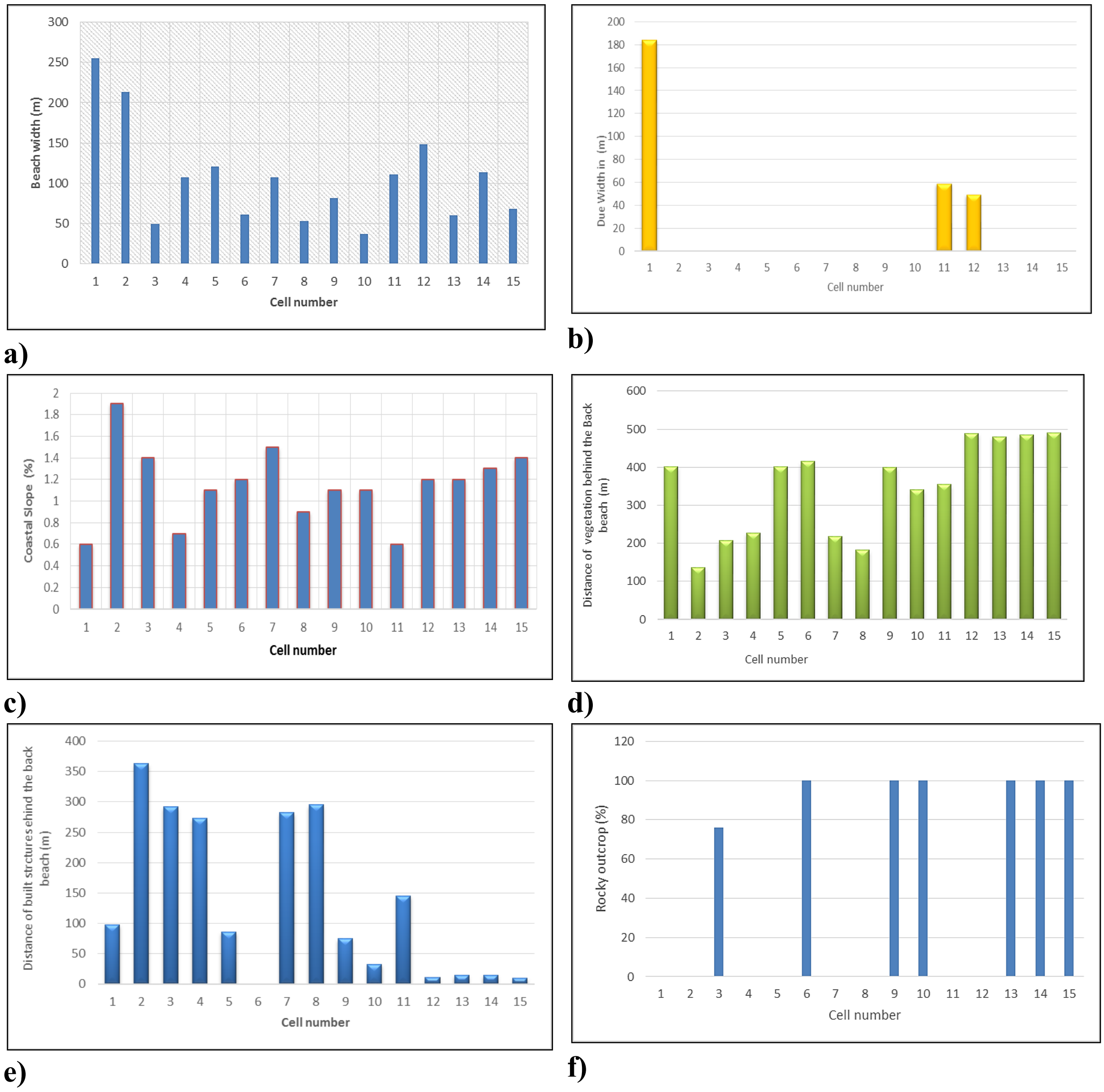


Figure 6.8: Graphical representations of Benbecula

6.10 Aberystwyth

The average beach width was 90.6 m between the maximum of 168 m recorded in the third cell and minimum of 63 m in the fifth cell, and 80% of cells recorded lower than the average values (Figure 6.9a). The average recorded coastal slope was 7.6%, between a maximum of 14.7% (cell 5) and minimum of 0.2 % (cell 2) and 60% of cells recorded lower than average values (Figure 6.9b). The average distance of vegetation behind the back beach was 147 m and 60% of cells recorded lower than the average values.

The maximum recorded in the fifth cell was 306 m and minimum in the fourth cell (44 m) (Figure 6.9c). The average distance of built structures behind the back beach was 201 m between the maximum (455 m; cell 3) and minimum (29 m; cell 5) recorded distances and 60% of cells lower than average values (Figure 6.9d). The entire shoreline frontage was protected by sea defence structures (Figure 6.9e), there are no dunes recorded, and rocky outcrops were only recorded in two cells.

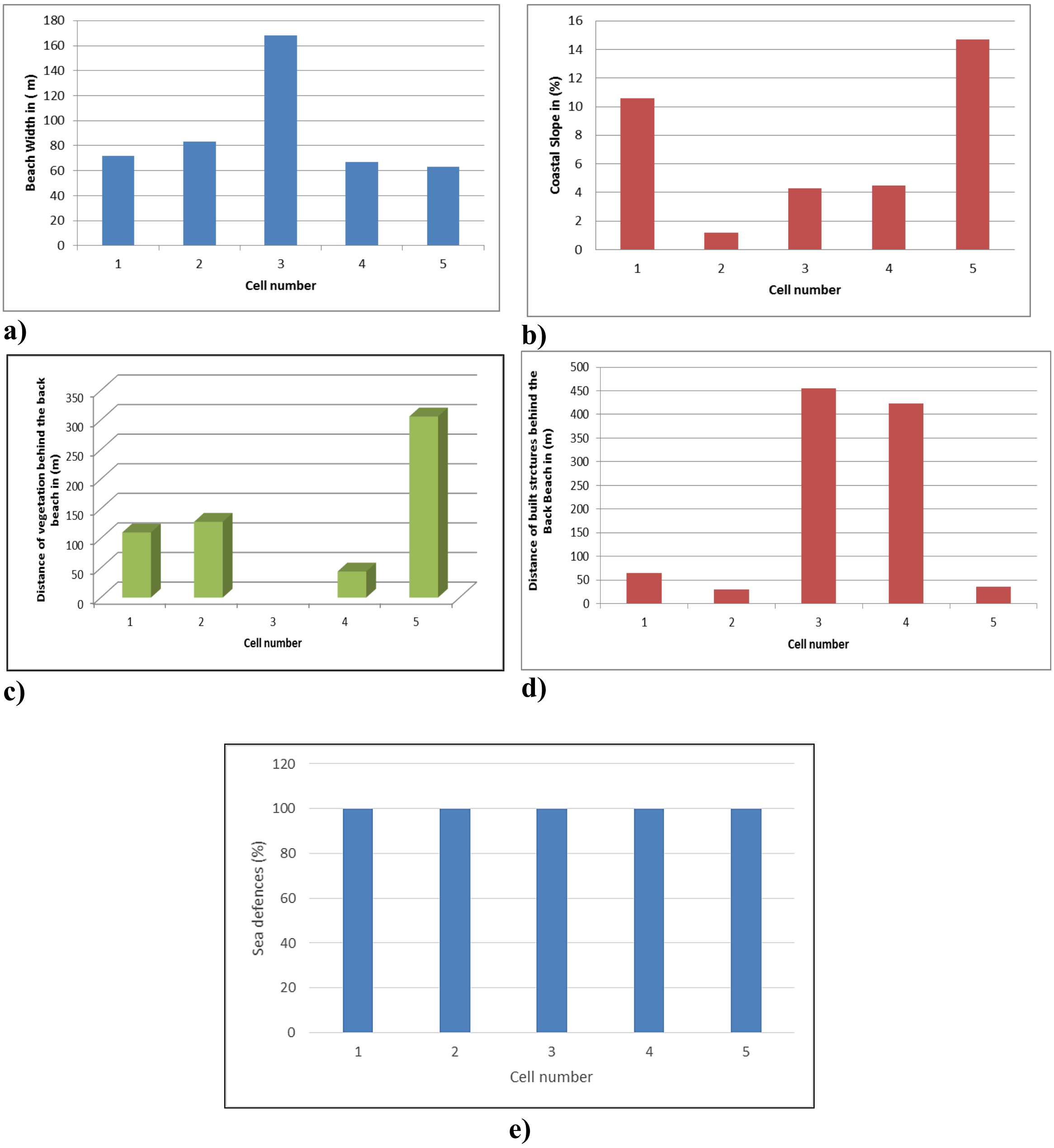


Figure 6.9: Graphical representations of Aberystwyth

6.11. Port Talbot

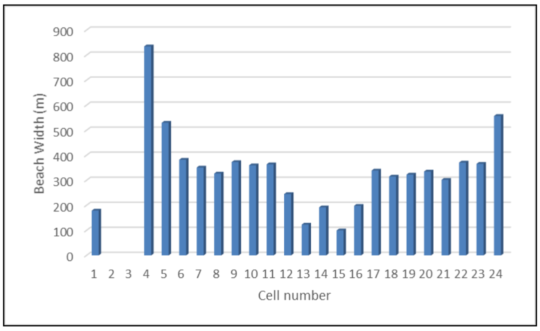
The average beach width was 339 m and 45% of cells recorded lower than the average values. The maximum recorded in the fourth cell was 835 m and minimum of 100 m in the fifteenth (Figure 6.10a). Dunes were recorded in less than half of the cells and the average of those cells between the maximum (515 m; cell 3) and minimum (29 m; cell 23) recorded values was 165 m and 29% of cells recorded higher than the average values (Figure 6.10b). The average recorded coastal slope was 3.3%, between a maximum of 15.6% recorded in the sixteenth cell and minimum of 1.1 % in the eleventh cell. Seventy percent of cells recorded lower than average values (Figure 6.8c).

The average distance of vegetation behind the back beach was 97 m, with the maximum distance of 500 m recorded in the third cell and minimum of 40 m in cell nineteen (Figure 6.8d). The average distance of built structures behind the back beach between the maximum (500 m; cell 7) and minimum (30 m; cell 5) was 389 and 58% of cells higher than average values (Figure 6.10e). The average rocky outcrop was 8.4% between the maximum 30%, recorded at cell 13 and minimum was 1%, recorded at twenty-second cell. More than >42 % of cells scored lower than average rocky outcrop (Figure 6.10f). The average sea defences was 89.6 % between the maximum 100%, and minimum 22%, and >50% of cells lower than average sea defence (Figure 6.10g).

6.12 Llanelli

The average beach width, between the maximum of 1900 m recorded in the eleventh and twelve cells and minimum of 37 m in the twenty fifth, was 668 m and 61% of cells recorded lower than average values (Figure 6.11a). The average recorded coastal slope was 3.3 %, between a maximum of 11% (cell 6) and minimum of 0.8 % (cell 21) and 57% of cells recorded lower than average values (Figure 6.11b). The average distance of vegetation behind the back beach was 330 m, with the maximum distance of 491 m recorded in cell 2; the minimum distance was recorded in cell 5 (102 m) and 53% of cells recorded more than the average distance (Figure 6.11c). The average distance of built structures behind the back beach was 102 m between the maximum (343 m; cell 5) and minimum (2.4 m; cell 23) recorded distances and 57% of cells lower than average values (Figure 6.11d).

The average rocky outcrop was 4.3%, between the maximum (117% 8 cell) and minimum (70.8% cell 14) and 42 % of cells recorded lower than (Figure 6.11e) average values. Sea defences protected almost the entire shoreline frontage, averaging 72.4% between the maximum (100% cells 11) and minimum (11.4% cell 10) values and 42 % of cells recorded lower than average values (Figure 6.11f).



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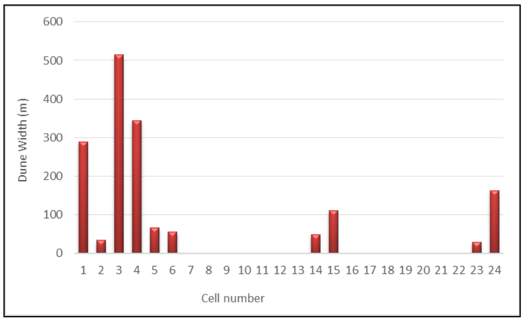

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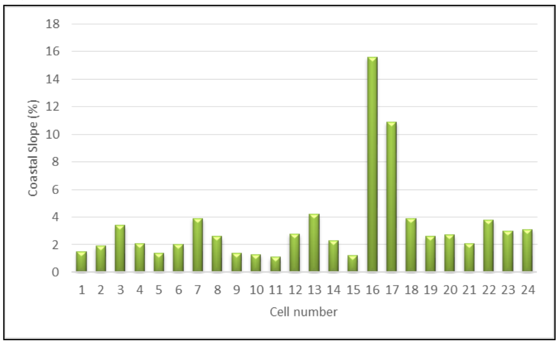

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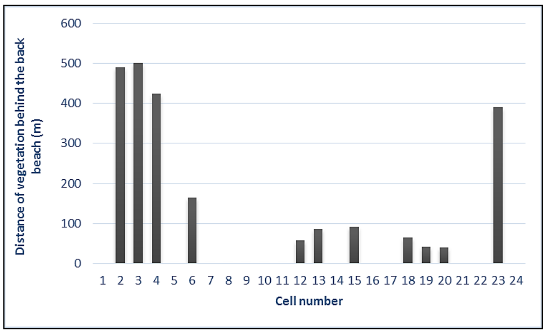

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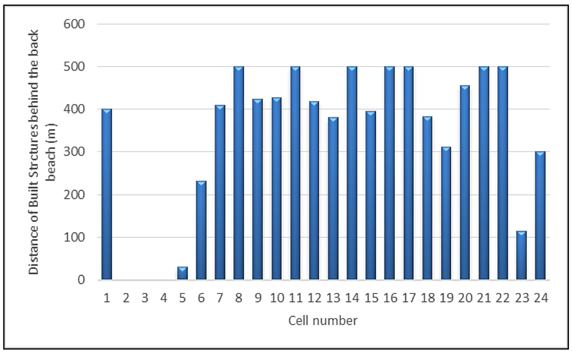

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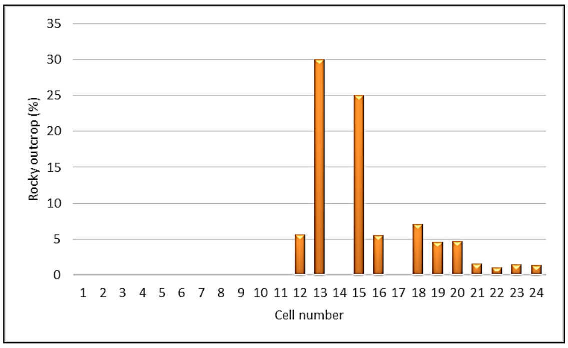

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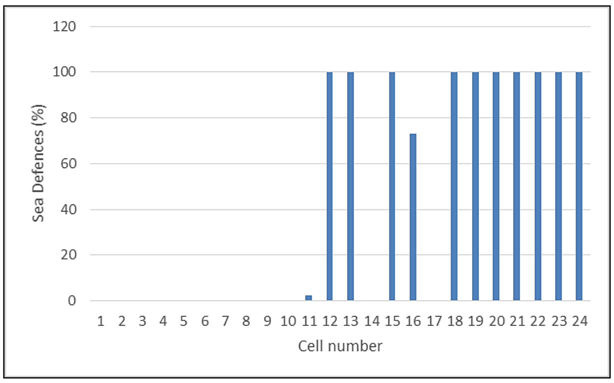


g)

Figure 6.10: Graphical representations of Port Talbot

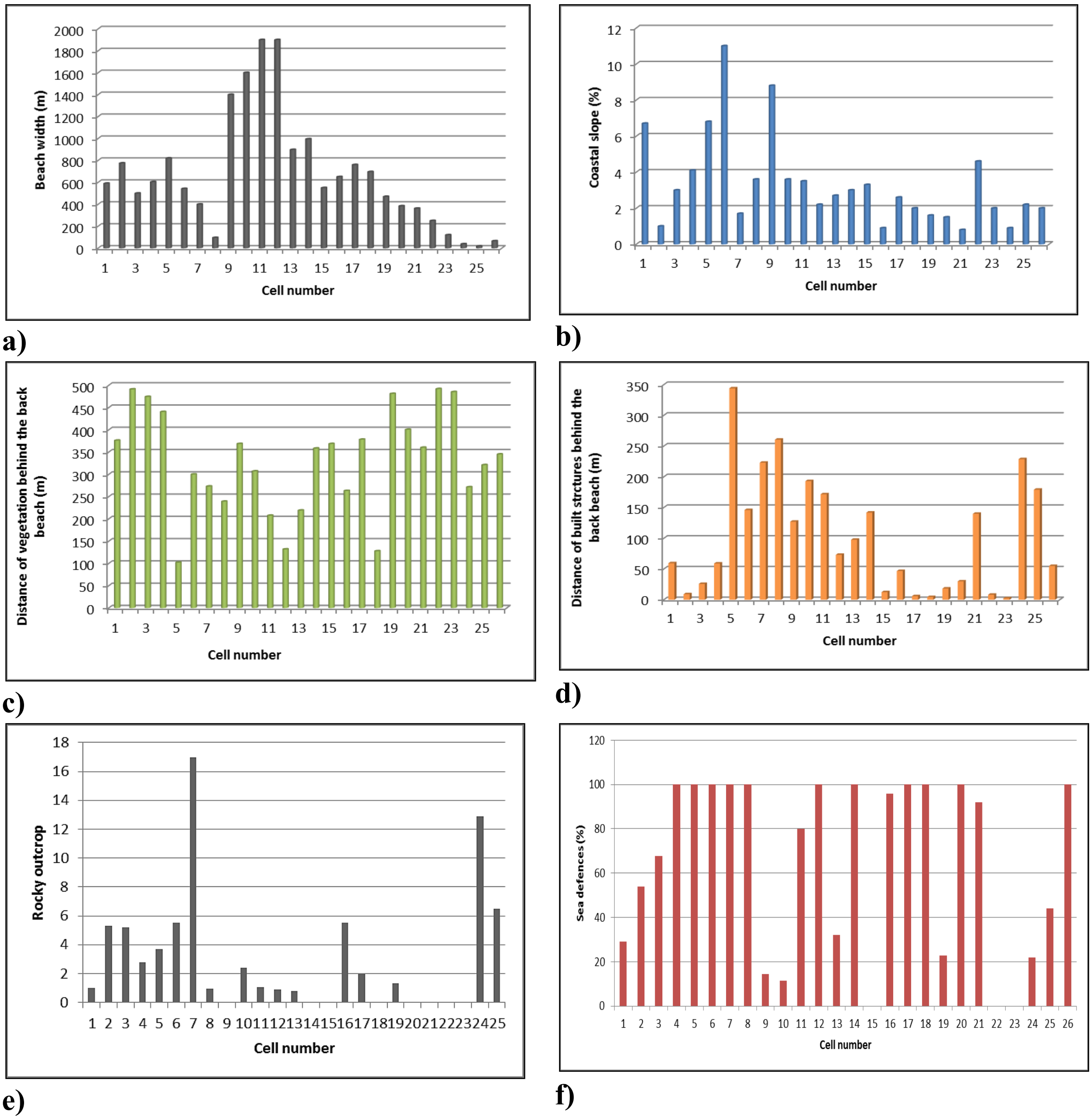


Figure 6.11: Graphical representations of Llanelli

6.13. Overall CVI measurement

Having evaluated the measurements of the 7 physical parameters determined in sections 4.6.1 and 5.7 respectively and applying them to the 11 selected coastal areas, it is now necessary to evaluate the overall CVI measurements. Table 6.2 shows the selected coastal areas alongside allocated cell numbers.

Table 6.2 Distribution of all shoreline measurements at selected sites

Cell	Site Name	Cell	Site Name	Cell	Site Name	Cell	Site Name
1	Spurn Head	41	Great Yarmouth	81	Skegness	121	Port Talbot
2	Spurn Head	42	Great Yarmouth	82	Skegness	122	Port Talbot
3	Spurn Head	43	Great Yarmouth	83	Skegness	123	Port Talbot
4	Spurn Head	44	Great Yarmouth	84	Skegness	124	Port Talbot
5	Spurn Head	45	Great Yarmouth	85	Skegness	125	Port Talbot
6	Spurn Head	46	Great Yarmouth	86	Skegness	126	Port Talbot
7	Hallsands	47	Great Yarmouth	87	Skegness	127	Port Talbot
8	Hallsands	48	Great Yarmouth	88	Skegness	128	Port Talbot
9	Hallsands	49	Great Yarmouth	89	Benbecula	129	Port Talbot
10	Hallsands	50	Great Yarmouth	90	Benbecula	130	Port Talbot
11	Hallsands	51	Great Yarmouth	91	Benbecula	131	Port Talbot
12	Hallsands	52	Great Yarmouth	92	Benbecula	132	Port Talbot
13	Hallsands	53	Great Yarmouth	93	Benbecula	133	Llanelli
14	Hallsands	54	Great Yarmouth	94	Benbecula	134	Llanelli
15	Lynmouth	55	Great Yarmouth	95	Benbecula	135	Llanelli
16	Lynmouth	56	Great Yarmouth	96	Benbecula	136	Llanelli
17	Lynmouth	57	Great Yarmouth	97	Benbecula	137	Llanelli
18	Lynmouth	58	Great Yarmouth	98	Benbecula	138	Llanelli
19	Happisburgh	59	Great Yarmouth	99	Benbecula	139	Llanelli
20	Happisburgh	60	Great Yarmouth	100	Benbecula	140	Llanelli
21	Happisburgh	61	Great Yarmouth	101	Benbecula	141	Llanelli
22	Happisburgh	62	Great Yarmouth	102	Benbecula	142	Llanelli
23	Happisburgh	63	Great Yarmouth	103	Benbecula	143	Llanelli
24	Happisburgh	64	Great Yarmouth	104	Aberystwyth	144	Llanelli
25	Happisburgh	65	Great Yarmouth	105	Aberystwyth	145	Llanelli
26	Happisburgh	66	Skegness	106	Aberystwyth	146	Llanelli
27	Dawlish	67	Skegness	107	Aberystwyth	147	Llanelli
28	Dawlish	68	Skegness	108	Aberystwyth	148	Llanelli
29	Dawlish	69	Skegness	109	Port Talbot	149	Llanelli
30	Dawlish	70	Skegness	110	Port Talbot	150	Llanelli
31	Dawlish	71	Skegness	111	Port Talbot	151	Llanelli
32	Dawlish	72	Skegness	112	Port Talbot	152	Llanelli
33	Dawlish	73	Skegness	113	Port Talbot	153	Llanelli
34	Dawlish	74	Skegness	114	Port Talbot	154	Llanelli
35	Dawlish	75	Skegness	115	Port Talbot	155	Llanelli
36	Dawlish	76	Skegness	116	Port Talbot	156	Llanelli
37	Dawlish	77	Skegness	117	Port Talbot	157	Llanelli
38	Great Yarmouth	78	Skegness	118	Port Talbot	158	Llanelli
39	Great Yarmouth	79	Skegness	119	Port Talbot		
40	Great Yarmouth	80	Skegness	120	Port Talbot		

Figures 6.12(a-d) respectively show graphically the overall parameter measurements produced from the data given in Appendix 1. The average beach width was 239.1 m, between the maximum of 1900 m recorded in cells 143 and 144 (Llanelli) and minimum of 1.4 m in cells 44 and 45 (Great Yarmouth) and 47% of cells recorded lower than 50 m. *i.e.* high vulnerability (Table 4.5; Figure 6.12a). The average dune width was 97.1 m, between the maximum of 515 m recorded in cell 111 (Port Talbot) and minimum of 9.5 m cell 74 (Skegness) and 71% of cells did not display any dune morphology (Figure 6.12b). The average coastal slope was 3.9% between the maximum of 48% recorded in cell 18 (Lynmouth) and minimum of 0.4%, m in cell 66 (Skegness) and 70% of cells recorded lower than average values (Figure 6.12c).

The average distance of vegetation behind the back beach was 243 m, between the maximum of 500 m recorded in cells 19, 41and 112 (Happisburgh, Great Yarmouth and Port Talbot respectively) and minimum of 4 m in cell 23 (Happisburgh), however, vegetation cover was recorded in 85% of the cells (Figure 6.12d). The average distance of built structures behind the back beach was 235 m, between the maximum of 500 m recorded in cell 13 (Hallsands) and minimum of 2.4 m in cell 155 (Llanelli) and only 10 % of cells contained no built structures (Figure 6.12e).

The average rocky outcrop was 27% between the maximum of 100% recorded in Aberystwyth and Benbecula and minimum of 0.8 % in cell 146 (Llanelli) and 72 % of cells did not have rocky outcrops (Figure 6.12f). The average sea defence coverage when recorded was 81.32 %, between the maximum of a 100% covering an entire cell (Dawlish, Skegness, Aberystwyth, Port Talbot, Llanelli and Benbecula) and minimum of 1 % in cell 120 (Port Talbot). Importantly, no sea defence structures were recorded in 63% of the cells. (Figure 6. 12g).

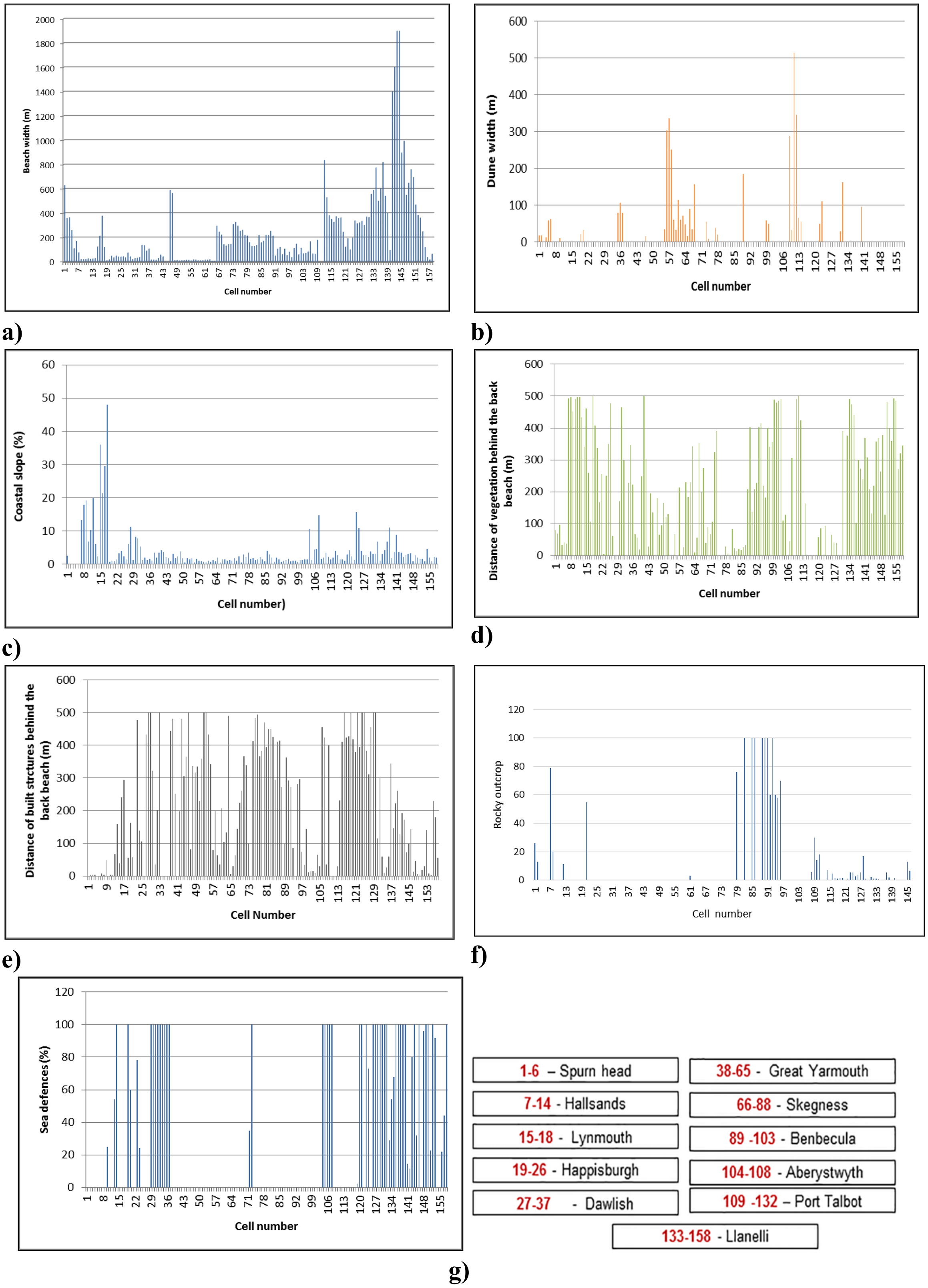


Figure 6.12: Graphical representations of overall CVI scores

6.14. Summary

This completes the descriptive assessment of the measurements taken for each of the physical parameters described in section 5.7, both on an individual case study and overall basis. From this point, the next Chapter will allocate CVI scores, compare in line with boundaries defined in Table 4.5. These will then be compared and from analysis a site-by-site and overall ranking according to PCVI will be determined.

CHAPTER 7 – PCVI ANALYSIS

7. Physical coastal vulnerability index (PCVI) Analysis

7.1 Introduction

Having evaluated the seven physical parameters and applying them to the 11 selected coastal areas described in Sections 4.4. It is now necessary to apply the measurements determined in chapter 6, to allocate vulnerability scores and develop a PCVI.

7.2 Spurn Head

The physical parameter ratings given in Table 4.5 (Chapter 4) were used to allocate vulnerability scores and construct Figure 7.1. As beach width ranged from 630 m to 109 m (section 6.2), it stands to reason that the vulnerability scores would range between 1 (extremely low) and 2 (low). Eighty percent of cells recorded lowest value (1) and importantly the overall average beach width CVI score was 1.3 (Figure 7. 1a). Dune width values varied from 63 m to 13 m and Table 4.4 vulnerability scores ranged between 3 (moderate) and 4 (high). Over half of the cells were allocated a score of 4, influencing the overall average of 3.2 (Figure 7.1b). When the aerial photographs were analysed within GIS only one cell could measure for coastal slope and allocated a score of 4. This score was distributed evenly for all cells, as the topography of this coastal feature appeared consistent on the aerial photograph (7.1c).

There was a considerable variance between the lowest and highest CVI values for distance of vegetation behind the back beach. However, because the measured distances ranged between 97 m and 34 m, Figure 7.1d shows that all cells were allocated a score of 4. Only 3 cells recorded built structures behind the back beach and these were allocated a score of 4 as they were only set back 3 m (Figure 7.1e). Unsurprisingly, there was no rocky Outcrop or sea defences recorded at Spurn Head and because of the importance of these aspects for the dissipation of waves and shoreline protection, both parameters were allocated scores of 4 throughout (Figures 7.1f and 7.1g respectively). Figure 7.1h shows the aggregated scores in one representation, the overall average score was 22, the maximum recorded score of 25 and minimum of 20 and the cumulative score of Spurn Head was 132.

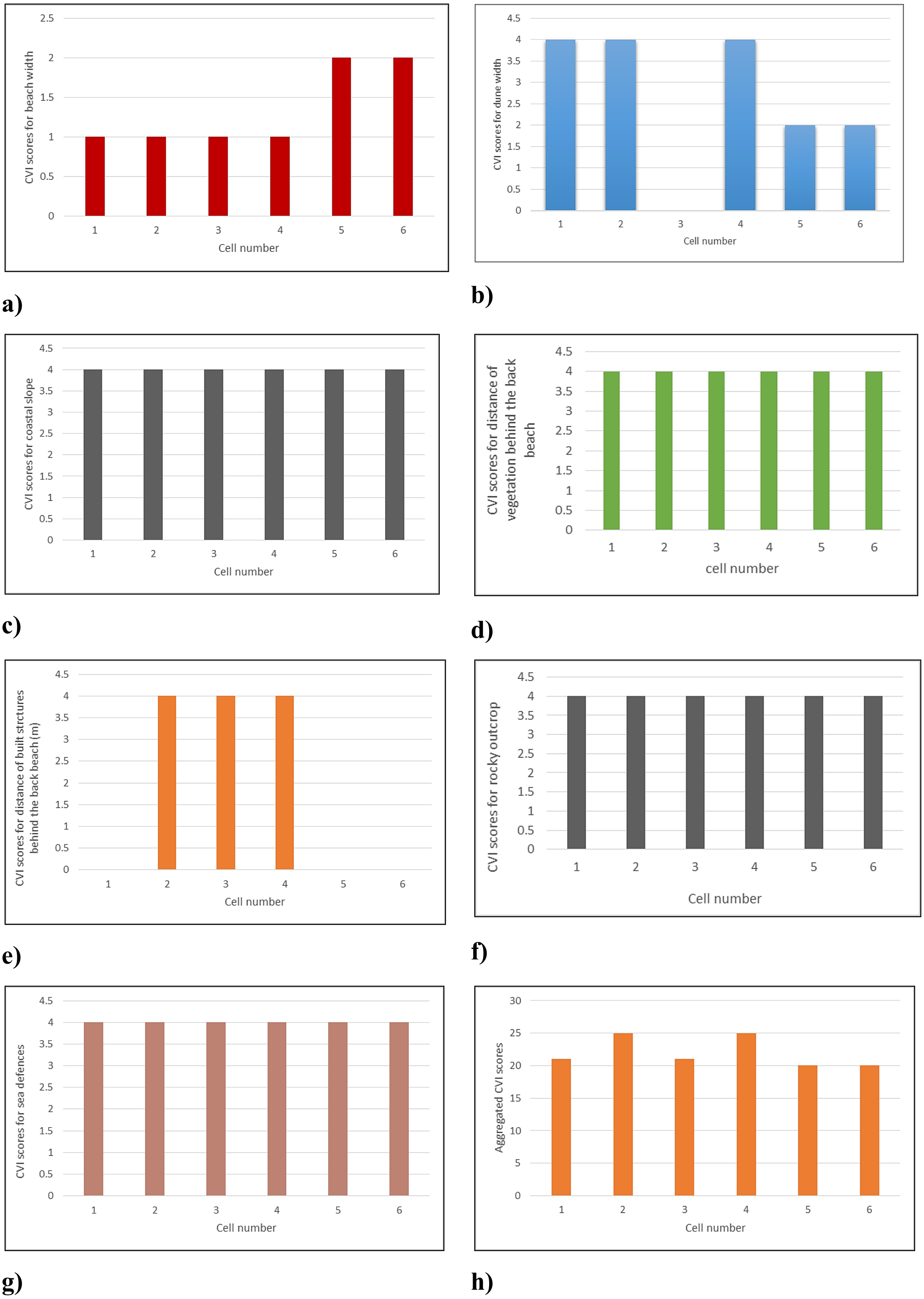


Figure 7.1: Distribution of CVI scores for Spurn Head

7.3 Hallsands

With the exception of the first cell (70 m) beach width ranged from 20 m to 27 m (section 6.3), it stands to reason that the vulnerability scores would range between 3 and 4. Eighty-seven percentage of the cells recorded a score of 4 and the average CVI score was 3.6 (Figure 7. 2a). Dunes only present in the fourth cell; therefore, the parameter was allocated score of 4, because no additional shoreline protection can be given (Figure 7.2b). The scores for coastal slope ranged between 1 and 4 with an average score of 1.8 (Figure 7.2c). Even though there was some variation in the measured distance of vegetation behind the back beach *i.e.* between 496 m and 340 m (Figure 7.2d), when compared to the respective value given in Table 4.4 all cells were allocated a score of 2. CVI scores allocated for the distance of built structures behind the back beach ranged between 3 and 4 with the average of 3.8 (Figure 7.1e). Only two cells recorded rocky outcrop and three cells sea defences but because of the importance of these natural and anthropogenic structures, for the dissipation of waves and shoreline protection. Consequently, scores of 4 were allocated and giving overall average CVI scores were 3.6 and 3 respectively (Figures 7.2f and 7.2g respectively). The aggregated scores are graphically represented in Figure 7.2h, giving an overall average score was 22, maximum of 24 and minimum of 19 and a cumulative score for Hallsands of 174.

7.4. Lynmouth

The beach width ranged between 378 m and 121 m (section 6.4) and the cells on either end of the studied area were allocated scores of 2 and mid cells 1 (Figure 7.3a). Dunes were absent and similar to previous; all cells were allocated CVI scores of 4 (Figure 7.3b). There was very little variation when consideration was given to coastal slope and since the values calculated in section 6.4 were all >12% (Table 4.4) all four cells were given scores of 1 (Figure 7.3c). Considering only 4 cells were located at this location, the measured distances of vegetation behind the back beach varied considerably, ranging between 500 m and 105 m. Table 4.4 data allocated CVI values of 2 and 3, averaging at 2.2 (Figure 7.1d). Built structures were identified in 3 of the 4 cells and a distance of < 100 m recorded in the first cell resulted in a score of 4, the remaining cells recorded distances > 600 m and were allocated scores of 1 (Figure 7.3e). There were no rocky outcrops or sea defences and as a consequence, both were allocated scores of 4 throughout (Figures 7.3f and 7.3g respectively). The aggregated scores represented graphically in Figure 7.1h, shows that the first cell is the most vulnerable with a score of 21 and the fourth cell the least vulnerable with a score of 17.

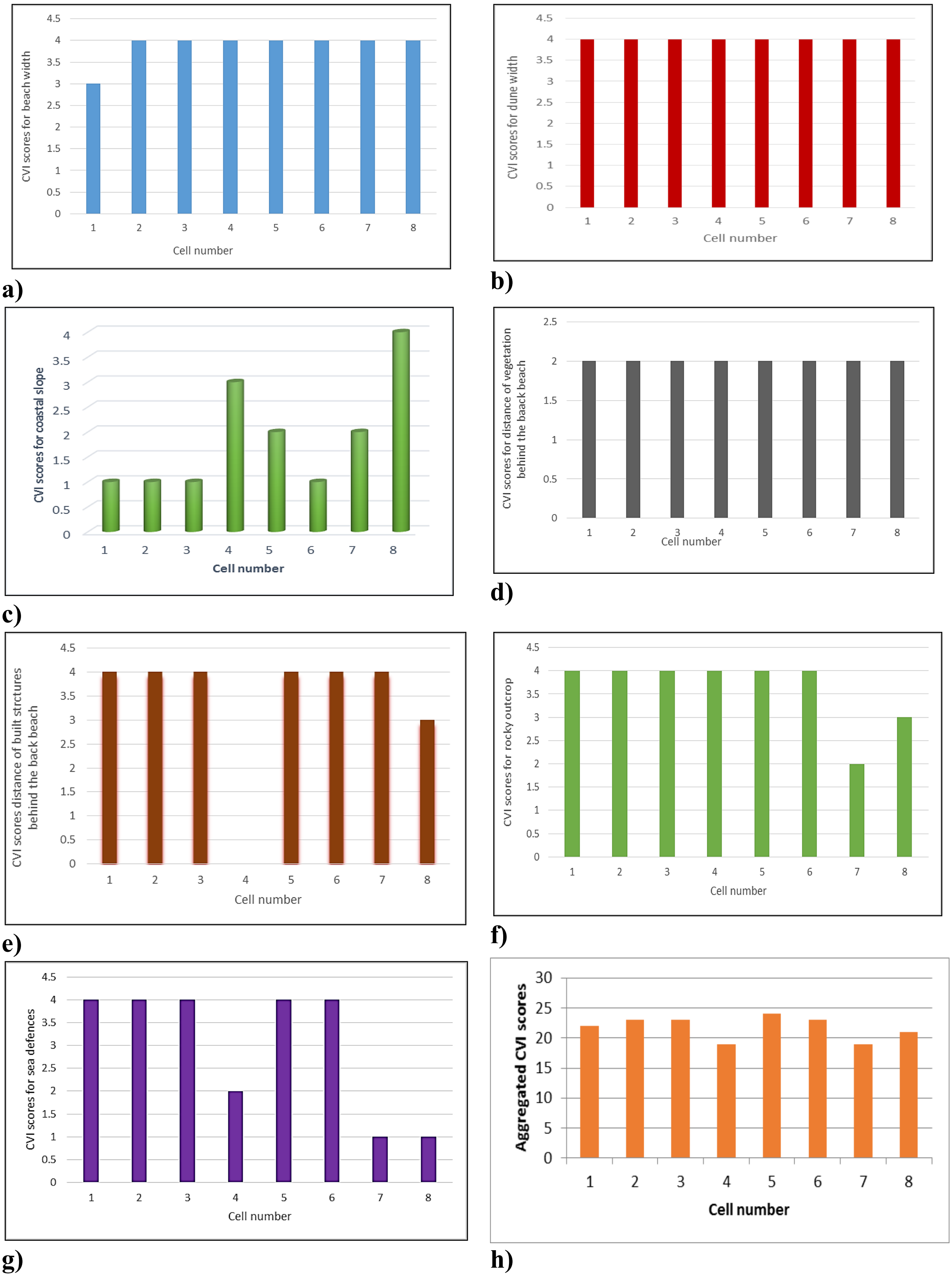


Figure 7.2: Distribution of CVI scores for Hallsands

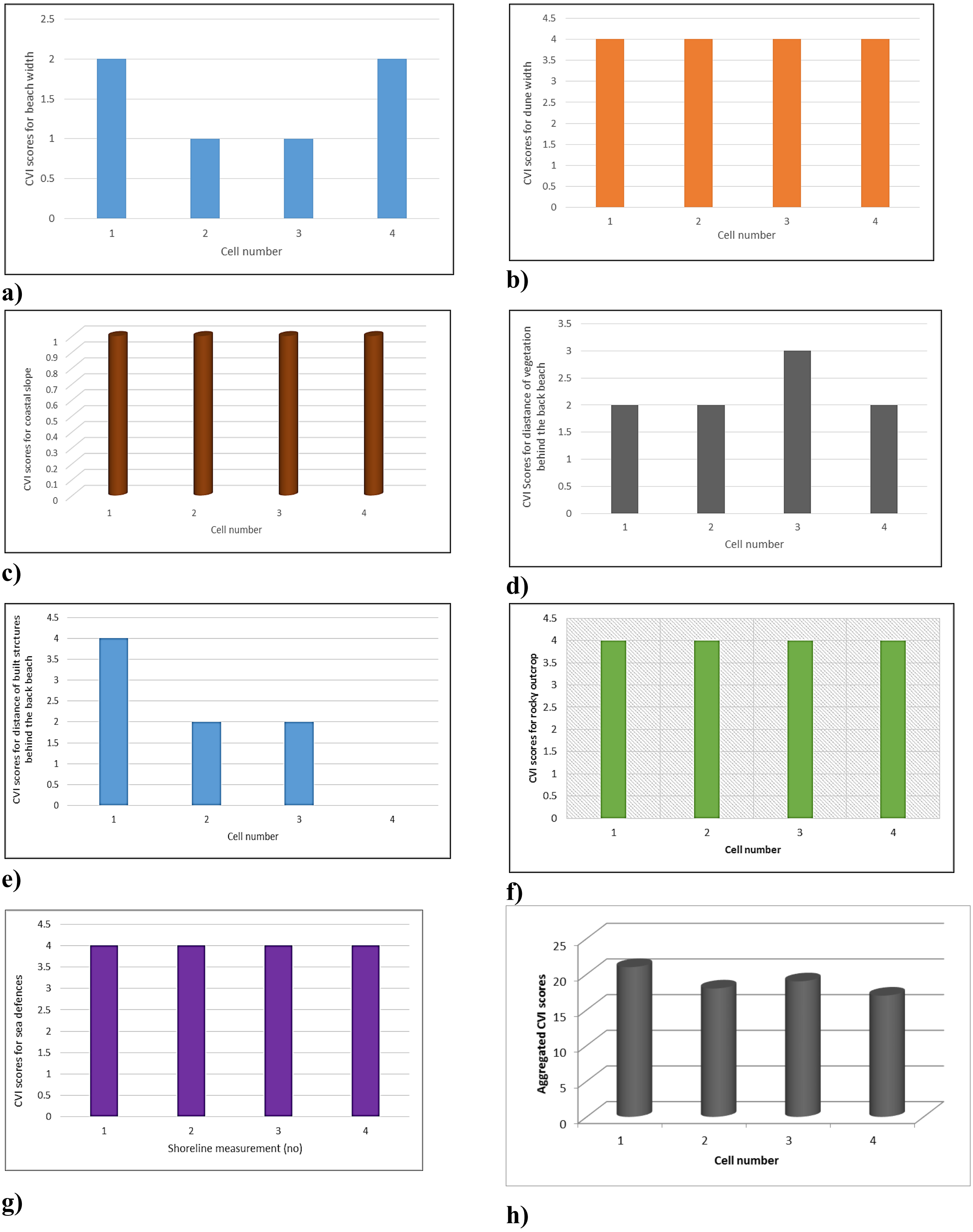


Figure 7.3: Distribution of CVI scores for Lynmouth

7.5 Happisburgh

The beach width ranged between 60 m and 11 m (Section 6.5) and since cells three and five exceeded 50 m they were allocated a CVI score of 3, the widths of the remaining cells were < 50 m and therefore given a score of 4 (Figure 7.4a). Dunes were only recorded in the first and second cells and allocated scores of 3 and 4 respectively and in line with previous given scores of 4 (Figure 7.4b). The coastal slope in all cells was < 4% and accordingly all cells were allocated scores of 4 (Figure 7.4c). Measured distances of vegetation behind the back beach ranged between 408 m, and 4 m with the third and fifth cell given CVI scores of 3 and 4 respectively. The distances recorded in the remaining cells ranged between 200 m and 600 m and were allocated scores of 2 (Figure 7.1d). Two cells (1 and 3) showed structures within 100 m of the shoreline and where given the highest score (4) and the scores varied between 2 and 3 in the remaining cells (Figure 7.4e). Rocky outcrops were recorded in three cells with cell one scoring 1 and cells two and six 3, the remaining cells were given the highest score of 4 (Figure 7.4f). Sea defences were present in 4 cells, of those measured, three protected > 50% of the frontage and were given the lowest score (1), the remaining cell was given a score of 2 and all remaining cells 4 (Figure 7.4g). The aggregated scores are represented graphically in Figure 7.4h and shows that the third cell is the most vulnerable with a score of 27 and first and second cells least vulnerable with a score of 20.

7.6 Dawlish

Beach width ranged from 139 m to 21.2 m (chapter 6, section 6.6), with six cells recording widths of < 50 m and allocated scores of 4, the remaining cells were allocated scores between 2 and 3 (Figure 7.5a). Dunes were recorded in the last three cells and given CVI scores of 2, and the remaining cells were allocated scores of 4 (Figure 7.5b). Over half the cells recorded coastal slopes of <4% and allocated a score of 4, while the remaining cell scores ranged between 2 and 3(Figure 7.5c). The distance of vegetation behind the back beach varied considerably and ranged between 464 m and 60 m. The first and last cells were allocated a score of 4 and fourth cell a score of 3, all remaining cells were given score of 2 (Figure 7.5d). With the exception of cells 5 and 6 with allocated CVI scores of 4 and 3 respectively, most structures, were set back 200 m to 600 m behind the back beach and given a CVI scores of 2 (Figure 7.5e). Rocky outcrop was only recorded in seventh cell and given a score of 1 and all remaining cells were allocated a score of 4 (Figure 7.5f). The shoreline frontage is protected by extensive sea defences resulting in a low vulnerability score of 1 throughout

(Figure 7.5g). Figure 7.5h shows the aggregated scores in one representation; the overall average score was 18, the maximum-recorded score of 22 and minimum of 15.

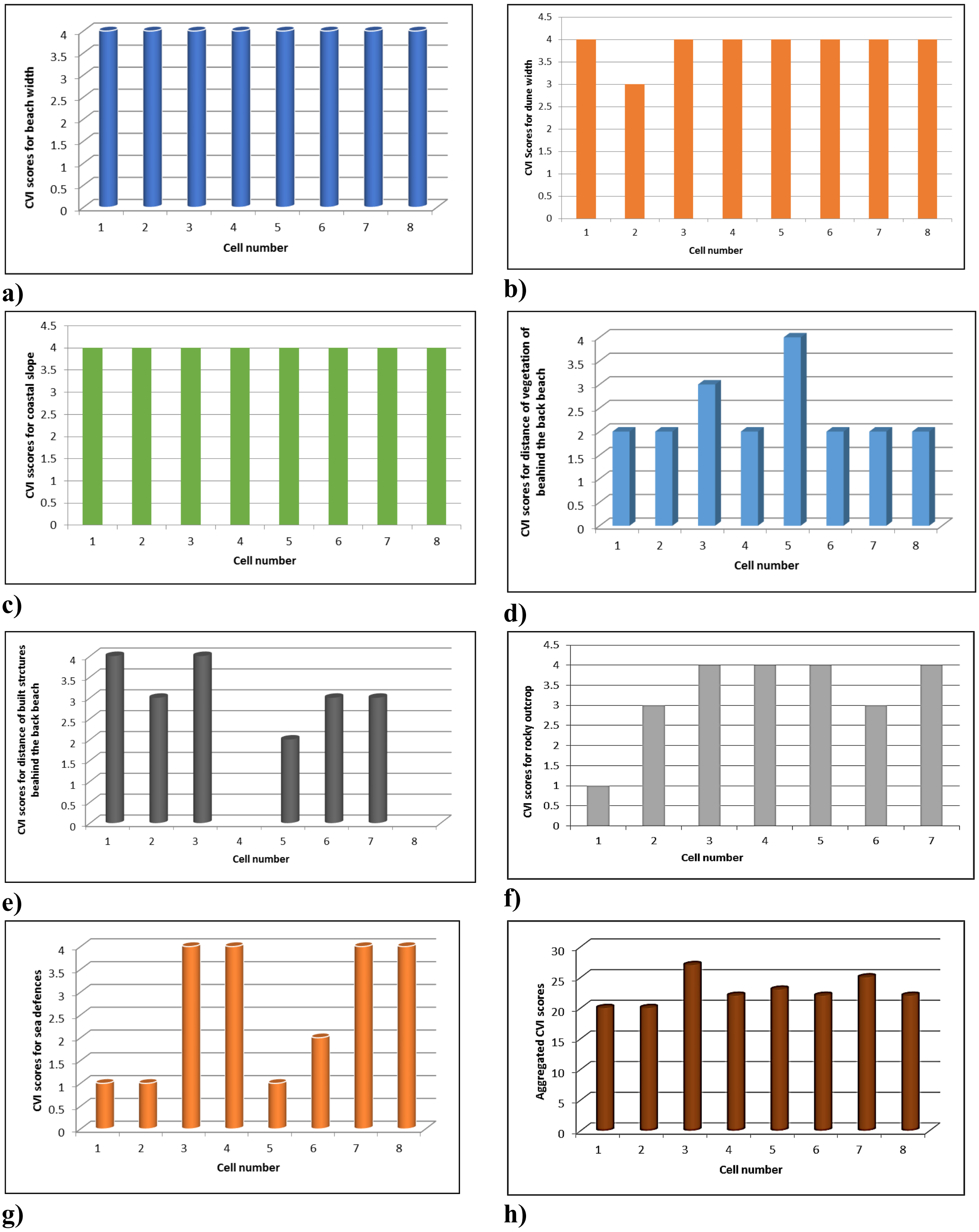


Figure 7.4: Distribution of CVI scores for Happisburgh

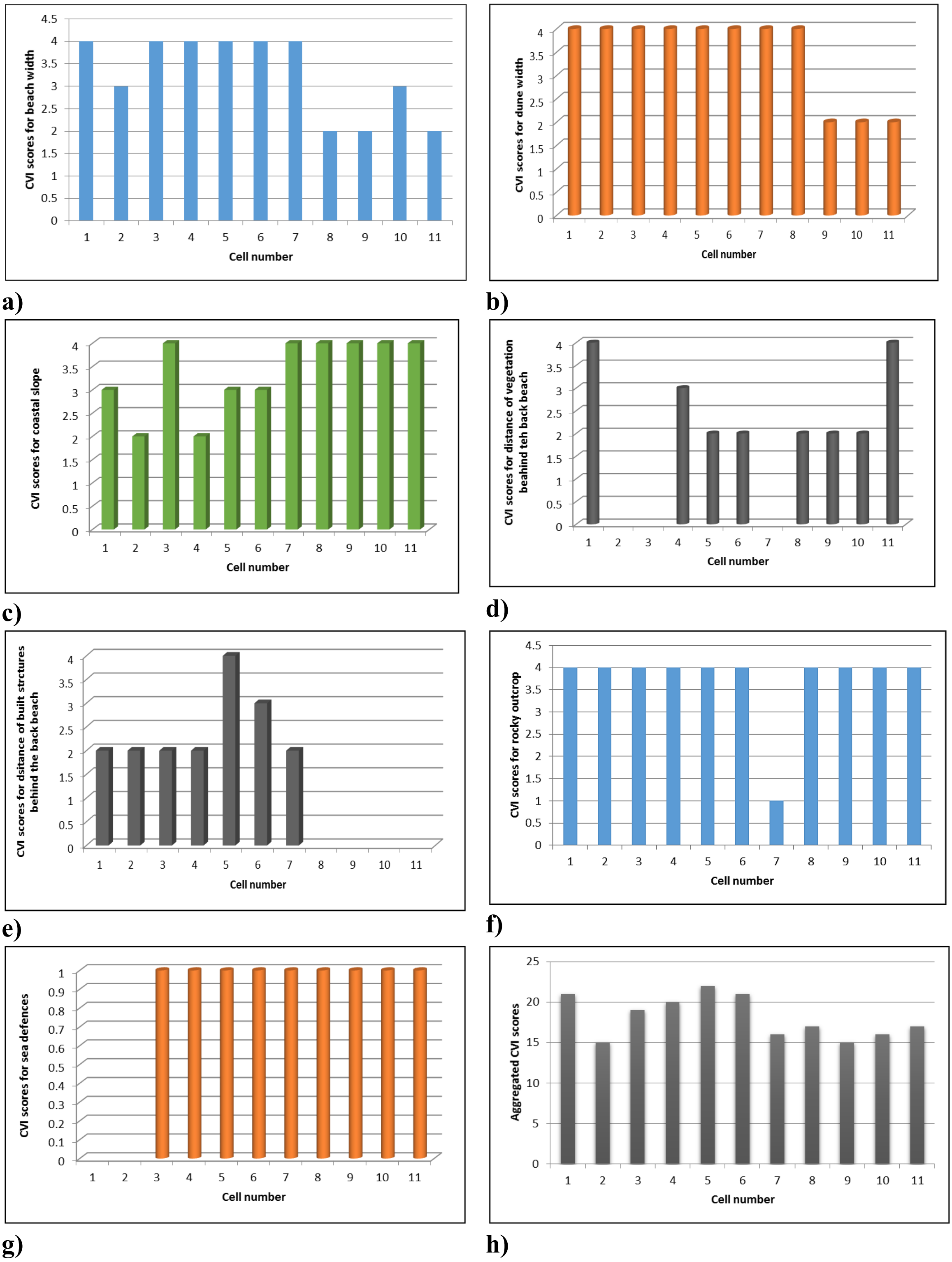


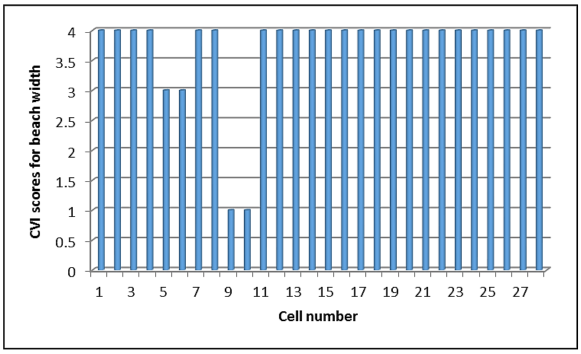
Figure 7.5: Distribution of CVI scores for Dawlish

7.7 Great Yarmouth

Beach width ranged from 590 m to 1.4 m (section 6.7) and 54% of cells were allocated high scores (4) (Figure 7.6a). Dunes were only recorded in 42% of the cells, and these were allocated scores between 1 and 4, all remaining cells given a score of 4 (Figure 7.6b). With the exception of cell 4 the coastal slope was <4% and as a consequence, almost all cells were allocated a score of 4 (Figure 7.6c). The measured distance of vegetation behind the back beach varied considerably and ranged between 500 m and 10 m. Consequently, cells were allocated scores between 4 and 2 (Figure 7.6d). There was also a considerable variance in the distance of built structures behind the back beach with allocated scores ranging between 4 and 2 (Figure 7.6e). Unsurprisingly, there was no rocky outcrop and almost no sea defences and because of shoreline protection given by both parameters scores of 4 were allocated throughout (Figures 7.6f and 7.6g respectively). Figure 7.6h shows the aggregated scores in one representation, the overall average score was 24, the maximum-recorded score of 28 and minimum of 19.

7.8 Skegness

A relatively wide beach ranged from 326 m to 128 m (section 6.8) and as a consequence most cells were allocated scores of either 1 or 2 (Figure 7.7a). Dunes were only recorded in approximately 50% of the cells and allocated scores that ranged between 2 and 4 (Figure 7.7b). The coastal maximum coastal slope was <4% and all cells were allocated scores of 4 (Figure 7.7c). The distances of vegetation behind the back beach, range between 390 m and 6 m. Consequently, scores were allocated between 2 and 4 (Figure 7.7d). Built structures behind the back beach also varied with allocated scores ranging between 2 and 4 (Figure 7.7e). Unsurprisingly, only one cell recorded rocky outcrop and two cells recorded sea defences because of the absence of shoreline protection, both parameters were allocated scores of 4 throughout (Figures 7.7f and 7.7g respectively). Figure 7.7h shows the aggregated scores in one representation, the overall average score was 22, the maximum-recorded score of 24 and minimum of 13.



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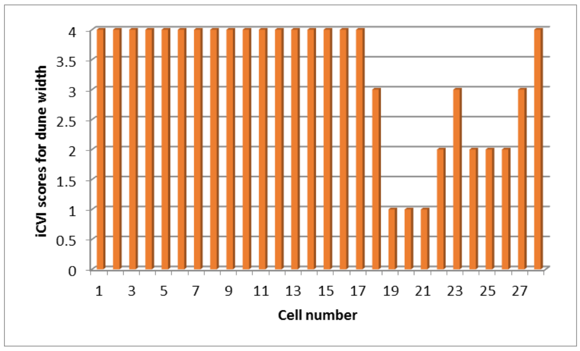

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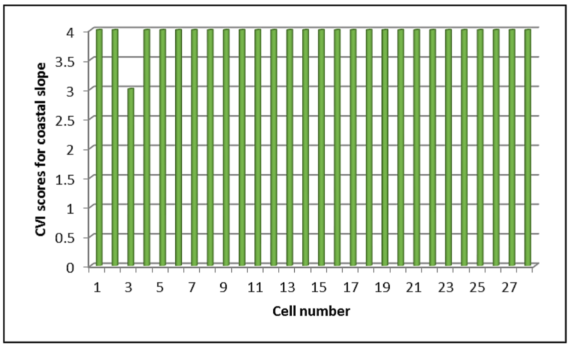

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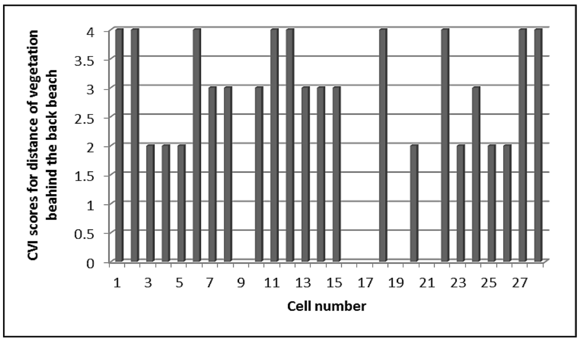

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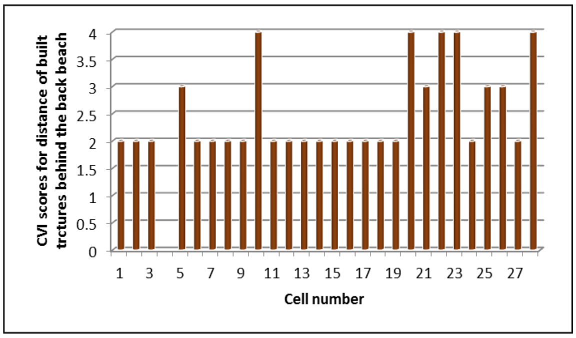

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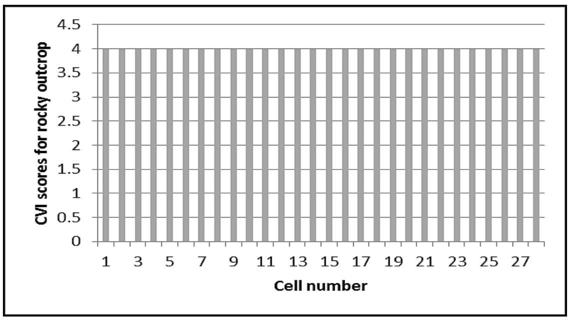

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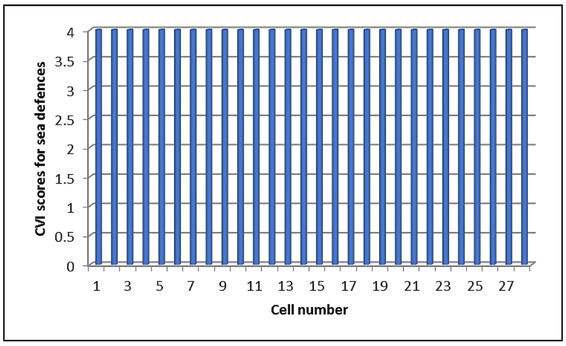

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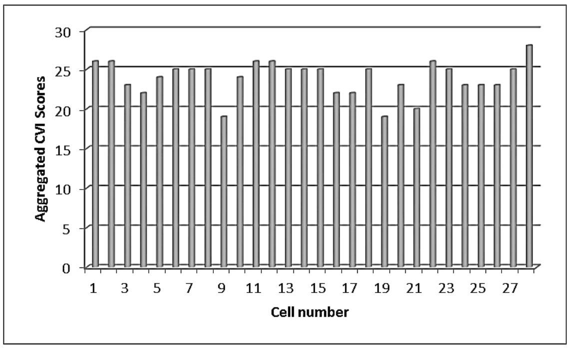


h)

Figure 7.6: Distribution of CVI scores for Great Yarmouth

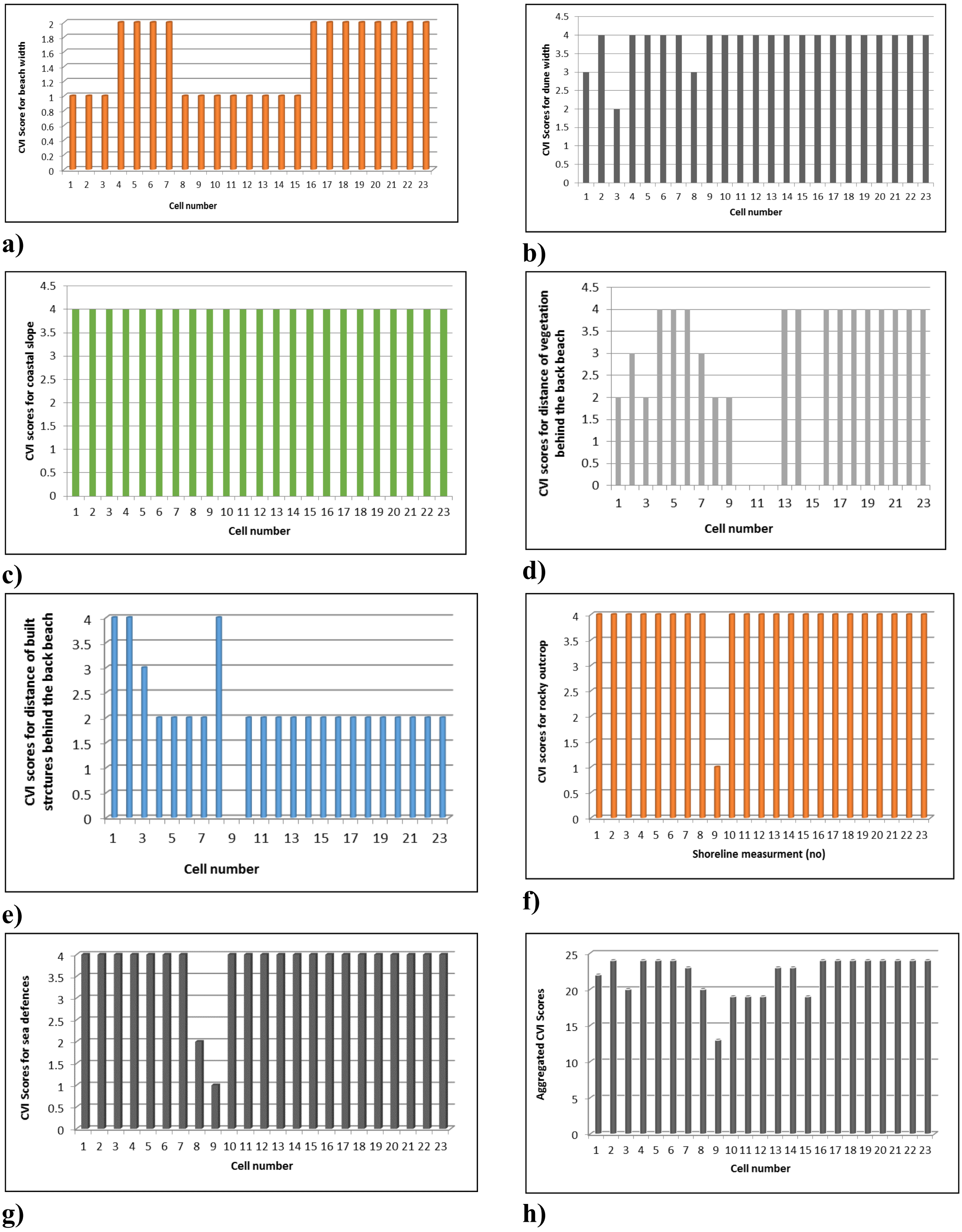


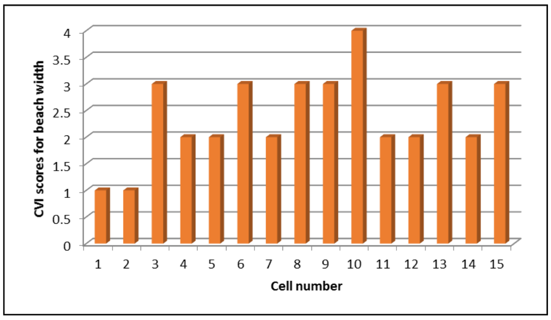
Figure 7.7: Distribution of CVI scores for Skegness

7.9 Benbecula

A varied beach width between 255 m and 37 m, resulted in scores of 2 to 4 being allocated (Figure 7.8a). Dunes were only recorded in 20% of the cells and allocated between 1 and 3, all remaining cells were allocated scores of 4 (Figure 7.8b). The coastal slope was <4% along the entire shoreline therefore, a score of 4 was allocated throughout (Figure 7.8c). Even though there was a considerable variation in the measured distance of vegetation behind the back beach, the allocated scores only ranged between 2 and 3 (Figure 7.8d). The measured distances of built structures behind the back beach was generally < 600 m and allocated scores ranged between 4 and 2, (Figure 7.8e). Rocky outcrops were recorded in less than 50% of the cells and all were given a score of 1, the remaining cells were allocated scores of 4 throughout (Figure 7.8f). There were no sea defences recorded and similar to previous were allocated scores of 4 throughout (Figures 7.8g). Figure 7.8h shows the aggregated scores in one representation, the overall average score was 22, the maximum recorded score of 24 and minimum of 18.

