A National Coastal Erosion Risk Assessment for Scotland

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Abstract

The geography of Scotland, with a highly undulating hinterland, long and indented coastline, together with a large number of islands, means that much social and economic activity is largely located at the coast. The importance of the coast is further highlighted by the large number of ecosystem services derived from the coast. The threat posed by climate change, particularly current and future sea level rise, is of considerable concern and the associated coastal erosion and coastal flooding has the potential to have a substantial effect on the socioeconomic activity of the whole country. Currently, the knowledge base of coastal erosion is poor, which serves to hinder the current and future management of the coast. This research reported here aimed to establish four key aspects of coastal erosion within Scotland: the physical susceptibility of the coast to erosion; the assets exposed to coastal erosion; the vulnerability of communities to coastal erosion; and the coastal erosion risk to those communities.

Coastal erosion susceptibility was modelled here within a GIS, using data for ground elevation, rockhead elevation, wave exposure and proximity to the open coast. Combining these data produced the Underlying Physical Susceptibility Model (UPSM), in the form of a 50 m^2 raster of national coverage. The Coastal Erosion Susceptibility Model (CESM) was produced with the addition of sediment supply and coastal defence data, which then moderates the outputs of the UPSM. Asset data for dwellings, key assets, transport infrastructure, historic assets, and natural assets were used along with the UPSM and CESM to assess their degree of exposure to coastal erosion. A Coastal Erosion Vulnerability Model (CEVM) was produced using Experian Mosaic Scotland (a geodemographic classification which identifies 44 different social groups within Scotland) to classify populations based upon 11 vulnerability variables. Dwellings were assigned a CESM and CEVM score in order to establish their coastal erosion risk.

The CESM identified 3,310 dwellings (a liability of £526m), 287 key assets, 179 km of roads (a liability of £1.16bn), 13 km of rail track (a liability of £2.0bn), 2 km^2 of golf courses (a liability of £4.20m per year), 316 listed buildings, and 2 km^2 of scheduled monuments, 26 km^2 of Sites of Special Scientific Interest (SSSI), 15 km^2 of Geological Conservation Review Sites (GCR), 14 km^2 of Special Areas of Conservation (GCR) sites, and 17 km^2 of Special Protected Area (SPA) sites as being exposed to coastal erosion. Nationally, 633,977 dwellings were classified with very high vulnerability by the CEVM. The combined CESM

and CEVM identified 1,273 dwellings that were both exposed and very highly vulnerable to coastal erosion.

This research demonstrated that the issue of coastal erosion will impact on a relatively low number of properties compared to those impacted by flooding (both coastal and fluvial) as many dwellings are already protected by coastal defences. There is therefore, a considerable future liability, and great pressure for coastal defences to be maintained and upgraded in their current form. The use of the CEVM is a novel inclusion within a coastal erosion assessment for Scotland. Use of the CEVM established that coastal erosion risk is not distributed equally amongst the Scottish coastal population and highlighted that risk can be reduced by either reducing exposure or reducing vulnerability. Thus far in Scotland, reducing exposure has been the primary management approach, which has a number of implications with regards social justice.

This research identified the existing data gaps that should be addressed by future research in order to further improve coastal management in Scotland. Future research should focus on assessing historical coastal change rates on a national scale, improve modelling of national scale wave exposure, enhance the information held about current coastal defences and, determine the direct and indirect economic cost associated with the loss of different asset types. It is also necessary to clarify the social justice implications of using adaptation approaches to manage coastal erosion as well as establishing a method to communicate the susceptibility, exposure, vulnerability and risk aspects whilst minimising the potential negative impacts (e.g. property blight) of releasing such information.

Table of Contents

List of Tables

List of Figures

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Finally, I would like to dedicate this PhD to my grandfather, Albert Royle. A man I admire and respect immensely for the way he led his life. The fact he could not access the education his intelligence and work ethic deserved makes me greatly appreciate the standard of education I have received throughout my school and university career. Consequently, I have always been eager to make the best of the educational opportunities offered to me. Without this motivation to ensure I make the most of my education, I'm not sure I would have ever been in the position to study for a PhD in the first place.

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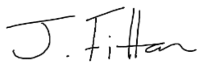
Authors Declaration

I declare that except where explicit reference is made to the contribution of others, that this thesis is the result of my own work and has not been submitted for any other degree at the University of Glasgow or any other institution.



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Abbreviations

BGS – British Geological Survey

CESM – Coastal Erosion Susceptibility Model

CEVM – Coastal Erosion Vulnerability Model

GCR – Geological Conservation Review

IPCC – Intergovernmental Panel on Climate Change

mAMHWS – Metres Above Mean High Water Springs

mAOD – Metres Above Ordnance Datum

MHWS – Mean High Water Springs

MSL – Mean Sea Level

OAC – Output Area Classification

OS – Ordnance Survey

RCP – Representative Concentration Pathway

RF – Radiative Forcing

SNH – Scottish Natural Heritage

SNIFFER - Scotland & Northern Ireland Forum for Environmental Research

SAC – Special Area of Conservation

SEPA – Scottish Environmental Protection Agency

SSSI – Site of Special Scientific Interest

SPA – Special Protected Area

Chapter 1: Introduction

The impacts of climate change are likely to exacerbate processes such as coastal erosion and flooding, resulting in significant problems for coastal managers in Scotland and the UK. The Climate Change Risk Assessment for Scotland (HR Wallingford, 2012) states that as a result of climate change:

- more frequent extreme weather and rising sea levels will instigate changes in coastal evolution which may impact upon coastal communities and habitats;
- the likely increases in the magnitude of extreme sea levels, and increased coastal flooding may affect people, property, infrastructure, natural habitats and a range of animal and plant species.

The geography of Scotland, with a highly undulating hinterland, long and indented coastline, together with a large number of islands, means that much of the social and economic activity within Scotland is largely located at the coast. Therefore, coastal erosion and coastal flooding has the potential to have a substantial effect on the socioeconomic activity of the whole country.

Within Scotland, the risk posed by the hazard of flooding (fluvial and coastal) has received much attention, primarily from the Scottish Environment Protection Agency (SEPA), yet coastal change and coastal erosion has seen minor in comparison. This bias was highlighted by Dr. Aileen McLeod, the Scottish Minister for Environment, Climate Change and Land Reform, who in her Ministerial Address at the annual Scotland & Northern Ireland Forum for Environmental Research (SNIFFER) Flood Risk Management Conference (2015) stated that "*coastal erosion and coastal flooding are unquestionably linked but there is a great deal of uncertainty around current evidence about coastal erosion*". Currently, there is a paucity of information about where coastal erosion is occurring and if so, at what rate. Furthermore, there is a complete absence of information concerning where coastal erosion could potentially occur in the future at a national scale. This is of particular relevance when considering the potential impacts of climate change (sea level rise, increased impact of extreme storms etc.) which could significantly alter the rate and extent of coastal erosion.

It is clear that more detailed information on coastal erosion is required in order that the risk of current and future coastal erosion that may impact upon coastal populations and assets can be fully assessed and managed. This is especially important due to the socioeconomic nature of coastal populations which tend to have high proportions of older residents, transient populations, low employment levels, and high seasonality of work, together with physical isolation and poor transport links. Such populations are highly vulnerable to climate change (Zsamboky et al., 2011). However, although socioeconomic vulnerability to flooding has previously been assessed for Scotland (e.g. Lindley et al., 2011), vulnerability (and subsequently risk) to coastal erosion has yet to be investigated. Areas with high coastal erosion risk need to be identified so coastal managers can prioritise, and subsequently allocate resources where it is needed most.

1.1 Aims of the Research

The overall aim of this research is to establish the susceptibility of the Scottish coast to erosion and thus identify where erosion might impact upon vulnerable coastal communities. The outputs of this research will support government, agencies, and coastal managers by increasing the knowledge base of coastal erosion on which to make decisions. This will make management of the coast potentially more efficient and sustainable. Given the current state of knowledge with regards the coastal erosion hazard within Scotland, this research aims to address this knowledge shortfall by addressing four aspects of the hazard. The aims are:

- **Physical Susceptibility** - establish coastal erosion susceptibility on a national, high resolution scale to establish the areas where coastal erosion may or may not occur;
- **Exposure** - identify the assets that are likely to be exposed to coastal erosion, and their economic value;
- **Vulnerability** - explore the use of geodemographies to establish socioeconomic vulnerability to coastal erosion in order to identify the sectors of society likely to suffer most if exposed to coastal erosion;
- **Risk** - combine both physical susceptibility and socioeconomic vulnerability to establish the risk to communities of coastal erosion at a national scale.

1.2 Thesis Outline

The overall aim of this research is to establish the susceptibility of the Scottish coast to erosion and identify where this erosion might impact upon vulnerable coastal communities. The research outputs will support government, agencies, and coastal managers with decision making, therefore the current and potential future challenges faced within the Scottish coastal zone will be established (Chapter 2). Coastal erosion susceptibility and socioeconomic vulnerability have been modelled for other coasts around the globe, consequently Chapter 2 will also review the methodologies used and assess whether they can be used within a Scottish context. Furthermore, as the vulnerability and risk literature uses terminology which has multiple definitions, which are often used interchangeably by researchers, vulnerability theory will be discussed and key terms defined. The review will inform the development of the geographic information system (GIS) methodologies used within this research, which will be explained in detail in Chapter 3. Chapter 4 focuses on the results of the modelling, presented in the form of point, polyline, and raster format, with the exposure and risk analysis collated by local authority. Within Chapter 5 the implications for coastal management of modelling the physical susceptibility, exposure, vulnerability and risk to coastal erosion will be considered. Finally, the key conclusions of this research will be detailed in Chapter 6 along with a critique and evaluation of the research and methods. Additionally, the areas of future research that could be conducted to further support coastal management in Scotland are detailed.

1.3 Summary

The impact of coastal erosion in Scotland is likely to worsen as a consequence of climate change. Currently, the knowledge base of coastal erosion is poor which serves to hinder the current and future management of the coast. This research aims to establish four aspects of coastal erosion within Scotland; physical susceptibility to coastal erosion, the assets exposed to coastal erosion, vulnerability of communities to coastal erosion, and risk. Achieving these aims will make management of coastal erosion potentially more efficient and sustainable. The thesis structure is summarised as follows:

- Chapter 1 has introduced the theme of coastal erosion in Scotland, identified the aim of the research and outlined the structure of the thesis;
- Chapter 2 provides the research context (both physical and socioeconomic), identifies the current knowledge base and its gaps, defines key terms used throughout the thesis and, reviews methodologies;
- Chapter 3 describes the methodologies used to accomplish the research aims;
- Chapter 4 reports the results of the physical susceptibility, exposure, vulnerability and risk assessments;

- Chapter 5 offers an interpretation of the results and discusses the wider implications of this research.

- Chapter 6 presents conclusions drawn from the interpretation of the results. A critique of the research in relation to the literature and an evaluation of the methodologies used, with an outline of possible future research themes are also included.

Chapter 2: Literature Review

2.1 Introduction

Coastal areas have historically been utilised for human settlement due to an abundance of the natural resources required for survival and development (Özyurt & Ergin, 2009). Coastal locations remain desirable today as a consequence of the vast range of ecosystem services they provide. Society's desire to live at or near the coast is demonstrated by the number of major cities located within coastal zones e.g. New York, Tokyo, Shanghai, and London (Nicholls, 1995), and population densities within coastal areas three times the global mean (Small & Nicholls, 2003). This is especially pertinent within the UK's highly varied coastal zones and due to the socioeconomic nature of coastal populations within the UK. These generally have high proportions of older residents, transient populations, low employment levels, high seasonality of work, physical isolation, and poor transport links. This makes people living at the coast more vulnerable to the coastal effects of climate change than inland dwellers (Zsamboky et al., 2011).

For countries with extensive coasts, such as Scotland, the coastal zone is a resource which offers opportunities, but which also requires careful management to allow all stakeholders to benefit (Scottish Government, 2014). However, such a task is problematic since the coastal zone is under pressure from both anthropogenic (e.g. urbanisation) and environmental factors (e.g. sea-level rise and erosion), which make management of the coast complex.

A full understanding of the importance of the coast, as well as determining current and future physical hazards within the coastal zone, needs to be established in order to explore efficient and successful management opportunities. Therefore, Chapter 2 aims to assess the importance of the coastal zone to society, determine the environmental issues and hazards at the Scottish coast, and discuss methods to identify the extent and impact of coastal erosion on a national scale. Additionally, the concepts of vulnerability and risk will be reviewed in order to clarify definitions used within this thesis. The methods used to assess vulnerability and risk in the natural hazard literature will be reviewed in order to establish a working approach applicable to a coastal context.

2.2 Importance of the Coastal Zone

The simplest way to understand the importance of the coastal zone is to explore the concept of ecosystem services. Department for Environment, Food and Rural Affairs (DEFRA)

(2007, p. 2) defines ecosystem services as "*services provided by the natural environment that benefit people*". The definition further explains that ecosystem services "*provide outputs or outcomes that directly and indirectly affect human wellbeing and these considerations can link well to taking an economic approach*". As a result the services provided can be converted into economic values, i.e. what would be the financial cost to society to artificially replace the service offered by nature.

Jones et al. (2011) as part of the UK National Ecosystem Assessment provided an analysis of the six main coastal habitats in the UK; sand dunes, machair, saltmarsh, shingle (gravel), coastal lagoons, and sea cliffs. From these habitats a number of services are derived. The services are categorised into three types:

- **Provisioning Services** – products derived directly from the habitat
- **Regulating Services** – benefits derived from regulation of ecosystem processes
- **Cultural Services** – non-material benefits that people obtain through spiritual enrichment, cognitive development and recreation etc.

Jones et al. (2011) identify that coastal habitats occupy only 0.6% of the UK's land area but account for approximately £48bn (adjusted to 2003 values) in ecosystem services. (COREPOINT, 2007). This equates to 3.4% of the UK's Global National Income (GNI)[1]. For comparison Ireland derives 9.6% of GNI from coastal habitats, France 1.1%, Netherlands 0.8% and Belgium < 0.1%. Table 2.1 details the large range of ecosystem services and goods/benefits derived from coastal zone habitats. The most important service provided is coastal defence with an estimated £3.1 to £33bn worth of capital savings along the soft coasts of England alone.

Ecosystem service valuations for Scotland are not readily available, however with a coastline length of 18,670 km (Angus et al., 2011), approximately 59% of the UK's total coastline (The British Cartographic Society, 2008) and all of some types of coastal habitats e.g. machair, biodiversity-rich low-lying dune grasslands (see Table 2.2), the ecosystem services derived from Scottish coastal habitats are likely to be significant.

[1] gross national income (GNI) is the total domestic and foreign output claimed by residents of a country, consisting of gross domestic product (GDP) plus factor incomes earned by foreign residents, minus income earned in the domestic economy by non-residents (Todaro & Smith, 2011, p 44).

Table 2.1: Goods and benefits provided by habitats within the coastal zone, plus potential anthropogenic alternatives and their associated costs and barriers to implementation. P = provisioning, R = regulating, C = cultural. Adapted from Jones et al. (2011). Alternative analysis conducted by author.

Service Group	Ecosystem Services	Goods/Benefits	Anthropogenic Alternative	Alternative cost/ barriers to implementation
P	Crops, plants, livestock, fish, etc. (wild and domesticated)	Crops: vegetables, cereals, animal feed	Move to non-coastal habitats, might not be possible to find new land	Loss in value of produce, monetary and opportunity cost of new land
		Meat: sheep/cattle, rabbits, fish/shellfish	Move to non-coastal habitats	Loss in value of produce, monetary and opportunity cost of new land, might not be possible to find new land
		Wild food: mushrooms, salicornia, other plants/berries, fish/shellfish, wildfowl	Farm in new location	Loss in value of produce, monetary and opportunity cost of new land, might not be possible to find new area to farm
		Wool: sheep	Move to non-coastal habitats	Loss in value of produce, monetary and opportunity cost of new land might not be possible to find new land
		Genetic resources of rare breeds, crops	Move to non-coastal habitats	Loss in value of produce, monetary and opportunity cost of new land, might not be possible to find new land
P	Trees, standing, vegetation and peat/other resources	Reed/Grass for thatching, mats and basket weaving	No alternative	-
		Timber for wood pulp, furniture.	Obtain from other source	Might not be possible to find suitable new source
		Turf/peat cutting	Obtain from other source	Might not be possible to find suitable new source
		Seaweed gathering for fertilisers	No alternative	-
		Extraction of sand, gravel	Obtain from other source	Might not be possible to find suitable new source
		Military use	No alternative	-
		Industrial use: pipeline landfall/energy generation	No alternative	-
R	Climate regulation	Carbon sequestration	Implement carbon capture scheme	Costly, unproven technology
P, R	Water quality	Water for irrigation, drinking	Obtain from other source	Might not be possible to find new source
R	Hazard regulation - vegetation and other habitats	Sea defence Preventing soil erosion	Engineered defences	Initial and maintenance costs, loss of natural beauty, potential exacerbation of problems elsewhere

Service Group	Ecosystem Services	Goods/Benefits	Anthropogenic Alternative	Alternative cost/ barriers to implementation
R	Waste breakdown and detoxification	Immobilisation of pollutants	No alternative	-
P, R	Wild species diversity including microbes	High diversity, or rare/unique plants, animals, and birds, insects	No alternative	-
		Ecosystem-specific protected areas	No alternative	-
		Nursery grounds for fish	No alternative	-
		Breeding, over-wintering, feeding grounds for birds	No alternative	-
R	Purification	Water filtration: groundwater, surface flow, seawater	Build water treatment plant	Costs of new plant, might not be possible to put new plant in the place it is needed, ongoing costs.
C	Environmental Settings: Religious/spiritual and cultural heritage and media	Sites of religious/cultural significance, World Heritage Sites, folklore, TV and radio programmes and film	No alternative	-
C	Environmental Settings: Aesthetic/ Inspirational	Paintings, sculpture, books	No alternative	-
C	Environmental Settings: Enfranchisement and Neighbourhood development	Beach cleaning/litter picking	No alternative	-
C	Environmental Settings: Recreation/tourism	Many opportunities for recreation: incl. sunbathing, walking, camping, boating, fishing, birdwatching etc.	No alternative	-
C	Environmental Settings: Physical/mental health and security and freedom	Opportunities for exercise, local meaningful space, wilderness, personal space	No alternative	-
C	Environmental Settings: Education/ecological knowledge	Resource for teaching, public information, scientific study	No alternative	-

Included in Table 2.1 is a basic assessment of potential anthropogenic alternatives and the likely costs and/or problems associated with implementing an alternative if the habitat is lost. This assessment further demonstrates the importance of coastal zone habitats as for many services there is simply no anthropogenic alternative, and where there is, the implementation is either costly, problematic, or both. Thus there is a need to preserve coastal habitats to continue to benefit from the associated ecosystem services.

The data shown thus far demonstrates the importance of coastal habitats to society. However, the coast does not consist solely of natural habitat, urbanised areas, transport links and ports etc. are key components with an important influence at the coast. In Scotland, 70% (3.5 million people) of the population live within 10 km of coast (Scottish Executive, 2005), much of it located in the main central belt urban areas of greater Edinburgh and Glasgow, with the population of other areas, such as the Borders, and the Highlands and Islands, remaining highly dispersed.

Coastal zones are attractive areas for people to live as there are a number of socioeconomic benefits derived from coastal environments. For example, within Scotland, the industrial ports in the Clyde, Forth, Sullum Voe, Lerwick, and Peterhead, account for an industry worth £15.4bn per year (Scottish Transport Statistics, 2010). As well as tangible benefits, many intangible cultural and recreational benefits are also derived which are more difficult to assess in terms of value. However, it is possible to estimate for coastal tourism, which in the UK is valued at £17bn per year (Jones et al., 2011).

Society's valuation of the coast is unlikely to diminish in the future and coasts will always be considered an attractive place to live and work. An understanding of future environmental pressures on the coastal zone is imperative in order to manage and maintain the coastal ecosystem services successfully. These pressures will be explored in the following section.

Table 2.2: Areas of different coastal habitats in Scotland and the UK. Data taken from Jones et al. (2011)

Habitat	**Scotland Extent (ha)**	**UK Extent (ha)**	**UK Percentage in Scotland (%)**
Sand Dune	50,000	71,569	70%
Machair	19,698	19,698	100%
Saltmarsh	6,000	44,512	14%
Shingle	670	5,852	11%
Sea Cliffs	2,450	4,554	54%
Coastal Lagoons	3,900	5,184	75%

2.3 Coastal Erosion: The Geomorphological Context

The coast is currently under a number of environmental pressures that are anticipated to worsen in the near future. The main drivers of these pressures from a geomorphological context relates to how climate change will impact on the coastal system. Therefore this section will review the current and future issues coastal managers have to address. The general environmental changes ongoing and expected as a result of climate change will be reviewed, as well as the specific issues of sea level rise, coastal flooding and coastal erosion. Furthermore, the section will review the methods used previously to model coastal erosion.

2.3.1 Climate Change

Burning of fossil fuels and changes in agricultural practices since the start of the industrial revolution in 1750 has led to an increase in the levels of nitrous oxide (NO), methane (CH_4) and carbon dioxide (CO_2) in the atmosphere (Intergovernmental Panel on Climate Change (IPCC), 2007). The increases in these atmospheric gases result in a positive 'radiative forcing' (RF) which increases the uptake of energy by the climate system. CO_2 is the largest contributor to a positive RF, and alone contributed 1.68 (1.33 to 2.03)[2] Watts per square metre (W m^{-2}) out of a total of 2.29 (1.13 to 3.33) W m^{-2} in 2011. This has increased from an RF of 0.57 (0.29 to 0.85) W m^{-2} in 1950. By 2100 it is estimated that the RF will be 2.7 to 8.4 W m^{-2} due to anthropogenic activity, depending on which climate scenario is realised.

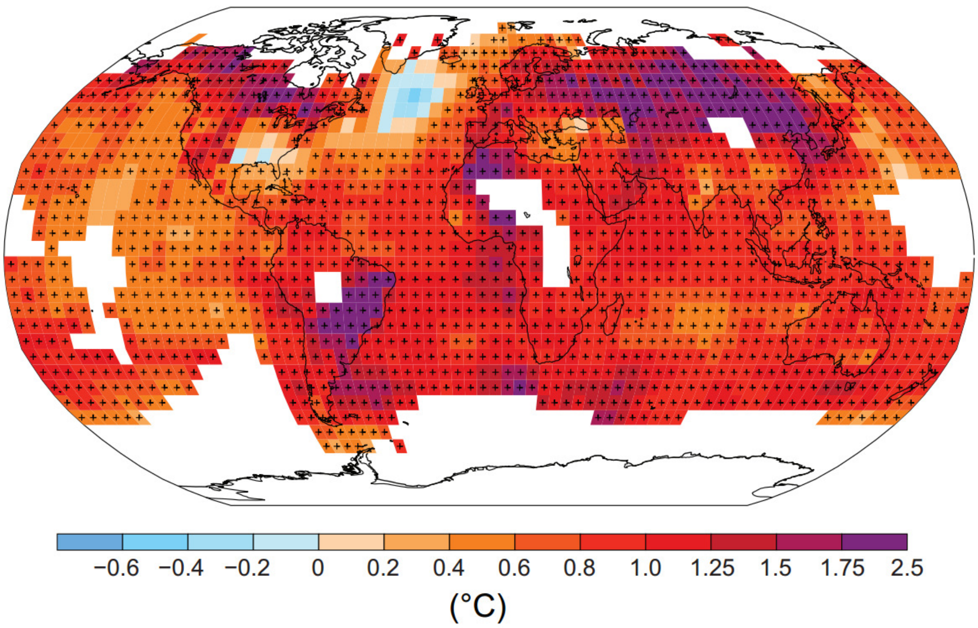

Figure 2.1: Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression. Taken from Stocker et al. (2013).

[2] Values in parentheses are 90% confidence intervals.

With an increase in the amount of energy in the climate system, the land and sea surface temperature has increased commensurately. For the time period 1880 to 2012, when multiple independently produced datasets exist, temperatures show a warming of 0.85 (0.65 to 1.06) °C (Bindoff et al., 2007). Figure 2.1 shows the surface temperature record for 1901 to 2012 from a single dataset and shows considerable variation (-0.6 to 2.5 °C) around the globe, however in the majority of areas the trend is an increase in temperatures since 1901 (Stocker et al., 2013).

Modelling of Representative Concentration Pathways (RCP) i.e. future climate scenarios, has led to predictions of surface air temperatures which could potentially reach between 2.6 and 4.8 °C by 2100 (see Table 2.3). The confidence in these predictions ranges from *likely* to *very high* therefore it seems likely that global mean surface temperature will increase significantly in the future.

In addition to increasing temperatures, climate change is likely to influence other natural processes. Rising sea levels are almost certainly related to climate change and may create issues for coastal management. Sea level rise is likely to cause a rise in the occurrence of coastal flooding and escalate coastal erosion rates (Masselink and Russell, 2013; Zhang et al., 2004). It is therefore imperative that the magnitude and spatial and temporal scales of global and local (Scotland) sea level rise is understood.

Table 2.3: Four modelled Representative Concentration Pathways (RCPs) showing change in global mean surface air temperature for the mid- and late 21st century relative to the reference period of 1986–2005. Taken from Stocker et al. (2013). The figure after RCP e.g. RCP2.6 represents the amount of radiative forcing in 2100 in W m^{-2} relative to pre-industrial levels.

	Scenario	2046-2065		2081-2100	
		Mean	**Likely Range**	**Mean**	**Likely Range**
Global Mean Surface Air Temperature Change (°C)	RCP2.6 ‘Low Emission Scenario’	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5 ‘High Emission Scenario’	2.0	1.4 to 2.6	3.7	2.6 to 4.8

2.3.1.1 Current Rates of Global Sea Level Rise

Considerable scientific effort has been focused on attempting to establish the global sea level rise rate over the past 130 years or so (Table 2.4). Variation in the estimates exist due to the time period analysed, poor spatial and temporal coverage of the sea level data sets, and the glacial isostatic adjustments (GIA) made to these data. Despite this, the margins of error in Table 2.4 are not of sufficient magnitude to infer a stable or reducing sea level. Church et al.

(2013) assert that likely historical global sea level rise rates are 1.7 ± 0.2 mm yr^{-1} for the period 1901 to 2010 and an increased rate of 3.2 ± 0.4 mm yr^{-1} for the more recent time period of 1993 to 2010.

Table 2.4: Rates of global sea level rise for a range of time periods and methods collated from the literature. More recent time periods are highlighted in grey and largely based on satellite data. Publications from 2001 and before are taken from Douglas (2001).

Publication	**Time Period Assessed**	**Sea Level Rise Rate (mm yr^{-1})**
Douglas (1991)	1880-1980	1.8 ± 0.1
Mitrovica and Davis (1995)	1880-1990	1.55 ± 0.05
Douglas (1997)	1880-1991	1.8 ± 0.1
Barnett (1990)	1881-1980	1.43 ± 0.14
Trupin and Wahr (1990)	1900-1980	1.75 ± 0.13
Church et al. (2001)	1900-2000	1.5 ± 0.5
Douglas (2001)	1900-2000	1.76 ± 0.55
Peltier (2001)	1900-2000	1.85 ± 0.35
Miller and Douglas (2004)	1900-2000	1.75 ± 0.25
Church and White (2006)	1900-2000	1.7 ± 0.3
Shennan and Woodworth (1992)	1901-1986	1.0 ± 0.15
Church et al. (2013)	1901-2010	1.7 ± 0.2
Peltier and Tushingham (1991)	1920-1970	2.4 ± 0.9
Nakiboglu and Lambeck (1991)	1930-1980	2.27 ± 0.23
Holgate and Woodworth (2004)	1948-2002	1.7 ± 0.4
Nakiboglu and Lambeck (1991)	1950-1990	1.15 ± 0.38
Church et al. (2004)	1950-2000	1.8 ± 0.3
Bindoff et al. (2007)	1961-2003	1.8 ± 0.5
Domingues et al. (2008)	1961-2003	1.6 ± 0.2
Beckley et al. (2007)	1993-2003	3.1 ± 0.7
Beckley et al. (2007)	1993-2007	3.36 ± 0.41
Cazenave and Llovel (2010)	1993-2007	3.3 ± 0.4
Church and White (2011)	1993-2010	3.2 ± 0.4
Church and White (2011)	1993-2010	2.8 ± 0.8
Church et al. (2013)	1993-2010	3.2 ± 0.4

As global temperatures increase as a result of climate change, thermal expansion of the surface layers of the ocean, together with increased run off from glacier melt has contributed to global sea level rise (Stocker et al., 2013). There is, however, a time lag between the rise in temperature and sea level rise due to the time it takes for global processes to operate.

Consequently, sea level rise rates observed for the present, are higher than for previous time periods. This can be seen in Table 2.4 where the more recent sea level rise rates calculated from 1993 onwards (highlighted in the table) are equal to or above 2.8 mm yr^{-1} compared to earlier rates in the 21st Century of ca. 1.7 mm yr^{-1}. The increase in rate is shown in **Error! Reference source not found.**. Between 1700 and 1880 global sea level rise rates were relatively constant. However, from 1880 onwards the rate begins to increase. The rate fluctuates considerably, with Boening et al. (2012) observing a decrease in global sea levels (Figure 2.3) in 2010-2011 related to the mass transport of water from the ocean to the continents (primarily Australia, northern South America and Southeast Asia) via increased rainfalls brought on by the 2010/11 La Niña. By mid-2012, global mean sea level had recovered. Even with short term fluctuations in sea level highlighted here (such as the effect on tidal amplitude due to the 18.6 Lunar Nodal Cycle which occurs as a result of the Moon's orbit around the Earth, with this node moving westward around the Earth every 18.6 years (Baart et al., 2012; McMillan et al., 2011)) the global sea level rise rate has accelerated over the past 20 years or so. The following section will discuss how sea level may change in the future.

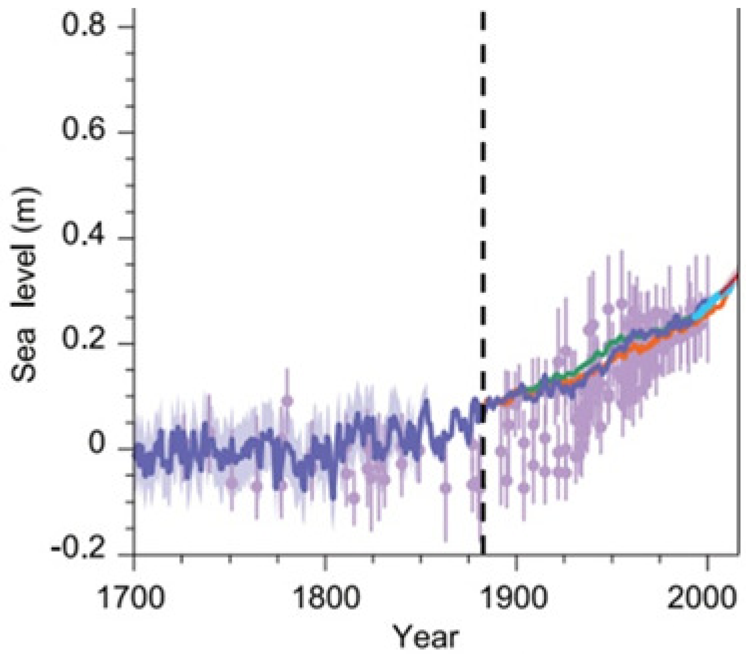

Figure 2.2: Comparison of the palaeo sea level data from salt marshes (purple symbols), and tide gauge data (orange from Church & White (2011) blue from Jevrejeva et al. (2008), green from Ray & Douglas (2011) and altimetry data (bright blue line: altimetry data sets from five groups (University of Colorado (CU), National Oceanic and Atmospheric Administration (NOAA), Goddard Space Flight Centre (GSFC), Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO), Commonwealth Scientific and Industrial Research Organisation (CSIRO)) with mean of the five shown . Dashed black line marks 1880. All relative to pre-industrial values. The increase in sea level rise rate can be seen over the period 1880 to 2010. Adapted from Church et al. (2013).

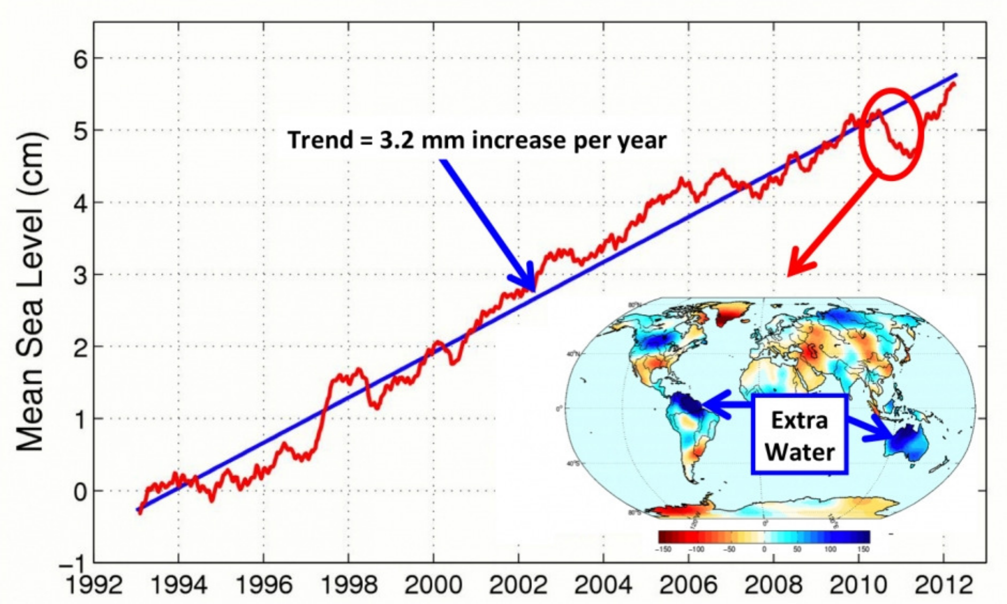

Figure 2.3: Global mean sea level change for 1993 to 2012 from satellite altimetry (NASA/CNES Topex/Poseidon and Jason-1; and NASA/CNES/NOAA/EUMETSAT Jason-2). Red circle highlights decrease in global sea level due the mass transport of water from the ocean to the continents (primarily Australia, northern South America and Southeast Asia (blue arrows)). While the ocean "lost" water, the continents experienced a gain because of increased rainfalls brought on by the 2010/11 La Niña. By mid-2012, global mean sea level had recovered by more than the 5 millimetres it dropped in 2010/11. Taken from NASA (2013).

2.3.1.2 Future Rates of Global Sea Level Rise

Church et al. (2013) present estimates for global sea level rise for a range of emission scenarios (Table 2.5). The high emissions scenario (RCP8.5) predicts the global sea level rise rate for the time period 2081-2100 to reach 0.112 (0.75 to 0.157) cm yr^{-1} in comparison with a low emissions scenario (RCP2.6) rate of 0.44 (0.20 to 0.68) cm yr^{-1}. Using these rates, the mean sea levels for 2081-2100 for a high emissions scenario (RCP8.5) are modelled as 63 (45 to 82) cm higher than the 1986-2005 sea level, in comparison with a low emissions scenario (RCP2.6) of 40 (26 to 55) cm higher.