7.10 Aberystwyth

Beach width ranged from 168 m to 63 m and 80 % of cells were allocated a score of 3 (Figure 7.9a). No dunes were recorded and all cells were allocated a score of 4 (Figure 7.9b). The coastal slope values ranged between 14.7% and 0.2% and allocated scores between 1 and 4 (Figure 7.9c). The considerable variation in measured distances of vegetation behind the back beach resulted in scores that ranged between 2 and 3 (Figure 7.9d). The close proximity of built structures behind the back beach resulted in scores ranging between 2 and 4 (Figure 7.9e and Figure 7.9f). The shoreline protection given by both Rocky outcrops and sea defences, resulted in a low score being allocated throughout (Figures 7.9g). Figure 7.9h shows the aggregated scores in one representation, the overall average score was 17, the maximum-recorded score of 22 and minimum of twelve.



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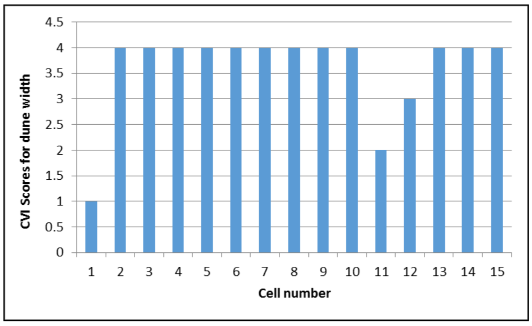

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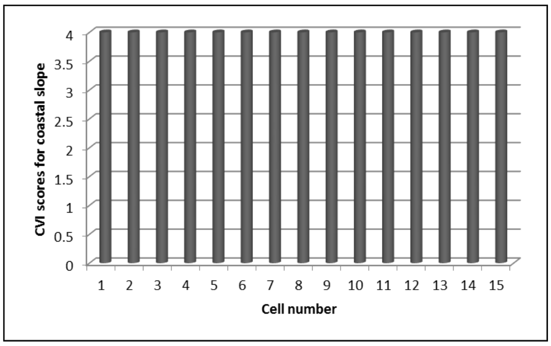

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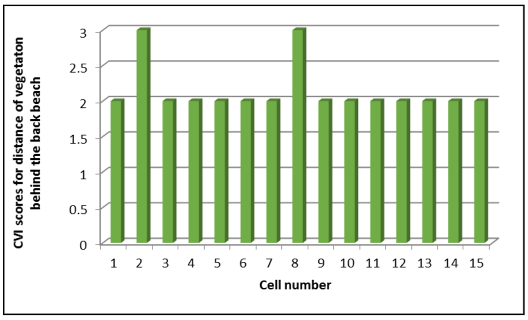

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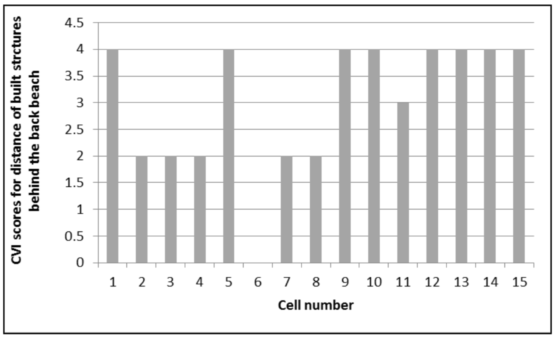

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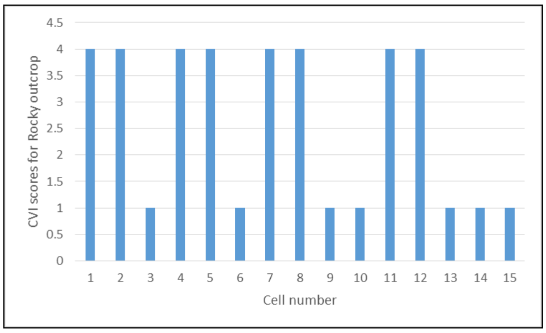

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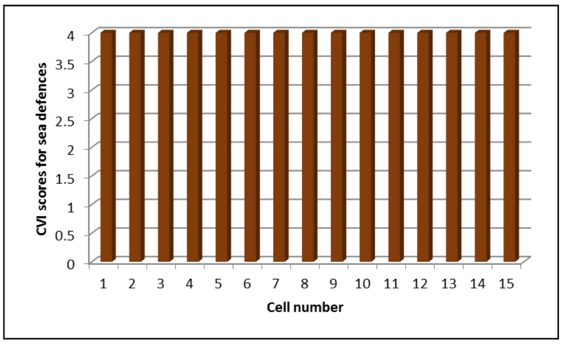

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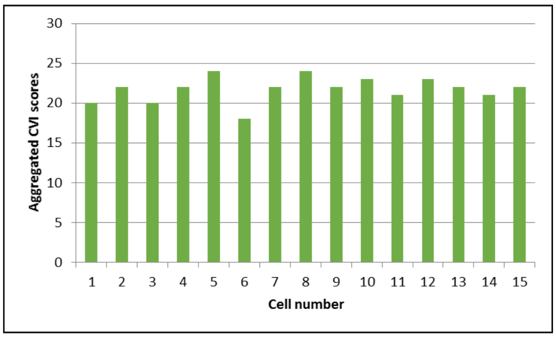
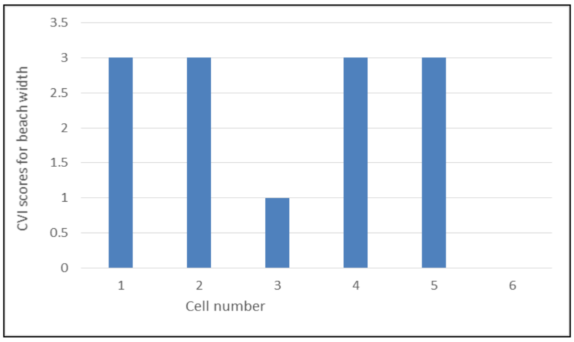


h)

Figure 7.8 Distribution of CVI scores for Benbecula



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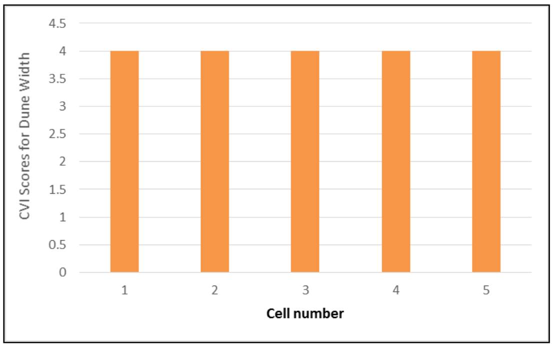

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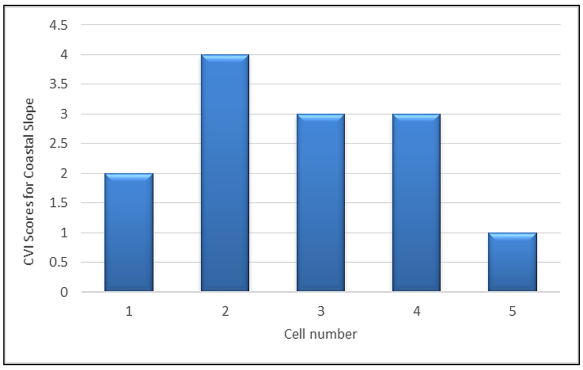

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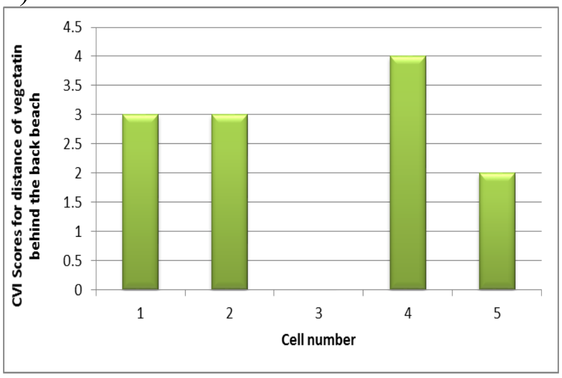

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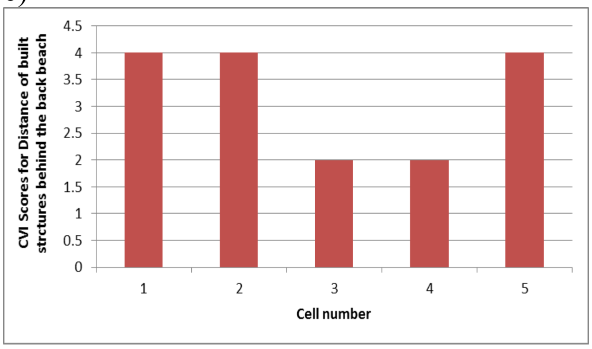

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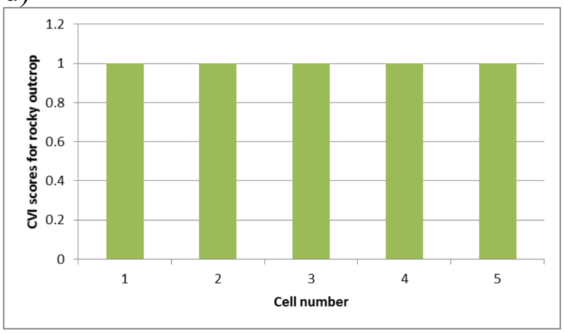

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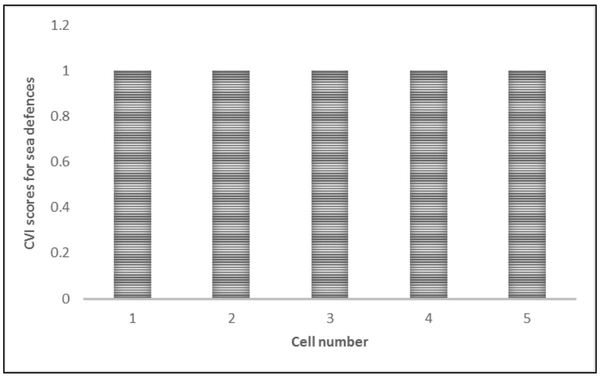

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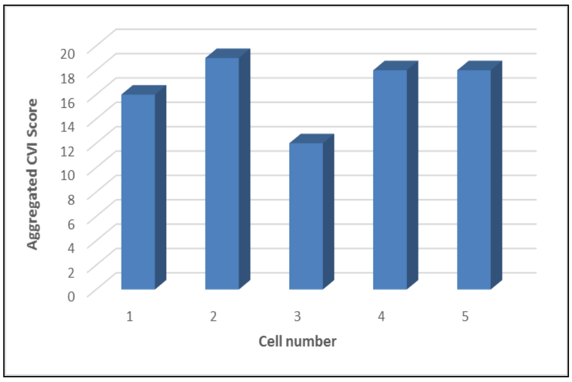


h)

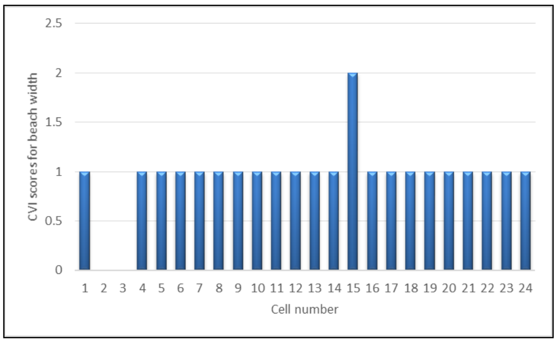
Figure 7.9: Distribution of CVI scores for Aberystwyth

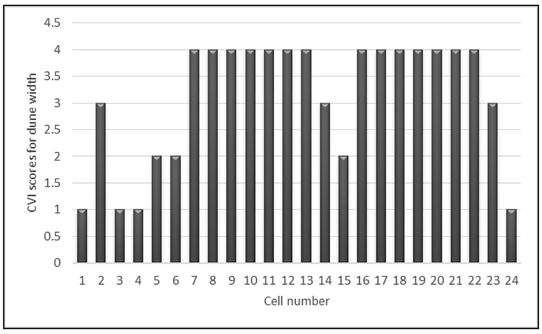
7.11. Port Talbot

Beach width ranged from 835 m to 100 m and 91 % of cells were allocated scores of 1 (Figure 7.10a). Dunes were recorded in less than half the cells, those that were measured were allocated scores between 1 and 3 and all remaining cells were given scores of 4 (Figure 7.10b). There was a considerable variation in coastal slope resulting in scores between 1 and 4 Figure 7.10c). The measured distance of vegetation behind the back beach, ranged between 500 m and 40 m and were allocated scores that ranged between 2 and 4 (Figure 7.10d). The scores allocated for built structures behind the back beach ranged between 2 and 4 (Figure 7.10e). Variable distribution of rock out crops resulted in score of between 2 and 4 being allocated throughout (Figure 7.10f). Fifty percent of the shoreline was protected by sea defence structures and allocated a low score of 1 and the remaining cells given scores of 4 (Figure 7.10g). Figure 7.10h shows the aggregated scores, the overall average score was 17, the maximum recorded score of 20 and minimum of ten.

7.12 Llanelli

Even though beach width ranged from 1900 m to 1 m, and 80% of cells were allocated extremely low scores (Figure 7.11a). Dunes were only recorded in one cell and all remaining cells were allocated a score of 4 (Figure 7.11b). There was a considerable variation in coastal slope values resulting in score of between 1 and 4 being allocated (Figure 7.11c). The measured distance of vegetation behind the back beach, ranged between 491 m and 102 m and this resulted in scores of between 2 and 3 being allocated (Figure 7.11d). The distances of built structures behind the back beach varied and were allocated scores between 2 and 4 (Figure 7.11e). Even though 61% of the cells recorded rocky outcrop, 90% cells were allocated scores of 4 (Figure 7.11f). Fifty percent of shoreline was protected by sea defence structures and given a score of 1, the remaining cells were given a score 0f 4 (Figure 7.11g). Figure 7.11h shows the aggregated scores in one representation; the overall average score was 18, the maximum-recorded score of 22 and minimum of 14.





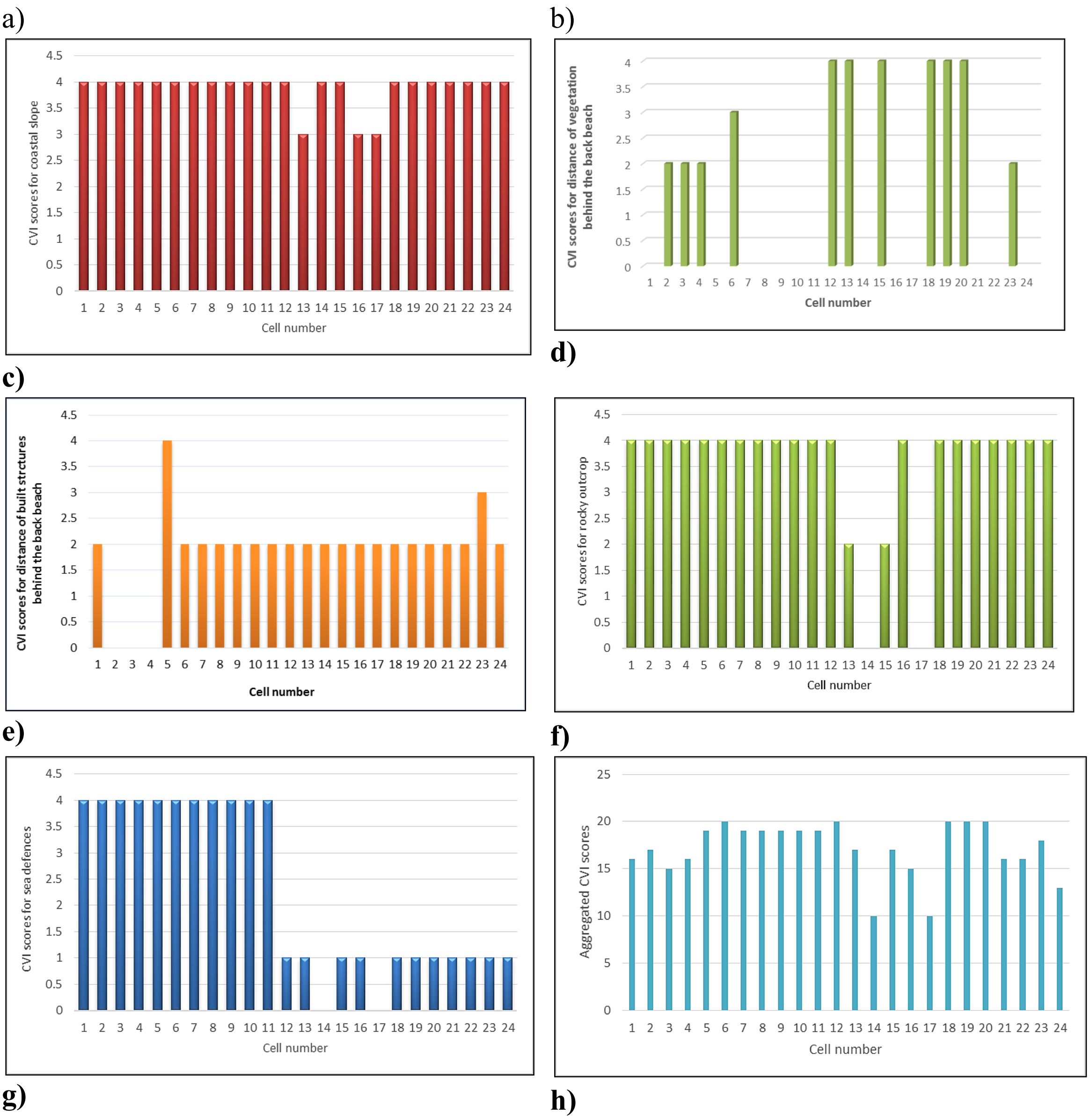
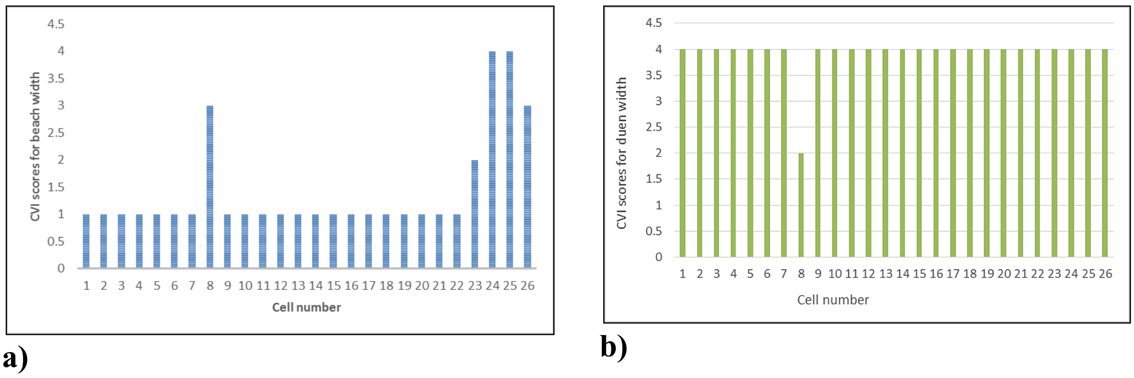
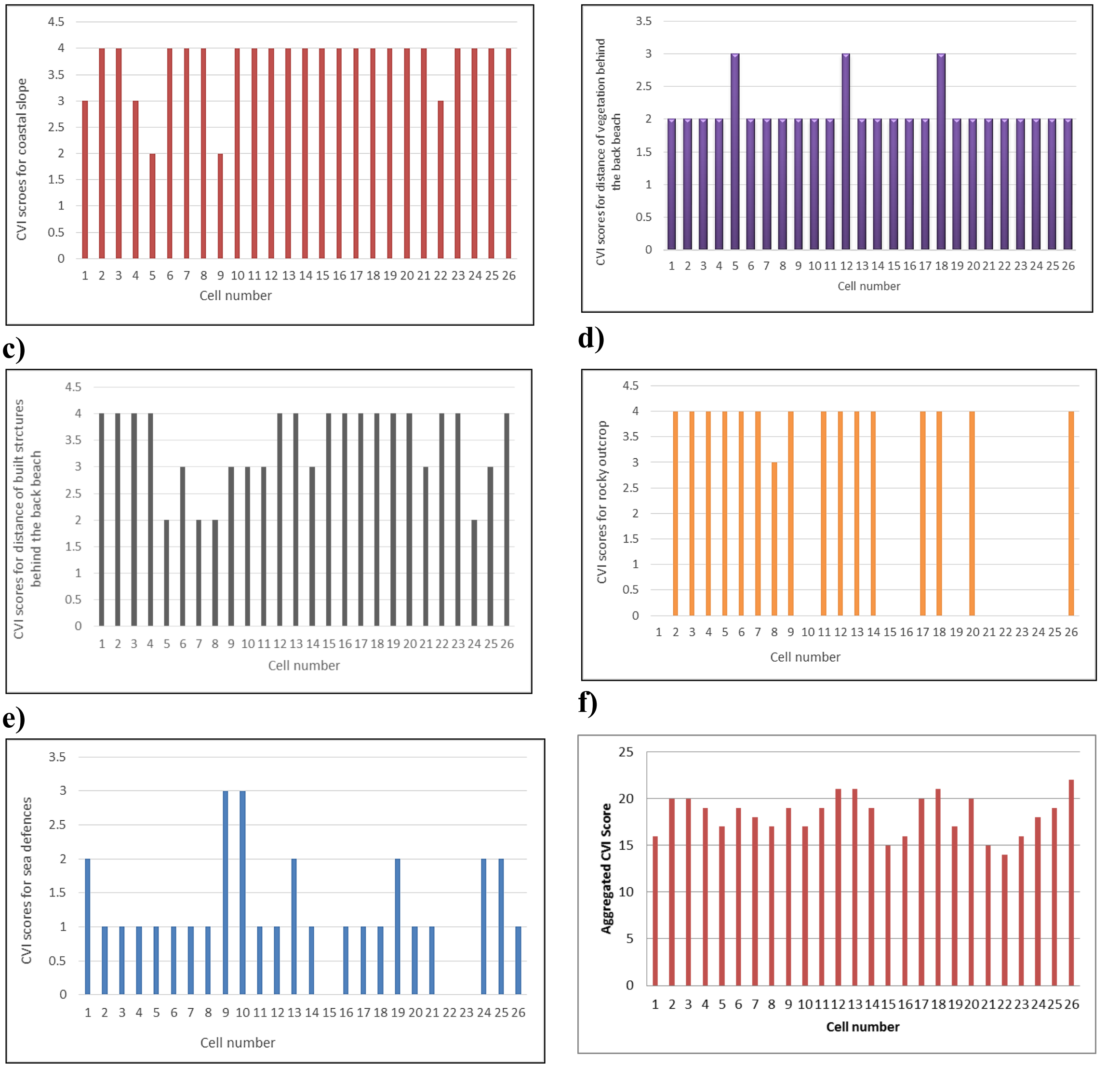


Figure 7.10 Distribution of CVI scores for Port Talbot





c) d) e) f) g) h)

Figure 7.11: Distribution of CVI scores for Llanelli

7.13. Overall descriptive analysis

The 11 selected coastal areas were critically analysed from a physical perspective by applying the CVI index. Results suggest that the English case study locations were more vulnerable than those in Wales and Scotland, and this is because of high industrial growth, population and the lack of natural and man-made shoreline protection measures. Some coastal cells have few or no dunes (Lynmouth, Llanelli) and others little or no rocky outcrops (Lynmouth and Spurn Head). For these reasons, most shoreline measurements were at the lower end of the scale and fell between low and moderate and relatively few cells were classified as being high in the terms of relative vulnerability. However, cumulative CVI scores of each region are relatively high.

7.14 CVI Analysis for individual parameters

a) Beach width

The average CVI score for beach width was 2.3, and the highest was four recorded at 48 cells (30%). Most of the highest values recorded at Llanelli (Wales), Hallsands Village, Happisburgh Dawlish, Great Yarmouth (England) and Benbecula (Scotland). The lowest score was one and 64 cells recorded this value. CVI scores for beach width parameter clearly indicated that England is high vulnerability than the Wales and Scotland (Figure 7.12a).

b) Dune width

A considerable variance exists between the dune width CVI values for 158 shoreline cells. The average CVI score was 3.5, and the highest score was 4 recorded at 124 cells (78%). Those that scored highly were found at Spurn Head, Hallsands, Dawlish, Happisburgh Great Yarmouth, Skegness (England) and Benbecula. The dune width CVI scores indicated that, English sites are more physically vulnerable than those in Scotland and Wales (Figure 7.12b).

c) Coastal slope

The average CVI score was 3.6 and the highest score was recorded at 129 (81%) cells. Most of the high values were again recorded at Llanelli and Port Talbot (Wales), Happisburgh, Dawlish, Great Yarmouth and Skegness (England) and Benbecula (Scotland), while the minimum was recorded at Aberystwyth (Wales) and Hallsands and Lynmouth (England). CVI scores for coastal slope reflect high vulnerability throughout the survey area with some site-specific variations (Figure 7.12c).

d) Distance of vegetation behind the back beach

A considerable variance exists between the CVI values for distance of vegetation behind the back beach. The average CVI score was 2.7 and the highest was 4, recorded at 38 (24%) cells. Most of the highest values recorded at Port Talbot (Wales), Great Yarmouth and Skegness (England). Lowest CVI value was one, recorded at Llanelli, Hallsands (England) and Benbecula (Scotland). Seventy-five cells (47%) scored lowest values. CVI scores for a distance of vegetation behind the back beach explicitly specified that England and Wales have the highest vulnerability in the subject of vegetation (Figure 7.12d).

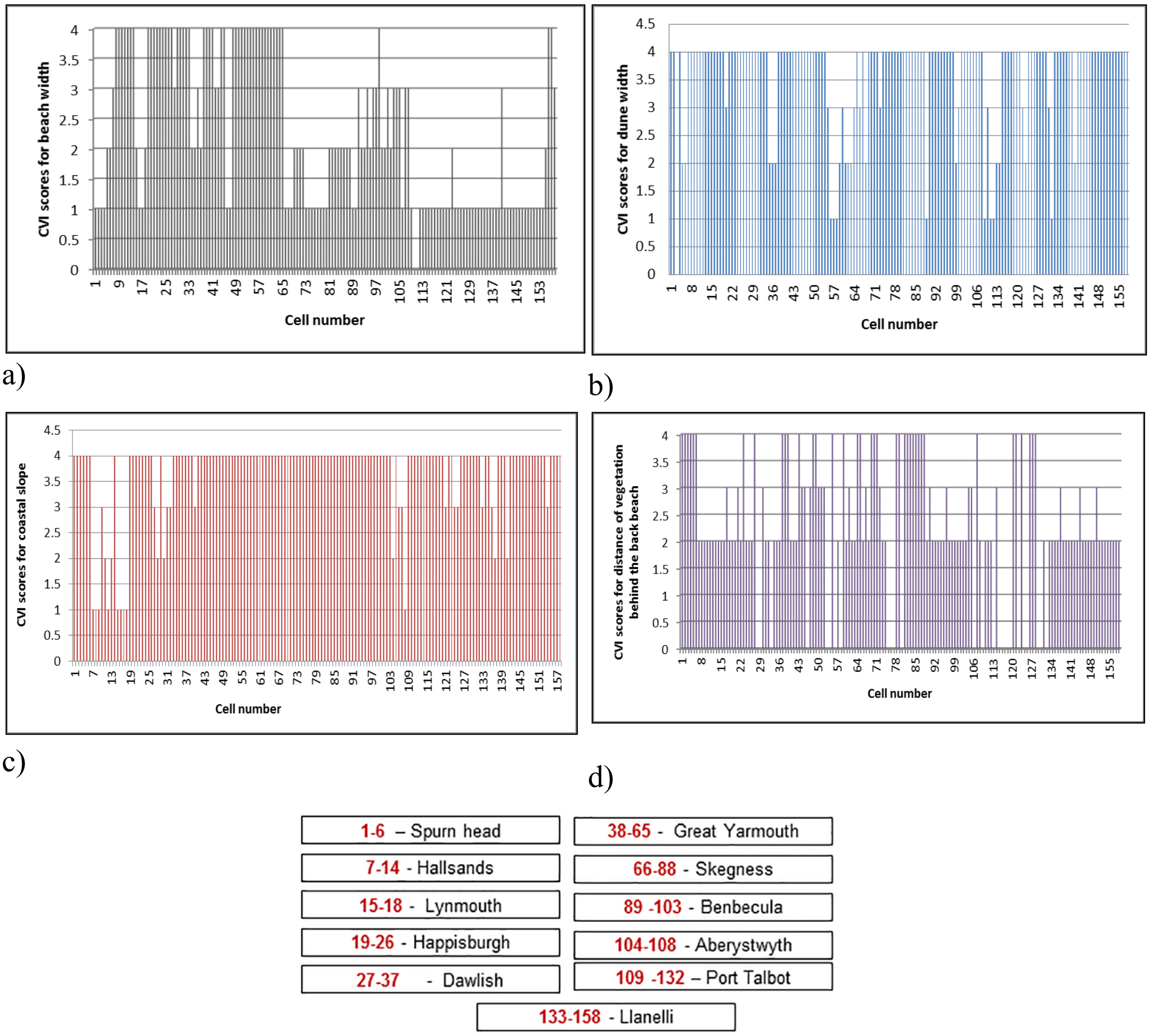


Figure 7.12: Distribution of overall CVI scores

e) Distance of built structures behind the back beach

The average CVI score for the distance of built structures behind the back beach was 2.8 and the highest CVI score was 4, recorded at 48 (30%) cells. The highest values were recorded at Aberystwyth, Llanelli (Wales), Hallsands, Happisburgh (England) and Benbecula (Scotland). The lowest score was 2, recorded at 74 (46%) (Skegness), and 15 cells did not record built structures (Figure 7.13a).

f) Rocky outcrop

A considerable variance exists between the rocky outcrop CVI values for 158 shoreline cells. The average CVI score for rocky outcrop was 3.6, and the highest CVI score was four, recorded at 124 (78%) cells. Most of the highest values were recorded at Llanelli (Wales), Great Yarmouth, Skegness, Dawlish, and Benbecula. Of the sites surveyed, CVI scores for rocky outcrop suggest that English locations require more coastal protection procedures (Figure 7.13b) than Wales and Scotland.

g) Sea defences

The average CVI score for sea defences was 3.5 and highest CVI score was 4, recorded at 84 (59%) cells. Highest values were recorded at Port Talbot (Wales), Great Yarmouth, Skegness, Dawlish, Lynmouth, Spurn Head (England) and Benbecula (Scotland). Of the sites surveyed, CVI scores for sea defences highlight that vulnerability at English sites need for more coastal protection (figure 7.13c).

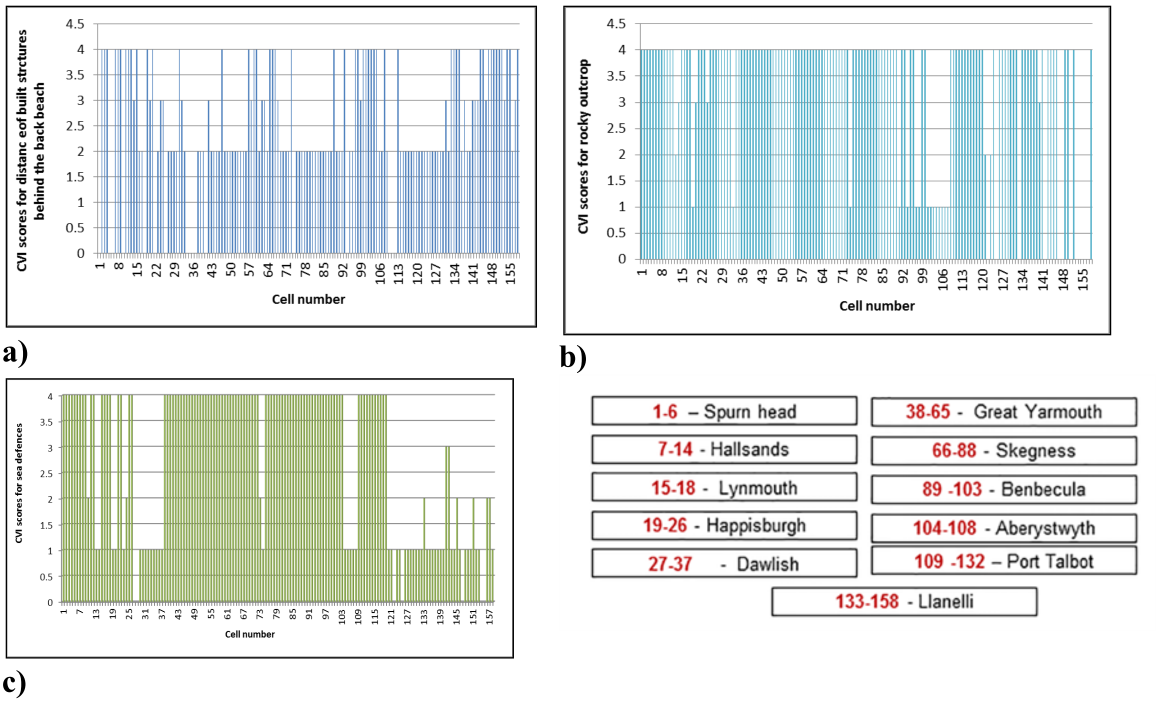


Figure 7.13: Distribution of overall CVI scores

7.15 Overall CVI scores

Figure 7.14 and 7.15 show a significant difference exists between the 158 cells in respect of CVI values. The average value was 20.33, a figure located in the high category. However, the maximum CVI value (28) was recorded at Great Yarmouth, while the lowest (10) was recorded at Lynmouth. More than 22% (n=35) of cells were rated with extremely high vulnerability (24-28), and 52% of cells of high vulnerable (19-23). In addition, 17% of cells were found to be moderately vulnerable (16-18), but overall CVI scores clearly indicated that physical vulnerability for selected areas in the UK have either extremely high or high vulnerability.

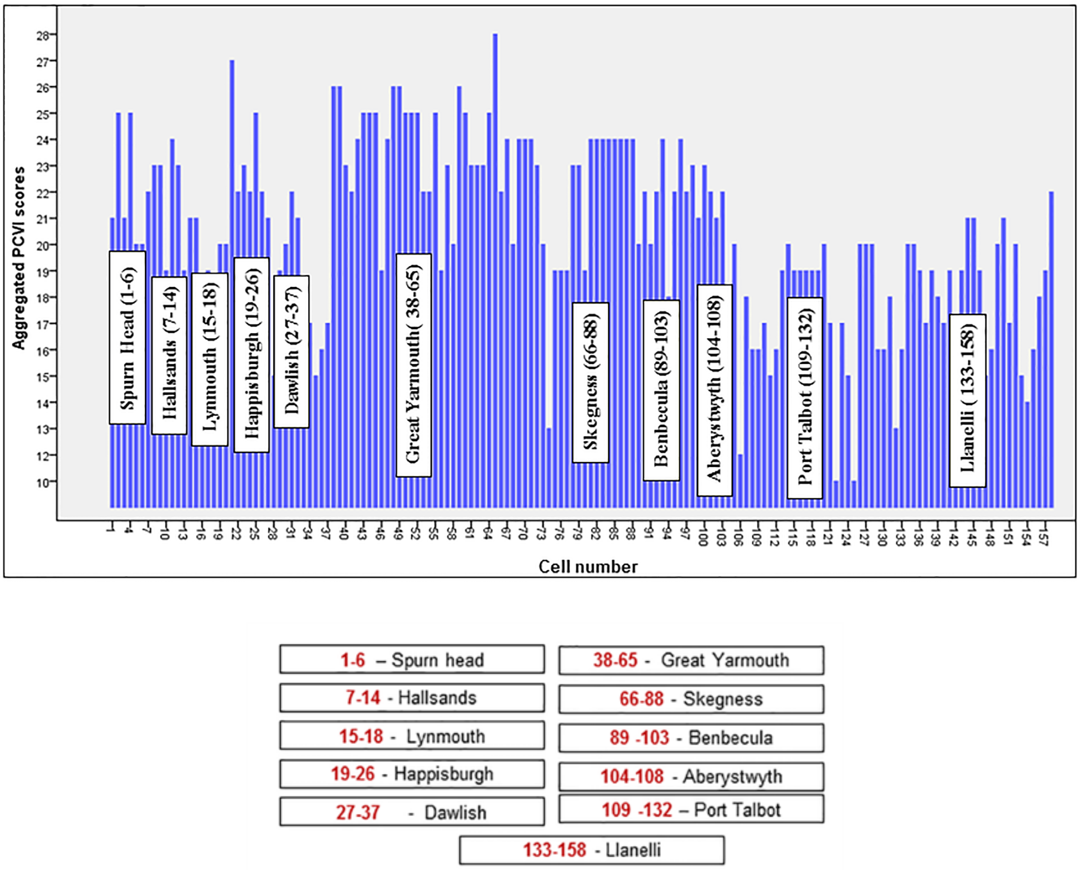


Figure 7.14: Cumulative CVI scores

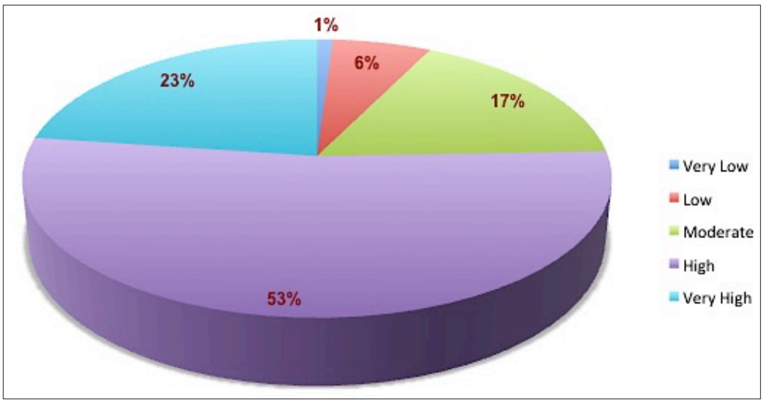


Figure 7.15: Distribution of aggregated CVI scores and ranking

7.16 Cumulative Physical Vulnerability

After PCVI development, these scores were aggregated to rank the eleven coastal vulnerability zones to identify the severity of coastal vulnerability (Table 7.1) (Figure 7.16). Great Yarmouth was found to be the most vulnerable with average CVI score of 24, while, Aberystwyth and Port Talbot were found to be the least vulnerable. Crucially, these cumulative scores provide the opportunity to consider management options where physical vulnerability is highlighted. It should also focus efforts for future research on a wider scale at such sites.

Table 7.1 PCVI scores and site ranking

Location	CVI Score	Number of Cells	Average CVI Score
Great Yarmouth	670	28	24
Happisburgh	181	8	23
Skegness	508	23	22
Spurn Head	132	6	22
Hallsands	174	8	22
Benbecula	326	15	22
Lynmouth	75	4	19
Llanelli	475	26	18
Dawlish	199	11	18
Port Talbot	410	24	17
Aberystwyth	84	5	17

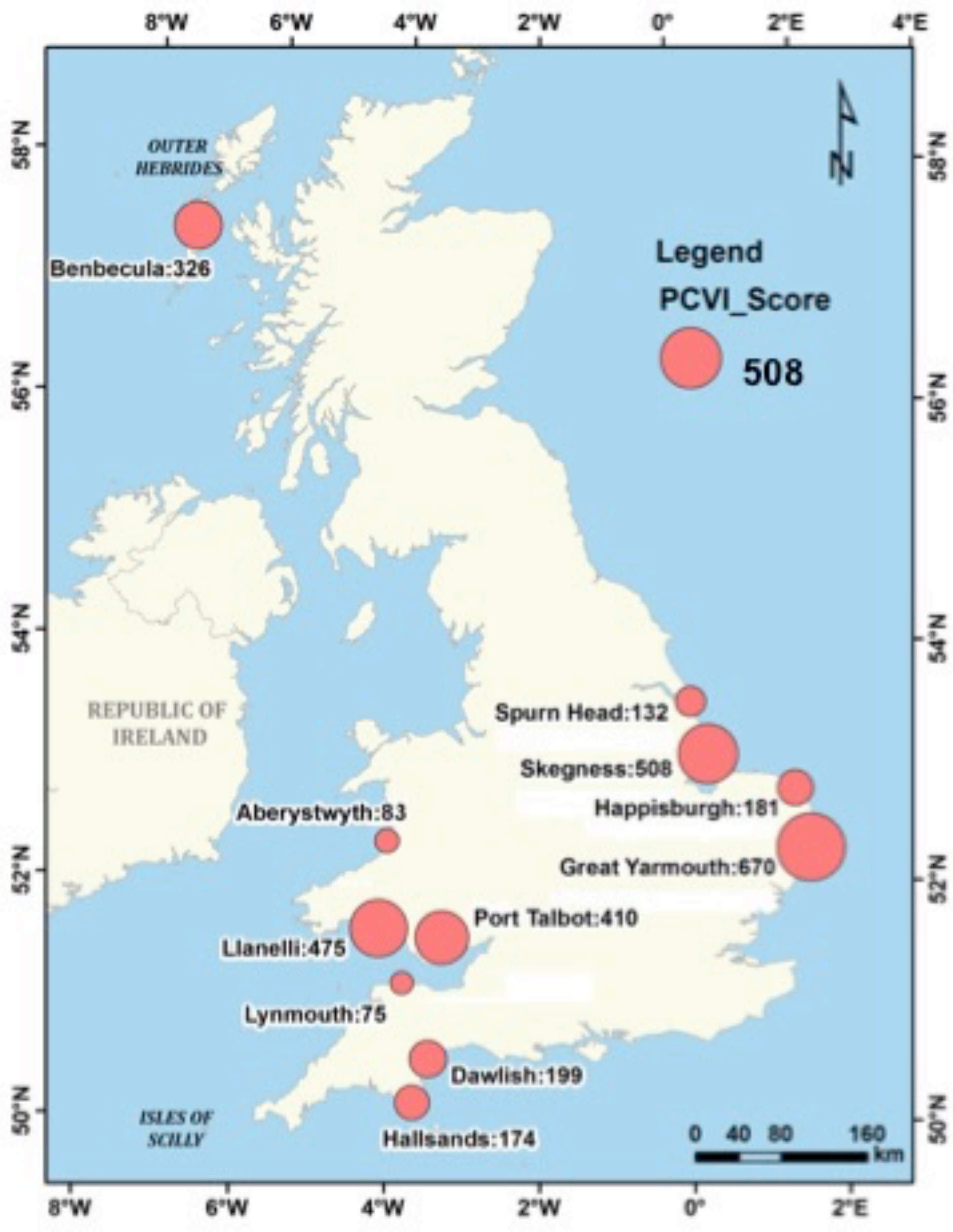


Figure 7.16: PCVI map

7.17. Summary

This chapter has focused on the CVI analysis and development of seven individual physical parameters for the eleven selected sites. From this point, it is now necessary to consider the economic coastal vulnerability index for these study sites using and applying the six economic parameters (Section 5.6).

CHAPTER 8 – ECVI

8. Economic Coastal Vulnerability Index (ECVI)

8.1 Introduction

Following completion of the physical coastal vulnerability index (PCVI) analyses in Chapter 7, this Chapter will start focusing on the development of the Economic Coastal Vulnerability Index (ECVI) and its consequences. Analysis of the six economic parameters, justified for identifying economic vulnerability (Section 4.5, Table 4.2, Section 5.5), will enable a simple numerical model to be developed to rank coastline sections in terms of their change potential. Therefore, the resulting ECVI will support managers in the development of sound economic coastal management policies and procedures designed to improve resilience under various scenarios of climate change and sea level rise, by focusing on areas with relatively high economic vulnerability.

8.2. Population and properties

As presented in Section 4.4, chosen coastal locations were each subdivided into 1 km cells along the shoreline frontage. In total 80 cells along 80 km of coastline were identified (Table 8.1). Three locations in Wales representing *circa* 26 km of coastline (26 cells), seven in England representing 49 km (49 cells) and one area in Scotland *circa* 5 km (5 cells) were chosen alongside the physical CVI. Figures 8.1 – 8.11 show yellow lines that represent the cells from which measurements were taken, red horizontal lines indicate the approximate shore alignment and red vertical arrows represent boundaries of each 1 km coastal cell. While the boundaries of the 1 km coastal cells were determined according to geographical area and economic importance.

Table 8.1: Total transect line and 1 km coastal cells

Site	Shoreline length (km)	No. of 1 km Cells	Population (No)	Commercial Properties (No)	Residential properties (No)
Spurn Head	2	2	50	7 +2	
Hallsands	4	4	>50	6	57
Lynmouth	2	2	490	106	179
Happisburgh	4	4	1372	64	423
Dawlish	6	6	13161	680	7899
Great Yarmouth	13	13	97277	6169	42079
Skegness	18	18	19579	973	7342
Benbecula	5	5	861	132	647
Aberystwyth	2	2	15139	758	6591
Port Talbot	12	12	37276	25833	1829
Llanelli	12	12	35000	1672	7253

Spurn Head forms part of an extensive spit > 5 km long and as such, this rural environment only has 9 properties (commercial and residential) and just 50 inhabitants (Table 8.1). As a consequence, the studied section of coastline was 2.5 km long and therefore, 2 No. 1 km cells were chosen as representative of where commercial and residential properties were located, from which measurements were collected (Figure 8.1). Hallsands, a village located on the Devon coastline has 57 residential and 6 commercial properties. Most private dwellings can be described as holiday homes rather than permanent residencies. For safety reasons the local authority closed the village to tourists, leaving just a limited access footpath. Properties and valuable agricultural landed is threatened by coastal erosion and floods. The shoreline frontage is 4.5 km long and therefore, 4 cells were used for taking measurements (Figure 8.2). Lynmouth has a population of 490 with 179 residential and 106 commercial properties. The shoreline frontage is 2.3 km and 2 representative 1 km cells were used to take measurements (Figure 8.3). Happisburgh has 1372 habitants, 423 households and 64 commercial properties. Four 1 km cells represented the shoreline frontage of 4.5 km were used for data acquisition (Figure 8.4).

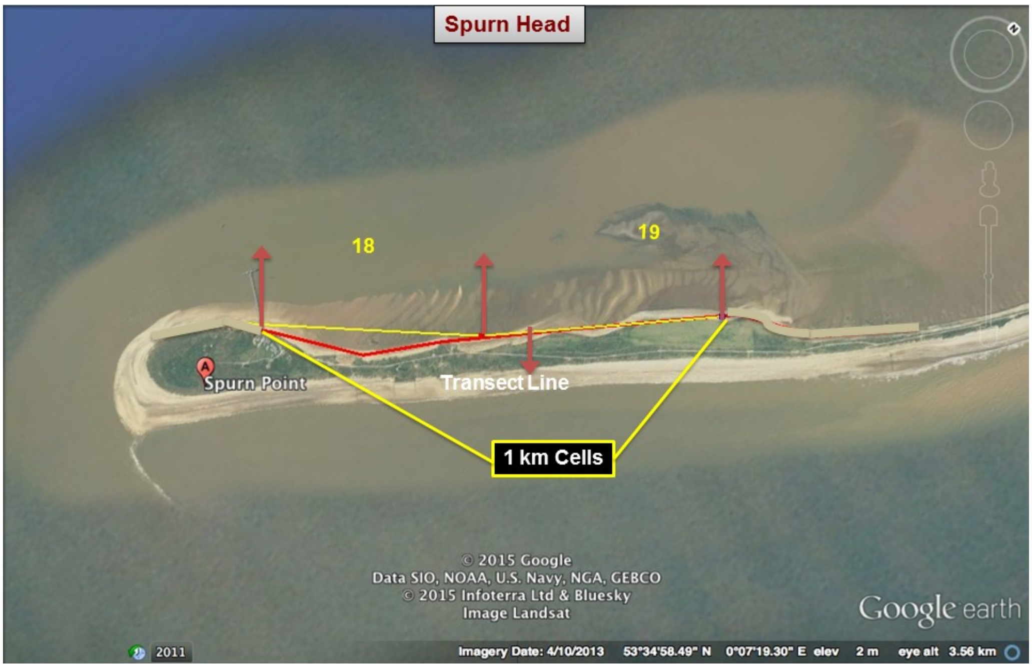


Figure 8.1: Transect line showing 1 km coastal cells: Spurn Head

Figure 8.2: Transect Line showing 1 km coastal cells: Hallsands

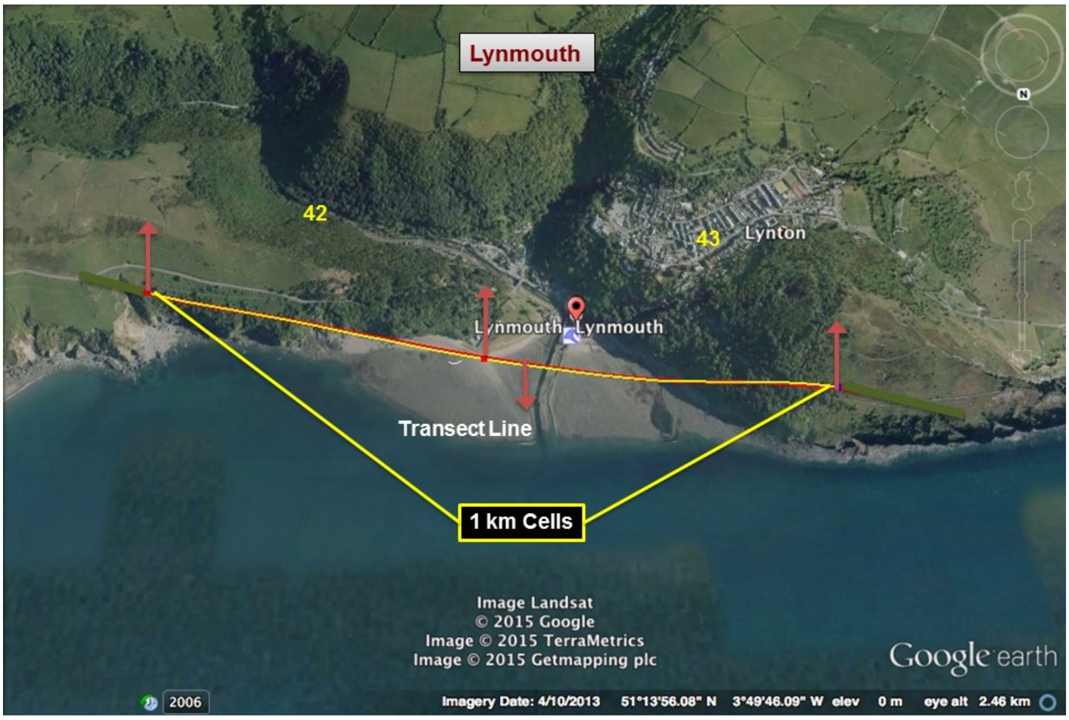


Figure 8.3: Transect line showing 1 km coastal cells: Lynmouth

Figure 8.4: Transect line showing 1 km coastal cells: Happisburgh

Dawlish has a population of 13161 with 7889 residential and 680 commercial properties. The shoreline frontage is *circa* 6 km and contains 6 cells from which measurements were taken (Figure 8.5). Great Yarmouth is situated at the mouth of the River Yare with a population exceeding 97000 along > 20 km of coastline. The regional economic prosperity relies on the port, light industry and tourism. There are 42079 residential and 6169 commercial properties along a shoreline frontage of approximately 15 km from which 13 cells were chosen for measurement (Figure 8.6). Skegness is predominantly a tourism destination, contributing significantly to the local, as well as national economy. There are currently > 19000 inhabitants, 973 commercial and 7342 residential properties. The shoreline frontage of 20 km was split into 19 cells from which measurements were taken (Figure 8.7). Benbecula, a low-lying island with a population is 861 has 647 homes and 132commercial properties located along a shoreline frontage of *circ*a 7.5 km. Five representative 1 km cells were chosen from which measurements were taken (Figure 8.8).

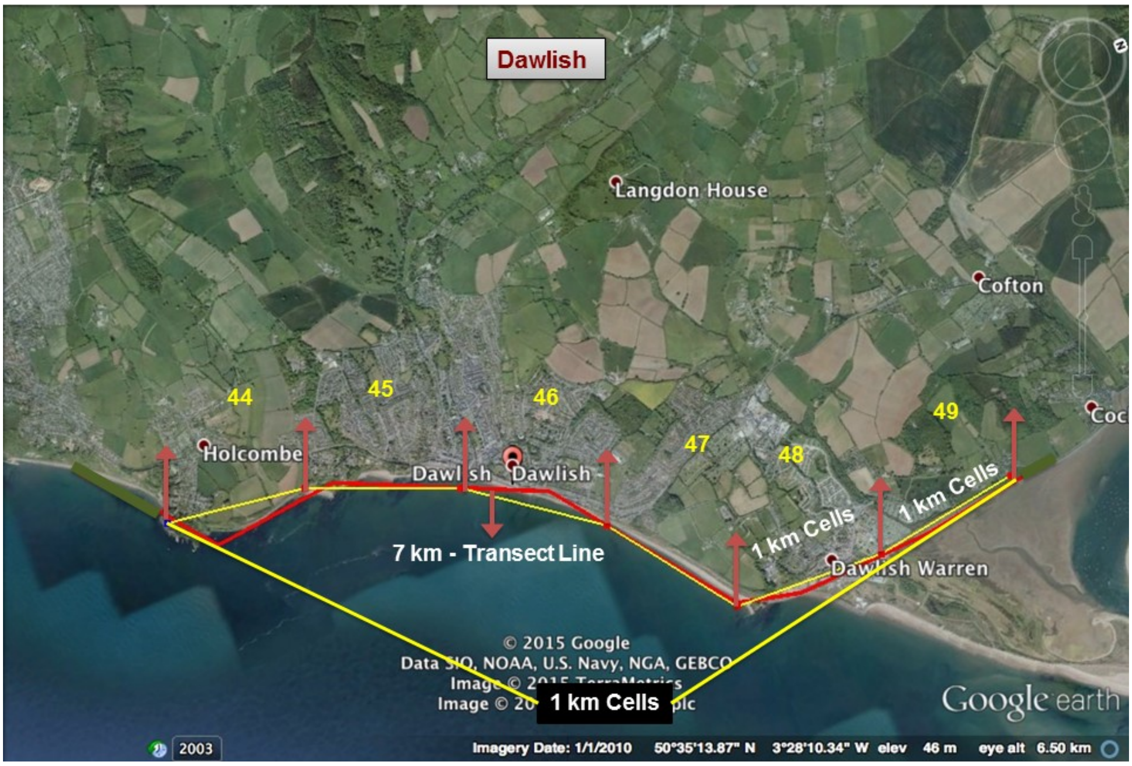


Figure 8.5: Transect line showing 1 km coastal cells: Dawlish

Figure 8.6: Transect line showing 1 km coastal cells: Great Yarmouth

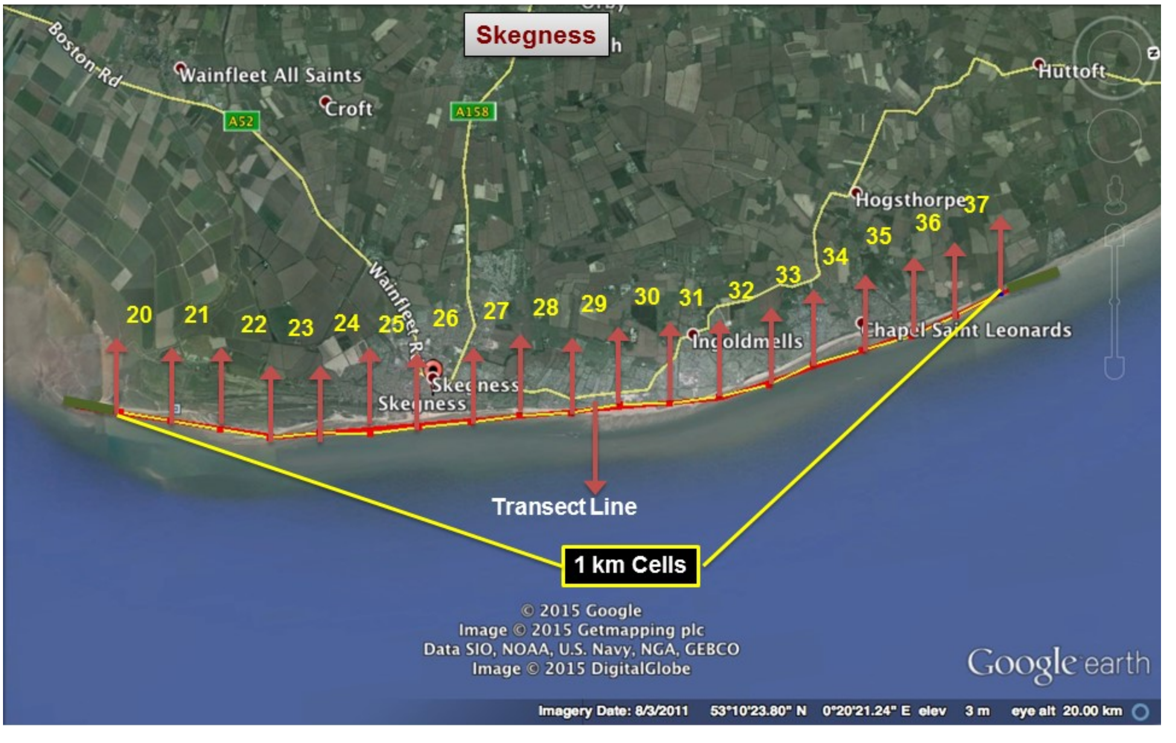


Figure 8.7: Transect line showing 1 km coastal cells: Skegness

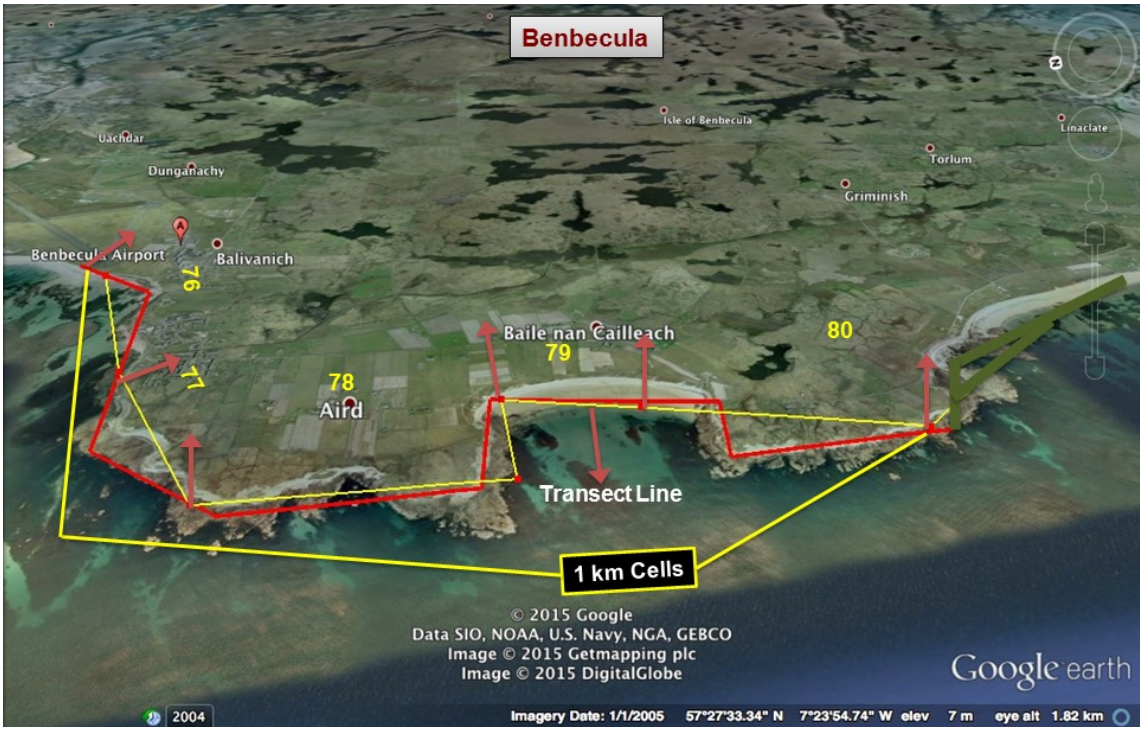


Figure 8.8: Transect line showing 1 km coastal cells: Benbecula

Aberystwyth has a population of 15139 with 758 commercial and 6591 residential properties. Two cells were used for data acquisition, as representative of a shoreline frontage of approximately 2.2 km (Figure 8.9)**.** Port Talbot has a shoreline frontage of *circa* 13 km and a population of 37276 and 12 cells were used to collect data. This includes > 25000 residential and > 1800 commercial properties (Figure 8.10). There are 7253 residential and 1672 commercial properties in Llanelli with a 35000 population. The shoreline frontage of approximately 15 km included 12 cells from which measurements were taken (Figure 8.11).

Figure 8.9: Transect line showing 1 km coastal cells: Aberystwyth

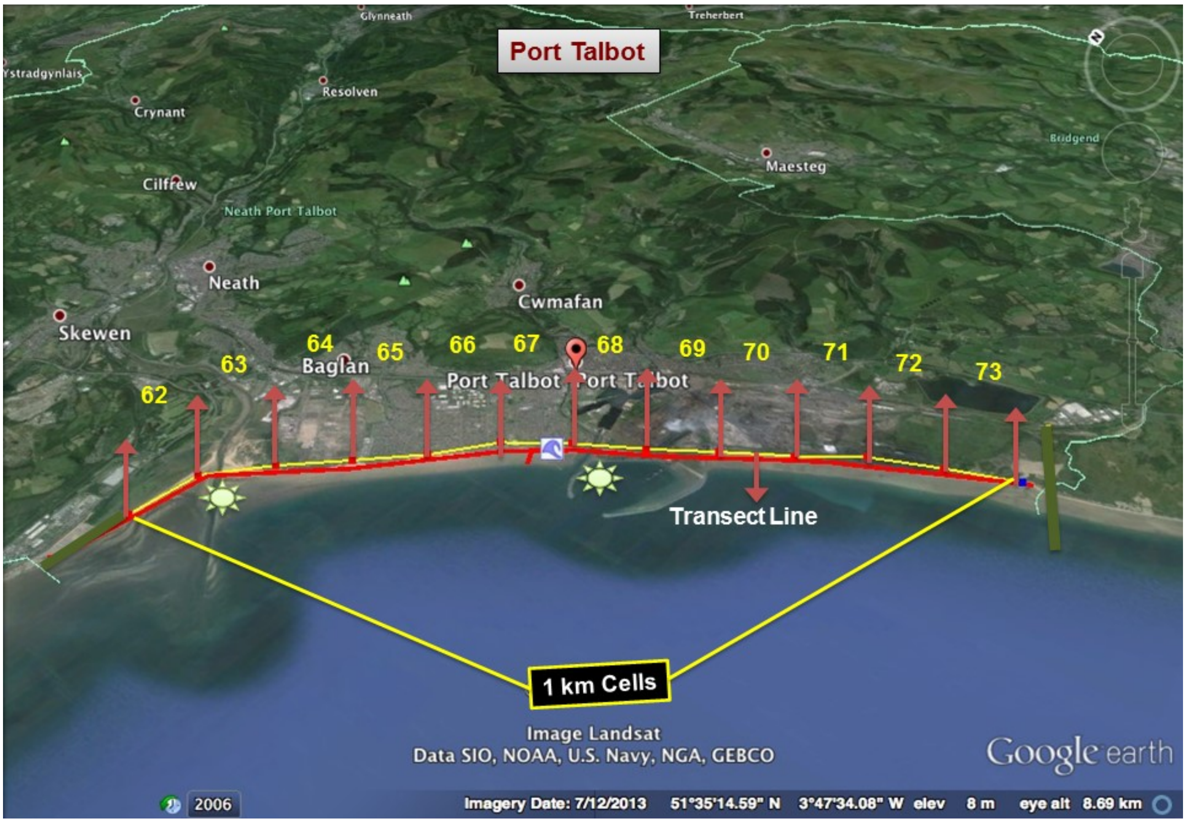


Figure 8.10: Transect line showing 1 km coastal cells: Port Talbot

Figure 8.11: Transect line showing 1 km coastal cells: Llanelli

8.3 Economic analysis

8.3.1 Commercial properties

Economic data was obtained from various government and insurance sources, as discussed in Section 4.5, with six representative parameters chosen (Table 4.2), and this was applied to information acquired from analysis of the 1 km coastal cells. Consequently, an average commercial property value was derived from the range of facilities surveyed with a maximum of £105M recorded in cell 8 at Great Yarmouth (Figure 8.6), to a minimum of £0.02M in cell 73 at Port Talbot (Figure 8.10). An average commercial value of £15.5M was determined and 27% of cells had higher than the average value, meaning 70% of cells were lower with two cells (38 and 80) not having commercial properties (Figure 8.12 and Table 8.2).