Table 2.5: Projected change in global mean sea level rise for the mid and late 21st century relative to the reference period of 1986–2005. Taken from Church et al. (2013)

		2046-2065		**2081-2100**	
	Scenario	**Mean**	**Likely Range**	**Mean**	**Likely Range**
Global Mean Sea Level Rise (cm)	RCP2.6 ‘Low Emission Scenario’	24	17 to 32	0.4	0.26 to 0.55
	RCP4.5	26	19 to 33	0.47	0.32 to 0.63
	RCP6.0	25	18 to 32	0.48	0.33 to 0.63
	RCP8.5 ‘High Emission Scenario’	3	22 to 38	0.63	0.45 to 0.82

Figure 2.4 shows the modelled sea level rise rates from Church et al. (2013). Included are the individual components that contribute to sea level rise rates. The sea level rise rates predicted for the 21st century are predominately due to thermal expansion of the water (which accounts for 30 to 55% of the predicted rate) and contributions from the melting of glaciers (15 to 35%). The remaining contribution is from Greenland and Antarctic ice sheet melt, and increased abstraction from groundwater.

The world's oceans do not have a uniform altitude as they are influenced by density and gravitational differences around the globe (Hwang et al., 2002). Whilst the levels and rates of sea level rise quoted are global averages, it is expected that sea level rise around the oceans will not be uniform and IPCC (2013: 26) claim that by 2100, more than 95% of the ocean area will experience sea level rise. Yet this is followed by the statement that "*70% of the coastlines worldwide are projected to experience sea level change within 20% of the global mean sea level change*" indicating that the sea level rise experienced on a regional to local scale will vary considerably. Therefore the local sea level rise experienced in Scotland needs to be assessed in order to understand the ongoing and future sea level changes on a local scale.

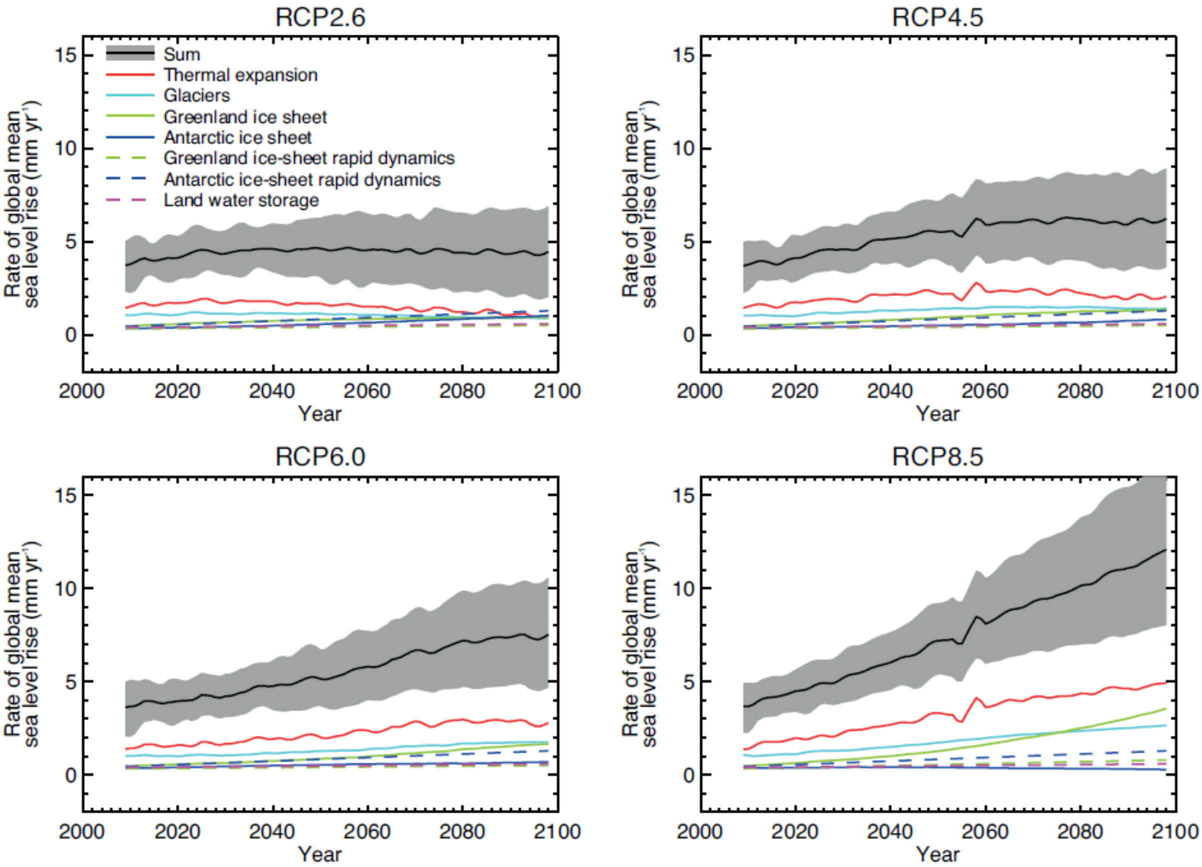

Figure 2.4: Projections of the rates of global mean sea level (GMSL) rise and the projections of the individual eustatic component contributions. Taken from Church et al. (2013)

2.3.2 Sea Level Rise in Scotland

Global sea level rise rates do not equate with regional or local rates due to basin-scale polarities, and inter-decadal variability (Beckley et al., 2007), and natural climatic signals e.g. El Niño and the Southern Oscillation (ENSO) (Boening et al., 2012), and North Atlantic Oscillations (Yan et al., 2004). To explain rates of relative sea level (RSL) rise in Scotland a simple formula is utilised;

$$\delta RSL = \delta E \pm \delta L$$

where δE is eustatic sea level change (changes in ocean volume) and δL is vertical land movement, both usually in mm (or mm yr^{-1} if given as a rate). Despite being a simple formula, obtaining reliable values for δE and δL is problematic as datasets for Scotland have poor spatial and temporal coverage. Nevertheless, the information currently available is presented below.

2.3.2.1 Eustatic Component

The main contributors to eustatic sea level change are thermal expansion, glacier and ice sheet melt, and surface and ground water (Dawson et al., 2001). During the 20th century eustatic sea levels rose at a rate of approximately 1.4 ± 0.2 mm yr^{-1} around the UK (Woodworth et al., 2009). However, there is considerable spatial variability. Nevertheless, the data allows comparisons to global data, and it appears that eustatic changes are similar to the global rates over the same time period (Table 2.4). For the more recent time period (ca. 1993-2007), UK and global rates diverge, with Teferle et al. (2006) stating UK rates of between 0.6 and 1.9 mm yr^{-1} (for 1995-2004) which is much lower than the global rate of 3.2 ± 0.4 mm yr^{-1} for the more recent time period of 1993 to 2010 (Table 2.4).

A potential explanation for this difference is the global influence of thermal expansion as the major contributor to sea level rise. Church et al. (2013) state thermal expansion alone has contributed 1.1 (0.8 to 1.4) mm yr^{-1} to global sea level rise for the time period 1993 to 2010. For the waters surrounding the UK there is no empirical evidence that thermal expansion has contributed to sea level rise (the most recent data used within the analysis was 1997), with some areas of ocean thought to show cooling (Dawson et al., 2001). However, on examination of the data used by Dawson et al. (2001), it appears they interpolated the location of the data incorrectly, using data from east rather than west of the prime median, potentially as a consequence of the raw data being supplied as east of the prime meridian i.e. 8°W is reported as 252°E in the raw data. Consequently, the work (using the same methodology as Dawson et al. (2001)) has been updated here with the inclusion of recent data. The spatial location of this data is shown in Figure 2.5. The data was acquired from the International Comprehensive Ocean-Atmosphere Data Set (Available here: http://icoads.noaa.gov/index.shtml).

Table 2.6 shows that in the majority of locations there has been a warming of the sea around the Scottish coast. These rates are comparable to recent UK trends (Jenkins et al., 2008) which show the rate of sea surface temperature increase between 1992 and 2006 was 0.037 °C yr^{-1} (Figure 2.6). The 1992-2014 data suggests some areas of minor winter cooling at 8°W 56°N over the long time scale, and minor cooling at location 8°W 56°N over the short time scale. However, in both cases the summer trends show an increase. There is a slight cooling at 16°W 56°N in the summer and winter over intermediate time scales however increases in the long and short term are observed.

Using the rates of change calculated in Table 2.6 it is possible to extrapolate the average sea surface temperature increase over the long time period of the dataset (Table 2.7). The mean increase in temperature is 0.37 ± 0.08 °C and 0.52 ± 0.2 °C for the summer and winter months respectively. This is consistent with Figure 2.1 which shows the sea around Scotland has been observed to have warmed by approximately 0.2 to 0.6 °C since 1901.

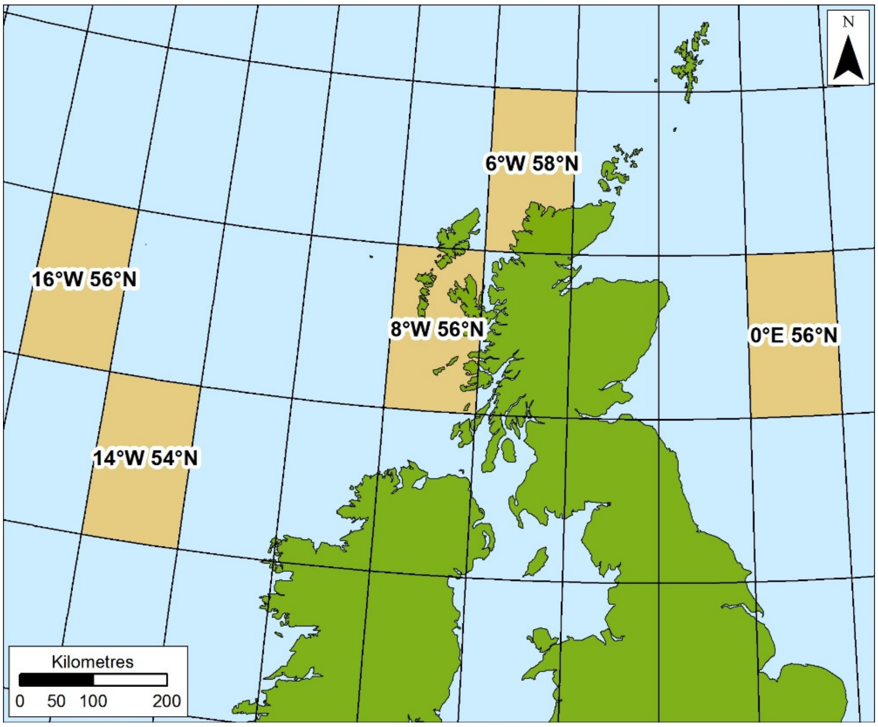

Figure 2.5: The location of data used for the sea surface temperature analysis by Dawson et al. (2001)

On a global scale the sea surface temperature increase around Scotland is not as great as other oceans. However, the water temperature in the North Atlantic is increasing despite claims from Dawson et al. (2001) to the contrary. Therefore, thermal expansion will contribute to the eustatic sea level change around Scotland according to the assessment carried out in this thesis (Table 2.6 and Table 2.7).

Table 2.6: Summer (July) and winter (January) mean sea surface temperature change rates for five locations around Scotland calculated by the author. Data obtained from International Comprehensive Ocean-Atmosphere Data Set.

	Summer (July)					
Area	**Rate of Change (°C yr^{-1})**	**Time Period**	**Rate of Change (°C yr^{-1})**	**Time Period**	**Rate of Change (°C yr^{-1})**	**Time Period**
8°W 56°N	0.0008	1853-2012	0.022	1977-1997	0.0399	1992-2012
14°W 54°N	0.0027	1849-2013	0.0428	1977-1997	0.0238	1992-2013
16°W 56°N	0.0013	1849-2013	-0.0261	1977-1997	0.0305	1992-2013
6°W 58°N	0.0043	1870-2013	0.0125	1977-1997	0.0548	1992-2013
0°E 56°N	0.0029	1856-2013	0.0688	1977-1997	0.0511	1992-2013

	Winter (January)					
Area	**Rate of Change (°C yr^{-1})**	**Time Period**	**Rate of Change (°C yr^{-1})**	**Time Period**	**Rate of Change (°C yr^{-1})**	**Time Period**
8°W 56°N	-0.0007	1871-2014	0.0167	1977-1997	0.0026	1992-2014
14°W 54°N	0.0025	1876-2014	0.0042	1977-1997	0.0273	1992-2014
16°W 56°N	0.0082	1891-2013	-0.019	1977-1997	0.017	1992-2013
6°W 58°N	0.0033	1890-2013	0.0284	1977-1997	0.0193	1992-2013
0°E 56°N	0.0086	1904-2014	0.0402	1977-1997	-0.0049	1992-2014

Table 2.7: Summer (July) and winter (January) total sea surface temperature changes over time calculated from the rates in Table 2.6 for five locations around Scotland. SE = Standard Error.

	Summer (July)					
	Data Start	**Data End**	**Number of Years**	**Rate of Change (°C yr^{-1})**	**Change (°C)**	**Mean Change (°C)**
8°W 56°N	1853	2012	159	0.0008	0.18	0.37 (SE = 0.08)
14°W 54°N	1849	2013	164	0.0027	0.44	
16°W 56°N	1849	2013	164	0.0013	0.21	
6°W 58°N	1870	2013	143	0.0043	0.61	
0°E 56°N	1856	2013	157	0.0029	0.46	

	Winter (January)					
	Data Start	**Data End**	**Number of Years**	**Rate of Change (°C yr^{-1})**	**Change (°C)**	**Mean Change (°C)**
8°W 56°N	1871	2014	143	-0.0007	-0.10	0.52 (SE = 0.2)
14°W 54°N	1876	2014	138	0.0025	0.35	
16°W 56°N	1891	2013	122	0.0082	1.00	
6°W 58°N	1890	2013	123	0.0033	0.41	
0°E 56°N	1904	2014	110	0.0086	0.94	

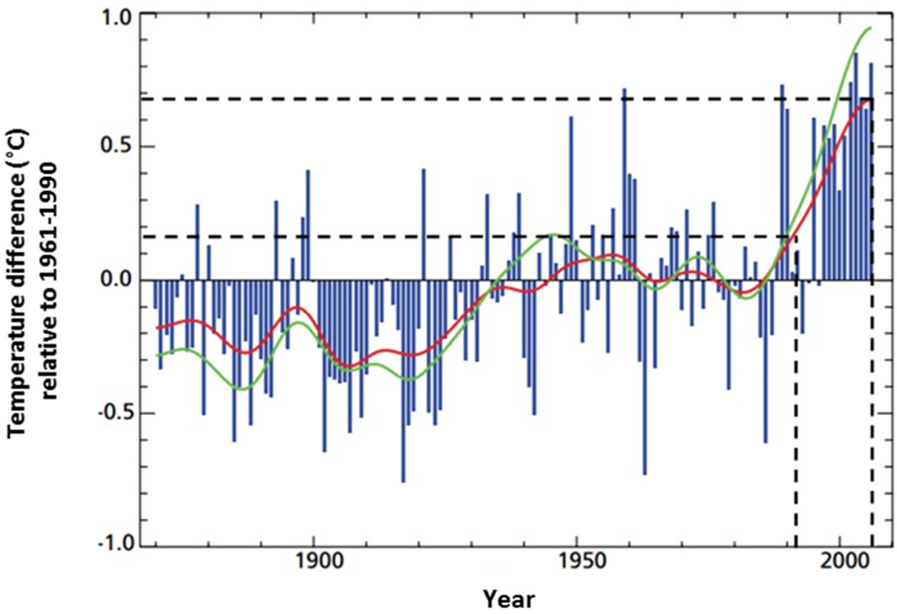

Figure 2.6: Annual-mean sea-surface temperature averaged around the UK coastline, for the period 1870-2006 (blue bars extending from the 1961-90 average of 11.3 ºC); the smoothed red line emphasises decadal variations. The green line shows night marine air temperature over roughly the same area, with the same smoothing. Change in temperature between 1992 and 2006 is estimated as 0.52 ºC (taken from change in the red line over the period marked with the dotted lines) over 14 years which equals a rate of 0.037 ºC y^{-1}. Data sourced from MOHC HadISST1.1. Adapted from Jenkins et al. (2008).

2.3.2.2 Vertical Land Movement

Vertical land movement (VLM) is influenced by a number of factors; glacio-isostatic and hydro-isostatic loading, tectonic activity, and sediment compaction (Shennan, 2009). However, in Scotland VLM is predominantly driven by glacio-isostatic recovery as consequence of deglaciation of the British and Irish Ice Sheet (BIIS). Due to the weight of the overlying ice, the crust directly under and surrounding the ice is deformed, with the removal of the ice (via deglaciation) the crust begins to rebound. The BIIS reached maximum extent approximately 22 ka BP (Bowen et al., 2002) and was thickest in the central west Highlands (Figure 2.7), with decreasing levels of thickness radiating from this point (Dawson et al., 2001; Milne et al., 2006). As well as the local influence of the BIIS, the isostatic recovery in Scotland is influenced by the Scandinavian Ice Sheet, which between c. 30 to 25 ka BP, connected with the BIIS (Bradwell et al., 2008; Shennan and Horton, 2002).

The amount of crustal deformation is proportional to the weight of the overlying ice, therefore when the ice is removed during deglaciation, higher crustal rebound rates are found in the area that had the thickest ice. In Scotland, the highest rates are found at Rannoch Moor, central west Highlands with a rate of 1.5 mm yr^{-1} (Shennan and Horton, 2002). Areas towards the periphery of the ice sheet, including the western and northern isles, experienced thinner ice consequently the crust was deformed much less, resulting in far more modest or absent post-glacial uplift. Furthermore, the crust surrounding the ice is often uplifted slightly during glaciation (fore bulge), which will subside once the ice has been removed (Bradley et al, 2009).

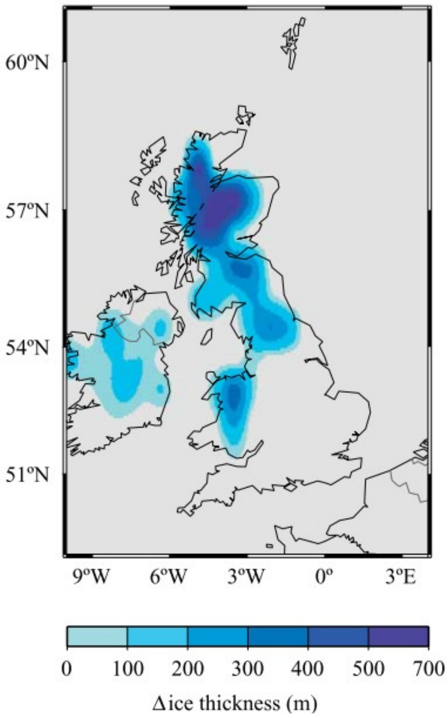

Figure 2.7: Glacial ice thickness at the last glacial maximum. Taken from Milne et al. (2006)

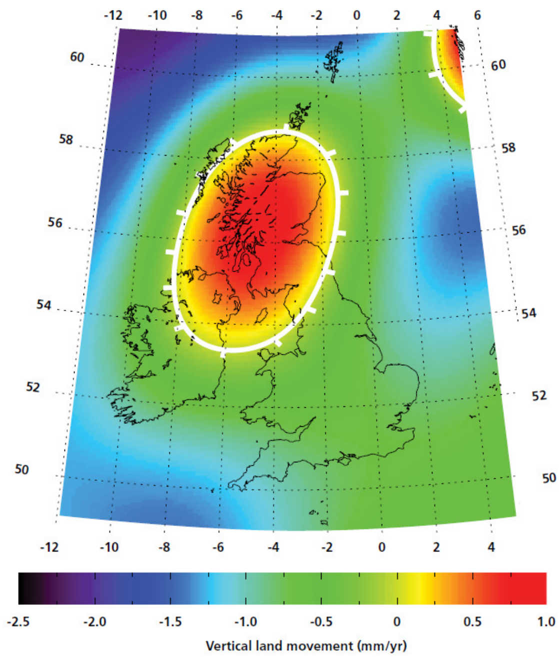

Figure 2.8: Rates of vertical land movement in the UK. Adapted from Lowe et al. (2009) based upon Bradley et al. (2009) note the white line marks the zero land uplift, not the zero-isobase of relative sea level rise.

Uplift and subsidence are still occurring today despite the completion of deglaciation by 11.7 ka BP (Jacobi et al., 2009). The current rates of VLM used within the Lowe et al. (2009)

model are shown in Figure 2.8. The figure shows much of Scotland is experiencing modest uplift, with some areas on the periphery subsiding e.g. western and northern isles. With time, the isostatic influence will diminish and the eustatic component will have an increasingly greater influence on overall RSL. This means that the zero isobase (the contour defining equal rates of sea level and land level rise) will move towards the centre of uplift (at an as yet unknown rate), and areas of presently emergent coast may begin to subside in the future (Rennie & Hansom, 2011).

2.3.2.3 Current Rates of Sea Level Rise in Scotland

Due to the variable uplift and subsidence of land, RSL change is not uniform across Scotland. There have been a number of studies conducted to determine RSL change in the UK e.g. Shennan & Woodworth, 1992; Lambeck, 1993a; Lambeck, 1993b; Milne et al., 2006; Woodworth et al., 2009; Shennan, 2009; Rennie & Hansom, 2011. Figure 2.9a displays the average rates of RSL between 1000 BP and A.D.1950. The rates in Scotland vary from a low of -0.9 mm yr^{-1} in Shetland (the only location in Scotland where a sea level decrease is modelled) to a high of 1.4 mm yr^{-1} in Central Scotland. These data represent up to 1950 and do not include data for the late 20th century acceleration in RSL rise rates (Shennan, 2009) and should therefore act as a baseline for future RSL rise estimates (Rennie and Hansom, 2011).

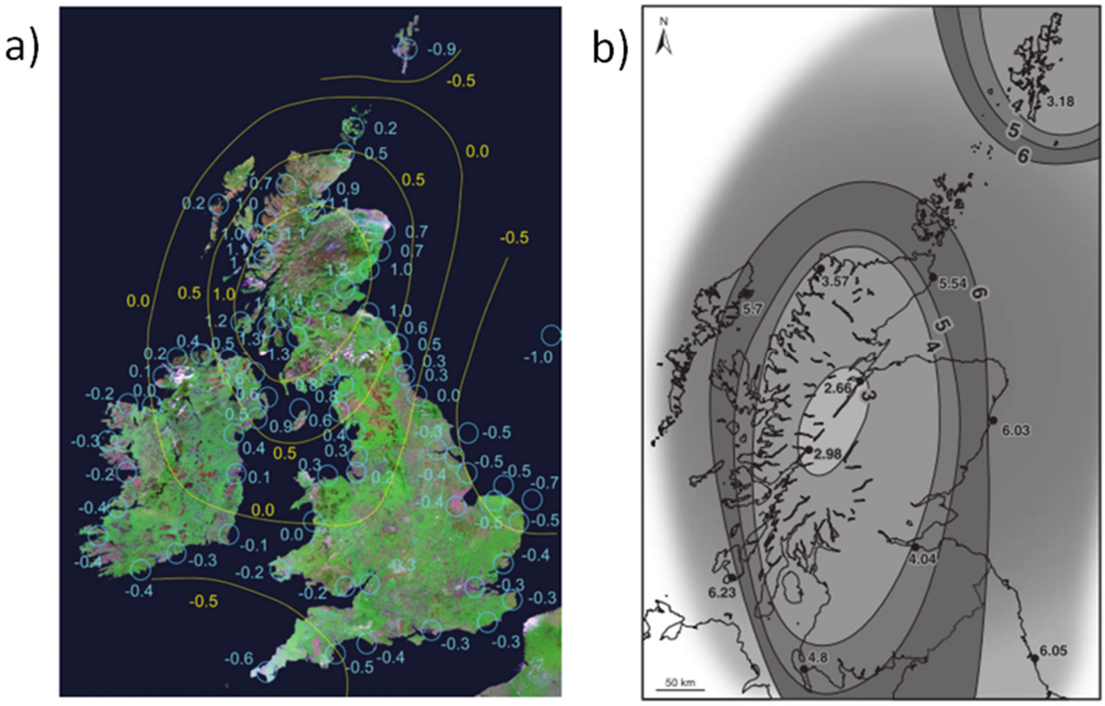

Figure 2.9: a) Average rate of RSL (mm y^{-1}) from 1000 BP to A.D. 1950 (Shennan, 2009) b) Recent rates of RSL (mm y^{-1}) from between 1992 and 2007 (Rennie & Hansom, 2011).

Rennie & Hansom (2011) present RSL change observations for Scotland using data from various time periods between 1957 and 2007. During this period rates of RSL rise between 0.87-2.2 mm yr^{-1} are observed. However, if data for the time period 1992-2007 are used then RSL rise around Scotland can be shown to reach much higher rates. Some parts of the coast (Islay) are experiencing rates as high as 6.23 ± 3.24 mm yr^{-1} (Figure 2.9b). The results should be taken with caution as the associated errors are high due to missing data and a temporally short dataset. However, as discussed previously, recent acceleration in global RSL rise rates have been recorded for the past 20 years or so (Beckley et al., 2007; Bindoff et al., 2007; Church et al., 2013) and lend support to the results obtained by Rennie & Hansom, (2011)

Table 2.8: Long term and updated mean sea level (MSL) change rates for 1992 to 2013. The 1992 to 2007 rates are taken from Rennie and Hansom (2011). Note Islay and Portpatrick data is only available up to 2010.

	Time Period of Data (years)	**Trend of Whole Dataset** (mm yr^{-1})	**Trend between 1992-2007 (A)** (mm yr^{-1})	**Trend between 1992-End of Data (B)** (mm yr^{-1})	**Change between A and B** (mm yr^{-1})
Aberdeen	1932 – 2013	0.96	6.03	1.76	-4.26
Islay	1992 – 2010	8.35	6.23	8.35	2.12
Kinlochbrevie	1992 – 2013	2.92	3.57	2.92	-0.65
Leith	1989 – 2013	2.2	4.04	2.54	-1.50
Lerwick	1957 – 2013	-0.08	3.18	2.77	-0.41
Portpatrick	1968 – 2010	2.13	4.80	4.33	-0.47
Stornoway	1977 – 2013	1.89	5.70	4.29	-1.41
Wick	1965 - 2012	1.31	5.54	3.06	-2.48

Using data from the Permanent Service for Mean Sea Level (PSMSL) (POL, 2013) the data used by Rennie & Hansom 2011 can now be updated to 2013 and the sea level change trends reanalysed. Table 2.8 shows the reanalysed data which demonstrates that at most locations the MSL rise rate has decreased slightly (except Islay where an increase is observed (the Islay and Portpatrick data end in 2010). Even with a decrease in the rate, the observed rates for 1992 to 2013 are generally still above the long term trends of between -0.08 and 2.92 mm yr^{-1} and equates to a mean rate for Scotland of 3.8 mm yr^{-1}. The data used is short term and caution needs to be applied when interpreting the results as the MSL may be influenced by only short term processes (e.g. the 18.6 Lunar Nodal Cycle (Gratiot et al., 2008)) However, the recalculated rates of MSL rise are all consistent with Rennie & Hansom (2011) and the short term global rates in Table 2.4.

2.3.2.4 Future Rates of Sea Level Rise in Scotland

The current RSL rise rates produced by Rennie and Hansom (2011) for 1992-2007 are comparable with rates modelled for the UKCP09 (2009) 95th percentile value of the medium and high emissions scenarios (MES and HES) for the next few decades. Despite the short time period dataset used, the recent RSL rise rates should not be dismissed as averaging data for a longer time period has the effect of masking the current values of RSL rise.

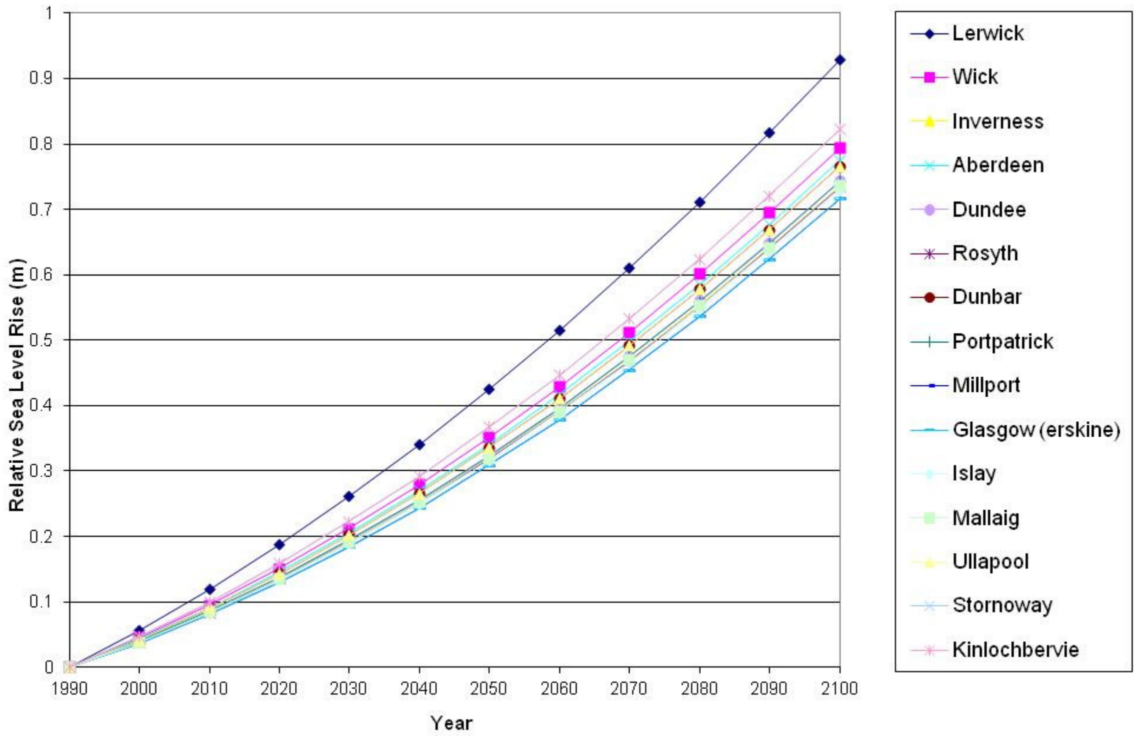

Figure 2.10: Comparison of RSLR (m) of Scottish Ports (95% value, High Emissions & based on 1990 levels). Taken from Rennie and Hansom (2011).

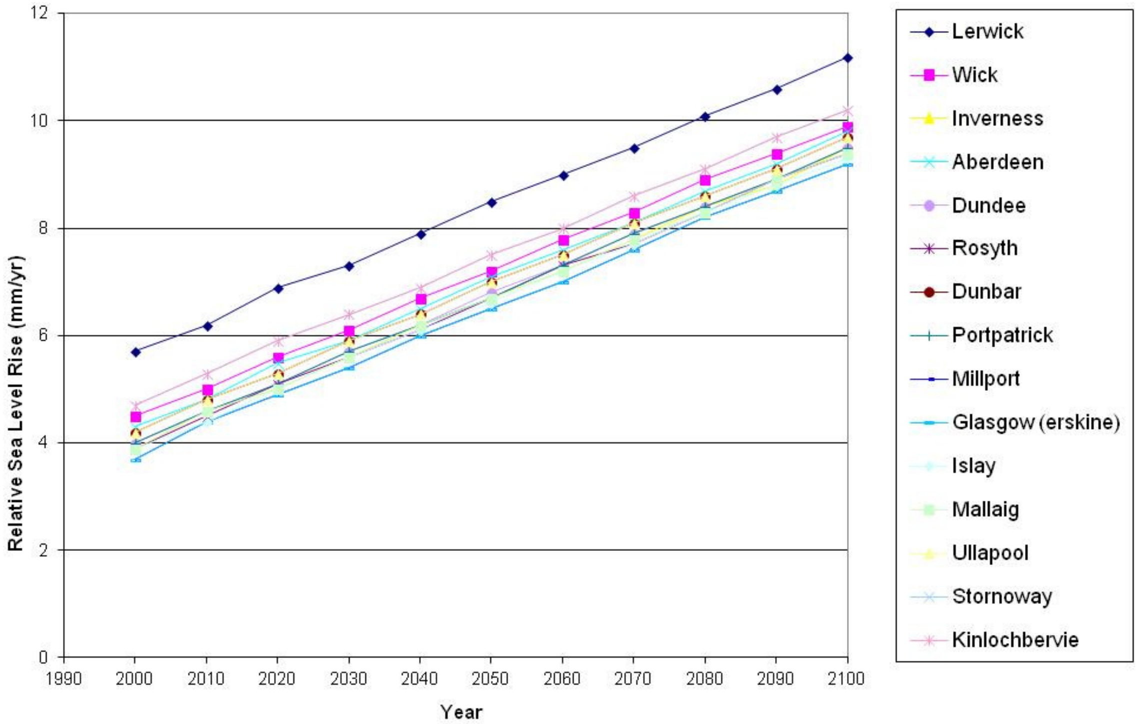

Figure 2.11: Comparison of RSLR (mm/yr) of Scottish Ports (95% value, High Emissions & based on 1990 levels). Taken from Rennie and Hansom (2011).

Coincidentally, other researchers have used similar lengths of data series (see Table 2.4). As the current rates of sea level rise are comparable to the rates modelled by the high emissions scenario, this rate might be justifiably used for future RSL predications. The 95th percentile of the UKCP09 high emissions scenario predicts that within Scotland RSL will increase by 0.72-0.93 m (Figure 2.10), with rates reaching 9.2-11.2 mm yr^{-1} by 2100 (Lerwick has the largest rise with Glasgow (Erskine) the least) (Figure 2.11). Even under a more conservative medium emission scenario sea level rise is predicted to range from 0.39-0.61 m and 0.52-0.72 mm yr^{-1} by 2100. Whilst MES and HES are comparable up to 2050s, when one considers the global emissions, and despite the global economic down turn since 2008, emission rates remain high and in line with HES (UKCP09, 2009).

2.3.3 Coastal Hazards

The influence of terrestrial, atmospheric and marine processes mean the coast is a highly dynamic environment. When this is combined with relatively high socioeconomic activity, the result is that coastlines are often the location of a number of natural hazards that pose a threat to people and society. Ramieri et al. (2011) list the coastal hazards that could result from, or are exacerbated by, climate change (Table 2.9). This section will discuss two of the major problems that coastal managers in Scotland have to address as a result of present and future coastal change: flooding and erosion.

Table 2.9: Problems that require management at the coast. Highlighted in grey are the problems discussed further in this chapter. Taken from Ramieri et al. (2011).