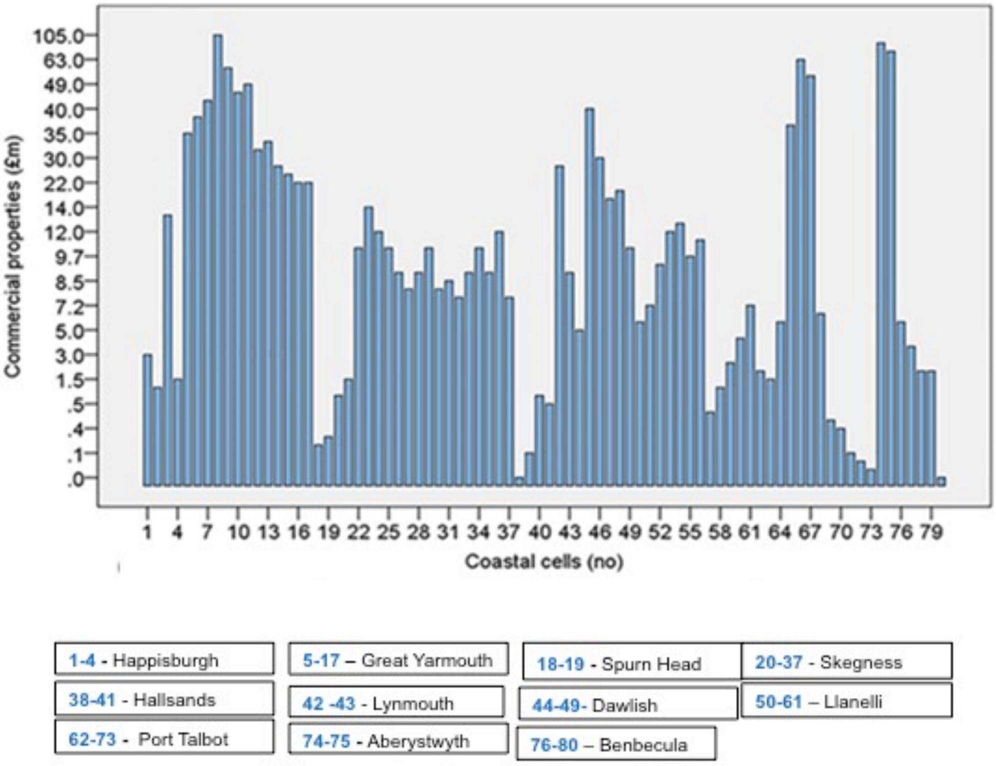


Figure 8.12: Commercial properties (£M-£B)

Table 8.2: Economic Value: Commercial Properties

Coastal Cell	Coastal Area	Commercial Properties (£ Million)	Coastal Cell	Coastal Area	Commercial Properties (£Million)
1	Happisburgh	3	41	Hallsands	0.5
2	Happisburgh	1.2	42	Lynmouth	28
3	Happisburgh	13.5	43	Lynmouth	9
4	Happisburgh	1.5	44	Dawlish	5
5	Great Yarmouth	35	45	Dawlish	40
6	Great Yarmouth	38	46	Dawlish	30
7	Great Yarmouth	42	47	Dawlish	16
8	Great Yarmouth	105	48	Dawlish	18
9	Great Yarmouth	55	49	Dawlish	10
10	Great Yarmouth	45	50	Llanelli	6
11	Great Yarmouth	49	51	Llanelli	7.2
12	Great Yarmouth	31	52	Llanelli	9.6
13	Great Yarmouth	33	53	Llanelli	12
14	Great Yarmouth	28	54	Llanelli	13.2
15	Great Yarmouth	26	55	Llanelli	9.7
16	Great Yarmouth	22	56	Llanelli	10.8
17	Great Yarmouth	22	57	Llanelli	0.48
18	Spurn Head	0.2	58	Llanelli	1.2
19	Spurn Head	0.25	59	Llanelli	2.4
20	Skegness	1	60	Llanelli	4.8
21	Skegness	1.5	61	Llanelli	7.2
22	Skegness	10	62	Port Talbot	2
23	Skegness	14	63	Port Talbot	1.5
24	Skegness	12	64	Port Talbot	6
25	Skegness	10	65	Port Talbot	36
26	Skegness	9	66	Port Talbot	63
27	Skegness	8	67	Port Talbot	51
28	Skegness	9	68	Port Talbot	7
29	Skegness	10	69	Port Talbot	0.4
30	Skegness	8	70	Port Talbot	0.35
31	Skegness	8.5	71	Port Talbot	0.1
32	Skegness	7.5	72	Port Talbot	0.04
33	Skegness	9	73	Port Talbot	0.02
34	Skegness	10	74	Aberystwyth	66
35	Skegness	9	75	Aberystwyth	42
36	Skegness	12	76	Benbecula	6
37	Skegness	7.5	77	Benbecula	4
38	Hallsands	0.0	78	Benbecula	2
39	Hallsands	0.1	79	Benbecula	2
40	Hallsands	1	80	Benbecula	0

8.3.2 Residential properties

The average value of residential properties within the 80 cells is £135M, with a maximum of £780M in cell 66 (Port Talbot) and a minimum of £0.02M in cells 18 and 19 (Spurn Head; Figure 8.13 and Table 8.3). Twenty-six percent and 67% of cells recorded higher and lower values than the average respectively, while three cells (71-73 inclusive) did not include residential properties (Figure 8.13 and Table 8.3).

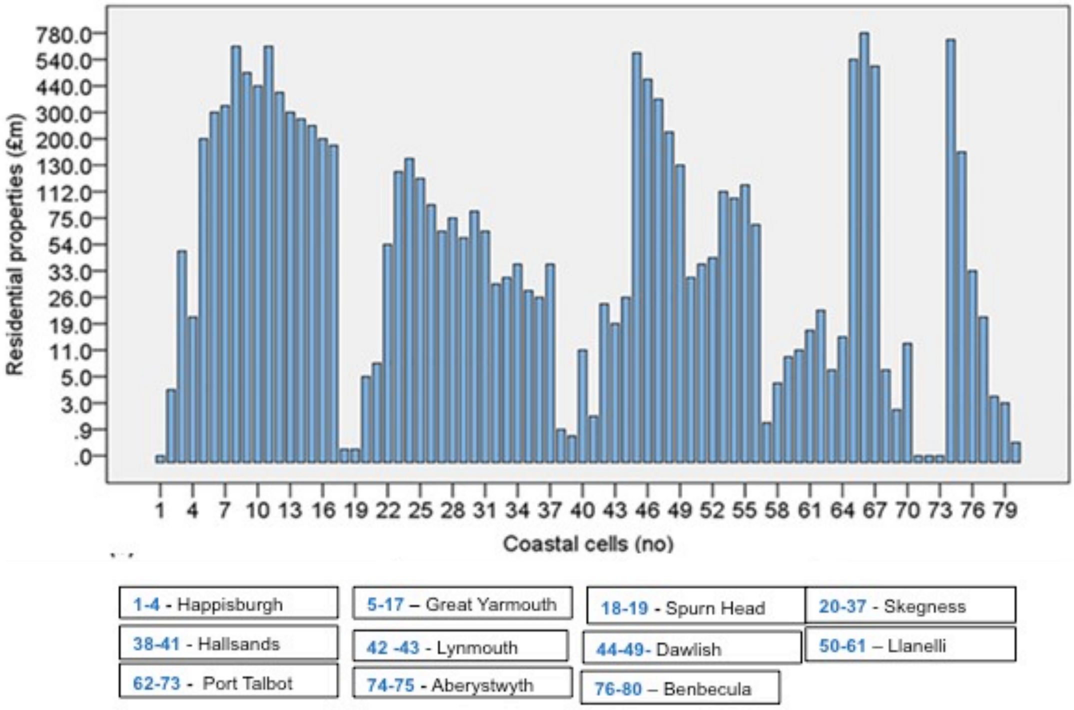


Figure 8.13: Residential properties (£M-£B)

Table 8.3 Economic Value: Residential Properties

Coastal Cell	Site Area	Residential Properties (in £Million)	Coastal Cell	Site Area	Residential Properties (in £Million)
1	Happisburgh	8	41	Hallsands	2
2	Happisburgh	4	42	Lynmouth	25
3	Happisburgh	50	43	Lynmouth	19
4	Happisburgh	20	44	Dawlish	26
5	Great Yarmouth	200	45	Dawlish	598
6	Great Yarmouth	300	46	Dawlish	468
7	Great Yarmouth	320	47	Dawlish	390
8	Great Yarmouth	600	48	Dawlish	208
9	Great Yarmouth	500	49	Dawlish	130
10	Great Yarmouth	440	50	Llanelli	32
11	Great Yarmouth	600	51	Llanelli	40
12	Great Yarmouth	400	52	Llanelli	48
13	Great Yarmouth	300	53	Llanelli	112
14	Great Yarmouth	240	54	Llanelli	104
15	Great Yarmouth	220	55	Llanelli	113
16	Great Yarmouth	200	56	Llanelli	72
17	Great Yarmouth	190	57	Llanelli	1.6
18	Spurn Head	0.2	58	Llanelli	4.8
19	Spurn Head	0.2	59	Llanelli	9.6
20	Skegness	5	60	Llanelli	11
21	Skegness	8	61	Llanelli	12.7
22	Skegness	54	62	Port Talbot	24
23	Skegness	121	63	Port Talbot	6
24	Skegness	135	64	Port Talbot	12
25	Skegness	120	65	Port Talbot	540
26	Skegness	94	66	Port Talbot	780
27	Skegness	67	67	Port Talbot	504
28	Skegness	75	68	Port Talbot	6
29	Skegness	63	69	Port Talbot	2.4
30	Skegness	81	70	Port Talbot	11.5
31	Skegness	67	71	Port Talbot	0
32	Skegness	27	72	Port Talbot	0
33	Skegness	32	73	Port Talbot	0
34	Skegness	40	74	Aberystwyth	594
35	Skegness	26.6	75	Aberystwyth	167
36	Skegness	26	76	Benbecula	33
37	Skegness	40	77	Benbecula	20
38	Hallsands	0.9	78	Benbecula	3.1
39	Hallsands	0.6	79	Benbecula	3
40	Hallsands	11	80	Benbecula	0.4

8.3.3 Economic value of site

The average economic value of all sites is approximately £103M from a total value of approximately £8.3B (Table 8.4). Assessments showed maximum site values of £1000M (£1B) occurred in cells 70 and 71 (Port Talbot) and a minimum value of £2M in cell 18 (Spurn Head) and therefore, it can be seen that approximately 30% and 70% of cells had higher and lower values than the mean respectively (Figure 8.14 and Table 8.4).

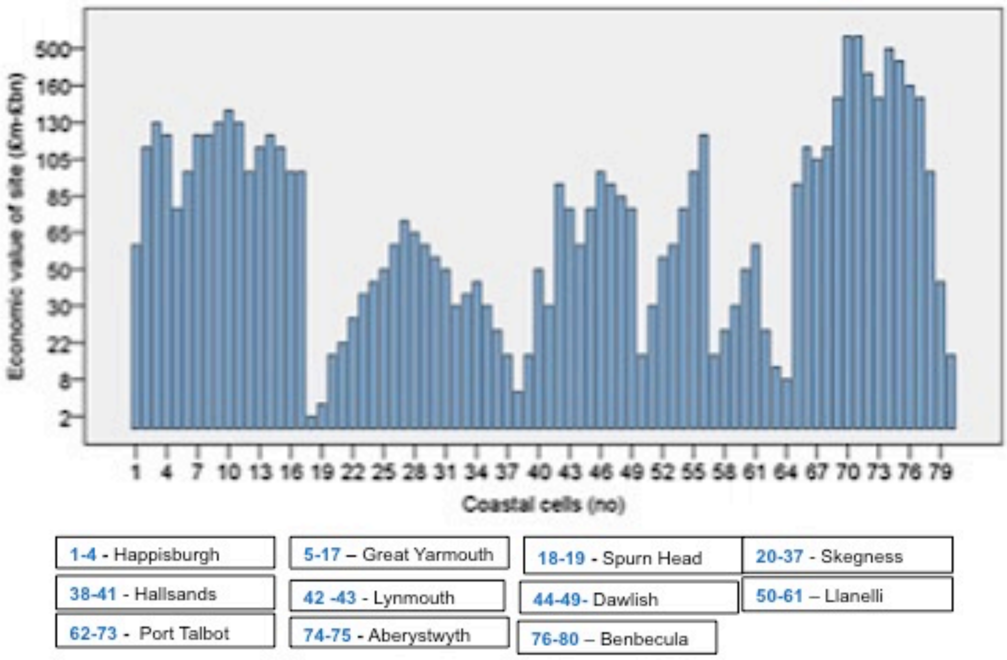


Figure 8.14: Economic value of site (£M-£B)

Table 8.4: Economic Value of Site

Coastal Cell	Coastal Site	Economic Value of Place (£Million)	Coastal Cell	Coastal Site	Economic Value of Place (£Million)
1	Happisburgh	60	**41**	Hallsands	30
2	Happisburgh	110	**42**	Lynmouth	90
3	Happisburgh	130	**43**	Lynmouth	80
4	Happisburgh	120	**44**	Dawlish	60
5	Great Yarmouth	80	**45**	Dawlish	80
6	Great Yarmouth	100	**46**	Dawlish	100
7	Great Yarmouth	120	**47**	Dawlish	90
8	Great Yarmouth	120	**48**	Dawlish	85
9	Great Yarmouth	130	**49**	Dawlish	80
10	Great Yarmouth	135	**50**	Llanelli	20
11	Great Yarmouth	130	**51**	Llanelli	30
12	Great Yarmouth	100	**52**	Llanelli	55
13	Great Yarmouth	110	**53**	Llanelli	60
14	Great Yarmouth	120	**54**	Llanelli	80
15	Great Yarmouth	110	**55**	Llanelli	100
16	Great Yarmouth	100	**56**	Llanelli	120
17	Great Yarmouth	100	**57**	Llanelli	20
18	Spurn Head	2	**58**	Llanelli	25
19	Spurn Head	3	**59**	Llanelli	30
20	Skegness	20	**60**	Llanelli	50
21	Skegness	22	**61**	Llanelli	60
22	Skegness	28	**62**	Port Talbot	25
23	Skegness	35	**63**	Port Talbot	15
24	Skegness	40	**64**	Port Talbot	8
25	Skegness	50	**65**	Port Talbot	90
26	Skegness	60	**66**	Port Talbot	110
27	Skegness	68	**67**	Port Talbot	105
28	Skegness	65	**68**	Port Talbot	110
29	Skegness	60	**69**	Port Talbot	150
30	Skegness	55	**70**	Port Talbot	1000
31	Skegness	50	**71**	Port Talbot	1000
32	Skegness	30	**72**	Port Talbot	200
33	Skegness	35	**73**	Port Talbot	150
34	Skegness	40	**74**	Aberystwyth	500
35	Skegness	30	**75**	Aberystwyth	300
36	Skegness	25	**76**	Benbecula	160
37	Skegness	20	**77**	Benbecula	150
38	Hallsands	5	**78**	Benbecula	100
39	Hallsands	20	**79**	Benbecula	40
40	Hallsands	50	**80**	Benbecula	20

8.3.4 Population

The average population in all cells was found to be approximately 1480 with a maximum of 10000 in cell 66 (Port Talbot) and minimum of 1 in cell 38 (Hallsands; Table 8.5). Sixty-seven percent of cells had lower than the average populations, while 30% recorded higher than average figures (Figure 8.15 and Table 8.5).

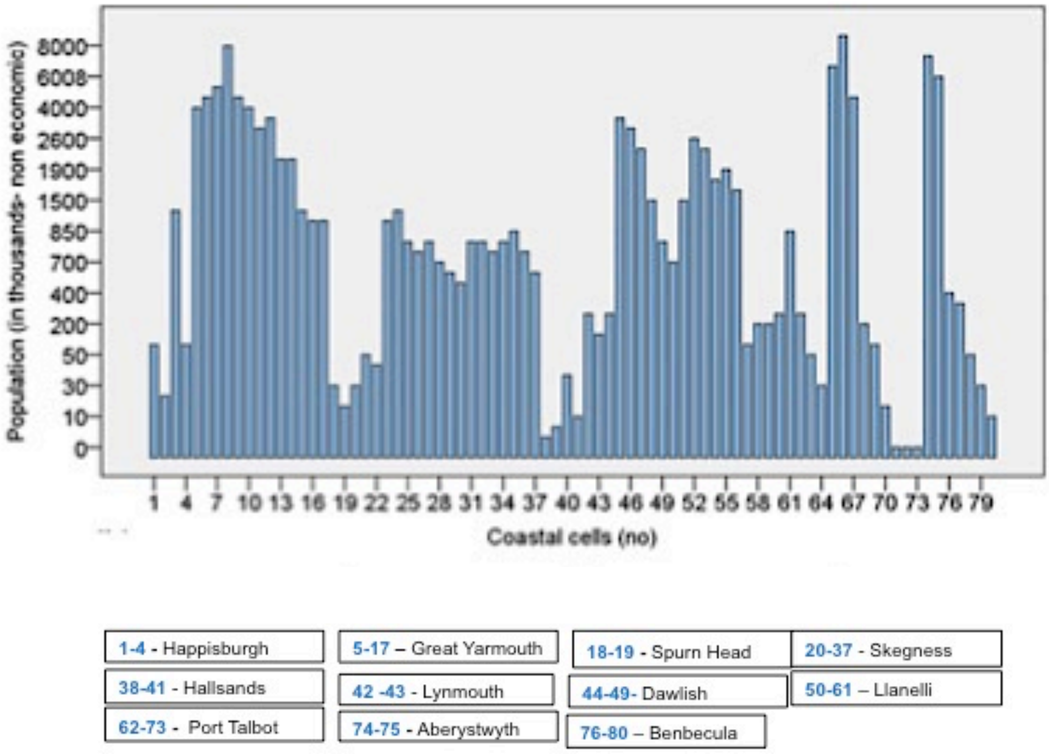


Figure 8.15: Population per coastal cell

Table 8.5: Population

Coastal Cell	Coastal Site	Population Numbers	Coastal Cell	Coastal Site	Population Numbers
1	Happisburgh	100	**41**	Hallsands	10
2	Happisburgh	27	**42**	Lynmouth	300
3	Happisburgh	1100	**43**	Lynmouth	190
4	Happisburgh	100	**44**	Dawlish	300
5	Great Yarmouth	4000	**45**	Dawlish	3500
6	Great Yarmouth	5000	**46**	Dawlish	3000
7	Great Yarmouth	6000	**47**	Dawlish	2200
8	Great Yarmouth	8000	**48**	Dawlish	1500
9	Great Yarmouth	5000	**49**	Dawlish	800
10	Great Yarmouth	4000	**50**	Llanelli	700
11	Great Yarmouth	3000	**51**	Llanelli	1500
12	Great Yarmouth	3500	**52**	Llanelli	2600
13	Great Yarmouth	2000	**53**	Llanelli	2200
14	Great Yarmouth	2000	**54**	Llanelli	1800
15	Great Yarmouth	1100	**55**	Llanelli	1900
16	Great Yarmouth	1000	**56**	Llanelli	1700
17	Great Yarmouth	1000	**57**	Llanelli	100
18	Spurn Head	30	**58**	Llanelli	200
19	Spurn Head	20	**59**	Llanelli	200
20	Skegness	30	**60**	Llanelli	300
21	Skegness	50	**61**	Llanelli	850
22	Skegness	40	**62**	Port Talbot	300
23	Skegness	1000	**63**	Port Talbot	50
24	Skegness	1100	**64**	Port Talbot	30
25	Skegness	800	**65**	Port Talbot	6700
26	Skegness	750	**66**	Port Talbot	10000
27	Skegness	800	**67**	Port Talbot	5000
28	Skegness	700	**68**	Port Talbot	200
29	Skegness	600	**69**	Port Talbot	100
30	Skegness	500	**70**	Port Talbot	20
31	Skegness	800	**71**	Port Talbot	0
32	Skegness	800	**72**	Port Talbot	0
33	Skegness	750	**73**	Port Talbot	0
34	Skegness	800	**74**	Aberystwyth	6600
35	Skegness	850	**75**	Aberystwyth	4000
36	Skegness	750	**76**	Benbecula	400
37	Skegness	600	**77**	Benbecula	350
38	Hallsands	1	**78**	Benbecula	50
39	Hallsands	4	**79**	Benbecula	30
40	Hallsands	36	**80**	Benbecula	10

8.3.5 Coastal erosion

The average cost of coastal erosion was £5.4M (Table 8.6) with a maximum of £20M in cells 2, 46, and 68 (Happisburgh, Dawlish and Port Talbot respectively) and minimum of 0.3M in cell 20 (Skegness). It can be seen that 62 % of cells had lower than average values, while 38% were higher (Figure 8.16 and Table 8.6), showing that coastal erosion would be an on-going economic challenge.

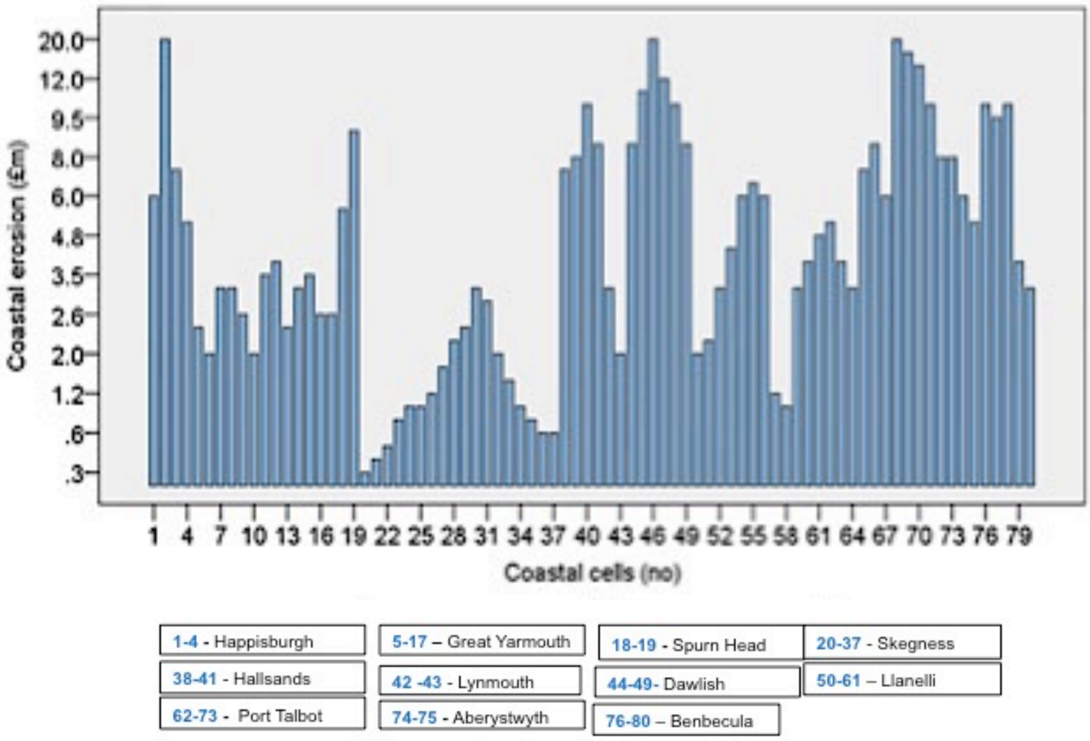


Figure 8.16: Coastal erosion (£M)

Table 8.6: Coastal erosion: economic cost

Coastal Cell	Coastal Site	Coastal Erosion (£Million)	Coastal Cell	Coastal Site	Coastal Erosion (£Million)
1	Happisburgh	6	41	Hallsands	9
2	Happisburgh	20	42	Lynmouth	3
3	Happisburgh	7	43	Lynmouth	2
4	Happisburgh	5	44	Dawlish	9
5	Great Yarmouth	2.5	45	Dawlish	11
6	Great Yarmouth	2	46	Dawlish	20
7	Great Yarmouth	3	47	Dawlish	12
8	Great Yarmouth	3	48	Dawlish	10
9	Great Yarmouth	2.6	49	Dawlish	9
10	Great Yarmouth	2	50	Llanelli	2
11	Great Yarmouth	3.5	51	Llanelli	2.2
12	Great Yarmouth	4	52	Llanelli	3
13	Great Yarmouth	2.5	53	Llanelli	4.5
14	Great Yarmouth	3	54	Llanelli	6
15	Great Yarmouth	3.5	55	Llanelli	6.5
16	Great Yarmouth	2.6	56	Llanelli	6
17	Great Yarmouth	2.6	57	Llanelli	1.2
18	Spurn Head	5.1	58	Llanelli	1
19	Spurn Head	9.1	59	Llanelli	3
20	Skegness	0.3	60	Llanelli	4
21	Skegness	0.4	61	Llanelli	4.8
22	Skegness	0.5	62	Port Talbot	5
23	Skegness	0.8	63	Port Talbot	4
24	Skegness	1	64	Port Talbot	3
25	Skegness	1	65	Port Talbot	7
26	Skegness	1.2	66	Port Talbot	9
27	Skegness	1.8	67	Port Talbot	6
28	Skegness	2.2	68	Port Talbot	20
29	Skegness	2.5	69	Port Talbot	18
30	Skegness	3	70	Port Talbot	15
31	Skegness	2.8	71	Port Talbot	10
32	Skegness	2	72	Port Talbot	8
33	Skegness	1.5	73	Port Talbot	8
34	Skegness	1	74	Aberystwyth	6
35	Skegness	0.8	75	Aberystwyth	5
36	Skegness	0.6	76	Benbecula	10
37	Skegness	0.6	77	Benbecula	9.5
38	Hallsands	7	78	Benbecula	10
39	Hallsands	8	79	Benbecula	4
40	Hallsands	10	80	Benbecula	3

8.3.6 Flood impact

Flooding costs were determined as approximately £1.6B across all 80 cells (Table 8.7), with an average flood impact of £20M ranging between a maximum of £40M in cells 8 and 14 (Great Yarmouth) and a minimum of £2M in cells 57, 64 and 80 (Llanelli, Port Talbot and Benbecula respectively). Therefore, 38% of cells recorded lower than the average and 62% more than the average flood impact values (Figure 8.17 and Table 8.7). Therefore, flooding can clearly be seen as an economic vulnerability.

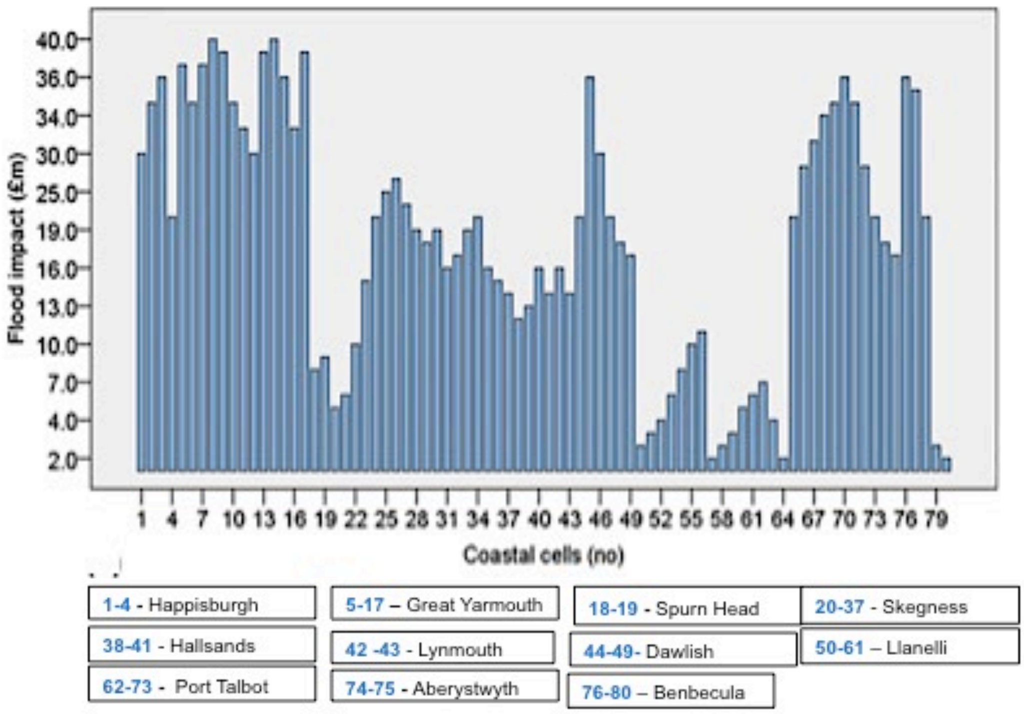


Figure 8.17: Flood Impact (£M- £B)

Table 8.7: Flood impact economic assessment

Coastal Cell	Coastal Site	Flood Impact (£Million)	Coastal Cell	Coastal Site	Flood Impact (£Million)
1	Happisburgh	30	**41**	Hallsands	14
2	Happisburgh	35	**42**	Lynmouth	16
3	Happisburgh	36	**43**	Lynmouth	14
4	Happisburgh	20	**44**	Dawlish	20
5	Great Yarmouth	37	**45**	Dawlish	36
6	Great Yarmouth	35	**46**	Dawlish	30
7	Great Yarmouth	37	**47**	Dawlish	20
8	Great Yarmouth	40	**48**	Dawlish	18
9	Great Yarmouth	38	**49**	Dawlish	17
10	Great Yarmouth	35	**50**	Llanelli	3
11	Great Yarmouth	32	**51**	Llanelli	3.2
12	Great Yarmouth	30	**52**	Llanelli	4
13	Great Yarmouth	38	**53**	Llanelli	6
14	Great Yarmouth	40	**54**	Llanelli	9
15	Great Yarmouth	36	**55**	Llanelli	10
16	Great Yarmouth	32	**56**	Llanelli	10.5
17	Great Yarmouth	38	**57**	Llanelli	2
18	Spurn Head	9	**58**	Llanelli	3
19	Spurn Head	9.5	**59**	Llanelli	3.2
20	Skegness	5	**60**	Llanelli	5
21	Skegness	6	**61**	Llanelli	6
22	Skegness	10	**62**	Port Talbot	7
23	Skegness	15	**63**	Port Talbot	4
24	Skegness	20	**64**	Port Talbot	2
25	Skegness	25	**65**	Port Talbot	20
26	Skegness	26	**66**	Port Talbot	28
27	Skegness	21	**67**	Port Talbot	31
28	Skegness	19	**68**	Port Talbot	34
29	Skegness	18	**69**	Port Talbot	35
30	Skegness	19	**70**	Port Talbot	36
31	Skegness	16	**71**	Port Talbot	35
32	Skegness	17	**72**	Port Talbot	28
33	Skegness	19	**73**	Port Talbot	20
34	Skegness	20	**74**	Aberystwyth	18
35	Skegness	16	**75**	Aberystwyth	17
36	Skegness	15	**76**	Benbecula	36
37	Skegness	14	**77**	Benbecula	35.5
38	Hallsands	12	**78**	Benbecula	20
39	Hallsands	13	**79**	Benbecula	3
40	Hallsands	16	**80**	Benbecula	2

8.4 ECVI values

Having evaluated the six economic parameters determined in Sections 4.5 and applying them to the 11 selected coastal areas, it is now necessary to assess these results and allocate vulnerability scores, and thereby develop an ECVI. From the descriptive analysis of the six parameters, vulnerability ranges and thresholds given in Table 4.3 will be applied.

8.4.1Commercial properties

Integrating data from Section 8.3.1 with parameter ranges in Table 4.3, ECVI values were determined as shown in Table 8.8. There was significant variation between ECVI values, as the overall mean value for commercial properties was 2.3, with only one cell at the maximum score of 5 (Great Yarmouth). Fourteen percent of cells exhibited high levels of vulnerability and were allocated scores of 4, and these were mainly concentrated in Great Yarmouth, Port Talbot and Aberystwyth. Most Great Yarmouth cells have high vulnerability scores for commercial properties, while unsurprisingly the lowest vulnerability was recorded at Spurn Head due to lack of commercial infrastructure. ECVI economic threshold parameter scores for commercial properties clearly indicate that both the England and Wales case study sites have high economic vulnerability (Figure 8.18 and Table 8.8).

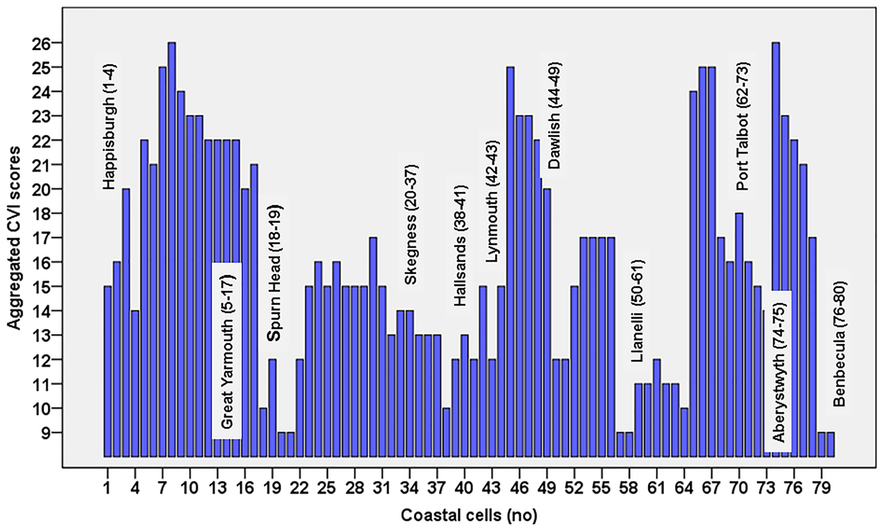


Figure 8.18: ECVI scores for commercial properties

Table 8.8: ECVI scores for commercial properties

Coastal Cell	Commercial Properties (£Million)	Coastal Cell	Commercial Properties (£Million)
1	2	**41**	1
2	1	**42**	3
3	3	**43**	2
4	1	**44**	2
5	4	**45**	4
6	4	**46**	3
7	4	**47**	3
8	5	**48**	3
9	4	**49**	2
10	4	**50**	2
11	4	**51**	2
12	4	**52**	2
13	4	**53**	3
14	3	**54**	3
15	3	**55**	2
16	3	**56**	2
17	3	**57**	1
18	1	**58**	1
19	1	**59**	2
20	1	**60**	2
21	1	**61**	2
22	2	**62**	2
23	3	**63**	2
24	3	**64**	2
25	2	**65**	4
26	2	**66**	4
27	2	**67**	4
28	2	**68**	2
29	2	**69**	1
30	2	**70**	1
31	2	**71**	1
32	2	**72**	1
33	2	**73**	1
34	2	**74**	4
35	2	**75**	4
36	3	**76**	2
37	2	**77**	2
38	0	**78**	2
39	1	**79**	1
40	1	**80**	0

1-4 - Happisburgh
5-17 – Great Yarmouth
18-19 - Spurn Head
20-37 - Skegness
38-41 - Hallsands
42 -43 - Lynmouth
44-49- Dawlish
50-61 – Llanelli
62-73 - Port Talbot
74-75 - Aberystwyth
76-80 – Benbecula

8.4.2 Residential properties

As for commercial properties, ECVI values for residential properties varied between locations, with an average score of 2.6, and once again the highest score at Great Yarmouth. Twenty-nine percent of the cells are considered to be extremely vulnerable and were allocated scores of 5, mainly at Great Yarmouth and Dawlish. Conversely, Spurn Head was considered to have low economic vulnerability for residential properties, although overall, ECVI scores clearly indicate that sites in England have high economic vulnerability due to numbers of residential properties (Figure 8.19 and Table 8.9).

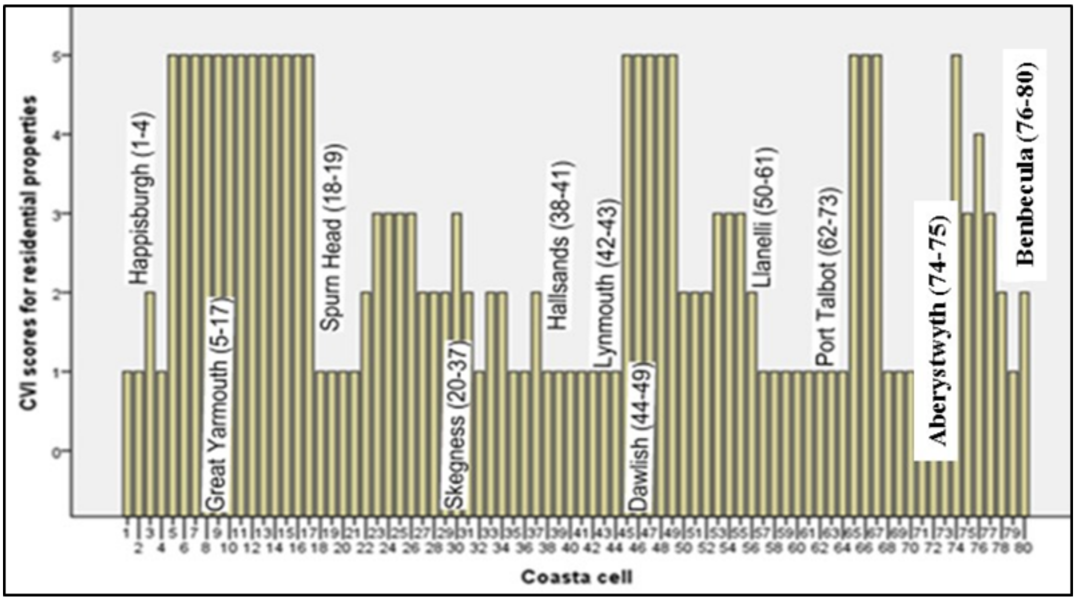


Figure 8.19: ECVI scores for residential properties

Table 8.9: ECVI scores for residential properties

Coastal Cell	Residential Properties (£Million)	Coastal Cell	Residential Properties (£Million)
1	1	**41**	1
2	1	**42**	1
3	2	**43**	1
4	1	**44**	1
5	5	**45**	5
6	5	**46**	5
7	5	**47**	5
8	5	**48**	5
9	5	**49**	5
10	5	**50**	2
11	5	**51**	2
12	5	**52**	2
13	5	**53**	3
14	5	**54**	3
15	5	**55**	3
16	5	**56**	2
17	5	**57**	1
18	1	**58**	1
19	1	**59**	1
20	1	**60**	1
21	1	**61**	1
22	2	**62**	1
23	3	**63**	1
24	3	**64**	1
25	3	**65**	5
26	3	**66**	5
27	2	**67**	5
28	2	**68**	1
29	2	**69**	1
30	3	**70**	1
31	2	**71**	0
32	1	**72**	0
33	2	**73**	0
34	2	**74**	5
35	1	**75**	3
36	1	**76**	4
37	2	**77**	3
38	1	**78**	2
39	1	**79**	1
40	1	**80**	2

1-4 - Happisburgh | 5-17 – Great Yarmouth | 18-19 - Spurn Head | 20-37 - Skegness
38-41 - Hallsands | 42 -43 - Lynmouth | 44-49- Dawlish | 50-61 – Llanelli
62-73 - Port Talbot | 74-75 - Aberystwyth | 76-80 – Benbecula

8.4.3 Economic value of site

The average parameter score for site economic value was 2.9, with the highest score of 5 was mostly being recorded at Aberystwyth and Port Talbot. Thirty percent of the cells had either high or extremely high vulnerability scores (4 and 5), with most being distributed in Great Yarmouth, Port Talbot, Aberystwyth and Benbecula. ECVI scores for site economic values showed that England, Wales and Scotland have a high economic vulnerability due to their natural environment (Figure 8.20 and Table 8.10).

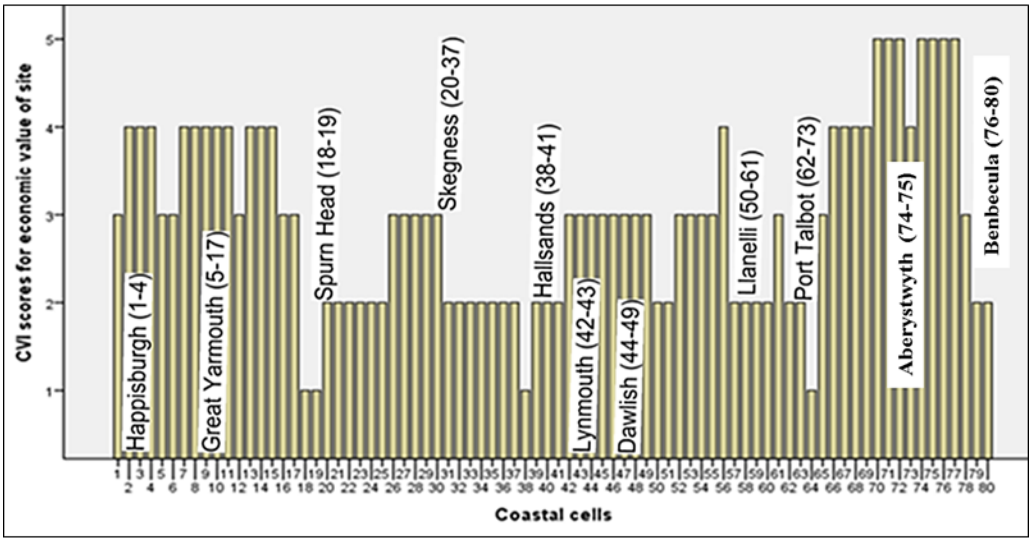


Figure 8.20: ECVI scores for economic value of site

Table 8.10: ECVI scores for economic value of site

Coastal Cell	Economic Value of Place (£Million)	Coastal Cell	Economic Value of Place (£Million)
1	3	41	2
2	4	42	3
3	4	43	3
4	4	44	3
5	3	45	3
6	3	46	3
7	4	47	3
8	4	48	3
9	4	49	3
10	4	50	2
11	4	51	2
12	3	52	3
13	4	53	3
14	4	54	3
15	4	55	3
16	3	56	4
17	3	57	2
18	1	58	2
19	1	59	2
20	2	60	2
21	2	61	3
22	2	62	2
23	2	63	2
24	2	64	1
25	2	65	3
26	3	66	4
27	3	67	4
28	3	68	4
29	3	69	4
30	3	70	5
31	2	71	5
32	2	72	5
33	2	73	4
34	2	74	5
35	2	75	5
36	2	76	5
37	2	77	5
38	1	78	3
39	2	79	2
40	2	80	2

1-4 - Happisburgh; 5-17 – Great Yarmouth; 18-19 - Spurn Head; 20-37 - Skegness
38-41 - Hallsands; 42 -43 - Lynmouth; 44-49- Dawlish; 50-61 – Llanelli
62-73 - Port Talbot; 74-75 - Aberystwyth; 76-80 – Benbecula

8.4.4 Population

There was variance between parameter scores for population and an average score of 1.8 was determined (Table 8.11). The highest parameter score of 4 was recorded at Great Yarmouth Aberystwyth and Port Talbot with 42% of cells scoring 1, most of these being at Hallsands, Spurn Head and Benbecula (Figure 8.21 and Table 8.11).

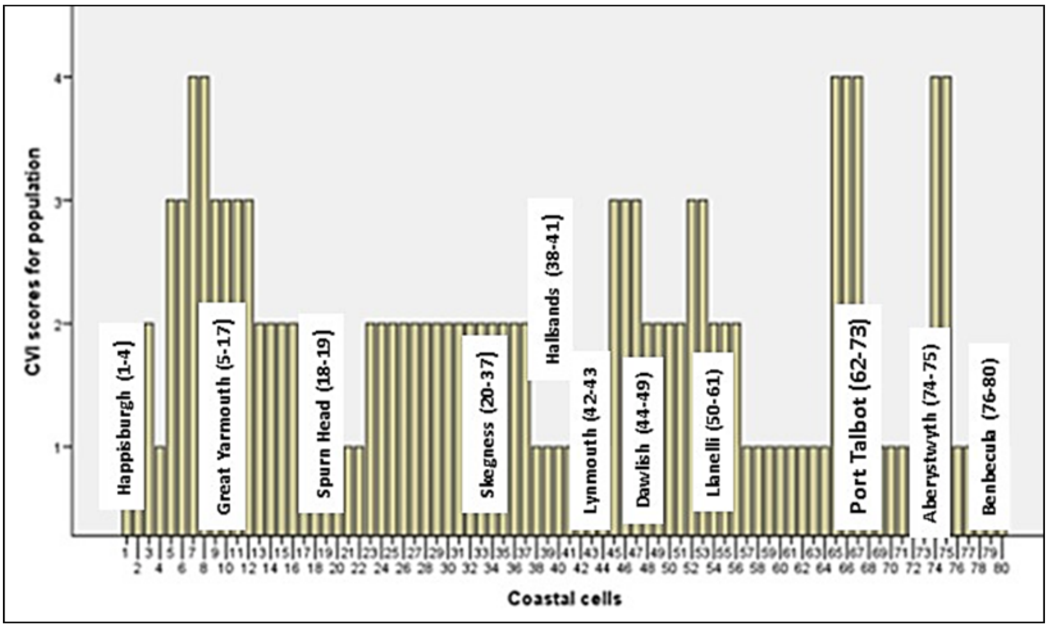


Figure 8.21: ECVI scores for population

Table 8.11: ECVI scores for population

Coastal Cell	Population (in Thousands)	Coastal Cell	Population (in Thousands)
1	1	**41**	1
2	1	**42**	1
3	2	**43**	1
4	1	**44**	1
5	3	**45**	3
6	3	**46**	3
7	4	**47**	3
8	4	**48**	2
9	3	**49**	2
10	3	**50**	2
11	3	**51**	2
12	3	**52**	3
13	2	**53**	3
14	2	**54**	2
15	2	**55**	2
16	2	**56**	2
17	2	**57**	1
18	1	**58**	1
19	1	**59**	1
20	1	**60**	1
21	1	**61**	1
22	1	**62**	1
23	2	**63**	1
24	2	**64**	1
25	2	**65**	4
26	2	**66**	4
27	2	**67**	4
28	2	**68**	1
29	2	**69**	1
30	2	**70**	1
31	2	**71**	1
32	2	**72**	1
33	2	**73**	1
34	2	**74**	4
35	2	**75**	4
36	2	**76**	1
37	2	**77**	1
38	1	**78**	1
39	1	**79**	1
40	1	**80**	1

1-4 - Happisburgh | 5-17 – Great Yarmouth | 18-19 - Spurn Head | 20-37 - Skegness
38-41 - Hallsands | 42 -43 - Lynmouth | 44-49- Dawlish | 50-61 – Llanelli
62-73 - Port Talbot | 74-75 - Aberystwyth | 76-80 – Benbecula

8.4.5 Coastal erosion

The average parameter score for coastal erosion was 3.2, with > 17% of the coastal cells assessed in the extremely high range (Table 8.12). Most of these sites were concentrated in Dawlish, Port Talbot, and Benbecula with 20% of the cells having high vulnerability and given scores of 4, mainly at Happisburgh, Hallsands, Llanelli, and Port Talbot. However, 31% of the cells were given scores of 2, indicative of low vulnerability and these were mostly concentrated along the Skegness coastline (Figure 8.22 and Table 8.12).

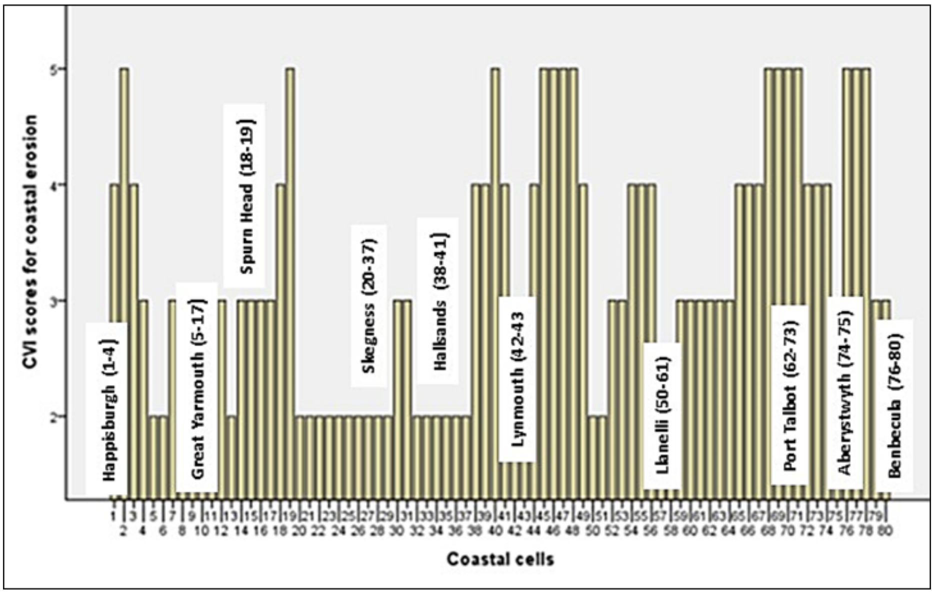


Figure 8.22: ECVI scores for coastal erosion

Table 8.12: ECVI scores for coastal erosion

Coastal Cell	Coastal Erosion (in £Millions)	Coastal Cell	Coastal Erosion (in £Millions)
1	4	**41**	4
2	5	**42**	3
3	4	**43**	2
4	3	**44**	4
5	2	**45**	5
6	2	**46**	5
7	3	**47**	5
8	3	**48**	5
9	3	**49**	4
10	2	**50**	2
11	3	**51**	2
12	3	**52**	3
13	2	**53**	3
14	3	**54**	4
15	3	**55**	4
16	3	**56**	4
17	3	**57**	2
18	4	**58**	2
19	5	**59**	3
20	2	**60**	3
21	2	**61**	3
22	2	**62**	3
23	2	**63**	3
24	2	**64**	3
25	2	**65**	4
26	2	**66**	4
27	2	**67**	4
28	2	**68**	5
29	2	**69**	5
30	3	**70**	5
31	3	**71**	5
32	2	**72**	4
33	2	**73**	4
34	2	**74**	4
35	2	**75**	3
36	2	**76**	5
37	2	**77**	5
38	4	**78**	5
39	4	**79**	3
40	5	**80**	3

1-4 - Happisburgh	5-17 – Great Yarmouth	18-19 - Spurn Head	20-37 - Skegness
38-41 - Hallsands	42 -43 - Lynmouth	44-49- Dawlish	50-61 – Llanelli
62-73 - Port Talbot	74-75 - Aberystwyth	76-80 – Benbecula	

8.4.6 Flood impact

The average ECVI parameter score for flood impact was 3.5 (Table 8.13), indicative of > 18% of the coastal cells, mostly concentrated in Great Yarmouth and Benbecula, having extremely high vulnerability. Forty-five percent of the cells were assessed as high vulnerability with scores of 4 and these were mainly concentrated in Happisburgh, Skegness, Dawlish, Port Talbot, and Aberystwyth. As well as having two sites scored as 5, the lowest score of 1 was also recorded at Benbecula. While, ECVI scores for the flood impact parameter indicate high economic vulnerability in a number of the English and Welsh case studies, Benbecula scores were due to it being a low lying island (Figure 8.23 and Table 8.13).

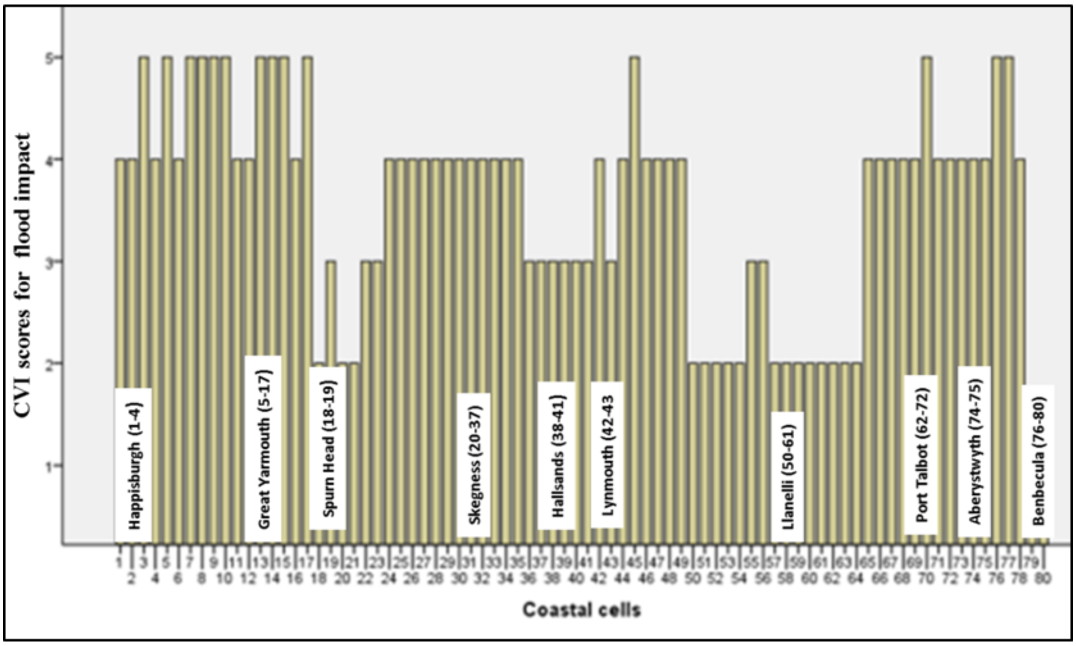


Figure 8.23: ECVI scores for flood impact

Table 8.13: ECVI scores for flood impact

Coastal Cell	Flood Impact (in £million)	Coastal Cell	Flood Impact (in £million)
1	4	**41**	3
2	4	**42**	4
3	5	**43**	3
4	4	**44**	4
5	5	**45**	5
6	4	**46**	4
7	5	**47**	4
8	5	**48**	4
9	5	**49**	4
10	5	**50**	2
11	4	**51**	2
12	4	**52**	2
13	5	**53**	2
14	5	**54**	2
15	5	**55**	3
16	4	**56**	3
17	5	**57**	2
18	2	**58**	2
19	3	**59**	2
20	2	**60**	2
21	2	**61**	2
22	3	**62**	2
23	3	**63**	2
24	4	**64**	2
25	4	**65**	4
26	4	**66**	4
27	4	**67**	4
28	4	**68**	4
29	4	**69**	4
30	4	**70**	5
31	4	**71**	4
32	4	**72**	4
33	4	**73**	4
34	4	**74**	4
35	4	**75**	4
36	3	**76**	5
37	3	**77**	5
38	3	**78**	4
39	3	**79**	1
40	3	**80**	1

1-4 - Happisburgh | 5-17 – Great Yarmouth | 18-19 - Spurn Head | 20-37 - Skegness
38-41 - Hallsands | 42 -43 - Lynmouth | 44-49- Dawlish | 50-61 – Llanelli
62-73 - Port Talbot | 74-75 - Aberystwyth | 76-80 – Benbecula

8.5 ECVI evaluation

The economic analysis undertaken in Section 8.4 obtained a parameter score for each of the 80 coastal cells for commercial properties, residential properties, and economic value of site, coastal erosion and flood event impact. Consequently, parameter values were combined for each site as per the methodology of Phillips and House (2009) for a scenic parameters and Phillips *et al*. (2007) for physical and human use parameters in Function Analysis. Consequently, Table 8.14 shows the accumulated parameter scores taken from Tables 8.8, 8.9, 8.10, 8.12 and 8.13 for each coastal cell. Population was also considered (Table 8.11) but these parameters will be utilised later in the analysis.

Table 8.14: Cumulative ECVI scores

Coastal Cell	ECVI Score	Coastal Cell	ECVI Score
1	15	**41**	12
2	15	**42**	15
3	20	**43**	12
4	14	**44**	15
5	22	**45**	25
6	21	**46**	23
7	25	**47**	23
8	26	**48**	22
9	24	**49**	20
10	23	**50**	12
11	23	**51**	12
12	22	**52**	16
13	22	**53**	17
14	22	**54**	17
15	22	**55**	17
16	20	**56**	17
17	21	**57**	9
18	10	**58**	9
19	12	**59**	11
20	9	**60**	11
21	9	**61**	12
22	12	**62**	11
23	15	**63**	11
24	16	**64**	10
25	15	**65**	24
26	16	**66**	25
27	15	**67**	25
28	15	**68**	17
29	15	**69**	16
30	17	**70**	18
31	15	**71**	16
32	13	**72**	15
33	14	**73**	14
34	14	**74**	26
35	13	**75**	23
36	13	**76**	22
37	13	**77**	21
38	10	**78**	17
39	12	**79**	9
40	13	**80**	9

- 1-4 - Happisburgh
- 5-17 – Great Yarmouth
- 18-19 - Spurn Head
- 20-37 - Skegness
- 38-41 - Hallsands
- 42 -43 - Lynmouth
- 44-49- Dawlish
- 50-61 – Llanelli
- 62-73 - Port Talbot
- 74-75 - Aberystwyth
- 76-80 – Benbecula

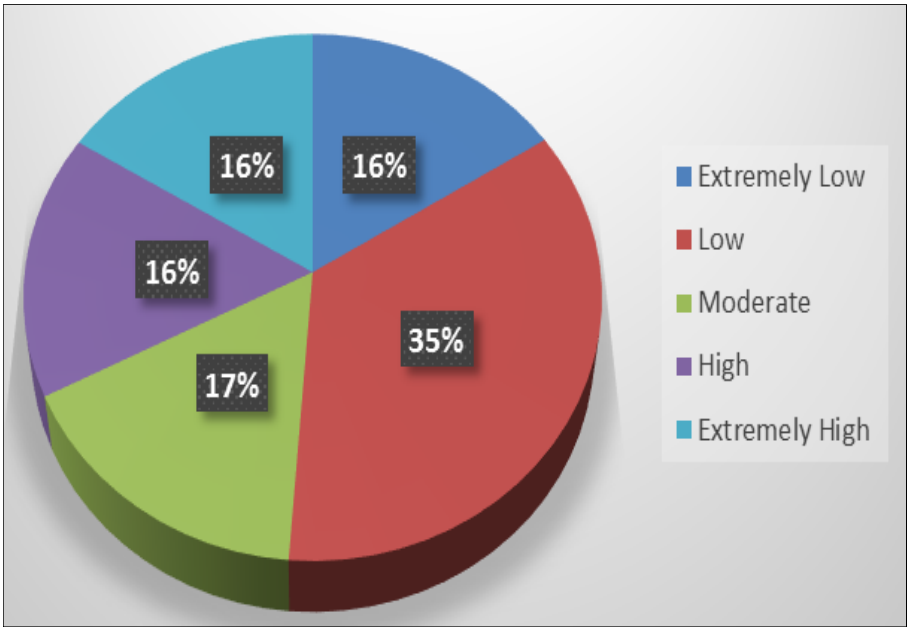


Figure 8.24: Percentage distribution of ECVI categories

A considerable variance exists between the coastal cells and cumulative ECVI parameter scores. The average ECVI score was 16.4, with the highest score of 26 recorded at Great Yarmouth and Aberystwyth coasts and the lowest being 9, recorded in six cells at Skegness, Llanelli and Benbecula (Table 8.14). However, more than 16% of cells fall into the extremely high category with a further 16% having high economic vulnerability. Thirty-five percent of cells fall into the lower category, with 16% belonging to extremely low categories. Figure 8.24 graphically shows the percentage distribution of ECVI categories defined in Table 4.4. This is important for helping decision-makers assess economic vulnerability against physical vulnerability; for example, coastal areas may have high physical vulnerability but low economic consequences regarding loss. The significance of this high/low vulnerability will be discussed later in Chapter 9.

Figure 8.25 represents the distribution of economic vulnerability by coastal cell and location and cumulative ECVI scores clearly show that Great Yarmouth is highly vulnerable in terms of economic risk and parts of the Llanelli and Benbecula coastlines have extremely low economic vulnerability (Figure 8.25 and Table 8.14).

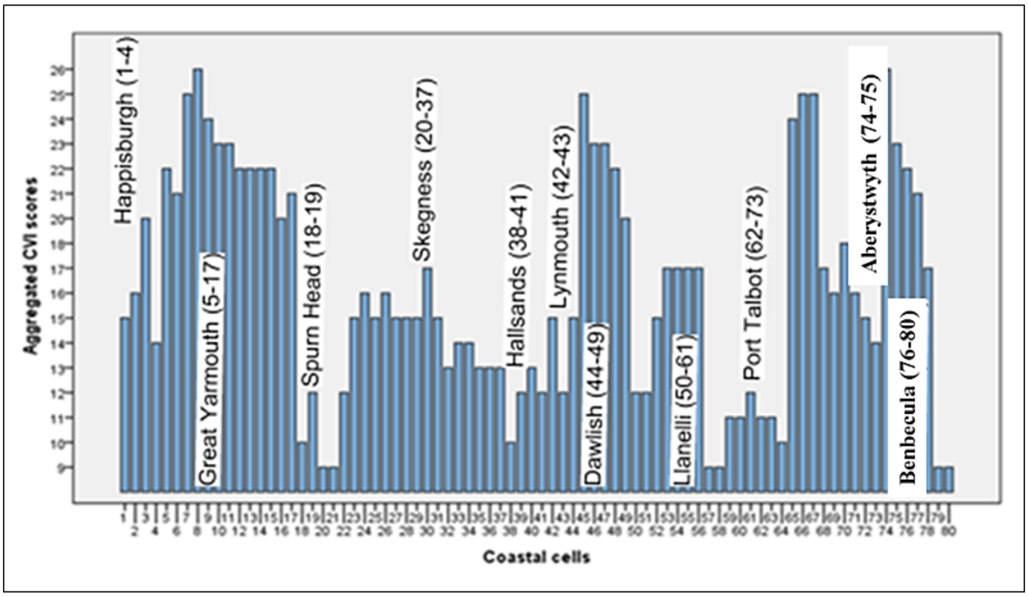


Figure 8.25: Coastal Cells and Cumulative ECVI

Although Table 8.14 indicates cumulative ECVI by coastal cell, and Figure 8.25 identifies location by coastal cells, the next stage requires a basis for comparison between coastal locations. Consequently, mean ECVI values were determined from Table 8.14 and Figure 8.25 for each coastal location. For example, Happisburgh is represented by coastal cells 1 to 4 (Table 8.14) and the ECVI for each km cell was added together i.e. 15+15+20+14 = 64. This was then averaged to get a mean ECVI value for Happisburgh, i.e. 64/4 = 16. Data was entered in Table 8.15 and the process replicated for all eleven coastal locations. Effectively, it could also be considered as a mean ECVI per km of coastline.

Table 8.15: Cumulative and mean ECVI scores

Coastal Cell	Coastal Site	Number of Sections	Coastal Cell	Coastal Site	Number Of Sections
1	Happisburgh	4 coastal cells (1-4) Total ECVI score = 64 Mean Happisburgh ECVI = 64/4 = 16	41	Hallsands	
2	Happisburgh		42	Lynmouth	2 coastal cells (42-43) Total ECVI score = 27 Mean Lynmouth ECVI = 27/2 = 13.5
3	Happisburgh		43	Lynmouth	
4	Happisburgh		44	Dawlish	6 coastal cells (44-49) Total ECVI score = 128 Mean Dawlish ECVI = 128/6 = 21.3
5	Great Yarmouth	13 coastal cells (5-17) Total ECVI score = 293 Mean Great Yarmouth ECVI = 293/13 = 22.5	45	Dawlish	
6	Great Yarmouth		46	Dawlish	
7	Great Yarmouth		47	Dawlish	
8	Great Yarmouth		48	Dawlish	
9	Great Yarmouth		49	Dawlish	
10	Great Yarmouth		50	Llanelli	12 coastal cells (50-61) Total ECVI score = 160 Mean Llanelli ECVI = 160/12 = 13.3
11	Great Yarmouth		51	Llanelli	
12	Great Yarmouth		52	Llanelli	
13	Great Yarmouth		53	Llanelli	
14	Great Yarmouth		54	Llanelli	
15	Great Yarmouth		55	Llanelli	
16	Great Yarmouth		56	Llanelli	
17	Great Yarmouth		57	Llanelli	
18	Spurn Head	2 coastal cells (18-19) Total ECVI score = 22 Mean Spurn Head ECVI = 22/2 = 11	58	Llanelli	
19	Spurn Head		59	Llanelli	
20	Skegness	18 coastal cells (20-37) Total ECVI score = 249 Mean Skegness ECVI = 249/18 = 13.8	60	Llanelli	
21	Skegness		61	Llanelli	
22	Skegness		62	Port Talbot	12 coastal cells (62-73) Total ECVI score = 202 Mean Port Talbot ECVI = 202/12 = 16.8
23	Skegness		63	Port Talbot	
24	Skegness		64	Port Talbot	
25	Skegness		65	Port Talbot	
26	Skegness		66	Port Talbot	
27	Skegness		67	Port Talbot	
28	Skegness		68	Port Talbot	
29	Skegness		69	Port Talbot	
30	Skegness		70	Port Talbot	
31	Skegness		71	Port Talbot	
32	Skegness		72	Port Talbot	
33	Skegness		73	Port Talbot	
34	Skegness		74	Aberystwyth	2 coastal cells (74-75) Total ECVI score = 49 Mean Aberystwyth ECVI = 49/2 = 24.5
35	Skegness		75	Aberystwyth	
36	Skegness		76	Benbecula	5 coastal cells (76-80)
37	Skegness		77	Benbecula	
38	Hallsands	4 coastal cells (38-41)	78	Benbecula	

39	Hallsands	Total ECVI score = 47 Mean Hallsands ECVI = 47/4 =11.8	79	Benbecula	Total ECVI score = 78 Mean Benbecula ECVI = 78/5 = 15.6
40	Hallsands		80	Benbecula	

1-4 - Happisburgh | 5-17 – Great Yarmouth | 18-19 - Spurn Head | 20-37 - Skegness
38-41 - Hallsands | 42 -43 - Lynmouth | 44-49- Dawlish | 50-61 – Llanelli
62-73 - Port Talbot | 74-75 - Aberystwyth | 76-80 – Benbecula

8.6 Economic costs/values

Tables 8.2, 8.3, 8.4, 8.6 and 8.7 identified the economic value/cost for each coastal cell according to commercial property, residential property, economic value of site, erosion and flood impact. These are summed for each coastal cell and results are shown in Table 8.16. The total value for all coastal locations > £22B, which means the selected sites represent a vulnerability value/cost > £22 billion.