Biogeophysical effect		**Other Relevant Factors**	
		Climate	**Non-climate**
Permanent inundation		Sea level rise	Vertical land movement (uplift and subsidence, land use and land planning
Flooding and storm damage	Surge (open coast)	Wave and storm climate, morphological change, sediment supply	Sediment supply, flood management, morphological change, land claim
	Backwater effect (river)	Run-off	Catchment management and land use
Wetland loss (and change)		CO_2 fertilisation, sediment supply	Sediment supply, migration space, direct destruction
Erosion	Direct effect (open coast)	Sediment supply, wave and storm climate	Sediment supply
	Indirect effect (near inlets)		
Saltwater Intrusion	Surface waters	Run-off	Catchment management and land use
	Groundwater	Rainfall	Land use, aquifer use
Rising water tables/impeded drainage		Rainfall	Land use, aquifer use

2.3.3.1 Coastal Flooding

Even though permanent inundation due to RSL rise could be considered as a type of flooding, short term flooding, as a consequence of storm surges, is considered a more pressing management hazard and will therefore be discussed in more detail here.

Storm surges occur when the barometric low pressure associated with storms raises the water level (1 cm rise for every 1 mb decrease in pressure) above the predicted tidal level (Viles and Spencer, 1995). Often low pressure coincides with strong onshore winds, which can produce large waves and exacerbate coastal flooding. A UK example is the storm surge event in 1953 which killed ca. 350 people in England and coastal flooding at a number of locations in Scotland (Hickey, 2001). The same event caused severe flooding on the Netherland's coast, caused thousands of deaths and led to the development of the Delta Works plan (Deltawerken Online, 2004). In the time period between 1849 and 2008 Scotland has been impacted by 304 coastal floods (Ball et al., 2008). The risk of coastal flooding varies widely across the Scottish coast primarily due to coastal hydrodynamic variations and analysis by Ball et al. (2008) shows that 72% of the coastal flood events occurred in the northeast and southwest of Scotland. Ball et al. (2008) analysed tidal data from Aberdeen, Millport, Lerwick, and Stornoway and state probable storm surges at Millport were 1.2 m above the highest predicted tide levels compared with 0.6 m at Aberdeen and Lerwick, and 0.5 m at Stornoway. The difference has been attributed by Ball et al. (2008) to the narrow inlet of Millport compared to more open coasts at the other locations analysed. SEPA (2013) have mapped the areas most likely to be exposed to coastal flooding within Scotland. However, these maps do not currently take account of coastal erosion. This is an important factor and will be discussed further in Section 2.3.3.3.

Complicating future flood analysis is estimating the impact climate change will have on storm climate. It is thought that an increase in storm events will occur globally as a result of climate change (Lowe and Gregory, 2005; Lowe et al., 2001). Despite this, no research has yet proven that storm occurrence has increased in Britain since the 1970s (Palutikof, 2000). Nevertheless, storm events in Scotland are highly correlated with positive index values of the North Atlantic Oscillation (NAO)[3] (Dawson et al., 2001). Jenkins et al. (2008) identify that the 1920s and 1990s were decades of "*sustained positive NAO index*" and received a relatively high number of storms compared with the intervening decades (Figure 2.12). It is

[3] Yan et al. (2004, p.743) state that the "*North Atlantic oscillation (NAO) is a large-scale atmospheric circulation pattern influencing the regional climate of Europe* (Hurrell, 1995; Jones et al., 1997). *It is characterized by the pressure difference between two active centres of the atmospheric pressure field: the Icelandic low to the north and the subtropical high to the south*". It is this change in atmospheric pressure which can influence sea level.

thought in the future fluctuation between positive and negative NAO phases will occur more often (Goodkin et al., 2008) potentially increasing storm occurrence, and therefore flood frequency in Scotland.

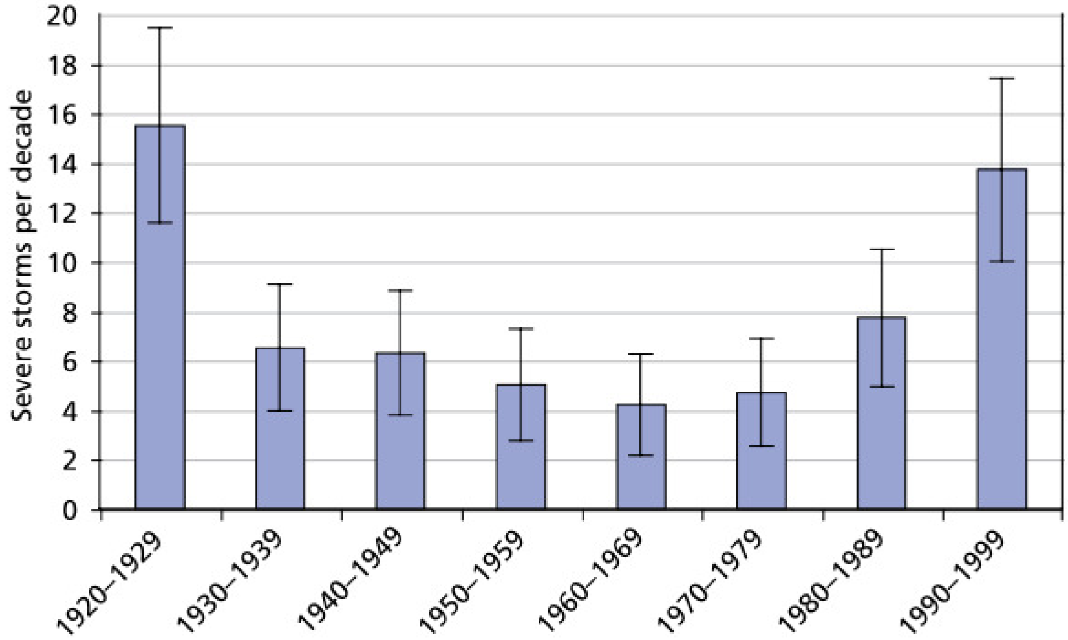

Figure 2.12: The total number of severe storms per decade over the UK and Ireland during the half year period October to March, from the 1920s to the 1990s. Error bars show ± one standard deviation. Taken from Jenkins et al. (2008).

Even without an increase in the number of storms, it has been suggested that the intensity of the storms has increased in the North Atlantic over recent decades (Hansom et al., 2008). The significant wave height (Hs) increased 2.5–7.5 mm yr^{-1} over the period 1955–94 (Gunther et al., 1998). This is supported by Gulev & Hasse (1999) who observed a 1–3 mm yr^{-1} increase in North Atlantic wave height from 1964 to 1993, and Komar & Allan (2008) who report similar increases in both annual and winter Hs between 1976 and 2006 in the Northwest Atlantic. Hence, if more intense storms are occurring at the coast, it could be inferred that due to the increase in energy, there will be an increase in the rate and/or extent of coastal erosion in Scotland. In addition to an increase in storm intensity, rising sea levels will reduce the return period of coastal flooding events (Church et al, 2001). For instance, de la Vega-Leinert and Nicholls (2008) present an example where the 100 year event in Norfolk, potentially becomes a 5 year event by 2050. Using SEPA's calculated storm surge return periods and expected elevations (McMillan et al., 2011), similar analysis to that of de la Vega-Leinert and Nicholls work can be performed by adding the predicted future sea level rise on to the storm surge elevations for Scotland. Table 2.10 shows that the average current surge elevation for a 1 year return period around the Scottish coast is 2.9 metres above Ordnance Datum (mAOD). When a sea level rise rate of 8.25 mm yr^{-1} (the average RSL rise estimate for a high emission scenario in UKCP09), in 50 years' time this becomes a 3.3 mAOD surge, and 3.8 mAOD in 100 years i.e. the current one in 500 year storm surge event becomes less than the yearly event in 100 years. This analysis shows that in 100 years' time, the average yearly storm surge elevation will be greater than the current 500 year storm surge. Storm surge elevation varies markedly around the coast (as seen by the minimum and maximum elevations in Table 2.10), and the analysis assumes a linear RSL rise rate. Nevertheless, the conclusion remains valid that the return periods of more extreme surges will decrease with sea level rise. This has potential to cause significant disruption in the future and is therefore a critical issue for coastal managers (Pettit, 2014).

Table 2.10: Predicted current storm surge elevations with estimates of future elevations when a relative sea level rise rate of 8.25 mm yr^{-1} (the average RSL rise estimate for a high emission scenario in UKCP09) is taken into account for 50 and 100 years in the future. RSL = Relative Sea Level Rise. Data used is described in McMillan et al. (2011)

		Storm Surge Return Period (years)						
Time Period	**Statistic**	**1**	**25**	**50**	**75**	**100**	**200**	**500**
		Storm Surge Height (m)						
Current	Average	2.9	3.4	3.4	3.5	3.5	3.6	3.7
	Min	1.4	1.8	1.8	1.8	1.8	1.9	1.9
	Max	6.1	7.2	7.4	7.6	7.7	7.9	8.3
+ 50 Years (0.41 m of RSL rise)	Average	3.3	3.8	3.9	3.9	3.9	4.0	4.1
	Min	1.8	2.2	2.2	2.2	2.2	2.3	2.3
	Max	6.5	7.6	7.8	8.0	8.1	8.3	8.7
+ 100 Years (0.82 m of RSL rise)	Average	3.8	4.2	4.3	4.3	4.4	4.4	4.6
	Min	2.2	2.6	2.6	2.6	2.7	2.7	2.7
	Max	6.9	8.0	8.2	8.4	8.5	8.8	9.1

2.3.3.2 Coastal Erosion

Over millennia the present form of the Scottish coast has been shaped through the processes of erosion and accretion. The balance of these two processes dictates whether a stretch of coast is stable, erosional or accretional. For example, when a beach is in equilibrium sediment is eroded from the beach via processes such as wave action or wind, and fully replenished by sediment from other sources, such as rivers or other beaches. At larger scales, coastal cells which can be defined as "*lengths of coastline where the movement of sand and gravel is relatively self-contained*" (Hansom et al., 2004: 228). Erosion and accretion are clearly linked. However, it is the erosion aspect which causes the most problems for coastal management. In Europe, an estimated 15 km^2 area of land is lost each year to coastal erosion (van Rijn, 2011) with approximately €3 billon spent on mitigation measures per year (Eurosion, 2004a). Within the UK it is estimated coastal erosion causes £15 million of damage per year, which could rise to £126 million per year by 2080 (Foresight, 2004).

Within Scotland it is thought that 11.6% (or 1,298 km) of coastline is eroding (Eurosion, 2004a).

Erosion rates at the coast differ with some coasts retreating more rapidly than others. The rate of erosion is controlled by the geology of the coastline, wave climate, surge levels, beach slope, exposure, and sediment composition (van Rijn, 2011). However, it is the areas where the rates of erosion are highest (coasts with unconsolidated materials such as glacial till, gravels and beach sands) where the primary management concerns exist. The human impact of coastal erosion depends very much on the landuse adjacent to the coast. Coasts are often areas that attract urban settlements, and therefore coastal erosion poses a great threat to property and infrastructure e.g. transport and power generation (Cooper and McKenna, 2008; Hutchinson et al., 2001). However, the problem goes beyond just the direct loss of property, and therefore economic loss. There are also many social implications tied to the loss, such as unemployment, health impacts and loss of community. As a result, enormous pressure is placed on governments to act, often by constructing sea defences (Cooper & McKenna 2008). At the coast many hard engineered sea defences have been constructed, which can increase wave reflectance and reduce the sediment supply by withholding sediment that otherwise would have been produced by the erosion process. As a result erosion downstream of the defence may be created or exacerbated (French, 2002; Taylor et al., 2004). It is also argued that coastal intervention does not promote social justice (defined as the manner by which benefits and costs associated with the coast are distributed through society) due to both the economic, and environmental cost of such action (Cooper & McKenna 2008). In other words, intervention at the coast often benefits a few, but the cost of intervention is paid for by the many (both in economic terms, and potential damage to the environment). It is therefore thought best by Cooper and McKenna from a social justice and economic view, and more sustainable from an environmental view, to minimise the use of hard engineered coastal defences.

The volume of coastal sediment available to beaches has also been reduced by capital and maintenance dredging, sand and gravel extraction, and reclamation (de la Vega-Leinert & Nicholls, 2008). With a reduction in sediment availability the erosional and accretional balance of local coastlines or coastal cells is disrupted. Consequently coastal processes attempt to reach a new equilibrium to compensate for the loss of sediment (in addition to other adjustments, such as RSL). It has been suggested that with an increase in sea level this may 'unlock' new sources of sediment and augment the amount of sediment within a coastal system (Carter, 1988; Hall et al., 2005; Pearson et al., 2005). Determining whether sufficient sediment will be released to fully replenish and balance the sediment budgets is complex, and therefore cannot be relied upon as a management option at present.

If the sediment budget of a coastal cell remains unbalanced for long periods of time, the coastline becomes erosional and coastal steepening may result where upper beach losses are restricted, particularly with defences. Coastal steepening occurs when a cross-shore coastal profile does not retreat or accrete in equilibrium (Soulsby et al., 1999). Coastal steepening reduces the amount of wave attenuation along the coasts, and therefore has major implications for coastal management (Taylor et al., 2004). This process can be identified by assessing the migration of mean high (MHWS) and low water marks (MLWS) over time (Taylor et al., 2004). There is evidence that coastal steepening has occurred in Scotland (Hansom, 2010; Taylor et al., 2004), and steepening seems set to continue in the future as MLWS is moving landwards at a higher rate than MHWS.

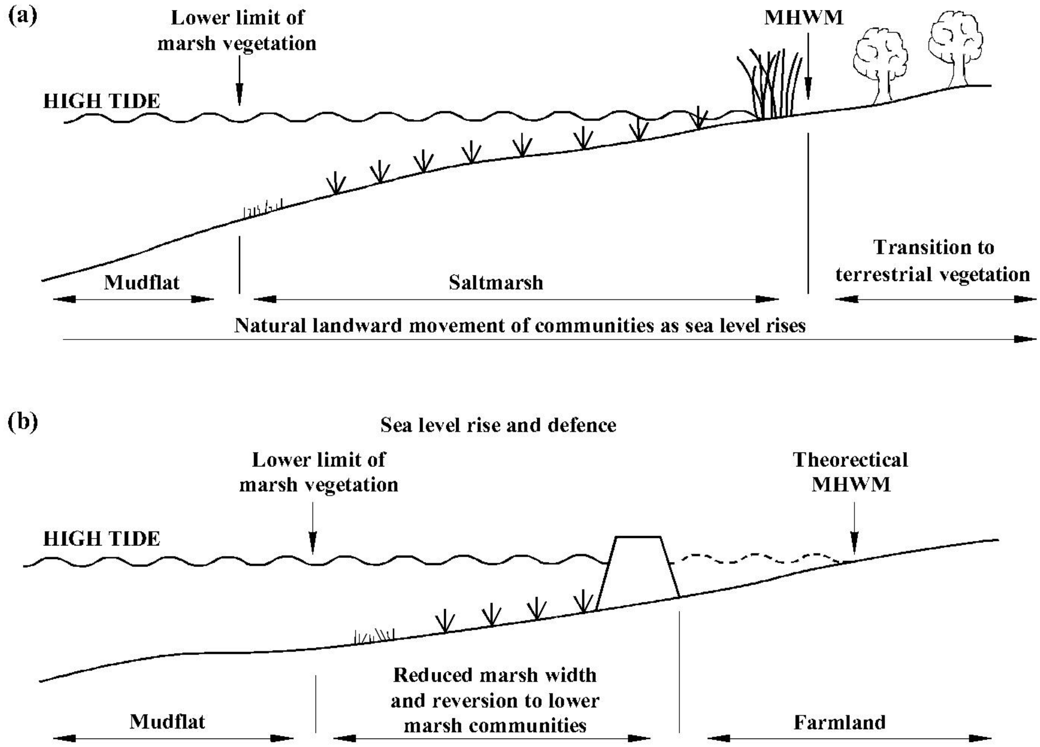

Figure 2.13: Illustration of coastal squeeze a) before construction of sea wall b) after construction of sea wall which shows a reduction in the lateral extent of saltmarsh, and an increase in mudflat. Taken from French (1997).

Coastal steepening in areas of hard sea defence, e.g. sea walls, is of particular concern. The UK has a long history of reclaiming land from the sea (French, 1997; Rippon, 1997). The main driver for past land reclamation was to obtain new agricultural land, usually from within estuaries, but in recent times the land has been utilised for industrial and residential use (de la Vega-Leinert and Nicholls, 2008). The rate of land claim has significantly reduced since the 1980s; however, historically claimed land is still in use today and subject to a number of development proposals, e.g. Dundee and Aberdeen waterfronts. As much of the claimed land is low-lying, it is highly susceptible to coastal flooding and erosion. Consequently the reclaimed areas are protected by hard sea defences. Under a rising sea level scenario coastal ecosystems would naturally move landward. However the sea defences do not allow this process to happen, a process termed ‘coastal squeeze’ (Figure 2.13). Coastal squeeze further exacerbates coastal steepening and therefore a progressive disappearance of coastal habitats is likely to occur (Haslett, 2000). This is a major concern since coastal habitats offer much in the way of ecosystem services e.g. sea defence and erosion prevention, see Table 2.1.

2.3.3.3 Relationship between Flooding and Erosion

Although coastal flooding and erosion have been addressed separately they are intrinsically linked to each other due to positive feedback. A hypothetical example is shown in Figure 2.14.

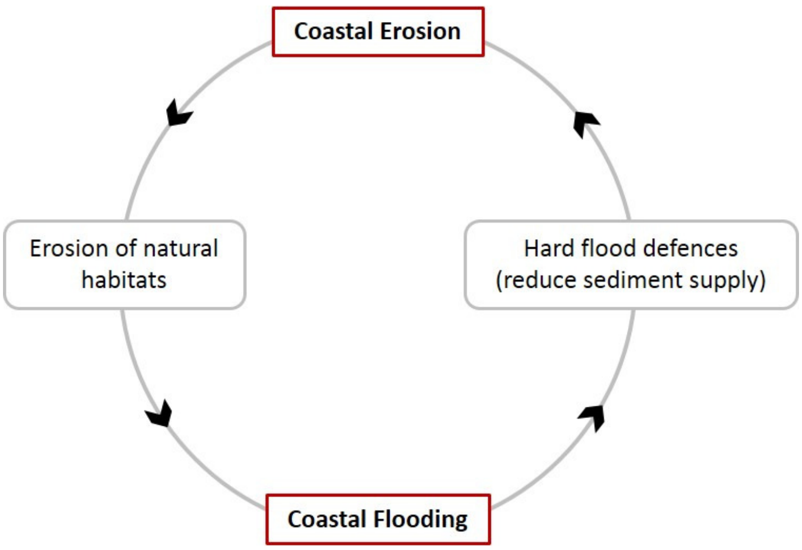

Figure 2.14: A hypothetical example created by the author showing the relationship between coastal erosion and coastal flooding, demonstrating the exacerbation of both problems due to internal feedback.

During a storm surge event, powerful waves strike the coast and hard engineered or natural defences may be breached, overtopped, or removed resulting in flooding. Post flooding, an engineered hard defence may be built in response to the flooding risk due to local pressure if important assets are impacted/threatened, yet the very presence of the hard defences may reduce sediment availability making coastal erosion more likely. Consequently coastal squeeze will transpire and the extent of natural habitats will be reduced, removing the sea defence ecosystem service, and increasing the likelihood of coastal flooding; and the process continues. Consequential wave reflection, beach lowering and erosional bights then propagate the problems in front and adjacent to the structural intervention. If this intervention was not in place, it is possible that the natural habitats would, over time, return to their original state and continue to deliver coastal protection as an ecosystem service

The loss of coastal habitats can be a major concern for coastal managers. Areas of coastal habitats around the UK have reduced by 16.8% between 1945 and 2010, and are predicted to continue into the future with an 8.1% reduction between 2010 and 2060 (Jones et al., 2011). The trend in Scotland also follows the UK trend with areas such as sand dunes predicted to reduce by 36% by 2060 from the 1900 levels (Beaumont et al., 2014). This change is a result of both natural long-term coastal processes (coastal erosion and relative sea level rise), and human induced, relatively short term actions (coastal squeeze, development for industry, housing, and tourism). Combined with the changes in sea level, potentially more money and resources will have to be spent on protecting the coast from future erosion and flooding. It is therefore important for coastal managers to be able to prioritise management towards those areas where it is most needed. It should also be noted that erosion is not necessarily a negative process. For accretion to occur elsewhere along the coast, sediment must be sourced from somewhere else. Therefore, erosion at point A could in fact improve the coastal protection ecosystem service supplied by an area of accretion at point B (in the same way as artificial protection at point A many have negative erosional impacts at point B).

Table 2.11: Scottish coastal margin habitats areas since 1900 and predicted areas for 2060. Data taken from Beaumont et al. (2014).

Habitat	**1900** (ha)	**1945** (ha)	**1970** (ha)	**2000** (ha)	**2010** (ha)	**2060** (ha)	**Predicted Change from 1900/1945 to 2060** (%)
Sand Dune	71,429	60,714	52,143	50,000	49,500	45,857	- 36
Saltmarsh	-	6,900	-	6,000	5,865	5,190	- 25
Machair	-	20,171	-	-	19,698	18,516	- 8

2.3.4 Coastal Erosion Modelling

To assist government, agencies, and coastal managers the locations where management effort should be prioritised need to be identified. Much of the published literature relates to coastal engineering approaches to coastal erosion and these approaches are often reflected in the engineering bias of the Shoreline Management Plans (SMPs) of local authorities at a local and regional scale. However, at a national scale, where high resolution data is not already available or cannot be collected, the methodologies employed in SMPs are difficult, if not impossible, to extrapolate to the national scale. As a result, SMPs are of limited value to coastal managers at the government level and working with a large spatial scale remit.

Large spatial scale erosion assessments are difficult to produce as the coastal processes are complex and require significant amounts of data. To assist with this, the use of Geographical Information Systems (GIS) can help to integrate and analyse multidisciplinary spatial data. This allows coastal managers to assess erosion susceptibility and vulnerability[4] in a simpler, more interpretable fashion. GIS permit assessments to be performed at global, continental, national, regional, and local scales. Presented in Table 2.12 is a selection of publications that assess coastal erosion susceptibility (some also include socioeconomic vulnerability) and the data types used in each study. There is, however, limited examples of national scale coastal erosion models within the literature, with much of the research focussing primarily on coastal flooding. The studies use data from three main areas; physical data, coastal processes data, and socioeconomic data (for assessments that include vulnerability).

Research at a national level is constrained by the nature of the data which already exists as since to produce the data will be costly and/or time consuming. Therefore, many of the assessments are at regional scales where a mixture of "off the shelf" data and self-acquired data can be utilised. Only two publications (Eurosion, 2004a; McLaughlin and Cooper, 2010) attempt to produce coastal erosion assessments that can be used at a national scale. Eurosion was an EU-wide project across 20 countries (including Scotland) aimed at understanding and quantifying the erosion situation within Europe. The project created data that could be used at national scales to give a general overview of the erosion status within and between countries. However, the outputs are now dated, lack detail and when used to further inform management at regional scales, proved difficult to use without other complimentary assessments (the generation of which was beyond the scope of the original Eurosion project). A possible way around this was developed by McLaughlin & Cooper (2010) who produced an erosion vulnerability assessment for Northern Island at various different scales: national (output is a 500 m^2 raster), regional (25 m^2 raster) and local (1 m^2 raster). This nested method allows consistent management decision-making at a range of spatial scales.

McLaughlin & Cooper also differ from Eurosion in the output format. Eurosion and many other publications in Table 2.12 output the assessment as a sectioned line (usually along the coastline) depending on the categorisation of the assessment. This line normally represents

[4] The definition of susceptibility and vulnerability are given in Section 2.4.3.

data that occurs at the coastline or sometimes it also takes into account data from offshore or inland. McLaughlin & Cooper (plus Hegde & Reju, (2007), and Alves et al. (2011)) used a raster output which represents the information for the area overlain by the raster cells. The raster output could be considered easier to interpret as it allows the potential changes in erosion susceptibility both along the coast and inland to be observed. Arguably the rasterised approach of McLaughlin & Cooper's work offers considerable benefits over the linear approach used, including the ability take into account a range of spatial scales and produce an easily interpreted raster output.

Table 2.12: Summary of the datasets used within regional to national scale coastal erosion susceptibility assessments.

Publication (Study Area)	Physical Attributes	Coastal Processes	Socioeconomic Attributes	Scale Analysed	Output
Eurosion, 2004 (Europe)	Elevation	Relative sea level rise	Urbanisation	Continental (000's km) for national use	Line
	Geological coastal type	Shoreline evolution trend			
	Protection structures	Highest water level			
		River sediment supply			
Domínguez et al., 2005 (Spain)		Erosion rates	Land cover	Local/Regional (20 km)	Line
Hegde and Reju, 2007 (India)	Slope	Shoreline evolution	Population	Local/Regional (20 km)	Raster (1°)
	Geomorphology				
Anfuso and Martínez Del Pozo, 2009 (Italy)	Shore evolution	Significant wave height	Land cover	Regional (90 km)	Line
McLaughlin & Cooper, 2010 (Northern Ireland)	Shoreline Type	Significant wave height	Settlement Size	National (650km), Regional (5-10 km) and Local (1 km)	Raster (500 m^2, 25 m^2, & 1 m^2)
	Rivers	Tidal Range	Cultural Heritage		
	Solid Geology	Difference in modal and storm wave height	Roads		
	Drift Geology	Storm Frequency/Probability	Railways		
	Elevation	Morphodynamic State (Dean's Parameter)	Land cover		
	Coastal Orientation		Conservation Designation		
	Distance to Coast		Population		
	Landform				
Reeder et al., 2010 (California, USA)	Distance to Coast	Wave Height	Urban Areas and Expansion	Regional (50 km)	Line
	Slope of Coast	Historical erosion rates			
	Geomorphology				
Martins et al., 2012 (Portugal)	Lithology		Highway/rail track Network	Regional (50 km)	Line with 500m inland extent
	Coastal Systems		Population Density		
	Hydrology		Population Growth		
			Urban Land Cover		

Publication (Study Area)	Physical Attributes	Coastal Processes	Socioeconomic Attributes	Scale Analysed	Output
Sheik Mujabar and Chandrasekar, 2011 (India)	Geomorphology	Relative sea level change		Regional (100 km)	Line
	Shoreline change rate	Mean wave height			
	Coastal slope	Mean tide			
Lins-de-Barros and Muehe, 2011 (Brazil)	Shoreline type	Storm Wave Height	Urban inhabitants	Local/Regional (50 km)	Line
	Exposure	Morphodynamics	Population density		
	Hinterland features		Monthly income		
	Backbeach feature				
	Grain size				
	Backbeach height				
	Surfzone gradient				
Alves et al., 2011 (Portugal)	Elevation	Maximum tidal range		Regional (50 km)	Raster (resolution unknown)
	Distance to coast	Maximum significant wave height			
	Geology	Average rates of erosion/accretion			
	Geomorphology				
	Land cover				
	Anthropogenic actions				
Arun Kumar and Kunte, 2012 (India)	Shoreline change rate	Sea level change rate		Regional (50 km)	Line
	Bathymetry	Significant wave height			
	Coastal elevation	Tidal range			
	Geomorphology	Extreme storm surges			
Jana and Bhattacharya, 2013 (India)	Shoreline change rate		Population density	Regional (50 km)	Line
	Land use				

Table 2.13: Description and scale of variables included in the analysis, as well as the frequency of sites within each category. Taken from Reeder et al. (2010)

	1, "Very low"	2, "Low"	3, "Moderate"	4, "High"	5, "Very high"
Distance to coast	>1000 m (n=779)	500–1000 m (n=423)	100–500 m (n=638)	50–100 m (n=182)	0–50 m (n=306)
Slope of coast	>10° (n=659)	7.5–10° (n=169)	5–7.5° (n=316)	2.5–5° (n=327)	0–2.5° (n=857)
Geomorphology	Rocky cliffs (n=261)	Medium cliffs (n=823)	Low cliffs (n=979)	Cobble beaches, estuaries (n=156)	Sand beaches and flats (n=109)
Historical erosion rates (m/year)	1.33–2.17 (n=7)	0.48–1.33 (n=20)	−0.362–0.48 (n=1029)	−1.206–0.362 (n=1249)	−2.05–1.206 (n=23)
Wave height	1–1.1 m (n=1017)	1.1–1.3 m (n=219)	1.3–1.6 m (n=70)	1.6–1.8 m (n=46)	1.8–2.0 m (n=976)
Human threat index[a]	no positive criteria (n=197)1	1 positive criterion n=150	2 positive criteria n=60	3 positive criteria n=35	all positive criteria n=112
Coastal vulnerability index	4.75–6.7 (n=302)	6.7–8.65 (n=481)	8.65–10.6 (n=494)	10.6–12.55 (n=497)	12.55–14.5 (n=553)
Cultural resource vulnerability index	0–5.3 (n=485)	5.3–7.6 (n=685)	7.6–9.9 (n=831)	9.9–12.2 (n=270)	12.2–15.4 (n=57)

[a] Criteria include: inclusion within 2000 urban area, inclusion within projected 2020 urban area, inclusion within projected 2050 urban area, and location on privately owned land

It is not just the data and output type that needs to be considered; the method by which the different datasets are analysed is also crucial. Almost all the publications listed in Table 2.12

use a method by which each variable is ranked (usually into five categories) based on a parameter's relationship with coastal erosion susceptibility. An example from Reeder et al. (2010) is shown in Table 2.13. Typically, a high ranking is given to a parameter if it increases erosion susceptibility, and vice versa.

Once rankings for each parameter have been determined, they are then combined in a number of ways. Many of the publications use a method derived from the United States Geological Survey (USGS) assessment of sea level rise impact on national parks (Thieler and Hammar-Klose, 1999) where data are ranked and then aggregated to calculate a coastal vulnerability index (CVI) using the following equation:

$$CVI = \sqrt{\frac{a \times b \times c \times d \times e \times f}{N}}$$

Equation 1: Method of aggregation first used by Thieler & Hammar-Klose (1999)

where a = geomorphology, b = coastal slope, c =relative sea-level rise rate, d = shoreline erosion/accretion rate, e = mean tide range, and f = mean wave height, N = the number of data sets used. This method is used extensively in the literature for both sea level rise and coastal erosion assessments as the approach can be adapted by modifying the ranking and datasets used.

An alternative method using coastal characteristics, coastal forcing and socioeconomic conditions summed together is used by McLaughlin & Cooper (2010). For example, for coastal characteristics (CC) drift geology, elevation, rivers, inland buffer, geology, orientation, and shoreline type are ranked 1 to 5 and summed to give a minimum score of 7 and a maximum of 35. To allow comparison with the two other indices of coastal forcing and socioeconomic conditions, which use a different number of datasets, they standardise the results to a 0 to 100 scale using Equation 2. To create an overall index an average of the three standardised datasets is calculated.

$$\left(\frac{Sum\ of\ CC\ variable\ ranks - 7}{28}\right) \times 100$$

Equation 2: Method used to standardise indices used by McLaughlin & Cooper (2010).

The methodology used by Thieler & Hammar-Klose (1999) and McLaughlin & Cooper (2010) are valid as both are flexible. However, since McLaughlin & Cooper's approach allows greater flexibility with regards the type and number of datasets used it is potentially more useful in a Scottish context (where the data types used by Thieler and Hammar-Klose are generally unavailable).

Coastal erosion modelling on a national scale is not without its problems and there are a number of approaches that could be utilised in Scotland. The methodology of McLaughlin & Cooper (2010) is capable of producing outputs that are usable over a range of spatial scales set within a raster format. It is also a method that is easily adapted and transported into other contexts with relative ease. Therefore, this approach is a good candidate as the basis for creating a coastal erosion susceptibility model for Scotland.

2.3.4.1 Shoreline Management Plans

Within Scotland, some areas of the coast are managed via Shoreline Management Plans (SMPs). These are documents that outline a "*strategy for coastal defence for specific lengths of coast, taking into account both natural coastal processes and human and environmental influences*" (Hansom et al., 2004a: 228). A key part of an SMP is to inform the management of coastal erosion. The methodology within SMPs is based on the use of historic maps to determine the past coastline position, which is then compared to the current coastline position. From this, linear coastal change rates are produced which can be used to estimate the coastline position at various future time intervals. SMPs developed out of a need for coastal management to take a more holistic approach, and to avoid situations where construction of coastal defences in one location impacted negatively on an adjacent area. SMPs can also highlight where coastal management can take a more adaptational approach by identifying the coastlines that can be used for managed realignment or are unsuitable for any structural intervention. In 2015, only four local authorities (LAs) in Scotland have an operational SMP (Figure 2.15) which relates to 7% (1,232 km) of Scotland's shoreline, with a further two LAs currently developing one (the two SMPs that are in development will cover a further 2% (371 km) of the shoreline) (Hansom et al., 2015). SMPs are extensively used within England and Wales. Hansom et al. (2004) suggest the adoption of SMPs in Scotland has been limited due to the following reasons:

- Only 12% of the Scottish coast is developed (urbanised) compared to 27% and 32% of the Welsh and English coastline respectively;
- There are no bodies with statutory obligation responsible for coastal erosion in Scotland;
- Coastal erosion is locally severe but recently has not impacted upon wide-spread areas of developed land;

- The highly indented coastline (particularly the west coast and islands) reduces the amount of littoral drift between adjacent areas, therefore the likelihood of coastal defence negatively impacting on other areas is reduced.

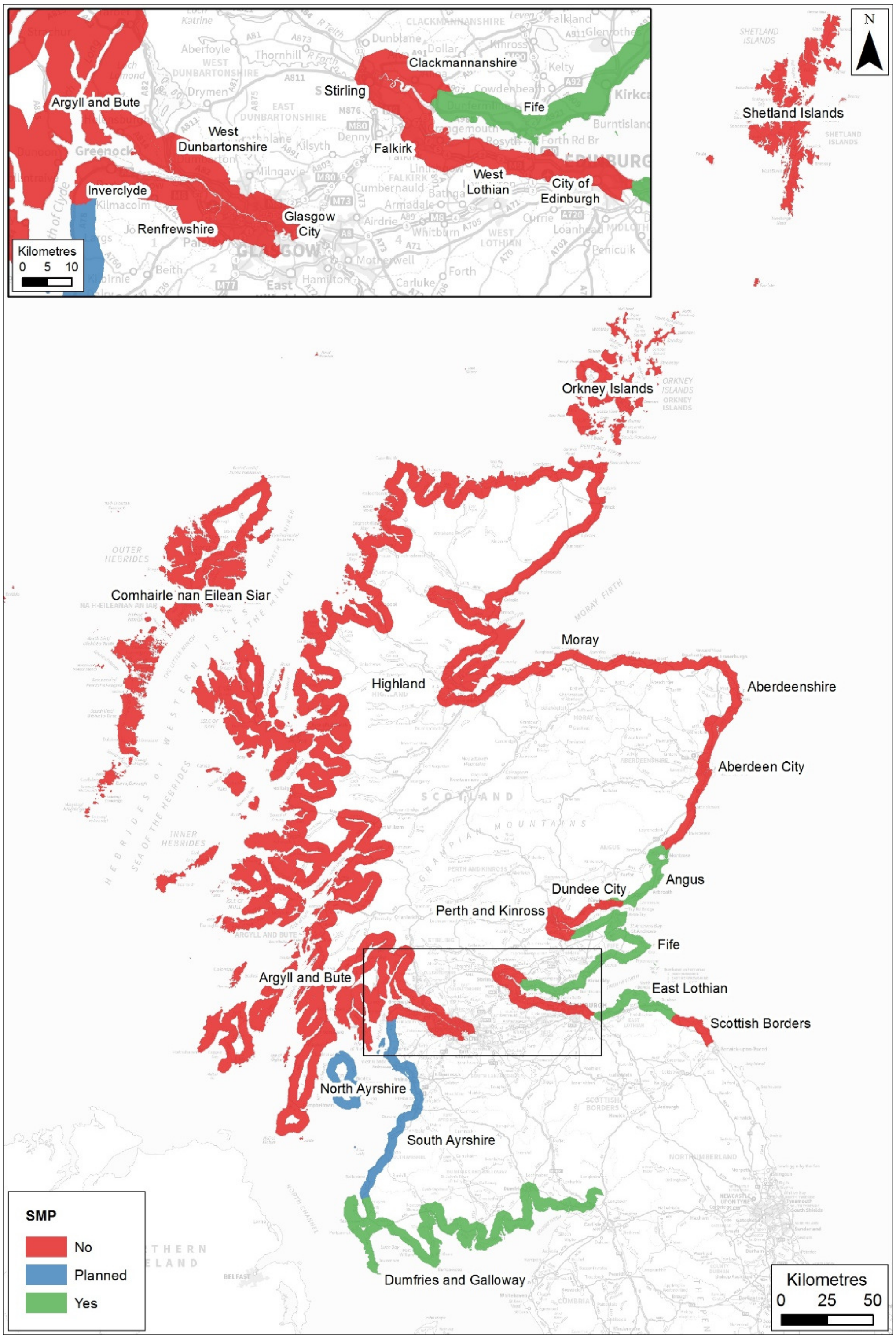

Figure 2.15: Local authorities with Shoreline Management Plans. Taken from Hansom & Fitton (2015).

The data required to create SMPs can be used in a number of other applications, hence if the whole of the Scottish coastline had been subject to an SMP, this data could have been fed into a coastal erosion model similar to the ones discussed in Section 2.3.4. However, a national approach for collation and dissemination of this information has thus far been lacking, hindering further application of the data and curtailing national level strategy planning. Therefore, the few SMPs that are available in Scotland are best used to support, rather than inform a national coastal erosion model.

2.3.5 Section Summary

Section 2.3 has described a range of coastal management literature that can be summarised as follows:

- In Scotland 70% (5 million people) of the population live within 10 km of coast, with population densities highly varied throughout the country. Coastal habitats in Scotland provide provisioning, regulating and cultural ecosystem services. Their economic value in Scotland is under researched however, but for comparison within England it is thought that the regulating service of coastal defence is worth an estimated £3.1 to £33bn worth of capital savings along soft coasts. Therefore, it is of major concern for coastal managers that coastal habitats around the UK have reduced by 16.8% between 1945 and 2010. Within Scotland, habitats such as sand dune are predicted to reduce by 36% by 2060 from 1900 levels;

- Global land and sea surface temperature have increased as a result of climate change. For the time period 1880 to 2012 temperatures show a warming of 0.85 (0.65 to 1.06) °C. Globally, rising sea levels have also been observed. In Scotland, between 1957 and 2007, a RSL rise rate of between 0.87-2.2 mm yr^{-1} has been measured. Using a more recent time period (1992-2007), RSL rise around Scotland has reached rates as high as 6.23 ± 3.24 mm yr^{-1}. If this accelerating trend continues, by 2100 rates of 9.2-11.2 mm yr^{-1} may be attained;

- The hazard of coastal flooding associated with storm surge events is a major challenge for coastal managers. In the time period between 1849 and 2008 Scotland has been impacted by 304 floods. Analysis of these floods shows that 72% of the flood events occurred in the northeast and southwest of Scotland. It is thought that rising sea levels will reduce the return period of coastal flooding events. Additionally, mean surge levels have been increasing in magnitude by between 1.17 and 2.18 mm yr^{-1}. Most of the locations around Scotland could see storms surges greater than 2 m above current mean sea level by 2050;

- In addition to flooding, erosion also creates a number of problems. Within the UK it is estimated coastal erosion causes £15 million of damage per year, which could rise to £126 million per year by 2080. Within Scotland it is thought that 11.6% (or 1,298 km) of coastline is eroding (Eurosion, 2004a). Coastal erosion poses a great threat to property and infrastructure e.g. transport and power generation. If a person is impacted by erosion a number of social problems such as unemployment and health issues can result. In order to manage coastal erosion, engineered coastal defences have been used. However, this intervention is creating a shortage of sediment, creating or exacerbating erosion downstream, and this is why management needs to be well informed via erosion susceptibility assessments;

- Large spatial scale erosion assessments are difficult to produce as the processes which occur at the coast are complex and require significant amounts of data. Listed were a selection of publications that assess coastal erosion susceptibility which used data from three main parameter areas; physical, coastal processes, and socioeconomic data. McLaughlin & Cooper (2010) produced an overview of erosion in Northern Ireland for national, (output is a 500m^2 raster), regional (25m^2 raster) and local scale (1 m^2 raster). This provides management with a useful tool to consistently make decisions at all spatial scales. The superior output format is the raster, as it is more flexible and easily understood in comparison with a line output. McLaughlin & Cooper's work produced an output usable over a range of spatial scales within a raster format and should be considered as the basis for creating a coastal erosion susceptibility model for Scotland.

Evaluation of how the above physical component interacts with the socioeconomic side of a hazard has thus far not been addressed. This is usually termed 'risk' or 'vulnerability'; however within the literature the use of such terminology is used in a variety of ways by different authors. Therefore, there is a need to establish the definition of risk and vulnerability, how it can be quantified, and how the physical and socioeconomic elements of a hazard can be incorporated into a comprehensive erosion assessment.

2.4 Coastal Erosion: The Socioeconomic Context

The impacts of coastal erosion vary depending upon the asset exposed and the vulnerability of the people affected. It is important to identify the areas at risk, as vulnerable communities are often disproportionately affected by a hazard and more likely to be pushed into crisis relative to the general population (Felsenstein and Lichter, 2013). Vulnerability is often defined differently depending upon its context and the academic discipline in question (Füssel, 2007) making it difficult to compare between 'vulnerabilities'. It is necessary when discussing risk and vulnerability to define the terminology as "*the value of a definition is… the degree to which it gives new and useful insights to the nature of the problem at hand and the choices of action to be adopted*" (McFadden and Green, 2007: 122). Therefore, defining terms ultimately aids decision-makers to reduce vulnerability and therefore risk. This section will consider the concepts of risk and vulnerability, design a risk and vulnerability workflow, and detail methods to quantify vulnerability.

2.4.1 Risk and Vulnerability

2.4.1.1 The Concept of Risk

The term risk, in a disaster management sense, has been the subject of much study over recent years. A disaster is the function of two components; an extreme event (or hazard), and a vulnerable population. A hazard can be defined as "*the probability or possibility that an external event manifests itself in a certain geographical area within a certain interval of time*" (Villagrán de León, 2006: 8). The hazard can occur episodically (e.g. earthquake) or continually (e.g. famine). Hazards can additionally be classified as natural (e.g. earthquakes, volcanic eruptions), technological (e.g. spills, and release of toxic chemicals), and as human induced (e.g. civil riots, terrorist attacks) (Villagrán de León, 2006). The concept of risk can be used to assess the potential effects of a hazard before the disaster occurs. In a basic form risk is defined by the International Strategy for Disaster Reduction (ISDR) (2004) as:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability}$$

Hazard includes the idea of probability. However, many definitions are unclear as to whether this is the probability of the hazard occurring or the probability of a negative outcome (Brooks, 2003). Other authors have suggested that coping (White et al., 2005), deficiencies in preparedness (Villagrán de León, 2001), or exposure (Dilley et al., 2005) should be included within the risk equation. However, these could be considered under the concept of vulnerability and susceptibility. Hence, to fully understand risk, the concepts of vulnerability should be explored in further detail.

2.4.1.2 The Concept of Vulnerability

The theories and concepts of vulnerability have been developed from disaster management research. O'Keefe et al. (1976) identified an increasing trend in the amount of disasters (and deaths per disaster) globally over the period of 1947 to 1970 as a result of natural hazards, particularly in "*underdeveloped*" countries. This was explained as a consequence of disasters being a result of two elements; an extreme event (hazard), and a vulnerable population. O'Keefe et al. (1976) could not identify any evidence to suggest that the occurrence of natural hazard events were increasing over time, and therefore only an increasing vulnerable population can account for the increase in disasters. The impact of natural hazards can therefore vary considerably depending upon the socioeconomic attributes of the people exposed (Zakour and Gillespie, 2013).

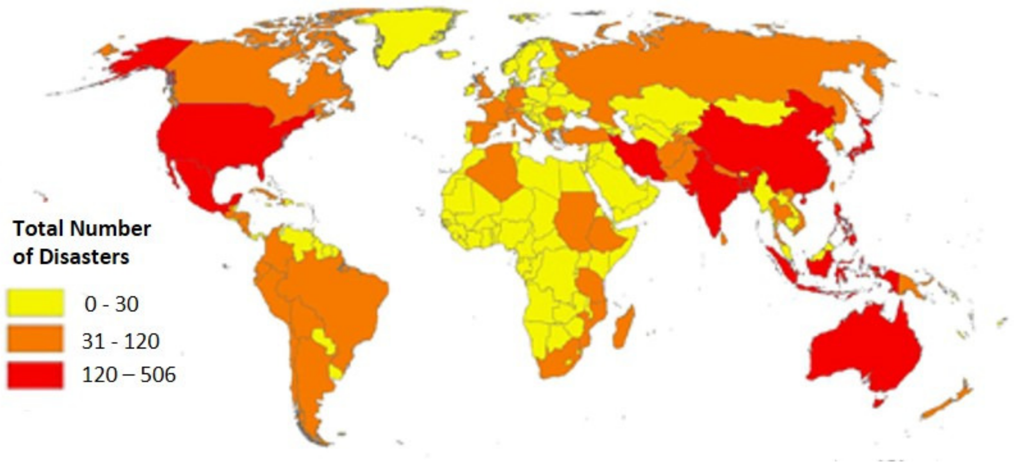

Figure 2.16: Total number of disasters by country 1974 to 2003. Adapted from EM-DAT (2013)

Zakour & Gillespie (2013) demonstrate that this trend has continued beyond the 1970s using EM-DAT (2013) data. Figure 2.16 shows the number and distribution of disasters between 1974 and 2003, with a high number in North America and Australia. Figure 2.17 shows the number of deaths per 100,000 people as a result of these disasters and considerably more deaths occur in countries in the global south i.e. in countries where the most vulnerable people live.

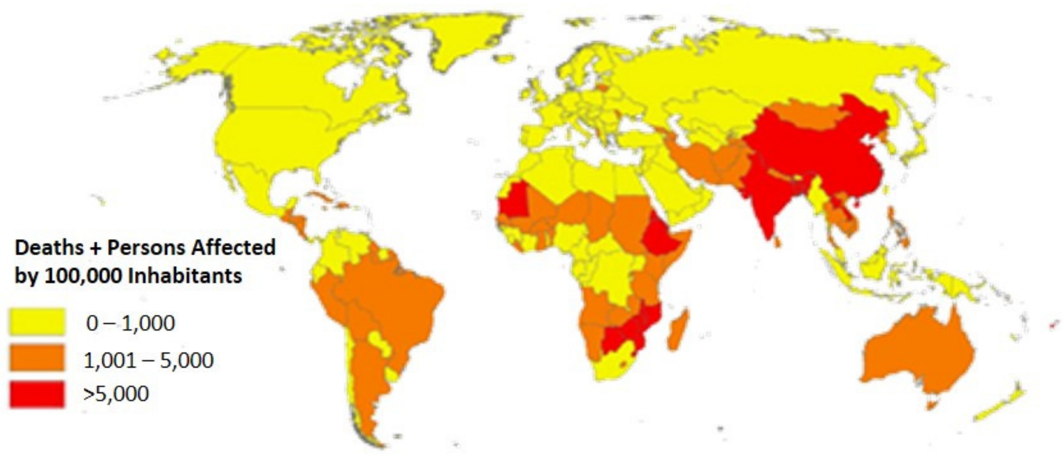

Figure 2.17: Total number of deaths and of people affected by natural disasters by 100,000 inhabitants: 1974–2003. Adapted from EM-DAT (2013).

Consequently, by understanding vulnerability, measures can be taken to mitigate the impacts of natural hazards, and therefore reduce the number and/or degree to which people are affected. Vulnerability modelling is a key component of disaster management; however the definition of vulnerability and how it is assessed has been the subject of much discussion within the literature. The next section explores some of the models that have been developed to explain/define vulnerability.

2.4.2 Vulnerability Models

The definition of vulnerability is highly varied, however the term is often used to represent "*the capacity to be wounded i.e. the degree to which a system is likely to experience harm due to exposure to a hazard*" (Füssel, 2007: 155). Thus, vulnerability can be considered as a state that exists within a person regardless of the exposure to a hazard (Allen, 2003; Brooks, 2003). This concept of vulnerability is a straightforward idea. However, the question of *why* people are or become vulnerable is highly complex. As a result within the literature, there are a multitude of vulnerability models used within different research contexts, each with associated terminology which endeavours to explain/define vulnerability. Four vulnerability models have been selected to be explored in more detail; the 'Internal/External Model', the 'Pressure and Release' and 'Access Model', the 'Hazard of Place Model', and the 'Expanded Model'. These models were chosen for further examination as:

- The Internal/External Model is one of the earlier models that conceptualises vulnerability as the result of wider social and economic processes, which ultimately impact upon individuals;
- This idea is developed further by the Pressure and Release and Access Model, however how the wider social and economic processes manifest into unsafe conditions and therefore potential for disaster is examined in more detail;
- The Hazards of Place Model focuses less on the wider social and economic processes and more on the local scale. It considers both the social and economic context of the individual/household as well as the biophysical context;
- The Expanded Model of Vulnerability is the latest model out of the four and builds upon the ideas of the Pressure and Release Model and the Hazards of Place model to produce a model where vulnerability is the result of exposure, sensitivity and resilience.

By examining these four models, it is possible to explore the development of vulnerability theory, as well as identifying the key concepts behind vulnerability which can be adapted for use in coastal erosion vulnerability assessments.

2.4.2.1 The Internal/External Model

The internal and external model was first conceived by Chambers (1989) and theorises that vulnerability consists of two processes; internal and external. The internal processes focus on an individual or household's ability to cope with an external shock or stress. The external processes consist of potential shocks (sudden and unpredictable events e.g. floods and earthquakes) and stresses (long term pressures e.g. resource shortage) that can act upon an individual or household. Chambers (1989) highlights that being vulnerable is related to poverty, but it is not equivalent. Chambers states "*vulnerability, more than poverty, is linked with net assets. Poverty, in the sense of low income, can be reduced by borrowing and investing; but such debt makes households more vulnerable*" (Chambers, 1989: 1). Therefore being able to cope with shocks and stresses is dependent upon how people are able to manage their assets (Villagrán de León, 2006).

The model was developed further by Watt and Bohle (1993) and Bohle (2001) who renamed internal and external processes as coping and exposure respectively (Figure 2.18).

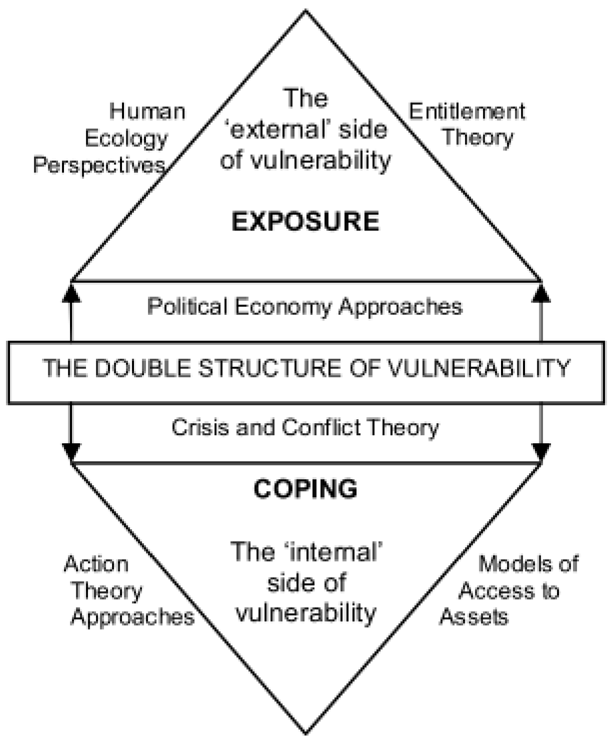

Figure 2.18: The internal and external vulnerability model developed by Chambers (1989) and expanded by Watt and Bohle (1993) and Bohle (2001). Taken from Bohle (2001).

Watt and Bohle include other existing theories into the model, which influence and explain the exposure and coping sides of vulnerability. Villagrán de León (2006) summaries these theories and how they relate to vulnerability. On the coping (internal) side of vulnerability the theories include:

- **Action Theory** - which explains the possible means and ways people can act, either by free will or as a result of societal, governmental, or economic constraints;
- **Models of Access to Assets** - which explains how people may mitigate their vulnerability via access to particular assets;
- **Crisis and Conflict Theory** - which focuses on the control of resources and assets, and the capacity to manage and resolve crisis situations.

On the exposure (external) side of vulnerability the theories include:

- **Human Ecology** - which explains population dynamics and the capacities (of individuals, groups and communities) to manage the environment;
- **Entitlement Theory** - which focuses on the capacity of people to obtain or manage assets via legitimate economic means;
- **Political Economy** - which relate to the exposure of some people to social inequalities and the control of assets by higher social classes, which can lead to conflicts.

Through the inclusion of the above theories into the vulnerability model Watt and Bohle consider vulnerability as "*a multi-layered and multidimensional social space defined by the determinate political, economic and institutional capabilities of people in specific places at specific times*" (Villagrán de León, 2006: 12; Watts and Bohle, 1993). Hence, this is the first vulnerability model to realise the complexity of vulnerability as the result of 'distant' processes. Wisner et al. (2004) describe that processes can be 'distant' in a combination of the following ways:

- **Spatially** - arising in a distant centre of economic or political power;
- **Temporally** - decisions/events which have happened at some point in history;
- **Cultural assumptions** - the processes are so inherent that they become 'invisible' or 'taken for granted'.

The model does not fully explain vulnerability however. Marchand (2009) highlight that entitlement theory does not sufficiently explain why people are exposed to natural hazards. Even if a person has sufficient ability to obtain or manage their assets, they can still be vulnerable to certain types of natural hazards. The model therefore needs increased detail to explain vulnerability sufficiently. Additionally, the scale is too large and complex to assess local scale vulnerability accurately. It is therefore necessary to identify a model that operates on the more geographical and physical components of vulnerability that would be useable by local management.

2.4.2.2 The 'Pressure and Release' and 'Access Model'

The Pressure and Release (PAR) model developed by Wisner et al. (2004) interprets a disaster as the result of a natural hazard event coinciding with a vulnerable population. The 'pressure' is the build-up of vulnerability through root causes which lead to dynamic pressures, and ultimately, unsafe conditions (Figure 2.19). 'Release' is the concept of taking measures to reduce vulnerability i.e. the build-up of vulnerability 'pressure' is relieved by 'release' actions. Wisner et al. (2004) utilise the ideas of Watt and Bohle (1993) and Bohle (2001) and recognise that vulnerability has a number of 'distant' root causes. The root causes identified are economic, demographic and political processes, which "*affect the allocation and distribution of resources among different groups of people*" (Wisner et al., 2004: 52).

Whereas Watt and Bohle (1993) and Bohle (2001) conclude their explanation of vulnerability at this point, Wisner et al. (2004) explain how these root causes are translated into unsafe conditions via dynamic pressures. Examples of dynamic pressures include the manifestation of economic, social and political policies by governments; epidemic disease, rapid urbanisation, military conflicts etc. Dynamic pressures are not always negative but can indirectly result in unsafe conditions.

The unsafe conditions are "*the specific forms in which the vulnerability of a population is expressed in time and space*" (Wisner et al., 2004: 55). The unsafe conditions could include poor quality housing, living in a hazardous location, health issues, dangerous livelihoods etc. Unsafe conditions (which can be considered as vulnerability) can intersect with hazards to produce a disaster. The disaster potential, otherwise known as the risk, is described as 'vulnerability x hazard'.

Wisner et al. (2004) state that unsafe conditions are a result of many interrelated causes, but underlying them is the idea of degree of access to resources, both tangible e.g. cash, food, shelter etc. and intangible e.g. support network, knowledge of survival etc., is the ultimate cause of vulnerability. To fully explain how access to resources affects vulnerability at the person/household level Wisner et al. (2004) created the Access model to compliment the PAR model. The Access model (Figure 2.20) offers a more complete explanation of how unsafe conditions and hazards can intersect to produce a disaster. The model provides a framework for adaptation and intervention to help reduce vulnerability.

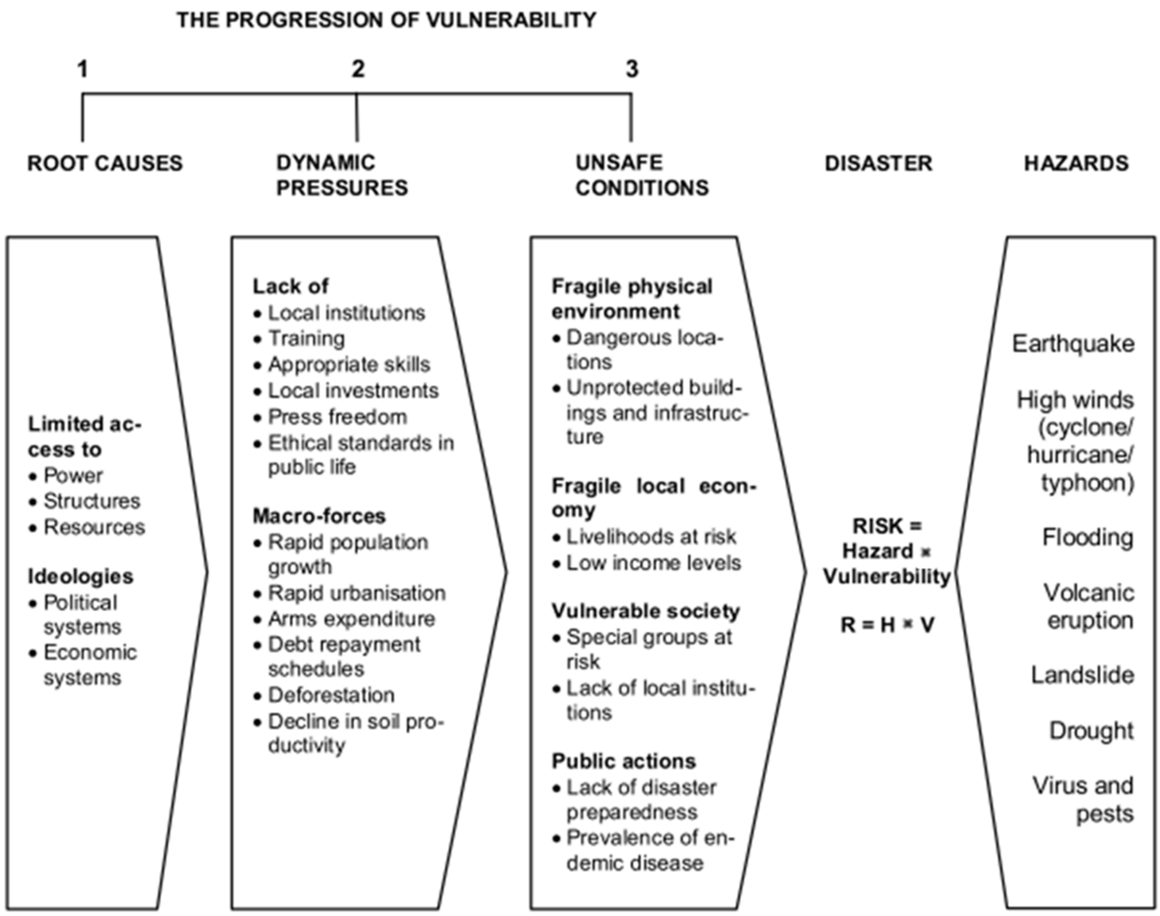

Figure 2.19: The Pressure and Release model. Adapted from Wisner et al. (2004).

The Access model level of detail is more suited to producing a coastal erosion vulnerability assessment, and is therefore a considerable improvement upon the Internal/External model. The PAR also retains the concept that vulnerability has a number of wider, root causes which while important to bear in mind, can be challenging when it comes to assessing local vulnerability. The problem arises as collecting indicators which fairly represents these 'distant' processes and the uncertainty and knowledge gaps about causal linkages grows as we move from the unsafe conditions (local) towards the root causes (national/global).

However, it is worth highlighting a root cause (see Figure 2.19) that may be applicable to coastal management in Scotland is the concept of being of 'unimportant' to government. The variation in access to resources amongst the population results in people becoming marginalised, both in an economic (e.g. poor quality housing) and environmental (e.g. living in a flood prone area) sense, but also in a political sense (Wisner et al., 2004). This means that the government is less motivated to reduce the vulnerability of an individual or household, as the political repercussions of not doing so are negligible, or the political impetus to initiate action does not exist. For coastal communities in rural areas, political marginalisation may occur and impact on the level of management (e.g. building of defences) received when exposed to flooding or erosion.

The PAR model is the most suited to discussing the concepts of vulnerability at all operational scales and describes the ‘cascade of vulnerability’ clearly. However, in terms of local vulnerability assessments a model that functions at a similar scale to the Access model aspect of the PAR is required, which considers both the socioeconomic and physical components of a hazard.

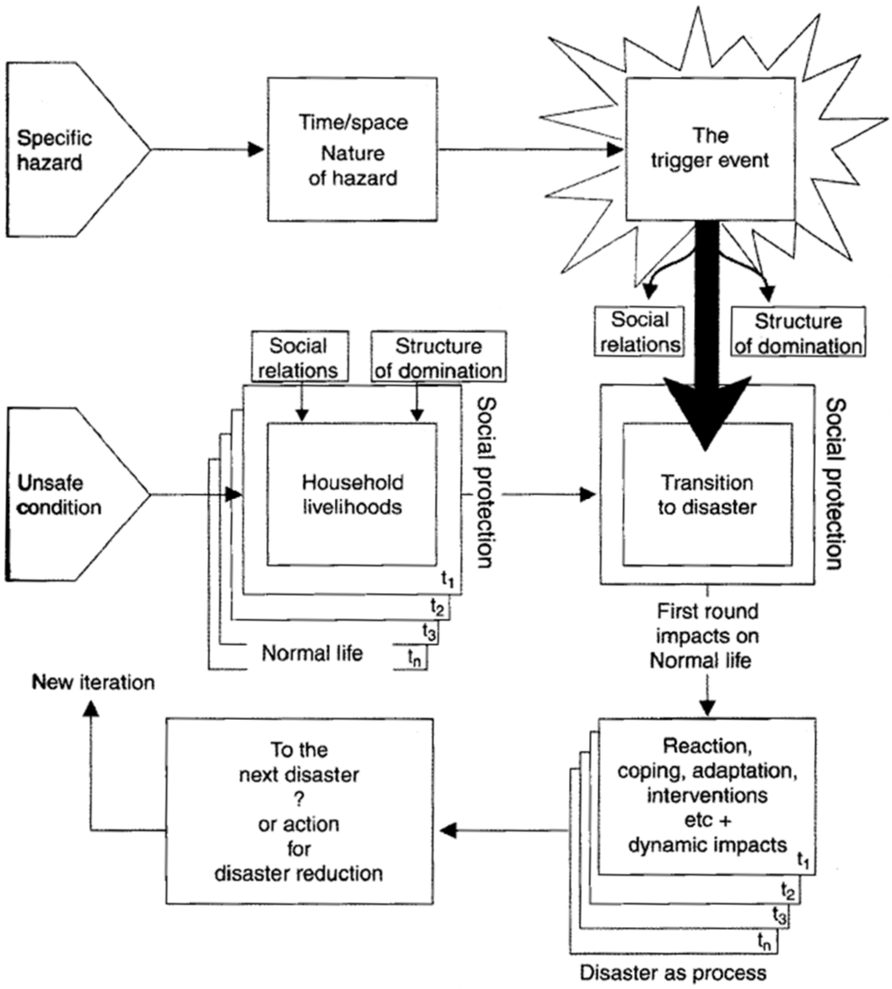

Figure 2.20: The Access model, complimentary to the Pressure and Release Model. Adapted from Wisner et al. (2004).

2.4.2.3 The Hazard of Place Model

The Hazard of Place model was developed over a number of years by Cutter (1996) based upon previous work by Hewitt and Burton (1971) and Cutter and Solecki (1989). Cutter explains that the hazard potential is ‘filtered’ through the social fabric (i.e. housing quality, ability to respond) to and the geographic context (i.e. proximity, site and situation) to determine social vulnerability and biophysical vulnerability respectively (Figure 2.21).

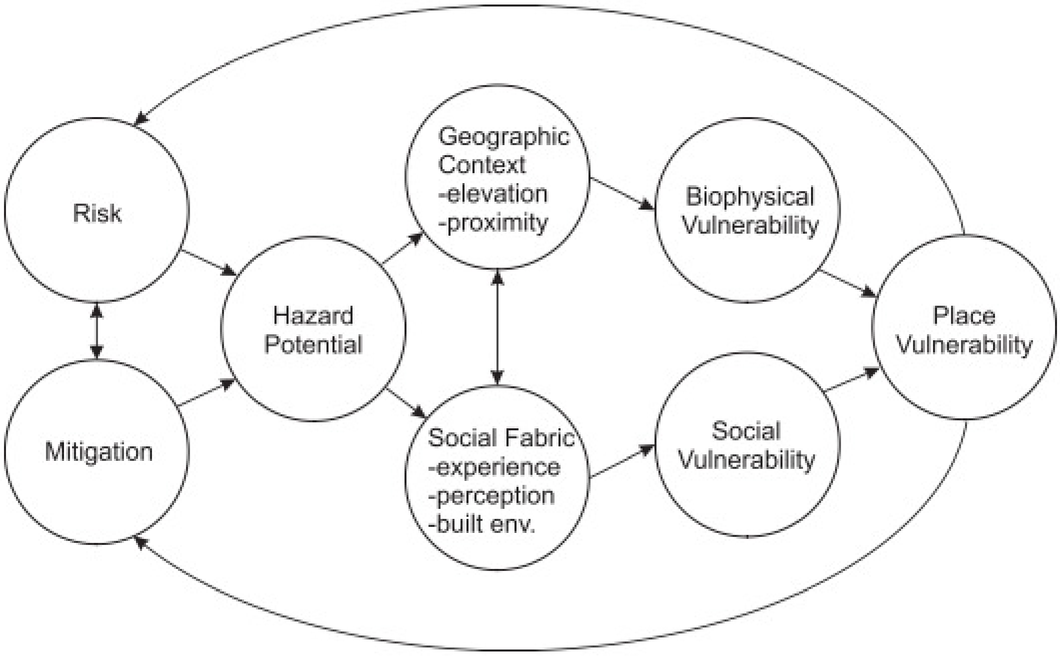

Figure 2.21: Hazards of Place model. Taken from Cutter (2003).

The model conceptualises that social vulnerability is the result of underlying social conditions which are ‘distant’ from the hazard, an idea shared in the Internal/External and PAR models. Cutter et al. (2003) explain how they used a number of socioeconomic indicators (taken from census data) to generate a social vulnerability index e.g. income, gender, age, rural/urban, and education, which are much simpler to assess than the ‘distant’ processes identified in the Internal/External and PAR models.

The biophysical vulnerability element of the model is a function of spatial proximity to the hazard (Alexander, 1993; Cutter, 1996) and is therefore dependent upon the spatial boundaries of where the hazard will/could occur. This is a similar concept to the “Dangerous Locations” aspect of unsafe conditions in the PAR model (Hufschmidt, 2011). Note that according to the Hazards of Place model, an individual or household can have a high social vulnerability, but if there is no biophysical vulnerability, there is no place vulnerability.

The place vulnerability is derived by combining the social and biophysical vulnerability elements. Place vulnerability then feeds back into risk and mitigation, to reflect the dynamic nature of vulnerability and account for changes in vulnerability over time. The model describes risk as the likelihood of occurrence of a hazard. When efforts are taken to reduce risk, via mitigation, the result is the overall hazard potential.

The terminology used within this model differs from other vulnerability models. Firstly, Cutter (1996: 536) describes risk as “the likelihood of occurrence”, which differs from the view that risk is a result of vulnerability interacting with the hazard (hazard x vulnerability). Secondly, the model uses the term biophysical vulnerability, however Wisner et al. (2003: 15) state they understand that vulnerability “refers only to people” and words such as susceptible, fragile, hazardous or hazard prone are more applicable when referring to non-human entities. Referring to non-human entities as vulnerable is common place in the literature e.g. Pelling (2003), and it can be difficult to understand who or what the author is referring to.

Nevertheless, the Hazard of Place Model is considered a good compromise between the various thoughts of vulnerability. If necessary it could potentially be integrated into the PAR model (in a similar way the Access model is included) to further assess how local scale aspects of vulnerability are manifested. The next model will explore the various components that vulnerability consists of in more detail, in order to assess local scale vulnerability.

2.4.2.4 Expanded Vulnerability Model

Based on the shortcomings of both the PAR and the Hazards of Place model, Turner et al. (2003) developed an expanded model of vulnerability for use in the sustainability/environmental change discipline. Turner et al. agree with the PAR model’s notion that vulnerability is the result of processes at multiple scales (spatial and temporal), resulting in varying degrees of vulnerability within a population. However, the PAR model is not suited to fully addressing the biophysical element of vulnerability and “*provides little detail on the structure of the hazard’s causal sequence*” (Turner et al., 2003: 8074). Turner et al. reviewed existing vulnerability models and concluded that vulnerability comprises a number of components such as entitlement, coping ability and resilience.

The concept of entitlement is similar to the idea of access to resources, i.e. the difference in the ability of people to access a resource (food, money, water, shelter etc.) during or after a hazard event explains why people are more sensitive to a hazard than others. Their entitlements can be social/human capital and endowments, or natural capital and biophysical endowments. Therefore, the entitlement concept can be seen as a person’s sensitivity to a hazard. Entitlements are also linked with ability to cope during or after a hazard event, and again are reliant on social and environmental entitlements, as well as political and economic. Coping ability also depends upon the proactive responses taken to avert harm in the first instance.