Table 8.16: Economic cost/value of coastal cells

Coastal Cell	Commercial Property £M	Residential Property £M	Economic Value of Site £M	Erosion £M	Flood Impact £M	Value of Coastal Cell £M
1	3	8	60	6	30	107
2	1.2	4	110	20	35	170.2
3	13.5	50	130	7	36	236.5
4	1.5	20	120	5	20	166.5
5	35	200	80	2.5	37	354.5
6	38	300	100	2	35	475
7	42	320	120	3	37	522
8	105	600	120	3	40	868
9	55	500	130	2.6	38	725.6
10	45	440	135	2	35	657
11	49	600	130	3.5	32	814.5
12	31	400	100	4	30	565
13	33	300	110	2.5	38	483.5
14	28	240	120	3	40	431
15	26	220	110	3.5	36	395.5
16	22	200	100	2.6	32	356.6
17	22	190	100	2.6	38	352.6
18	0.2	0.2	2	5.1	9	16.5
19	0.25	0.2	3	9.1	9.5	22.05
20	1	5	20	0.3	5	31.3
21	1.5	8	22	0.4	6	37.9
22	10	54	28	0.5	10	102.5
23	14	121	35	0.8	15	185.8
24	12	135	40	1	20	208
25	10	120	50	1	25	206
26	9	94	60	1.2	26	190.2
27	8	67	68	1.8	21	165.8
28	9	75	65	2.2	19	170.2
29	10	63	60	2.5	18	153.5
30	8	81	55	3	19	166
31	8.5	67	50	2.8	16	144.3

32	7.5	27	30	2	17	83.5
33	9	32	35	1.5	19	96.5
34	10	40	40	1	20	111
35	9	26.6	30	0.8	16	82.4
36	12	26	25	0.6	15	78.6
37	7.5	40	20	0.6	14	82.1
38	0	0.9	5	7	12	24.9
39	0.1	0.6	20	8	13	41.7
40	1	11	50	10	16	88
41	0.5	2	30	9	14	55.5
42	28	25	90	3	16	162
43	9	19	80	2	14	124
44	5	26	60	9	20	120
45	40	598	80	11	36	765
46	30	468	100	20	30	648
47	16	390	90	12	20	528
48	18	208	85	10	18	339
49	10	130	80	9	17	246
50	6	32	20	2	3	63
51	7.2	40	30	2.2	3.2	82.6
52	9.6	48	55	3	4	119.6
53	12	112	60	4.5	6	194.5
54	13.2	104	80	6	9	212.2
55	9.7	113	100	6.5	10	239.2
56	10.8	72	120	6	10.5	219.3
57	0.48	1.6	20	1.2	2	25.28
58	1.2	4.8	25	1	3	35
59	2.4	9.6	30	3	3.2	48.2
60	4.8	11	50	4	5	74.8
61	7.2	12.7	60	4.8	6	90.7
62	2	24	25	5	7	63
63	1.5	6	15	4	4	30.5
64	6	12	8	3	2	31
65	36	540	90	7	20	693
66	63	780	110	9	28	990
67	51	504	105	6	31	697
68	7	6	110	20	34	177
69	0.4	2.4	150	18	35	205.8
70	0.35	11.5	1000	15	36	1062.85
71	0.1	0	1000	10	35	1045.1
72	0.04	0	200	8	28	236.04
73	0.02	0	150	8	20	178.02
74	66	594	500	6	18	1184
75	42	167	300	5	17	531

76	6	33	160	10	36	245
77	4	20	150	9.5	35.5	219
78	2	3.1	100	10	20	135.1
79	2	3	40	4	3	52
80	0	0.4	20	3	2	25.4
Economic vulnerability of all coastal cells						22362.44

1-4 - Happisburgh | 5-17 – Great Yarmouth | 18-19 - Spurn Head | 20-37 - Skegness
38-41 - Hallsands | 42-43 - Lynmouth | 44-49 - Dawlish | 50-61 – Llanelli
62-73 - Port Talbot | 74-75 - Aberystwyth | 76-80 – Benbecula

Similar to the determination of mean ECVI values; economic value per km length was calculated for each of the eleven coastal sites. For example, Happisburgh is represented by coastal cells 1 to 4 (Figure 8.25, Table 8.16) and the value of each coastal cell was added together to get a total value for Happisburgh, i.e. 107+170.2+236.5+166.5 = £680.2M. This was then averaged to obtain a mean value per km length for Happisburgh, i.e. 680.2/4 = £170.05M km^{-1}. This procedure was replicated for all 11 coastal sites and calculated data was included in Table 8.17. Mean ECVI values from Table 8.15 were also included in the order of most to least vulnerability, and finally, population data from Table 8.5 was transposed for each coastal site to obtain population per km (km^{-1}).

Table 8.17: Site Ranking according to ECVI, including cost/value and population data

Coastal Site	Mean Cost/Value (£M km^{-1})	Mean Population (No. km^{-1})	ECVI (km^{-1})
Aberystwyth	857.5	5300	24.5
Great Yarmouth	538.5	3508	22.5
Dawlish	441	1883	21.3
Port Talbot	450.8	1867	16.8
Happisburgh	170.1	332	16
Benbecula	135.3	168	15.6
Skegness	129.7	651	13.8
Lynmouth	143	245	13.5
Llanelli	117	1171	13.3
Hallsands	52.5	13	11.8
Spurn Head	19.3	25	11

The ECVI enabled the ranking of the eleven coastal sites in order of severity of economic vulnerability (Table 8.17), and relative site economic vulnerabilities according to ECVI are illustrated in Figure 8.26. The eleven sites represent a total economic risk of £22.4B under current scenarios (Table 8.16), which includes >50,000 residential properties (0.2% of UK total) and >6000 commercial properties (0.37% of UK total). Furthermore, approximately 118400 people (0.2% of the UK population) are at risk of displacement from flooding, etc.

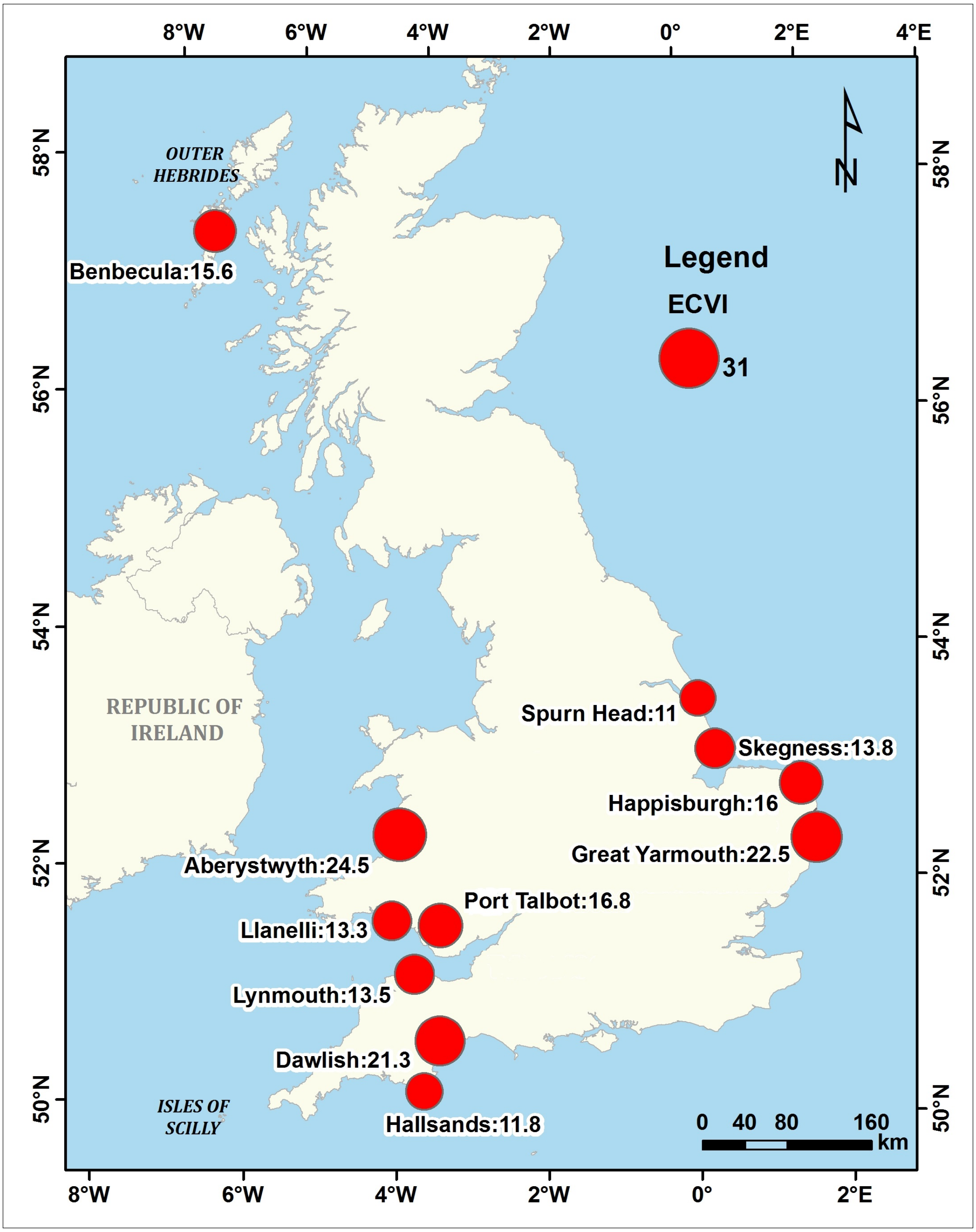


Figure 8.26: Average economic vulnerability according to ECVI

Table 8.17 clearly shows that Aberystwyth has the highest ECVI, population km^{-1} and economic vulnerability, and sites with the three highest ECVI scores also have very high relative economic values and populations. Historically, Aberystwyth has been vulnerable to wave attacks and since the turn of the twenty-first century, it has been severely affected by a series of storms with high waves, tides and storm surges, i.e. 2008, 2010, 2013, and 2014. The tidal range is higher than at the other sites with the greatest incidence of waves coming from the southwest, which is also the direction of the most frequent storms. In 2014, a storm struck this area and caused >£1.5M worth of damage (Ceredigion County Council, 2014) and Figure 8.27 shows storm damage and subsequent remedial works. There is an economic risk of £857.5M km^{-1} including 530 commercial properties and 4613 residential properties. There are 10597 inhabitants at risk of displacement from coastal flooding and an ECVI of 24.5 puts Aberystwyth in the 'extremely high vulnerability' range (Table 4.4).

Figure 8.27: Aberystwyth: Coastal damage and consequent defence improvements

Great Yarmouth is a medium-sized seaport and industrial corridor, as well as a major tourist attraction (Section 4.4). It was the longest frontage considered and results showed it was also in the 'extremely high vulnerability' range (Table 4.4) with an ECVI of 22.5 (Table 8.17). Its economic importance was assessed at £538M km^{-1} with a population of 3507 km^{-1} at risk of displacement from coastal flooding.

Dawlish is very likely to be at constant risk from sea level rise, storms, storm surges and resulting coastal erosion. Infrastructure at Dawlish is very close to the shoreline and therefore has high coastal vulnerability. Recent storm events in 2012, 2013 and 2014 caused billions of pounds worth of damage. The 2014 storm damage shown in Figure 8.28 caused a two month rail closure at a cost of £1.2B with resulting repairs costing £35M, making an overall total of £1.235B (Dawson *et al.,* 2016). Dawlish's ECVI is 21.3 (Table 8.17) giving it a high relative vulnerability score (Table 4.4). Currently, the economic risk includes residential and commercial properties, worth £441M km^{-1} with a population of approximately 1883 km^{-1} at risk (Table 8.17).

Figure 8.28: Infrastructure damage and flooding at Dawlish (2014)

Port Talbot is highly industrialised and has significant economic value. Exposed to significant southwesterly storms the Steelworks is protected by revetments made from blast furnace slag. The area is considered to be one of the most economically vulnerable coastal locations although Port Talbot's ECVI of 16.8 (Table 8.17) puts it in the moderate category for its relative vulnerability (Table 4.4). With an approximate population of 1867 km^{-1} and an economic value of £450.8M km^{-1} it was fourth of the eleven sites in terms of economic vulnerability. Happisburgh has experienced severe coastal erosion over many years due to its geology, which provides little resistance to storms and surges. This had led to residential properties being at risk of falling into the sea and homeowners are unable to get insurance (Phillips, 2008). This vulnerability is likely to increase with predicted increases in storm severity meaning the rate of erosion will also increase. Assessment showed that Happisburgh ECVI is 16 (Table 8.17), which puts it in the moderate relative vulnerability category (Table 4.4), with a population of 332 km^{-1} and an economic value of £170.1M km^{-1}. It is suggested that the ECVI is not higher because the actual number of properties at risk is small in comparison to the total number, i.e. 423 residential and 64 commercial properties.

Benbecula Island was severely affected by a 2005 storm event which caused > £20M (converted to 2014 rates) worth of infrastructure damage (Dawson *et al.,* 2007). Therefore, following storm events there is an extremely high risk of coastal erosion. Benbecula ECVI was determined as 15.6 (Table 8.17), which puts it on boundary of the moderate/low relative vulnerability categories (Table 4.4), having an economic value/cost of £135.3M km^{-1} and a population of 168 km^{-1}. Once again, the relatively low number of residential and commercial properties influenced the site ECVI. The next site in the ranking was Skegness, a popular tourism destination which is considered as one of the best places for holidays, as well as being an ideal place to live for those who are retired (Butler, 2006). Accordingly, Skegness is considered as a highly valuable location from a socio-economic perspective. However, this is currently changing due to unprecedented flooding, rapid changes in weather patterns and rising incidence of storms even in the summer period (Zsamboky *et al.,* 2011; Montreuil and Bullard, 2012). An ECVI score of 13.8 (Table 8.17) puts Skegness in the low vulnerability category (Table 4.4), having an economic value/cost of £129.7M km^{-1} and a population of 651 km^{-1}. However, as Skegness is influenced by shoreline exposure, there will be a significant number of people at risk should current trends of flooding and storms continue. Due to current climatic fluctuations, Lynmouth experienced severe weather conditions, including storm surges and high winds during the 2012 and 2014 storms. These events highlighted the coastal vulnerability of this particular area and Figure 8.29 shows both cliff-face erosion and how precariously properties have been constructed on the cliff. Therefore, the ECVI for Lynmouth was determined as 13.5 (Table 8.17), which like Skegness puts it in the low vulnerability category (Table 4.4), and its economic value/cost was assessed at £143M km^{-1} with a population of 245 km^{-1} (Table 8.17).

Figure 8.29: Coastal vulnerability: Lynmouth

Llanelli is at high risk from storm events, surges and coastal erosion. Recent storm events, particularly the 2010 storm, ravaged the £27m Millennium Coastal Path with high waves and tides, costing the Local Authorities > £400,000 in repairs (Phillips *et al.*, 2009). Following analysis of the economic parameters, the ECVI for Llanelli was 13.3, in the low vulnerability category. With an economic value of £117M km^{-1} and population of 1171 km^{-1} Llanelli's economic vulnerability is not equally distributed along its coastal frontage. During the storm of 1917, a major part of Hallsands vanished into the sea. Landslides are also a big concern here and the area is currently closed off due to coastal risk associated with coastal erosion. Most homeowners use their properties as holiday homes rather than permanent residences. Consequently, Hallsands has an economic risk of £52.5M km^{-1} and a population of 13 km^{-1} who are at risk of displacement, giving it an ECVI of 11.8, i.e. an extremely low relative economic vulnerability (Table 4.4). However, Hallsands properties are at risk from coastal flooding and erosion (Figure 8.30), which affects its PCVI and not ECVI score.

Figure 8.30: Coastal risk at Hallsands

Spurn Head is ecologically very important for bird migration and is considered to be one of the most vulnerable of the sites due to rapid erosion rates. However, its ECVI is 11 (Table 8.17) giving it an extremely low relative vulnerability score. However, erosion has greater impact on Spurn Head's PCVI score and in monetary terms, has an economic vulnerability of £19.3M km^{-1}, comprised of its site value and 9 residential/commercial properties. With a population of only 25 km^{-1}, displacement costs are also low, thereby justifying the lowest

ECVI score of all sites. Therefore, even though Hallsands and Spurn Head have high decadal erosion rates, due to them having relatively few commercial and residential properties they have lowest ECVI values.

8.7 Summary

This chapter started by defining the coastal cells and population numbers, which would be used to determine site ECVIs. Economic parameters justified in Table 4.3 were assessed, i.e. residential properties, commercial properties, economic value of site, population, coastal erosion and flood event/impact. These were subsequently quantified according to monetary value and also range in line with boundaries defined in Table 4.5 and 8.16. ECVI values for each parameter were then combined to produce a cumulative ECVI for each coastal location and then averaged according to the number of cells per coastal site. The total economic value for each cell was determined and an overall site value calculated which was also averaged to obtain a value per km. Population numbers were similarly converted per km. These were then compared and from analysis a Site Ranking according to ECVI was determined, which also included cost/value and population data per km. Aberystwyth had the highest ECVI, population km^{-1} and relative economic vulnerability, a situation mirrored in the three sites with the highest ECVI scores. Chapter 8 concluded by analysing ECVI results for all eleven coastal locations, highlighting areas at risk and under threat, and categorising them according to range and relative vulnerability. The next Chapter will compare PCVI and ECVI results to get a better understanding of both magnitude of change and economic consequences; and subsequently develop a combined coastal vulnerability index (CCVI).

CHAPTER 9 - DISCUSSION

9. Discussion

9.1 Introduction

The world's coastlines are under increasing physical, environmental and socio-economic pressures that is often at the forefront of discussions and of great concern for all stakeholders. Therefore, a better understanding of both the magnitude of change and economic consequences is vital and was the main rationale for this research. Assessment of physical vulnerability and PCVI (Chapters 5, 6 and 7) followed by derivation of the economic coastal vulnerability and ECVI (Chapters 5 and 8) allows coastal areas to be evaluated according to physical environment constraints and socio-economic costs. Consequently, this Chapter will integrate PCVI and ECVI results to develop a combined coastal vulnerability index (CCVI) and subsequently evaluate implications of both for coastal managers and decision-makers.

9.2 PCVI

Several physical coastal vulnerability indices have been developed and many tools employed to assess the scale of coastal vulnerability around the world (e.g. Denner *et al.,* 2015; Palmer *et al.,* 2011; Pethick and Crooks, 2000). However, these have not been extensively applied in the UK, with the exception of small-scale studies such as Llanelli and Northern Ireland. The present PCVI was developed using physical parameters recognised to be significant in relation to vulnerability, which was then applied to eleven coastal zones. PCVI development was explained in Section 4.5 and results showed that physical vulnerability varies according to UK location, despite all eleven sites having suffered consequences of coastal storms and flooding. The site of greatest vulnerability was shown to be Great Yarmouth. Accordingly, coastal planners and developers can use this kind of PCVI analysis in conjunction with socio-economic conditions without the need for in-depth knowledge of technical issues and coastal processes.

This research adapted the PCVI methodology of Denner *et al.* (2015) to evaluate physical coastal vulnerability based upon physical environment parameters. An important feature of this PCVI is its ease of application to any geographical area based on the availability of relevant data. Use of physical vulnerability data is also vital for communicating research results and enlightening a broader audience regarding coastal processes and physical consequences. Physical parameters can be adapted and social, economic and ecological factors can be considered alongside to categorise an area under definitive environmental conditions.

The selection of physical parameters can be complicated, due to the number of driving forces within specific coastal environments. In the case of Llanelli, the movement of deep-water channels had an important influence upon erosion on the northern shore (Section 5.4), while dunes, rocky outcrops and sea defences played vital roles in shoreline protection, which delayed the consequences of erosion becoming evident (Phillips *et al.,* 2009). However, in some places such as Benbecula (Scotland) and Aberystwyth (Wales) there are no dunes, and generally these are more vulnerable than areas that have dunes. Modifications to the methodology included sea defences, because physical interventions make the shoreline less vulnerable. Consequently, the highest PCVI score was allocated to dune width, coastal slope, rocky outcrop and sea defence. The highest overall PCVI was recorded at Great Yarmouth (27) and the lowest at Port Talbot and Aberystwyth (17), which reflected that all eleven sites are subject to damage from storms. PCVI scores suggest that Great Yarmouth and Happisburgh are areas of highest vulnerability, although sites where the majority of properties are located within 0.6 km of the coastline; Aberystwyth, Dawlish, Hallsands and Skegness, are also vulnerable. Flooding and erosion were the two major issues impacting the coastal areas (Section 3.8 and 3.9; Figure 3.7 & 3.8) and in locations such as Aberystwyth and Llanelli, the addition of new developments in these areas of high vulnerability will increase pressures, leading to even greater economic loss from flooding and storm damage (Denner *et al.,* 2015; Kantamaneni, 2015).

Conversely, the use of the PCVI in determining the vulnerability of specific sites can identify shorelines that are less vulnerable and therefore, will inform future redevelopment decisions. It is recognised that the identification and assessment of socio-economic and ecological components and their association with zones of high vulnerability is also significant and needs consideration when assessing coastal zone vulnerability and management options. These aspects are subjects of on-going research but this method of estimating vulnerability will ultimately allow cost-benefit analysis. Coastal vulnerability assessments can also be employed to justify the economic feasibility and benefits of coastal defence enabling more effective targeting of increasingly limited public funding. This method makes it easier to generate data and quantify risk to fulfil the requirements delegated to local authorities in the National Strategy for Flood and Coastal Erosion Risk Management in the UK.

9.3 ECVI

The Literature Review (Chapter 2) identified that vulnerability classifications can be achieved in many ways, but most vulnerability methodologies do not predict economic consequences of coastal erosion, storms and flooding. While the work of Palmer *et al.* (2011) and Balica *et al.* (2012) included socio-economic variables under human use categories, e.g. fishing, etc., these were integrated on a regional and not site basis. The ECVI was determined from six economic parameters that were assessed on a site/coastal location basis. Consequently, this methodology can be used by coastal developers, decision and policy makers to evaluate financial risk, without needing to assess complex economic data, as the model provides an innovative way to evaluate economic vulnerability. Development of ECVI scores per cell (Chapter 8) showed that economic vulnerability varies both within and between sites. Great Yarmouth had the highest PCVI and second highest ECVI and generally urban areas were most vulnerable, having larger populations than rural communities. Understanding population numbers at risk is important for both physical and socio-economic aspects of coastal research (Simone 2004). Assessments of population in monetary terms requires a cost to be allocated to a human life and based on 2011 US EPA (Environmental Protection Agency) estimates, it is £6.9 million adjusted for 2015 inflation rates (Appelbaum, 2011). However, coastal populations represent diverse age groups and communities with different economic status and an average figure of £4M for a life could be argued (Kantamaneni, 2016a). Even though population numbers are available, it would be unrealistic to include population costs at £4M head^{-1} in the ECVI methodology because there are relatively few deaths recorded in the UK during severe storms. Therefore, this ECVI methodology, which includes population numbers, can be applied at regional and sub regional levels to determine levels of economic vulnerability.

Unrestricted and rapid settlement in coastal areas increases pressure (Section 5.3; Figure 5.2), both physically and economically, which leads to further vulnerability and risk (Nicholls, 2007). For example, Great Yarmouth and Skegness populations have increased year on year ultimately causing increased coastal vulnerability and as a consequence was considered as a significant site for this research. ECVI values for Aberystwyth, Great Yarmouth and Dawlish showed the majority of the coastal cells were highly vulnerable, not only with respect to site value and commercial and residential properties (Section 8.5), but also with population numbers. Spurn Head and Hallsands were identified as having the lowest economic vulnerability, as although Spurn Head has a high erosion rate, the lack of properties and population reduced its ECVI. The Llanelli coastline ECVI was variable according to cell location due to expensive developments alternating with rural locations, while Port Talbot's economic vulnerability was based on the value of its industries, including

TATA Steel. However, its coastal risk is reduced due to a buffer zone between the sea and many of Port Talbot's properties.

The majority of residential and commercial properties are located within 0.6 km of the shoreline in all eleven sites. Therefore, predicted increases in storm occurrences and associated flooding events, winds and storm surges that often result in coastal erosion are major problems in these areas. Denner *et al.* (2015) stated that Llanelli poses a high risk of present and future flooding and results from this research confirm that this is indeed the case. Kantamaneni (2016a) revealed that Aberystwyth has the highest risk of storm surges, flooding and erosion and consequently, it received the highest ECVI score. Of the coastal defences built to protect several of the study sites, particularly Llanelli, the protection of new properties and infrastructure relies on *circa* 25% - 35% having less than a 20-year lifespan remaining (Denner *et al.,* 2015). This highlights an on-going problem in that not enough money is available for coastal protection, whilst storms, sea level rise (Section 3.3; Figure 3.2) and inundation events are likely to become more frequent. The problem is compounded by there not being updated government reports on coastal defences and protection measures for the eleven sites, particularly Aberystwyth (Kantamaneni and Phillips, Kantamaneni, 2016a), and that where data is available, most is more than 5-10 years old and will not help accurate assessment. Accordingly, the capability of local authorities without sufficient resources to defend coastal infrastructure, especially for Llanelli and Aberystwyth, has been questioned (Phillips *et al.,* 2009; Kantamaneni, 2016a).

Except when events make the television news, e.g. Aberystwyth, etc. in 2014, there is a general lack of public awareness of coastal issues from both economic and physical perspectives. Consequently, regeneration strategies have already led to further coastal erosion and flooding. New developments may get short-term monetary gain from improvements to coastal real estate and investment, but if there is a vulnerability to erosion and flooding, the investment is at risk. Meanwhile, there are no rigorous policies or procedures that can be immediately implemented to avert such situations, and it becomes more complex when developers call on Local Authorities to provide protection because they were encouraged to build on the coast as part of a regeneration strategy (Phillips *et al.,* 2009). These situations represent failures of coastal management strategies instead of an economic gain. Therefore, using the ECVI to assess economic vulnerability will quantify the relative vulnerability of coastal areas to various hazards and consequently will be a useful tool for planning authorities to assess economic risk.

9.4 Comparison of ECVI and PCVI

Comparison of PCVI and ECVI drivers (Figure 9.1; Table 9.1) allows for a better estimation of the overall vulnerability of any site. This is why both were developed using economic and physical parameters and applied to the eleven selected UK coastal sites: Spurn Head, Hallsands, Lynmouth, Happisburgh, Dawlish, Great Yarmouth and Skegness (England); Benbecula (Scotland); and Aberystwyth, Port Talbot and Llanelli (Wales).

Table 9.1 Physical and economic drivers

Physical drivers	Economic Drivers
• Beach width	• Commercial properties
• Dune width	• Residential properties
• Coastal erosion	• Economic value of the site
• Distance of vegetation behind the back beach	• Population
• Distance of built structures behind the back beach	• Coastal erosion
• Rocky outcrop	• Flood impact
• Sea defences	

Figure 9.1: Interlinking physical and economic impacts

Both indices gave interesting results as shown in Table 9.2 and Figure 9.2. In Great Yarmouth, the PCVI (27) is higher than the ECVI (22.3), but Aberystwyth's ECVI (24.5) is higher than its PCVI (17). In Spurn Head, physical vulnerability is much higher (22) than its economic vulnerability (11), probably due to the lack of coastal defences and rocky outcrops, as well as having fewer commercial and residential properties per km. Port Talbot is an interesting site because it PCVI and ECVI are more or less the same, 17 and 16.8 respectively. For Hallsands, physical vulnerability is much higher indicated by a PCVI of 22 compared with economic vulnerability i.e. an ECVI of 11.7. Furthermore, Dawlish's economic vulnerability (ECVI = 21.3) is more than its physical vulnerability (PCVI = 18), and this can be explained by the number of expensive properties located near the shoreline.

To assess potential links between PCVI and ECVI and get a better understanding of both the magnitude of change and economic consequences Table 9.2 shows PCVI and ECVI values for each of the eleven areas, from which Figure 9.2 was produced.

Table 9.2: PCVI and PCVI average values

Site	PCVI	ECVI
Great Yarmouth	27	22.5
Happisburgh	23	16
Spurn head	22	11
Hallsands	22	11.7
Lynmouth	19	13.5
Skegness	22	13.8
Benbecula	22	15.6
Dawlish	18	21.3
Llanelli	18	13.3
Aberystwyth	17	24.5
Port Talbot	17	16.8

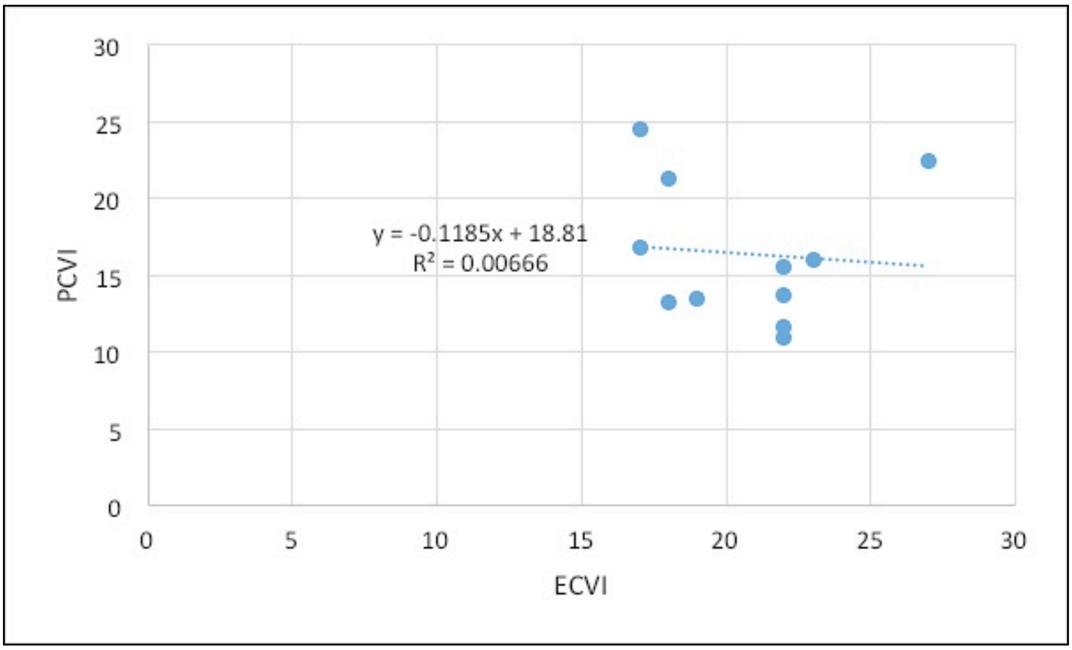


Figure 9.2: Variation of PCVI and ECVI

Figure 9.2 graphically illustrates the variation of PCVI with ECVI from which strengths of the inter-relationship and correlation were determined. It is clearly seen that there is little correlation between the variation of PCVI and ECVI, highlighted by a very low coefficient of determination ($R^2 = 0.0067$). The reason for this is that PCVI values are based on physical environment parameters, e.g. beach width, etc., while ECVI values are influenced by varying market prices, development and infrastructure, e.g. number of commercial properties, etc. Therefore, the greater the number of properties, the higher the economic value and this is independent of the physical environment.

Phillips *et al.* (2007) amongst others, graphically represented beach areas according to environmental and human use parameters. This approach has been adopted for site PCVI and ECVI values, as shown in Figure 9.3.

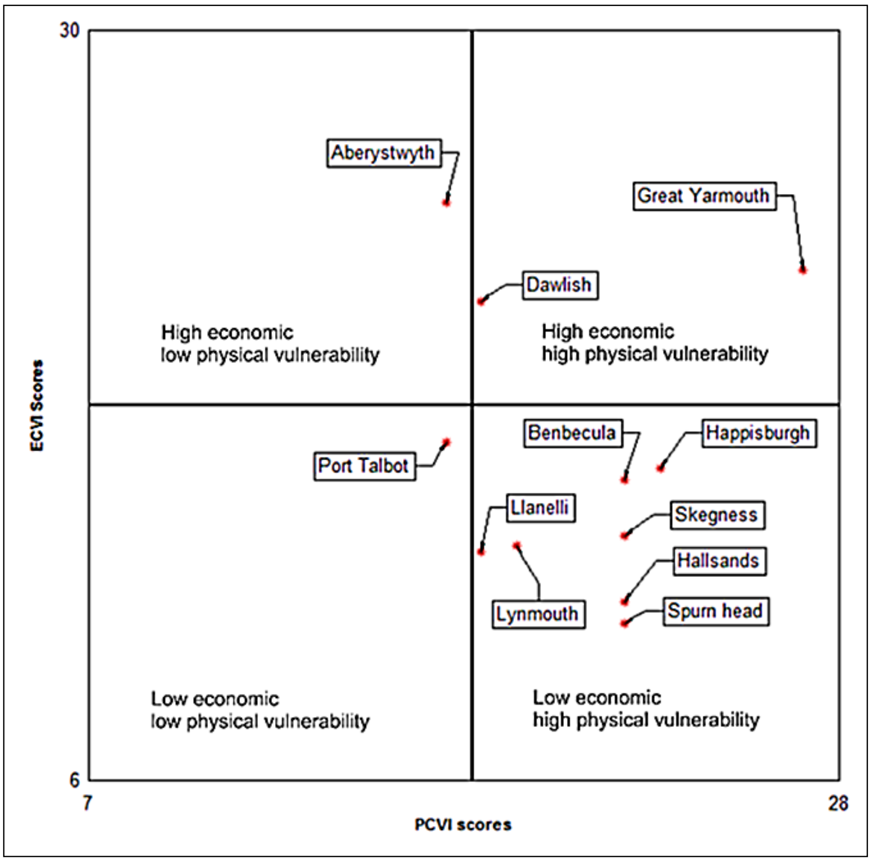


Figure 9.3: Graphical Representation of sites by PCVI and ECVI

The graphical quadrants represent sites according to low physical/low economic, low physical/high economic, high physical/low economic and high physical/high economic categories. Therefore, this graphical representation can be used at various resolutions to compare coastal areas, which in turn will help decision-makes prioritise limited funding to protect areas at most risk.

9.5 Combined coastal vulnerability Index (CCVI)

Further interpretation of PCVI and ECVI was undertaken via the formulation of a Combined Coastal Vulnerability Index (CCVI), as described in Chapter 4. Data from Table 9.2 was combined to form a CCVI for each site, as shown in Table 9.3. Results showed that Great Yarmouth has the highest overall vulnerability demonstrated by a CCVI of 25, followed by Aberystwyth (21), Happisburgh and Dawlish (20). Llanelli and Lynmouth have the joint lowest CCVI (16) with Spurn Head and Port Talbot just above with a CCVI of 17.

Table 9.3: CCVI values and site ranking

Site	CCVI	Rank
Great Yarmouth	25	1
Aberystwyth	21	2
Happisburgh	20	3
Dawlish	20	3
Benbecula	19	5
Skegness	18	6
Hallsands	18	6
Port Talbot	17	8
Spurn Head	17	8
Lynmouth	16	10
Llanelli	16	10

Table 9.3 indicates that overall, the English sites were generally the most vulnerable, although that is also a function of number of sites assessed. Therefore, to enable comparison of sites by PCVI, ECVI and CCVI, Figure 9.4 was produced. Unsurprisingly, Great Yarmouth has the highest physical and second highest economic rankings. While, the highest economic ranking at Aberystwyth is offset by the lowest recorded physical ranking, obviously, influenced by shoreline protection structures. Contrastingly, Spurn Head has a high physical ranking but low economic ranking, influenced by sand and shingle spit morphology that is not conducive to construction and population growth. Port Talbot and Llanelli areas are centred on industry and consequently, high numbers of residential and commercial properties. However, these areas are generally protected by sea defences, although the sustainability of these protection measures have been questioned by both Phillips *et al.* (2007) and Denner *et al.* (2015). In these cases the protection measures are a function of the industrial importance, resulting in similar physical and economic ranking. To enable easy reference the PVCI and ECVI and CCVI results are superimposed upon a map of the UK (Figures 9.5a and 9.5b respectively).

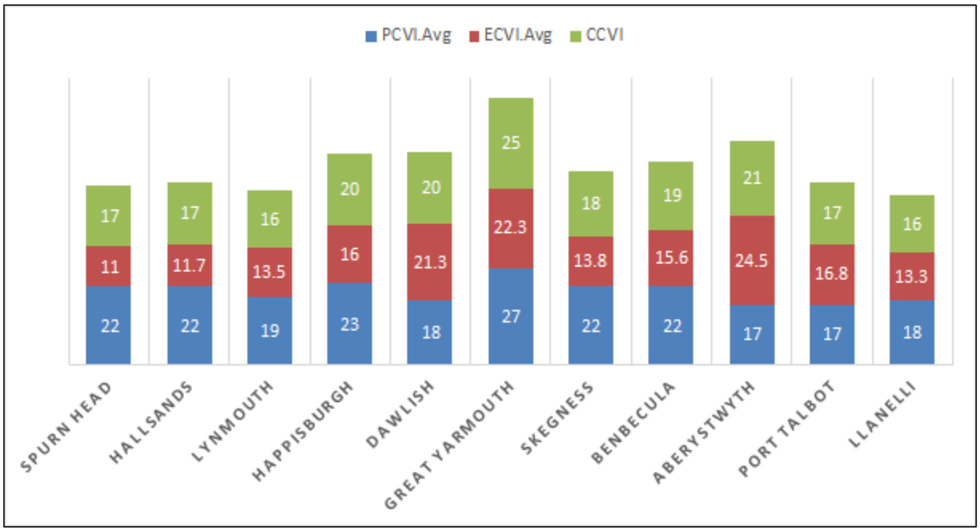
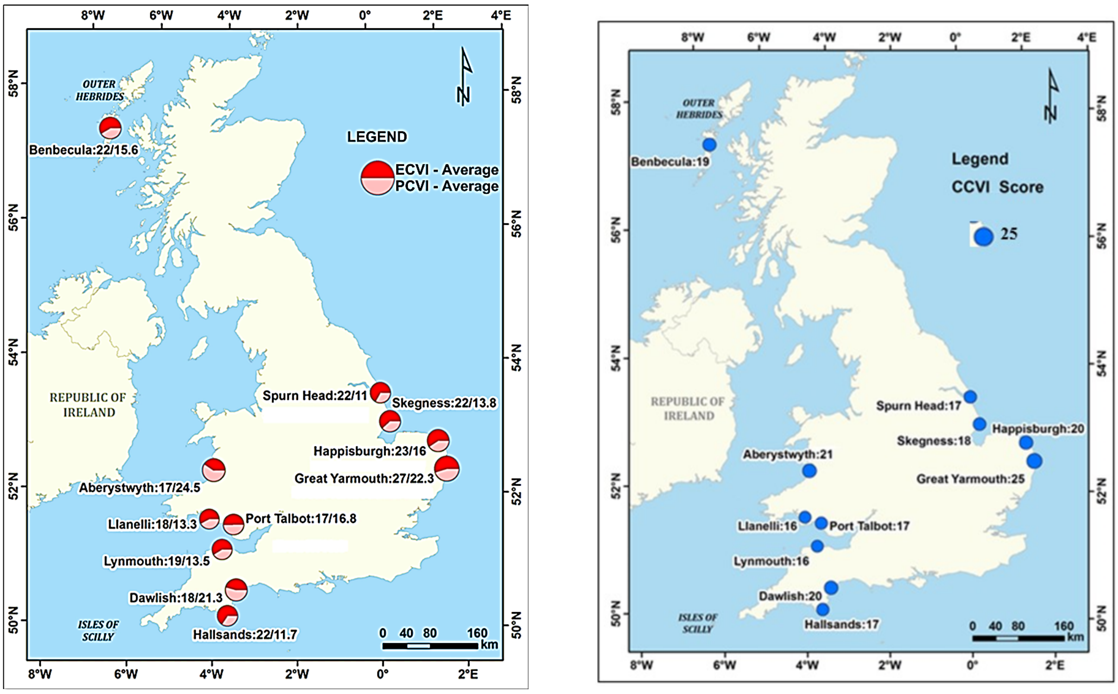


Figure 9.4: Representation of vulnerability indexes



a) b)

Figure 9.5: Coastal vulnerability maps showing a) ECVI and PCVI average values and b) combined values (Key: red ECVI; amber PCVI; blue CCVI).

9.6 Summary

This chapter completes the research project by presenting a PCVI, developed using parameters recognised to be significant in relation to physical vulnerability and an ECVI, designed to quantify relative economic vulnerability to various hazards. These were then applied to eleven coastal zones and the PCVIs and ECVIs were combined to form a CCVI which produced a useful tool for assessing physical and economic risk. Results of this research will improve understanding of both physical and economic consequences of changing environmental conditions, particularly in highly populated low-lying areas and can be used to inform effective planning of coastal management strategies in both physically and/or economically important areas.

CHAPTER 10 - CONCLUSIONS

10. Conclusions

10.1 Introduction

Predicted future climate change, sea level rise and increasing storm intensities will result in increasing physical, environmental and socioeconomic pressures, particularly for communities living in low lying coastal areas around the world. Although this is affected by uncertainty due to environmental complexity, potential effects could be mitigate by a comprehensive understanding of both physical and economic vulnerability. Literature searches identified that some research has been conducted on physical and to a lesser extent on the socio-economic aspects of coastal vulnerability, and there is a lack of current research detailing economic coastal vulnerability. Therefore, this work that details both economic and physical vulnerability aspects of 11 case study areas with contrasting environmental and economic conditions, provides additional information to improve confidence and will inform coastal management strategies for locations most at risk.

10.2 PCVI

The selection of physical parameters used to develop a PVCI was complicated, due to the number of driving forces within specific coastal environments. Dunes, rocky outcrops and sea defences play a vital natural role in shoreline protection, by delaying the consequences of erosion becoming evident. However, in some places no dunes or rocky outcrops exist and generally these are more vulnerable than areas that have dunes. Modifications to the methodology included sea defences, because physical interventions make the shoreline less vulnerable. Consequently, the highest PCVI score was allocated to dune width, coastal slope, rocky outcrop and sea defence. The highest overall PCVI was recorded at Great Yarmouth (27) and the lowest at Port Talbot and Aberystwyth (17), which suggests that all eleven sites are subject to damage from storms. PCVI scores suggest that Great Yarmouth and Happisburgh area are areas of highest vulnerability centred on postglacial rebound, sea level rise and a relatively weak geomorphology. Also vulnerable are areas where the majority of properties are located close to coastline, for example, Aberystwyth, Dawlish, Hallsands and Skegness. This research recognised the importance of identification and assessment of socio-economic and ecological components and their association with zones of high vulnerability and these aspects must be considered when assessing coastal zone vulnerability and management options. It was also recognised that these physical coastal vulnerability assessments can also be employed to justify the economic feasibility and benefits of defending the coast to enable more effective targeting of increasingly limited public funding.

This method makes it easier to generate data and quantify risk to fulfil the requirements delegated to local authorities in the National Strategy for Flood and Coastal Erosion Risk Management in the UK.

10.3 ECVI

When applied to the eleven selected coastal areas, results showed that economic vulnerability varies both within and between sites. Great Yarmouth had the highest PCVI and second highest ECVI and generally urban areas were most vulnerable, having larger populations than rural communities. The study recognised the importance of understanding population numbers at risk for both physical and socio-economic aspects of coastal research. The study highlighted that unrestricted and rapid settlement in coastal areas increases pressure leading to vulnerability and risk. Great Yarmouth and Skegness populations have increased and are the cause augmented coastal vulnerability and as a consequence was considered as a significant site for this research. ECVI values for Aberystwyth, Great Yarmouth and Dawlish showed that most coastal cells were highly vulnerable, with respect to site value, commercial and residential properties and population numbers. It was no surprise that Spurn Head and Hallsands were identified as having the lowest economic vulnerability, as the lack of properties and population reduced its ECVI. Using an ECVI to assess economic vulnerability will quantify the relative vulnerability of coastal areas to various hazards and consequently will be a useful tool for planning. The ECVI was determined from six economic parameters to provide a useful coastal management tool assessed on a site/coastal location basis. It is argued that coastal developers and policy makers could apply this model to evaluate financial risk without needing complex economic data as the methodology provides an innovative way to evaluate economic vulnerability.

10.4 Comparison of PCVI and ECVI/ Combined coastal vulnerability, CCVI

Results from the two indices (PCVI and ECVI) were compared to estimate the relative severity of physical and economic vulnerability in the selected sites. Accordingly, Great Yarmouth and Aberystwyth have the highest combined vulnerability, both economically and physically with the highest scores. Lynmouth and Spurn Head were the least physically and economically vulnerable sites, with the lowest recorded scores. Furthermore, based on CCVI (combined coastal vulnerability index) values, Great Yarmouth is highly vulnerable with the highest average score (25) followed by Aberystwyth, Dawlish, and Happisburgh. Llanelli and Lynmouth are the least vulnerable sites with lowest recorded scores. To improve results from PCVI, ECVI and CCVI analysis, it is suggested that future work should include 'fuzzy logic' techniques to apply a weighting system to parameters.

10.5 Justification of aims and objectives

Section 1.3 identified the main aim of this research, i.e. to develop a combined physical and economic coastal vulnerability index. Accordingly, three indices were generated (PCVI, ECVI and CCVI) (Sections 4.1 to 4.3, 4.5, 4.6) and applied to eleven selected coastal areas (Section 4.4) which enabled the evaluation of physical and economic parameters. The methodological frameworks which were developed for this study, can easily be applied to any geographical area following similar data acquisition techniques. In summary, this research achieved all stated aims and objectives and future projects are in the process of being developed.

10.6 Limitations of research

Though the current research has achieved its aims and objectives, there are some limitations which will underpin recommendations for future work. Due to the lack of decadal or census data regarding the number of deaths caused by flooding events in coastal areas, this research was unable to consider economic consequences for local populations. It was not possible to allocate the same economic value to all coastal areas, e.g. Aberystwyth has a higher economic value than Port Talbot if the Welsh Government's Social Deprivation Index is considered. It was also not possible to determine actual economic value of populations in the eleven coastal areas due to time and data restrictions. Time and resource restrictions also meant it was not possible to fully assess implications of large infrastructure such as transportation and bridges for the ECVI. This study could not assess accurate flood damage information before 2007 because Met Office systematic information is unavailable for periods prior to this date. However, the use of population census data to augment data acquired from the Local Authority would have improved estimates.

10.7 Data collection and challenges

With these concerns in mind, factors such as GDP, local economy, and redevelopment strategies would need to be carefully assessed in any effort of simplification of findings. During the data collection process, many obstacles were faced. Some Local Authorities did not respond to requests for information, and while others offered to arrange meetings and interviews, sadly not all appointments were kept. To overcome these challenges, statistical information was requested via the Freedom of Information (FOI) Act, 2000. Access to information in some areas was prohibited (Dawlish) due to political and economic tensions as infrastructure (a railway) was being rebuilt. Despite these difficulties, most of the key statistical data were obtained during the data collection period.

10.8 Summary

This section summarises how the research aims and objectives were achieved by developing and applying a combined coastal vulnerability index (physical and economic) along with the development of coastal vulnerability GIS maps at various scales. Future projects offer varied applications and with climate change impacts showing no sign of reducing in magnitude, such tools give authorities information needed for appropriate decision making.

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APPENDICES

Please see the volume 2

Assessing coastal vulnerability: development of a combined physical and economic index

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Submitted to the University of Wales Trinity Saint David in partial fulfilment for the degree of Doctor of Philosophy

University of Wales Trinity Saint David

Faculty of Architecture, Computing and Engineering

April 2017

Volume 2

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This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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APPENDICES

1. Appendix – PCVI and ECVI Data

Table 1: Beach width (m)

Shoreline Measurement No	Beach Width (m)	Shoreline Measurement No	Beach Width (m)	Shoreline Measurement No	Beach Width (m)	Shoreline Measurement No	Beach Width (m)
1	630	41	28.3	81	129	121	123
2	360	42	58.19	82	128	122	192
3	364	43	42.22	83	139	123	100
4	260	44	1.4	84	219	124	198
5	109	45	1.4	85	159	125	339
6	170	46	590	86	173	126	315
7	76	47	565	87	220	127	323
8	21	48	12	88	220	128	335
9	20.71	49	13.75	89	255	129	302
10	21.26	50	10.05	90	213	130	371
11	26.3	51	11.61	91	50	131	366
12	24	52	12.54	92	107	132	557
13	25.6	53	14.72	93	121	133	590
14	27.34	54	14.53	94	61	134	775
15	125	55	10.16	95	107	135	500
16	213	56	18.48	96	53	136	604
17	378	57	17.35	97	82	137	820
18	121	58	11	98	37	138	542
19	11.39	59	10.39	99	111.35	139	400
20	18.76	60	12.36	100	148	140	95
21	48.13	61	17.26	101	60	141	1400
22	34.7	62	16.68	102	113.7	142	1600
23	49.57	63	19.29	103	67.99	143	1900
24	41.64	64	6.72	104	72	144	1900
25	41.25	65	7.4	105	83	145	898
26	42.9	66	296	106	168	146	995
27	35.1	67	246	107	67	147	550
28	74.73	68	223	108	63	148	650
29	42.23	69	143	109	179	149	760
30	21.22	70	132	110		150	696
31	27.29	71	143.76	111		151	470
32	32.42	72	145.93	112	835	152	384
33	37.63	73	309	113	530	153	362
34	139	74	326	114	382	154	250
35	135	75	296	115	351	155	120
36	91.56	76	255	116	327	156	38
37	107	77	263	117	373	157	18
38	17.44	78	220	118	360	158	65
39	17.34	79	214	119	364		
40	15.78	80	160	120	245		

Table 2: Dune width (m)

Shoreline Measurement No	Dune Width (m)	Shoreline Measurement No	Dune Width (m)	Shoreline Measurement No	Dune Width (m)	Shoreline Measurement No	Dune Width (m)
1	17.49	41		81		121	
2	18	42		82		122	49
3		43		83		123	110.68
4	13	44		84		124	
5	59	45		85		125	
6	63	46		86		126	
7		47	16	87		127	
8		48		88		128	
9		49		89	184	129	
10	10	50		90		130	
11		51		91		131	29
12		52		92		132	163
13		53		93		133	
14		54		94		134	
15		55	35	95		135	
16		56	304	96		136	
17		57	336	97		137	
18		58	251	98		138	
19	21.44	59	60	99	58.91	139	
20	33	60	33	100	49.81	140	95
21		61	115	101		141	
22		62	60	102		142	
23		63	71	103		143	
24		64	47	104		144	
25		65	17	105		145	
26		66	91	106		146	
27		67	34.32	107		147	
28		68	157	108		148	
29		69		109	289	149	
30		70		110	33.75	150	
31		71		111	515	151	
32		72		112	345	152	
33		73	55.17	113	66	153	
34		74	9.5	114	55	154	
35	78.79	75		115		155	
36	107.8	76		116		156	
37	79	77	39.36	117		157	
38		78	20	118		158	
39		79		119			
40		80		120			

Table 3: Coastal slope (%)

Shoreline Measurement No	Coastal Slope (%)	Shoreline Measurement No	Coastal Slope (%)	Shoreline Measurement No	Coastal Slope (%)	Shoreline Measurement No	Coastal Slope (%)
1	2.5	41	4.1	81	1.2	121	4.2
2		42	3.6	82	1.3	122	2.3
3		43	2.2	83	2.2	123	1.2
4		44	1.7	84	1.3	124	15.6
5		45	0.9	85	0.9	125	10.9
6		46	3.1	86	3.9	126	3.9
7	13.3	47	1.8	87	2.9	127	2.6
8	17.8	48	2.3	88	2	128	2.7
9	19.2	49	3.8	89	0.6	129	2.1
10	6.8	50	1.7	90	1.9	130	3.8
11	10.3	51	0.5	91	1.4	131	3
12	19.8	52	1.8	92	0.7	132	3.1
13	6	53	1.4	93	1.1	133	6.7
14	2.4	54	1.7	94	1.2	134	1
15	36	55	0.5	95	1.5	135	3
16	21.3	56	1.5	96	0.9	136	4.1
17	29.5	57	1.1	97	1.1	137	6.8
18	48	58	0.9	98	1.1	138	11
19	0.6	59	0.7	99	0.6	139	1.7
20	1.1	60	0.6	100	1.2	140	3.6
21	0.9	61	1	101	1.2	141	8.8
22	1.3	62	0.7	102	1.3	142	3.6
23	3.3	63	1.2	103	1.4	143	3.5
24	3.9	64	0.8	104	10.6	144	2.2
25	2.4	65	2	105	1.2	145	2.7
26	1.4	66	0.4	106	4.3	146	3
27	6	67	1.4	107	4.5	147	3.3
28	11.2	68	1.3	108	14.7	148	0.9
29	1.2	69	1.1	109	1.5	149	2.6
30	8.2	70	1.2	110	1.9	150	2
31	7.7	71	1.1	111	3.4	151	1.6
32	5.3	72	1.8	112	2.1	152	1.5
33	1.2	73	1	113	1.4	153	0.8
34	1.9	74	2.4	114	2	154	4.6
35	1.2	75	0.5	115	3.9	155	2
36	1.6	76	2.9	116	2.6	156	0.9
37	1.1	77	2.1	117	1.4	157	2.2
38	3.4	78	3.4	118	1.3	158	2
39	2	79	1.5	119	1.1		
40	3.4	80	1.7	120	2.8		

Table 4: Distance of vegetation behind the back beach (m)

Shoreline Measurement No	Distance of vegetation behind the back beach (m)	Shoreline Measurement No	Distance of vegetation behind the back beach (m)	Shoreline Measurement No	Distance of vegetation behind the back beach (m)	Shoreline Measurement No	Distance of vegetation behind the back beach (m)
1	79.5	41	500	81	84	121	86
2	69	42	302.22	82	22	122	
3	97	43	28	83	13.35	123	92
4	34	44	193.76	84	20	124	
5	41	45	135.71	85	17.05	125	
6	37	46		86	25.83	126	65
7	492	47	180	87	33	127	40.87
8	496	48	65.65	88	207	128	40
9	452	49	95	89	402	129	
10	490	50	164.65	90	137	130	
11	496	51	120	91	208	131	390
12	496	52	129	92	227.19	132	
13	433	53		93	402	133	376
14	340	54		94	415	134	491
15	461	55	66.3	95	217.83	135	474.2
16	260	56		96	181.94	136	440.41
17	105	57	214	97	400	137	102
18	500	58		98	340.5	138	300
19	408	59	27	99	354.88	139	273
20	337.04	60	230	100	488.79	140	239
21	167	61	183.5	101	480	141	368.49
22	256.08	62	229.3	102	485	142	307
23	4	63	343.39	103	490	143	207.51
24	251	64	10	104	110	144	131.78
25	350	65	55	105	128	145	219.03
26	477.55	66	352.63	106		146	358.27
27	60.66	67	198.87	107	44	147	368.47
28		68	274.96	108	306	148	263
29		69	38.65	109		149	378.24
30	170.7	70	88.81	110	490	150	127.59
31	464.39	71	67	111	500	151	481
32	299	72	105	112	424	152	400.5
33		73	325	113		153	360.09
34	228.32	74	390	114	164	154	491.83
35	347	75		115		155	485.04
36	222	76		116		156	271.28
37	67	77		117		157	321
38	56.62	78	28	118		158	345
39	18.51	79	6	119			
40	249	80		120	57.02		

Table 5: Distance of built structures behind the back beach (m)

Shoreline Measurement No	Distance of Built Structures behind the back beach (m)	Shoreline Measurement No	Distance of Built Structures behind the back beach (m)	Shoreline Measurement No	Distance of Built Structures behind the back beach (m)	Shoreline Measurement No	Distance of Built Structures behind the back beach (m)
1		41		81	394	121	380
2	3	42	197.78	82	450	122	500
3	3	43	482	83	449	123	395
4	3.1	44	306.24	84	426	124	500
5		45	364.29	85	294	125	500
6		46	500	86	410	126	383
7	8	47	82	87	415	127	311
8	4	48	337.14	88	273	128	455
9	48	49	316	89	98	129	500
10		50	335.35	90	363	130	500
11	4	51	230	91	292	131	114
12	4	52	359	92	272.81	132	300
13	67	53	500	93	86	133	59.37
14	160	54	500	94		134	9
15	39	55	433.7	95	282.17	135	25.8
16	240	56	342	96	295.47	136	59
17	295	57	80	97	75	137	343.9
18		58	198.73	98	32.87	138	146
19	56.1	59	63.28	99	145.12	139	223
20	162.96	60	35	100	11.21	140	260.44
21	57.28	61	208	101	15	141	127
22		62	103	102	15	142	193
23	477	63	133.38	103	10	143	171.56
24	138.22	64	490	104	65	144	73.12
25	105	65	5	105	29.45	145	97.65
26		66	30.18	106	455	146	141.82
27	433.34	67	63	107	423	147	12.4
28	500	68	145.21	108	36	148	46.79
29	500	69	223.98	109	400	149	5.9
30	322.3	70	261.16	110		150	4.39
31	35.61	71	367	111		151	18.26
32	201	72	338	112		152	29.87
33	500	73	100	113	30	153	139.91
34		74		114	231	154	8.17
35		75	413	115	410	155	2.4
36		76	484	116	500	156	228.72
37		77	494	117	424	157	179
38	443.58	78	366	118	428	158	55
39	481.49	79	383	119	500		
40	251	80	470	120	419		

Table 6: Rocky outcrop (%)

Shoreline Measurement No	Rocky Outcrop (%)	Shoreline Measurement No	Rocky Outcrop (%)	Shoreline Measurement No	Rocky Outcrop (%)	Shoreline Measurement No	Rocky Outcrop (%)
1		41		81		121	30
2		42		82		122	14
3		43		83		123	18
4		44		84		124	
5		45		85		125	
6		46		86		126	7.1
7		47		87		127	
8		48		88		128	4.7
9		49		89		129	1.5
10		50		90		130	1
11		51		91	76	131	1.4
12		52		92		132	1.3
13	26	53		93		133	
14	13	54		94	100	134	
15		55		95		135	
16		56		96		136	
17		57		97	100	137	
18		58		98	100	138	
19	79	59		99		139	
20	20	60		100		140	
21		61		101	100	141	
22		62		102	100	142	
23		63		103	100	143	
24	11.14	64		104		144	
25		65		105	100	145	
26		66		106		146	
27		67		107		147	
28		68		108		148	
29		69		109		149	
30		70		110		150	
31		71		111		151	
32		72		112		152	
33	55	73	3.09	113		153	
34		74		114		154	
35		75		115		155	
36		76		116		156	
37		77		117		157	
38		78		118		158	42.714
39		79		119			
40		80		120	5.62		

Table 7: Sea defences (%)

Shoreline Measurement No	Sea Defences (%)	Shoreline Measurement No	Sea Defences (%)	Shoreline Measurement No	Sea Defences (%)	Shoreline Measurement No	Sea Defences (%)
1		41		81		121	100
2		42		82		122	
3		43		83		123	100
4		44		84		124	73
5		45		85		125	
6		46		86		126	100
7		47		87		127	100
8		48		88		128	100
9		49		89		129	100
10	25	50		90		130	100
11		51		91		131	100
12		52		92		132	100
13	54	53		93		133	29
14	100	54		94		134	54
15		55		95		135	67.8
16		56		96		136	100
17		57		97		137	100
18		58		98		138	100
19	100	59		99		139	100
20	60	60		100		140	100
21		61		101		141	14.4
22		62		102		142	11.4
23	78	63		103		143	80
24	24	64		104	100	144	100
25		65		105	100	145	32
26		66		106	100	146	100
27		67		107	100	147	
28		68		108	100	148	96
29	100	69		109		149	100
30	100	70		110		150	100
31	100	71		111		151	22.8
32	100	72	35	112		152	100
33	100	73	100	113		153	92
34	100	74		114		154	
35	100	75		115		155	
36	100	76		116		156	22
37	100	77		117		157	44
38		78		118		158	100
39		79		119	2.2		
40		80		120	100		

Table 8: CVI scores for beach width

Shoreline Measurement No	Beach Width CVI Scores	Shoreline Measurement No	Beach Width CVI Scores	Shoreline Measurement No	Beach Width CVI Scores	Shoreline Measurement No	Beach Width CVI Scores
1	3	41	1	81	4	121	4
2	3	42	1	82	4	122	4
3	1	43	1	83	3	123	4
4	3	44	1	84	4	124	4
5	3	45	1	85	4	125	4
6	1	46	2	86	4	126	4
7	1	47	1	87	4	127	4
8	1	48	1	88	4	128	4
9	1	49	1	89	2	129	4
10	1	50	1	90	2	130	4
11	1	51	1	91	3	131	4
12	1	52	1	92	2	132	4
13	3	53	1	93	1	133	4
14	1	54	1	94	1	134	4
15	1	55	1	95	3	135	4
16	1	56	1	96	2	136	1
17	1	57	1	97	2	137	1
18	1	58	1	98	3	138	1
19	1	59	1	99	2	139	2
20	1	60	2	100	3	140	2
21	1	61	2	101	3	141	2
22	1	62	3	102	4	142	2
23	1	63	4	103	2	143	1
24	1	64	4	104	2	144	1
25	1	65	4	105	3	145	1
26	1	66	4	106	2	146	1
27	1	67	4	107	3	147	1
28	2	68	4	108	4	148	1
29	4	69	4	109	4	149	1
30	4	70	2	110	4	150	1
31	3	71	1	111	4	151	2
32	1	72	1	112	3	152	2
33		73	2	113	3	153	2
34		74	4	114	4	154	2
35	1	75	4	115	4	155	2
36	1	76	4	116	1	156	2
37	1	77	4	117	1	157	2
38	1	78	4	118	4	158	2
39	1	79	4	119	4		
40	1	80	4	120	4		

Table 9: CVI scores for dune width

Shoreline Measurement No	Dune Width CVI Scores	Shoreline Measurement No	Dune Width CVI Scores	Shoreline Measurement No	Dune Width CVI Scores	Shoreline Measurement No	Dune Width CVI Scores
1	4	41	4	81	4	121	4
2	4	42	4	82	4	122	3
3		43	4	83	4	123	2
4	4	44	4	84	4	124	4
5	2	45	4	85	4	125	4
6	2	46	4	86	4	126	4
7	**4**	47	4	87	4	127	4
8	**4**	48	4	88	4	128	4
9	**4**	49	4	89	1	129	4
10	**4**	50	4	90	4	130	4
11	**4**	51	4	91	4	131	3
12	**4**	52	4	92	4	132	1
13	**4**	53	4	93	4	133	4
14	**4**	54	4	94	4	134	4
15	**4**	55	3	95	4	135	4
16	**4**	56	1	96	4	136	4
17	**4**	57	1	97	4	137	4
18	**4**	58	1	98	4	138	4
19	4	59	2	99	2	139	4
20	3	60	3	100	3	140	2
21	4	61	2	101	4	141	4
22	4	62	2	102	4	142	4
23	4	63	2	103	4	143	4
24	4	64	3	104	4	144	4
25	4	65	4	105	4	145	4
26	4	66	3	106	4	146	4
27	4	67	4	107	4	147	4
28	4	68	2	108	4	148	4
29	4	69	4	109	1	149	4
30	4	70	4	110	3	150	4
31	4	71	4	111	1	151	4
32	4	72	4	112	1	152	4
33	4	73	3	113	2	153	4
34	4	74	4	114	2	154	4
35	2	75	4	115	4	155	4
36	2	76	4	116	4	156	4
37	2	77	4	117	4	157	4
38	4	78	4	118	4	158	4
39	4	79	4	119	4		
40	4	80	4	120	4		

Table 10: CVI scores for coastal slope

Shoreline Measurement No	Coastal Slope CVI Scores	Shoreline Measurement No	Coastal Slope CVI Scores	Shoreline Measurement No	Coastal Slope CVI Scores	Shoreline Measurement No	Coastal Slope CVI Scores
1	2	41	4	81	4	121	4
2	4	42	4	82	3	122	4
3	3	43	4	83	2	123	4
4	3	44	3	84	4	124	4
5	1	45	4	85	2	125	4
6	3	46	4	86	3	126	4
7	4	47	3	87	3	127	4
8	4	48	3	88	4	128	4
9	3	49	4	89	4	129	4
10	2	50	4	90	4	130	4
11	4	51	4	91	4	131	4
12	4	52	4	92	4	132	4
13	4	53	4	93	4	133	4
14	2	54	4	94	4	134	4
15	4	55	4	95	4	135	4
16	4	56	4	96	4	136	4
17	4	57	_	97	4	137	4
18	4	58	_	98	4	138	4
19	4	59	_	99	4	139	4
20	4	60	_	100	4	140	4
21	4	61	_	101	4	141	4
22	4	62	1	102	4	142	4
23	4	63	1	103	4	143	4
24	4	64	1	104	4	144	4
25	4	65	3	105	4	145	4
26	4	66	2	106	4	146	4
27	3	67	1	107	4	147	4
28	4	68	2	108	4	148	4
29	4	69	4	109	4	149	4
30	4	70	1	110	3	150	4
31	4	71	1	111	4	151	4
32	4	72	1	112	4	152	4
33	4	73	1	113	4	153	4
34	4	74	4	114	4	154	4
35	4	75	4	115	4	155	4
36	4	76	4	116	4	156	4
37	4	77	4	117	4	157	4
38	4	78	4	118	4	158	4
39	4	79	4	119	4		
40	4	80	4	120	4		