The resilience concept can be defined as "*the amount of change a given system can undergo…and still remain within the set of natural or desirable states*" (Turner et al., 2003: 8075). Resilience characteristics depend upon social, economic and political factors. Included within resilience is the concept of adaptive capacity, where society learns and responds to hazards based on past experience and/or new knowledge. The Expanded Model is the only model discussed here to include resilience as a key part of vulnerability.

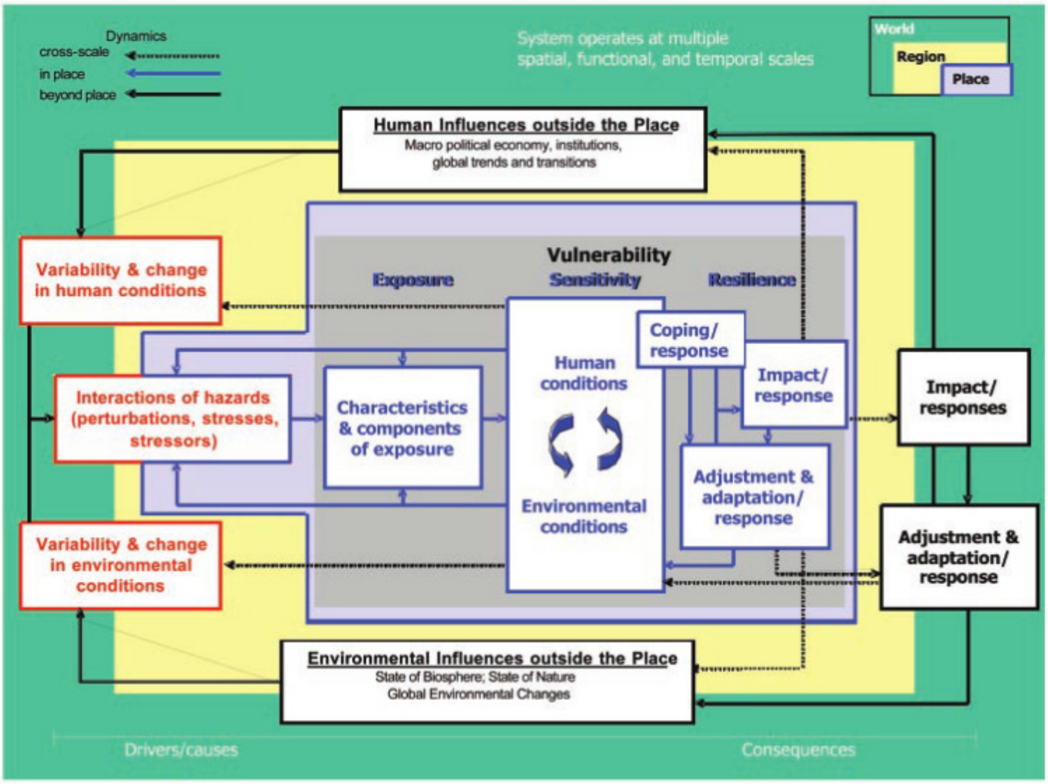

Figure 2.22: Expanded Model Framework. Taken from Turner et al. (2003).

The model Turner et al. propose is shown in Figure 2.22. Similar to the PAR model it operates at global, regional and place scales, and details how a diverse range of human and environmental processes ultimately contribute to the vulnerability of a place. The vulnerability of a place is explained in more detail within Figure 2.23 where the ideas of entitlement, coping and resilience are included along with the concept of exposure. The level of exposure depends upon the nature and characteristics of the hazard in question as well as the presence of an element at risk e.g. property. However, including exposure within this model as a component of vulnerability is problematic (Hufschmidt, 2011).

Including exposure within vulnerability could imply that if an individual is exposed, then a degree of vulnerability must exist. If resilience is high and sensitivity is low, then when an individual is exposed the harm will be insignificant. If we considered vulnerability as the capacity to be harmed, then in this instance vulnerability should not exist, despite exposure to the hazard. Treating vulnerability and exposure as separate entities removes the potential for misinterpretation, as it allows a degree of vulnerability to exist, even if there is no exposure and vice versa.

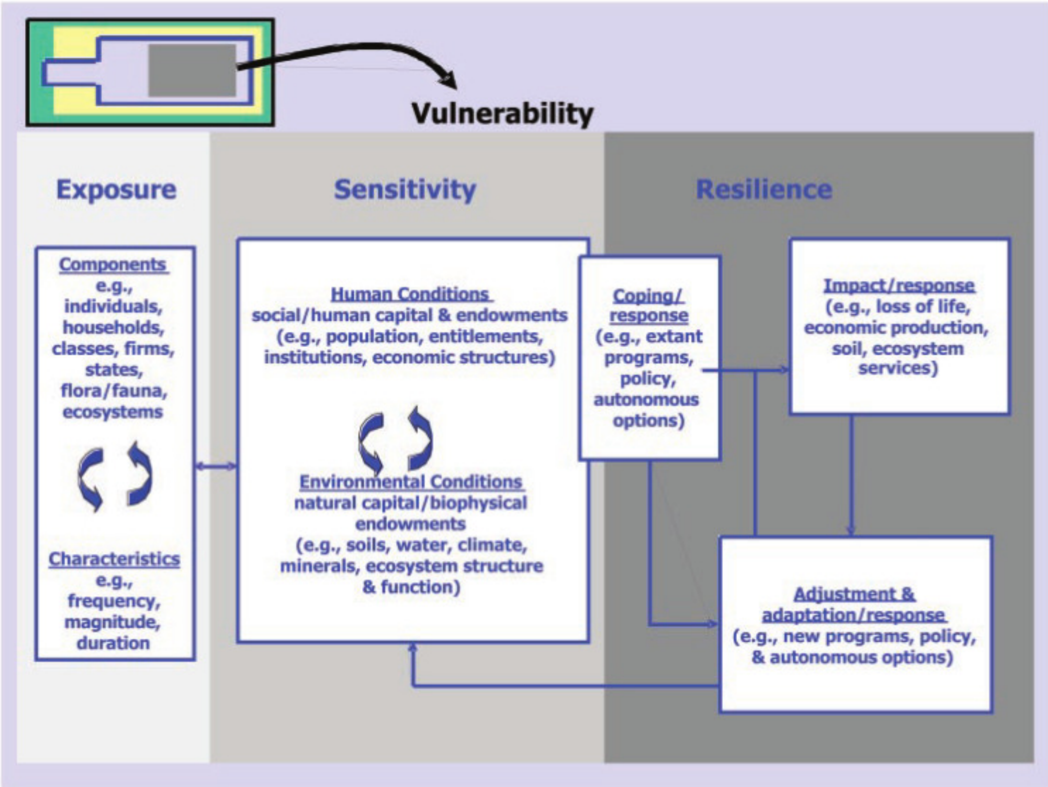

Figure 2.23: An expanded view of the place vulnerability from the Expanded Vulnerability Model. Taken from Turner et al. (2003).

It is recognised that a relationship between vulnerability and exposure is present, as being highly vulnerable may result in increased exposure. For example, an individual with low socioeconomic status may live in an area prone to flooding where property/rent is cheaper. This is an idea incorporated in the unsafe conditions aspect of the PAR model (Hufschmidt, 2011).

Additionally, when discussing risk, Hufschmidt (2011) state that including exposure in vulnerability can produce a conflict. As discussed previously the accepted definition of risk is 'hazard x vulnerability'. Hazard in the risk equation, refers to a process magnitude and the likelihood, of a specific hazard occurring. However, if exposure is included within vulnerability, the process magnitude is also included within vulnerability. Hence, when calculating risk, there is a double counting of the process magnitude factor. Therefore, when using vulnerability for assessing risk, exposure should not be included as a component of vulnerability.

Nevertheless, as a conceptual model for vulnerability the Expanded Vulnerability model is the most complete, and should be considered a good starting point when beginning to assess vulnerability. This is stated by Turner et al. who see this model as a template which should be reduced down into a form relevant for its intended use, but maintaining the notion that vulnerability is a consequence of multi-scale processes and actions.

2.4.2.5 Section Summary

From the models discussed in Section 2.4.2 it is possible to deduce a number of key concepts about vulnerability:

- The social, economic and political processes which ultimately determine vulnerability operate on vast and complex scales. These processes can be considered to be spatially, temporally and/or culturally 'distant' and are extremely difficult to quantify, both qualitatively and quantitatively.

- These processes eventually manifest themselves into unsafe conditions i.e. the current social, economic and political condition/state of an individual or household. The unsafe conditions of an individual or household that makes them more vulnerable can be identified using a number of indicators derived from datasets, such as census data.

- Vulnerability consists of a resilience and sensitivity component. Some models include exposure within vulnerability, but as ultimately vulnerability is to be used within the context of risk, exposure is best considered outside of vulnerability.

- The interaction of individuals/households with a hazard will determine the disaster risk. However, the extent of this interaction i.e. the exposure, depends on local physical factors such as proximity to the hazard, elevation etc. With exposure not considered as an element of vulnerability, it is possible to be exposed to a hazard but not be harmed if vulnerability is sufficiently low.

- Therefore, a vulnerability assessment needs to consider both the physical and socioeconomic context of vulnerability. This should be at the local scale where the unsafe conditions can be easily identified and explored. For management it is important to remember that vulnerability is the result of large scale processes, and therefore vulnerability management can potentially occur locally and/or nationally, and seek to reduce exposure and sensitivity or increase resilience.

To make best use of this information, the various vulnerability concepts need to be distilled into a working model of vulnerability. The next section will therefore outline a working approach for assessing vulnerability and define the associated terminology that will be used throughout the remainder of this thesis.

2.4.3 Vulnerability and Risk: A Working Approach

As discussed previously, there are numerous definitions for vulnerability and risk within the literature. Therefore, to reduce confusion with regards the terminology and the understanding of conceptual ideas, vulnerability and risk will be defined in this section.

The workflow shown in Figure 2.24 summarises the vulnerability literature, and is based upon the work of Cutter (1996), Turner et al. (2003), and Wisner et al. (2004). The form of the workflow is based upon the ideas of the Hazards of Place model, with the geographic (here altered to geomorphological) and socioeconomic context separated and the various stages involved in conducting a vulnerability or risk assessment in sequence. This workflow represents the approach used to inform and structure the methodology, hence it is best considered prior to the methods, rather than within the methodological chapter.

The model begins with the *Hazard Potential,* which can be considered as the likelihood of a hazard event (natural, technological or human induced event) occurring and the degree of harm to an individual or household. The hazard potential has a *Geomorphological Context*, which explores the differential impacts of a hazard depending on the spatial location e.g. elevation, geology, proximity to the hazard. The geomorphological context consists of two components *sensitivity* and *resilience*, which are combined to form *physical susceptibility*.

Using the physical susceptibility, *Exposure* can be derived by including an asset that would be threatened by a hazard (Hollenstein, 2005). A threatened asset could be social (e.g. a person), economic (e.g. property, transport infrastructure), cultural (e.g. archaeological sites) or environmental (e.g. beaches, forestry, saltmarsh).

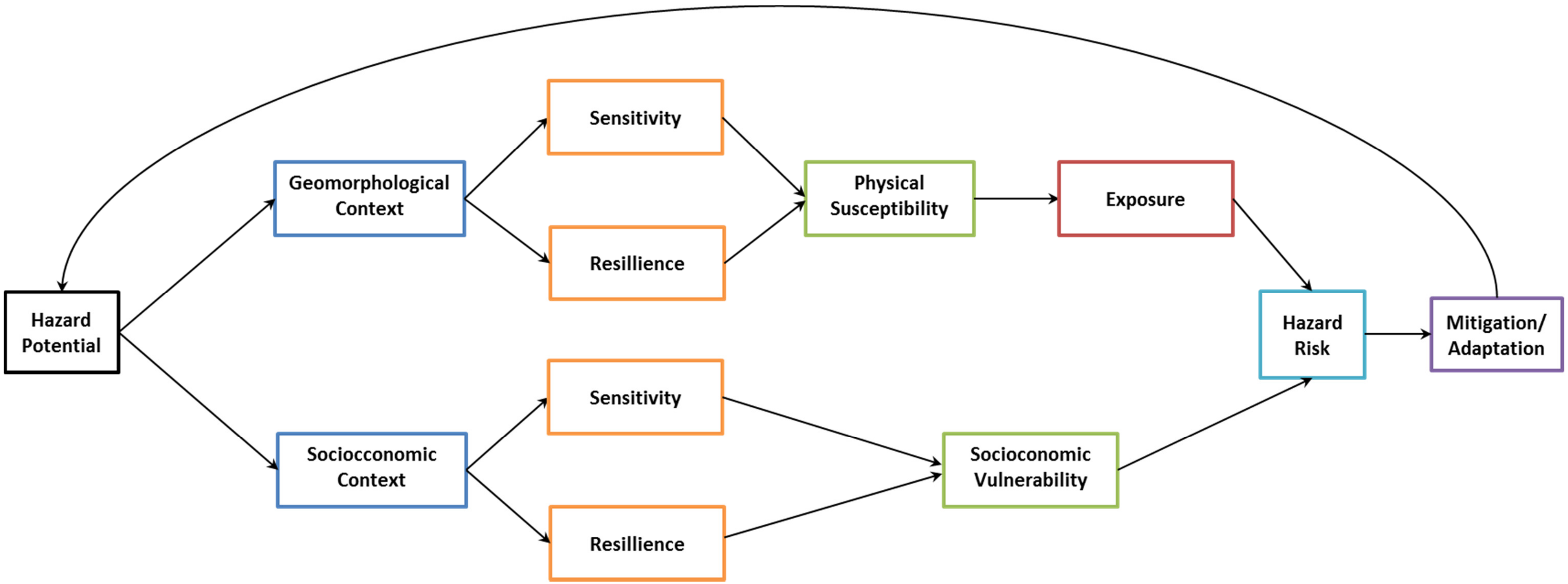

Figure 2.24: Vulnerability and Risk model used throughout this thesis. Based upon the work of Cutter (1996) and Wisner et al. (2004).

The *Socioeconomic Context* addresses the human element of the hazard potential and aspects such as income, education, health etc. are considered. Based upon the work by Turner et al. (2003) the socioeconomic context can be seen to mirror the geographic context and has two components; *sensitivity* and *resilience*. Socioeconomic sensitivity can be defined as the degree to which an individual/household would be affected if they were exposed to a hazard e.g. an individual with a mobility disability would be more sensitive than an able bodied individual if evacuation was required. Socioeconomic resilience can be defined as the "*amount of change a given system can undergo…and still remain within the set of natural or desirable states*" (Turner et al., 2003). For example, if an individual is flooded, they may have access to money and/or insurance allowing a quick recovery from the impacts (e.g. repair damage, relocate etc.). Within socioeconomic resilience is the concept of *adaptive capacity,* which can be considered as the ability to modify behaviour or social, political or economic characteristics in order to increase the ability to cope with a hazard e.g. installing flood barriers across doorways. Therefore, *socioeconomic vulnerability* can be defined as "*the extent to which a person…is likely to be affected by a hazard (related to their capacity to anticipate it, cope with it, resist it and recover from its impact)*" (Twigg, 2001, p6). Hence, vulnerability is independent of geographical extent of the hazard at this stage (Allen, 2003; Brooks, 2003).

The outcome of combining the socioeconomic vulnerability and exposure is *hazard risk* (i.e. this brings the element of the geographical extent of the hazard into the vulnerability analysis). This can be considered as the interaction of a vulnerable individual/household with the likely spatial attributes of a hazard e.g. high flood risk would be where an area highly likely to flood intersects with the location of highly vulnerable people. Once the hazard risk has been determined, measures to reduce this hazard risk by the means of M*itigation* and *Adaptation* can be implemented. This can be either by reducing the physical susceptibility or reducing the socioeconomic vulnerability (by increasing resilience and/or decreasing sensitivity). Therefore, the hazard potential is the product of hazard risk and the mitigation measures enacted to reduce this risk. The model is cyclical, demonstrating that once mitigation has taken place, the hazard potential is continually reassessed to take into account the temporal and spatial changes in susceptibility and vulnerability.

The model outlined here should not be considered as a replacement for the models discussed previously. It is the distillation of the models and ideas of vulnerability and risk into a useable, practical, and workable modelling approach. It therefore represents the thought processes behind the research methodology proposed within this thesis.

2.4.4 Calculating Socioeconomic Vulnerability

As discussed in the previous section it is important to assess vulnerability in order to manage the impacts of natural hazards. There are a number of methods that allow socioeconomic vulnerability to be assessed at national to local scales (e.g. Bjarnadottir et al., 2011; Cutter et al., 2003; Felsenstein & Lichter, 2013; McLaughlin & Cooper, 2010; Rygel et al., 2006; Wu et al., 2002). The identification of socioeconomically vulnerable people within this research is based upon using geodemographic classifications. Geodemographic classification is a way to "*organise [spatial] areas into categories sharing similarities across multiple socioeconomic attributes*" (Singleton and Spielman, 2013: 558). In simple terms, it suggests that where you live, says something about who you are and how you live your life (Harris et al., 2005). The history, development, their current use, and reliability will be discussed further, as well as an analysis of which factors increase socioeconomic vulnerability.

2.4.4.1 History of Geodemography

The first example of geodemographies can be traced back to Charles Booth's (1886) Descriptive Map of London Poverty, which he revised in 1898 (Harris et al., 2005). An example of Booth's map is shown in Figure 2.25.

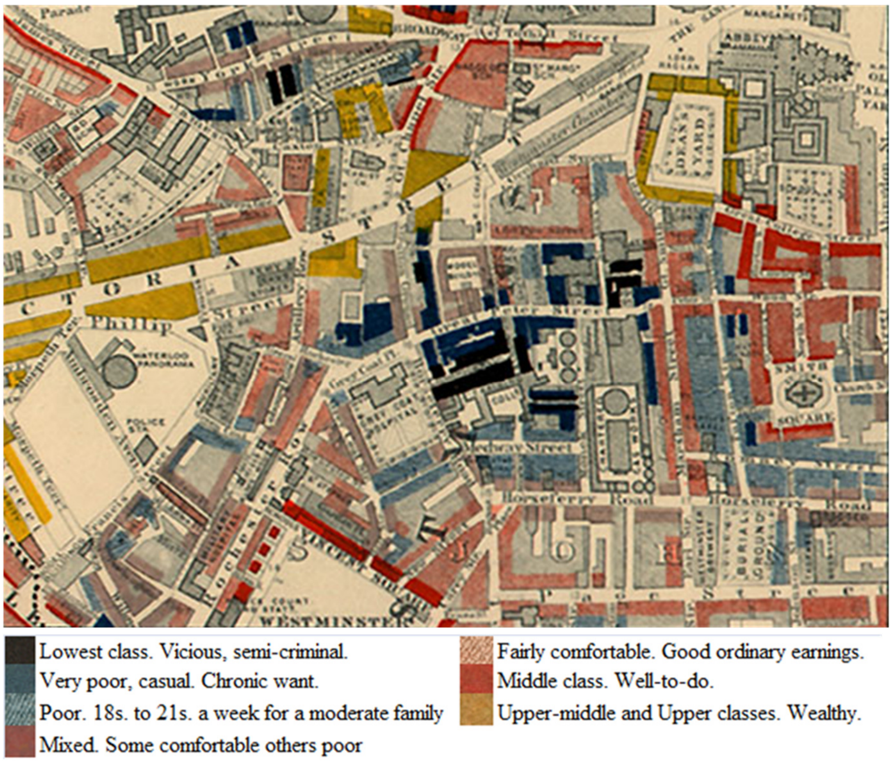

Figure 2.25: An example of the map produced by Booth (1898) to identify the distribution of different socioeconomic groups within London. Definitions of groups are found in Table 2.14.

The data used by Booth were school board representatives who visited households on each street with school age children and noted various information (Harris et al., 2005). Based upon these data each street could be classified into neighbourhood types (Booth, 1902). The classification used is shown in Table 2.14. Harris (2005) note that Booth's classification differs from modern geodemographies in that Booth allowed the same street to be classified into more than one classification, modern geodemographies employ a mutually exclusive rule. Booth therefore acknowledged that within "wealthy neighbourhoods" pockets of poverty could exist, and vice versa.

Table 2.14: Neighbourhood classifications used by Booth (1902). Taken from Harris (2005)

Colour	Description	Class	Description
Black	The lowest grade (corresponding to Class A), inhabited principally by occasional labourers, loaders and semi-criminals - the elements of disorder	A	The lowest class - occasional labourers, loafers, and semi-criminals
Dark Blue	Very poor (corresponding to Class B), inhabited principally by casual labourers and others living from hand to mouth	B	The very poor - casual labour, hand-to-mouth existence, chronic want
Light Blue	Standard poverty (corresponding to Classes C and D) inhabited principally by those whore earning are small (say 18 s to 21 s a week for a moderate family), whether they are so because of irregularity of work (C) or because of low rate of pay (D)	C and D	The poor - including alike those whose earnings are small, because of irregularity of employment and those whose work, though regular, is ill-paid
Purple	Street mixed with poverty (usually C and D with E and F, but including Class B in many cases)	E and F	The regular employed and fairly paid working class of all grades
Pink	Working class comfort (Corresponding to Classes E and G, but containing also a large proportion of the lower middle class of small tradesman and Class G).	G and H	Lower and upper middle class and all above this level
Red	Well-to-do; inhabited by middle-class families who keep one or two servants		
Yellow	Wealthy; hardly found in East London and little found in South London; inhabited by families who keep three or more servants and whose houses are rated at £100 or more		

The work of Booth heavily influenced the research direction of human ecologists, particularly within the United States (Harris et al., 2005; Pfautz, 1967). A substantial amount of research took place at the 'Chicago School', with one of the most well-known outputs being Burgess' concentric ring urban system model published in 1925 (Figure 2.26). This model is not a true geodemographic model as it represents an urban process of immigration to Chicago, rather than a static classification of neighbourhood types. However, urban processes can be inferred from a model showing geodemographic neighbourhood distribution (Harris et al., 2005).

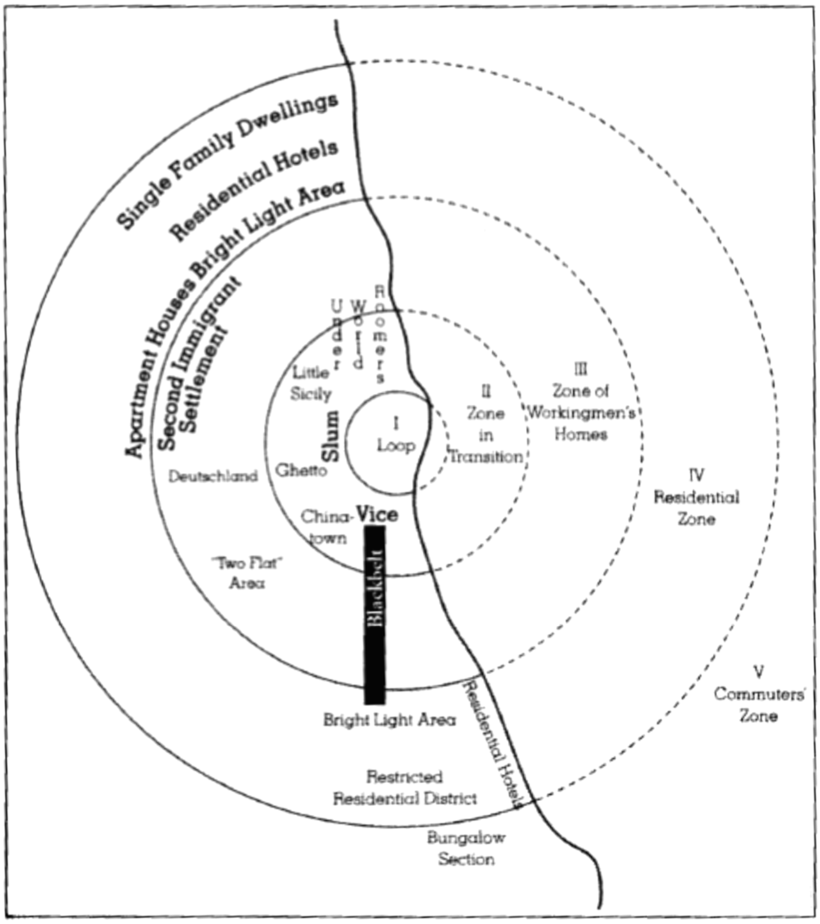

Figure 2.26: Concentric ring model of 1920's Chicago. Loop is the central business district, and the line bisecting the circle is the shore of Lake Michigan. Original from Burgess (1925), but taken from Gottdiener and Hutchinson (2011: 63).

Increasing availability of US Census data led to the publication of social area analysis research, with key works being Shevky & Williams (1949) which focussed upon Los Angeles, and Shevky & Bell (1955) which expanded on the theory of social area analysis. Shevky & Williams used US Census data to create three indices (using one to three census variables) which measured economic, family and ethnic status within an area (Harris et al., 2005). However, when the methodology was applied to a wider range of cities the original census variables, which were applicable to Los Angeles, provided unsatisfactory results in other locations. Nevertheless, with the advancement of computing technology in the 1960s researchers were able to include more variables into their methodology and use more complex factor analysis to derive common underlying factors (Hutchinson, 2010). This led to the development of the term factorial ecology (Berry and Kasarda, 1977).

Within the UK, census data were available at enumeration district (ED) level, the units used to collect census data, from 1951 onwards (Harris et al., 2005). The 1961 Census was analysed by Howard (1969), who used principle component analysis (PCA) and least-squared cluster analysis to classify inner London into six categories (Upper Class, Bed Sitter, Poor, Stable Working Class, Local Authority Housing, and Almost Suburban). A similar study was produced for Liverpool to identify areas with social problems within the city (Liverpool City Council, 1969). Following on from local scale analysis, Webber in the 1970s produced a national classification scheme related to postcodes (Webber and Craig, 1978; Webber, 1978, 1977). Along with the development of Geographic Information Systems (GIS) and the realisation of the commercial possibilities of geodemographies, the sector continued to grow, and within the UK there are now 10 major geodemographic classifications available (Table 2.15).

Table 2.15: General purpose geodemographic classifications available within the UK. The number of levels refers to the number of socioeconomic classifications within each level (the classifications are often hierarchical in structure, with level two classifying areas assigned a level one classification into further socioeconomic classifications, and so on). Adapted from Singleton and Spielman (2013).

Name	Level 1	Level 2	Level 3	Micro level	Variables	Taxonomic units
Output area classification, Office for National Statistics	7	21	52		41	Output areas
P2 People and Places, Beacon Dodsworth	14	41		157	~ 80	Output areas
Mosaic, Experian	15	67		252	440	Unit postcode
Acorn, CACI	5	17	56		~ 400	Unit postcode
Cameo, Callcredit Information Group	10	58				Unit postcode
Cloud Client, Cloud Client Ltd.	15				29	Output area
Sonar, Redmoran	6	24	80		225	
Censation, Maw Data Solutions	5	19	53		600	Output area
Personicx Geo, Acxiom	60				~ 400	Postcode
Citizen, Marketing Metrix	6	28				Postcode

2.4.4.2 Uses of Geodemographies

Geodemographic databases are primarily used commercially for marketing purposes (Figure 2.27). These include market research, market analysis, advertising and direct marketing (Curry, 1993; Harris et al., 2005; Sleight, 1997; Webber, 1985). Within the public sector the use of geodemographies has been relatively minor (Harris et al., 2005). However, more recently the Office for National Statistics has produced area classifications using the 2001 and 2011 census data for England and Wales (ONS, 2014). Within Scotland, the Government has produced a Scottish Index of Multiple Deprivation (SIMD) database, with the most recent version produced using 2012 data. Governments use information derived from the SIMD to aid decision making and government spending in a range of policy areas such as employment, health, education, crime, and housing.

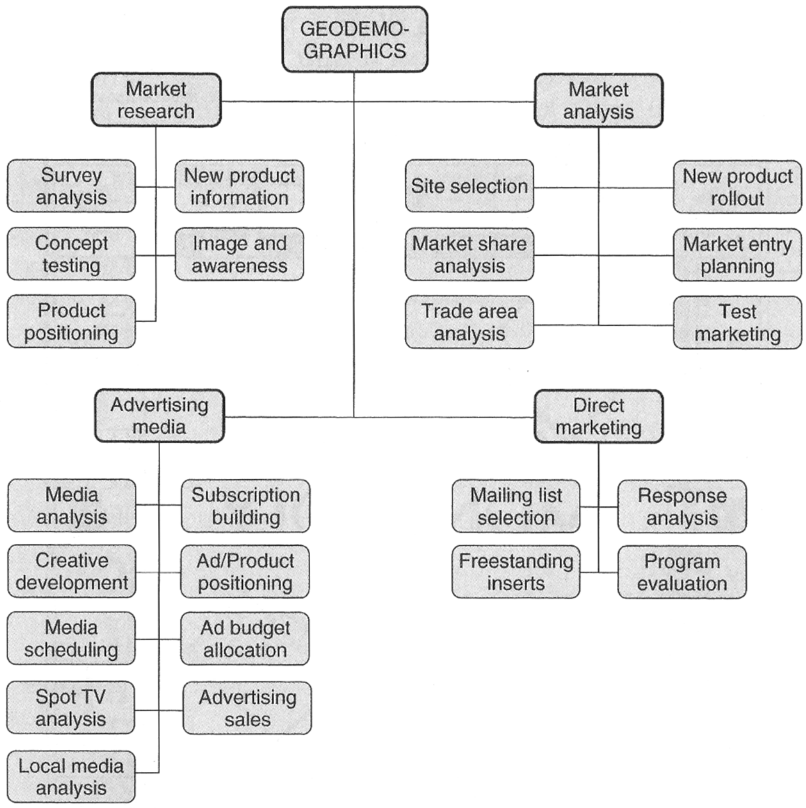

Figure 2.27: Commercial Applications of geodemographic databases. Taken from Harris et al. (2005).

Within academia, geodemographies are used by a number of research disciplines (Figure 2.28). Singleton & Spielman (2013) collected the data for Figure 2.28 by classifying the results of searches within Google Scholar and Scopus in June 2012 for the terms geodemographics, geodemography and the names of UK and US classification products. Within the UK, geodemographies are used mostly within the 'Health/Well Being' research domain (25 out of 68 references), with 'Education' being the second (11 out of 68 references). There are a number of references classified within the 'Environment/Resource Management' research domain which is the intended use of geodemographies within this thesis. Three publications which use geodemographies are worthy of further discussion here; Cutter et al. (2003); Tomlinson et al. (2011); and Willis et al. (2010).

Cutter et al. (2003) used 1990 Census data at the counties level to assess social vulnerability to potential environmental hazards within the United States. Using a factor analytic methodology, 42 variables were reduced to 11 independent factors, a very similar approach used by the factorial ecologists approach mentioned earlier. The 11 factors and the dominant variables used within the research are shown in Table 2.16. Even though Cutter et al. do not use a commercial geodemographic classification, it is still of importance as it demonstrates a methodology that can be repeated for any area where census data is available, and additionally highlights the factors which can influence vulnerability with regards to environmental hazards.

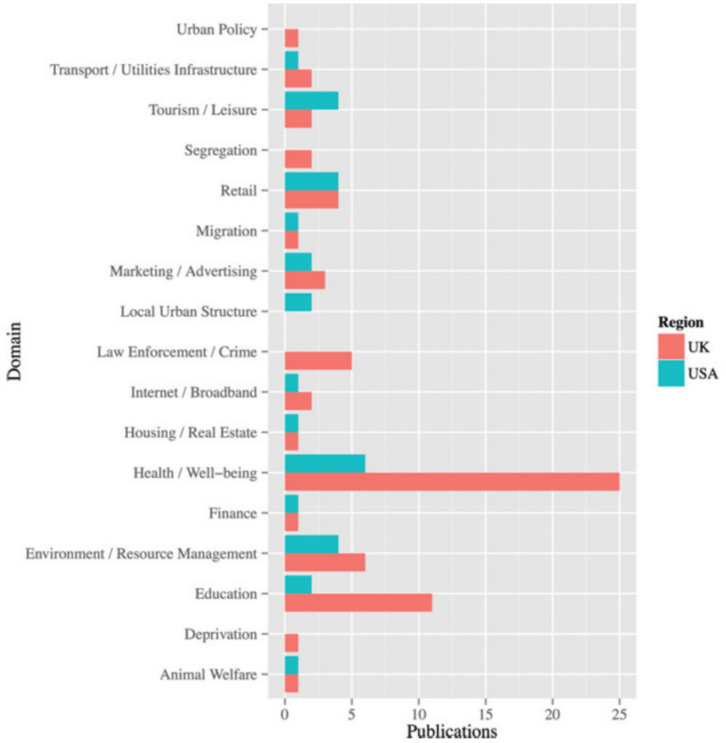

Figure 2.28: The academic applications of geodemographic systems in the United Kingdom and United States. Taken from Singleton and Spielman (2013).

Table 2.16: Dimensions of social vulnerability used by Cutter et al. (2003) to estimate social vulnerability to environmental hazards. Taken from Cutter et al. (2003).

Factor	Name	Percent Variation Explained	Dominant Variable	Correlation
1	Personal wealth	12.4	Per capita income	+0.87
2	Age	11.9	Median age	−0.90
3	Density of the built environment	11.2	No. commercial establishments/mi^2	+0.98
4	Single-sector economic dependence	8.6	% employed in extractive industries	+0.80
5	Housing stock and tenancy	7.0	% housing units that are mobile homes	−0.75
6	Race—African American	6.9	% African American	+0.80
7	Ethnicity—Hispanic	4.2	% Hispanic	+0.89
8	Ethnicity—Native American	4.1	% Native American	+0.75
9	Race—Asian	3.9	% Asian	+0.71
10	Occupation	3.2	% employed in service occupations	+0.76
11	Infrastructure dependence	2.9	% employed in transportation, communication, and public utilities	+0.77

The research of Tomlinson et al. (2011) uses a commercial geodemographic product in the form of the Experian Mosaic 2009 to assess vulnerability to urban heatwaves in Birmingham, UK. Using the Mosaic database they identified the neighbourhood classifications where elderly people and/or ill people predominate (as these are the people who are most vulnerable to heatwaves). Using GIS and Ordnance Survey MasterMap data, the authors also identified those who live in high population density areas, and those living in high rise flats. Once the vulnerability model was produced, it was combined with an urban heatwave exposure model to produce a final risk model (Figure 2.29). By combining both physical and social data it is possible to inform decision making with regards environmental hazard management. By using a geodemographic product that is available in over 29 countries (Experian, 2009) Tomlinson and others have developed a methodology that can be potentially adapted for use in other countries to assess heatwave vulnerability.