Table 11: CVI scores for vegetation behind the back beach

Shoreline Measurement No	Vegetation Behind the Back Beach CVI Scores	Shoreline Measurement No	Vegetation Behind the Back Beach CVI Scores	Shoreline Measurement No	Vegetation Behind the Back Beach CVI Scores	Shoreline Measurement No	Vegetation Behind the Back Beach CVI Scores
1	3	41	_	81	2	121	3
2	3	42	_	82	4	122	3
3	_	43	4	83	_	123	_
4	4	44	4	84	_	124	_
5	2	45	_	85	3	125	4
6	2	46	4	86	2	126	
7	2	47	_	87	2	127	2
8	2	48	_	88	_	128	
9	2	49	4	89	2	129	4
10	3	50	4	90	2	130	2
11	2	51	4	91	2	131	3
12	2	52	_	92	4	132	2
13	2	53	_	93	2	133	2
14	2	54	2	94	3	134	4
15	2	55	_	95	2	135	4
16	2	56	4	96	2	136	2
17	3	57	4	97	2	137	3
18	2	58	4	98	2	138	2
19	2	59	4	99	2	139	4
20	2	60	4	100	3	140	4
21	2	61	4	101	2	141	4
22	2	62	2	102	2	142	3
23	3	63	2	103	2	143	2
24	2	64	2	104	2	144	2
25	2	65	2	105	2	145	_
26	2	66	2	106	2	146	_
27	2	67	2	107	2	147	_
28	2	68	2	108	4	148	4
29	2	69	2	109	4	149	4
30	2	70	2	110	2	150	_
31	2	71	2	111	2	151	4
32		72	3	112	2	152	4
33	2	73	2	113	4	153	4
34	2	74	2	114	3	154	4
35	2	75	2	115	3	155	4
36	_	76	3	116	_	156	4
37	3	77	2	117	3	157	4
38	_	78	4	118	4	158	4
39	_	79	2	119	4		
40	_	80	2	120	3		

Table 12: CVI scores for built structures behind the back beach

Shoreline Measurement No	Built Structures Behind the Back Beach CVI Scores	Shoreline Measurement No	Built Structures Behind the Back Beach CVI Scores	Shoreline Measurement No	Built Structures Behind the Back Beach CVI Scores	Shoreline Measurement No	Built Structures Behind the Back Beach CVI Scores
1	4	41	2	81	_	121	2
2	4	42	2	82	2	122	2
3	2	43	2	83	2	123	2
4	2	44	2	84	2	124	2
5	4	45	2	85	2	125	2
6	4	46	2	86	4	126	2
7	4	47	2	87	3	127	4
8	4	48	2	88	2	128	3
9	4	49	2	89	_	129	4
10	2	50	2	90	_	130	4
11	3	51	2	91	_	131	2
12	2	52	2	92	_	132	3
13	2	53	2	93	4	133	3
14	3	54	3	94	2	134	2
15	3	55	2	95	2	135	4
16	3	56	_	96	2	136	4
17	4	57	4	97	4	137	4
18	4	58	4	98	_	138	3
19	3	59	4	99	2	139	2
20	4	60	_	100	2	140	2
21	4	61	_	101	4	141	2
22	4	62	4	102	4	142	2
23	4	63	4	103	3	143	4
24	4	64	4	104	4	144	_
25	4	65	_	105	4	145	2
26	3	66	4	106	4	146	2
27	4	67	4	107	4	147	2
28	4	68	4	108	2	148	2
29	2	69	3	109	2	149	2
30	3	70	4	110	2	150	2
31	4	71	2	111		151	2
32	2	72	2	112	3	152	2
33	_	73	_	113	2	153	2
34	_	74	4	114	2	154	2
35	_	75	3	115	2	155	2
36	4	76	4	116	2	156	2
37	2	77		117	4	157	2
38	2	78	2	118	2	158	2
39	2	79	3	119	2		
40	2	80	3	120	2		

Table 13: CVI scores for rocky outcrop

Shoreline Measurement No	Rocky Outcrop CVI Scores	Shoreline Measurement No	Rocky Outcrop CVI Scores	Shoreline Measurement No	Rocky Outcrop CVI Scores	Shoreline Measurement No	Rocky Outcrop CVI Scores
1	4	41	4	81	4	121	2
2	4	42	4	82	4	122	
3	4	43	4	83	4	123	2
4	4	44	4	84	4	124	4
5	4	45	4	85	4	125	
6	4	46	4	86	4	126	4
7	4	47	4	87	4	127	4
8	4	48	4	88	4	128	4
9	4	49	4	89	4	129	4
10	4	50	4	90	4	130	4
11	4	51	4	91	1	131	4
12	4	52	4	92	4	132	4
13	2	53	4	93	4	133	
14	3	54	4	94	1	134	4
15	4	55	4	95	4	135	4
16	4	56	4	96	4	136	4
17	4	57	4	97	1	137	4
18	4	58	4	98	1	138	4
19	1	59	4	99	4	139	4
20	3	60	4	100	4	140	3
21	4	61	4	101	1	141	4
22	4	62	4	102	1	142	
23	4	63	4	103	1	143	4
24	3	64	4	104	1	144	4
25	4	65	4	105	1	145	4
26	4	66	4	106	1	146	4
27	4	67	4	107	1	147	
28	4	68	4	108	1	148	
29	4	69	4	109	4	149	4
30	4	70	4	110	4	150	4
31	4	71	4	111	4	151	
32	4	72	4	112	4	152	4
33	1	73	4	113	4	153	
34	4	74	1	114	4	154	
35	4	75	4	115	4	155	
36	4	76	4	116	4	156	
37	4	77	4	117	4	157	
38	4	78	4	118	4	158	4
39	4	79	4	119	4		
40	4	80	4	120	4		

Table 14: CVI scores for sea defences

Shoreline Measurement No	Sea Defences CVI Scores	Shoreline Measurement No	CVI Scores	Shoreline Measurement No	CVI Scores	Shoreline Measurement No	CVI Scores
1	4	41	4	81	4	121	1
2	4	42	4	82	4	122	
3	4	43	4	83	4	123	1
4	4	44	4	84	4	124	1
5	4	45	4	85	4	125	
6	4	46	4	86	4	126	1
7	**4**	47	4	87	4	127	1
8	**4**	48	4	88	4	128	1
9	**4**	49	4	89	4	129	1
10	**2**	50	4	90	4	130	1
11	**4**	51	4	91	4	131	1
12	**4**	52	4	92	4	132	1
13	**1**	53	4	93	4	133	2
14	**1**	54	4	94	4	134	1
15	**4**	55	4	95	4	135	1
16	**4**	56	4	96	4	136	1
17	**4**	57	4	97	4	137	1
18	**4**	58	4	98	4	138	1
19	1	59	4	99	4	139	1
20	1	60	4	100	4	140	1
21	4	61	4	101	4	141	3
22	4	62	4	102	4	142	3
23	1	63	4	103	4	143	1
24	2	64	4	104	1	144	1
25	4	65	4	105	1	145	2
26	4	66	4	106	1	146	1
27		67	4	107	1	147	
28		68	4	108	1	148	1
29	1	69	4	109	4	149	1
30	1	70	4	110	4	150	1
31	1	71	4	111	4	151	2
32	1	72	4	112	4	152	1
33	1	73	2	113	4	153	1
34	1	74	1	114	4	154	
35	1	75	4	115	4	155	
36	1	76	4	116	4	156	2
37	1	77	4	117	4	157	2
38	4	78	4	118	4	158	1
39	4	79	4	119	4		
40	4	80	4	120	1		

Table 15: Aggregated CVI scores for PCVI

Shoreline Measurement No	CVI Scores	Shoreline Measurement No	CVI Scores	Shoreline Measurement No	CVI Scores	Shoreline Measurement No	CVI Scores
1	21	41	22	81	24	121	17
2	21	42	24	82	24	122	10
3	17	43	25	83	24	123	17
4	21	44	25	84	24	124	15
5	16	45	25	85	24	125	10
6	16	46	19	86	24	126	20
7	22	47	24	87	24	127	20
8	23	48	26	88	24	128	20
9	23	49	26	89	20	129	16
10	19	50	25	90	22	130	16
11	24	51	25	91	20	131	18
12	23	52	25	92	22	132	13
13	19	53	22	93	24	133	16
14	21	54	22	94	18	134	20
15	21	55	25	95	22	135	20
16	18	56	19	96	24	136	19
17	19	57	23	97	22	137	17
18	17	58	20	98	23	138	19
19	20	59	26	99	21	139	18
20	20	60	25	100	23	140	17
21	27	61	23	101	22	141	19
22	22	62	23	102	21	142	17
23	23	63	23	103	22	143	19
24	22	64	25	104	16	144	21
25	25	65	28	105	19	145	21
26	22	66	22	106	12	146	19
27	21	67	24	107	18	147	15
28	15	68	20	108	18	148	16
29	19	69	24	109	16	149	20
30	20	70	24	110	17	150	21
31	22	71	24	111	15	151	17
32	21	72	23	112	16	152	20
33	16	73	20	113	19	153	15
34	17	74	13	114	20	154	14
35	15	75	19	115	19	155	16
36	16	76	19	116	19	156	18
37	17	77	19	117	19	157	19
38	26	78	23	118	19	158	22
39	26	79	23	119	19		
40	23	80	19	120	20		

Table 16: PCVI measurements for seven physical parameters (overall)

Shoreline No	Beach Width	Dune Width	Coastal Slope	Dis Vegetation	Dist. Built Structures	Rocky Outcrop	Sea Defences	Region
1	630	17.49	2.5	79.5				Spurn Head
2	360	18		69	3			Spurn Head
3	364			97	3			Spurn Head
4	260	13		34	3.1			Spurn Head
5	109	59		41				Spurn Head
6	170	63		37				Spurn Head
7	76		13.3	492	8			Hallsands
8	21		17.8	496	4			Hallsands
9	20.71		19.2	452	48			Hallsands
10	21.26	10	6.8	490			25	Hallsands
11	26.3		10.3	496	4			Hallsands
12	24		19.8	496	4			Hallsands
13	25.6		6	433	67	26	54	Hallsands
14	27.34		2.4	340	160	13	100	Hallsands
15	125		36	461	39			Lynmouth
16	213		21.3	260	240			Lynmouth
17	378		29.5	105	295			Lynmouth
18	121		48	500				Lynmouth
19	11.39	21.44	0.6	408	56.1	79	100	Happisburgh
20	18.76	33	1.1	337.04	162.96	20	60	Happisburgh
21	54.13		0.9	167	57.28			Happisburgh
22	34.7		1.3	256.08				Happisburgh
23	60.57		3.3	4	477		78	Happisburgh
24	41.64		3.9	251	138.22	11.14	24	Happisburgh
25	41.25		2.4	350	105			Happisburgh
26	42.9		1.4	477.55				Happisburgh
27	35.1		6	60.66	433.34			Dawlish
28	74.73		11.2		500			Dawlish
29	42.23		1.2		500		100	Dawlish
30	21.22		8.2	170.7	322.3		100	Dawlish
31	27.29		7.7	464.39	35.61		100	Dawlish
32	32.42		5.3	299	201		100	Dawlish
33	37.63		1.2		500	55	100	Dawlish
34	139		1.9	228.32			100	Dawlish
35	135	78.79	1.2	347			100	Dawlish
36	91.56	107.8	1.6	222			100	Dawlish
37	107	79	1.1	67			100	Dawlish
38	17.44		3.4	56.62	443.58			Great Yarmouth
39	17.34		2	18.51	481.49			Great Yarmouth
40	15.78		3.4	249	251			Great Yarmouth
41	28.3		4.1	500				Great Yarmouth
42	58.19		3.6	302.22	197.78			Great Yarmouth

43	42.22		2.2	28	482			Great Yarmouth
44	1.4		1.7	193.76	306.24			Great Yarmouth
45	1.4		0.9	135.71	364.29			Great Yarmouth
46	590		3.1		500			Great Yarmouth
47	565	16	1.8	180	82			Great Yarmouth
48	12		2.3	65.65	337.14			Great Yarmouth
49	13.75		3.8	95	316			Great Yarmouth
50	10.05		1.7	164.65	335.35			Great Yarmouth
51	11.61		0.5	120	230			Great Yarmouth
52	12.54		1.8	129	359			Great Yarmouth
53	14.72		1.4		500			Great Yarmouth
54	14.53		1.7		500			Great Yarmouth
55	10.16	35	0.5	66.3	433.7			Great Yarmouth
56	18.48	304	1.5		342			Great Yarmouth
57	17.35	336	1.1	214	80			Great Yarmouth
58	11	251	0.9		198.73			Great Yarmouth
59	10.39	60	0.7	27	63.28			Great Yarmouth
60	12.36	33	0.6	230	35			Great Yarmouth
61	17.26	115	1	183.5	208			Great Yarmouth
62	16.68	60	0.7	229.3	103			Great Yarmouth
63	19.29	71	1.2	343.39	133.38			Great Yarmouth
64	6.72	47	0.8	10	490			Great Yarmouth
65	7.4	17	2	55	5			Great Yarmouth
66	296	91	0.4	352.63	30.18			Skegness
67	246	34.32	1.4	198.87	63			Skegness
68	223	157	1.3	274.96	145.21			Skegness
69	143		1.1	38.65	223.98			Skegness
70	132		1.2	88.81	261.16			Skegness
71	143.76		1.1	67	367			Skegness
72	145.93		1.8	105	338		35	Skegness
73	309	55.17	1	325	100	3.09	100	Skegness
74	326	9.5	2.4	390				Skegness
75	296		0.5		413			Skegness
76	255		2.9		484			Skegness
77	263	39.36	2.1		494			Skegness
78	220	20	3.4	28	366			Skegness
79	214		1.5	6	383			Skegness
80	160		1.7		470			Skegness
81	129		1.2	84	394			Skegness
82	128		1.3	22	450			Skegness
83	139		2.2	13.35	449			Skegness
84	219		1.3	20	426			Skegness
85	159		0.9	17.05	294			Skegness
86	173		3.9	25.83	410			Skegness

87	220		2.9	33	415			Skegness
88	220		2	207	273			Skegness
89	255	184	0.6	402	98			Benbecula
90	213		1.9	137	363			Benbecula
91	50		1.4	208	292	76		Benbecula
92	107		0.7	227.19	272.81			Benbecula
93	121		1.1	402	86			Benbecula
94	61		1.2	415		100		Benbecula
95	107		1.5	217.83	282.17			Benbecula
96	53		0.9	181.94	295.47			Benbecula
97	82		1.1	400	75	100		Benbecula
98	37		1.1	340.5	32.87	100		Benbecula
99	111.35	58.91	0.6	354.88	145.12			Benbecula
100	148	49.81	1.2	488.79	11.21			Benbecula
101	60		1.2	480	15	100		Benbecula
102	113.7		1.3	485	15	100		Benbecula
103	67.99		1.4	490	10	100		Benbecula
104	72		10.6	110	65		100	Aberystwyth
105	83		1.2	128	29.45	100	100	Aberystwyth
106	168		4.3		455		100	Aberystwyth
107	67		4.5	44	423		100	Aberystwyth
108	63		14.7	306	36		100	Aberystwyth
109	179	289	1.5		400			Port Talbot
110		33.75	1.9	490				Port Talbot
111		515	3.4	500				Port Talbot
112	835	345	2.1	424				Port Talbot
113	530	66	1.4		30			Port Talbot
114	382	55	2	164	231			Port Talbot
115	351		3.9		410			Port Talbot
116	327		2.6		500			Port Talbot
117	373		1.4		424			Port Talbot
118	360		1.3		428			Port Talbot
119	364		1.1		500		2.2	Port Talbot
120	245		2.8	57.02	419	5.62	100	Port Talbot
121	123		4.2	86	380	30	100	Port Talbot
122	192	49	2.3		500	14		Port Talbot
123	100	110.68	1.2	92	395	18	100	Port Talbot
124	198		15.6		500		73	Port Talbot
125	339		10.9		500			Port Talbot
126	315		3.9	65	383	7.1	100	Port Talbot
127	323		2.6	40.87	311		100	Port Talbot
128	335		2.7	40	455	4.7	100	Port Talbot
129	302		2.1		500	1.5	100	Port Talbot
130	371		3.8		500	1	100	Port Talbot

131	366	29	3	390	114	1.4	100	Port Talbot
132	557	163	3.1		300	1.3	100	Port Talbot
133	590		6.7	376	59.37		29	Llanelli
134	775		1	491	9	1	54	Llanelli
135	500		3	474.2	25.8	5.3	67.8	Llanelli
136	604		4.1	440.41	59	5.22	100	Llanelli
137	820		6.8	102	343.9	2.77	100	Llanelli
138	542		11	300	146	3.7	100	Llanelli
139	400		1.7	273	223	5.5	100	Llanelli
140	95	95	3.6	239	260.44	17	100	Llanelli
141	1400		8.8	368.49	127	0.94	14.4	Llanelli
142	1600		3.6	307	193		11.4	Llanelli
143	1900		3.5	207.51	171.56	2.38	80	Llanelli
144	1900		2.2	131.78	73.12	1.03	100	Llanelli
145	898		2.7	219.03	97.65	0.87	32	Llanelli
146	995		3	358.27	141.82	0.8	100	Llanelli
147	550		3.3	368.47	12.4			Llanelli
148	650		0.9	263	46.79		96	Llanelli
149	760		2.6	378.24	5.9	5.53	100	Llanelli
150	696		2	127.59	4.39	1.97	100	Llanelli
151	470		1.6	481	18.26		22.8	Llanelli
152	384		1.5	400.5	29.87	1.3	100	Llanelli
153	362		0.8	360.09	139.91		92	Llanelli
154	250		4.6	491.83	8.17			Llanelli
155	120		2	485.04	2.4			Llanelli
156	38		0.9	271.28	228.72		22	Llanelli
157	18		2.2	321	179	12.9	44	Llanelli
158	65		2	345	55	6.47	100	Llanelli

Table 17: CVI scores for physical analysis

Shoreline No	Beach Width	Dune Width	Coastal Slope	Dist. Vegetation	Dist. Built Str	Rocky Outcrop	Sea Defences	Aggregated CVI	Region
1	1	4	4	4		4	4	21	Spurn Head
2	1	4	4	4	4	4	4	25	Spurn Head
3	1		4	4	4	4	4	21	Spurn Head
4	1	4	4	4	4	4	4	25	Spurn Head
5	2	2	4	4		4	4	20	Spurn Head
6	2	2	4	4		4	4	20	Spurn Head
7	3	4	1	2	4	4	4	22	Hallsands
8	4	4	1	2	4	4	4	23	Hallsands
9	4	4	1	2	4	4	4	23	Hallsands
10	4	4	3	2		4	2	19	Hallsands
11	4	4	2	2	4	4	4	24	Hallsands
12	4	4	1	2	4	4	4	23	Hallsands
13	4	4	2	2	4	2	1	19	Hallsands
14	4	4	4	2	3	3	1	21	Hallsands
15	2	4	1	2	4	4	4	21	Lynmouth
16	1	4	1	2	2	4	4	18	Lynmouth
17	1	4	1	3	2	4	4	19	Lynmouth
18	2	4	1	2		4	4	17	Lynmouth
19	4	4	4	2	4	1	1	20	Happisburgh
20	4	3	4	2	3	3	1	20	Happisburgh
21	4	4	4	3	4	4	4	27	Happisburgh
22	4	4	4	2		4	4	22	Happisburgh
23	4	4	4	4	2	4	1	23	Happisburgh
24	4	4	4	2	3	3	2	22	Happisburgh
25	4	4	4	2	3	4	4	25	Happisburgh
26	4	4	4	2		4	4	22	Happisburgh
27	4	4	3	4	2	4		21	Dawlish
28	3	4	2		2	4		15	Dawlish
29	4	4	4		2	4	1	19	Dawlish
30	4	4	2	3	2	4	1	20	Dawlish
31	4	4	3	2	4	4	1	22	Dawlish
32	4	4	3	2	3	4	1	21	Dawlish
33	4	4	4		2	1	1	16	Dawlish
34	2	4	4	2		4	1	17	Dawlish
35	2	2	4	2		4	1	15	Dawlish
36	3	2	4	2		4	1	16	Dawlish
37	2	2	4	4		4	1	17	Dawlish

38	4	4	4	4	2	4	4	26	Great Yarmouth
39	4	4	4	4	2	4	4	26	Great Yarmouth
40	4	4	3	2	2	4	4	23	Great Yarmouth
41	4	4	4	2		4	4	22	Great Yarmouth
42	3	4	4	2	3	4	4	24	Great Yarmouth
43	3	4	4	4	2	4	4	25	Great Yarmouth
44	4	4	4	3	2	4	4	25	Great Yarmouth
45	4	4	4	3	2	4	4	25	Great Yarmouth
46	1	4	4		2	4	4	19	Great Yarmouth
47	1	4	4	3	4	4	4	24	Great Yarmouth
48	4	4	4	4	2	4	4	26	Great Yarmouth
49	4	4	4	4	2	4	4	26	Great Yarmouth
50	4	4	4	3	2	4	4	25	Great Yarmouth
51	4	4	4	3	2	4	4	25	Great Yarmouth
52	4	4	4	3	2	4	4	25	Great Yarmouth
53	4	4	4		2	4	4	22	Great Yarmouth
54	4	4	4		2	4	4	22	Great Yarmouth
55	4	3	4	4	2	4	4	25	Great Yarmouth
56	4	1	4		2	4	4	19	Great Yarmouth
57	4	1	4	2	4	4	4	23	Great Yarmouth
58	4	1	4		3	4	4	20	Great Yarmouth
59	4	2	4	4	4	4	4	26	Great Yarmouth
60	4	3	4	2	4	4	4	25	Great Yarmouth
61	4	2	4	3	2	4	4	23	Great Yarmouth
62	4	2	4	2	3	4	4	23	Great Yarmouth
63	4	2	4	2	3	4	4	23	Great Yarmouth
64	4	3	4	4	2	4	4	25	Great Yarmouth
65	4	4	4	4	4	4	4	28	Great Yarmouth
66	1	3	4	2	4	4	4	22	Skegness
67	1	4	4	3	4	4	4	24	Skegness
68	1	2	4	2	3	4	4	20	Skegness
69	2	4	4	4	2	4	4	24	Skegness
70	2	4	4	4	2	4	4	24	Skegness
71	2	4	4	4	2	4	4	24	Skegness
72	2	4	4	3	2	4	4	23	Skegness
73	1	3	4	2	4	4	2	20	Skegness
74	1	4	4	2		1	1	13	Skegness
75	1	4	4		2	4	4	19	Skegness
76	1	4	4		2	4	4	19	Skegness
77	1	4	4		2	4	4	19	Skegness
78	1	4	4	4	2	4	4	23	Skegness
79	1	4	4	4	2	4	4	23	Skegness
80	1	4	4		2	4	4	19	Skegness
81	2	4	4	4	2	4	4	24	Skegness

82	2	4	4	4	2	4	4	24	Skegness
83	2	4	4	4	2	4	4	24	Skegness
84	2	4	4	4	2	4	4	24	Skegness
85	2	4	4	4	2	4	4	24	Skegness
86	2	4	4	4	2	4	4	24	Skegness
87	2	4	4	4	2	4	4	24	Skegness
88	2	4	4	4	2	4	4	24	Skegness
89	1	1	4	2	4	4	4	20	Benbecula
90	1	4	4	3	2	4	4	22	Benbecula
91	3	4	4	2	2	1	4	20	Benbecula
92	2	4	4	2	2	4	4	22	Benbecula
93	2	4	4	2	4	4	4	24	Benbecula
94	3	4	4	2		1	4	18	Benbecula
95	2	4	4	2	2	4	4	22	Benbecula
96	3	4	4	3	2	4	4	24	Benbecula
97	3	4	4	2	4	1	4	22	Benbecula
98	4	4	4	2	4	1	4	23	Benbecula
99	2	2	4	2	3	4	4	21	Benbecula
100	2	3	4	2	4	4	4	23	Benbecula
101	3	4	4	2	4	1	4	22	Benbecula
102	2	4	4	2	4	1	4	21	Benbecula
103	3	4	4	2	4	1	4	22	Benbecula
104	3	4	2	3	4	1	1	18	Aberystwyth
105	3	4	4	3	4	1	1	20	Aberystwyth
106	1	4	3		2	1	1	12	Aberystwyth
107	3	4	3	4	2	1	1	18	Aberystwyth
108	3	4	1	2	4	1	1	16	Aberystwyth
109	1	1	4		2	4	4	16	Port Talbot
110		3	4	2		4	4	17	Port Talbot
111		1	4	2		4	4	15	Port Talbot
112	1	1	4	2		4	4	16	Port Talbot
113	1	2	4		4	4	4	19	Port Talbot
114	1	2	4	3	2	4	4	20	Port Talbot
115	1	4	4		2	4	4	19	Port Talbot
116	1	4	4		2	4	4	19	Port Talbot
117	1	4	4		2	4	4	19	Port Talbot
118	1	4	4		2	4	4	19	Port Talbot
119	1	4	4		2	4	4	19	Port Talbot
120	1	4	4	4	2	4	1	20	Port Talbot
121	1	4	3	4	2	2	1	17	Port Talbot
122	1	3	4		2			10	Port Talbot
123	2	2	4	4	2	2	1	17	Port Talbot
124	1	4	3		2	4	1	15	Port Talbot
125	1	4	3		2			10	Port Talbot

126	1	4	4	4	2	4	1	20	Port Talbot
127	1	4	4	4	2	4	1	20	Port Talbot
128	1	4	4	4	2	4	1	20	Port Talbot
129	1	4	4		2	4	1	16	Port Talbot
130	1	4	4		2	4	1	16	Port Talbot
131	1	3	4	2	3	4	1	18	Port Talbot
132	1	1	4		2	4	1	13	Port Talbot
133	1	4	3	2	4		2	16	Llanelli
134	1	4	4	2	4	4	1	20	Llanelli
135	1	4	4	2	4	4	1	20	Llanelli
136	1	4	3	2	4	4	1	19	Llanelli
137	1	4	2	3	2	4	1	17	Llanelli
138	1	4	4	2	3	4	1	19	Llanelli
139	1	4	4	2	2	4	1	18	Llanelli
140	3	2	4	2	2	3	1	17	Llanelli
141	1	4	2	2	3	4	3	19	Llanelli
142	1	4	4	2	3		3	17	Llanelli
143	1	4	4	2	3	4	1	19	Llanelli
144	1	4	4	3	4	4	1	21	Llanelli
145	1	4	4	2	4	4	2	21	Llanelli
146	1	4	4	2	3	4	1	19	Llanelli
147	1	4	4	2	4			15	Llanelli
148	1	4	4	2	4		1	16	Llanelli
149	1	4	4	2	4	4	1	20	Llanelli
150	1	4	4	3	4	4	1	21	Llanelli
151	1	4	4	2	4		2	17	Llanelli
152	1	4	4	2	4	4	1	20	Llanelli
153	1	4	4	2	3		1	15	Llanelli
154	1	4	3	2	4			14	Llanelli
155	2	4	4	2	4			16	Llanelli
156	4	4	4	2	2		2	18	Llanelli
157	4	4	4	2	3		2	19	Llanelli
158	3	4	4	2	4	4	1	22	Llanelli

Table 18: Economic parameters and selection process

Parameters	Description
Population in Coastal Vulnerability Zones	More than 50% of population is living near to the UK coastlines and 139 coastal regions across the UK (Eurostat, 2013)
Infrastructures **(Properties, roads, etc.)**	More than 6 million properties are at coastal risk (5.3 m in England and >170, 000 in Scotland) Very valuable infrastructure located in the coastal zones (E.g.: Dawlish, Aberystwyth, Great Yarmouth, etc.) (Hooper and Chapman, 2012; Turner et al., 1997)
Land Use	Around 60 per cent of the best agricultural land is 5 m or less above sea level (Zsamboky et al., 2011)
Rain Fall	Heavy rain fall trends/ events across the UK in recent decades (Osborn et al., 2002; Maraun et al., 2008)
Erosion	High coastal erosion at some places of the UK; E.g.; Happisburgh; Spurn Head; Hallsands, etc. (Poulton et al., 2006; Saye et al., 2005; Macfarlane, 2013)
Unpopulated coastal Zones	In some areas population is very less (Benbecula 9 people per sq. (Richards et al., 2007;)
Coastal Discharges	Coastal discharges are not even across the UK and some regions are in high amounts (Morris et al., 2000; Turner et al., 1998; Walling and Webb, 1985;
Urbanised Area	Urbanised zones with huge population and risks (Small, 2003)
Frequency of Floods	Increased trends in frequency of floods (Hannaford and Marsh, 2008; Robson, 2002; Pall et al., 2011; Watts et al., 2015)
Damage Costs	Great upsurge in disaster damage and coastal damage (Nicholas, 2007)
Flood/storm impact	Increased the severity of flood/storm impact in recent periods (Schwierz et al., 2010; Kron et al., 2012)
Economic value of place	Economic value of the place plays vital role in economic studies as well as disaster management studies (Porter, 2000; Hall, 2000; North, 1955; Kusumasari et al., 2010)
Return period of storms	Return period of storm are highly changed in recent years (Prudhomme et al., 2003; Wheater, 2006)
Coastal defences	Coastal defences advantages and disadvantages (Garbutt et al., 2006; Airoldi et al., 2005; Phillips et al., 2009) (Successful and unsuccessful coastal defences)
High growth of civilisation alongside the coasts	Fast growth of civilisation alongside of coasts (Turner et al., 1998; Walton, 2000; Cave et al., 2003) (Eg: Skegness, Great Yarmouth, etc.)
Marine Industry Growth **(Ports business, warships, artificial constructions on the sea's and rivers, etc.)**	Marine Industry Growth (Ports business, warships, artificial constructions on the sea's and rivers, etc.) 90% of trade is commuting through the seaports (Warwick University, 2010). Maritime industries and the service sector annually contribute >£17 billion to the UK economy and it will be £25 billion by 2020 (Marine Industries Leadership

	Council, 2011)
Drainage System	Poor Drainage system cause to the severe problems particularly during flooding strikes (Mark et al., 2004; Tunstall et al., 2004)
Awareness and Preparedness	Public awareness and preparedness is very impartment during storm strikes (Bingunath Ingirige and Kaluarachchi, 2013; Kohn et al., 2012)
Storm Insurance	Storm Insurance face a big factor in damage estimation studies (Pielke Jr et al., 2008; Huber, 2004; Lamond et al., 2009) in particular in developed countries
Urban Growth	Rapid urban growth in coastal zones increase the vulnerability (McGranahan et al., 2007; Nicholls et al., 2007)
Warning System	How much UK has the robust warning system about natural disasters (Egg: nor waning system during tornado strikes (Kantamaneni, 2015)
Topography	UK consists different land scape structures and this also plays a role in coastal vulnerability (Sutherland et al., 2006; Johnson and Priest, 2008)
Transportation	Roads and railways are plays very important role in the economic evaluation studies particularly in the economic disaster management studies. A number of storm events significantly damaged transportation infrastructure in last two decades ((Bosher et al., 2007; Dawson et al., 2016)
Penetration of warning /awareness	Sometimes disaster warning systems are not reaching to the people particularly to the remote areas (Bankoff et al., 2004; Kantamaneni et al., 2015)
Coastal Communities and age	> 274 coastal communities in England and Wales most of the coastal communities are over >60 (Atterton, 2006)
Politics and Polices	Changing political situation also plays a vital role in assessment of coastal vulnerability (Berry et al., 2006; Bogardi et al., 2006) (Eg: 2008 – Less budgets for coastal defences, huge budget in 2012); strict policy implementation in since 2012

Table 19: Economic parameters analysis

Coastal Cell	Commercial Properties	Residential Properties	Economic Value of Site	Population	Coastal Erosion	Flood Event Impact	Region
1	3	8	60	100	6	30	Happisburgh
2	1.2	4	110	27	20	35	Happisburgh
3	13.5	50	130	1100	7	36	Happisburgh
4	1.5	20	120	100	5	20	Happisburgh
5	35	200	80	4000	2.5	37	Great Yarmouth
6	38	300	100	5000	2	35	Great Yarmouth
7	42	320	120	6000	3	37	Great Yarmouth
8	105	600	120	8000	3	40	Great Yarmouth
9	55	500	130	5000	2.6	38	Great Yarmouth
10	45	440	135	4000	2	35	Great Yarmouth
11	49	600	130	3000	3.5	32	Great Yarmouth
12	31	400	100	3500	4	30	Great Yarmouth
13	33	300	110	2000	2.5	38	Great Yarmouth
14	28	240	120	2000	3	40	Great Yarmouth
15	26	220	110	1100	3.5	36	Great Yarmouth
16	22	200	100	1000	2.6	32	Great Yarmouth
17	22	190	100	1000	2.6	38	Great Yarmouth
18	0.2	0.2	2	30	5.1	9	Spurn Head
19	0.25	0.2	3	20	9.1	9.5	Spurn Head
20	1	5	20	30	0.3	5	Skegness
21	1.5	8	22	50	0.4	6	Skegness
22	10	54	28	40	0.5	10	Skegness
23	14	121	35	1000	0.8	15	Skegness
24	12	135	40	1100	1	20	Skegness
25	10	120	50	800	1	25	Skegness
26	9	94	60	750	1.2	26	Skegness
27	8	67	68	800	1.8	21	Skegness
28	9	75	65	700	2.2	19	Skegness
29	10	63	60	600	2.5	18	Skegness
30	8	81	55	500	3	19	Skegness
31	8.5	67	50	800	2.8	16	Skegness
32	7.5	27	30	800	2	17	Skegness
33	9	32	35	750	1.5	19	Skegness
34	10	40	40	800	1	20	Skegness
35	9	26.6	30	850	0.8	16	Skegness
36	12	26	25	750	0.6	15	Skegness
37	7.5	40	20	600	0.6	14	Skegness
38	0	0.9	5	1	7	12	Hallsands
39	0.1	0.6	20	4	8	13	Hallsands
40	1	11	50	36	10	16	Hallsands
41	0.5	2	30	10	9	14	Hallsands
42	28	25	90	300	3	16	Lynmouth
43	9	19	80	190	2	14	Lynmouth
44	5	26	60	300	9	20	Dawlish
45	40	598	80	3500	11	36	Dawlish
46	30	468	100	3000	20	30	Dawlish
47	16	390	90	2200	12	20	Dawlish
48	18	208	85	1500	10	18	Dawlish

49	10	130	80	800	9	17	Dawlish
50	6	32	20	700	2	3	Llanelli
51	7.2	40	30	1500	2.2	3.2	Llanelli
52	9.6	48	55	2600	3	4	Llanelli
53	12	112	60	2200	4.5	6	Llanelli
54	13.2	104	80	1800	6	9	Llanelli
55	9.7	113	100	1900	6.5	10	Llanelli
56	10.8	72	120	1700	6	10.5	Llanelli
57	0.48	1.6	20	100	1.2	2	Llanelli
58	1.2	4.8	25	200	1	3	Llanelli
59	2.4	9.6	30	200	3	3.2	Llanelli
60	4.8	11	50	300	4	5	Llanelli
61	7.2	12.7	60	850	4.8	6	Llanelli
62	2	24	25	300	5	7	Port Talbot
63	1.5	6	15	50	4	4	Port Talbot
64	6	12	8	30	3	2	Port Talbot
65	36	540	90	6700	7	20	Port Talbot
66	63	780	110	10000	9	28	Port Talbot
67	51	504	105	5000	6	31	Port Talbot
68	7	6	110	200	20	34	Port Talbot
69	0.4	2.4	150	100	18	35	Port Talbot
70	0.35	11.5	1000	20	15	36	Port Talbot
71	0.1	0	1000	0	10	35	Port Talbot
72	0.04	0	200	0	8	28	Port Talbot
73	0.02	0	150	0	8	20	Port Talbot
74	66	594	500	6600	6	18	Aberystwyth
75	42	167	300	4000	5	17	Aberystwyth
76	6	33	160	400	10	36	Benbecula
77	4	20	150	350	9.5	35.5	Benbecula
78	2	3.1	100	50	10	20	Benbecula
79	2	3	40	30	4	3	Benbecula
80	0	0.4	20	10	3	2	Benbecula

Table 20. CVI scores for economic analysis

Coastal Cell	Commercial Properties	Residential Properties	Economic Value of Site	Population	Coastal Erosion	Flood Event Impact	Aggregated CVI	Region
1	2	1	3	1	4	4	15	Happisburgh
2	1	1	4	1	5	4	16	Happisburgh
3	3	2	4	2	4	5	20	Happisburgh
4	1	1	4	1	3	4	14	Happisburgh
5	4	5	3	3	2	5	22	Great Yarmouth
6	4	5	3	3	2	4	21	Great Yarmouth
7	4	5	4	4	3	5	25	Great Yarmouth
8	5	5	4	4	3	5	26	Great Yarmouth
9	4	5	4	3	3	5	24	Great Yarmouth
10	4	5	4	3	2	5	23	Great Yarmouth
11	4	5	4	3	3	4	23	Great Yarmouth
12	4	5	3	3	3	4	22	Great Yarmouth
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14	3	5	4	2	3	5	22	Great Yarmouth
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17	3	5	3	2	3	5	21	Great Yarmouth
18	1	1	1	1	4	2	10	Spurn Head
19	1	1	1	1	5	3	12	Spurn Head
20	1	1	2	1	2	2	9	Skegness
21	1	1	2	1	2	2	9	Skegness
22	2	2	2	1	2	3	12	Skegness
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24	3	3	2	2	2	4	16	Skegness
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79	1	1	2	1	3	1	9	Benbecula
80	0	2	2	1	3	1	9	Benbecula

2. Appendix - Professional Achievements and Awards

I. RISC-KIT: Resilience-Increasing Strategies for Coasts – toolkit
EU –Funding Project – Portugal – 2017 (Won partial funding)

II. Invited Guest Researcher-British Council/Newton Fund - London –2016

III. Conference Chair/Presenter – Imperial College, London- 2016

IV. Graduate Scholar Award – 2016 (Imperial College, London)

V. Graduate Scholar Award – 2015 (University of British Colombia, Canada)

VI. Graduate Scholar Award – 2014 (Iceland)

VII. Visiting Scholar– IISc – Indian Institute of Science - Bengaluru, India (June 2nd to 2nd July 2015)

VIII. Summer Institute for Disaster and Risk Research (SIDRR) Scholarship - Beijing, China 2014

IX. Financial Support for Conference Attendance – Delhi University, 2014

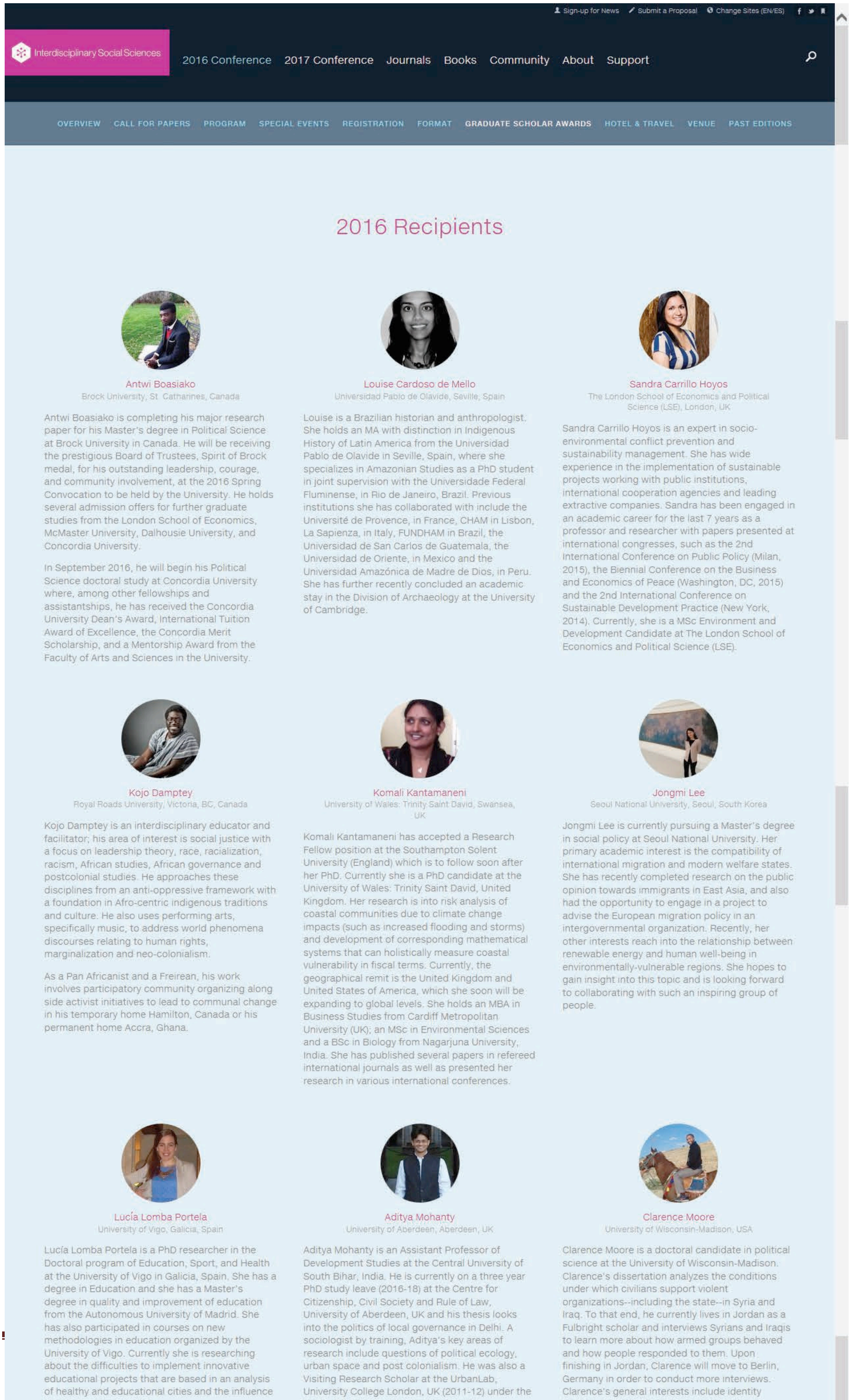
X. Financial Support for Conference Attendance – Exeter University 2013

EU –Funding Project –Portugal – 2017

Invited Guest Researcher – British Council/Newton Fund

Conference Chair/Presenter – Imperial College London-2016

Graduate Scholar Awards - (2014 -2016)



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2016 Recipients

Antwi Boasiako
Brock University, St. Catharines, Canada

Antwi Boasiako is completing his major research paper for his Master's degree in Political Science at Brock University in Canada. He will be receiving the prestigious Board of Trustees, Spirit of Brock medal, for his outstanding leadership, courage, and community involvement, at the 2016 Spring Convocation to be held by the University. He holds several admission offers for further graduate studies from the London School of Economics, McMaster University, Dalhousie University, and Concordia University.

In September 2016, he will begin his Political Science doctoral study at Concordia University where, among other fellowships and assistantships, he has received the Concordia University Dean's Award, International Tuition Award of Excellence, the Concordia Merit Scholarship, and a Mentorship Award from the Faculty of Arts and Sciences in the University.

Louise Cardoso de Mello
Universidad Pablo de Olavide, Seville, Spain

Louise is a Brazilian historian and anthropologist. She holds an MA with distinction in Indigenous History of Latin America from the Universidad Pablo de Olavide in Seville, Spain, where she specializes in Amazonian Studies as a PhD student in joint supervision with the Universidade Federal Fluminense, in Rio de Janeiro, Brazil. Previous institutions she has collaborated with include the Université de Provence, in France, CHAM in Lisbon, La Sapienza, in Italy, FUNDHAM in Brazil, the Universidad de San Carlos de Guatemala, the Universidad de Oriente, in Mexico and the Universidad Amazónica de Madre de Dios, in Peru. She has further recently concluded an academic stay in the Division of Archaeology at the University of Cambridge.

Sandra Carrillo Hoyos
The London School of Economics and Political Science (LSE), London, UK

Sandra Carrillo Hoyos is an expert in socio-environmental conflict prevention and sustainability management. She has wide experience in the implementation of sustainable projects working with public institutions, international cooperation agencies and leading extractive companies. Sandra has been engaged in an academic career for the last 7 years as a professor and researcher with papers presented at international congresses, such as the 2nd International Conference on Public Policy (Milan, 2015), the Biennial Conference on the Business and Economics of Peace (Washington, DC, 2015) and the 2nd International Conference on Sustainable Development Practice (New York, 2014). Currently, she is a MSc Environment and Development Candidate at The London School of Economics and Political Science (LSE).

Kojo Damptey
Royal Roads University, Victoria, BC, Canada

Kojo Damptey is an interdisciplinary educator and facilitator; his area of interest is social justice with a focus on leadership theory, race, racialization, racism, African studies, African governance and postcolonial studies. He approaches these disciplines from an anti-oppressive framework with a foundation in Afro-centric indigenous traditions and culture. He also uses performing arts, specifically music, to address world phenomena discourses relating to human rights, marginalization and neo-colonialism.

As a Pan Africanist and a Freirean, his work involves participatory community organizing along side activist initiatives to lead to communal change in his temporary home Hamilton, Canada or his permanent home Accra, Ghana.

Komali Kantamaneni
University of Wales: Trinity Saint David, Swansea, UK

Komali Kantamaneni has accepted a Research Fellow position at the Southampton Solent University (England) which is to follow soon after her PhD. Currently she is a PhD candidate at the University of Wales: Trinity Saint David, United Kingdom. Her research is into risk analysis of coastal communities due to climate change impacts (such as increased flooding and storms) and development of corresponding mathematical systems that can holistically measure coastal vulnerability in fiscal terms. Currently, the geographical remit is the United Kingdom and United States of America, which she soon will be expanding to global levels. She holds an MBA in Business Studies from Cardiff Metropolitan University (UK); an MSc in Environmental Sciences and a BSc in Biology from Nagarjuna University, India. She has published several papers in refereed international journals as well as presented her research in various international conferences.

Jongmi Lee
Seoul National University, Seoul, South Korea

Jongmi Lee is currently pursuing a Master's degree in social policy at Seoul National University. Her primary academic interest is the compatibility of international migration and modern welfare states. She has recently completed research on the public opinion towards immigrants in East Asia, and also had the opportunity to engage in a project to advise the European migration policy in an intergovernmental organization. Recently, her other interests reach into the relationship between renewable energy and human well-being in environmentally-vulnerable regions. She hopes to gain insight into this topic and is looking forward to collaborating with such an inspiring group of people.

Lucía Lomba Portela
University of Vigo, Galicia, Spain

Lucía Lomba Portela is a PhD researcher in the Doctoral program of Education, Sport, and Health at the University of Vigo in Galicia, Spain. She has a degree in Education and she has a Master's degree in quality and improvement of education from the Autonomous University of Madrid. She has also participated in courses on new methodologies in education organized by the University of Vigo. Currently she is researching about the difficulties to implement innovative educational projects that are based in an analysis of healthy and educational cities and the influence

Aditya Mohanty
University of Aberdeen, Aberdeen, UK

Aditya Mohanty is an Assistant Professor of Development Studies at the Central University of South Bihar, India. He is currently on a three year PhD study leave (2016-18) at the Centre for Citizenship, Civil Society and Rule of Law, University of Aberdeen, UK and his thesis looks into the politics of local governance in Delhi. A sociologist by training, Aditya's key areas of research include questions of political ecology, urban space and post colonialism. He was also a Visiting Research Scholar at the UrbanLab, University College London, UK (2011-12) under the

Clarence Moore
University of Wisconsin-Madison, USA

Clarence Moore is a doctoral candidate in political science at the University of Wisconsin-Madison. Clarence's dissertation analyzes the conditions under which civilians support violent organizations--including the state--in Syria and Iraq. To that end, he currently lives in Jordan as a Fulbright scholar and interviews Syrians and Iraqis to learn more about how armed groups behaved and how people responded to them. Upon finishing in Jordan, Clarence will move to Berlin, Germany in order to conduct more interviews. Clarence's general interests include identity

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GRADUATE SCHOLAR AWARDS | 2016 RECIPIENTS

Mukesh Dev Bhattarai

Mukesh Dev Bhattarai is a doctoral candidate under Environmental Resource and Policy Program at Southern Illinois University Carbondale, USA (SIUC). His dissertation focuses on the roles of key ingredients of agriculture in aggravating and/or mitigating impacts of climate change and identification of possible policy instruments to address the impacts of climate change. For his research, he is conducting a life cycle analysis (including carbon footprint) and implementing an interdisciplinary approach (climate science, modeling, economics, management and human behavior) to understanding the real-world impact of climate change on agriculture and business performance and practices. He holds a MS in Environmental Science and Technology from International Institute for Hydraulic and Environmental Engineering and MS in Chemical Engineering from Kirov Forest Science and Technology Academy, St. Pittsburgh, Russia. He is also associated with a SIUC project funded by US National Science Foundation on climate change impact, focusing on agriculture and water resources in the United States heartland. Prior to joining SIUC, he served as a Director, Research and Planning Department of Asian Productivity Organization in Japan.

Sabrina Dekker

Sabrina Dekker is currently undertaking her PhD at University College Dublin, where she is researching how cities are addressing the impacts of climate change on human health. Recently, she was a visiting PhD Researcher with the International Centre for Climate Governance (FEEM) in Venice, Italy, where she contributed to their work on climate change and health. Prior to commencing her PhD, Sabrina worked with Sustainable Cities in Vancouver, Canada; researching the implementation of integrated sustainability plans in Canadian and international cities to develop a framework for cities within the Sustainable Cities Plus Network. Sabrina holds a double Master's degree in Public Affairs from Sciences Po (Paris, France) and Public Policy from the Lee Kuan Yew School of Public Policy (LKY) at the National University of Singapore (Singapore). She specialized in Human Security, and Economic and Territorial Development at Sciences Po, and in Public and Global Health Policy, and Urban Development Policy at LKY. During her studies she was involved in the evaluation of Red Cross aid projects in Indonesia; and consulted the Bureau International des Expositions in the development of an evaluation framework for EXPO host cities.

Adekunle Dosumu

Adekunle Dosumu is a PhD candidate at School of Biological Sciences, University of Essex, Colchester, UK. He completed a BSc (Hons.) in Zoology and MSc in Ecology/ Environmental Biology at University of Ibadan, Nigeria. His PhD research is on environmental impact and wellbeing benefits of spectator and participant dominated sport. Adekunle is currently an Instructor Service Operator and an Environmental Champion with Transport for London (TfL). He is a member of Institute of Environmental Management and Assessment (IEMA), Essex Sustainability Institute (ESI), The Aerosol Society, The Institute of Environmental Sciences and Chartered Institute of Waste Management (CIWM). He is interested in environmental management, environmental sustainability, workplace safety and public health. He is very passionate about preserving the natural environment. His latest publication is on Greenhouse Gas Emissions: Contributions Made by Football Clubs in England.

Hamed Hakim

Hamed Hakim is a Ph.D. student at the University of Florida and is working as a graduate research assistant at Powell Center for Construction & Environment. Parallel to his Ph.D. in Construction Management, Hamed is following a Master of Science in Finance at Warrington College of Business Administration. He received his B.Sc. in Civil Engineering with an emphasis on Water Resources from Isfahan University of Technology and his M.Sc. in Construction Engineering Management from University of Florida. Since 2012, he has devoted his time to study and conduct research on green buildings and the sustainable built environment. Hamed has written case-studies and paper publications on the status of Net-Zero Energy Schools and is developing this topic over the course of his Ph.D. Hamed has over three years of working experience as a project engineer in commercial building projects, as well as experience in the heavy civil construction.

Komali Kantamaneni

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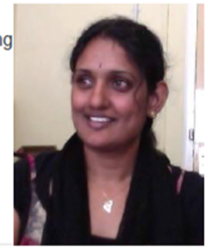
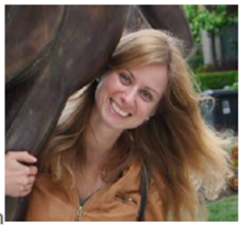


Komali Kantamaneni is a PhD research student based at the University of Wales: Trinity Saint David, United Kingdom. Her research area primarily focuses on the United Kingdom and United States of America, examining the fiscal costs incurred by coastal communities who face increasing vulnerability to coastal storm and sea level rise because of climate change. She holds a MBA in Business studies from Cardiff Metropolitan University, United Kingdom as well as a MSc degree in Environmental Sciences and a BSc in Biology from Nagarjuna University, India. To date, she has successfully published 10 papers and in addition to that, further 13 conference papers accepted for poster and oral presentations.

Lindsay Luke

Lindsay Luke has worked in resource management and environmental assessment throughout British Columbia and in the Northwest Territories. She is an alumna from Camosun College and Royal Roads University in BC. She is currently a graduate student at the University of Saskatchewan.

Miriam Matejova



Miriam Matejova is a PhD student of Political Science, a Vanier Scholar, a Killam Laureate and a Liu Scholar at the University of British Columbia in Vancouver. Her research interests are international security and global environmental politics. She has written and co-authored papers on international peacebuilding, Canada's foreign intelligence, and environmental security. Prior to coming to UBC, Miriam worked as an analyst at the Canadian International Development Agency and as an economist at Environment Canada where she specialized in federal environmental impact assessment and protection of species at risk. Miriam holds a BA (Hons) in International Studies from the University of Northern British Columbia and an MA in International Affairs from Carleton University's Norman Paterson School of International Affairs.

Kelly Stevens

Kelly Stevens grew up in Rochester, New York before moving to Tallahassee, Florida in pursuit of a master's in meteorology at Florida State University, and later a master's in public administration from the same institution. While in Florida, she also worked as a meteorologist at the Florida Department of Environmental Protection's Division of Air Resource Management in the Office of Policy Analysis and Program Management for over five years. During her time in Florida, she worked on Florida's electric utility greenhouse gas cap-and-trade rule development, co-authoring a study on offset protocols that was later published in the International Journal of Climate Change Strategies and Management. Currently, she is a PhD candidate in public administration and international affairs at the Maxwell School at Syracuse University. She works with Peter Wilcoxen and David Popp in the Center for Policy Research on energy, environmental, and technology policy research. Her dissertation focuses on changes in natural gas

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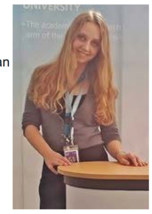
KRISTINE BELESOVA



Kristine Belesova is a doctoral student of Public Health at the London School of Hygiene and Tropical Medicine. Her research interests include climate change impacts and responses, vulnerability reduction, human security, and sustainability science. In her Ph.D. research she uses mixed methods to identify risk factors explaining child undernutrition and its health consequences in Burkina Faso. Previously, she worked on research projects at the United Nations Institute for Environment and Human Security in Germany and at the Dalla Lana School of Public Health, University of Toronto, in Canada. She also worked in finance for sustainability at the Latvian Environmental Investment Fund. She holds a BSc(Hons) in Sustainable Development from the University of St Andrews.

BRIAN BULLA

Brian Bulla is a doctoral candidate in the Department of Forestry and Environmental Resources at North Carolina State University in Raleigh, North Carolina. He is a policy scientist, interested in how people problematize and research vulnerability to climate change. More specifically, he is interested in the environmental and social justice implications of the policy responses that emerge from different conceptualizations of vulnerability to climate change. He is working on a case study about public participation and water resource management in Kruger National Park, South Africa, and a community-based participatory research project utilizing photovoice with small-scale farmers in central North Carolina. Prior to beginning his PhD studies, he completed a Master of Public Administration and a Master in International Studies at North Carolina State University.

ADEKUNLE DOSUMU

Adekunle Dosumu is a PhD candidate at School of Biological Sciences, University of Essex; Colchester, UK. He completed a BSc (Hons.) in Zoology and MSc in Ecology/ Environmental Biology at University of Ibadan, Nigeria. His PhD research is on the impacts of sport on the environment. He is currently an Instructor Service Operator and an Environmental Champion with London Underground. He is a member of both Essex Sustainability Institute (ESI) and Chartered Institute of Waste Management (CIWM). He is also an affiliate member of Institute of Environmental Management and Assessment (IEMA).His undertaking research work on climate change, environmental management, environmental sustainability, workplace safety and public health. He is very passionate about preserving the natural environment.

GEORGE FREDUAH

George Freduah is a PhD researcher at the Sustainability Research Center (SRC), University of the Sunshine Coast (USC), Australia. He has completed a BA in Geography and Resource Development at the University of Ghana and an MPhil in Development Geography at the University of Bergen, Norway. His research interests include climate change adaptations, livelihoods and natural resource management. His PhD research seeks to assess adaptive capacity of small-scale coastal fisheries for current and future stressors in light of climate change by using Ghana as a case study. Prior to enrolling at USC, he had worked with the Institute of Local Government Studies in Ghana as a Lecturer.

KOMALI KANTAMANENI

Komali Kantamaneni is a PhD research student based at the University of Wales: Trinity Saint David, United Kingdom. Her research area primarily focuses on the United Kingdom and United States of America, examining the economic costs incurred by coastal communities who face increasing vulnerability to coastal storm and sea level rise because of climate change. She holds a MBA in Business studies from Cardiff Metropolitan University, UK as well as a MSc degree in Environmental Studies and a BSC in Biology from Nagarjuna University, India. To date, she has successfully published 4 papers and in addition to that, further 10 conference papers accepted for poster and oral presentations.

Visiting Scholar Award - 2015

Department of Civil Engineering
INDIAN INSTITUTE OF SCIENCE
BANGALORE – 560 012, India

Dr. D. NAGESH KUMAR
Professor &
Chairman, Centre for Earth Sciences

July 03, 2015

Certificate

This is to certify that Ms. Komali Kantamaneni has worked with me as visiting scholar during the period June 03, 2015 to July 03, 2015 in our Department of Civil Engineering, IISc, Bangalore. During this period she has worked broadly on climate change with in physical and fiscal perspectives with a focus on storm damage costs in developed and developing countries. She has shown keen interest to learn GIS and its applications for map projections and information extraction approaches. During this period she has attended several seminars organized in our department on related topics. She has also worked on her thesis related work and publications during this period. I wish to place on record my appreciation for her sincere efforts and hard work in learning new things and applying them in her research domain during this one month period.

(D. Nagesh Kumar)

Phone: +91 80 2293 2666 (Off); +91 80 2360 3085 (Resi); Fax: +91 80 2360 0404
Email: nagesh@civil.iisc.ernet.in; URL: http://civil.iisc.ernet.in/~nagesh

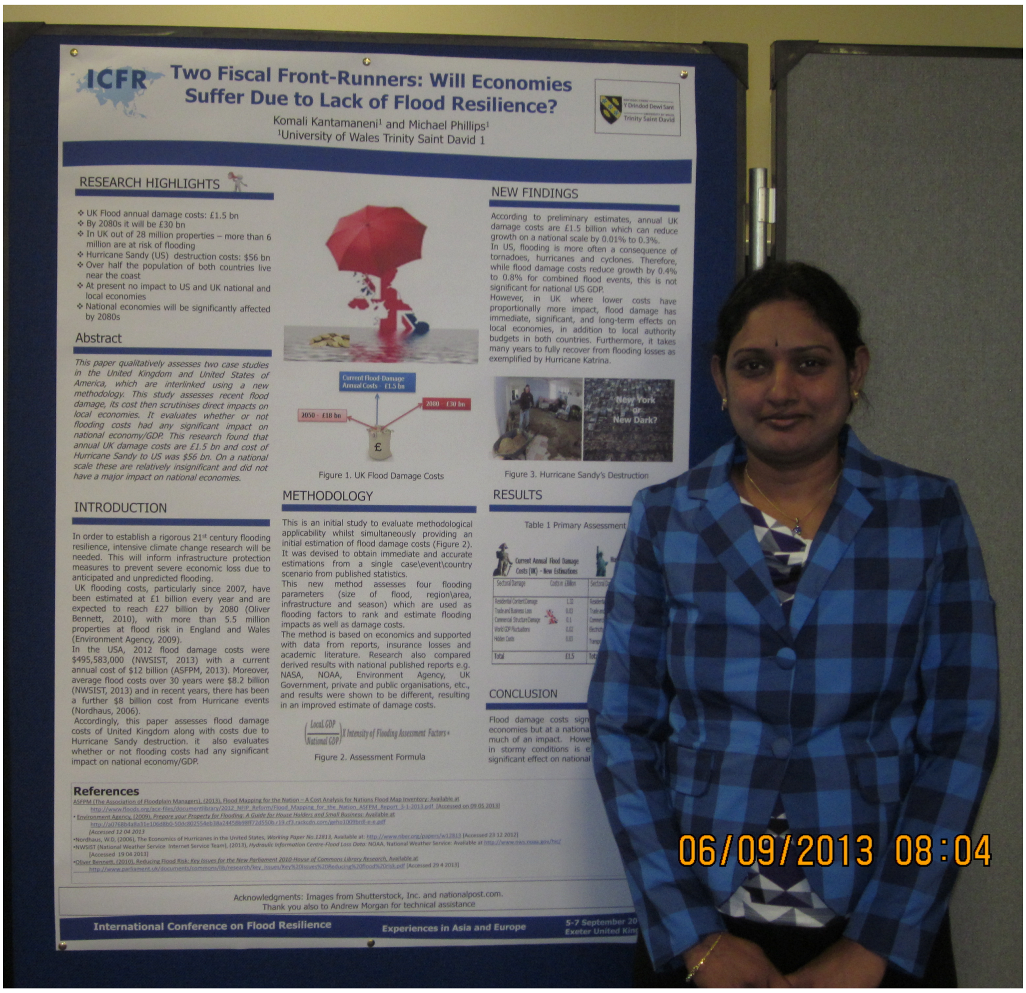
As a Conference Chair - Iceland, 2014

As a Principal Investigator –China, 2014
(Republic of China's Funded Project)

During Visit of Chinese Academy of Sciences (CAS)

Beijing, China - 2014

Poster - Exeter University, 2013



Presentation at Tyndall Centre - Cardiff University, 2013

Key Publications

Ocean & Coastal Management 132 (2016) 155–169

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Counting the cost of coastal vulnerability

Komali Kantamaneni [a, b]

[a] Faculty of Architecture, Computing and Engineering, University of Wales, Trinity Saint David, Mount Pleasant, Swansea, SA1 6ED, United Kingdom
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Costs
2 Path analysis
Coastal vulnerability sites
United Kingdom

ABSTRACT

Significant coastal vulnerability (CV) in the United Kingdom (UK) endangers the population and the infrastructure and distorts the national economy, yet present and proposed literature only quotes previous circumstances that failed to deliver factual fiscal assessment. The current estimate models for coastal vulnerability are useful for decision-making in some magnitudes, but coastal vulnerability models need to be extended to comprise a wider choice of economic effects. These are real problems that need to be addressed for an estimation of fiscal coastal vulnerability with novel models of science and economics to limit destruction costs or spend with greater resilience. To address the current research gap, this study appraised coastal vulnerability by establishing an innovative model: a *Fiscal Coastal Vulnerability Index (FCVI)* with fiscal parameters by 2 Path analysis (2 PA). It identifies the coastal vulnerability hotspots in Path One (P1) and develops an FCVI and GIS maps in Path Two (P2). Primary results revealed that 11 sites across the UK (seven in England, three in Wales, and one in Scotland) were identified as fiscally vulnerable coastal areas. Identified sites currently contain £22.36 billion worth of coastal vulnerability, and >100,000 people are at high risk of flooding, erosion, storm surge, and high winds. The Fiscal Coastal Vulnerability Index can be adapted depending on kind of coastal environment and used as a planning tool to establish economic susceptibility. This work explains that the methodological framework can be adjusted for any suitable coastal sites at global or regional scales, and can be used to vindicate in-depth studies for coastal defences and budget.

1. Introduction

Coasts are greatly vulnerable to extreme weather events, such as storms, which impose significant costs on coastal civilisations. Historical information shows an extensive and fundamental association between coastal zones and anthropological settlements (Smit and Pilifosova, 2003; Singh, 2006; Smith, 2013). Coastal settlement increased dramatically during the 20th century, while a growing number of people and assets on the coasts are subject to additional stresses due to land use and hydrological changes in catchments (Jongman et al., 2012). More than 44% of the world's population lives within 150 km of the coast and eight of the ten largest cities in the world are near the shoreline (Atlas, 2012). Several recent extreme storm events across the globe have triggered devastating human and fiscal losses in catchment areas, such as Hurricane Sandy (United States of America-2012), Typhoon Haiyan (Philippines-2013), Cyclone Hudhud (India and Nepal-2014) and Cyclone Pam (Vanuatu, Tuvalu and New Zealand-2015). According to Nicholls et al. (2007), in excess of 120 million people are exposed to cyclone hazards every year, and 250,000 fatalities were caused by flooding between 1980 and 2000. Globally, floods affect 46 million people every year, and may rise to as many as 60 million a year by 2100 as a consequence of predicted climate change and associated sea level rise (Hoozemans et al., 1993). Increased flood events are greatly affecting socio-economic costs particularly in coastal regions (Hinkel et al., 2010). Populated estuaries, low-lying coastal urban areas, and islands are important communal hotspots of coastal vulnerability (De Sherbinin et al., 2007; Nicholls et al., 2007). The impact of regional and global climate change, sea level rise and rapid weather fluctuations, together with terrestrial processes, are a huge threat to coastal communities (Oliver-Smith, 2009; Zsamboky et al., 2011).

The coastline diverges significantly in terms of morphology and human usage. There are several segments of the UK coast, which are renowned for their natural beauty while others are distinguished by their distinctive and subtle environments such as Mumbles and Aberystwyth coasts. In some areas, there has been intensive tourism growth, while other parts have suffered from intensive industrial expansion. Suffolk and north Norfolk face

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http://dx.doi.org/10.1016/j.ocecoaman.2016.08.019
0964-5691/

extensive coastal erosion with property and vital natural territories under threat (Doody, 2001; Cooper and McKenna, 2008), all of which indicates that coastal vulnerability greatly impact the UK economy in near future. Recent storm activity as evidenced in 2007, 2012, 2013 and 2014 has exacerbated the vulnerability of various coastal regions. England and Wales are highly affected by these severe storms (Kantamaneni et al., 2015b); therefore, UK coastal vulnerability needs evaluation to a greater degree to ameliorate current problems and to prevent further decline.

Vulnerability evaluations are performed to appraise the amount of loss that could result from a hazardous incident of a given severity, comprising destruction to infrastructure, interruption of monetary activities, and the effect on livelihoods. The four main methods to evaluate coastal vulnerability are: index based (1), indicator based (2), GIS based decision support systems (3), and dynamic computer models (Ramieri et al., 2011). Several researchers across the globe: Gornitz (1990), Pethick and Crooks (2000), Martinez et al. (2006), Vittal Hegde and Radhakrishnan Reju (2007), Abuodha and Woodroffe (2010), Palmer et al. (2011), Balica et al. (2012), Addo (2013), Gorokhovich et al. (2013), Kunte et al. (2014) evaluated coastal vulnerability in geomorphological and physical perspectives but not from an economic point of view. Some studies added very few socio-economic variables (Population, cultural heritage, roads and railways, residential and commercial density, etc.) (Cutter et al., 2003; Vincent, 2004; Schröter et al., 2005; Rygel et al., 2006; Hahn et al., 2009; Mazumdar and Paul, 2016). Some other researchers (Wolters and Kuenzer, 2015; Rani et al., 2015; Nguyen et al., 2016) analysed the recent trends and methodological frameworks for assessing coastal vulnerability. Very few studies conducted research on the coastal vulnerability of the UK (McLaughlin et al., 2002; McLaughlin and Cooper, 2010; Denner et al., 2015; Kantamaneni, 2016). Despite research being conducted on individual locations, there is no CVI for the entire UK coast. In these particular conditions, there is a real need to develop CVIs that evaluate vulnerability within economic and geomorphological perspectives. Consequently, this study attempted to develop an FCVI via 2 Path analysis to fill the vital research gap in the field of coastal studies.

2. Description of study area

The United Kingdom is an island nation located in Western Europe, between latitudes 49°N and 59°N and longitudes 8°W to 2°E. It consists of four governed regions: England, Wales, Scotland and Northern Ireland and bounded by four bodies of water, Celtic

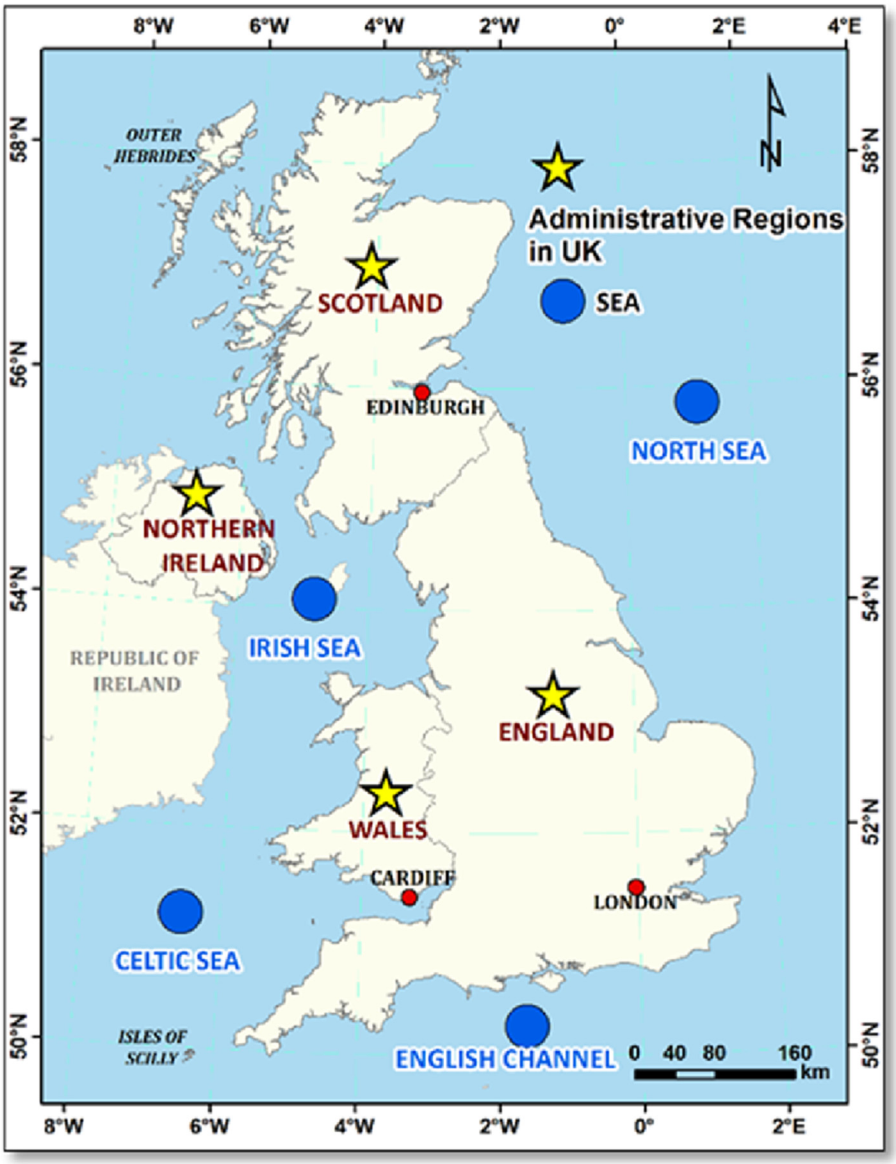

Fig. 1. Map of the study area.

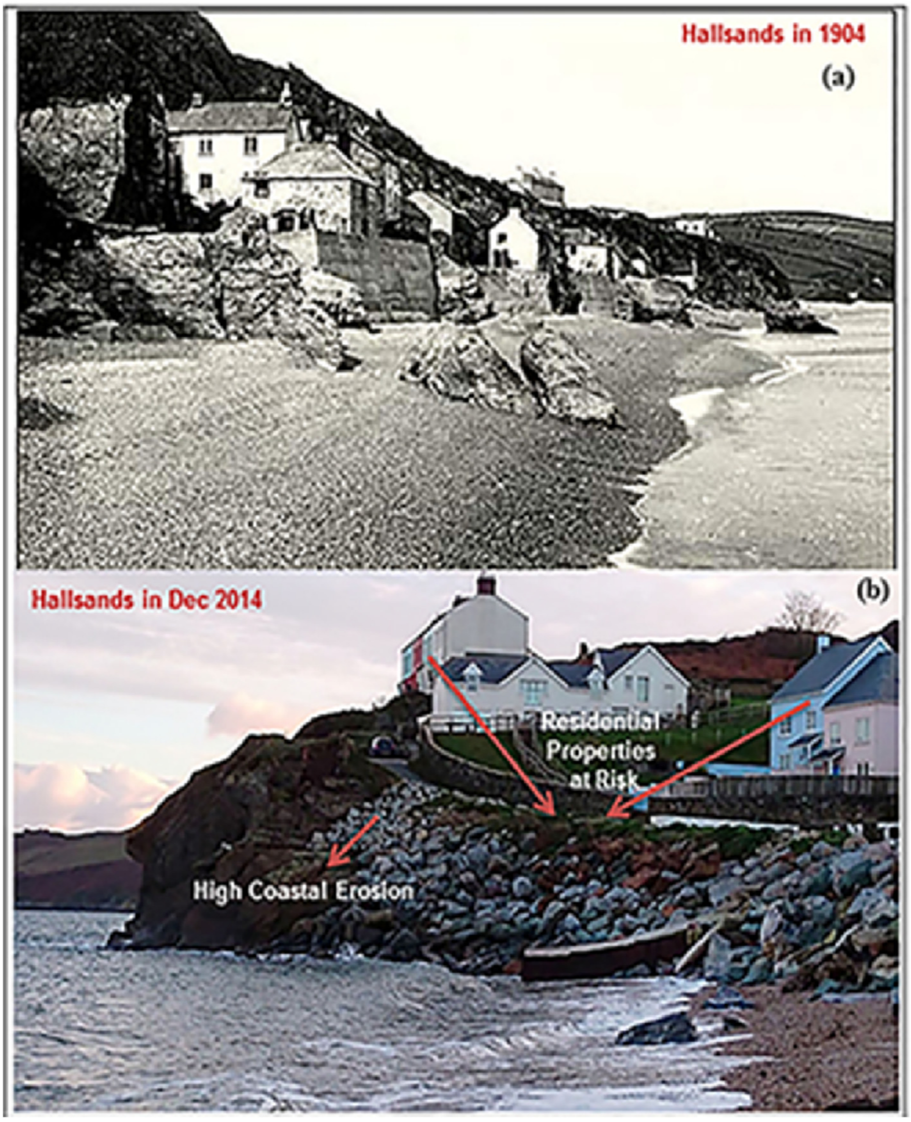

Fig. 2. (a &b). Decadal coastal erosion in Hallsands, England.
Source: Fig. 2a - BBC (2014); Fig. 2b – Kantamaneni (2016).

Sea, North Sea, Irish Sea, and the English Channel (Fig. 1) (Ordnance Survey, 2013). It has a *circa* 17,381 km long coastline and over 60% of it situated in offshore islands and Scotland (Masselink and Russell, 2007). Coastal zones of the UK are rich in significant natural habitats, tourism, heritage sites, recreational opportunities, and other business: nearly half of the population is living near to the coast (Jones and Phillips, 2009; Atlas, 2012). Approximately 40% of manufacturing industry and 60% of the fertile agricultural land is very near to the coast (Zsamboky et al., 2011), while 90% of trade is commuting by sea (Warwick University, 2010). Maritime industries and the service sector annually contribute >£17 billion to the UK economy and it will be £25 billion by 2020 (Marine Industries Leadership Council, 2011).

The maritime service sector made a £13.8 billion (direct value-added) contribution to national GDP (0.9% of total) and £2.7 billion of tax revenue to the economy in 2011 (Economics, 2013). Although tourism and coastal recreation activities are important contributors to national, local and sub-local economies, continuous occupation, rapid population growth and other substantial business activities have recently intensified the current risk of coastal flooding and erosion. Coastlines are always subject to change through erosion and other natural processes: more than 17% of the UK coastline is suffering from erosion (Fig. 2(a & b) and coastal erosion costs are over £15 million per year, and it could be £126 million by 2080 (in worst case scenarios) (Masselink and Russell, 2013).

2.1. Vulnerability associated with the UK coast

Coastal vulnerability can be allied with diverse hazards such as: natural (sea level rise, various storm events, coastal inundation and storm surges, etc.), socio–economic (population and economic recovery, etc.) and human-made hazards (nuclear waste) (Fletcher III et al., 2002; Papathoma and Dominey-Howes, 2003); these hazards cause more severe destruction in both fiscal and causalities. There have been substantial changes during the last two decades in the UK coastal zones due to distinctive storm events and powerful winds that were considered as extreme events (Phillips and Jones, 2006). However, storm occurrences were not only the reasons that were making the coast vulnerable, but also other significant factors like sea level rise, shoreline erosion, tides and currents. At present, sea level rise (SLR) and anthropogenic activities like an upsurge in coastal population and disruption of

Table 1
Coastal hazards of the United Kingdom.

Principal coastal regions	Coastal hazards	Impacts
North Sea	• Coastal flooding • Various storm events • Coastal erosion • Storm surge • High waves and tides • High winds with tornado strikes	• Infrastructure damage • Community loss • Land degradation • Changes to the coastline • Loss of marine habitats
Celtic Sea	• Coastal flooding • Various storm events • Coastal erosion • Storm surge • High waves and tides • High winds with tornado strikes	• Infrastructure damage • Community loss • Land degradation • Damage to the coastline • Landslides and cliffs erosion
Irish Sea	• Coastal flooding • Various storm events • Coastal erosion • Storm surge • High waves	• Infrastructure damage • Community loss • Land degradation • Mudslides and landslides
English Channel	• High waves • Coastal flooding • Coastal erosion	• Infrastructure damage • Community loss • Land degradation • Loss of marine habitats • Loss of marine ecosystem and biodiversity

Source: Adapted from Ramieri et al. (2011).

hydrological cycles over the construction of properties along the coastline are making the actual natural system more vulnerable (Moser et al., 2012). However, following hazards (Table 1) are the main reason for the vulnerability of the UK at several coastal zones.

3. Materials and methods

3.1. Materials (data)

Statistical data regarding population, commercial and residential properties were obtained from the Office for National Statistics (ONS), together with county and district councils of England, Wales and Scotland. Property data related to the identified sites i.e. Llanelli, Happisburgh, Skegness and Benbecula was obtained from the UK government under the freedom of information Act. Flood data was obtained from Meteorological Office, Environment Agencies and local councils. Coastal erosion data was collected from British Geological Survey and United Kingdom Climate Impact Predictions. Estimated values of both commercial and residential properties and land values were obtained from Her Majesties Revenue Office for England, Wales and Scotland, Association of British Insurers (ABI) and the Agricultural Mortgage Corporation (AMC). In addition to the aforementioned, this study also utilised the data, obtained from multiple observations of the various coastal locations in the United Kingdom between 2013 and 2015. This work used the data of rateable properties but did not take into consideration heritage properties such as Churches and Museums together with large construction structures, such as, Bridges. In addition, statistical package for social sciences (SPSS) (21st version) was used for analysis and exploration of FCVI values and further construction of FCVI. Geographical information system (ArcGIS –10.3 version) was used in the development of coastal vulnerability maps in various resolutions.

3.2. Methods

There are many methodological frameworks (mentioned in literature review) for estimating coastal vulnerability at global and regional levels in relation to climate change particularly within physical and geomorphological perspectives. There are no rigorous and precise methodologies (collective method) for an evaluation and estimating coastal vulnerability within fiscal perspectives in a standardised format. Accordingly, a coherent and concise framework

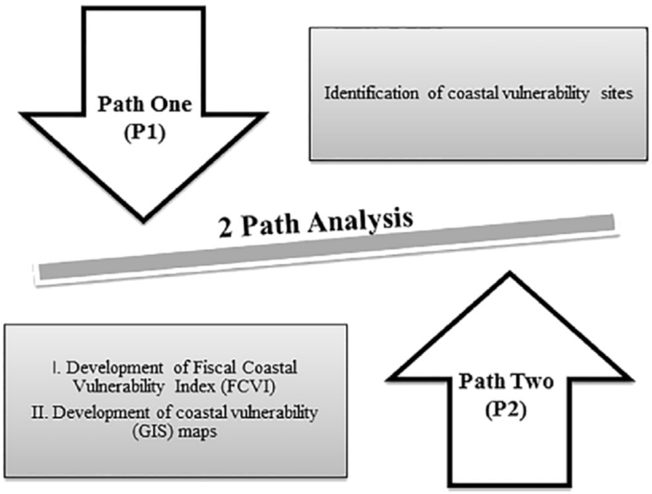

Fig. 3. 2 Path analysis (2 PA).
Source: Modified from Kantamaneni et al. (2015).

has been adapted based upon the work of Kantamaneni et al. (2015a) i.e., 2 PA (Two Path Analysis) (Fig. 3). This methodology comprises two vital paths as follows:

3.3. Path One (P1)

Identification of coastal vulnerability sites across the UK based

Table 2
Fiscal parameters.

No.	Parameter	Designated symbol for FCVI	Measurable units
1	Commercial properties	a	In £millions (economic)
2	Residential properties	b	In £millions (economic)
3	Economic value of site	c	In £millions to £billion (economic)
4	Population	d	In thousands (non-economic)
5	Coastal erosion	e	In £millions (economic)
6	Flood (event) impact	f	In £millions (economic)

on collected data and multiple site (coastal) observations. Sea level rise, precipitation and population trends were analysed to identify the fiscal vulnerability hotspots. In addition, recent climatic events were also used to find the most vulnerable sites all with varying physical and economic characteristics.

3.4. Path Two (P2)

Development of an FCVI as well as coastal vulnerability GIS maps: in order to achieve these aims, a part of Kantamaneni's (2016) basic concept of coastal vulnerability assessment method has been adapted for an establishment of FCVI and accordingly, a coastal vulnerability index (CVI) methodology and selection of fiscal parameters concepts were adapted for this research.

3.5. Selection of fiscal parameters

For coastal vulnerability assessment parameters are vital elements, and they could have diverse levels of response depending on impact magnitude (Palmer et al., 2011). Aligning with Kantamaneni's (2016) work on the Welsh coast, six fiscal parameters (Table 2) were used to estimate economic vulnerability. However, this study did not measure the population in monetary terms because it is unusual to offer the economic consequences to the communities (with the exception of Kantamaneni (2016) work) particularly in the UK. All of the chosen parameters were assigned equal weightage even though they have different fiscal values. Each parameter has been classified with 1 to 5 ranking representing a range from extremely low to extremely high. .

3.6. Technical description and calculation of FCVI

Using the 2014 aerial photograph, a transect baseline was drawn across the frontage (i.e. parallel to the coast) on each of the identified coastal vulnerability sites and 1 km grid square (or cell) was drawn inland from the baseline (Fig. 4). Subsequently, detailed measurements based upon each parameter are recorded within each identified cell.

Data was collected from the various organisations (mentioned in earlier paragraphs) regarding number of properties and cost,

Table 3
Rating fiscal coastal vulnerability parameters (£m-millions).

Fiscal Parameter	Fiscal threshold				
	Extremely low (1)	Low (2)	Moderate (3)	High (4)	Extremely high (5)
Commercial Properties	<2 m	2 −10 m	>10 −30 m	>30–70 m	>70 m
Residential Properties	<30 m	30 −80 m	>80 −130 m	>130 −180 m	>180 m
Economic Value of Site	<10 m	10 −50 m	>50 −100 m	>100 −150 m	>150 m
Population	<500	500-2000	>2000 −5000	>5000 −10,000	>10,000
Coastal Erosion	<0.3 m	0.3 −2.5 m	2.6 − 5 m	>5 − 9 m	>9 m
Flood (event) Impact	<3 m	3- 9 m	>9–15 m	>15–35 m	>35 m

Table 4
FCVI relative scores.

a = Commercial properties	5 (max)
b = Residential properties	5 (max)
c = Economic value of site	5 (max)
d = Population	5 (max)
e = Coastal erosion	5 (max)
f = Flood (event) impact	5 (max)
Maximum FCVI value	***30***
Minimum FCVI Value	***06***

Table 5
FCVI relative ranking (Vulnerability level ratings grouped by total relative vulnerability score).

Total relative vulnerability score	Range of vulnerability
<12	Extremely Low
12–15	Low
16–18	Moderate
19–22	High
23–30	Extremely high

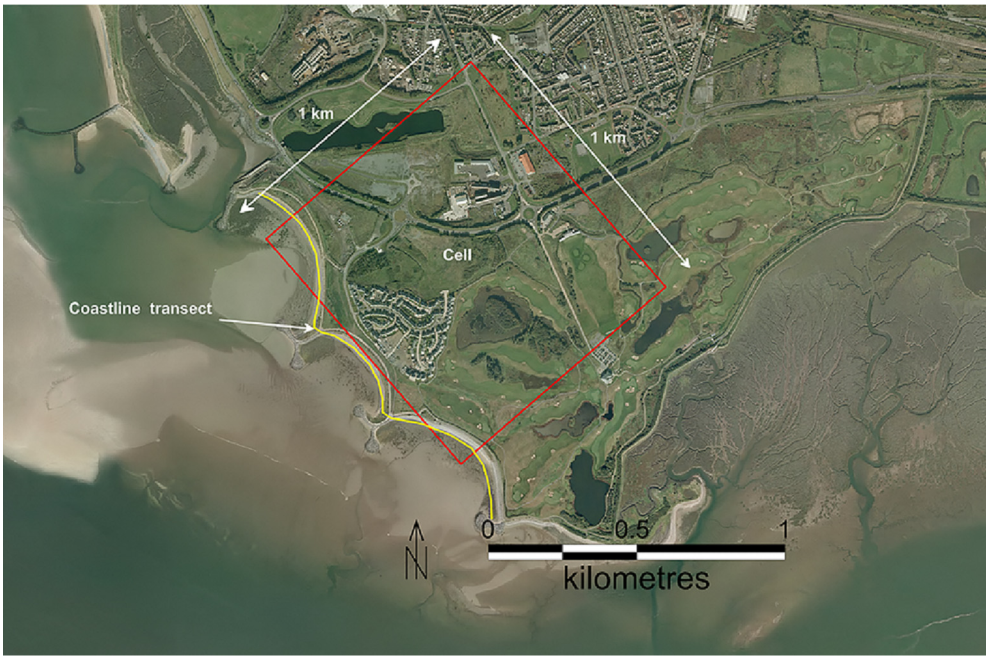

Fig. 4. 1 km Coastal section/cell on transect line.

economic value of the site, population, and flood impact. These economic values were then used to construct Table 3 detailing economic thresholds for each parameter and assign a ranking score between 1 and 5. The individual cell measurements were then compared and contrasted with Table 4 and assigned a ranking score between extremely low (1), low (2), moderate (3) high (4) and extremely high (5) to assess vulnerability quantitatively. With rankings applied, these values were then summed for each location to provide a relative CVI score using Comparative FCVI (equation (1)). The FCVI value would range between a minimum value of 6 and a maximum of 30 (Table 4). These scores were utilised (Table 5) to categorise the level of relative economic vulnerability for each location.

$$\text{Relative FCVI} = a + b + c + d + e + f \quad (1)$$

4. Results

4.1. Path One (P1) – identification of coastal vulnerability sites

Based on collected data and multiple site observations, this study identified eleven coastal vulnerability sites across the UK (see Table 6 below).

Table 6
Identified fiscal coastal vulnerability sites.

England	Wales	Scotland
Spurn Head	Port Talbot	Benbecula
Skegness	Llanelli	
Happisburgh	Aberystwyth	
Great Yarmouth		
Hallsands		
Dawlish		
Lynmouth		

Of the 11 identified there are seven in England, three in Wales and one in Scotland (Fig. 5). There is no significant vulnerability to the coastline of Northern Ireland at current scenarios.

4.2. Path Two (P2) – FCVI development and assessment

A total of 94.1 km of transect line was drawn on the 11 identified coastal vulnerability sites across the UK, and accordingly 80 cells (I km square cells) were identified (Table 7). Based on different

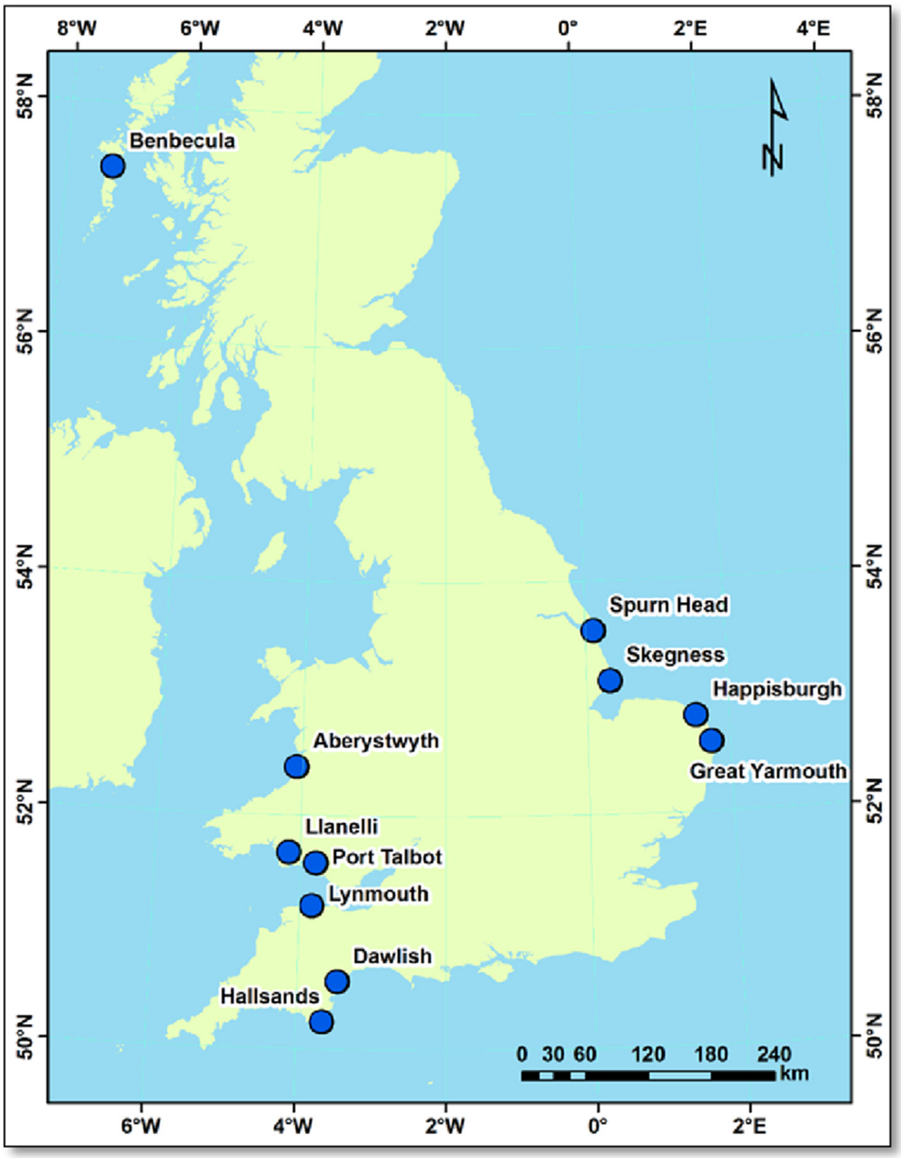

Fig. 5. Coastal vulnerability sites.

Table 7
Coastal vulnerability sites with 1 km cells.

Number	Coastal vulnerability sites	Transect line in km	1 km cells
1	Happisburgh	4.5	4
2	Great Yarmouth	15.0	13
3	Spurn Head	3.0	2
4	Skegness	20.0	18
5	Hallsands	4.5	4
6	Lynmouth	2.3	2
7	Dawlish	7.0	6
8	Llanelli	15.0	12
9	Port Talbot	13.0	12
10	Aberystwyth	2.3	2
11	Benbecula	7.5	5
		94.1 ***(total)***	**80** ***(total)***

lengths of coastline, some coastal sites consists several number of coastal cells and some have fewer number of coastal cells.

4.2.1. Appraisal of fiscal parameters

Economic data was obtained from various government and insurance sources, as discussed in Section 3 with six representative parameters chosen (Table 2), and this was applied to information acquired from analysis of the 1 km coastal cells. Consequently, an average commercial property value was derived from the range of facilities surveyed with a maximum of £105 m recorded in cell 8 at Great Yarmouth (Fig. 6a), to a minimum of £0.02 m in cell 73 at Port Talbot (Fig. 6a). An average commercial value of £15.5 m was determined and 27% of cells had higher than the average value, meaning 70% of cells were lower with two cells (38 and 80) not having commercial properties (Fig. 6b). The average value of residential properties within the 80 cells is £135 m, with a maximum of £780 m in cell 66 (Port Talbot) and a minimum of £0.02 m in cells 18 and 19 (Spurn Head; Fig. 6b). Twenty-six percent and 67% of cells recorded higher and lower values than the average respectively, while three cells (71–73 inclusive) did not include residential properties.

The average economic value of all sites is approximately £103 m from a total value of approximately £8.3bn. Assessments showed maximum site values of £1000 m (£1bn) occurred in cells 70 and 71 (Port Talbot) and a minimum value of £2 m in cell 18 (Spurn Head) and therefore, it can be seen that approximately 30% and 70% of cells had higher and lower values than the mean respectively (Fig. 7a). The average population in all cells was found to be approximately 1480 with a maximum of 10,000 in cell 66 (Port Talbot) and minimum of 1 in cell 38 (Hallsands). Sixty-seven percent of cells had lower than the average populations, while 30% recorded higher than average figures (Fig. 7b).

The average cost of coastal erosion was £5.4 m with a maximum

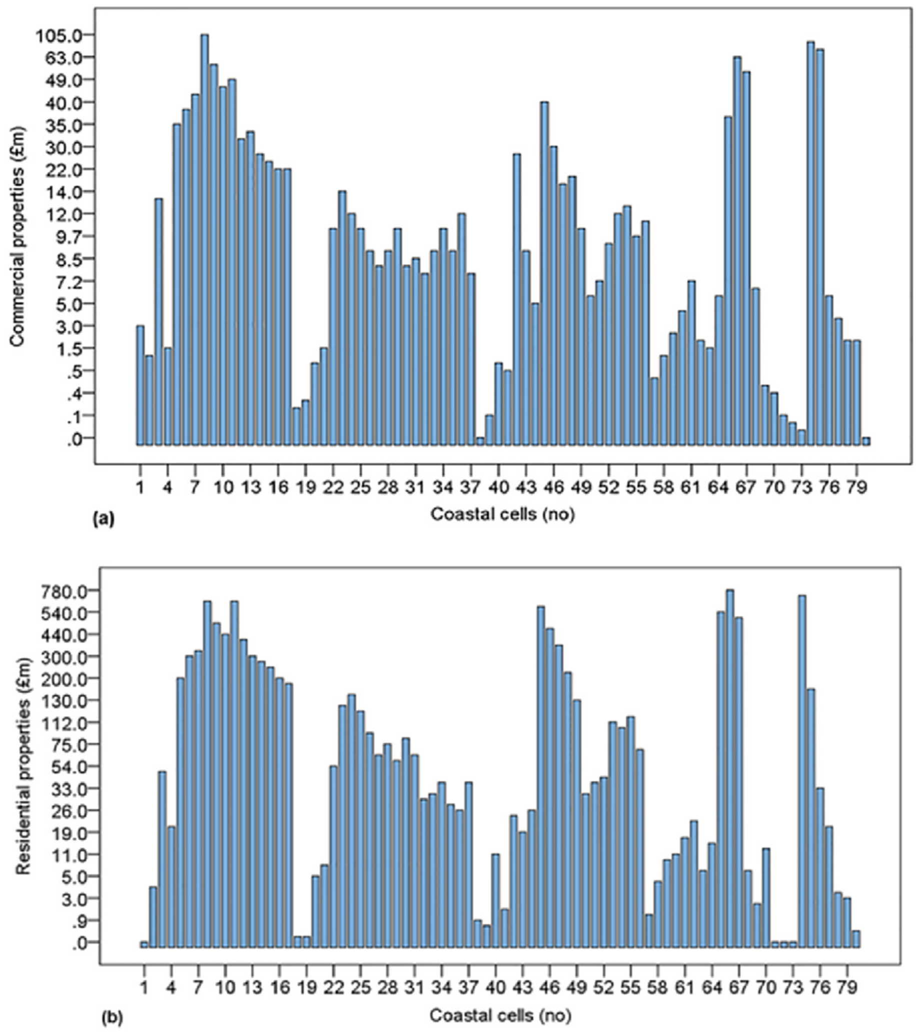

Fig. 6. Fiscal parameters assessment a) commercial properties and b) residential properties.

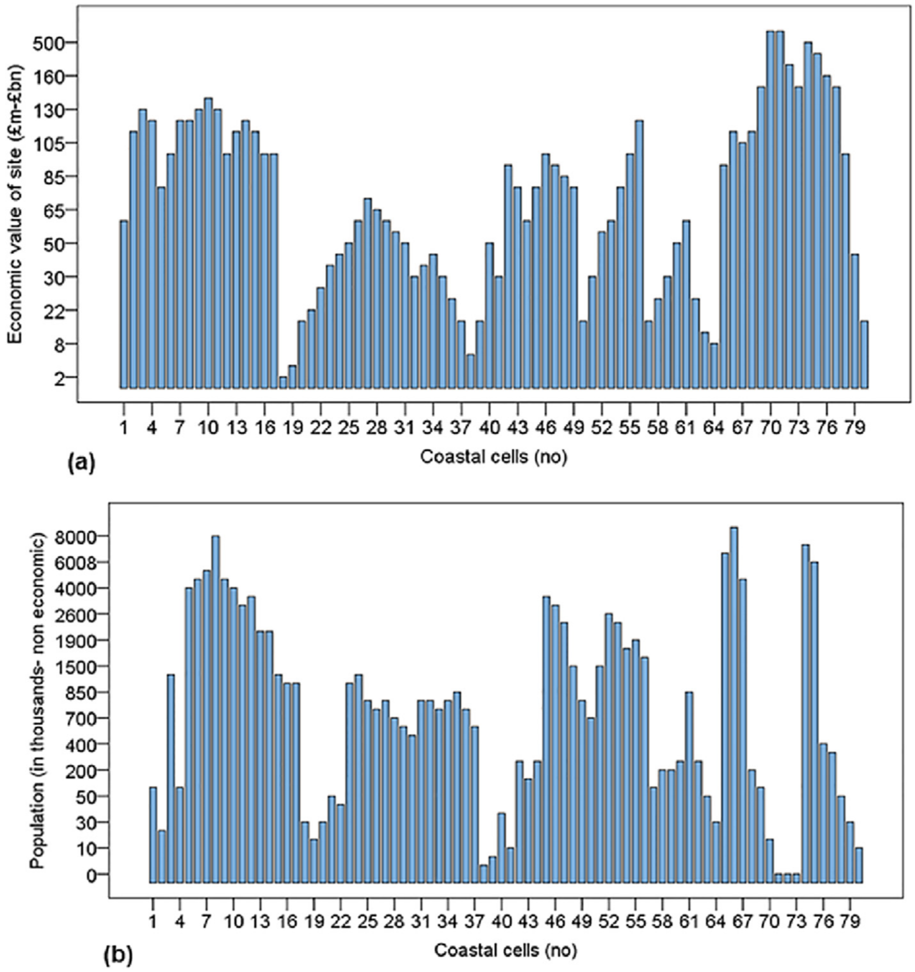

Fig. 7. Fiscal parameters assessment a) economic value of site and b) population.

of £20 m in cells 2, 46, and 68 (Happisburgh, Dawlish and Port Talbot respectively) and minimum of 0.3 m in cell 20 (Skegness). It can be seen that 62% of cells had lower than average values, while 38% were higher (Fig. 8a), showing that coastal erosion would be an on-going economic challenge. Flooding costs were determined as approximately £1.6bn across all 80 cells, with an average flood impact of £20 m ranging between a maximum of £40 m in cells 8 and 14 (Great Yarmouth) and a minimum of £2 m in cells 57, 64 and 80 (Llanelli, Port Talbot and Benbecula respectively). Therefore, 38% of cells recorded lower than the average and 62% more than the average flood impact values (Fig. 8b). Therefore, flooding can clearly be seen as an economic vulnerability.

The fiscal value was calculated for each of the eleven coastal sites. For example, Happisburgh is represented by coastal cells 1 to 4 and the value of each coastal cell was added together to get a total value for Happisburgh, i.e. 107 + 170.2+236.5 + 166.5 = £680.2 m. This procedure was replicated for all 11 coastal sites, and calculated data was included in the order of most to least vulnerability, and finally, population data from was transposed for each coastal site to obtain population per cell.

4.2.2. Establishment of fiscal coastal vulnerability index

The fiscal analysis obtained a parameter score for each of the 80 coastal cells for commercial properties, residential properties, the economic value of site, coastal erosion and flood event impact. Consequently, parameter values were combined for each site as per the methodology. Results showed that considerable variance exists between the coastal cells and FCVI parameter scores. The average FCVI score was 16.4, with the highest score of 26 recorded at Great Yarmouth and the lowest being 9, recorded in six cells at Skegness, Llanelli and Benbecula. However, more than 16% of cells fall into the extremely high category with a further 16% having high economic vulnerability. Thirty-five percent of cells fall into the lower category, with 16% belonging to extremely low categories. Fig. 9 graphically shows the percentage distribution of FCVI categories.

4.2.3. Ranking of sites based on FCVI cumulative scores

FCVI values were determined for each coastal location by aggregating CVI scores. For example, Happisburgh is represented by coastal cells 1 to 4, and for each km cell was added together i.e. 15 + 15+20 + 14 = 64. The process replicated for all eleven coastal locations and accordingly scores were allocated to 11 coastal sites (Table 7). This kind of summing approach offer more accurate results and helps to recognise the intensity of fiscal vulnerability of particular site. Fig. 10 represents the distribution of fiscal vulnerability by coastal cell and location: cumulative FCVI scores clearly show that Great Yarmouth is highly vulnerable in terms of fiscal risk and parts of the Llanelli and Benbecula coastlines have extremely low economic vulnerability.

The FCVI enabled the ranking of the eleven coastal sites in order of severity of the economic vulnerability, and site fiscal vulnerabilities according to FCVI scores were shown and illustrated in

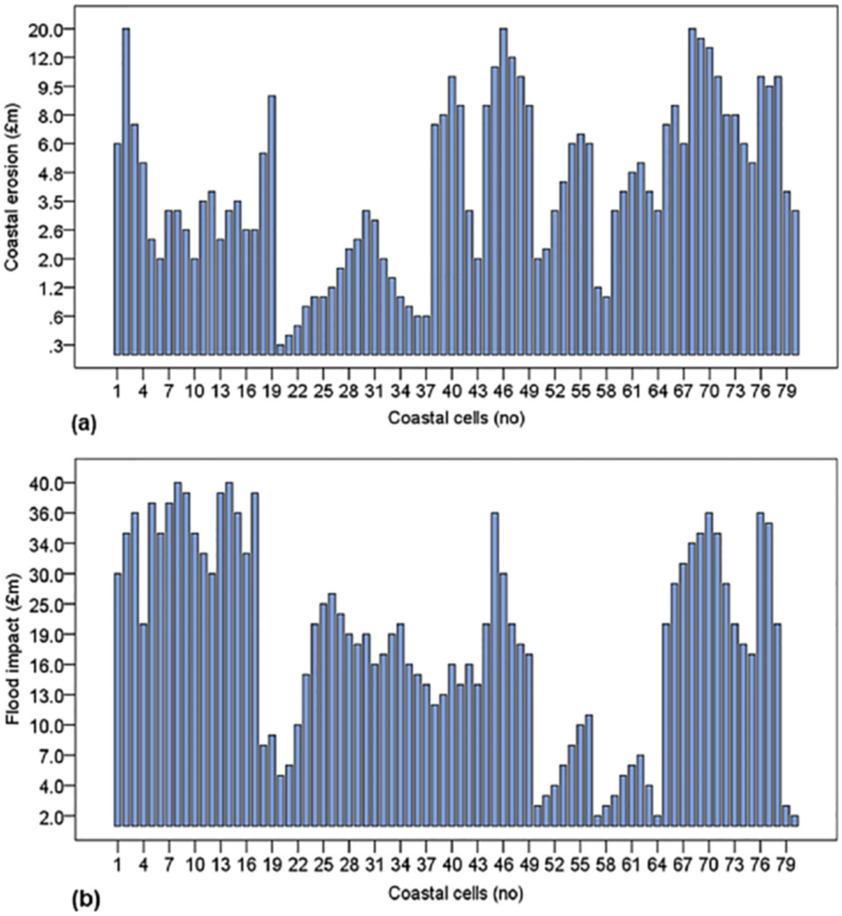

Fig. 8. Fiscal parameters assessment a) coastal erosion and b) flood impact.

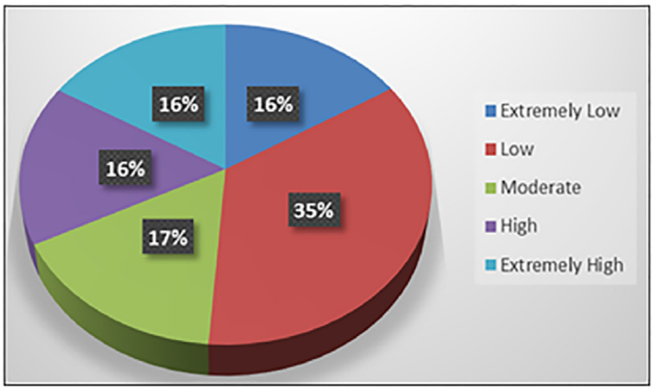

Fig. 9. Percentage distribution of FCVI categories.

Table 8
Ranking of coastal vulnerability sites based on FCVI cumulative scores.

Site name	FCVI score	Site ranking
Great Yarmouth	293	1
Skegness	249	2
Port Talbot	202	3
Llanelli	160	4
Dawlish	128	5
Benbecula	78	6
Happisburgh	64	7
Aberystwyth	49	8
Hallsands	47	8
Lynmouth	27	10
Spurn Head	22	11

Table 8 and Fig. 11. The eleven sites represent a total economic risk of £22.3bn under current scenarios, which includes >50,000 residential properties (0.2% of UK total) and >6000 commercial properties (0.37% of UK total). Furthermore, approximately 118,400 people (0.2% of the UK population) are at risk of displacement from flooding, etc.

4.2.4. *Fiscal coastal vulnerability assessment for identified sites*

Great Yarmouth is a medium-sized seaport and industrial corridor, as well as a major tourist attraction. It was the longest frontage considered and results showed that it has high vulnerability with an FCVI of 293. Its economic importance was assessed which was £7bn with a population of 45, 00 people at risk of displacement from coastal flooding. Skegness, a popular tourism destination which is considered as one of the best places for holidays, as well as being an ideal place to live for those who are retired (Butler, 2006). Accordingly, Skegness is considered as a highly valuable location from a socio-economic perspective. However, this is currently changing due to unprecedented flooding, rapid changes in weather patterns and rising incidence of storms even in the summer period (Zsamboky et al., 2011). An FCVI score of 249 makes Skegness as second vulnerable site after Great Yarmouth, having an economic value/cost of £2.29 bn and a population of >10,000. However, as Skegness is influenced by shoreline exposure, there will be a significant number of people at risk should current trends of flooding and storms. Port Talbot is highly industrialised (Fig. 12) and has significant economic value. Exposed to significant south-westerly storms, the TATA steelworks is protected by revetments made from blast furnace slag. The region is considered to be one of

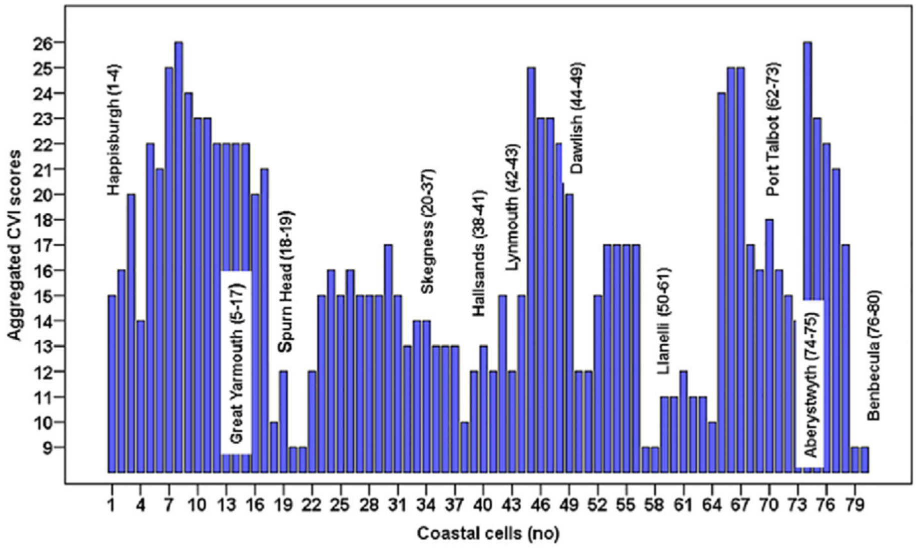

Fig. 10. Coastal cells and cumulative FCVI.

the most economically vulnerable coastal locations with FCVI of 202. With an approximate population of 1867 and an economic value of £5.4bn and it was third of the eleven sites in terms of fiscal vulnerability. Llanelli is at high risk from storm events, surges and coastal erosion. Recent storm events, particularly the 2010 storm, ravaged the £27 m Millennium Coastal Path with high waves and tides, costing the local council > £400,000 in repairs (Phillips et al., 2009). Following analysis of the economic parameters, the FCVI for Llanelli was 160 with an economic value of £1.4bn and population 15,750 Llanelli's economic vulnerability is not equally distributed along its coastal frontage and accordingly, it was fourth of the eleven sites in the terms of economic vulnerability.

Dawlish is very likely to be at constant risk from sea level rise, storms, storm surges and resulting coastal erosion. Infrastructure at Dawlish is very close to the shoreline (Fig. 13) and therefore has a high coastal vulnerability. Recent storm events in 2012, 2013 and 2014 caused billions (£) worth of damage. The 2014 storm damage caused a two month rail closure at a cost of £1.2bn with resulting repairs costing £35 m, making an overall total of £1.235bn (Dawson et al., 2016). Dawlish's FCVI was 128 giving it a high vulnerability with the economic risk includes residential and commercial properties, worth £2.6bn with a population of >12,000 at risk.

Benbecula Island was severely affected by a 2005 storm event which caused > £20 m (converted to 2014 rates) worth of infrastructure damage (Dawson et al., 2007). Therefore, following storm events there is an extremely high risk of coastal erosion. Benbecula FCVI was determined as 78, which puts it on boundary of the moderatevulnerability, having an economic value/cost of >£676 m and a population of 861. The relatively low number of residential and commercial properties influenced the site FCVI. Happisburgh has experienced severe coastal erosion over many years due to its geology, which provides little resistance to storms and surges. This had led to residential properties being at risk of falling into the sea and homeowners are unable to get insurance. This vulnerability is likely to increase with predicted increases in storm severity meaning the rate of erosion will also increase. Assessment showed that Happisburgh FCVI was 64 with a population of 1372 and an economic value of £680 m. It is suggested that the FCVI is not higher because the actual number of properties at risk is small in comparison to the total number, i.e. 423 residential and 64 commercial properties. Aberystwyth has 49 FCVI. Historically, Aberystwyth has been vulnerable to wave attacks and since the turn of the twenty-first century; it has been severely affected by a series of storms with high waves, tides and storm surges, i.e. 2008, 2010, 2013, and 2014. The tidal range is higher than at the other sites with the greatest incidence of waves coming from the southwest, which is also the direction of the most frequent storms. In 2014, a storm struck this region and caused £1.5 m worth of damage (Ceredigion County Council, 2014). There is an economic risk of £1.7bn including 530 commercial properties and 4613 residential properties (Fig. 14). There are 10,597 inhabitants at risk of displacement from coastal flooding.

During the storm of 1917, a major part of Hallsands vanished into the sea. Landslides are also a big concern here and the area is currently closed off due to coastal risk associated with coastal erosion. Most homeowners use their properties as holiday homes rather than permanent residences. Consequently, Hallsands has an economic risk of £210 m with FCVI of 47. Hallsands properties are at risk from coastal flooding and erosion. Due to current climatic fluctuations, Lynmouth experienced severe weather conditions, including storm surges and high winds during the 2012 and 2014 storms. These events highlighted the coastal vulnerability of this particular region and Fig. 15 shows both cliff-face erosion and how precariously properties have been constructed on the cliff. Therefore, the FCVI for Lynmouth was determined as 27 which put it in the low vulnerability (Fig. 15), and its economic value/cost was assessed at >£286 m with a population of 250. Spurn Head is ecologically very important for bird migration. However, its FCVI is 22 giving it an extremely low vulnerability score. Erosion has greater impact on Spurn Head's FCVI score and has an economic vulnerability of £38.5 m comprised of its site value and 9 residential/commercial properties. With a population of only >50, displacement costs are also low, thereby justifying the lowest FCVI score of all sites. Therefore, even though Hallsands and Spurn Head have high decadal erosion rates, due to them having relatively few commercial and residential properties they have lowest FCVI values.

5. Discussion

This research adapted a part of recently established coastal vulnerability assessment methodology of Kantamaneni (2016) by aggregating cumulative FCVI scores to rank the identified coastal vulnerability sites in the UK. However, the process of identification

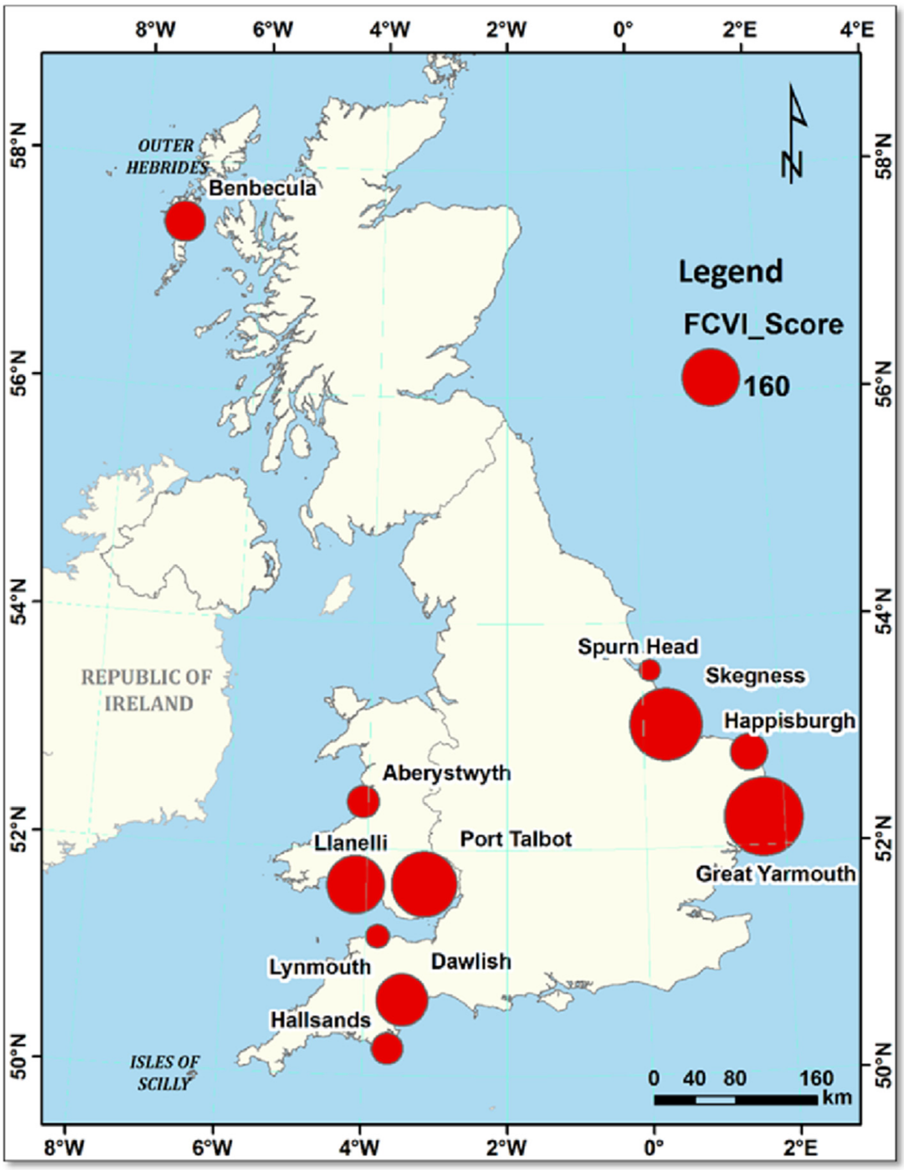

Fig. 11. Fiscal coastal vulnerability of the UK.

Fig. 12. TATA steel industry at Port Talbot coast.

Fig. 13. Dawlish coastal properties.

Fig. 14. Coastal properties and construction of the new coastal wall at Aberystwyth.

Fig. 15. Lynmouth properties.

of coastal vulnerability sites across the UK and summing of cumulative coastal vulnerability index scores reflect the particular site economic situation and these things made this specific study unique. The FCVI was determined from six fiscal parameters that were assessed on a site/coastal location basis. Development of FCVI scores per cell showed that fiscal vulnerability varies between sites. Great Yarmouth had the highest FCVI and generally urban areas were most vulnerable, having larger populations than rural communities. Understanding population numbers at risk is important for both physical and socio-economic aspects of coastal research. Assessments of population in monetary terms requires a cost to be allocated to a human life and based on 2011 US EPA estimates, it is £6.9 million adjusted for 2015 inflation rates (Appelbaum, 2011). However, coastal populations represent diverse age groups and communities with different economic status and an average figure of £4 m for a life could be argued (Kantamaneni, 2016). Even though population numbers are available, it would be unrealistic to include population costs at £4 m head^{-1} in the FCVI methodology because of presence of diverse physical and economic conditions at 11 identified sites. Therefore, this FCVI methodology, which includes population numbers, can be applied at local, regional and strategic to determine levels of economic vulnerability.

Unrestricted and rapid settlement in coastal regions increases pressure, both physically and economically, which leads to further vulnerability and risk (Nicholls et al., 2007). For example, Great Yarmouth and Skegness populations have increased year on year ultimately causing increased coastal vulnerability and as a consequence was considered as a significant site for this research. FCVI values for Great Yarmouth and Skegness showed the majority of the coastal cells were highly vulnerable, not only with respect to sites value and commercial and residential properties, but also with population numbers. Spurn Head and Hallsands were identified as having the lowest economic vulnerability, as although Spurn Head has a high erosion rate, the lack of properties and population reduced its FCVI. The Llanelli coastline FCVI was variable according to cell location due to expensive developments alternating with rural locations, while Port Talbot's economic vulnerability was based on the value of its industries, including TATA Steel.

The majority of residential and commercial properties are located within 0.6 km of the shoreline in all eleven sites. Therefore, predicted increases in storm occurrences and associated flooding events, winds and storm surges that often result in coastal erosion are major problems in these areas. Denner et al. (2015) stated that Llanelli poses a high risk of present and future flooding and results from this research confirm that this is indeed the case. Kantamaneni (2016) revealed that Aberystwyth has the highest risk of storm surges, flooding. Of the coastal defences built to protect several of the study sites, particularly Llanelli, the protection of new properties and infrastructure relies on *circa* 25%–35% having less than a 20-year lifespan remaining (Denner et al., 2015). This highlights an on-going problem in that not enough money is available for coastal protection, whilst storms, sea level rise and inundation events are likely to become more frequent. The problem is compounded by there not being updated government reports on coastal defences and protection measures for the eleven sites, particularly Aberystwyth (Kantamaneni and Phillips, 2016; Kantamaneni, 2016), and that where data is available, most is more than 5–10 years old and will not help accurate assessment. Accordingly, the capability of local authorities without sufficient resources to defend coastal infrastructure, especially for Llanelli and Aberystwyth, has been questioned (Phillips et al., 2009; Kantamaneni, 2016).

Except when events make the television news, e.g. Aberystwyth, etc. in 2014; there is a general lack of public awareness of coastal issues from both economic and physical perspectives. Consequently, regeneration strategies have already led to further coastal erosion and flooding. New developments may get short-term monetary gain from improvements to coastal real estate and investment, but if there is a vulnerability to erosion and flooding, the investment is at risk. Meanwhile, there are no rigorous policies or procedures that can be immediately implemented to avert such situations, and it becomes more complex when developers call on Local Authorities to provide protection because they were encouraged to build on the coast as a part of regeneration strategy (Phillips et al., 2009). These situations represent failures of coastal management strategies instead of an economic gain. Therefore, using the FCVI to assess fiscal vulnerability will quantify the relative vulnerability of coastal areas to various hazards and consequently will be a useful tool for planning authorities to assess economic risk.

6. Conclusion

Assessing the fiscal coastal vulnerability of a particular site is crucial for imminent spatial planning in accordance with environmental development principles. This study categorically demonstrates the coastal vulnerability of the UK by identification and mapping of coastal vulnerability sites in conjunction with the establishment of an FCVI via 2 Path Analysis (2 PA). The FCVI was determined from six fiscal parameters that were assessed on a site/coastal location basis, and it is suggested that coastal developers and decision and policy makers could use this methodology to evaluate financial risk without needing to assess complex economic data as the model provides an innovative way to evaluate economic vulnerability. When applied to the eleven-identified coastal regions, results showed that economic vulnerability varies between sites. Current UK coastal vulnerability is £22.3 bn and is comparatively uneven across the country. The study highlighted that unrestricted and rapid settlement in coastal regions increases pressure leading to vulnerability and risk. Great Yarmouth and Skegness populations have increased and are the cause augmented coastal vulnerability and as a consequence was considered as significant sites for this research. FCVI values for Great Yarmouth and Skegness showed that most of the coastal cells were highly vulnerable. It was no surprise that Spurn Head and Hallsands were identified as having the lowest economic vulnerability, as the lack of properties and population reduced its FCVI. Using an FCVI to assess economic vulnerability will quantify the relative vulnerability of coastal areas to various hazards. This is a numerical approach to demonstrate the magnitude of fiscal coastal vulnerability at eleven identified sites. This method enables the production of economic data and quantification of various quantities of vulnerability to fulfil standards substitute to national and regional authorities in the nationalised policy for control of climate change and its related coastal hazards in the UK. This technique of assessing vulnerability can drive as an initial susceptibility assessment from which a map of probable intensities of susceptibility can be made to allow cost–benefit analysis. The FCVI can also be employed to define economic feasibility of coastal defence structures and the allocation of coastal budget. This tool can be modified depending on kind of geographical area and used as a framework for fiscal vulnerability evaluation.

7. Recommendations

Coastal vulnerability costs are major concerns in the UK at current scenarios. These issues affect the national GDP, local GDP, infrastructure, communities, etc. in several ways. As discussed in previous sections this research recommends for pro-active actions to avoid considerable damage costs as follows:

➢ Allocate an appropriate budget to coastal defence based on the severity of assessed coastal vulnerability and susceptibility to storm damage;
➢ Inform government policy and procedures for insurance aspects of coastal management;
➢ Economic coastal vulnerability assessments should be undertaken by statutory authorities every five years;
➢ Met Office, Environment Agency (EA) and Office of National Statistics (ONS) should maintain records and statistics of various weather events, GDP (past, present, and future) and storm damage costs;
➢ Information on coastal statistics and physical environment data such as wind, wave and directional components should be made easily available to researchers.

It is proposed that implementing the above-mentioned recommendations would help to create sustainable coastal management strategies for future generations. These should form the economic basis of shoreline management plans and consequently, inform the efficacy of the construction of new coastal defence structures and also ensure appropriate planning of infrastructure projects. This would ensure continued protection of vulnerable coastal communities, particularly in areas prone to severe flooding, erosion and other coastal related hazards.

Conflict of interest

This manuscript has not been previously published and is not under consideration in the same or substantially similar form in any other peer-reviewed media. To the best of my knowledge, no conflict of interest, financial or other, exists.

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ORIGINAL PAPER

Coastal infrastructure vulnerability: an integrated assessment model

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Abstract The significance of coastal regions to the infrastructure and the need to protect such assets are crucial to the economy of countries. Therefore, there is a real need to enhance the understanding of coastal infrastructure susceptibility as well as to develop methodologies to estimate vulnerability. A review of the literature regarding coastal vulnerability reveals that the focus has been on geomorphological and physical parameters but not infrastructure and the associated fiscal factors. In order to address this knowledge gap, an innovative model is developed, i.e., the Coastal Infrastructure Vulnerability Index (CIVI). Then the model is applied to the case of the Aberystwyth coast demonstrating how the model estimates the vulnerability of the coastal infrastructure (comprising population, commercial and residential properties). Subsequently, the CIVI scores were used to rank coastal sections into five classes, ranging from extremely low to extremely high, based on the relative magnitude of the vulnerability. The rankings for each parameter were combined, and then an index value was calculated. Results revealed that Aberystwyth contains more than £40 billion of coastal infrastructure vulnerability and more than 10,000 inhabitants are at the high coastal risk posed by flooding, erosion, storm surges, and strong winds.

Keywords Integrated model · Coastal infrastructure vulnerability index (CIVI) · Aberystwyth · Costs

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1 Introduction

Several coastal regions across the world are endangered to both natural and anthropogenic hazards, which are expected to increase in the near future (Nicholls et al. 2007; Kron 2008; Weisse et al. 2012). The construction of a variety of infrastructures such as properties (commercial and residential), roads, ports, and breakwaters completely dominates the natural habitats and leads to further rapid coastal damage. Humans have changed coastal regions by introducing artificial constructions in 2580 BCE on the Red Sea shores in the Egypt (Tallet and Marouard 2014), and these structures affect geomorphology and coastal systems (Bulleri and Chapman 2010) in a negative way; however, this impact severity depends on the particular geographical area. Climate change induced elements such as sea-level rise, coastal flooding, erosion, and storm surge are the main reasons for coastal infrastructure damage as well as vulnerability (Dolan and Walker 2006; Phillips and Jones 2006; Bosello and De Cian 2014). Increased weather events also affect the socio-economic circumstances of coastal regions significantly (Hinkel et al. 2010). Therefore, coastal infrastructure vulnerability needs assessment to a greater degree to ameliorate existing problems and to prevent further decline.

1.1 Coastal vulnerability appraisal methods

Since three decades several works have been made to establish strategies and procedures for evaluating coastal vulnerability to climate change and other related aspects, accompanied with economics (Cutter et al. 2003; Lewsey et al. 2004; Vincent 2004; Rygel et al. 2006; Phillips and Jones 2006; Hinkel et al. 2009; Torresan et al. 2012; Addo 2013; Tang et al. 2013; Wolters and Kuenzer 2015; Denner et al. 2015; Wu et al. 2016). A summary of several methodologies established and applied globally is provided here. The four primary methods (Ramieri et al. 2011) to evaluate coastal vulnerability to climate change are as follows:

1. Index-based methodology
2. Indicator-based methodology
3. GIS (geographical information systems) based decision support systems
4. Dynamic computer models

1.1.1 Index-based methodology

Index-based methods evaluate coastal vulnerability by a single magnitude and are normally unit less. This method measures by the quantitative or semi-quantitative assessment as well as an amalgamation of diverse variables. These methods are not directly transparent since the final index does not allow for the understanding of the expectations and combinations that led to its measurement. The CVI outcomes can be shown on vulnerability maps at various scales to identify regions where the elements that add to coastal changes make greatest contributions to coastline retreat (Harvey and Woodroffe 2008; Pendleton et al. 2010). First coastal vulnerability index was developed by Gornitz (1990) followed by several researchers developing diverse CVI indices across the globe (McLaughlin and Cooper 2010; Palmer et al. 2011; Yin et al. 2012; Denner et al. 2015).

1.1.2 Indicator-based methodology

An indicator-based index is a popular tool for measuring the intensity of exposure of communities to hazards and coastal vulnerability. The index comprises several indicators, which are interlinked with the specific formula. In recent decades, some researchers have established several vulnerability indicators within the socio-economic and ecological system context (King and MacGregor 2000; Brooks et al. 2005; Barnett et al. 2008; Torresan et al. 2008; Abson et al. 2012; Balica et al. 2012).

1.1.3 GIS-based decision support systems (GIS-DSS)

GIS-based methodologies are useful for evaluating the physical condition of a particular system and the development of risk maps. It is useful to acquire further information about the physical geography of particular region through computerisation to transmute vast databases into thematic maps. The GIS-DSS is two types; development of an information technology tool for the management of Southern European lagoons under the influence of river-basin runoff (DITTY-DSS) (Agnetis et al. 2006; Mocenni et al. 2009; Casini et al. 2015) and decision support system for coastal climate change impact assessment (DESYCO-DSS) (Santoro et al. 2013; Zanuttigh et al. 2014).

1.1.4 Dynamic computer models

Dynamic computer simulations are useful for analysing and mapping susceptibility and risks of coastal systems (Cowell et al. 1995; Brown et al. 2006). Available methods for this procedure can be divided into two parts; sector models and integrated assessment models. Sector models focus on the examination of coastal vulnerability linked to a specific coastal system, and integrated assessment models appraise the coastal vulnerability systems to multiple climate change impacts (Mcleod et al. 2010).

1.2 Common framework for evaluation of coastal vulnerability

In 1990, IPCC published a standard methodology for assessing the vulnerability of coastal areas to sea-level rise; it contains seven systematic stages (seven indicators) (Table 1) that permit for the identification of population, natural and physical resources at risk and costs and possibility of potential responses to adverse impacts (Nicholls 1995).

Though several other methods have been developed for coastal vulnerability assessment, most of the researchers focused their interest on the index- and indicator-based methods. However, there is no standard evaluation method on town/city scale to estimate the current infrastructure vulnerability of the Aberystwyth at current scenarios. Therefore, this study developed an integrated CIVI and subsequently analysed the infrastructure vulnerability of the population, commercial and residential properties of Aberystwyth, UK.

2 Description of study area

Aberystwyth (52°25′N 4°05′W) is a small sea-side (Irish Sea) town in the county of Ceredigion in the Wales, UK (Aberystwyth Guide 2014) (Fig. 1), located towards the centre of the falcate of Cardigan Bay and also positioned between three hills. Aberystwyth

Table 1 Indicators of the Coastal vulnerability—IPCC common approach (Gilbert and Vellinga 1990)

Indicator	Explanation
Affected Population	Number of people living in the hazard region affected by sea-level rise
Population at risk	The average annual number of people inundated by storm surge
Investment value at loss	Current market value of infrastructure which could be lost due to sea-level rise
Land at loss	Size of land that would be lost due to rise of sea-level rise
Wetland at loss	Size of area of wetland that would be lost due to sea-level rise
Adaptation costs	Adaptation costs to sea-level rise, with an overwhelming importance on defence
Population at risk	The average number of people flooded by storm surge per year, supposing the cost of adaptation to be in residence

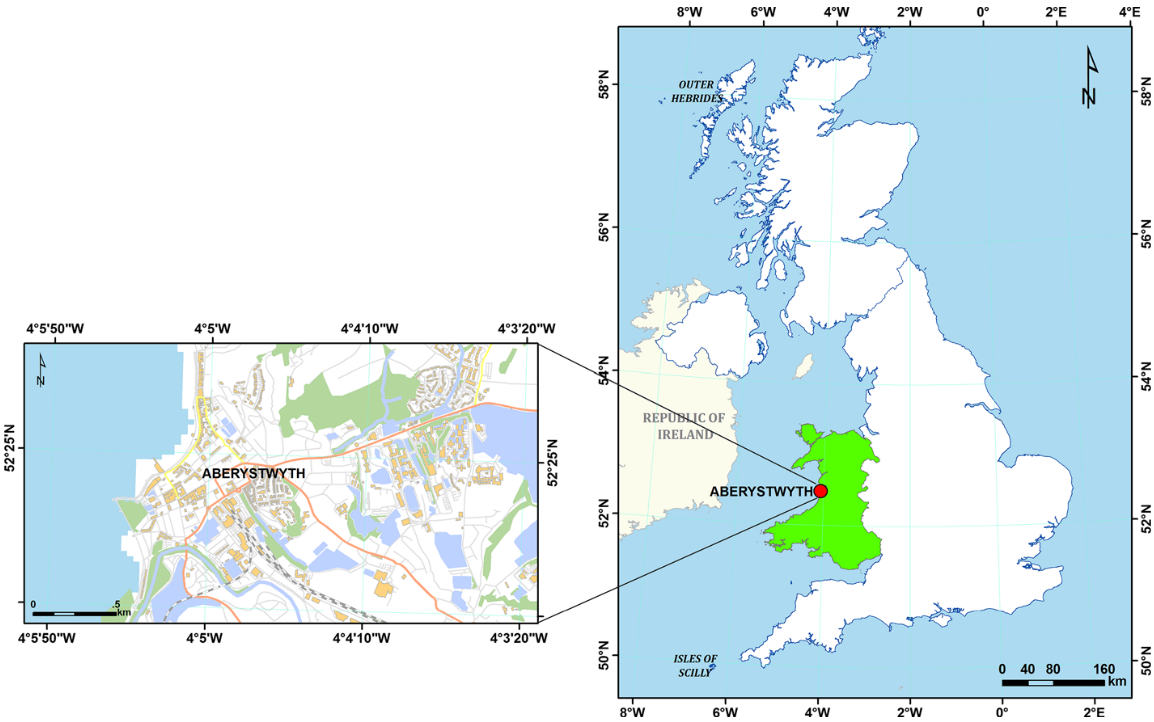

Fig. 1 Map of the study area

is the main touristic spot and administrative region of the west coast of Wales; though it has a small coastline (>2 km) (Aberystwyth Guide 2014), it has a high socio-economic value because the town's economy is based mainly on tourism, education, and retail sectors.