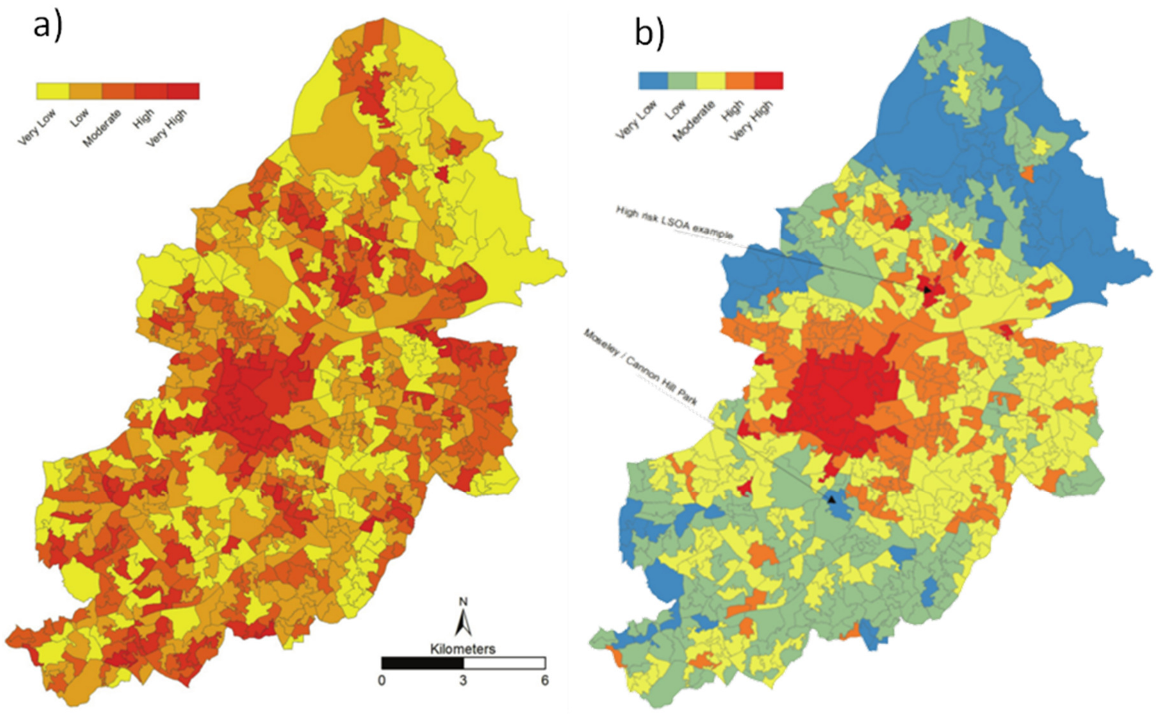

Figure 2.29: a) a vulnerability to heatwaves model for Birmingham, UK derived from Experian Mosaic database (Red = High Vulnerability, Yellow = Low Vulnerability) b) The vulnerability model combined with the heatwave exposure model to produce a final heatwave risk model (Red = High Risk, Blue = Low Risk). Taken from Tomlinson et al. (2011).

It is not solely heatwave vulnerability that can be assessed using the Experian geodemographies. Using the Italian version of Experian Mosaic, Willis et al. (2010) assessed vulnerability to volcanic eruptions around Mount Vesuvius in Italy. From the Mosaic database a total of seven variables were identified which represent various components of vulnerability to volcanic eruptions, such as age, building type, and daily movement. The authors used a range of statistical methods (Lorenz curves and Gini coefficients) to weight the variables in the final vulnerability model. The vulnerability model is then combined with a physical exposure model for Vesuvius eruptions to generate a risk model. The use of a commercial product allows the methodology for calculating vulnerability to be applied to different environmental hazards and therefore, brings a level of consistency between vulnerability models for different areas/countries. In addition, as the methodology has been established within the literature, it simplifies the modelling of vulnerability, and can therefore be easily used within a range of research disciplines. Currently, however, no socioeconomic vulnerability assessment specific to coastal erosion has been performed for Scotland.

2.4.4.3 Reliability

With any method of averaging and classifying of society there will be concerns about whether the geodemographic classifications fairly represent the real-life situation. The shortcomings of geodemographies were noted by Booth within his Descriptive Map of London Poverty (1889) research, who realised that geodemographies is a method of highlighting only the average socioeconomic attributes of an area (Harris et al., 2005). Consequently, the methodology Booth used allowed him to assign more than one geodemographic group to an area. Harris and Johnston (2003) state this is of particular importance when identifying deprivation by governments in order to allocate funding. Within an area unit (e.g. census unit, postcode, or street) not classified as ‘deprived’ may still have within it ‘deprived’ households, and therefore government funding aimed at alleviating poverty may not always be assigned to the correct locations. This problem can be termed an ‘ecological fallacy’ and can be defined as:

> “*the false assumption that knowledge of the general characteristics of a neighbourhood will always yield accurate and precise information about specific individuals…within those neighbourhoods*” (Harris et al., 2005: 33)

Related to the ecological fallacy issue is the modifiable area unit problem (MAUP) which is of particular relevance when dealing with socioeconomic data (Wise and Craglia, 2008). A modifiable area unit is a method used to aggregate data from a small area into a larger area to simplify analysis. For example, data collected from individual houses can be averaged and represented at postcode level. The problem arises as socioeconomics is a continuous geographical phenomena and by imposing artificial units (e.g. postcodes) to report the data may result in artificial spatial patterns (Heywood et al., 1998).

Dark & Bram (2007) describe the two components of the MAUP: the effects of aggregation and the effects of zoning systems. With aggregation of small areal units into larger units, the variation of the data decreases, potentially affecting further statistical analysis (Figure 2.30, a-c). The zoning component is the variation in results a consequence of using different areal units; even though they are of similar scales (Figure 2.30, d-f).

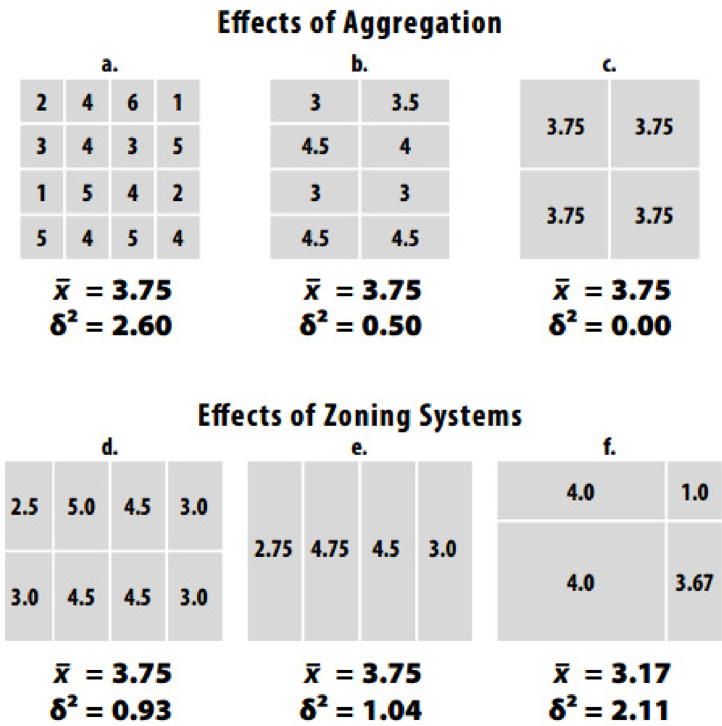

Figure 2.30: (a-c) In these figures the mean value does not change with aggregation, but the variance declines. In (d-f) the units have been aggregated into zones with varying orientations of the cardinal directions. For d and e there is no change in the mean, but the variance changes substantially. Taken from Dark & Bram (2007).

Despite the potential problems outlined above, geodemographies have been heavily used within the marketing industry (Table 2.17). The reason for this, according to Harris et al. (2005), is because they have been used in a variety of ways and produced successful results. There is a lack of literature that evaluates the accuracy and precision of geodemographics. However, one such assessment took place in Luton, UK. Leventhal (2005) describes how, in 1995, the Market Research Society set up a working party to assess whether geodemographic classification sufficiently predict how market consumption rates vary by geography. The research concluded that the geodemographic systems did sufficiently discriminate consumption patterns between neighbourhoods.

The limitations of geodemographies, however, do not deter their use for a wide range of academic and industrial applications. The small areal units (e.g. household, postcode) compared to census output area data allows accurate local scale vulnerability assessments to be generated. Use of geodemographics as part of environmental management is a relatively new development. However, their use will likely grow as they can be adapted to an extensive range of potential end uses.

Table 2.17: Examples of the businesses that have used geodemographies for target marketing campaigns in the UK. Taken from Harris et al. (2005).

Group/affiliation	Brand	Product
Brighthouse	Brighthouse	Retailer
Camelot	Lotto	Lottery
Centura Foods	Bisto	Gravy Mix
Centura Foods	Paxo	Stuffing Mix
Colgate-Palmolive	Colgate	Toothpaste
Reckitt Benckiser	Calgon	Calcium eliminator
Jacobs Bakery Ltd	Jacobs Cream Crackers	Biscuits
Lever Fabergé	Arctic Breeze	Air freshener
Lever Fabergé	Persil	Washing detergent
Marks and Spencer	Marks and Spencer	Luggage
Nestlé	Branston Smooth	Pickle
Nestlé	Cross and Blackwell Snackstop	Snack foods
Ocado Ltd	Ocado	Online Shopping
Reckitt Benckiser	Airwick	Air freshener
Seasons Holidays PLC	Seasons Holiday	Holidays
TUI	Thomas Cook	Holidays
Tussauds Group	Thorpe Park and Chessington World of Adventures	Theme Parks
Unilever Bestfoods	Flora Proactiv	Spread
Unilever Bestfoods	Bertolli	Olive Oil
Virgin Group	Virgin Holidays	Holidays
Warner	Warner Holidays	Holidays

2.4.4.4 Factors Influencing Social Vulnerability

In Section 2.4.2 it was stated that people become vulnerable due to a combination of global, regional and local scale processes. However, in order to assess social vulnerability at the local scale, indicators that manifest as a result of these broad processes need to be identified. The relevance of an indicator to vulnerability depends upon the nature of the hazard in question. For example, for a hurricane hazard car ownership may be an important factor as it related to the ability for evacuation. However, for an earthquake hazard, this is not necessarily as important. Cutter et al. (2003) identified the indicators relevant to unspecific US environmental hazards (Table 2.18). The rationale for including each indicator is shown in the Table 2.18, as well as the academic sources on which they are based.

Table 2.18: Indicators which can be used to identify social vulnerability to environmental hazards in the US. Adapted from Cutter et al. (2003).

Concept	Description	Increases (+) or Decreases (-) Social Vulnerability
Socioeconomic status (income, political power, prestige)	The ability to absorb losses and enhance resilience to hazard impacts. Wealth enables communities to absorb and recover from losses more quickly due to insurance, social safety nets, and entitlement programs. **Source:** Burton et al. (1993), Cutter et al. (2000), Hewitt, (1997), Peacock et al. (1997), Platt (1999), and Puente (1999)	High status (+/-) Low income or status (+)
Gender	Women can have a more difficult time during recovery than men, often due to the sector-specific employment, lower wages, and family care responsibilities. **Source:** Cutter (1996), Enarson & Morrow (1998), Enarson & Scanlon (1999), Fothergill (1996), Hewitt (1997), Morrow & Phillips (1999), and Peacock et al. (1997)	Gender (+)
Race and ethnicity	Imposes language and cultural barriers that affect access to post-disaster funding and residential locations in high hazard areas **Source:** Bolin and Stanford (1998), Bolin (1993), Peacock et al. (1997), and Pulido (2000)	Non white (+) Non Anglo (+)
Age	Extremes of the age spectrum affect the movement out of harm's way. Parents lose time and money caring for children when day-care facilities are affected; elderly may have mobility constraints or mobility concerns increase the burden of care and lack of resilience. **Source:** Cutter et al. (2000), Hewitt (1997), Ngo (2001), O'Brien & Mileti (1992)	Elderly (+) Children (+)
Commercial and industrial development	The value, quality, and density of commercial and industrial buildings provide an indicator of the state of economic health of a community, and potential losses in the business community and loner-term issues with recovery after an event. **Source:** Heinz Center for Science Economics and the Environment (2000), and Webb et al. (2000)	High Density (+) High value (+/-)
Employment loss	The potential loss of employment following a disaster exacerbates the number of unemployed workers in a community, contributing to a slower recovery from the disaster. **Source:** Mileti (1999)	Employment loss (+)
Rural/Urban	Rural residents may be more vulnerable due to lower incomes and more dependent on locally based resource extraction economies (e.g. farming, fishing). High-density areas (urban) complicate evacuation out of harm's way. **Source:** Cova & Church (1997), Cutter et al. (2000), and Mitchell (1999)	Rural (+) Urban (+)
Residential property	The value, quality, and density of residential construction affects potential losses and recovery. Expensive homes on the coast are costly to replace; mobile homes are easily destroyed and less resilient to hazards. **Source:** Bolin and Stanford (1991), Cutter et al. (2000), and Heinz Center for Science Economics and the Environment (2000)	Mobile Homes (+)

Concept	Description	Increases (+) or Decreases (-) Social Vulnerability
Infrastructure and lifelines	Loss of sewers, bridges, water, communications, and transportation infrastructure compounds the potential disaster losses. The loss of infrastructure may place an insurmountable financial burden on smaller communities that lack the financial resources to rebuild. **Source:** Heinz Center for Science Economics and the Environment (2000), and Platt (1995)	Extensive infrastructure (+)
Renters	People that rent do so because they are either transient or don't have the financial resources for home ownership. They often lack access to information about financial aid during recovery. In the most extreme cases, renters lack sufficient shelter options when lodging becomes uninhabitable or too costly to afford. **Source:** Heinz Center for Science Economics and the Environment (2000) and Morrow (1999)	Renters (+)
Occupation	Some occupations, especially those involving resource extraction, may be severely impacted by a hazard event. Self-employed fisherman suffer when their means of production is lost and may not have the requisite capital to resume work in a timely fashion and thus will seek alternative employment. Those migrant workers engaged in agriculture and low-skilled service jobs (housekeeping, childcare, and gardening) may similarly suffer, as disposable income fades and the need for services declines. Immigration status all affects occupational recovery. **Source:** Heinz Center for Science Economics and the Environment (2000), Hewitt (1997), and Puente (1999)	Professional or managerial (-) Clerical or labourer (+) Service sector (+)
Family Structure	Families with large numbers of dependents or single-parent households often have limited finances to outsource care for dependents, and thus must juggle work responsibilities and care for family members. All affect the resilience to and recovery from hazards. **Source:** Heinz Center for Science Economics and the Environment (2000), Morrow (1999), and Puente (1999)	High birth rates (+) Large families (+) Single Parent households (+)
Education	Education is linked to socioeconomic status, with higher educational attainment resulting in greater lifetime earnings. Lower education constrains the ability to understand warning information and access to recovery information. **Source:** Heinz Center for Science Economics and the Environment (2000)	Little education (+) Highly educated (-)
Population growth	Counties experiencing rapid growth lack available quality housing, and the social services network may not have had time to adjust to increased populations. New migrants may not speak the language and not be familiar with bureaucracies for obtaining relief or recovery information, all of which increase vulnerability. **Source:** Cutter et al. (2000), Heinz Center for Science Economics and the Environment (2000), Morrow (1999), and Puente (1999)	Rapid Growth (+)
Medical services	Health care providers, including physicians, nursing homes, and hospitals, are important post-event sources of relief. The lack of proximate medicals services will lengthen immediate relief and longer-term recovery from disasters. **Source:** Heinz Center for Science Economics and the Environment (2000), Hewitt (1997), and Morrow (1999)	Higher density of medical services (-)

Concept	Description	Increases (+) or Decreases (-) Social Vulnerability
Social dependence	Those people who are totally dependent on social services for survival are already economically and socially marginalised and require additional support in the post-disaster period. **Source:** Drabek (1996), Heinz Center for Science Economics and the Environment (2000), Hewitt (2000), and Morrow (1999)	High dependence (+) Low dependence (-)
Special needs populations	Special needs populations (infirm, institutionalised, transient, homeless), while difficult to identify and measure, are disproportionately affected during disasters and, because of their invisibility in communities, mostly ignored during recovery. **Source:** Morrow (1999), and Tobin and Ollenburger (1993)	Large special needs population (+)

The indicators listed in Table 2.18 all support the idea that people who are on the margins of society are likely to be the most vulnerable. However, if we consider the indicators identified by Cutter and others (2003) within the context of a coastal erosion hazard, then they are not all applicable. In fact, for three of the indicators that Cutter et al. indicate as increasing vulnerability, it could be argued that they would decrease vulnerability with respect to a coastal erosion hazard. These indicators are:

- *Rural/Urban*: living in an urban environment complicates the evacuation procedure; however mass evacuation does not often occur with coastal erosion hazards. In fact living in an urban area can decrease vulnerability to coastal erosion as coastal defences are often situated where they are most cost effective i.e. where they protect the most assets. In addition, urban areas by their nature have more people; therefore they have greater political influence than in rural areas and can therefore put pressure on politicians to act on their behalf to protect their properties;

- *Renters*: people rent do so because they lack the financial means to purchase a property. However, if your property is exposed to coastal erosion it is highly likely that the property will lose a significant part, if not all, of its value. Therefore, there is a benefit to not having assets tied up in property. If a renter loses their home due to coastal erosion they can move to a new property with relative ease (as long as there are rental properties available in the area) compared to someone who still has to pay a mortgage on a house which is no longer habitable, as well as find a new place to live;

- *Residential Property*: homeowners with high value homes tend to have high income and have the opportunity to diversify their wealth by obtaining other assets (e.g.

investments, stocks and shares, art, other property). Therefore, the loss of a single high value property is likely to make up less of a proportion of their overall wealth compared to low value home owners whose only significant asset is their home. Hence people who own high value property are potentially less vulnerable to coastal erosion as they have the financial means to recover. The build quality is insignificant when coastal erosion is considered. No matter how well the building is built, if it is significantly undermined by coastal erosion it will be uninhabitable or collapse.

Cutter et al. (2003) also omitted a key indicator which should be included in vulnerability assessments. Car ownership has a large impact on the ability of people to evacuate before and during a hazard. Additionally car ownership reduces the dependence on local goods, services, and resources and therefore increases the options available to an individual and increases the ability to cope after a hazard event. For example, if a person becomes unemployed as a consequence of their workplace being destroyed, a car gives them the option to seek employment in locations further from their home that would otherwise unavailable to them.

Subsequent work by Lee (2014) includes more recent sources which identify a similar selection of vulnerability variables as Cutter et al. (2003). However, these generalised hazard indicator summaries need to be tailored to suit the hazard in question. Currently no coastal erosion vulnerability assessment within the literature has been attempted to assess vulnerability at a scale where identifying individual socioeconomic variables is appropriate. The highest 'resolution' coastal erosion vulnerability index thus far is the work of Mclaughlin & Cooper (2010). The variable they used to assess vulnerability of people was population density (with increasing density increasing vulnerability). The other variables used in the socioeconomic domain of this research focused more upon transport infrastructure, cultural heritage, land use, and conservation designations. Therefore, the vulnerability of the population was not fully assessed in the manner Cutter et al. (2003) and other researchers have suggested. In order to produce a coastal erosion vulnerability assessment this research proposes to use Experian Mosaic Scotland which has been used in previous hazard management studies (Tomlinson et al., 2011; Willis et al., 2010). A fuller description of Experian Mosaic Scotland is given within Chapter 3.

2.4.4.5 Vulnerability of Economic Assets

Coastal managers are not only interested in the vulnerability of people, they are also concerned with key assets and infrastructure such as oil refineries, power stations, roads and rail track, golf courses, etc. all of which are potentially vulnerable. However, sensitivity and resilience varies considerably from one asset to another. For example a large wealthy golf club may be able to install mitigation measures at the coast, where as a smaller less wealthy club may not. Additionally, national datasets dealing with this type of data are much more difficult to obtain. Therefore, the exposure of key assets rather than their vulnerability will be assessed within this thesis.

However, this is not the case for all assets, specifically the ones used by the public i.e. transport infrastructure. For example, some roads can be seen as more vulnerable than others if they are a fundamental part of an area's transport network. If a road is lost to coastal erosion in a highly populated area, there may be a number of alternative routes already in existence that can be used with little disruption to travel journeys. However, if a coastal road is lost in a more remote area, then that road may be the only road available with no alternative routes, and therefore the disruption would be significant. Hence, combining transport data with urban/rural data can assist in identifying critical infrastructure.

2.4.5 Section Summary

Section 2.4.4 has described the risk and vulnerability literature from a number of aspects which are summarised as follows:

- The social, economic and political processes which ultimately determine vulnerability operate on vast and complex scales. These processes eventually manifest themselves into unsafe conditions. Vulnerability can be defined as the extent to which a person, group or socioeconomic structure is likely to be affected by a hazard. Vulnerability consists of a resilience and sensitivity component. Some models include exposure within vulnerability, but as ultimately vulnerability is to be used within the context of risk, exposure is best considered outside of vulnerability;

- The working approach for assessing vulnerability and risk begins with the *Hazard Potential* which has a *Geomorphological Context* and a *Socioeconomic Context*. Both of these contexts consist of two components; *sensitivity* and *resilience*. Taking into account these two components for the geomorphological context allows the *Physical Susceptibility* to be derived. This represents the most likely spatial extent of a hazard. *Exposure* can be obtained by including an asset that would be threatened by the hazard, such as a household. When socioeconomic sensitivity and resilience are assessed *socioeconomic vulnerability* can be deduced. The outcome of combining the socioeconomic vulnerability and the physical susceptibility is the *hazard risk.* Once the hazard risk has been determined it is then possible to take measures to reduce this hazard risk by the means of *mitigation* and *adaptation;*

- Socioeconomic vulnerability can be assessed using geodemographies. Geodemographies have a number of reliability issues, but are generally seen as a viable way to identify the attributes which increase vulnerability. Vulnerability indicators have been discussed within this section and include attributes such as old and young people, poor health, the economically deprived, and many others. Delineation of vulnerable economic assets is much more complex than with vulnerability of people, therefore only exposure will be assessed when analysing assets.

2.5 Chapter Summary

Chapter 2 has established that society globally and within Scotland derives a number of benefits and ecosystem services from the coast and the coast is therefore of high importance to society. However, the threat posed by climate change, particularly current and future sea level rise, is of considerable concern. It is expected that with a rise in sea levels, coastal erosion rates will increase and more areas of coast will become erosional. This has major implications for both erosion and coastal flood risk management. Currently unknown in Scotland is where coastal erosion is likely to occur, and which assets are likely to be exposed as a result.

Coastal erosion can also significantly impact upon people, therefore this review analysed risk and vulnerability theory in order to inform a working approach to assess coastal erosion risk. This review identified a number of environmental hazard vulnerability assessments. However, at present no such assessment exists for Scotland at national or local scales. Additionally, there are few publications assessing socioeconomic vulnerability to coastal erosion and even the assessments that do exist use rudimentary indicators to assess social vulnerability.

Bearing in the mind the limited information available to coastal managers with regards to the present state of the coastal erosion hazard in Scotland, this research aims to achieve the following:

- **Physical Susceptibility** - establish coastal erosion susceptibility on a national, high resolution scale to establish the areas where coastal erosion may or may not occur;

- **Exposure** - identify the assets that are likely to be exposed to coastal erosion, and their economic value;

- **Vulnerability** - explore the use of geodemographies to establish socioeconomic vulnerability to coastal erosion in order to identify the sectors of society likely to suffer most if exposed to coastal erosion;

- **Risk** - combine both physical susceptibility and socioeconomic vulnerability to establish the risk to communities of coastal erosion at a national scale.

Achieving these aims will produce data and information that can be used within GIS by coastal managers to assess the coastal erosion exposure (and risk when people are considered) in Scotland, and to assist in the implementation and development of mitigation and adaptation strategies. The methodologies used to accomplish these aims will be described in the following chapter.

Chapter 3: Methodology

To achieve the aims stated in Chapter 2 this chapter will describe the methods used within this research to:

- generate a coastal erosion physical susceptibility model;
- identify the assets which are exposed to coastal erosion, and determine their economic value where possible;
- generate a coastal erosion socioeconomic vulnerability model;
- utilise both the physical susceptibility and socioeconomic vulnerability models to produce a coastal erosion risk assessment.

3.1 Physical Susceptibility

As discussed in the previous chapter hazards have both a geomorphological and socioeconomic component. This section will detail the development of the coastal erosion physical susceptibility model. ESRI ArcGIS™ 10.2, and ModelBuilder were used for all of the following processing steps. The python scripts used within ModelBuilder are included within Appendix A, and included on the DVD at the rear of this thesis.

The physical susceptibility model is generated in two stages. The first stage is to produce the Underlying Physical Susceptibility Model (UPSM). This model represents the inherent erosion susceptibility of the coastline without coastal defences or sediment accretion. With coastal defences and sediment accretion data included, the model is termed the Coastal Erosion Susceptibility Model (CESM).

3.1.1 Parameters for the UPSM

The UPSM utilises four key parameters each of which is available as a national dataset. These parameters are ground elevation, rockhead elevation, distance from the open coast (i.e. Mean High Water Spring (MHWS)), and exposure to wave activity. The rationale for using these parameters is described in Table 3.1.

Table 3.1: Rationale for using the chosen parameters within the CESM

Parameter	Rationale	Parameter Used Previously in the Literature?
Ground Elevation	Areas of low elevation are more susceptible to coastal erosion than higher elevations as a consequence of having a closer proximity to coastal process i.e. wave action and inundation.	**Yes** (Alves et al., 2011; Arun Kumar and Kunte, 2012; Eurosion, 2004b; McLaughlin and Cooper, 2010)
Rockhead Elevation	The elevation of the rockhead (i.e. hard resistant bedrock) greatly influences whether the land at or near MHWS is erodible i.e. areas with low rockhead elevation have superficial (erodible) deposits above rockhead and are susceptible to erosion, whereas areas with high rockhead (e.g. hard rock cliffs), erosion is minimal.	**No**
Proximity to 'Open Coast'	Land closer to MHWS is more susceptible to coastal erosion as it is more exposed to coastal processes than land further inland.	**Yes** (Alves et al., 2011; McLaughlin and Cooper, 2010; Reeder et al., 2010)
Wave Exposure	Coastal erosion often occurs in highly energetic environments, therefore areas exposed to high wave energy are more susceptible to coastal erosion.	**Yes** (Alves et al., 2011; Anfuso and Martínez Del Pozo, 2009; Arun Kumar and Kunte, 2012; Lins-de-Barros and Muehe, 2011; McLaughlin and Cooper, 2010; Reeder et al., 2010)

In some published coastal erosion susceptibility models there is a geological parameter included as a proxy for the 'hardness' of the lithology. In previous iterations of the UPSM such a parameter was included, however it was decided to remove this parameter as:

- in the Scottish context, most lithologies may be classed as hard or moderately hard. With very few instances of soft bedrock on the Scottish coast (May & Hansom, 2003) the influence of lithology was deemed a minor factor, particularly since the erodible overburden above rockhead has been accounted for by inclusion of rockhead elevation within the model;

- the elevation of the rockhead is the more dominant control on erodability compared to lithology type. The material above rockhead and below ground level is the superficial component that is most readily eroded. Exclusion of the lithology type data layer has been tested at a pan-Scotland scale with little discernible effect on the model output;

- the data limitation factor in the British Geological Survey (BGS) geological data is not mapped to a common scale across Scotland. For most of Scotland mapping is at a resolution of 1:50,000. However, some of the Orkney Isles and all of the Western Isles (important areas for coastal erosion susceptibility issues) have been mapped only at a scale of 1:100,000. This scale was deemed incompatible with the scale of the model output and inclusion of geological data with inconsistent scales would result in a dataset of variable resolution and accuracy.

The parameters included within the UPSM were derived from data originating from a number of different sources. The original sources and formats of each dataset are detailed in Table 3.2.

Table 3.2: Original data sources and formats for the parameters used within the UPSM

Parameter	Original Data Source	Original GIS Format & Resolution	Original Data Producer	Copyright
Ground Elevation	OS Terrain 50	Raster: 50 m	Ordnance Survey	Open
Rockhead Elevation	Superficial Deposit Thickness Model	Raster: 50 m	British Geological Survey	Closed (Licensed)
Proximity to 'Open Coast'	Mean High Water Springs	Polyline: 1:10,000	Ordnance Survey	Open
Wave Exposure	Wave Fetch Model	Raster: 200 m	SNIFFER	Open

3.1.2 UPSM Data Processing

The data listed in Table 3.2 was supplied in a number of formats and therefore required processing into a consistent format. The data could then be categorised in terms of erosion susceptibility to allow it to be incorporated into the UPSM. The processing steps required for each parameter are described in detail below.

3.1.2.1 Datum Adjustment

The datasets which are relative to Ordnance Datum (OD) (OS Terrain 50 and the BGS Superficial Thickness Model) all have a consistent datum. However, as the MHWS elevation varies markedly around Scotland the data was adjusted so that the elevations are relative to the regional MHWS elevation (the effect of this adjustment is described further in 3.1.2.2.1). To adjust the datasets, information from 133 tidal gauges around Scotland were utilised (datum data supplied by Scottish Natural Heritage (SNH) derived from Admiralty data). The processing steps are as follows (the python code used within ArcGIS ModelBuilder to create his data is included in Appendix A.1):

- For each tidal gauge the elevation of MHWS was converted from Chart Datum (CD) to OD (MHWS CD + Gauge OD elevation)

- A raster representing the sea area of Scotland plus 100 m inland from MHWS was created and assigned a constant value of 1. This is a cost surface and termed the UK seas raster.

- Using the 'Cost Allocation' tool[5], the tidal gauge location, and the UK seas raster (the cost surface[6]) which had a constant value of 1, an output raster representing which tidal gauge is nearest to each grid cell taking into account obstructions caused by the land was produced i.e. the tidal gauge nearest each raster cell was calculated "as the fish swims" rather than "as the crow flies". This raster is termed the Tidal Gauge Allocation Raster.

- A raster representing the land area to MHWS of Scotland is created and assigned a value of 1.

- The Cost Allocation tool was used again to project the tidal gauge data inland, using the Scotland land raster generated above as the cost raster and the Tidal Gauge Allocation Raster.

- The inland raster was converted to polygons so that the MHWS elevation relative to OD data could be joined to the appropriate polygon.

- The polygon was then converted to a raster using the MHWS OD elevation as the raster value. This raster was termed the MHWS OD Adjustment Raster.

The MHWS OD Adjustment Raster is an intermediate (Figure 3.1) dataset used to adjust the OS Terrain 50 and BGS Superficial Thickness Model. This process is explained further in the following section.

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[5] This tool assigns each cell the value of the nearest source data based on the least accumulative cost over a cost surface. For the tidal adjustment, the cost surface has a uniform value of 1.

[6] A raster dataset that identifies the cost (not necessarily an economic cost) of traveling through each cell in the raster, which in this case was used to create process 'barriers', which ensure the data were allocated on a 'as the fish swims', rather than 'as the crow flies' basis.

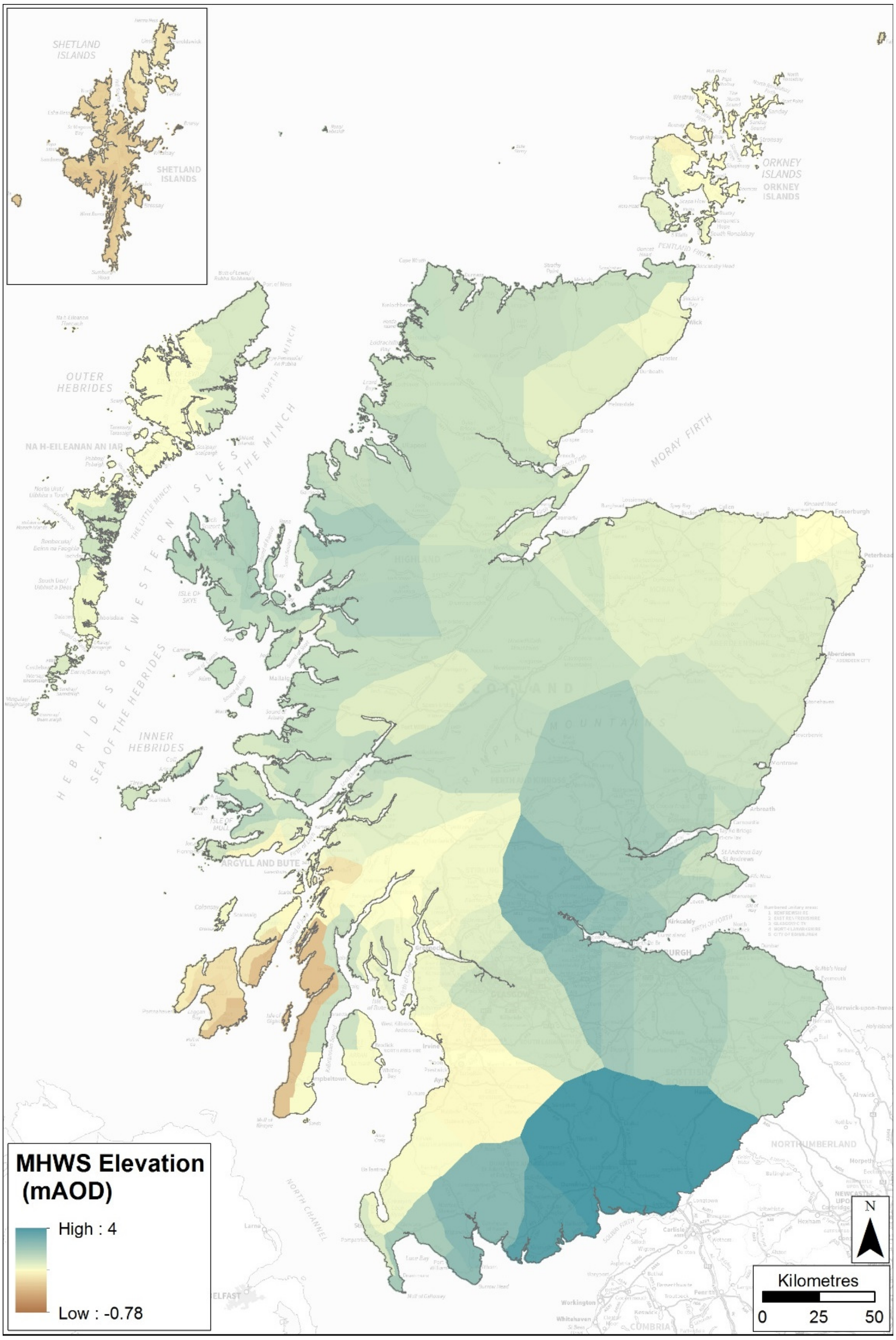

Figure 3.1: The elevation of MHWS relative to Ordnance Datum (Newlyn). Units are metres above Ordnance Datum (mAOD). Note this only has meaning along the coastline. Mapping courtesy of the OS.

3.1.2.2 Elevation Data Layer

The elevation data used for the UPSM was the Ordnance Survey (OS) Terrain 50 Digital Terrain Model (DTM). This is an Open Source DTM produced by the Ordnance Survey derived from aerial photography. The format of this data is a 50 m raster.