2.1 Coastal infrastructure damage

Frequent storm strikes in Aberystwyth are not unusual phenomena. Starting several decades ago, repeated storms ravaged this region and damaged several £million to £billion worth of infrastructure (Fig. 2a–d as evidenced in 1927, 2008, 2013 and 2014 (major events). In particular, the 2014 massive tides (>20 feet) damaged >2 km of railway track

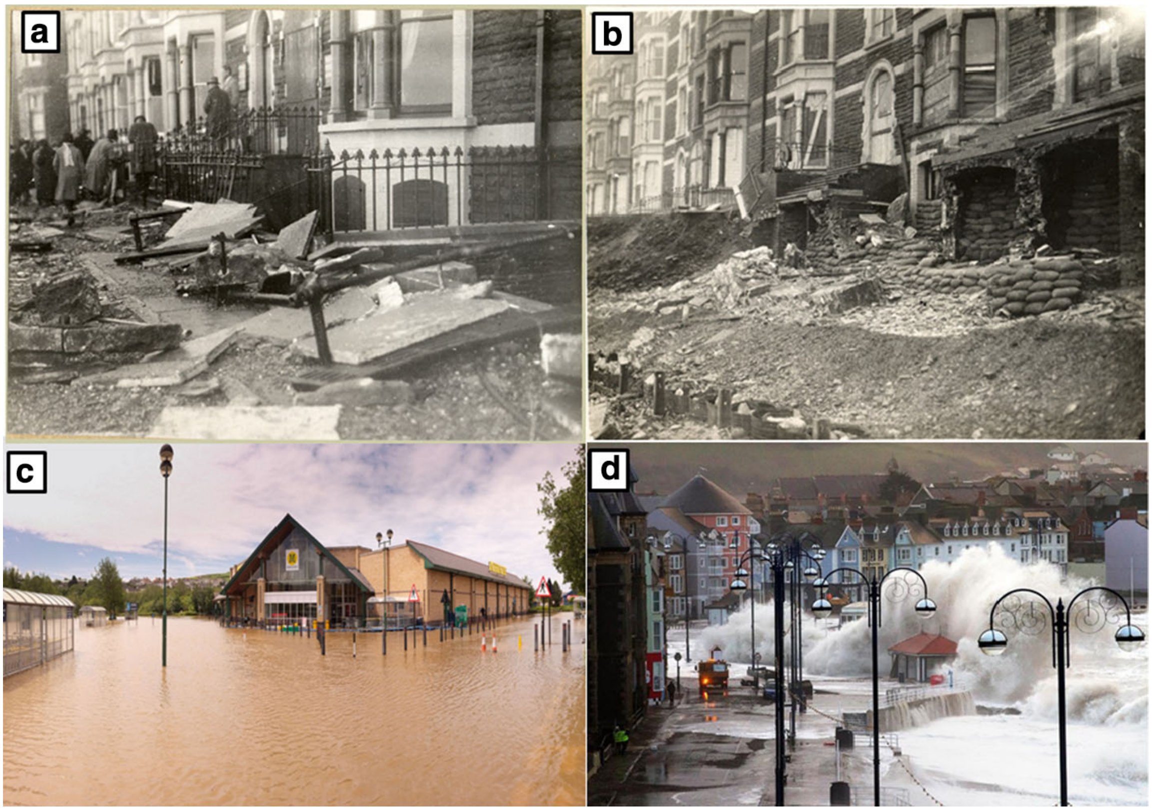

Fig. 2 Decadal Infrastructure Damage in Aberystwyth. **a** Residential property damage in 1927 (British Geological Survey 2014), **b** residential property damage in 1938 (British Geological Survey 2014), **c** commercial property damage in 2012 (Morris 2012), **d** commercial and residential property damage in 2014 (The Times 2014)

between Aberystwyth and Machynlleth severely, and nearly 2 weeks were needed for repairs. In addition, the widespread destruction of the seawall and walking path and the flooding of more than ten houses occurred (Welsh Government 2014). Future climatic conditions and levels of damage due to various coastal hazards (Table 2) will worsen the situation if strict adaptation and coastal defence procedures are not implemented in the near future (Slingo et al. 2014).

3 Data

Population, commercial and residential properties data were obtained from ONS (Office for National Statistics), local and sub-local Councils of Wales and Aberystwyth; fiscal data of commercial and residential properties obtained from HM Revenue and Customs (HMRC) offices of Wales and the Agricultural Mortgage Corporation (AMC). Along with the information as mentioned above, this study also utilised the data obtained by multiple observations of the coastal site of the Aberystwyth over 3 years (2012–2015) period. Parameter's statistics of each coastal cell (at 0.5 km resolution) was determined by using orthophotographs of Ordnance Survey, Welsh Assembly Government—Aerial Photographs and Google Earth maps. However, current study only used the data of rateable properties and did not take into consideration some heritage properties such as church and museums or massive structures like bridges and other constructions. While SPSS (statistical package for social sciences) (21st version) was used for analysis and exploration of

Table 2 Coastal hazards of the Aberystwyth (Adopted from Ramieri et al. 2011)

Principal Marine regions	Coastal hazards	Vulnerability/impacts
Celtic Sea	Coastal flooding	Infrastructure damage
	Various storm events	Community loss
	Coastal erosion	Land degradation
	Storm surge	Damage to the coastline
	High waves, tides and winds	Damage to infrastructure
Irish Sea	Coastal flooding	Infrastructure damage
	Various storm events	Community loss
	Coastal erosion	Land degradation
	Storm surge	Damage to infrastructure
	High waves	Damage to coastal wall and infrastructure

CIVI values and furtherer construction of CIVI. ArcGIS (10.3 version) and Welsh Assembly Government Arial and Google (Open Street) maps were used in the development of coastal vulnerability maps in various scales.

4 Methodology

4.1 Development of an integrated model

There is a real need to evaluate and compare the intensity of vulnerability of different sites, zones, and nations across the globe. The familiarity of coastal vulnerability will allow the researchers, policy, as well as decision makers to predict and perform on the adverse scenarios of existing and upcoming vicissitudes ensuing from global and regional sea-level rise and other impacts of climate change. A generalised and simple framework is required to illuminate explicit communication regarding coastal vulnerability and expressive comparison among susceptibility appraisals. Several kinds of technical, natural and social methods have already been employed (mentioned in the introduction section), but the process of applying the framework regionally and globally (from a fiscal perspective) is still in the embryonic stage. A definite procedure is then required to categorise the vulnerability of the coastal infrastructure; accordingly, a novel integrated model has been developed for the evaluation of coastal infrastructure vulnerability of the Aberystwyth coast, i.e., CIVI.

Two coastal vulnerability index (CVI) approaches were adopted for this study, based on an adaptation of the work of Balica et al. (2012) and Palmer et al. (2011). Accordingly, an integrated model (Fig. 3) was established to evaluate the vulnerability of the Aberystwyth coast by amalgamating indicator and index-based methods. The fiscal parameters were selected using the indicator-based method of Balica et al. (2012), and the concept of development of CIVI was taken from the index-based approach of Palmer et al. (2011). The fiscal values threshold for parameters was inspired by Aberystwyth fiscal consequences.

4.2 Fiscal parameters selection

Current study scrutinised various events in relation to a coastal vulnerability in the UK, such as population, commercial and residential properties, storm conditions, rainfall trends,

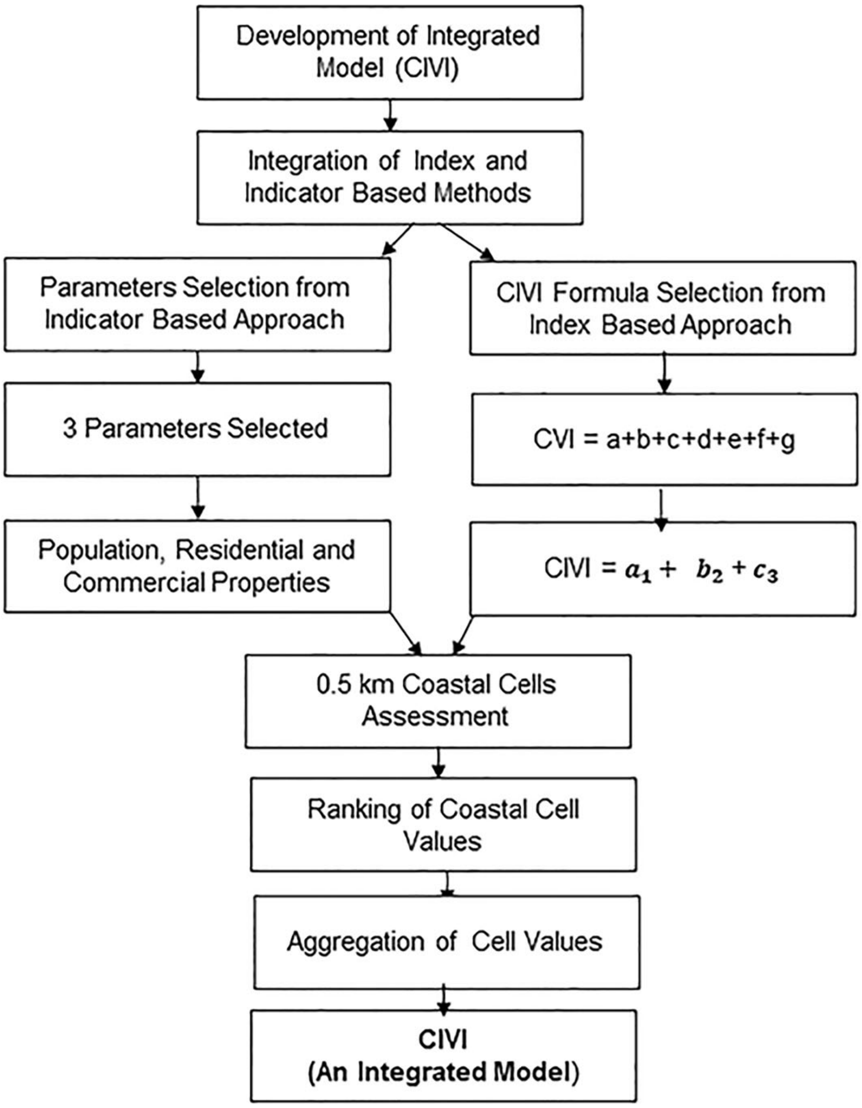

Fig. 3 Flow chart of development of integrated model

coastal erosion, etc. Based on the analysis of various conditions, which are presented in Table 3, twelve parameters were selected, taking into account the UK coastal regions and their susceptibility and exposure to the coastal vulnerability events.

4.2.1 Reduction of parameters

Reduction of parameters for an evaluation of fiscal coastal vulnerability at city or town scale is necessary. A large number of parameters (12) does not offer factual results in this particular scenario, so to simplify the methodological process, they are reduced and restricted to 3, based on the potentiality of the parameters (Table 4). Parameter reduction is not a new procedure in coastal vulnerability assessment studies, and several researchers have already implemented this technique successfully. Balica et al. (2012) initially considered 71 indicators and then reduced their number to 12, and the Canadian Council of Ministries of Environment (2003) selected nearly 100 indicators, which were reduced to 12 as well.

Table 3 Parameters selection procedure

Number	Parameter	Selection process and reason
1	Population in coastal vulnerability zones	More than 50 % of population is living near the coastline (Small and Nicholls 2003)
2	Infrastructure (properties, roads, etc.)	Nearly 6 million properties (one in six) are at risk of coastal flooding and erosion (Ramsbottom et al. 2012)
3	Land use	Around 60 % of the best agricultural land is 5 m or less above sea level (Zsamboky et al. 2011)
4	Rainfall	Heavy rainfall trends across the country in recent decades (Osborn and Hulme 2002; Maraun et al. 2008)
5	Flood/storm impact	Increased severity of flood/storm impact in recent periods (Reynard et al. 2001; Woodworth et al. 2007; Stevens et al. 2014)
6	Fiscal value of the place	The economic value of the area plays a vital role in fiscal studies, as well as disaster management studies (Swarbrooke 1999; Haigh and Amaratunga 2010)
7	Coastal erosion	High coastal erosion at some regions of the UK (Phillips and Jones 2006; Kantamaneni and Phillips 2016)
8	High growth of population alongside coasts	High growth of population expected alongside coasts (Small and Nicholls 2003).
9	Drainage system	A poor drainage system causes severe problems particularly when flooding strikes (Coulthard and Frostick 2010; Butler and Davies 2004)
10	Warning system	The robustness of the UK's warning system for natural disasters, e.g. no warning system during tornado strikes (Kantamaneni et al. 2015)
11	Marine Industry Growth	Maritime industries and the service sector annually contributes >£17 billion to the UK economy and it will be £25 billion by 2020 (Marine Industries Leadership Council 2011)
12	Politics and Policies	Changing the political situation also plays a vital role in the assessment of coastal vulnerability (White and Howe 2002; Patt et al. 2009)

Table 4 Fiscal (coastal infrastructure vulnerability) parameters

No.	Parameter	Designated symbol for CIVI	Measurable units (£)
1	Population	$a1$	Million–billion (economic)
2	Residential property	$b2$	Million–billion (economic)
3	Commercial property	$c3$	Million–billion (economic)

4.2.2 Parameters description

The population is widely accepted imperative parameter in both physical and socio-economic sections of coastal research, and it also considers as one of the vital infrastructures (Simone 2004). Current study measures the population in monetary terms and sets a cost to the human life based on US—2011—Environment Protection Agency estimations, i.e., £6.9 million (adjusted for 2015 inflation £rates) (Appelbaum 2011). However, Aberystwyth population has diverse age groups and communities with different economic status;

therefore, this study offers on average £4 m to the life of the UK (Aberystwyth) people at current scenarios.[1]

Residential and commercial properties are also important parameters in the coastal vulnerability studies. Using these structures as parameters in coastal vulnerability studies is not new; several researchers used in their studies to evaluate vulnerability in both physical and socio-economic studies throughout the world (Klein et al. 2003; Jacob et al. 2007; Kubal et al. 2009; Thatcher et al. 2013; Arkema et al. 2013; Wu et al. 2016; Mazumdar and Paul 2016). The Economic threshold was offered by identifying a number of properties in 0.5 km cells and then estimated the commercial value of those properties and then provided the range of values from extremely low to extremely high.

4.3 Technical description and calculation of CIVI

A certain length of transect line was drawn on the Aberystwyth coastline, and then a 0.5 km square measurement was placed on the transect line from the coast point to outside of coast, i.e., towards the civilisation/communities (Fig. 4) to appraise coastal infrastructure vulnerability within the economic perspective, while, as shown in Fig. 4, second and third cells are overlapped. Therefore, these overlapped properties did not take into consideration for an evaluation. However, uncovered properties which are located in-between the cells of first and second as well as third and fourth are taken into account for an assessment. This consideration helps to attain factual fiscal figures.

Besides that, fiscal parameter ranking was (Table 5) used to measure the coastal vulnerability and subsequently each cell was assigned a CIVI score and then all the cells of the parameters were calculated.

This study categorised the CIVI scores into five categories: extremely low (1), low (2), moderate (3), high (4) and extremely high (5). The scores of all cells of three parameters aggregated to rank the coastal infrastructure vulnerability. With rankings applied these values were then put into a simple equation (Eq. 1) to analyse CIVI score for each coastal section. Simple summation of individual rankings provided a total relative vulnerability score. The minimum possible score was 3, and the maximum was 15.

$$\text{Relative CIVI} = a_1 + b_2 + c_3 \tag{1}$$

a_1—Population	5 (max)
b_2—Residential property	5 (max)
c_3—Commercial Property	5 (max)

Maximum CIVI score	15
Minimum CIVI score	3

[1] It is not possible to give same fiscal consequences to all age groups of population of Aberystwyth and, accordingly this study offer the costs on average £4 m to the life of the human.

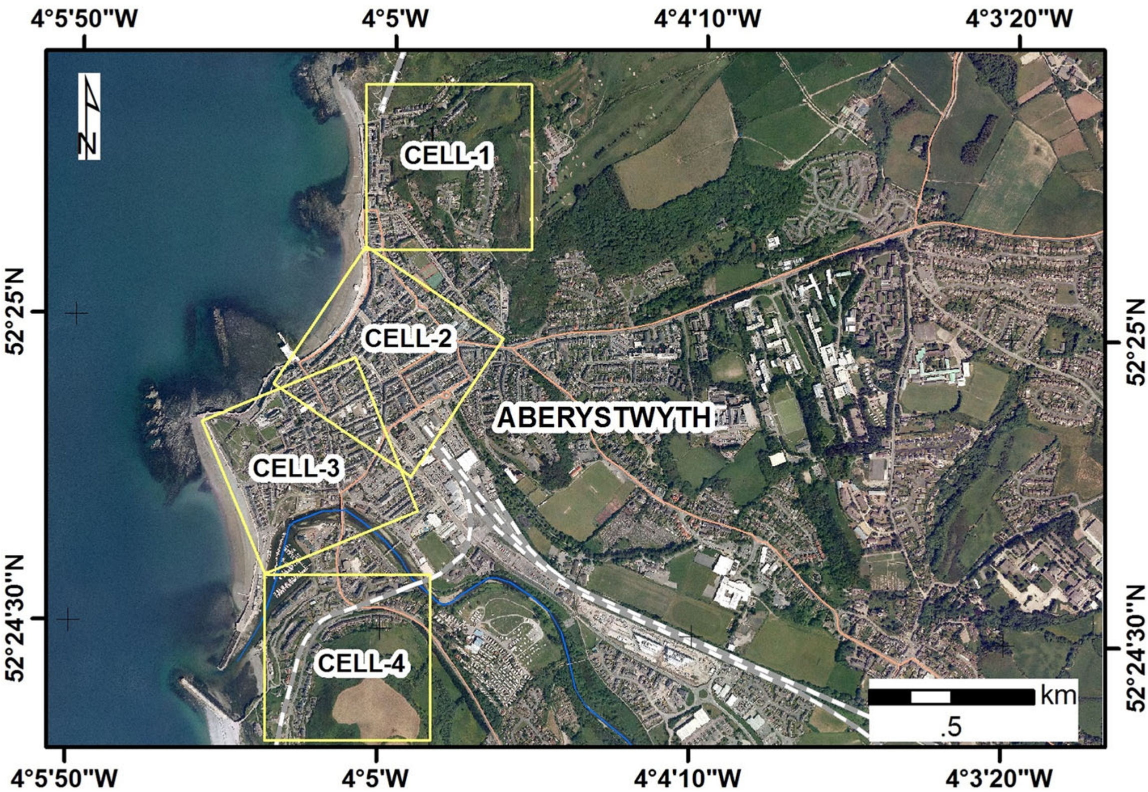

Fig. 4 Coastal cell (0.5 km) on transect line

Table 5 CIVI Parameter Ranking

Fiscal Parameter	1 Extremely Low £	2 Low £	3 Moderate £	4 High £	5 Extremely High £
Population	<1 bn	1 bn–6 bn	>6 bn–12 bn	>12 bn–20 bn	>20 bn–28 bn
Residential property	<30 m	30 m–80 m	>80n–30 m	>130 m–180 m	>180 m–1 bn
Commercial property	<2 m	2 m–10 m	>10 m–30 m	>30 m–70 m	>70–300 m

(*m* million, *bn* billion)

Coastal sections scoring within the mid-range (7–9) were ranked as moderate vulnerability, and coastal sections scoring in between 13 and 15 were categorised as an extremely high vulnerability. However, the ranking system as follows (Table 6);

5 Results and discussion

More than two km transect line was drawn on Aberystwyth coast and accordingly, four 0.5 km cells placed and then measured. Currently, this town has thousands of coastal population and very expensive properties (commercial and residential) (Table 7).

Moreover, Aberystwyth is critically vulnerable to wave attacks and high tides (Fig. 5). For several decades, it has been affected severely by a series of storms with high waves, tides, and storm surges, particularly in 2008, 2010, 2013, and 2014. Specifically, 2014 storm ravaged this region and caused an astonishing >£1.5 m worth of damage to the

Table 6 Vulnerability level ratings classified by total relative vulnerability score

Relative vulnerability score	Rating of vulnerability
Extremely high vulnerability	13–15
High vulnerability	10–12
Moderate vulnerability	7–9
Low vulnerability	4–6
Extremely low vulnerability	1–3

Table 7 Infrastructure details of Aberystwyth

Infrastructure name	Number
Commercial properties	758
Residential properties	6591
Population	15,139

Fig. 5 **a** Construction of new coastal wall (during 2014 flood strike, coastal wall was severally damaged), **b** commercial and residential properties near the coastline in Aberystwyth (photographs were taken by author—2015)

infrastructure (Ceredigion County Council 2014). The tidal range in the area is always greater than on other sites, with the largest increase of waves coming from the south-west, which is also the direction of the most frequent storms.

Though Aberystwyth has a shorter coastline, it has a high coastal infrastructure vulnerability and comparatively uneven across the coast. Some coastal cells are extremely high, and some are high to moderate vulnerability. Extremely high CIVI scores were recorded at the second and third cells, high at the fourth cell, and moderate at the first cell (Fig. 6). Currently, Aberystwyth has >40 bn worth of CIV (Fig. 7) with 4613 residential properties, 530 commercial properties, and >10,017 people are at high coastal risk.

6 Limitations

Due to the lack of recent literature (most of the research information is more than 10 years old) on Aberystwyth coastal vulnerability in both physical and fiscal aspects, there is not much scope to compare with other similar existing studies, especially at regional and

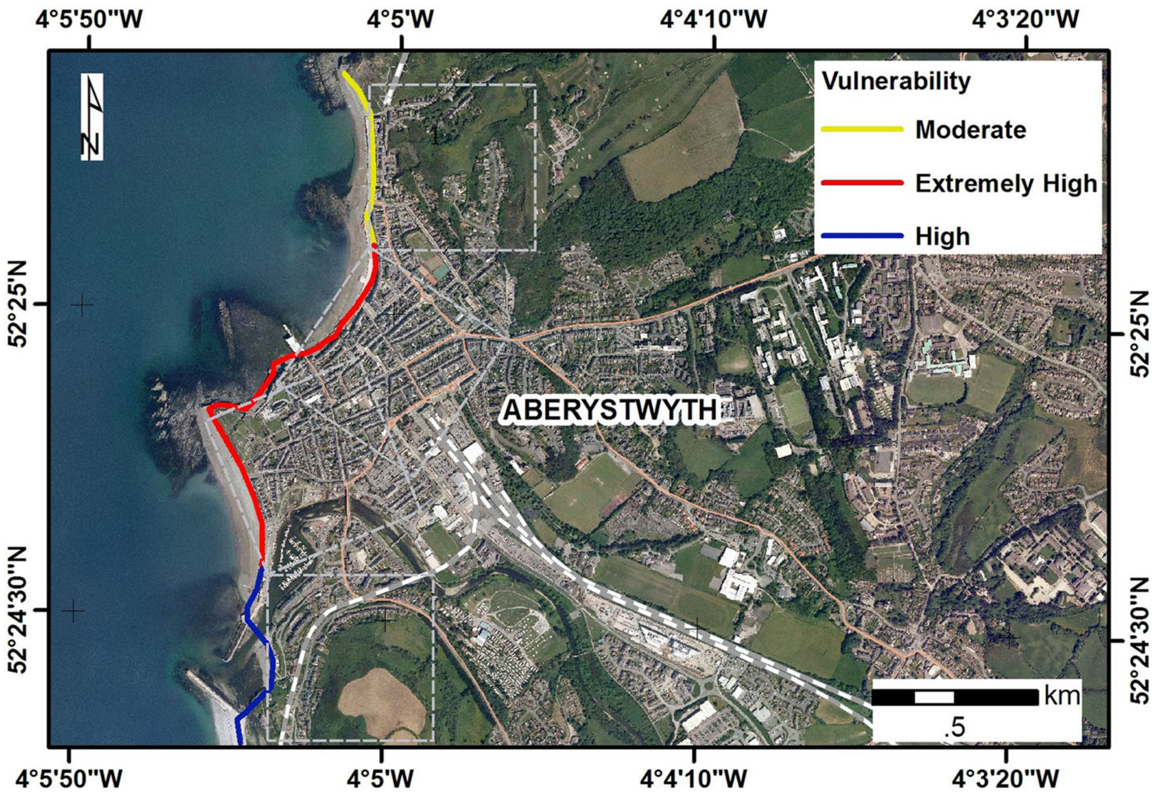

Fig. 6 Coastline vulnerability rates superimposed upon the aerial photograph

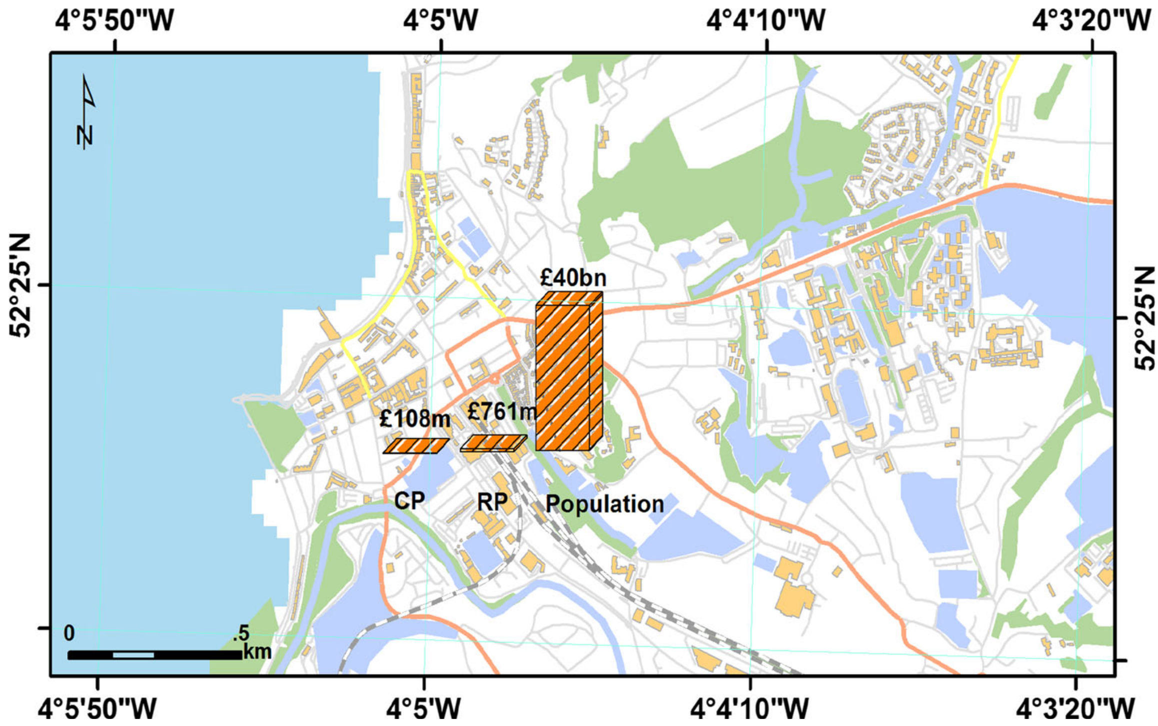

Fig. 7 Fiscal coastal vulnerability map of Aberystwyth (CP-commercial properties; RP-residential properties)

city/town scales. With these concerns in mind, the subsequent vital subjects in any effort of simplification of the findings would need to be certified carefully, such as GDP, local economy, and redevelopment procedures.

7 Conclusion

This study revealed the coastal infrastructure vulnerability of the Aberystwyth by the establishment of a novel integrated model, i.e., CIVI. Fiscal parameters that considered the existing economic conditions of the population, commercial and residential properties were used to appraise the relative economic coastal infrastructure vulnerability. Results showed that Aberystwyth consists of >£40 billion worth of CIV. Efficient and factual results for CIVI computation are intensely reliant on the quality and varied type of data used, which influence the vulnerability of a particular coastal stretch. This is a statistical and objective approach to illustrate the intensity of coastal infrastructure vulnerability at Aberystwyth coast. This integrated method enables the production of statistics and quantification of different levels of vulnerability to fulfil standards substitute to regional, local and sub-local authorities in the nationalised policy for control of climate change related coastal hazards in North Wales, UK. This technique of assessing infrastructure vulnerability can purpose as a primary susceptibility appraisal from which a map of probable intensities of vulnerability can be generated to allow cost–benefit scrutinise. The use of an appraisal of coastal infrastructure vulnerability can also be employed to define fiscal viability of coastal defence and the distribution of compelled funding. This model will be very useful to coastal economists, engineers and planning managers for better planning to reduce the coastal vulnerability.

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Compliance with ethical standards

Conflict of interest This manuscript has not been previously published and is not under consideration in the same or substantially similar form in any other peer-reviewed media. To the best of my knowledge, no conflict of interest, financial or other, exists.

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Could the UK Economy Be Impacted by an Increase in Tornado Occurrence?

A Consequence of Climate Change in the 21st Century

KOMALI KANTAMANENI, MIKE PHILLIPS, RHIAN JENKINS, JUDITH OAKLEY, KELECHI OBINNA IBEABUCHI

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Could the UK Economy Be Impacted by an Increase in Tornado Occurrence?: A Consequence of Climate Change in the 21st Century

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Abstract: Violent tornadoes are uncommon in the United Kingdom when compared with the US tornado alleys where significant storms occur frequently. However, the UK does occasionally suffer moderate to strong tornadoes, as evidenced in Birmingham (2005), London (2006), and Essex (2013), all of which caused damage that cost approximately £68.5 million and a number of fatalities. These events inevitability lead to increased interest in UK tornado research in the 21st century. Consequently, this qualitative study primarily analyses the UK tornado damage costs in recent periods by incorporating an innovative methodology: the Three Path Analysis (3PA). Chronological records of destruction costs from tornadoes in the United Kingdom are taken and adjusted to current inflation and market rates. These amendments offer a more reliable comparative process, evaluating losses over time against a framework of significant social and economic change. Between 1050 and 2013, the most extensive and violent tornado (T8) occurred on 23rd October 1091 in London. However, the costliest tornado on record occurred in Birmingham on 28th July 2005. This tornado (T5) had a £51 million damage cost (adjusted to 2013 inflation rates). Rapid climate change scenarios suggest that weather patterns will favour tornado generation, and if strong to violent tornadoes travel through some of the world's trading centres such as London, Birmingham, or Manchester, damage costs would likely amount to more than £1billion, negatively affecting national GDP during the 21st century. Therefore, this research provides an important contribution to extremely sparse literature with respect to the economic impact of UK tornadoes.

Keywords: Tornadoes, UK Economy, Destruction Costs

Introduction

The expected increase in the occurrence and intensity of severe climate events is probably the most important consequence of the continuous global temperature rise. Whilst temperature increases will possibly exceed the 2°C threshold by Dangerous Anthropogenic Interferences (DAI) (Ramanathan and Feng 2008), certain failures to establish a rigorous framework for securing degrees of emissions to pre-industrial levels and consequences could cause 6°C temperature increases by the end of the 21^{st} century (Le Quéré et al. 2009).

It is debated in the academic press that climate change has caused the severe UK weather events in recent periods, such as storms (floods, hurricane winds and tornadoes), heat waves, prolonged winters, and water scarcity (Beniston et al. 2007). Among the different natural disasters, a series of flooding events caused the major damages during the past seven years. While, 2007 summer floods in England turned into a nationwide catastrophe and established as one of the costliest flooding event on the records, which left £4 billion worth damage costs (Chatterton et al. 2010). In addition, more than 2000 additional deaths were recorded in England and Wales during the August 2003 heat wave (Johnson et al. 2005). The Environment Agency (2012) revealed a temperature increase of approximately 1°C in England since 1970, with 2006 being declared as warmest year in the 348 year record. Meanwhile, in the last 30 years sea surface temperatures have increased by approximately 0.7°C. Cumulatively, these weather patterns are stimulating very favourable conditions for tornado formation across the UK. However, research data on the nexus of UK tornadoes and climate change with an economical

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perspective is very limited. Therefore, this paper evaluates recent UK tornado occurrences and fiscal costs by applying novel methodology to fill the research gap.

Theory

Violent tornadoes are rare in the United Kingdom when compared with the US tornado alleys where violent storms occur frequently. However, the US leads the way, experiencing 75% of all tornadoes while Canada is in the second position with 5% and followed by Bangladesh (NOAA 2013). While, the UK tornado frequency per unit area is higher than other countries and experiences more than 30 tornadoes on average per year (Bolton 2003). But, the mean intensity of tornado magnitude is very low compared with many other areas of the globe such as US (Clark 2009): among those, nearly two thirds of UK tornadoes occur in early periods of winter as well as in the autumn seasons (January to September) (Reynolds 1999). Furthermore, there are two methods existed to measure the tornado intensity across the globe; Enhanced Fajita scale (EF1 to EF5) and TORRO scale (T1 –T10- open ended) (Table 1). EF is using all over the world (Doswell et al. 2009) except Europe and TORRO scale is widely using in Europe (including UK) and this scale was originally developed by Terence Meaden, based on wind speed (TORRO 2014).

Table 1: TORRO Scale

Tornado Intensity	*Description Of Tornado & Wind speeds*
T0	Light Tornado 17 - 24 m s-^{1}—(39 - 54 mi h-1)
T1	Mild Tornado 25 - 32 m s-^{1} -- (55 - 72 mi h-1)
T2	Moderate Tornado 33 - 41 m s-^{1} -- (73 - 92 mi h-1)
T3	Strong Tornado 42 - 51 m s^{-1} -- (93 - 114 mi h-1)
T4	Severe Tornado 52 - 61 m s-^{1} --- (115 - 136 mi h-1)
T5	Intense Tornado 62 - 72 m s-^{1} (137 - 160 mi h-1)
T6	Moderately-Destructive Tornado 73 - 83 m s^{-1} – (161 - 186 mi h-1)
T7	Strongly-Destructive Tornado 84 - 95 m s^{-1} --- (187 - 212 mi h-1)
T8	Severely-Destructive Tornado 96 - 107 m s-1 --- (213 - 240 mi h-1)
T9	Extremely-Destructive Tornado 108 - 120 m s^{-1} --- (241 - 269 mi h^{-1})
T10	Super Tornado 121 - 134 m s-^{1} – (270 - 299 mi h-^{1})

Weak Tornadoes

- T0
- T1
- T2
- T3

Strong Tornadoes

- T4
- T5
- T6
- T7

Violent Tornadoes

- T8
- T9
- T10

TORRO Scale is Open Ended

Source: Redeveloped From (TORRO 2014)

Tornado Generation

Due to the lack of much research data on tornado formation, it is still continuing an incomplete sub-sector in the field of tornadoes. However, NOAA (2013) suggested that tornadoes originate from super cell thunderstorms. An increase in ground temperatures causes moist air to warm and rise, and when this meets cool dry air, it immediately ruptures the above layer and creates favourable circumstances for the generation of super cell thunderstorm (BBC 2008). A strong vertical wind shear, which is present inside the thunderstorm, causes a horizontally spinning cylinder of air (Figure 1a). Rapid moment of air in both upward and downward directions push the rotating cylinder inside the super cell (Figure 1b). This tightens and becoming stretched, swirling faster and faster, creating a tornado (Figure 1c) (NOAA 2013). Due to climate change causing favourable weather conditions, there is likely to be an increase of UK tornadoes in near future (Holden and Wright 2004).

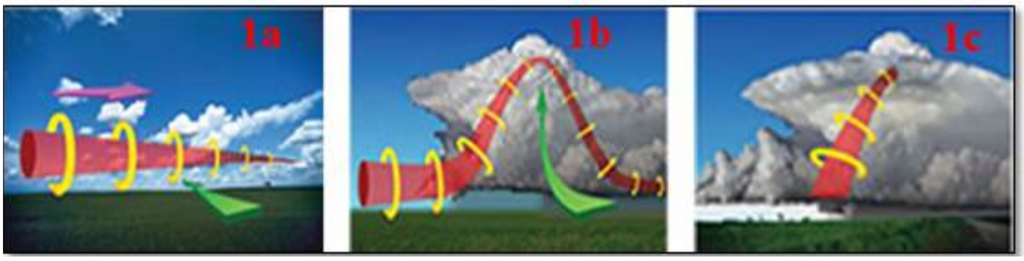

Figure 1(a, b & c): Tornado Formation
Source: NOAA 2013.

Fiscal Consequences of Tornadoes

The damage of tornado strikes mainly depends on gust speed. This force generally destroys the construction and properties within seconds. Normally, tornado events last for 1 minute to 10 hours based on category. However, destruction depends on intensity of tornado category rather than time (NOAA 2014). Violent tornadoes are usually long-lived and cause severe destruction to properties (residential and commercial) and infrastructure. It is well known that damage costs of tornadoes are huge in US, more than any other country, and this is generally the reason there are no data on global tornado damage costs, except from the US.

However, most UK tornadoes well documented (TORRO 2013; Holden and Wright 2004) (Table 2) in a systematic manner: based on the historical information, that first UK tornado (T8) was recorded on 23rd October (1091) at London, longest tornado (T5-T6) on 21st May (1950) at Buckinghamshire and widest tornado (T2) on 4th July (1946) at East Sussex. Historical evidence shows that only two violent (T8) tornadoes ravaged the UK since the 10th century, one in 1091 and another in 1810. However, 70% of UK tornadoes are T2 tornadoes (TORRO 2013).

Table 2: Tornado Occurrence across the UK (1995-1999)

Region	***Tornado Occurrence in %***
South-East England	31
Central England	29
North England	16
South-West England	15
Wales	6
Scotland	3
Northern Ireland	No historical information

Source: (Holden and Wright 2004)

Generally, tornado damage mainly comes from two vital segments: residential and commercial sectors. The devastation of residential and commercial properties owing to tornadoes is not a fresh problem. Every year thousands of homes are damaged permanently or partially across the globe by violent tornadoes. While, recent tornado events across the United Kingdom damaged residential properties (Figure 2), particularly terraced and individual houses with garages.

Figure 2: Birmingham (2005), London (2006) and Essex (2013) Tornadoes
Source: Pearman 2005; BBC 2006; The Telegraph 2013

Consequently, cumulative damage from these incidents was estimated at £55 million (Table 3). However, destruction was not serious except Birmingham tornado, because of them being low category tornado strikes.

Table 3: Recent Tornadoes and Fiscal Costs in the United Kingdom

Year	***Place***	***Damage Costs in £Millions***	***Tornado Intensity***
2005	Birmingham	40	T4-T5
2006	London	10	T4
2013	Essex	5	No official information
Cumulative Damage Costs		**£55**	

Source: ABI 2013; Spilsbury and Spilsbury 2008, 28.

Data and statistical information on tornado economics (UK) is very limited and no research papers produced in last five years particularly with in economic perspective. Consequently, there is no opportunity to examine the accuracy of long-term tornado fiscal destruction data. Accordingly, this study uses that limited data obtained from the TORRO centre, ABI (Association of British Insurers) and academic literature, for analysis of recent UK tornado damage costs. On the other hand, this study also qualitatively assessed the Birmingham, London and Essex events to compare fiscal information with existed (official) statistics. Then, estimates and results compared with previous estimations & ABI (Association of British Insurers) data. Differences are identified and new assessments of tornado damage costs are derived.

Methodology

Collection of statistics for tornado events is very difficult and it is a "method of madness"; however, it is strictly associated with scientific passion (Lott and Ross 2006). Meanwhile, there is no specific single government organisation to evaluate fiscal tornado data in the United Kingdom even in technical era. In addition, Met office has not been forecasting tornado events due to the lack of advanced Doppler radar technology. Because of these objects, there is a lot of ambiguity on damage costs as well as number of fatalities. However, UK-Tornado statistics are usually recorded by independent organisations, based on the path of event, place, intensity and date. It is very hard to offer factual damage costs for these events with in short period, and some times it takes from months to years (in worst case scenarios).

Meanwhile, there are no rigorous and precise methodologies for estimating tornado impacts in the United Kingdom particularly for monetary evaluation. Accordingly, a coherent and concise framework has been developed to assess tornado damage costs i.e. 3 Path analysis (Figure 3), based on three important phases: surveying (1), fiscal (financial) estimation (2) and mapping (3), to achieve research aims.

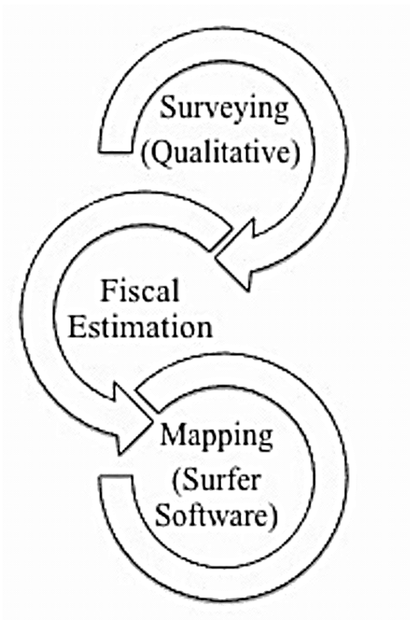

Figure 3: Three-Path Analysis

Surveying – Phase 1

A qualitative survey was undertaken in various parts of the UK in a 3 vs. 3 method, i.e. survey restricted to only 3 questions (Table – 4) with 3 possible answer choices. This questionnaire was distributed to participants in London, Birmingham, Essex, Manchester and Cardiff. Fifty-three respondents formed the pilot study group to assess both methodology and results. These fifty-three questionnaires were analysed to obtain tornado damage costs.

Table 4: Qualitative Survey Questions with Three Answer Choices

Number	***Questions***	***Possible Answers Choices***
1.	Are you getting sufficient tornado information and warnings from national and local governments?	1. Yes (Agree) 2. No (Disagree) 3. Not Known
2.	Do you think that climate change is the main reason for the formation of tornadoes in the UK?	
3.	Do you think there is adequate support from national and local governments to repair tornado damage?	

Fiscal Damage Cost Estimation – Phase 2

New estimates are determined for previous and future UK tornado damage costs; meanwhile, damage costs adjusted to 2013 UK inflation rates except Essex (2013) tornado.

Mapping – Phase 3

Surfer software (9th version) was used to map probable paths of tornado events in the United Kingdom, particularly in England because of relatively high number of past tornado strikes than Wales, Scotland and Northern Ireland.

Results and Discussion

Surveying – Phase 1

Qualitative survey results reflected the views of fifty-three responses of selected communities, who were participated from London (20), Birmingham (10), Manchester (15), Swansea (4) and Cardiff (4). These results were analysed (Figures 4, 5 and 6) and used as supporting data to evaluate the UK'S tornado damage costs.

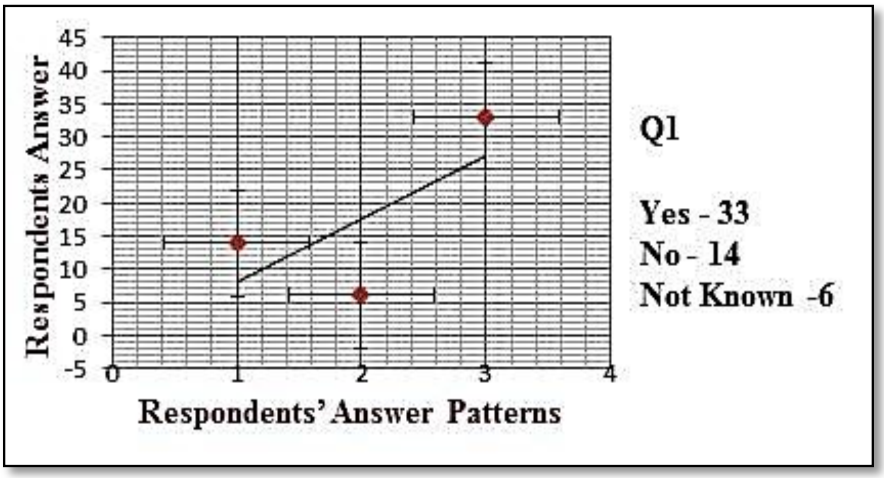

Figure 4: Qualitative Survey (Question - 1), Respondent Answer Patterns

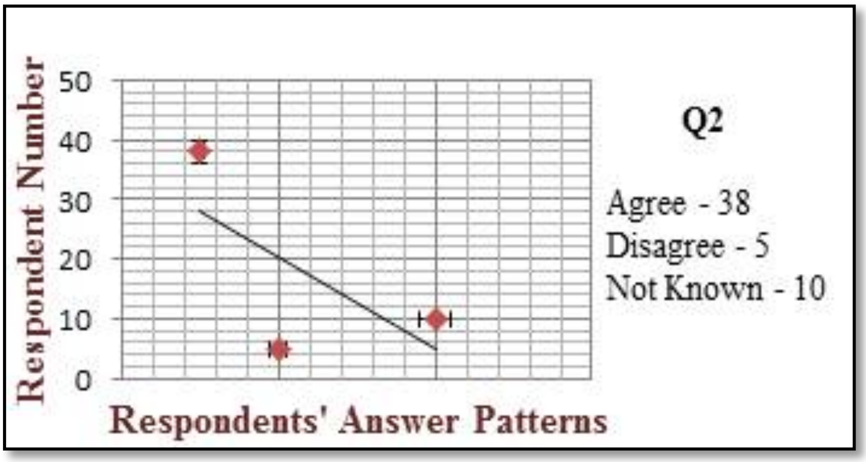

Figure 5: Qualitative survey (Question -2) Respondent answer Patterns

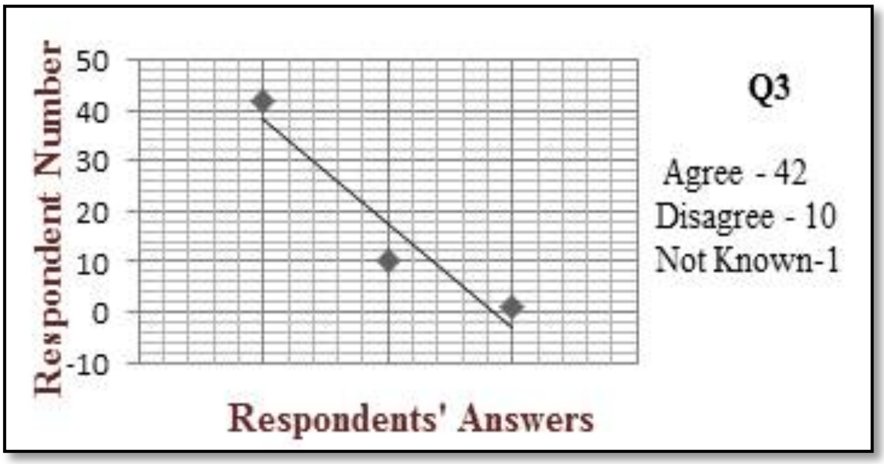

Figure 6: Qualitative survey (Question -3), Respondent answer Patterns

Fiscal Estimation – Phase 2

UK tornado damage costs (Table 5), are based on the analysis of qualitative-survey results, ABI (official) estimates and academic literature. Meanwhile, Birmingham (2005) tornado damaged circa 5000 houses, 600 businesses, and uprooted nearly 1000 trees. Cumulatively, these incidents caused £51 million of damage. On the other hand, the London tornado in 2006, caused £12.5 million damage by destroying 100 houses and 180 businesses. Moreover, the Essex tornado in 2013 damaged approximately 40 houses and 60 businesses and caused £5+ million in damages. However, this study did not offer the economical consequences of fatalities as well as environmental degradation caused by tornadoes.

Table 5: Recent Tornadoes and Novel Fiscal Costs in the United Kingdom

Year	*Region*	*Damage Costs in £Millions*	*Tornado Intensity*
2005	Birmingham	51	T4-T5
2007	London	12.5	T4
2013	Essex	5+	T2-T3
Cumulative Damage Costs ---- >£68.5			

Table 5 results revealed that, recent UK tornado events cost £68.5 million. Furthermore, this work also offers projected damage costs for future tornadoes and accordingly, a new tornado travel path was constructed. If tornadoes travel (T6 – T8) via international trade hubs, i.e. London, Birmingham and Manchester (Table 6), destruction costs will be >£1 Billion by 2080. During this fiscal assessment, some vital factors such as changing climate conditions, population growth and commercialization were considered.

Table 6: Novel Fiscal Costs for Future Tornadoes in the United Kingdom

Place	*Damage Costs in £ Millions*	*Tornado Intensity*
Birmingham	300	T4 - T8
London	650	T4 – T8
Manchester	150	T4 – T8
Future Tornado Damage Costs -- >£1 Billion		

Mapping – Phase 3

By the using surfer software (9^{th} version), a clear path was drawn for future tornadoes. This track illustrated prospective tornado damage costs in London (£650 million), Birmingham (£300 million) and Manchester (150 million), which were assessed in separate sub-maps (Figure 7).

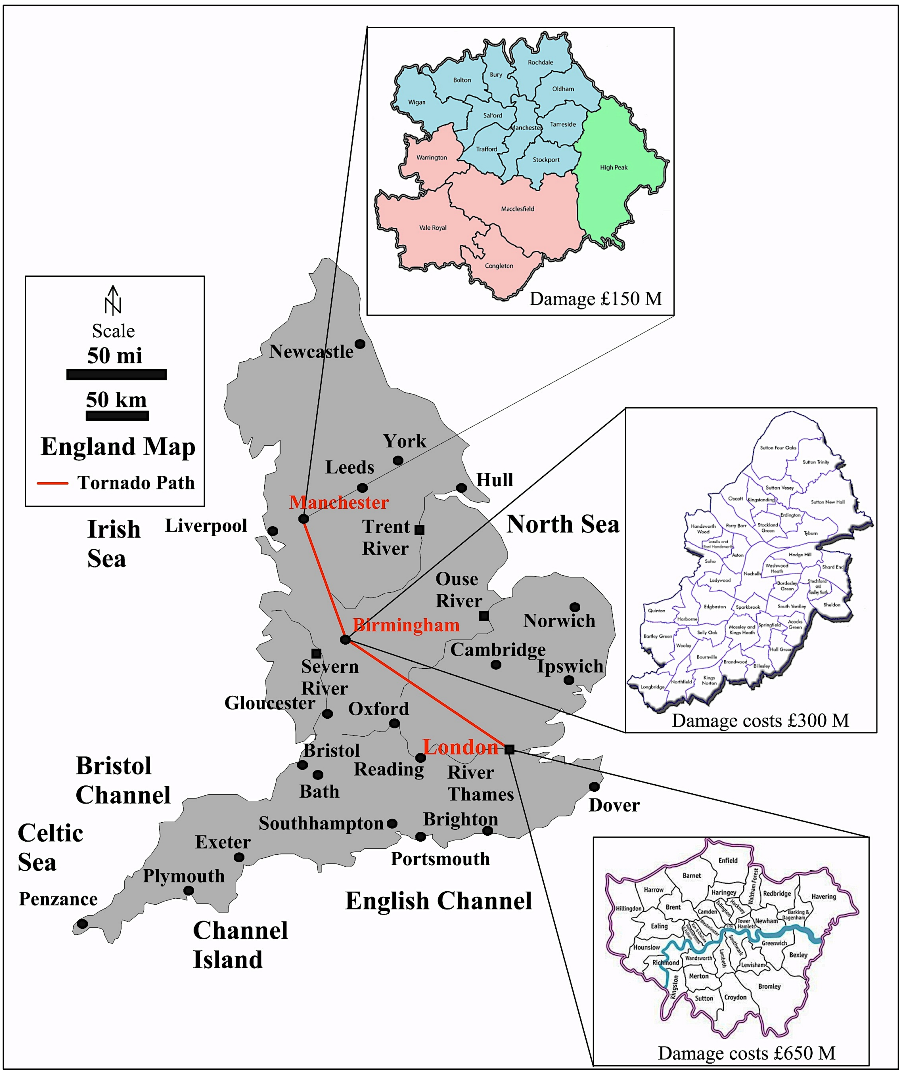

Figure 7: Tornado Travelling Path via London, Birmingham, Manchester

Source: Redeveloped (maps only) from (Maps of World 2013; London Council 2012; Birmingham City Council 2013; Highways Forecasting and Analytical Services 2012)

Conclusion

This study provided a comprehensive fiscal scaffold of recent tornado disasters in the United Kingdom along with innovative methodology (3 path analysis) for collecting and analysing statistical data for these events. This novel methodology was constructed in three vital phases: qualitative surveying, fiscal evaluation, and mapping. Results suggested that previous estimates are not significant and precise, while weather centres (Met Office) do not provide in-depth and accurate tornado information to the communities (path and future cost estimates). This research established a systematic framework to address these deficiencies and achieved a more realistic estimation of tornado damage costs. Recent tornado event (2005, 2006, and 2013) damages exceed £68.5 million and it will be >£1 billion, if future tornadoes travel through international trade centres like London, Birmingham, and Manchester in the future (by 2080). These costs would significantly affect national and local economics, and therefore, the United Kingdom must adopt rigorous climate change adaptations to protect future generations from human induced natural disasters such as tornadoes.

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Transformation of Climate

Will Floods and Coastal Erosion Crumble the UK Economy?

KOMALI KANTAMANENI AND MIKE PHILLIPS

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Transformation of Climate: Will Floods and Coastal Erosion Crumble the UK Economy?

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Abstract: Recent flooding events in the United Kingdom have raised concerns that climate change is increasing flood frequency and intensity. England and Wales were significantly affected by these extreme weather incidents. Rapid coastal erosion is becoming a major concern, particularly in England (Hallsands, Dawlish, and Lynmouth), South Wales (Llanelli), and Scotland (Balivanich) with circa 3008 km of coastline being lost to the sea. These situations result in significant losses of infrastructure mainly in coastal zones across the UK. Consequently, this qualitative study primarily analyses the UK flood damage costs for commercial and residential properties along with coastal erosion costs by using a methodology: 2PA (Two Path Analysis). Applications of the methodology provide more factual damage costs, which highlight potential climate change impacts on present and future generations. Primary results revealed that the UK flooding costs for properties and coastal erosion costs are to be £1.3 billion per year with more than 6 million properties at flood risk. These costs represent only 0.08% of national GDP, showing it to be small on a national scale. Predictions denote that socio-economic costs will negatively affect national GDP if flood resilience is not improved.

Keywords: Two Path Analysis, Climate Change, Flood Cost Assessment Tool, Coastal Erosion, National Economy

Introduction

Research on the nexus of climate change and storm intensity has widely been debated in the academic press, particularly regarding the rapid rise in the frequency and intensity of storms owing to either normal climatic variability or anthropogenic global warming (Knutson et al. 2010; Houghton et al. 2001; Easterling et al. 2000; Walsh et al. 2007; Doney et al. 2012). Already significant emissions commit the earth to certain levels of future warming and will possibly exceed the 20°C verge by dangerous anthropogenic interference (Ramanathan and Feng 2008). Greenhouse gases, in particular CO2 emissions, are the primary reason for rapid and recent climate change scenarios (Thomas et al. 2004; Meinshausen et al. 2009; Solomon et al. 2009). Approximately 40% of CO2 emissions, which are produced mainly from burning fossil fuels, increased for the period of 1990 to 2008. Since last century, the earth warmed by about 0.7°C and average UK temperature increased by 1°C from mid of the 1970s (Hulme et al. 2002). Due to these regional and global climatic changes, the UK is facing significant risks like sea level rise, severe storms, storm surge, and rapid coastal erosion (Bray, Hooke, and Carter 1997; Pye and Blott 2006; de Alegria-Arzaburu and Masselink 2010). Coastal communities are especially vulnerable to these problems and, unfortunately, these regions are hugely populated (Nicholls and Cazenave 2010; Boruff, Emrich, and Cutter 2005; McGranahan, Balk, and Anderson 2007). Consequently, this qualitative study evaluates the UK floods and coastal erosion costs by using a methodology, i.e., Two Path Analysis (2PA), while also scrutinising the impacts of damage costs on the national economy.

Description of Study Area

The UK is an island nation located in Western Europe, and the mainland lie between latitudes 49°N and 59°N and longitudes 8°W to 2°E. It is positioned between the North Atlantic Ocean and the North Sea. It is also made up of four administrative regions: England, Wales, Scotland, and Northern Ireland (Figure 1) (European Union 2013). The total area is 243,610 km^2 (CIA 2013) and coastline is 17,381 km (Ordnance Survey 2013) with approximately 60% of this

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coastline is in Scotland and the offshore islands (UK Coast Guide 2013). The population is 62.74 million (World Bank 2014) of which circa 30m are living in coastal areas (Zsamboky et al. 2011). The UK is the world's sixth largest economy with a £1.6 trillion GDP (World Bank 2014), and most of the GDP is generating through tourism (Phillips 2008). However, the UK is increasingly vulnerable to impacts of coastal erosion, flash and surface flooding, storm surges, and extremes in weather compared to recent memory. Nevertheless, the main climate change consequences are flooding and coastal erosion.

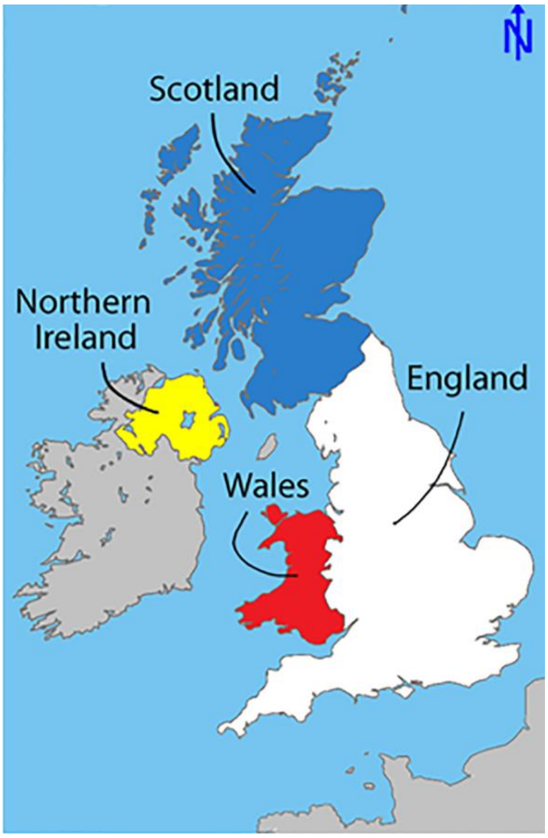

Figure 1: United Kingdom Administrative Regions
Source: British Council 2013

Physical Geography

Flooding

Prolonged time series data plays a vital role in understanding flood intensity in multiple dimensions (Kochel and Baker 1982; Ely et al. 1992). However, the majority of universal flood records are no longer than fifty years (Benito et al. 2004; Macklin Rumsby 2007). Meanwhile, there is no accurate statistical evidence in the UK regarding long-term flood damage costs as well as trends, but from 2007 onwards, the Environment Agency is providing detailed economic data in an agreed format. In 1952, a massive flood struck the coastal town of Lynmouth (Devon, England) and wrecked one hundred buildings and twenty-eight bridges (Figure 2a) (Dobbie and Wolf 1953; Marshall 1952). In 1953, North Sea floods struck England and Scotland and caused massive damage to 1,600 km of coastline (Pollard 1978). Moreover, in the autumn of 2000, major floods affected England and Wales and caused £1 billion of damage to >10,000 houses (Alexander and Jones 2000). Summer floods in 2007 caused £4 billion worth of damage, of which insured losses were approximately £3 billion (EA 2010) (Figure 2b). In 2012, 2013, and 2014, various flood events ravaged the United Kingdom with heavy rain and hurricane winds (Figure 2c)

Figure 2(a, b, and c): Various Flood Events in the United Kingdom
Source: (a) Joint 2008; (b) Reuters 2007; (c) Carrington 2012

Coastal Erosion

More than half of the global population, i.e., 3.2 billion people, lives within 200 km of the coastline (Hinrichsen 1999) and one-third of the UK population lives within 10 km of coastline (EA 1999). Coastlines are always subject to change through erosion and other natural processes. Continuous occupation and rapid population growth in UK coastal areas have aggravated current risks of coastal flooding and erosion (Dodman 2009); some of the UK coastline (3008 km) (Table 1) is currently undergoing erosion (Doody 2004).

Table 1: Coastal Erosion

Region	Coast Length (km)	Eroding Coast Length (km)	Eroding Coastline (%)
England	4273	1275	29.8
Wales	1498	346	23.1
Scotland	11154	1298	11.6
Northern Ireland	456	89	19.5
Total	17381	3008	17.3

Source: Adapted from Masselink and Russell 2010

Coastal erosion impacts can be clearly seen on tidal flats, cliffs, salt marshes, and beaches; the most significant risks from coastal erosion are flooding, rock falls, loss of land, and damage to commercial and residential properties (Figure 3). Coastal properties about 1,026,000 housing assets, 74,000 commercial assets, and some 432,000 hectares of farming land are potentially at risk from coastal flooding. Altogether this is equivalent to >£10 billion (Wallingford 2001).

Figure 3: Coastal Erosion in Happisburgh, England
Source: Satellite Images (Google Earth Pro 2014)

Data

Data were obtained from the Environment Agency (England, Wales, and Scotland), British Geological Survey, Association of British Insurers, and Parliamentary reports for both flooding (commercial and residential properties) and coastal erosion, while ONS (Office for National Statistics) data were used for the evaluation of population trends and number of existed properties across the United Kingdom. Data regarding GDP was collected from World Bank. Moreover, the research team of this current study conducted multiple observations to appraise the changes in both the intensity and severity of flooding and coastal erosion at various places and then evaluated the costs. Based on this information, aerial maps are developed from the Ordnance Survey and-Google Earth Pro with live pictures and subsequently analysed. Derived results compared with published national reports to offer new damage estimations.

Methodology

There are many methodologies for estimating of flood damage and coastal erosion costs at global and regional levels in relation to climate change. Existing literature on flood and coastal erosion estimation methods developed by applying numerical approaches such as Smith (1981); Dutta, Herath, and Musiake (2003); Jonkman et al. (2008); Merz et al. (2004); Thorne, Evans, and Penning-Rowsell (2007); Turner et al. (2007); Roebeling, Coelho, and Reis (2011). However, research context and assessment criteria are different for this study and accordingly, a coherent and concise framework has been adopted based upon the work of Kantamaneni, Alrashed, and Phillips (2015), i.e., 2PA (Two Path Analysis) (Figure 4). This methodology comprises two vital paths:

> Path One: Evaluation of flood damage costs for residential and commercial properties by applying Flood Cost Assessment Device.
>
> Path Two: Identification and mapping of coastal eroding areas along with appraisal of coastal erosion costs.

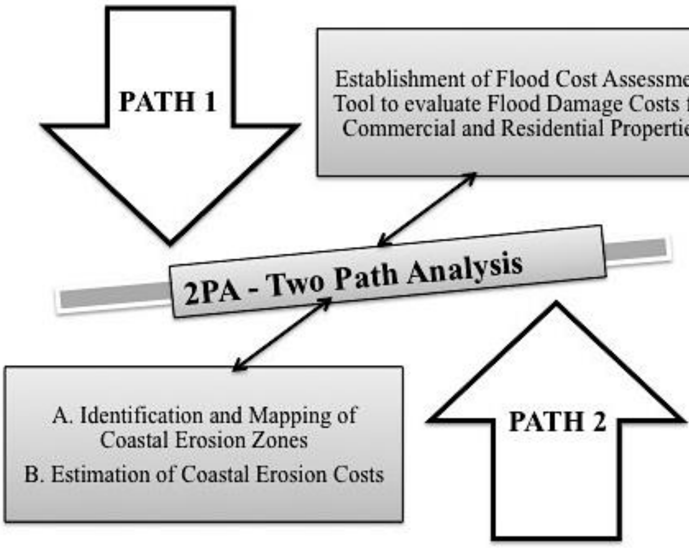

Figure 4: 2PA—Two Path Analysis
Source: Kantamaneni, Alrashed, and Phillips 2015

Path One (P1): Flood Cost Assessment Device

A Flood Cost Assessment Device (Figure 5) conceptual procedure was adopted for this research based upon an adaptation of the work of Kantamaneni et al. (2015) for evaluation of flood costs mainly for commercial and residential properties and, subsequently, applied to the UK scenarios.

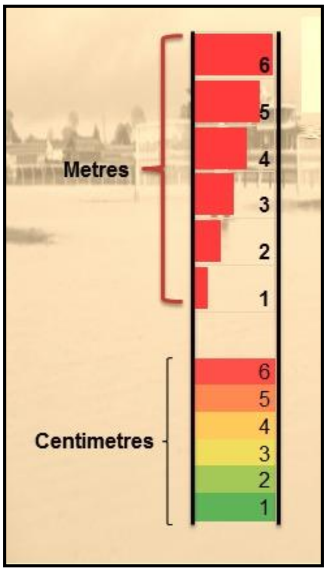

Figure 5: Flood Cost Assessment Device
Source: Kantamaneni et al. 2015

It has been established using a combination of *cm* and *m* flooding levels, indicated by colour codes on a scale, to identify the intensity of flood water levels. If water level reaches between 2 and 5 cm into properties, there is not much damage, but if flood waters reach between 0.6 and 1.5 metres, it should cause significant damage to assets, including construction, structural fittings, furniture, and household equipment (Figure 6). Replacement costs for carpets, fridges, sofas, beds, electrical equipment, and decorations are generally higher than those assets lost. This assessment method critically analyses property damage costs especially for residential and commercial structures and then other and related expenses.