3.1.2.2.1 Data Processing

The python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.2. However, the data processing steps are described below:

- The DTM was adjusted so that where the DTM has a value of 0 m, this represents the elevation of MHWS. Currently, the data is relative to OD in Newlyn, and a value of 0 mOAD, may represent an elevation above or below MHWS (Figure 3.2a). To adjust the DTM, the MHWS OD Adjustment raster derived in Section 3.1.2.1 was subtracted from the OS Terrain 50 data so that the elevations are relative to the regional MHWS elevation (Figure 3.2b). The adjusted elevation DTM was termed the MHWS Adjusted DTM.

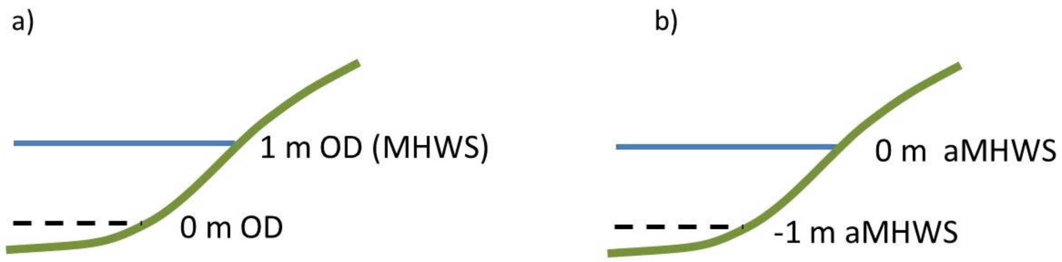

Figure 3.2: A hypothetical example showing the OS Terrain 50 adjusted to MHWS a) The raw OS Terrain 50 DTM is relative to OD, therefore if regional MHWS was at an elevation of 1 m OD, an elevation of 0 m OD would potentially be in the intertidal zone b) Once the OS Terrain 50 has been adjusted for the elevation of MHWS (OS Terrain 50 – 1 m) anything above 0 m represents elevations above the regional MHWS. m aMHWS = metres above MHWS.

- To determine the elevations to be categorised as susceptible to erosion, a review of published journal articles was undertaken (e.g. Hall et al., 2003; Boruff et al., 2005; Brown, 2006; Mclaughlin & Cooper, 2010; Reeder et al., 2010; Boateng, 2011; Lichter & Felsenstein, 2012; McInnes et al., 2013). The consensus from the literature is that erosional susceptibility declines markedly with altitude above MHWS. Expert judgement (Dr. Jim Hansom and Dr. Alistair Rennie) and local knowledge were also utilised to reclassify the ranking in known areas. The elevation data was classified into five categories according to Table 3.3, where elevation 2 m above MHWS (aMHWS) and below are regarded as highly susceptible to erosion, with susceptibility diminishing with 2 m increments in elevation. This data was termed the 'Elevation' data layer. Table 3.3 also shows mean, maximum, and minimum elevations of the unadjusted elevation dataset (i.e. relative to OD). These statistics confirm that some locations would have been misclassified if the adjustment relative to MHWS had not been used. For example, the maximum corresponding OD elevation in classification 5 is 7 mAOD, indicating that even though a location can be at 7 mAOD, in reality this location is a maximum of 2 metres above MHWS. Without the OD adjustment, this location would have been assigned with a susceptibility classification of 2, an underestimate of susceptibility.

Table 3.3: Susceptibility classification for the 'Elevation' data layer. The statistics from the unadjusted elevation dataset relative to OD are also shown for reference.

	More Susceptible				**Less Susceptible**
	5	**4**	**3**	**2**	**1**
Ground Elevation (m aMHWS)	< 2	2 – 4	4 – 6	6 – 8	> 8
Mean Corresponding OD Elevation (mAOD)	1.9	5.3	7.2	9.3	246.5
Maximum Corresponding OD Elevation (mAOD)	7	9	11	13	1345
Minimum Corresponding OD Elevation(mAOD)	-15.1	1.3	3.3	5.5	7.4

3.1.2.2.2 Confidence

- The accuracy of the Terrain 50 DTM was tested by the OS by comparing the DTM to known GPS data. This resulted in a root mean square error (RMSE) of 1.5 m in urban areas, and 2.5 m in rural, mountainous and moorland regions.

- The OS Terrain 50 DTM was selected for use over data with better quoted accuracies, such as the Intermap NEXTMap DTM, since the OS Terrain 50 DTM is more accurate in certain land use types. For example, when comparing the two datasets, the Intermap NEXTMap DTM performed poorly in areas of dense vegetation e.g. forestry. The interferometric synthetic aperture radar (IfSAR) process by which the NEXTMap DTM was collected means that the canopy of dense vegetation is often incorrectly recognised as the land surface. This error is minimal in the OS Terrain 50 DTM, as the raw data used is photography, rather than IfSAR.

3.1.2.3 Rockhead Data Layer

The rockhead parameter was produced using two datasets: the BGS Superficial Deposit Thickness Model (SDTM) and the OS Terrain 50 DTM. The SDTM is described by Lawley & Garcia-Bajo (2010: 4) as a:

"*raster-based dataset designed to demonstrate the variation in thickness of Quaternary-age superficial deposits across Great Britain...and this latest version of the model is based upon DiGMapGB-50 Version 5 geological mapping and borehole records registered with BGS before August 2000*"

It should be noted that Quaternary-age (2.6 Ma to present) superficial deposits are normally unlithified (e.g. unconsolidated glacial/fluvial/slope deposits) and are therefore much more susceptible to coastal erosion than lithified bedrock.

The BGS used two methodologies to derive superficial thickness. The model used for the UPSM is the Advanced Superficial Thickness Model (ASTM) which indirectly derives superficial thickness based on borehole records and map data. This was chosen ahead of the Basic Superficial Thickness Model (BSTM) as the ASTM is more appropriate for deriving the rockhead elevation. This is because OS Terrain 50 was used in the processing of the ASTM by BGS and produces a better output for areas that have minimal borehole coverage.

3.1.2.3.1 Data Processing

The python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.3. However, the data processing steps are described below:

- The ASTM model has a raster resolution of 50 m. To maintain spatial compatibility with other datasets the raster was snapped and clipped to the raw OS Terrain 50 DTM data.

- In order to establish the level of the rockhead the following raster calculation was performed:

  OS Terrain 50 DTM – ASTM = Rockhead data layer (50 m raster)

  This calculation provides an estimate of the rockhead elevation across Scotland and consequently can be used to identify where superficial deposits occur at or close to MHWS and thus are more susceptible to coastal erosion (i.e. where there is a negative or low rockhead elevation). This calculation is explained graphically in Figure 3.3.

- The OS Terrain 50 DTM had to be adjusted to the elevation of MHWS and the same is true for the Rockhead data as the elevations are relative to OD. The MHWS OD Adjustment raster was subtracted from the Rockhead data to create a rockhead layer which is relative to MHWS. The adjusted rockhead elevation data was termed the 'Adjusted Rockhead Elevation' data.

- After this adjustment the data were classified in terms of susceptibility to erosion. As a rockhead elevation parameter has yet to be used in any other coastal erosion assessment, classification of the data relied upon expert judgement to produce susceptibility rankings that paralleled those for the Elevation data layer. Consequently the data was classified according to Table 3.4. This data layer is termed the 'Rockhead' data layer.

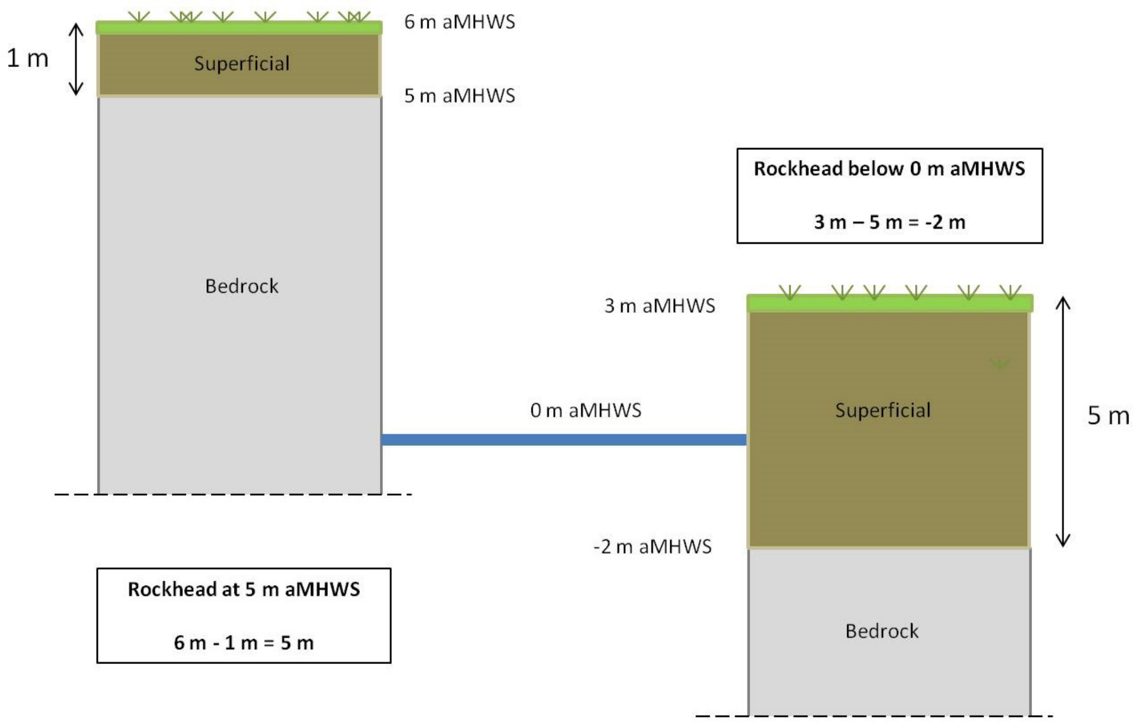

Figure 3.3: Hypothetical scenarios detailing the method by which rockhead elevation was derived using OS Terrain 50 DTM and the BGS Superficial Thickness Model. An elevation of 0 m aMHWS was assumed to equal mean sea level, therefore where a negative elevation of rockhead was calculated this indicates superficial deposits are present at or below sea level, increasing susceptibility to coastal erosion. The scenario on the left would have low susceptibility to erosion, whereas the scenario on the right would have high susceptibility as soft deposits are present at sea level.

Table 3.4: Susceptibility classification for the 'Rockhead' data layer

	More Susceptible				**Less Susceptible**
	5	**4**	**3**	**2**	**1**
Rockhead Elevation (m aMHWS)	< 0	0 - 2	2 - 4	4 - 6	> 6

3.1.2.3.2 Confidence

- The Superficial Thickness model is based upon the national database of approximately 77,000 borehole records held by the BGS. However, these data do not have a uniform spatial distribution and tend to be clustered around major urban areas, infrastructure sites and transport routeways. Consequently the accuracy of the model diminishes with distance from a borehole. BGS supply a dataset (DBUFF) that shows the locations of each borehole data point used in the model. A distance buffer is then applied to allow an assessment of the accuracy of the model in any area based on the distance from, and the location of, the borehole data (Figure 3.4). In this respect, the blanks on the distribution map (white patches within Figure 3.4) are infilled by an interpolated surface produced by an algorithm which introduces interpolation errors. In addition there is an element of 'cleaning and smoothing' to remove data edge effects in order to produce a standardised output surface.

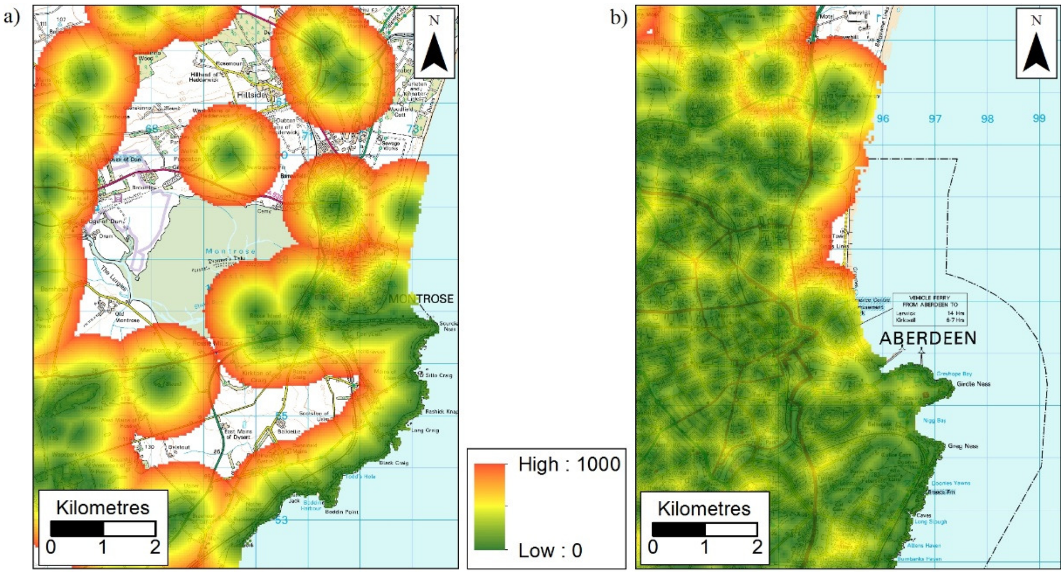

Figure 3.4: Two examples of the DBUFF layer showing the distribution of data points used in the BGS Superficial Thickness model for Montrose (a) and Aberdeen (b). Scale is in metres.

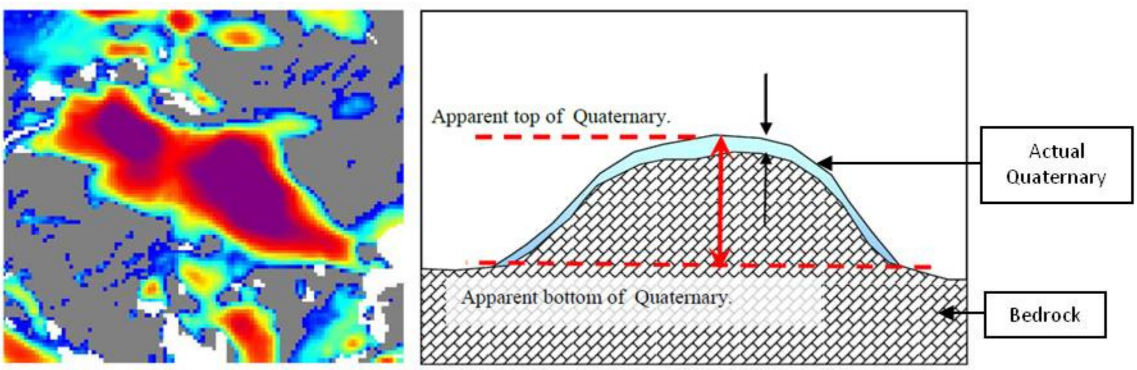

Figure 3.5: An example of the "through-hill error in the BGS Superficial Thickness Model. The map above shows an area of apparent increased thickness of superficial deposits (the red and purple areas on the map). However, there are no borehole data in this area to 'prove this thickness'; the schematic cross section

demonstrates that this apparent thickness (red arrow) is an artefact. Adapted from Lawley & Garcia-Bajo (2010).

- The dataset also includes issues with through-hill modelling caused "*partly by the nature of the geological deposits, the interpolation method, and the resolution of all the datasets*" (Lawley and Garcia-Bajo, 2010: 13). This creates issues where in reality the deposits are a thin veneer over the surface of the hill. However, the model interprets the whole hill as the superficial thickness (Figure 3.5). This error is more prevalent in areas where there are no/few data points and in areas of high undulation. Such areas tend to be remote from urban and industrial centres. Consultation of the DBUFF layer within the GIS allows areas to be identified where this interpolation error may occur.

- The extents of the superficial thickness model were derived from the BGS mapping data which, as discussed in Section 3.1.1, has variable accuracy across the country. In some areas the extent of the model may not fully represent reality and may therefore produce errors in the final model. As this is an issue with the BGS data, it was not possible to rectify this problem within this research.

3.1.2.4 Proximity to Open Coast

This parameter was generated using the OS Boundary MHWS (2009 version) data. The use of this data without modification resulted in several areas where MHWS extended substantial distance inland, e.g. at stream inlets and estuaries. Unedited this could result in the model enhancing the susceptibility of areas some distance from the outer coast. Coastal erosion is associated with energetic locations, which are unlikely to found within inlets and estuaries. It was therefore necessary to 'cut off' these inlets where the inlet width narrowed and shallowed sufficiently to cause attenuation of wave activity and thus a reduction in coastal erosional susceptibility. After considering numerous examples around the Scottish coast a distance of 500 m or less was chosen as a compromise between a wider or a narrower gap that would respectively include or exclude inner estuaries and river exits. The choice of 500 m effectively created a polyline which adequately represented the 'open coast' i.e. the areas where wave action is most prevalent resulting in elevated susceptibility to erosion. The processing steps are described below:

3.1.2.4.1 Data Processing

The python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.4. However, the data processing steps are described below:

- The MHWS polyline was used to create a polygon, which was buffered by 250 m (i.e. half of 500 m where two coasts approach from opposite directions as occurs at river exits) to extend seaward of MHWS. Where an inlet with a mouth of less than 500 m occurred, the buffer would meet and 'cut it off' from the open coast (Figure 3.6a).

- This 250 m buffer was then converted to a polygon and dissolved in order to remove areas of inland water, or "doughnuts", within the buffer i.e. this removed areas of 'no data' within the polygon (Figure 3.6b).

- A 'negative' buffer of 250 m was then applied to this polygon which effectively created a coastline that had been 'generalised' in the position of MHWS with inlets removed (Figure 3.6c).

- The 'negative' buffer was then converted to a polyline which represents the 'open coast' (Figure 3.6d).

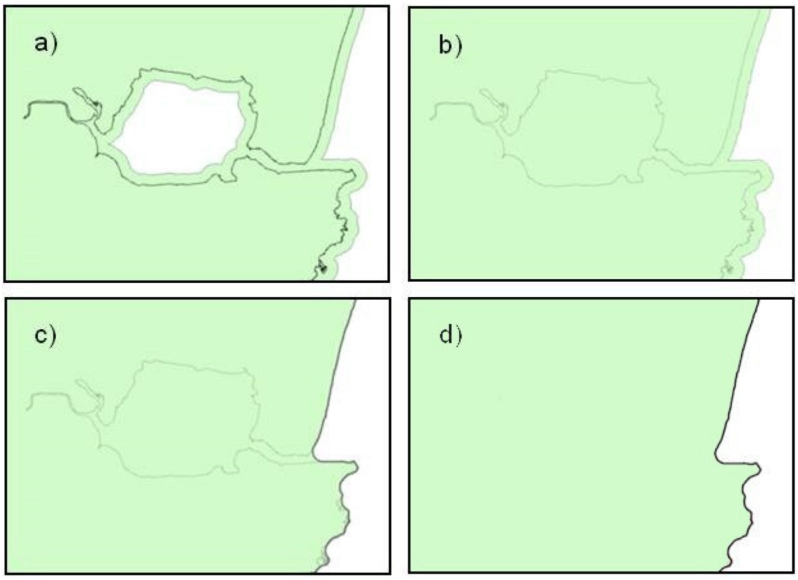

Figure 3.6: A series of images demonstrating the methodology by which the MHWS polyline was processed in order to produce an 'open coast' polyline using Montrose as an example. a) the MHWS polyline was buffered at a distance of 250 m which 'cut off' the mouth of Montrose Basin b) the resulting buffer was converted to a polygon and dissolved to remove inland 'donuts' such as Montrose Basin c) a 'negative' buffer was created which effectively moved the 'open coast' polyline to the current position of MHWS d) the 'negative' buffer was then converted to a polyline to create the 'open coast' data, open coast = black line.

- Using the 'open coast' polyline a Euclidean distance (perpendicular straight line from the coastline) raster was created and then reclassified according to Table 3.5 to identify the areas that are situated inland and adjacent to the open coast. This data layer is termed the 'Open Coast' data layer.

Table 3.5: Susceptibility classification for the 'Open Coast' data layer

	More Susceptible				**Less Susceptible**
	5	**4**	**3**	**2**	**1**
Distance from open coast (m)	< 100	100-200	200-300	300-400	>400

3.1.2.4.2 Confidence

- Even though the OS Boundary data is targeted to be updated yearly, there remain some areas that may not be updated regularly. As a result, the OS MHWS may not represent the reality on the ground. Research is ongoing to support the OS to address this issue (Hansom et al., 2015). However, on a national scale the extent of any inaccuracy is difficult to estimate but unlikely to significantly affect the veracity of the model. Any updates in the position of the MHWS from the OS can be rapidly updated when available. Currently there is no alternative to using the existing dataset. Therefore, it is used within this research with the knowledge that the UPSM will require updating when new MHWS positions are established.

3.1.2.5 Wave Exposure Data Layer

The wave exposure data included within the UPSM has been generated from the fetch data used originally by SNIFFER (2008) which was itself based upon a methodology devised by Burrows et al. (2008) and developed by Ball et al. (2013). The data consist of a 200 m raster along the Scottish coastline with a non-dimensional index value (ranging from 2 to 800) which takes into account wave fetch and wind exposure. The original format of this data is incompatible with the other data layers and so requires extensive processing before it is in a format suitable for use within the model. In spite of the limitations associated with this dataset, it is important to incorporate an estimation of coastal processes within the model. There exists no readily available dataset at a national scale that could be included and so, at this time, the SNIFFER Fetch data is currently the best national data available for use.

In some respects, coastlines are already adjusted to their respective wave climates i.e. areas of high wave exposure may be hard rock cliffs rather than sandy beaches. Therefore, the resultant landforms of highly exposed coastlines are more resilient than those found on more enclosed coastlines. Such antecedent adjustment suggests that the influence of wave exposure should be reduced when ranked alongside the other factors affecting susceptibility. This adjustment avoids over emphasis of areas of high exposure (likely to be more resilient to storm events) and under emphasis of areas of low exposure (likely to be less resilient to storm events).

3.1.2.5.1 Data Processing

The python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.5. However, the data processing steps are described below:

- The SNIFFER raster cells were clearly misaligned with the OS MHWS coastline, so the first step was to shift the data 200 m north, and 200 m west.

- The SNIFFER raster was then resampled using the ‘Nearest Neighbour’ method to a 50 m raster and snapped to the OS Terrain 50 raster.

- A raster distributing the SNIFFER data inland was created using the cost allocation tool, a 50 m raster representing the land of Scotland (the cost surface) with an outside buffer of 400 m and the 50 m SNIFFER raster.

- This raster was then clipped to 400 m inland from MHWS.

- The non-dimensional index values were then assessed to establish values to reflect very high, high, medium, low and very low wave exposures using expert knowledge from areas around Scotland. A high index value indicates a highly exposed coast and therefore areas that are potentially more susceptible to coastal erosion. The data was then reclassified according to Table 3.6 with susceptibility diminishing with increments of 75 in the index value. Anything beyond 400 m from MHWS was given a value of 1. This data layer is termed the ‘Wave Exposure’ data layer.

Table 3.6: Susceptibility classification for the ‘Wave Exposure 50 m’ data layer

	More Susceptible				**Less Susceptible**
	5	**4**	**3**	**2**	**1**
Wave Exposure	>300	225-300	150-225	75-150	<75

3.1.2.5.2 Confidence

- The original SNIFFER model uses a rasterised coastline which is based upon the 1:250,000 NOAA (see: www.ngdc.noaa.gov/mgg/shorelines/gshhs.html) coastal polyline data. The conversion from a polyline to a grid results in:

  > "*undesirable, but necessary, effects at very local scales. For example, straight coastlines running diagonally were rendered as step-like shapes. The consequence of this was that alternate cells along the coastline were blocked by their immediate neighbours, resulting in unrepresentative low values for wave fetch.*" (Burrows et al., 2008: 4)

- The processing steps required to convert the SNIFFER Fetch data into a useable format for the UPSM adds another level of potential error into the data. In spite of this extra error the dataset produces results that match expert knowledge of the coast at that location i.e. known sheltered coastal areas have a low wave exposure index and more exposed sections of the coast have a high wave exposure index. Therefore it is considered that the dataset is useable for a national-scale assessment.

3.1.3 UPSM Aggregation

The ranked four data layers which constitute the UPSM need to be aggregated in order to assess which areas are most susceptible to erosion overall. Of the four data layers used within the model, the most influential datasets were considered to be Elevation, Rockhead and Distance to the Open Coast. The measure of Wave Exposure was considered to be less influential (for the reasons mentioned in 3.1.2.5.2). Individual datasets were ranked into a 1 to 5 scoring system and aggregated using the associated weightings (Table 3.7).

The Wave Exposure data is weighted at a value of half relative to the other data layers, as concerns remain about overemphasis of susceptibility on exposed locations and the quality of the dataset. Nevertheless, it was deemed important to include a parameter that accommodates coastal processes, hence the data is included but the influence of this dataset in the final model output has been reduced somewhat.

The final output of the UPSM is a 50 m raster with dimensionless values which range from a minimum of 3.5 to a maximum of 17.5 (the python code used within ArcGIS ModelBuilder to create the UPSM is included in Appendix A.6). Locations that have high aggregate values are deemed to be highly susceptible to coastal erosion as they represent areas with attributes which are the most similar to category '5' of the susceptibility ranking (Table 3.7) i.e. low ground elevation, low rockhead elevation, very close to the open coast and high wave exposure.

Table 3.7: Overview of categorisation and susceptibility rankings for each the data layers used within the UPSM. The Wave Exposure data layer was given a weighting of 0.5 compared to the other three datasets (see text above).

	5 **More Susceptible**	**4**	**3**	**2**	**1** **Less Susceptible**	**Weighting**
Elevation (m aMHWS)	< 2	2 – 4	4 – 6	6 – 8	> 8	1
Rockhead (m aMHWS)	< 0	0 - 2	2 - 4	4 – 6	> 6	1
Distance to open coast (m)	< 100	100 - 200	200 – 300	300 - 400	> 400	1
Wave Exposure	>300	225 - 300	150 - 225	75 - 150	<75	0.5

3.1.4 Incorporation of Sediment Supply and Coastal Defences

The UPSM model defines the inherent susceptibility of the coastal zone, and excludes the dynamic supply of sediment to the soft shorelines or the influence of coastal defences. These two additional sets of parameters are required to update the UPSM to include factors which alter the erosion susceptibility. The data sources used are detailed in Table 3.8. With the inclusion of sediment supply and coastal defences the model is termed the Coastal Erosion Susceptibility Model (CESM).

Table 3.8: Data sources used to incorporate coastal defences and sediment supply in the UPSM

Data	Source
Coastal Defences	Halcrow (2011) – Revised by Hansom, Fitton and Rennie
Coastal Sediment Supply	Eurosion (2004) – Revised by Hansom, Fitton and Rennie
Sediment Drift Direction	Coastal Cell Reports (Ramsay and Brampton, 2000)

3.1.4.1 Sediment Supply

Sediment supply is known to have a large impact on the susceptibility to erosion on soft coastlines (Figure 3.7). Where sediment supply has been limited for a prolonged period, soft landforms are more likely to be erosional than where sediment supply is positive. Although this is likely to have an effect on instantaneous events, it has also had a significant effect in controlling the broader evolution of shorelines over long time periods. Additionally, there are a number of anthropogenic influences on sediment supply such as dredging and sediment recharge which have not been included within the model due to the lack of available national scale data and the complexity associated with determining the effect of these influences on national scale coastal processes.

In theory, coastal sediment supply is readily defined as sediment flux, i.e. the difference between sediment exiting a section of coast and that entering. However, its measurement is rarely undertaken. It should be noted that the term sediment supply is used here more loosely than the definition above. In this research the transit of sediment along a coastline is only important when it leads to a seaward advance of the upper foreshore (i.e. MHWS). This clarification is important as there are examples of shorelines which remain erodible even though there are large amounts of sediment moving along the shore (for example the eastern section of Culbin Sands, Moray Firth, which has much sediment transport, parallel to the shoreline, but there is no advance of MHWS).

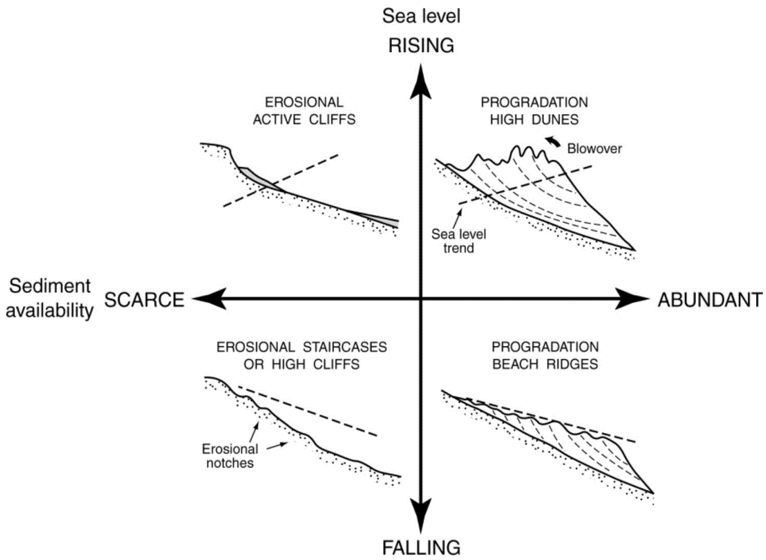

Figure 3.7: Coastal responses to sea level and sediment supply changes. Adjusted by Rennie (2006) after Carter (1988).

To identify areas of accretion the Eurosion (2004) data was used. Eurosion was a project sanctioned by the European Commission in order to ascertain where coastal erosion problems exist within Europe at 1:100,000 scale and displayed as a polyline around the European coastline. The method used in Eurosion was:

> "*an update of the 1990 CORINE Coastal Erosion (CCEr) methodology in which three criteria were used: i) morpho-sedimentology (rocky coasts, beaches, muddy coasts, etc.) ii) evolutionary trends (erosion, aggradation, stability) and iii) presence or not of coastal defence measures*" (Lenôtre et al., 2004: 1)

It is therefore the "evolution trends" data which are extracted and used within the CESM. The Scottish part of the Eurosion dataset was compiled by George Lees (former SNH Coastal Geomorphologist) based on all available published data (including Shoreline Management Plans and Coastal Cells Reports). Lees also investigated OS map data, to identify areas where roadways and rail track lines effectively formed defences. Lees did not have access to the aerial photography and high resolution digital topography data that currently exist which would have greatly improved the Eurosion output. It was therefore deemed necessary to update the Eurosion data where recent accretion is known to be ongoing.

3.1.4.1.1 Data processing

The python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.7. However, the data processing steps are described below:

- The Eurosion polyline was converted to points at the line vertices.

- Using these points Thiessen polygons[7] were created with the attribute information of the point assigned to the appropriate polygon.

- Using the Thiessen polygons, the attribute data was spatially joined to the OS MHWS polyline i.e. where the OS MHWS line intersected a polygon it was assigned the attribute information of that polygon.

- The 'MHWS' polyline sections with the following attribute code within the Eurosion Coastal Evolution category were extracted:

  6 Aggradation probable, but not documented

  70 Aggradation confirmed (available data) along parts of the segment

  71 Aggradation confirmed (available data) along almost the whole length of the segment

- The lateral extent of each line section was reduced by 200 m at both ends using end points and buffers.

- Areas of accretion were then validated and updated using published sources, expert knowledge, and cross-checked using high resolution aerial photography to assess

[7] Polygons generated from a set of sample points. Each Thiessen polygon defines an area of influence around its sample point, so that any location inside the polygon is closer to that point than any of the other sample points (ESRI, 2014).

whether the MHWS line had migrated seaward and if so, accretion could be verified (References used to support these changes include Angus and Hansom, 2006; Babtie Group and Hansom, 2001; Comber and Hansom, 1993; Gemmel et al., 1996; Hall et al., 2006; Hall et al., 2008; Hansom and Dunlop, 2010; Hansom and Rennie, 2004; Hansom, 2007b, 1999; Hansom et al., 2004, 2001; Hansom, 2007a; Hansom, 2001; May and Hansom, 2003; Rennie and J Hansom, 2011; Rennie, 2006). At this stage manual editing of the data was performed if any clear errors were identified. The output of this stage is a MHWS line with sections of accretion or no accretion identified.

- A 50 m raster distributing the accretion data inland was created using the cost allocation tool, a 50 m raster representing the land of Scotland with an outside buffer of 400 m (the cost surface), the MHWS polyline with accretion data and a maximum processing distance of 200 m. This raster was snapped to the OS Terrain 50 raster.

- The areas of accretion were then expanded using the cost allocation technique and a maximum processing distance, to create two rasters; the first representing areas 100 m, and the second 200 m around each area of accretion. This created a number of 'steps' around each area of accretion to represent the fact that the exact location that accretion starts/stops is ambiguous.

- The three rasters were mosaiced together with the main area of accretion assigned a value of -3, the 100 m buffered area a value of -2 and the 200 m buffered area a value of -1. The rationale for these values is discussed later in Section 3.1.4.3.

3.1.4.1.2 Confidence

- A considerable amount of sediment reworking/erosion takes place during high energy events i.e. storms play a considerable role in coastal erosion. The Wave Exposure dataset goes some way to assessing the potential impact of differential wave energies along the coast. However, the potential impact of extreme storms (e.g. low probability events) has not been modelled due to the highly complex nature i.e. refractional energy distribution and landfall characteristics of individual storm events.

- Within the Eurosion dataset each aggradation segment was coded as to whether the aggradation had been confirmed with evidence/data. The vast majority of aggradation segments (84%) in Scotland are coded '6' and therefore aggradation is only probable, not confirmed.

- The processing steps required to convert the Eurosion (2004) data into a useable format for modelling added a level of potential error into the data. However, in spite of this extra error the dataset produces results that replicate the original Eurosion data. Therefore it is considered that the dataset is useable.

3.1.4.2 Coastal Defences

The UPSM has been updated with the best understanding of coastal defences to produce the CESM. Currently there is no national dataset that contains information on the location, type, elevation, design life, condition and level of maintenance of coastal defences in Scotland. There are various national datasets which have a partial record of coastal defences, for example Eurosion (2004). Shoreline Management Plans (SMPs), and local authority data also detail the defences within given stretches of coast. The distribution of the six SMPs (two of which are currently in development) is limited to only 9% (approximately 1,603 km) of Scotland's coastline (Hansom and Fitton, 2015) therefore the SMP data cannot be used for the majority of the coast (**Error! Reference source not found.**).

The Eurosion (2004) data which was updated by Dr. Alistair Rennie and Halcrow (2011), was used to identify defences. From this point forward this data will be termed the Halcrow data. Using this dataset which utilised some SMPs as well as number of other data sources including SEPA data provided by some local authorities, it has been possible to collate information of 'Hard' (seawalls, embankments, revetments, breakwaters, rock armour/rip rap, and gabion baskets) and 'Soft' (groynes, beach nourishment projects, and sand dune stabilisation) coastal defences around Scotland (definitions of the different defence type are given in Appendix B). In addition to the Halcrow data, expert knowledge (Dr. Jim Hansom and Dr. Alistair Rennie) has been used to update information where necessary.