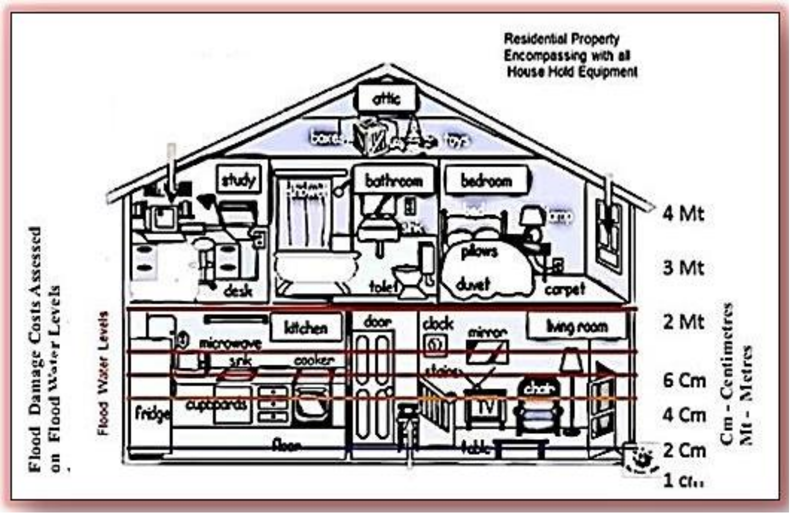

Figure 6: Applications of Flood Cost Assessment Device to Properties

This method used market values for each component and followed a systematic approach to obtain flood damage costs; the process being underpinned by a mathematical derivation as follows:

$$\left(\frac{Min. Property\ Damage\ Costs\ + Max. Property\ Damage\ Costs}{2}\right)\ x\ No. of\ Properties\ at\ Risk$$

Path Two (P2)

Identification and mapping of coastal erosion sites and evaluation of coastal erosion cost based on collated data.

Results and Discussion

Path One (P1): Flood Damage Costs for Commercial and Residential Properties

The derived formula was considered alongside minimum and maximum costs for various items (commercial and residential) and scenarios as shown in Table 2.

Table 2 shows how diverse the costs are for residential and commercial properties. These values have been set from a minimum to maximum costs for a particular item, i.e., £1,000 (minimum) to £22,000 (Maximum). From Table 2, summing the total maximum (£41,500) and minimum values (£18,500) enables the derivation of an average damage cost per property, which can be factored into the total number of properties at risk. This is currently estimated at 6 million, and flood damage costs for properties are compared with and are different from ABI (Association of British Insurers) results, which are between £20,000 and £40,000 for a single property. However, approximately (on average) 40,000 properties (0.6%) are affected by (major\minor) floods every year, which means UK average flood damage costs for properties are £1.2 billion per annum.

$$\left(\frac{£18{,}500 + £41{,}500}{2}\right) X\ 40{,}000 = £1.2\ billion$$

Table 2: Flood Damage Assessment for Commercial and Residential Properties

Flood Damage Cost per property	Damage Costs for Residential\Commercial properties (Minimum to Maximum)
Carpet\Wooden Floor	£1,000 to £3,000
Electrical Appliances	£2,000 to £5,000
Doors & Windows	£1,500 to £3,000
Living\ Dinning\ Kitchen\Bed room Furniture\ Infrastructure	£8,000 to £ 22,000
Personal Items	£1,000 to £1,500
Cleaning and Repairs	£3,000 to £4,000
Others	£2,000 to £3,000

Newly Adopted Device: Feasibility and Rationalisation

The newly adopted tool, i.e., Flood Cost Assessment Device, consists of innovative structures and this model is a significantly better model than existing methods, based on the following claims.

Claim 1

This model is not as complicated and contains only simple equations. This will be useful in evaluating the immediate aftermath of floods.

Claim 2

The Flood Cost Assessment tool is a combination of *cm* and *m* scales with defined colour bands representing codes for flood water level intensities. While being relatively simple in representation, the underlying methodology is mathematically based and refined.

Claim 3

The mechanism (described in Path Two) that is used in this device (useful for measuring flood water levels as well as for the assessment of flood damage costs) is completely innovative, fiscally effective, and a simple process. Based on the analysis, the current study concludes that the Flood Cost Assessment Tool is more consistent and cost-effective.

Path Two (P2): Coastal Erosion

This section evaluated the following two vital things: identified coastal erosion sites and developed maps and estimated coastal erosion costs.

Identification of Coastal Erosion Sites and Mapping

This study also identified highly rapid coastal erosion (vulnerable) sites (via multiple site visits as well as data collection) across the United Kingdom as follows:

Table 3: Coastal Erosion (Vulnerable) Sites

England	Wales	Scotland	Northern Ireland
Devon	**South Wales**		
▪ Hallsands ▪ Dawlish ▪ Lynmouth	▪ Llanelli	Balivanich, Benbecula Island	No Severe Coastal Vulnerability At present

Table 3 revealed the severe coastal erosion sites of the United Kingdom: three in England, one in South Wales, and one in Scotland. However, Northern Ireland is an exemption for severe coastal erosion.

Coastal Erosion Sites and Maps

I. Hallsands, England

Figure 7: Coastal Erosion in Hallsands, England

Hallsands is one of the most rapidly eroding sites in the United Kingdom. Residential properties and agricultural land are at huge risk of erosion and flooding, as shown in Figure 7. The distance from residential properties to the coast is small, i.e., 0.01km.

II. Dawlish, England

Dawlish is a tourist location in Devon, England. It is at severe risk of flooding and coastal erosion as evidenced in December 2014 (Figure 8). Massive infrastructure was severely affected by this winter floods.

Figure 8: Dawlish during and after Flooding in 2014
Source: BBC 2014 (8c)

III. Lynmouth, England

Lynmouth is a coastal village located in England. Currently, it is at greater risk of coastal erosion and flooding as shown in Figure 9. This site has been severely affected by a series of flooding events since 1952.

Figure 9: Coastal Erosion in Lynmouth in 2014

IV. Llanelli, South Wales
Llanelli is a Welsh town, and it is also at high risk of coastal erosion and flooding (Figure 10). The distance from the coast to properties is >1 km. Most of the commercial and residential properties are very near to the coast.

Figure 10: Coastal Erosion (Vulnerable) in Llanelli, South Wales

V. Balivanich, Benbecula Island, Scotland

Balivanich is a highly eroding site in Scotland due to the rapid disintegration of coastline into the sea (Figure 11). Most of the properties are at an enormous risk of coastal erosion. The distance from the coast to properties is >0.8 km.

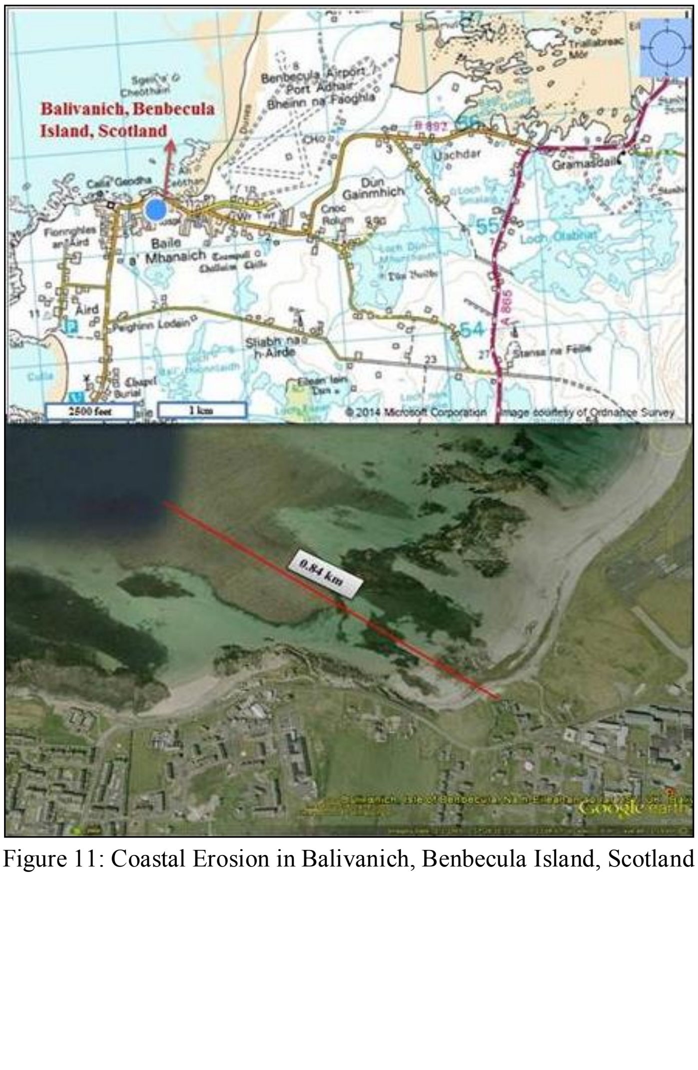

Figure 11: Coastal Erosion in Balivanich, Benbecula Island, Scotland

Evaluation of Coastal Erosion Costs

Estimations of coastal erosion (Table 3) are made using the data from UK Government\Foresight figures, which are currently £15 million as stated in the 2009 climate change projections and CCRA 2012 report. However, this study differed with these results and offered new estimations, i.e., >16.5 million per year. This study also found that the erosion rate is not the same throughout the UK; England is very vulnerable to erosion, Wales and Scotland are moderately vulnerable, and there is no risk to Northern Ireland. However, this study provided the cumulative of costs of coastal erosion rather than the sectoral assessment. In addition, during the estimation, this study considered the population trends, coastal zones, and yearly changes in the coastal areas, height of tides, and distance of properties from the coast.

Table 3: New estimations for Coastal Erosion

Coastal Erosion Costs		
Foresight, CCRA- GOV.UK- Estimations In £Millions		New Estimations In £Millions
Current Erosion costs	15+	>16.5

Analysis revealed that coastal depletion is growing faster than projected values, and it is likely to increase over the next fifty years. Climate change, particularly sea level rise and temperature fluctuations, are primary reasons for this. Each of these will cumulatively impact the UK coast. Consequently, England is the UK's most vulnerable zone for coastal erosion, but its fiscal impact is considerably less than the fiscal impact of coastal flooding. However, previous predictions were underestimated; accordingly this study has offered these new estimations.

Flood Damage (Properties) and Erosion Costs Impact on National Economy

Cumulative costs of flood damage (properties), as well as coastal erosion, are >£1.3 billion at current scenarios. This is a very fraction of the amount of national GDP, which is currently £1.6 trillion. These costs represent only 0.08% on a national scale (Figure 12) and do not have a significant current impact on the national economy. However, by 2080 it should be a more significant percentage. Therefore, if rigorous environmental protection and climate change policies and procedures are not followed, future generations will unquestionably be more frequently vulnerable to floods and coastal erosion.

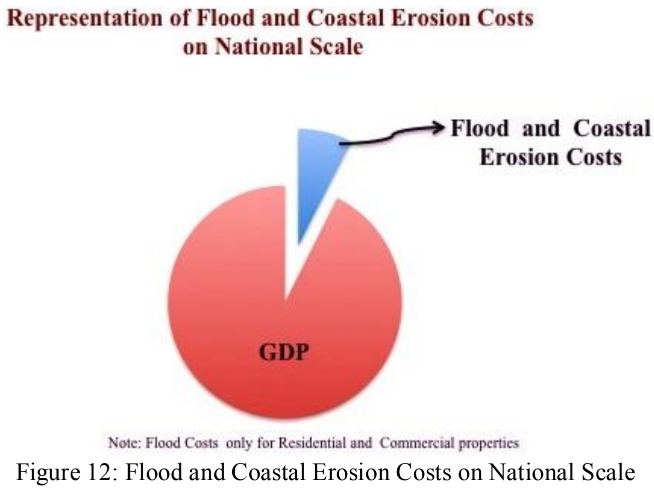

Figure 12: Flood and Coastal Erosion Costs on National Scale

Conclusion

This paper adopted a methodology, i.e., 2P (Two Path Analysis). This approach analysed the flood damage costs for properties by using the Flood Cost Assessment Tool as in path one and then it identified the coastal erosion zones along with an evaluation of coastal erosion costs in path two. In addition, this study also scrutinised the impact of damage costs on national GDP. Accordingly, this study revealed that the current flood and coastal erosion costs (£1.3 billion) insignificantly affects the national economy due to a fraction of the amount on the national scale. This study indicates that if flood risk planning and coastal protection measures are not improved, socio-economic costs will negatively affect national GDP in the future.

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FLOOD CRUNCH: A FISCAL APPRAISAL FOR COMMERCIAL AND RESIDENTIAL PROPERTIES IN ENGLAND

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Rhian JENKINS

Abstract

This paper establishes and applies a coherent and concise empirical framework for evaluating damage costs for commercial and residential properties during flooding in England by incorporating a novel methodology i.e. Flood Cost Assessment Tool. This research also analyses whether these damage costs significantly impact on the national economy as well as local economies. This strategy differs from previous economic flood damage estimation models by focusing on different grades of properties and level of damage in various flood events across England. Results reveal that Environment Agency and British Insurers estimations are too optimistic and some vital aspects are often neglected. Indeed, the new estimates for England's flooding costs for commercial and residential properties were found to be £1.6 Billion per year. While current English property damage costs represent only 0.1% of national (UK) and country (England) GDP, showing it to be inconsequential at either scale, it has considerable fiscal impact on local economies (County Councils) in both short and long term scenarios

Keywords: New Methodology- Flood Cost Assessing Tool, Floods, Damage Costs, National and Local Economy

JEL CODE: **Q540 – (**Climate; Natural Disasters; Global Warming)

1. Introduction

The study of flood costs has attracted global interest in both environmental and pure economics. Flood damage varies significantly from year to year and predictions identify increasing trends over the last century (Pielke, 2000). Europe's current annual flood damage costs are £5.2 Billion and it is likely to rise rapidly in the future (Ciscar *et al.* 2011).

Subsequently, this study questions whether flood damage data shaped by the Environment Agency and Association of British Insurers (ABI) really fulfil owner estimations? Are predictions realistic? Although extensive research has been undertaken, the answers to aforementioned queries remain indistinct, mainly due to lack of digitization of flood economic data over decades, as well as robust research methodologies. These issues prompted the present study to develop a novel and simple conceptual framework to estimate true flood damage costs for residential and commercial

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properties by grading properties. It also assesses the impact of flood damage costs at UK, English and local level GDP.

2. Study Area

England was selected as a study area because of the frequency of flooding incidents. It is bounded by the English Channel (south), Celtic Sea (southwest) and North Sea (East) (Figure 1) (Maps of World, 2013): its coastline is more than 5581 miles (Darkes, 2008) and the population is 52 million (ONS, 2013). England is vulnerable to all types of floods, as evidenced in various locations in 2007, 2009 and 2012 (Zhou *et al*. 2011 & Jha *et.al.* 2012). Consequently, this work estimates average annual flood damage costs of properties between 2007 and 2012.

Fig.1. Location of study identified for Primary Flood Assessment Conceptual Framework Application. (Source: Maps of World, 2013)

3. Theory

Approximately 5.2 million properties including 2 million commercial properties are at flood risk in England (Environment Agency, 2009). Summer floods (England) in 2007, turned into a nationwide catastrophe and caused £3.5 to £4 Billion worth of damage costs: of that amount, more than £3 Billion came from the housing sector (ABI, 2010, & Environment Agency, 2014). Besides, 2009 flooding costs £180 million and 2012 floods costs more than £600 million, and these events hugely impacted the England's economy (ABI, 2010, & Environment Agency, 2014).

3.1 UK and England GDP

The UK's economy is a paradox: while being the sixth largest economy in the world, with £1.6 trillion current (2012) GDP (World Bank, 2013) since 2007, its economic vigour has declined with a double credit crisis (The Economist, 2013). Consequently, for the last six to seven years, the economy has exhibited sluggish growth and flood costs have exacerbated the situation. Given the significance of these impacts, it is important to analyse residential and commercial property damage costs and impact of damage scenarios on national and local GDP.

4. Methodology - Conceptual Framework

This methodological approach contains two fundamental mechanisms. Primarily, it offers a conceptual framework for the precise evaluation of the flood water levels in properties. Secondly, implementing framework by establish three crude numerical equations to evaluate flood annual property damage costs as well as intensity of impact of damage costs on national and local economies. This approach was aggravated by FEMA's-USA (Federal Emergency Management Agency) flood cost tool. This crude numerical model relies on cm (centimetres) and m (metres) scales, indicated by various colour codes to categorise flood water levels (Figure 2).

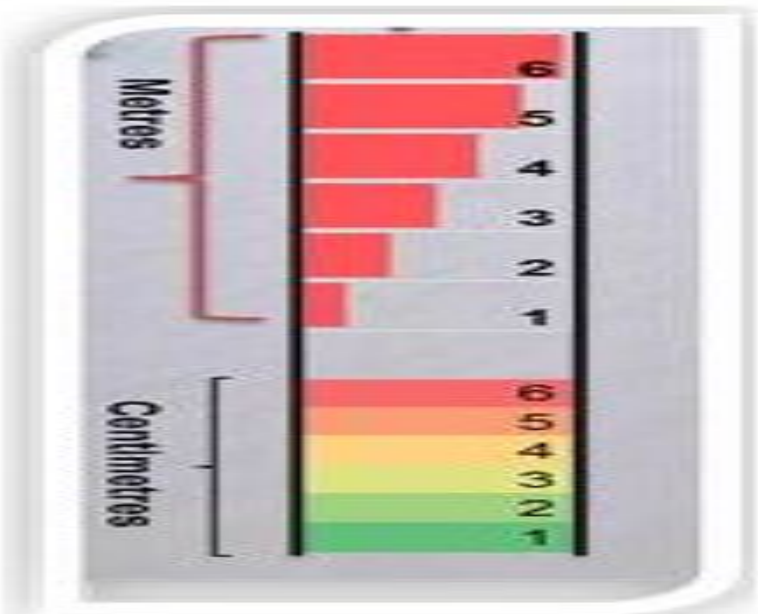

Fig. 2. Flooding Cost Assessment Tool

Accordingly, this linear model empirically measures floodwater levels and assesses effects in various qualitative property grades based on household income: Grade 1 (Very High); Grade 2 (High); Grade 3 (Medium) and Grade 4 (Low), in England to show clearly flood damage severity. Inundation into properties of between 3 cm and 5 cm generally causes no serious damage, but there is potential damage to construction, equipment, carpeted and wooden floors, walls and other materials if the flood water level reaches > 5 cm (Figure 3(a) and 3(b)). Consequently, this distinct measurement tool enables analysis of the magnitudes of commercial and residential property damage costs during recent flooding events.

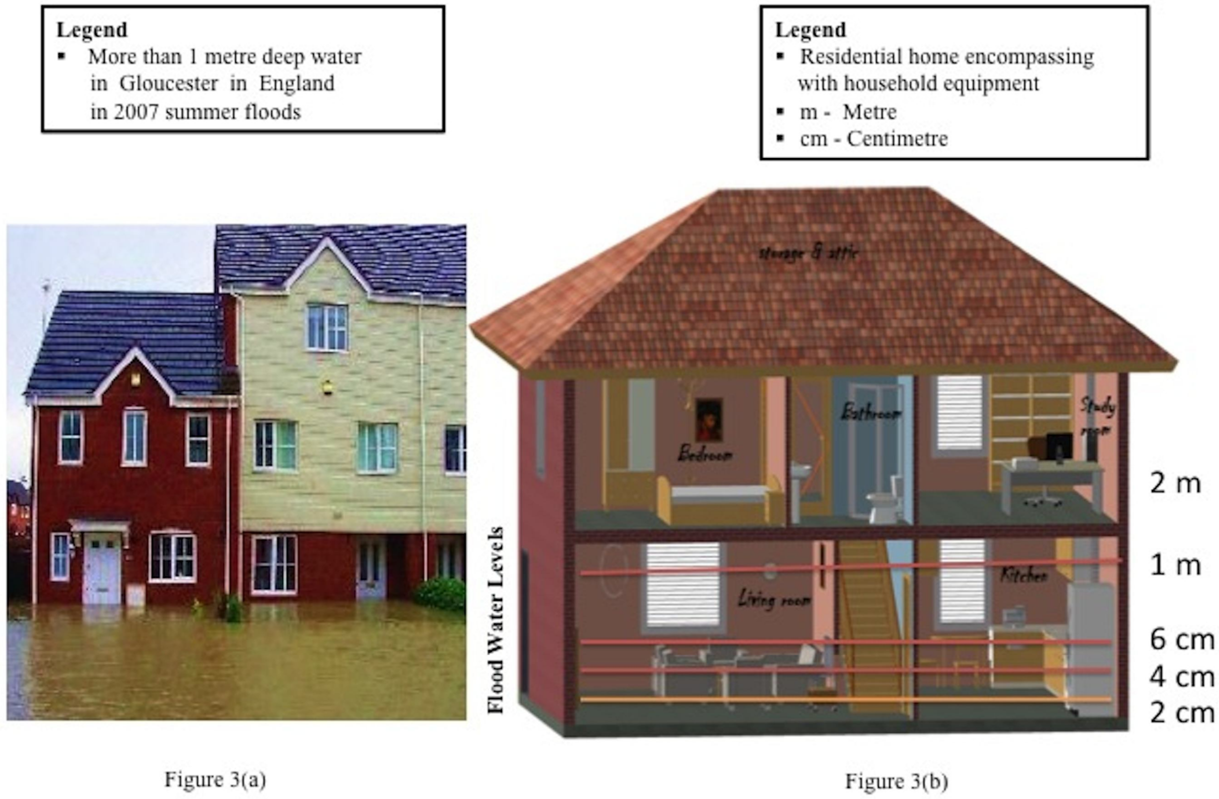

Fig. 3 (a & b): Applications of Flooding Cost Assessment Tool to Property (Source: (a)- BBC, 2009)

This framework also consists of three crude numerical formulas as support pillars to assess impact: % of flood damage costs on local and national economies along with evolution of mean values of properties. These are,

$$\left(\frac{FDCcr}{NGDP}\right) X \% \quad (1)$$

Here, FDCcr denotes flood damage costs of commercial and residential properties and NGDP signifies national gross domestic product.

$$\left(\frac{FDCcr}{LE}\right) X \% \quad (2)$$

From above equation, LE designates local economy.

$$\left(\frac{MFDC + MAFDC}{2}\right) X\ NDP \quad (3)$$

Where: MFDC is Minimum Flood Damage Costs
MAFD is Maximum Flood Damage Costs
NDP is Number of Damaged Properties

5. Data

This study uses data from British Insurers and the Environment Agency along with extensive academic literature. Data from these organisations were supplemented by information from UK Government Reports. While, this study divided properties into grades (G1 G2, G3 and G4 – Table 1) and also quotes the types of residential and commercial properties to evaluate fiscal damage with the novel flood cost assessment tool. Consequently, results were compared with statistics published by the British Insurers and Environment Agency and differences identified. Subsequently, new assessments of flood damage costs are derived.

Table 1
Grades of Property and Types of Residential and Commercial Properties

Grading of Properties				
PROPERTY TYPE	**GRADE 1**	**GRADE 2**	**GRADE 3**	**GRADE 4**
Residential [i]	Very high income	High income	Medium income	Low income
Commercial [ii]	Very high value	High value	Medium value	Low value
Heritage [iii]	Very high value	High value	Medium value	Low value
Property Description				
[i] **Residential** Detached, Semi-detached, Terraced, Bungalows., Apartments and Cottages				
[ii] **Commercial** Academic, Industry, Public transport infrastructure				
[iii] **Heritage** Museums, Art galleries etc.				

6. Results and Discussion

Data analysis showed that England is a major contributor to UK GDP and in 2013 was estimated at £1.35 trillion: this was calculated on UK regional GVA (Gross Value Added) figures (ONS, 2013). Subsequently, equation 3 was considered alongside minimum and maximum costs for various household items and flood scenarios as shown in Table 2.

Table 2. Flood Damage Assessment to Residential and Commercial properties

Structural and property components	**Damage Costs for Residential and Commercial properties (Minimum to Maximum)**
Carpet\Wooden Floor	£1,300 to £3,100
Electrical Appliances	£2,600 to £5,500
Doors & Windows	£1,800 to £4,500
Living\ Dinning\ Kitchen\ Bed room Furniture\ Infra structure	£9,700 to £ 23,200
Personal Items	£2,800 to £4,400
Cleaning and Repairs	£4,900 to £8,280
Hidden Costs	£2,800 to £5,250

Table 2 demonstrates cost implications for commercial and residential properties and show a range between £1,300 and £23,200, depending on the item damaged/lost. Based on data from Table 2, cumulative damage costs might range from a minimum of £25,900 to a maximum of £54,230. However, according to the Environment Agency (2013) flood damage costs for property are £1 Billion, and the Association of British Insurers (ABI) (2010) estimates are between £20,000 (minimum) and £40,000 (maximum) for a single property. Subsequently, flood damage costs for commercial and residential properties were compared with aforementioned organisations evaluations and differed and offered new estimations.

However, flood events are not an every year phenomenon and their generation is highly uncertain. Typically, an average of 40,000 properties (estimated on previous flood events) are affected by very severe floods, which results in England's average annual destruction costs for commercial and residential properties being > £1.6 Billion, as follows:

$$\left(\frac{\pounds 25{,}900 + \pounds 54{,}230}{2}\right) X\ 40{,}000 => \pounds 1.6\ Billion$$

It should be noted that indirect and secondary costs were not included in this assessment and the work does not distinguish between tangible and non-tangible aspects such as time lost from work, lives lost, emotional stress, etc. Consequently, the true costs could be much higher, but this is beyond the scope of this work.

7. Damage Cost Impacts on UK and English Economies

It has been shown that commercial and residential property flood damage costs in England are > £1.6 Billion and therefore, the anticipated impact on GDP is assessed using equation 1:

$$\left(\frac{1602600000}{1600000000000}\right) X\ \% = 0.10\%$$

Therefore, £1.6 Billion represents 0.1% of UK GDP and consequently its effects at the macro scale is not significant. Moreover, analysis of impact of flood damage costs on local GDP and economies are determined accordingly:

$$\left(\frac{1602600000}{1300000000000}\right) X\ \% = 0.12\%$$

At the English scale flood damage costs represent 0.12% of GDP, and again is relatively insignificant. However, major infrastructure damage and environmental degradation are not included and these could have a more significant effect on national GDP. Future research will look into these scenarios.

8. Conclusion

Research on fiscal flood damage evaluation for properties in England has assessed two different approaches to cost assessment. Results suggest that the Environment Agency and British Insurers flood damage estimates are optimistic and secondly, a more considered in-depth evaluation for commercial and residential properties should be undertaken. This research established a systematic framework to address these deficiencies and achieved a more realistic estimate of flood damage costs. This new approach differentiated flood levels by using a measurement tool, which is colour, coded and represented at cm and m scales. English flood damage costs exceed £1.6 Billion, which was shown to be a fraction of UK and English GDPs (0.1%). However, at a community level this remains a significant amount to local economies. Therefore, if flood adaptation processes are not enhanced, fiscal costs could ultimately negatively impact on future GDP.

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FULL LENGTH ARTICLE

Cost vs. safety: A novel design for tornado proof homes

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KEYWORDS

Novel design – 3D CAD model;
Tornado proof home;
Missile steel and shield technology;
Safety;
Construction costs

Abstract Tornadoes are dangerous and destructive weather phenomena. The strongest category of tornadoes on the enhanced Fujita and TORRO scales is responsible for 75% of property destruction and deaths across the globe. These issues highlight the need for new design practices aimed at producing tornado proof homes in particular 3D CAD models in tornado prone zones at current climatic scenarios. Previous studies were entirely based on traditional slants and failed to offer a reliable tornado proof home, other than small rooms and trailers, while, none of the literature concentrated on multiple factors (cost, safety and high-wind proof). Therefore, a knowledge gap exists. In order to address the current research gap, this study attempts to develop an innovative 3D CAD model for tornado resistant homes by incorporating *2 PA* (Two Path Analysis). Consequently, this study provides a new design using a 3D-CAD model for a tornado resistant home as in Path One and cost and safety scenarios in Path Two. However, this new design utilizes missile steel and shield technology. Preliminary results showed that, while this new design is safer and more technically sophisticated, it involves an increase of 25–30% in construction costs. However, this increased expense is low in comparison with rebuilding costs.

Introduction

Tornadoes cause moderate to serious infrastructure damage and fatalities. Specifically, recurrent strikes of tornadoes are high in the U.S.A. (75%) followed by Canada (5%) and Bangladesh (3%) (Fig. 1) [1–7]. On average, >1200 tornadoes occur annually at various locations in the U.S.A., and recent statistical data revealed that from 742 tornado incidents in 2013, there were 54 fatalities with damage costs of \$3.6 billion [8]. While, Structural damage costs at global and regional scales are >\$8 billion and >\$1.5 billion respectively, which comprises 60% of annual insurance loss [9].

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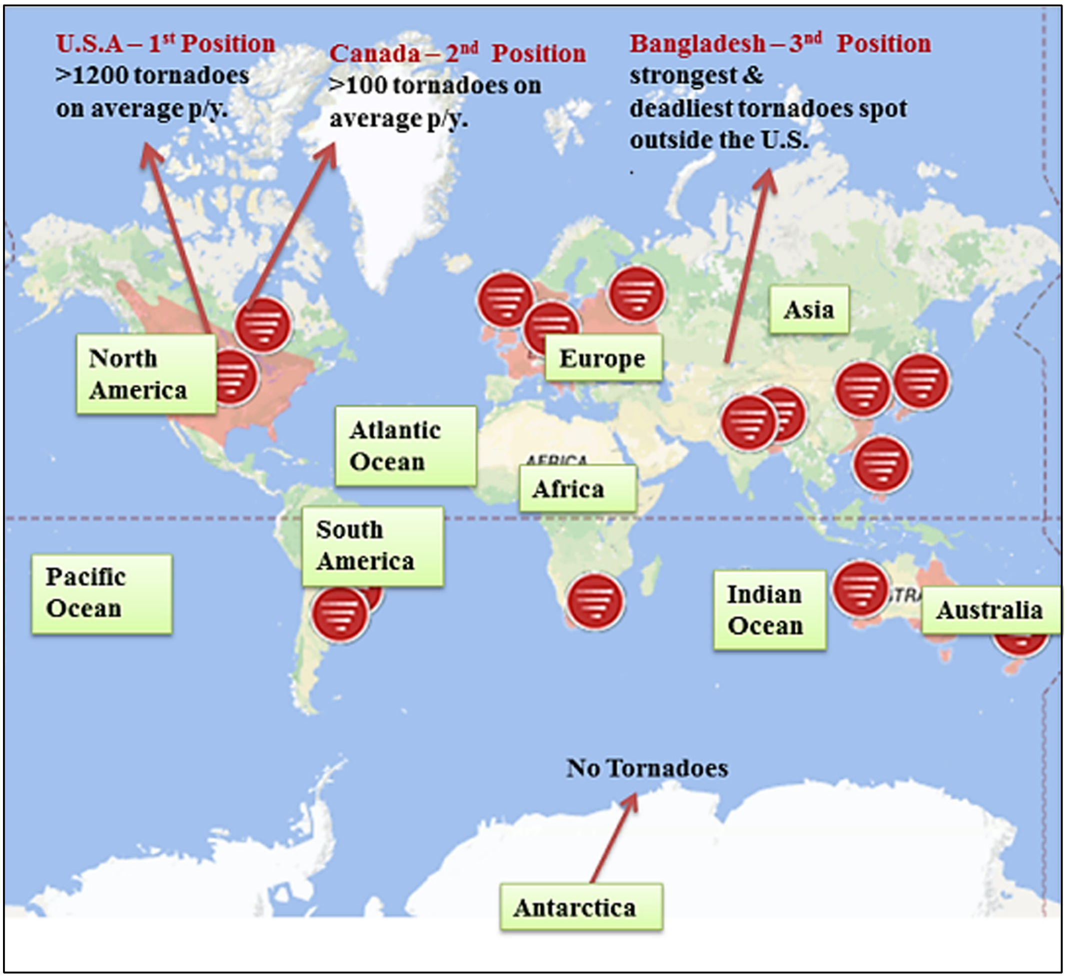

Fig. 1 Global incidences of tornadoes [12].

According to Brooks et al. [10], since the 16th century there have been more than 20,000 deaths in 3600 tornado strikes. Many tornadoes have relatively low wind speeds (< 180 km/h) and are between 40 and 100 m in diameter, potentially traveling many miles before dissipating. Some extremely violent tornadoes can reach speeds of > 450 km/h, and can expand to > 3 km in radius while traveling approximately 100 km [10,11].

Damage caused by tornadoes raises concerns regarding design methods and practices used for the construction of residential homes. However, the building of tornado resistant homes and the development of construction materials with steel components that are utilized to design residential structures against high winds are somewhat new. Consequently, this research paper will identify the importance of tornado proof homes, as well as financial consequences of loss. From a consideration of safety issues and utilizing a novel Three-Dimensional Computer Aided Design (3D CAD) model, a design for tornado proof houses will be developed. Subsequently, the novel designs will be analyzed and evaluated against construction cost and safety scenarios by incorporating 2PA – 2 Path Analysis methodology.

Background

There has been a considerable amount of research on the designs and practices of tornado resistant homes, but this research is fairly limited. Martin [13] designed tornado escape capsules (Figs. 2 and 3) for the house trailer, which comprises a strongly constructed escape capsule with a lockable entrance. Silen [14] designed a model for a tornado protection building (Fig. 4), which has top and sidewalls. This is resistant to tornado wind-forces because, the metal sheet covering is reinforced by upright and straight beams bonded together in a structural framework. Both are feasible from a safety perspective but not from a cost viewpoint. Gopu and Levitan [9] proposed a low-cost lightwood frame construction for tornado resistant homes, while Green [15] suggested a portable pre-fabricated tornado shelter for use in tornado prone zones. Furthermore, Weber [16], Marroquin [17], Reed [18], Hillje [19] and Zubieta [20] suggested novel designs for tornado proof building/shelters. More recently, Zhou et al. [21] proposed a tornado safety room. While all models as mentioned above had diverse success rates from both cost and safety perspectives, it highlights that current design practices are not adequate to sufficiently resist tornado wind forces (400 mph). Consequently, this study focused on

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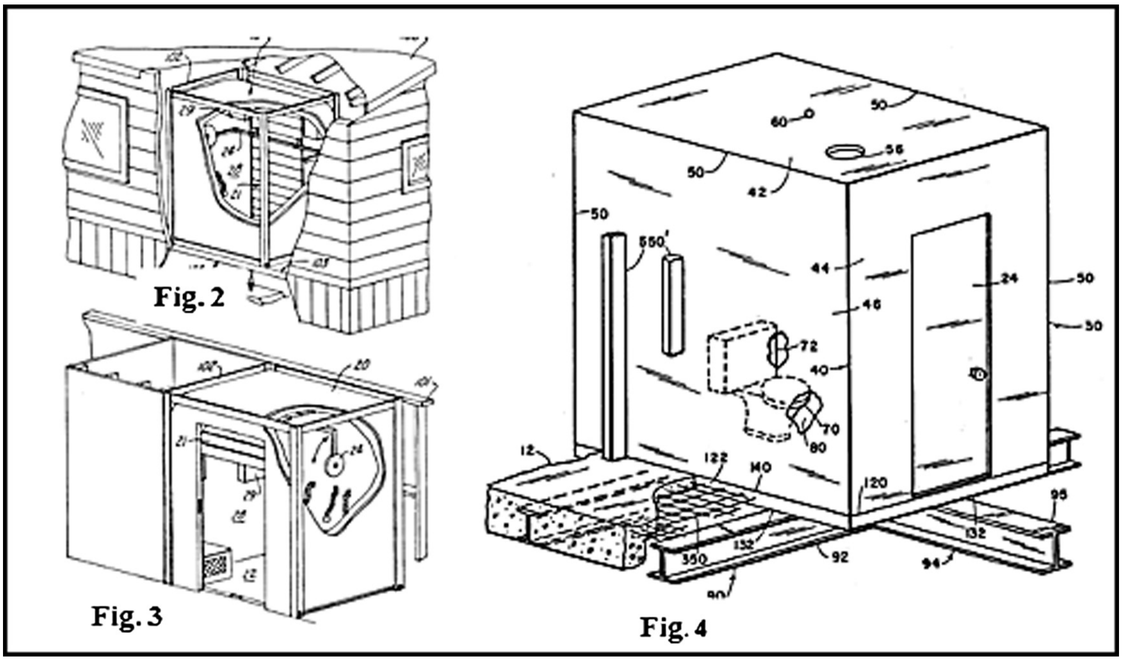

Figs. 2–4 (2 and 3) Tornado escape capsule [13]. (4) Tornado protection building [14].

construction designs for tornado resistant homes capable of resisting 400 mph winds using missile shield and steel technology. The designs utilized a new 3D-CAD model and considered cost and safety consequences.

Anatomy of tornado winds

Measurement of tornado wind speed in severe weather conditions is a challenging task because of their occurrences at remote locations and short-lived nature. However, most of the tornadoes were not recorded by meteorological station networks across the globe due to the lack of sophisticated radar system such as Doppler on Wheels (DOW) [22]. Nonetheless, the damage of tornado strikes mainly depends on gust speed. This force destroys the construction and properties within seconds. Meanwhile, violent tornadoes are usually long-lived and cause severe destruction to structures (residential and commercial) and infrastructure [23,24]. Estimation of wind speed will usually acquired from post-tornado strikes. Nevertheless, wind intensity has often been categorized either using the Enhanced Fujita scale –EF (modified from E scale to EF scale in 2007) [25] or using the T-scale (TORRO Scale –Europe only) [26] or using both classifications (Table 1). However, they were initially devised as wind speed scales, but in practice, they are established and applied as explanatory scales that differentiate several levels (EF0-EF5) of destruction to structures (Figs. 5 and 6). Furthermore, highest wind speed in tornado history is 318 mph, which was recorded on 3rd May 1999 at Oklahoma [27], and more recently, above 200 mph winds recorded at the same state in 2013 [28].

Tornado losses (insurances) in the USA

Based on insurances data for tornado damage in USA for the period of 1949–2006 explored that, more than 790 strong tornadoes caused > $6 trillion losses [32]. Nevertheless, in 2011

Table 1 Wind measurement on Enhanced Fujita (EF) TORRO (T) scale [25].

EF/T scale		
EF/T scale rating	Gust (mph) speed – 3 sec	Distinctive damage
EF0 (T0&T1)	65–85	Light damage
EF1 (T2&T3)	86–110	Moderate damage
EF2 (T4& T5)	111–135	Significant damage
EF3 (T6&T7)	136–165	Severe damage
EF4 (T8&T9)	166–200	Devastating damage
EF5 (T10&T11)	Over 200	Incredible damage
EF6 (T12 or Open Ended)	300 to 400 mph (Under Consideration of NOAA)	Inconvenience damage

thunderstorms and tornadoes together triggered the $29 billion property damage [33]. Chronological statistics revealed that, 2013 and 2011 stand out as the most destructive years of the past 63 years period and deliver an indication that extreme damage levels have the possibility to upsurge and should social change lead to growing exposure of fortune and property. Catastrophic tornado strikes and losses are very common in Oklahoma, Texas and Kansas.

Missile steel and shield technology[1]

The maraging steel was developed in 1959 and then induced a great attention, particularly in the aerospace, nuclear and

[1] Authors contacted steel companies and missile construction engineers for the possibility of transforming maraging steel into proposed models and designs.

Fig. 5 F0 to F5 tornadoes' damage [29,30].

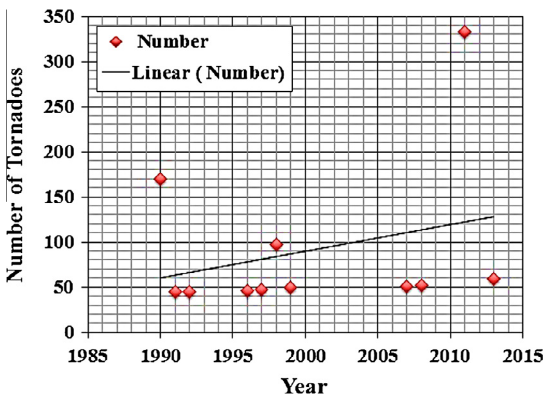

Fig. 6 F5 and EF5 tornados in the USA for the period of 1990–2013 [31].

military world because of its enormous mechanical properties. Maraging steel made up of high-nickel, extra-low-carbon, iron-base alloys held an inordinate promise of offering an amazing combination of structural strength and fracture robustness, while, these steels have high mechanical strength (1700–4000 MPa) and toughness, which means they can resist high winds and temperatures [34,35]. However, 0.0130 MPa are capable enough to resist the >400 mph winds [50,51,34]. Currently, some missiles are manufacturing alloys of one or two metals and composite materials [36–40]. Moreover, missile shield technology is a distinctive technology used in the formation of the body of the missile (Fig. 7). The steel is modified into a curved, arched, or sheet-like structure, based on the required properties and role of the missile; the steel is heated and then appropriately modified. Once formulated, it is then used to make the missile's outer casing [41–43]. This technology offers good results and high success rates and consequently, missile steel has been used for the construction of tornado proof homes. While, many modern houses are also constructed of steel and often have innovative designs (Figs. 8 and 9), TATA Steel that is one of the world's top 10 steel manufacturers offers many diverse steel structures and roofs (Fig. 10).

Methodology

There are no rigorous and precise methodologies (collective method) for designing and estimating the tornado proof homes within technical, fiscal and safety perspectives, while, most of the academic literature constructed on technical drawings [16,47,17–19,48,20,21]. Accordingly, a coherent and concise framework has been developed to design and assess tornado resistant homes and its costs by incorporating missile shield technology through – 2 Path Analysis (Fig. 11). This new methodology was constructed in two important paths:

Path One (P1): The practical applicability of providing new 3D-CAD designs for tornado-proof homes;
Path Two (P2): An initial estimate of construction costs and safety issues.

Consequently, this methodology utilizes 17th version of Archi-CAD software to design an innovative tornado resistant home and subsequently assesses construction costs and safety issues based on collected data.

Structural analysis of 3D-CAD design

This newly designed house consists of four vital structures (Fig. 12a and b) as follows:

1. A vertical reinforced concrete pillar is located in the middle of the house. It penetrates through the roof and extends 25% higher than roof height.
2. Secondly, a maraging steel sheet, is folded and located inside the pillar.
3. Thirdly, an electric engine which is fixed inside the bottom of the pillar is used for propelling the steel sheet prior to a tornado strike.
4. Fourthly, a tornado alarm is fixed to the pillar and located outside the roof.

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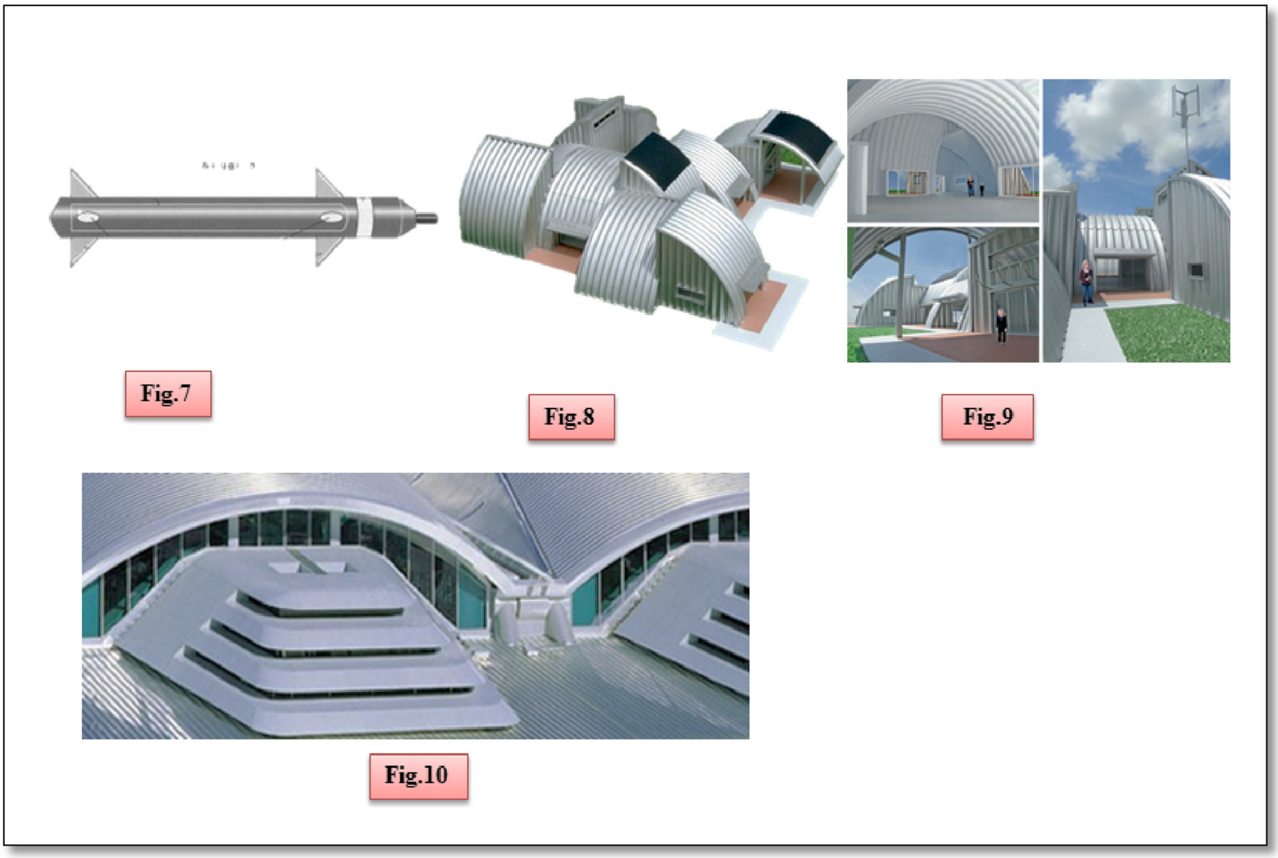

Figs. 7–10 (7) Missile body. (8) Steel home. (9) Inside the steel home. (10) TATA steel roof design for homes and commercial buildings [44–46].

Moreover, there is another special structure in this model that is an iron frame base, which stabilizes the maraging steel roof during a tornado strike.

Evaluation of construction costs and safety scenarios

The second phase of the methodology evaluates the cost of the missile steel roof. It also assesses how safe and technically feasible this model is compared with other designs.

Data

Tornado data were obtained from National Atmospheric Administration (NOAA), Storm Prediction Center (SPC) and TORRO databases. Besides, recent information regarding tornado proof homes and economic costs was obtained from the academic literature (Journals, Books, Conference papers), while, data relating to maraging steel and its costs were obtained from metal and steel companies as well as NASA website. In addition, global housing and construction statistics were obtained from legitimate construction databases across the world, such as U.S. Census Bureau, Office for National Statistics (ONS)-UK, and National Buildings Construction Corporation (NBCC)-India. Subsequently, these data were analyzed for factual results.

Results and discussion

Path One (P1)

Confronts in designing tornado proof homes

The design of the various components, materials and connections in a missile steel and shield construction to resist the anticipated level of wind loads is feasible. However, there are

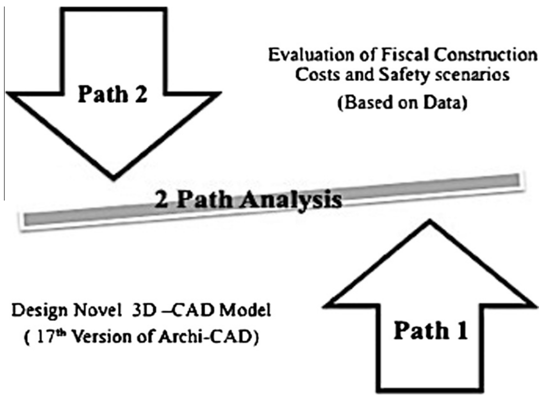

Fig. 11 Methodology – 2 Path Analysis.

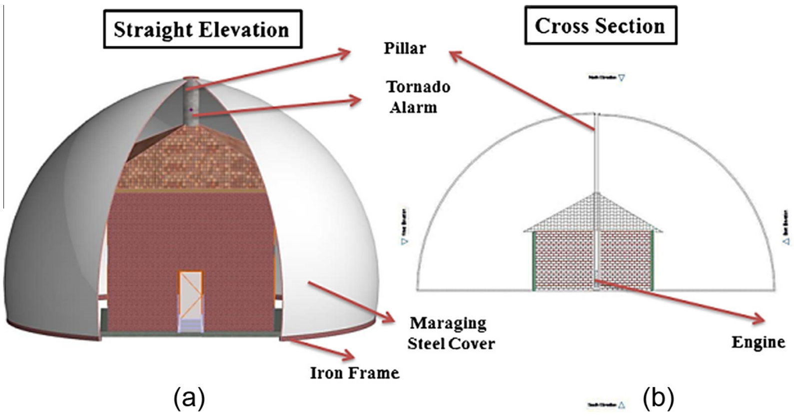

Fig. 12 3D CAD model – straight elevation of tornado proof home. (b) Cross section with missile steel and shield technology.

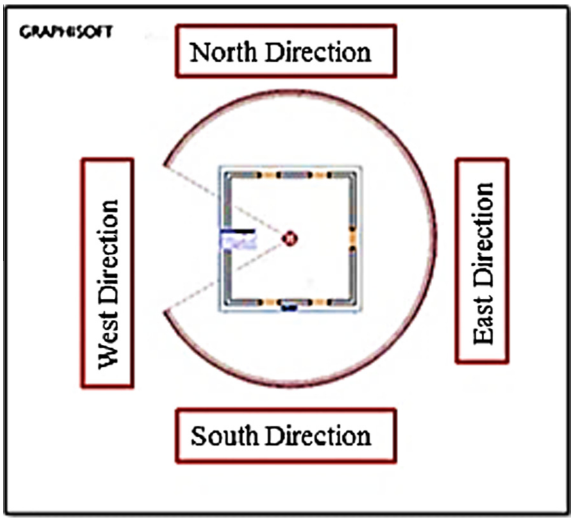

Fig. 13 Plan of tornado resistant home.

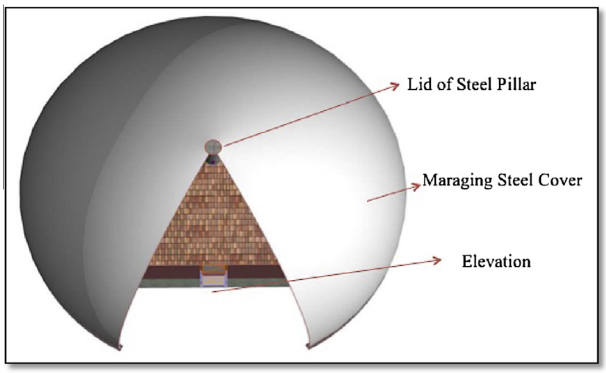

Fig. 15 Plan view of tornado resistant home.

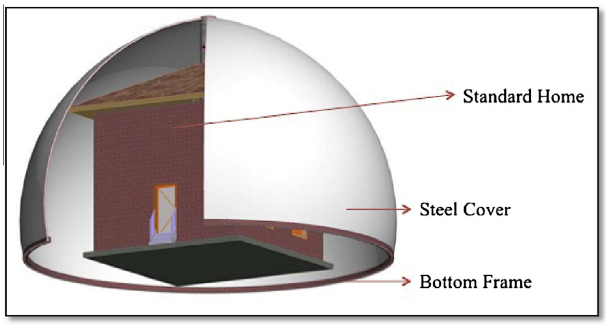

Fig. 14 3D-CAD model with steel cover with bottom frame.

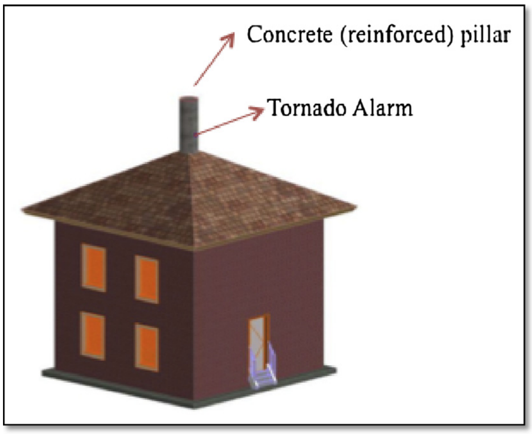

Fig. 16 Normal view of home, showing steel pillar.

some realistic confronts to developing these building models to be tornado resistant. In a tornado strike, the constructions are wedged by powerful winds (250 m/h); therefore, protecting the home from these winds without casualties is a huge challenge. If resistance home to wind impact has to be attained, subsequently the construction cost would rise substantially – in surplus of 25–30%, so raising the question regarding the cost of this extra investment. However, the current model is not an exemption for those extra costs, but could be accepted by homeowners due to its special characteristics.

Description of new invention

Analysis of the deadliest and costliest tornadoes across the globe showed current strategies needed to be significantly improved by developing innovative tornado-proof homes. They are needed to protect people and property from severe tornadoes and accordingly, the proposed model would meet

Fig. 17 House designs across the world (Asia, Europe, US and Canada) with different square foot (SF).

such objectives. Previous models failed to offer a reliable tornado proof home, other than small rooms and trailers. However, this innovative approach addresses all previous design disadvantages.

Structural (technical) portrayals

All figures (Figs. 13–16) showing the new design for the tornado resistant home were developed with 3D-CAD and Archi-CAD software.

Mechanism

As tornado alarms give (Fig. 12a) a warning approximately thirteen minutes before tornado strikes, there is time for the maraging steel sheet to be propelled to the top of the pillar by an electric engine fixed at the base. Subsequently, it opens like an umbrella, which covers the house on three sides, leaving one side open for access (Figs. 14 and 15), and its direction will depend on the country concerned. Strong winds generally approach from three directions with weak winds from the fourth and therefore, the new design covers three sides only. After the tornado event, the steel cover folds automatically, and the electric engine will then return close into the reinforced concrete pillar and the top. Electric engine (Fig. 12b) is a small and powerful device, and it is capable enough to impel any size of maraging steel sheet during tornado strike. Due to its super design, it is also very apt to pull back the maraging steel cover as in the form of folded manner after tornado event.

Path Two (P2)

Costs ($)

The newly proposed tornado resistant house will cost more than previous models because of the use of maraging steel.

Table 2 Tornado proof home – components and costs ($).

Components	Costs ($) – based on location and size
Maraging steel	$15,000–$55,000
Concrete reinforced pillar	$1800–$10,000
Engine	$1000–$5000
Tornado alarm	$100–$300
Iron frame	$2000–$8,000
Labor costs	$ 200–$2000
Total costs	$20,100–$80,300

Note: These are the extra costs for tornado proof homes along with normal construction costs.

Based on various maraging steel company data and quoted prices, costs are between $4000 and $10,000 per ton. The process of transformation from crude maraging steel to the highest quality steel roof is a complicated and costly process. However, it depends on various factors such as the area of the house, its location (e.g. Asia, America and Europe) (Fig. 17) and construction costs. Homes in many countries, e.g. US, Canada, UK, Bangladesh and India (Applicable to individual houses, bungalows and single story commercial buildings and not applicable to Chain houses, Flats, multi-story commercial buildings and hurts) have a floor area of between 600 and 3000 SF, and accordingly construction costs for these houses range between $90,000 and $300,000, while, the proposed tornado resistant home incurs 25–30% higher construction costs (along with normal construction costs) (Table 2), with maraging steel being the most significant component. However, in the long-term it is suggested that these increased costs would be returned as it will save on rebuilding costs and importantly reduce the loss of life.

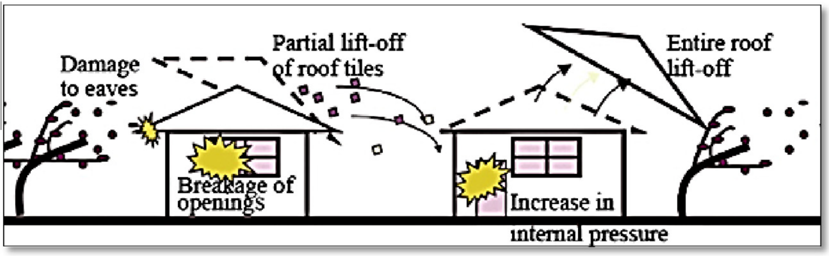

Fig. 18 Illustration of probable tornado wind and windborne debris damage to residential properties [49].

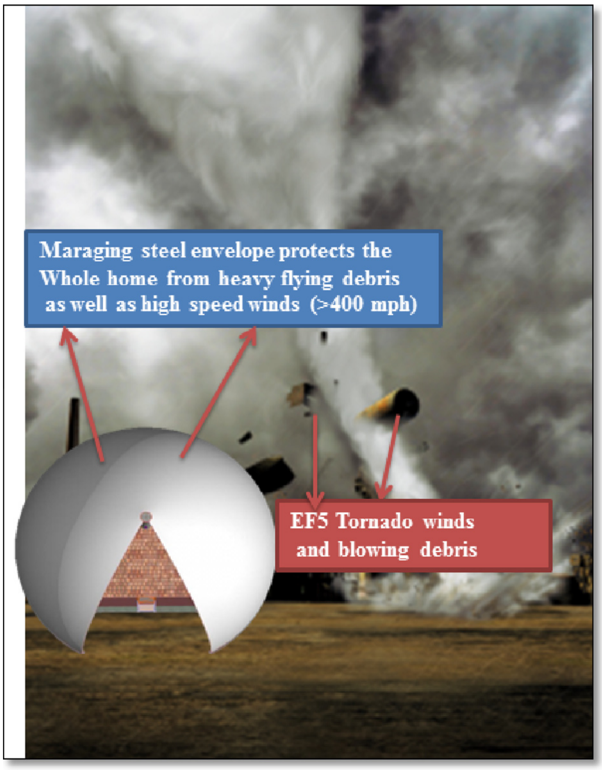

Fig. 19 3D-CAD model house during tornado strike.

Table 3 Comparison of structural safety of the proposed design and existing models.

Existing models	Protection	Newly proposed design
1. Tornado escape capsules	Did not offer the protection for whole home	
2. Low-cost light-wood frame construction model	Not resistant to > 400 mph winds	Newly proposed design protects the whole building through its specially designed unique mechanism and components (margining steel) from air pressure and flying debris caused by tornado-force winds (> 400 mph)
3. Portable pre-fabricated tornado shelter	Failed to offer protection for whole home	
4. Underground structure	Did not offer the protection for whole homes that are constructed on the land	Maraging Steel comprises high strength and can withstand in > 400 mph wind environment

Note: Explanation and reference of existing models are provided in the Background Section.

Safety

As previously explained, from a safety perspective this proposed design is significantly safer than other models because of the maraging steel. Maraging steel has higher tensile strength, resistance and durability. Its use enables the building to withstand very severe atmospheric conditions and it will be capable of resisting unexpected changes in wind speed (> 400 mph) and temperature, even under extreme circumstances. Material properties have made maraging steel a vital component of many missiles in use today, and based on this rationale, research has demonstrated its potential to produce a safe and resilient house.

Novel 3D CAD model: feasibility and rationalization

Four types of innovative structures and construction materials are introduced in the newly proposed 3D-CAD model, while, this model is significantly better model than existed models, based on flowing claims.

Claim 1

Maraging steel envelope offers an ultimate protection from > 400 winds as well as heavy flying objects (Figs. 18 and 19) for the whole home which were not provided by existing models (Table 3) due it its unique design and materials.

Claim 2

Maraging steel envelope also protects the human life from severe winds and flying objects, which also did not provide by previous designs, while there is no need to move to tornado shelters.

Claim 3

This model saves the repeated re-construction costs.

Claim 4

The mechanism (described in section 3) used in this design to propel Maraging steel from the base, is completely innovative, fiscally effective and simple process.

Based on aforementioned issues, this research is concluding that, this model is more reliable, practicable, relatively safer and cost-effective than previous designs though it has high construction costs. (High construction costs are comparatively lower than repeated re-building costs).

Conclusion

This work described a novel 3D-CAD model incorporating missile steel and shield technology for tornado proof homes. It identified safety aspects for the construction and used Archi-3D-CAD software in the development of drawings. The newly designed model shows substantial advantages over most of the conventional resistant home designs or safe rooms via a vulnerability research study. Consequently, in this new design, a reinforced concrete pillar is located in the middle of the home, which extends a further 25% of its length above the roof. This supports a tornado alarm, while a maraging steel sheet folded within the pillar. Based on current advanced warnings of tornadoes, generally thirteen minutes before a tornado strike, alarms are sounded, and the steel sheet is released from the pillar, protecting three sides of the structure, while allowing access and egress. Following the event, the maraging steel sheet is returned into the pillar, and the top closed.

The newly designed model shows substantial advantages over most of the conventional resistant home designs or safe rooms via a vulnerability research study. Therefore, this new 3D-CAD model provides a safer and more responsive construction than previous models. However, while tornado proof buildings/homes with missile shield technology are feasible construction costs are 25–30% higher than for standard construction. Therefore, a house can become a home for many years to come, even when in the midst of tornadoes.

Conflict of interest

The authors declare that they have no conflict of interest.

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Two Fiscal Front-Runners: Will Economies Suffer Due to Lack of Flood Resilience?

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RESEARCH HIGHLIGHTS

- UK Flood annual damage costs: £1.5 bn
- By 2080s it will be £30 bn
- In UK out of 28 million properties – more than 6 million are at risk of flooding
- Hurricane Sandy (US) destruction costs: $56 bn
- Over half the population of both countries live near the coast
- At present no impact to US and UK national economies
- National economies will be significantly affected by 2080s

Abstract

This paper qualitatively assesses two case studies in the United Kingdom and United States of America, which are interlinked using a new methodology. This study assesses recent flood damage, its cost then scrutinises direct impacts on local economies. It evaluates whether or not flooding costs had any significant impact on national economy/GDP. This research found that annual UK damage costs are £1.5 bn and cost of Hurricane Sandy to US was $56 bn. On a national scale these are relatively insignificant and did not have a major impact on national economies.

INTRODUCTION

In order to establish a rigorous 21st century flooding resilience, intensive climate change research will be needed. This will inform infrastructure protection measures to prevent severe economic loss due to anticipated and unpredicted flooding.

UK flooding costs, particularly since 2007, have been estimated at £1 billion every year and are expected to reach £27 billion by 2080 (Bennett, 2010), with more than 5.5 million properties at flood risk in England and Wales (Environment Agency, 2009).

In the USA, 2012 flood damage costs were $495,583,000 (NWSIST, 2013) with a current annual cost of $12 billion (ASFPM, 2013). Moreover, average flood costs over 30 years were $8.2 billion (NWSIST, 2013) and in recent years, there has been a further $8 billion cost from Hurricane events (Nordhaus, 2006).

Accordingly, this paper assesses flood damage costs of United Kingdom along with costs due to Hurricane Sandy destruction. it also evaluates whether or not flooding costs had any significant impact on national economy/GDP.

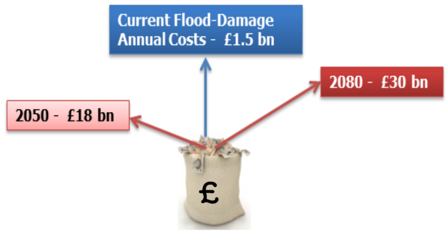

Figure 1. UK Flood Damage Costs

METHODOLOGY

This is an initial study to evaluate methodological applicability whilst simultaneously providing an initial estimation of flood damage costs (Figure 2). It was devised to obtain immediate and accurate estimations from a single case\event\country scenario from published statistics.

This new method assesses four flooding parameters (size of flood, region\area, infrastructure and season) which are used as flooding factors to rank and estimate flooding impacts as well as damage costs.

The method is based on economics and supported with data from reports, insurance losses and academic literature. Research also compared derived results with national published reports e.g. NASA, NOAA, Environment Agency, UK Government, private and public organisations, etc., and results were shown to be different, resulting in an improved estimate of damage costs.

$$\left(\frac{\text{Local GDP}}{\text{National GDP}}\right) X\ \text{Intensity of Flooding Assessment Factors} *$$

Figure 2. Assessment Formula

NEW FINDINGS

According to preliminary estimates, annual UK damage costs are £1.5 billion which can reduce growth on a national scale by 0.01% to 0.3%.

In US, flooding is more often a consequence of tornadoes, hurricanes and cyclones. Therefore, while flood damage costs reduce growth by 0.4% to 0.8% for combined flood events, this is not significant for national US GDP.

However, in UK where lower costs have proportionally more impact, flood damage has immediate, significant, and long-term effects on local economies, in addition to local authority budgets in both countries. Furthermore, it takes many years to fully recover from flooding losses as exemplified by Hurricane Katrina.

Figure 3. Hurricane Sandy's Destruction

RESULTS

Table 1 Primary Assessment Results.

Current Annual Flood Damage Costs (UK) – New Estimations		Hurricane Sandy (US) New Estimations	
Sectoral Damage	Costs in £Billion	Sectoral Damage	Costs in $Billion
Residential Content Damage	1.32	Residential Content Damage	20
Trade and Business Loss	0.03	Trade and Business Loss	5.5
Commercial Structure Damage	0.1	Commercial Structure Damage	10
World GDP Fluctuations	0.02	Electricity and Utility Damage	12.5
Hidden Costs	0.03	Transportation Damage	8
Total	**£1.5**	**Total**	**$56**

CONCLUSION

Flood damage costs significantly affect local economies but at a national level does not have much of an impact. Predictions indicate that socio-economic costs will negatively affect national GDP, if flood resilience is not improved.

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