3.1.4.2.1 Data processing

The python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.8. However, the data processing steps are described below:

- The first step was to convert the Halcrow polyline data set to points at the line vertices. The points are assigned the attribute information of the line at that spatial location.

- Using these points Thiessen polygons were created with the attribute information of the point assigned to the appropriate Thiessen polygon.

- Using the Thiessen polygons, the attribute data was spatially joined to the OS MHWS polyline i.e. where the OS MHWS polyline intersected a polygon it was assigned the attribute information of that polygon.

- Defence locations were then validated and updated where necessary using expert knowledge and cross-checked using high resolution aerial photography. At this stage manual editing of the data was performed if any clear errors were identified.

- A raster distributing the defence data inland was created using the cost allocation tool, a 50 m raster representing the land of Scotland with an outside buffer of 400 m (the cost surface), the MHWS polyline with coastal defence data and a maximum processing distance of 400 m.

- A handicap value of -5 was given to areas of 'Hard' coastal defences, and a value of -3 for 'Soft' coastal defences. The rationale for these values is discussed in Section 3.1.4.3.

3.1.4.2.2 Confidence

- The processing steps required to convert the Halcrow data into a useable format for modelling added a level of potential error into the data. However, in spite of this extra error the dataset produces results that replicate the original Halcrow data accurately. Therefore it is considered that the dataset is useable.

- The Halcrow data only includes information on the type of defence present and does not include any information of elevation, condition etc. However, it remains useful dataset and the only data which maps defences at a national scale.

- The Halcrow and other defence data sets may have been collected at different times, potentially introducing errors in actual extent. However, within this report, the entire coast was re-examined using recent aerial photography (none older than five years) and there is a high level of confidence that no major coastal defence works have been omitted.

3.1.4.3 Incorporating Coastal Defences and Sediment Supply

In order to incorporate coastal defences and sediment supply data into the UPSM, it was necessary to assign a 'handicap' value to the two datasets. This had the effect of reducing the UPSM model score where sediment accretion and/or defences are present. After testing the impact of various handicap levels on the final model output it was decided to assign the handicap values according to Table 3.9.

Table 3.9: Handicap values for incorporating coastal defences and sediment supply data into the UPSM

Data	Handicap
Main Accretion Zone	-3
100 m Buffer	-2
200 m Buffer	-1
'Hard' Defences	-5
'Soft' Defences	-3

To integrate the sediment supply and defence handicaps into the model the following processes were performed (the python code used within ArcGIS ModelBuilder to create the CESM is included in Appendix A.6.):

- Using the raster calculator, areas benefiting from defence and accretion were subtracted from the UPSM, creating the CESM

- Following this calculation some raster values of less than 3.5 were created. In order to maintain the UPSM range of 14 (maximum UPSM value is 17.5, the minimum is 3.5, hence 17.5 - 3.5 = 14), values of less than 3.5 were reclassified to 3.5.

3.1.4.3.1 Rationale for 'Handicap' Values

The values shown in Table 3.9 were decided upon after testing a range of possible handicap values in areas where the erosion susceptibility was well understood (via expert knowledge). For areas benefitting from accretion it was important to highlight that these areas are currently less susceptible to erosion. An accretional area is then represented within the UPSM as a reduction in the degree of susceptibility (e.g. an area with an aggregate score of 17.5 is reduced by a handicap to account for an accretion trend that will reduce its susceptibility to erosion). The level of handicap allocated was set at -3 after several field test iterations of the model. This was aimed at producing a result that matched known published trends and conformed to the expectations of expert knowledge. Thus, an accreting beach that had formerly been rated at 17.5 would reduce its aggregate score to 14.5 and therefore be deemed less susceptible to erosion on account of accretion. However, this might not be high enough to totally reduce the erosion susceptibility. For example, if a change in sediment supply occurs e.g. due to construction of ‘hard’ coastal defences updrift, then erosion susceptibility could increase. This is reflected in the handicap value of -3, as it reduces the susceptibility whilst still highlighting these areas as potential areas of erosion.

The sediment supply handicap has been applied with a buffer, so that the seaward 200 m of cells receives a handicap of -3 and the next 100 m of cells inland receives a handicap of -2, followed by the next 100 m of cells inland has a handicap of -1 (See Figure 3.8). These buffers also grade along the coast at the end of the areas considered to be accreting. This results in a more realistic and less abrupt output, whilst emphasising the protective function of the sediment supply has on the immediate interior.

For areas that benefit from the presence of coastal defences a handicap value of -5 for ‘hard’ defences and -3 for ‘soft’ defences was deemed appropriate (Figure 3.9). ‘Hard’ coastal defences significantly reduce the susceptibility to erosion therefore a handicap value of less than -3 was necessary. A handicap value of -5 had the desired effect of notably reducing erosion susceptibility within the final model output and creating a more representative output than the UPSM.

With regards to ‘soft’ defences, a handicap value of -3 was thought appropriate as this management approach is aimed at recreating natural processes i.e. accretion. The effect of these defences was therefore analogous to the natural benefit to such areas of accretion and therefore an equivalent handicap value was considered suitable.

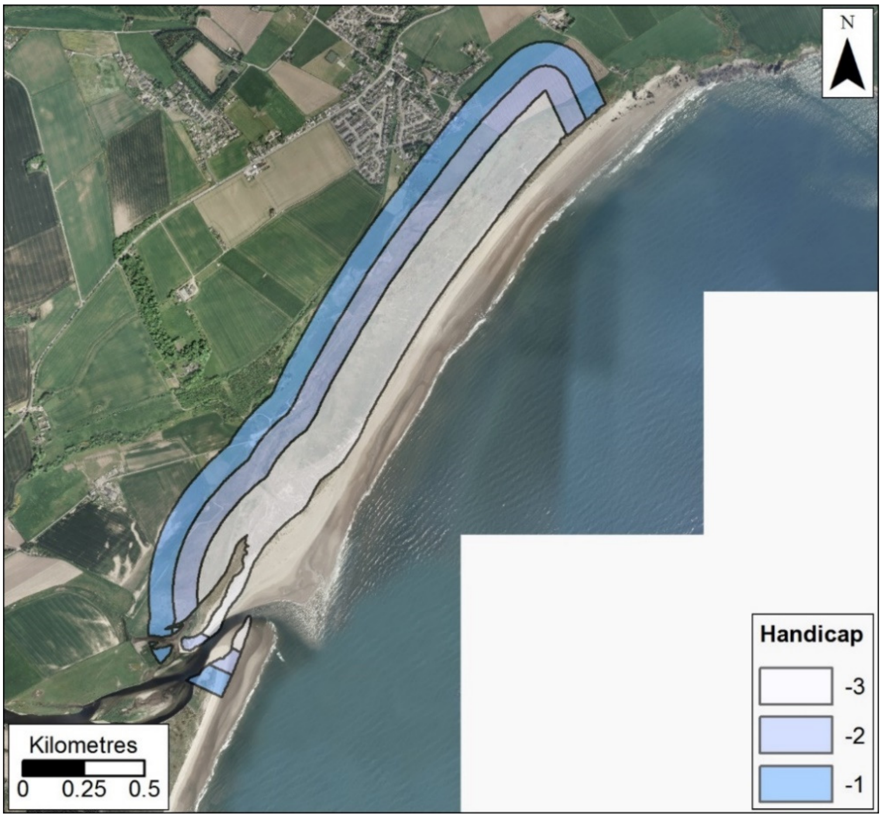

Figure 3.8: An example of the sediment supply data form within the CESM, at St. Cyrus, Angus. The sediment supply data shows that the northern end of the beach is accreting, which is represented by the handicap values of -3,-2, and -1, with the handicap value increasing with distance from the 'centre' of accretion. Aerial photography courtesy of the OS.

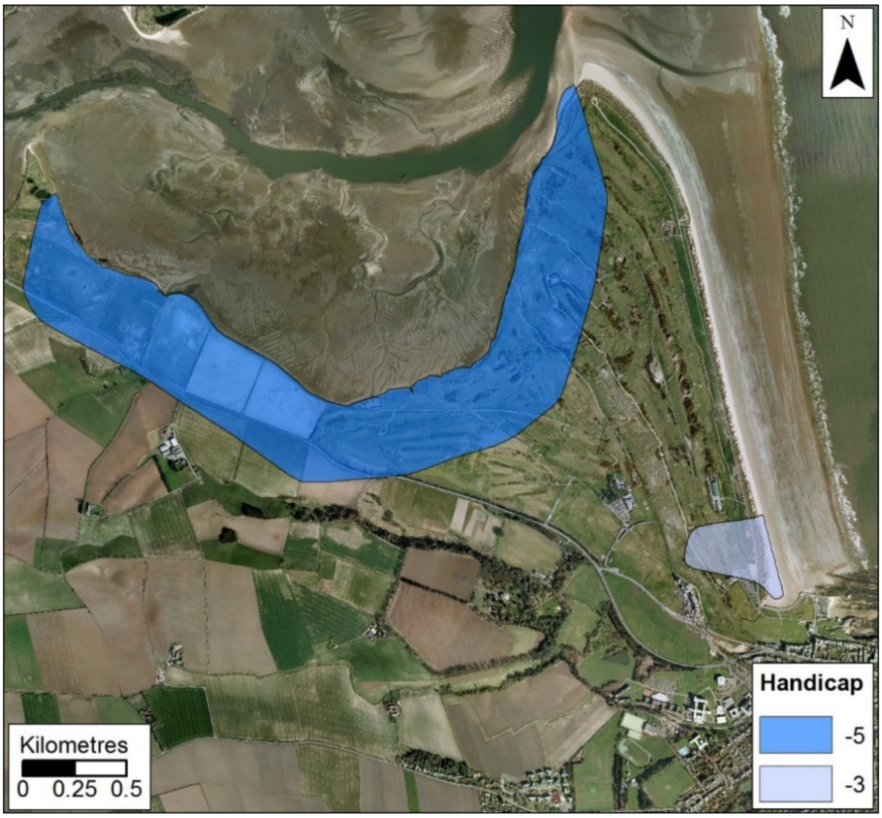

Figure 3.9: An example of the defence data form within the CESM at St. Andrews, Fife. The southern shore of the Eden Estuary is defended by riprap ('hard' defences), which is represented as a polygon that extends 400 m inland, and a handicap value of -5. At the southern end of West Sands, is a small area of managed dune, and therefore classed as 'soft' defences. A polygon extending 400 m inland, and given a handicap score of -3 is sued to represent this. Aerial photography courtesy of the OS.

3.1.5 UPSM & CESM Post Processing Edits

After the data layers in the UPSM were amalgamated, and the defence and sediment supply data were included to form the CESM, there were still areas with overestimated physical susceptibility. Therefore, a number of adjustments were made in the form of the following post-processing steps.

3.1.5.1 Surface Water Filter

Inland areas of water i.e. lochs, were occasionally picked out by the UPSM/CESM as susceptible to erosion as the water surfaces of many lochs have low elevations. In reality these lochs are highly unlikely to be susceptible and should therefore be removed from the model to ensure the user is not misled by the anomalous areas. This was performed using the OS VectorMap District data, which identifies areas of surface water as polygons. Where the OS VectorMap District data identified a polygon of surface water, this area within the UPSM and CESM was reclassified to a value of 3.5 (the python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.9).

3.1.5.2 Rockhead Filter

Areas where the rockhead elevation is greater than 6 m above MHWS are unlikely to erode significantly, even in areas close to the coast and where wave exposure is high. Therefore using the rockhead elevation data calculated in Section 3.1.2.3 a mask was applied to the UPSM and CESM. Where the rockhead elevation was 6 m above MHWS, the UPSM and CESM was reclassified to 3.5 (the python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.10).

3.1.5.3 Superficial Deposit Filter

Areas where bedrock is located at the surface level are unlikely to erode due to the hard and resistant nature of the bedrock geology. Due to their relative strength compared to superficial deposits the different lithologies can be treated equally, and using the BGS Superficial Thickness Model where no superficial deposits exist and bedrock is at the surface, the UPSM and CESM were reclassified to 3.5 (the python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.11). The superficial deposit filter was not applied to the Outer Hebrides as this area is not mapped at the same scale as the rest of Scotland (Outer Hebrides mapped at 100,000, compared to 50,000 for the rest of the country).

3.1.5.4 Fill Edit

At this stage, the model identifies some areas of elevated susceptibility relative to the surrounding area that are hydrologically disconnected from the coast. In reality, these areas of elevated susceptibility will never erode, as they are effectively protected by land that will not erode. An example is shown in the left image of Figure 3.10.

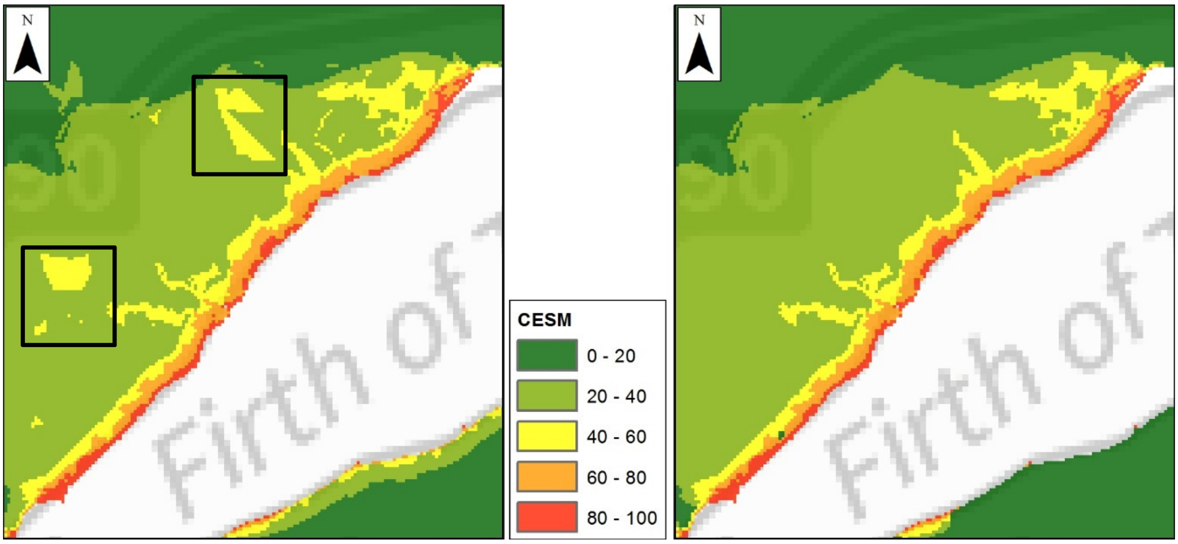

Figure 3.10: An example showing the before and after 'Fill Edit' post processing step. In the left image, areas of elevated erosion susceptibility relative to the surrounding area on the north side of the Firth of Tay can be seen (highlighted within black boxes). In the right image, these areas have been removed using the fill tool. The units of the CESM are dimensionless, with 0 equating to no erosion susceptibility, and 100, very high susceptibility. This is explained further in Section 3.1.6.

The peaks of high susceptibility need to be removed from the model to produce an output that better reflects reality. This is done using the 'Fill' tool in ArcGIS, with the peaks reduced to match the surround cell values. This has the effect of removing these peaks as seen in the right image of Figure 3.11 (the python code used within ArcGIS ModelBuilder to create this data is included in Appendix A.12).

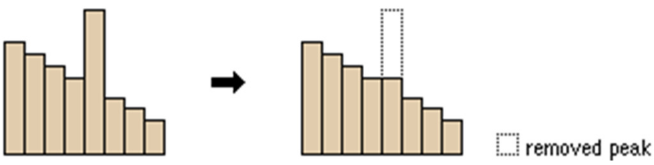

Figure 3.11: The effect of the Fill tool within ArcMap. Column heights represent the value of a hypothetical raster, with increasing height indicating an increasing value. Taken from ESRI (2012).

3.1.6 Interpreting the CESM

Unlike the UPSM, the CESM includes the influence of sediment supply and defences. Shorelines that benefit from sediment supply have been mapped and those sections receive a maximum reduction in their score of 3. In an example of a shoreline with low altitude, with deep bedrock, on an open and exposed coast (UPSM maximum value of 17.5) would result in a maximum score of 14.5 (i.e. 17.5 - 3 = 14.5) in the CESM. This therefore represents a reduction in the erosion susceptibility. Approximately, the same calculation would be true for areas benefiting from hard and soft coastal defences.

In some instances areas of accretion and coastal defence overlap and in such cases the two erosion handicap values were added together. Therefore it is possible for areas of the model to be reduced by a maximum handicap value of -8 (Defence Handicap (-5) + Accretion Handicap (-3) = -8).

To allow the results to be more easily interpreted and comparable with other outputs, the aggregated scores were converted to a dimensionless score using the following method:

$$\frac{(CESM\ Value - 3.5)}{14}\ x\ 100$$

hence a score of 3.5 becomes 0, 10.5 becomes 50, and 17.5 becomes 100.

Both the UPSM and CESM are output as a 50 m raster, but also the outer edge of this raster can be extracted to generate a polyline dataset that represents the coastline. This data is termed the UPSM or CESM coastline data accordingly.

3.1.7 Model Validation

To determine whether the CESM accurately represents coastal erosion susceptibility the model was quantitatively compared to two other datasets (SNH erosion data and Eurosion) and qualitatively validated by coastal scientists with an extensive knowledge of the Scottish coast. In addition to Hansom and Rennie, Professor Stewart Angus and Dr. George Lees (both of SNH) were not involved in any of the model development and so were able to provide an independent expert knowledge verification of the model. For the quantitative validation, both the SNH and Eurosion datasets highlighted where erosion is occurring and so the CESM should classify these areas with a high susceptibility score. The model could only be validated with data for locations where erosion is known to be active. The coast may not be erosional for one of two reasons: either the coast has low susceptibility and is therefore resistant to erosion, or the coast has high susceptibility but erosion has yet to occur (Table 3.10). Therefore it is not possible to validate the CESM accuracy along coasts where no erosion has occurred as the reason why the coast is not currently eroding cannot be determined. Additionally, as there is no other model of coastal erosion susceptibility to directly compare against, a qualitative validation was performed to allow coastal managers to use the CESM in a manner that is similar to the envisaged end use of the model. The validation methodologies are described below.

Table 3.10: A grid detailing the reasoning why it is only possible to validate the CESM using data for where coastal erosion is occurring. There are two reasons coasts may not be erosional; either the coast has low susceptibility, or the coast may have high susceptibility but erosion has yet to occur. There is no data to determine which state is true. Therefore, only by using data for where erosion is occurring, the accuracy of the CESM can be determined.

		Actual Situation	
		No Erosion	**Erosion**
Model Output	**Low Susceptibility**	The model is potentially accurate	The model is inaccurate
	High Susceptibility	The model is potentially accurate	The model is accurate

3.1.7.1 Quantitative Validation

Data was supplied by SNH which showed the approximate location of lengths of coast where coastal erosion casework had been carried by SNH since 2008. The data included 63 different locations equalling a coastal length of approximately 74 km. The Eurosion (2004) coastal evolution data includes information on where coastal erosion was occurring during or just before 2004. These are coded as 50 (erosion confirmed, localised on parts of the segment), 51 (erosion confirmed, generalised to almost the whole segment) and 4 (erosion probable but not documented). The data included 476 different locations equalling a coastal length of approximately 1,298 km. Both the SNH and Eurosion data were translated onto the UPSM/CESM coastline by buffering the data and intercepting the resulting polygon with the CESM coastline. The locations were manually checked to ensure the data was translated onto the correct stretch of coastline. The average CESM score was then calculated for each stretch of coast identified as eroding.

3.1.7.2 Qualitative Validation

Two experts from SNH (Stewart Angus and George Lees[8]) were asked to give feedback on the CESM as independent coastal scientists capable of offering balanced and unbiased comment on the model. Both have extensive knowledge of the Scottish coast and can be used to qualitatively validate points where the model either under or overestimates coastal erosion susceptibility. To facilitate their feedback both were asked to rank the CESM accuracy on a scale of 1 to 5 (1 = Low accuracy, 5 = High accuracy) for a number of key

[8] Angus and Lees have over 50 years combined of direct experience of coastal erosion on the Scottish coast.

locations around the Scottish coast (Table 3.11). They were also asked to comment on the CESM at these locations, and of the model output in general.

Table 3.11: Example of the questionnaire that Stewart Angus and George Lees were asked to complete.

	CESM Accuracy (1 to 5)	**Comments (Which areas were modelled well? Which areas need to be improved?)**
Aberdeen		
Ayr		
Dornoch		
Dundee		
Edinburgh		
Glasgow		
Inverness		
Kirkwall		
Stornoway		
South Uist		

3.2 Exposure

Once the CESM has been produced it is then possible to calculate which assets are potentially exposed to coastal erosion. Assets take a number of different forms, from small singular assets e.g. dwellings (in GIS terms ‘point’ data), transport infrastructure e.g. roads and rail track (‘polyline data’), and areal assets e.g. golf courses (‘polygon’ data). The following assets have been selected due to their importance to society (this importance due to either a social, economic or cultural (or a mix of all three) contribution to society).

3.2.1 Point data

A license was acquired to use the OS MasterMap Address Layer 2 data, which identifies 222 different asset types (both residential and commercial) and their location. Knowing the location of an asset allowed the point data to be spatially joined with the UPSM and CESM and allowed identification of any assets located in areas that are highly susceptible to coastal erosion. The same process was utilised to identify Listed Buildings exposed to coastal erosion using data from Historic Scotland (http://data.historic-scotland.gov.uk/). Historic Scotland assign listed buildings into either A, B or C categories, based on their importance according to the following criteria:

- **Category A** - Buildings of national or international importance, either architectural or historic, or fine little-altered examples of some particular period, style or building type. (Approximately 8% of the total).

- **Category B** - Buildings of regional or more than local importance, or major examples of some particular period, style or building type which may have been altered. (Approximately 50% of the total).

- **Category C** - Buildings of local importance, lesser examples of any period, style, or building type, as originally constructed or moderately altered; and simple traditional buildings which group well with other listed buildings. (Approximately 42% of the total).

It should be noted that the boundaries of dwellings, key assets and listed buildings are not represented within the point datasets. However, as the UPSM and CESM are at 50 m grid cell size, much larger than most buildings, this should minimise any error.

3.2.2 Polyline Data

To calculate the lengths of road and rail track (taken from OS Meridian 2 data) infrastructure that might be exposed to coastal erosion, the polyline data was split according to the CESM 50 m raster 'grid'. Once the polyline data had been split, the CESM score was assigned to the length of road/rail track. This allowed the calculation of the length of rail track/road located in highly susceptible areas.

3.2.3 Polygon data

Exposed areas of golf course (using OpenStreetMap data), Scheduled Monuments (Historic Scotland data), and areas of environmental protection[9] (Site of Special Scientific Interest (SSSIs)[10], Geological Conservation Review (GCR)[11] sites, Special Area of Conservation (SACs)[12] sites and Special Protected Area (SPAs)[13] – data from SNH) were calculated in a similar manner to the polyline data. The polygon data was split into individual polygon areas based upon the raster CESM raster 'grid'. The CESM value was then assigned to the now 50 x 50 m polygons. The area of the asset deemed highly susceptible to erosion was then calculated.

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[9] The World Heritage Site of St. Kilda was not assessed as it is situated outside of the boundaries of many national datasets.

[10] SSSIs are a UK level designation which includes geological and biological designations. An area of approximately 9,436 km^2 (93%) is located landward of MHWS.

[11] GCRs are a UK based review of nationally important Earth Science sites, listing those of national and international importance. An area of approximately 2,246 km^2 (81%) is located landward of MHWS.

[12] SACs are an EU level designation which includes a wide range of biological interests. An area of approximately 6,072 km^2 (15%) is located landward of MHWS.

[13] SPAs are an EU level designation for the protection of birds and their supporting habitats. An area of approximately 10,092 km^2 (79%) is located landward of MHWS.

3.2.4 Urban/Rural Classification

To determine whether the assets were located within either urban or rural environments, the Scottish Government (SG) Urban/Rural classification was used (The Scottish Government, 2014). This analysis is important as it assesses whether the assets that are exposed are likely to be locally important to the community i.e. if a road is lost in a more remote area, that road may be the only road available with no alternative routes, and therefore the disruption would be significant. Hence, combining transport data with urban/rural data can assist in identifying vulnerable infrastructure. The classification uses population and accessibility (in the form of drive time analysis) data to categorise areas into one of six urban/rural classes. The Urban/Rural Classification is available in shapefile format, which was intersected with the transport infrastructure data i.e. roads and rail track. This resulted in an Urban/Rural Classification being assigned to roads and rail track data, and an assessment of their likely importance to the local community established.

Table 3.12: The six classes of the Scottish Government Urban/Rural Classification 2013-2014.

Class	Class Name	Description
1	Large Urban Areas	Settlements of 125,000 or more people.
2	Other Urban Areas	Settlements of 10,000 to 124,999 people.
3	Accessible Small Towns	Settlements of 3,000 to 9,999 people and within 30 minute drive of a settlement of 10,000 or more.
4	Remote Small Towns	Settlements of 3,000 to 9,999 people and with a drive time of over 30 minutes to a settlement of 10,000 or more.
5	Accessible Rural	Areas with a population of less than 3,000 people, and within a 30 minute drive time of a settlement of 10,000 or more.
6	Remote Rural	Areas with a population of less than 3,000 people, and with a drive time of over 30 minutes to a settlement of 10,000 or more.

3.2.5 Economic Values

To assign an economic value to the assets exposed to coastal erosion a unit value has to be assigned to that asset. The economic values chosen are based on the information below.

3.2.5.1 House Prices

The Register of Scotland produces a quarterly assessment of house prices in Scotland. The data used in this research is taken from the July to September 2014 quarter (Registers of Scotland, 2014). The average house price for the dwellings within each local authority was used to estimate economic values, rather than a national average (Table 3.13). Note that coastal properties are often priced at a premium, therefore the average local authority house price may underestimate the value of properties at the coast.

Table 3.13: Average house prices in each local authority for quarter of July to September 2014. Taken from Register of Scotland (2014).

Local Authority	Jul-Sept 2014 (£)
Aberdeen City	221,268
Aberdeenshire	232,803
Angus	162,354
Argyll and Bute	149,928
City of Edinburgh	235,402
Clackmannanshire	140,162
Dumfries and Galloway	139,054
Dundee City	128,901
East Ayrshire	115,845
East Dunbartonshire	217,596
East Lothian	223,429
East Renfrewshire	234,651
Falkirk	131,383
Fife	143,075
Glasgow City	138,885
Highland	165,519
Inverclyde	130,377
Midlothian	178,405
Moray	153,560
Na h-Eileanan an Iar	98,160
North Ayrshire	119,549
North Lanarkshire	119,348
Orkney Islands	129,075
Perth and Kinross	192,154
Renfrewshire	137,072
Scottish Borders	164,448
Shetland Islands	126,089
South Ayrshire	152,219
South Lanarkshire	130,436
Stirling	197,690
West Dunbartonshire	115,299
West Lothian	153,458

3.2.5.2 Roads

Assigning a single value to coastal road repairs due to erosion is difficult since the costs associated with road repairs varies on a case by case basis. However, a proxy that can be utilised as an estimate is the repairs made to the A2 in Northern Ireland. The damage caused by coastal erosion associated with tidal surges in early January 2014, caused a collapse of half the carriageway along a 40 m length of the road. The repair costs were £260,000 which included the reconstruction of the fallen section of road and the provision of rock armouring sea defences (Northern Ireland Executive, 2014). Therefore, an approximate cost to repair a section of road affected by coastal erosion might average about £6,500 per metre.

3.2.5.3 Rail Track

In the same way rail track infrastructure costs vary considerably due to local conditions, it is therefore difficult to assign a standard cost to repair a stretch of rail track damaged by coastal erosion. However, a recent event in Dawlish, England during the winter storms of 2013/14 can be used as a proxy. During the storms the sea wall protecting the rail track failed resulting in approximately 100 m of rail track being damaged (Network Rail, 2014). The damaged section was repaired at a cost of £ 15 million (The Guardian, 2014) or £150,000 per metre, a value that can be used as an approximate cost of repairing a rail track affected by coastal erosion

3.2.5.4 Golf Courses

A report by KPMG (2013) states that the golf industry is worth £1.171 bn to Scotland's economy each year. Approximately, £319 million of this comes directly from running of the golf course facilities i.e. green fees, membership fees etc. This value better represents the value of the actual golf course itself, rather than the indirect benefits that the golf industry brings to Scotland. With the total area of golf courses in Scotland equalling 176 km^2 (calculated from OpenStreetMap data), every 1 m^2 of golf course contributes £1.81 to the Scottish economy each year (£319,000,000 ÷ 176,000,000 m^2). Given the perceived added value of coastal (links) golf courses, this national average may underestimate the contribution of coastal golf courses.

3.3 Socioeconomic Vulnerability

Following assessment of the geomorphological context of coastal erosion the socioeconomic context needs to be assessed. The methodology set out here aims to identify the people most vulnerable to coastal erosion and where they live. Vulnerability was defined in the previous chapter as "*the extent to which a person, group or socioeconomic structure is likely to be affected by a hazard (related to their capacity to anticipate it, cope with it, resist it and recover from its impact)*" (Twigg, 2001: 6). This section will discuss the data sources used, the socioeconomic indicators chosen and the rationale for their selection, and the method used to produce the Coastal Erosion Vulnerability Model (CEVM).

3.3.1 Socioeconomic Data Source

Census data has been used widely within the literature e.g. Cutter et al. (2003) to assess socioeconomic vulnerability. However, for this research census data was rejected as the Output Areas (OA) for which census data is published can cover a large area for some regions of Scotland. OAs are assembled using clusters of postcodes to give a minimum area to ensure data confidentiality and are designed to have similar population sizes. For areas where the population density is high, such as Glasgow, the OAs have a small area. However, for sparsely populated regions such as the Highlands, the OAs have a large area, and has the potential to obscure the range of different socioeconomic types within an area. To reduce ambiguity in the data, a smaller scale output unit is desirable, such as postcodes. Table 3.14 shows a statistical comparison between the two units within Scotland. Postcodes have a smaller mean area at 0.6 km^2 compared to OAs at 1.8 km^2, and are more uniform in terms of area as demonstrated by a postcode standard deviation of 4.96 km^2 compared to 14.20 km^2 for OAs. Data availability at postcode level would be more representative of that area and identify smaller ‘pockets’ of key socioeconomic types.

A reliable data source at postcode level is the Experian Mosaic geodemographic classification, which was used by Tomlinson et al. (2011) and Willis et al. (2010) as discussed in the previous chapter. For use within this research, Experian kindly agreed to allow the Mosaic Scotland data to be used. This geodemographic classification is tailored to the socioeconomic characteristics of Scotland.

Table 3.14: Statistical analysis of 2001 Census Output Area and Postcode units

	Number of Units	**Maximum (km^2)**	**Minimum Area (km^2)**	**Mean Area (km^2)**	**Standard Deviation (km^2)**
Census Output Area	42,604	797.3	0.000083	1.8	14.21
Postcode	145,783	435.6	0.0000001	0.6	4.96

Experian (2004) state that 400 variables were used to build Mosaic Scotland, of which 54% were sourced from the 2001 Scottish Census. The reliance on potentially out of date data is partly offset by assimilation with more recent datasets including the Electoral Roll, Experian Lifestyle Survey information, Consumer Credit activity, Post Office Address File, Shareholders Register, House Price and Council Tax information, and General Register Office for Scotland’s library of Neighbourhood Statistics. The data is used to identify the socioeconomic indicators shown in Figure 3.12.

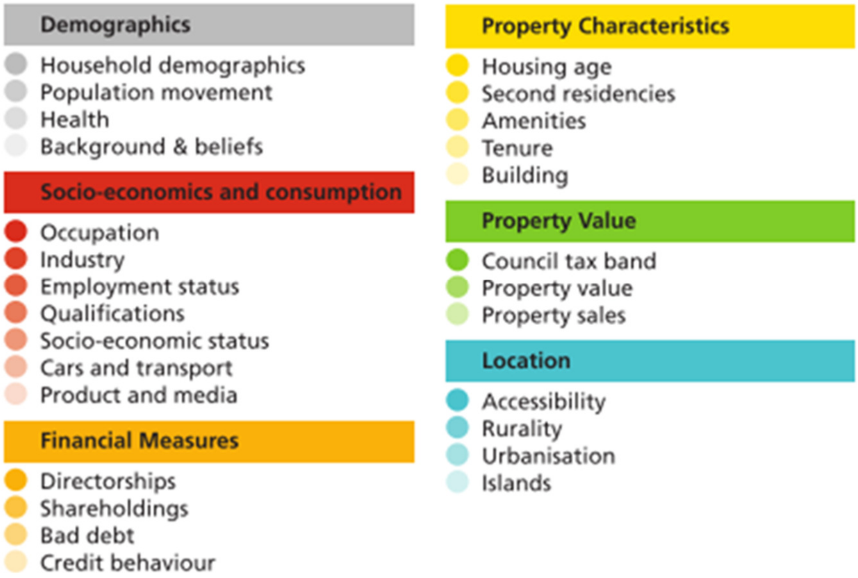

Figure 3.12: Types of socioeconomic indicators used in Mosaic Scotland. Taken from Experian (2004).

The data is then clustered using a range of statistical techniques by Experian. The variables are weighted and result in variables with "*differing importance to the clustering methodology, depending on how well they discriminate at differing levels of geography*" (Experian, 2004: 4). The categorisation is then validated through market research and fieldwork. The analysis resulted in 44 neighbourhood types being identified within Scotland. The types range from '*Captains of Industry'* who are characterised as being highly qualified wealthy professionals, with expensive homes and cars to '*Twilight Infirmity'* who are pensioners in sheltered accommodation on low incomes or capital. The neighbourhood types and some of their key characteristics are show in Table 3.15.

Supporting the Experian data is a spreadsheet termed the 'Grand Index' representing the background information used to construct the Mosaic Scotland geodemography. This spreadsheet shows the breakdown of the different data used (there are 536 different variables) and value (as a percentage) for each of the 44 groups. For example, for the amount of detached properties in each group, 75.73% of dwellings are detached properties in Group 1 (Captains of Industry), compared to 18.87% in Group 18 (Far Away Islanders). Each postcode was assigned to one of the 44 groups.

Table 3.15: Neighbourhood types used within Experian Mosaic Scotland and some of their key characteristics.

Group	Name	Selected Characteristics
1	Captains of Industry	Full nest families Powerful elite Very wealthy Top professionals Expensive homes Desirable locations Well qualified Well informed Expensive cars
2	Wealth of Experience	Empty nest families Retired couples Wealthy Sound investments Substantial homes Respectable suburbs Many holidays
3	New Influentials	Full nest families Young/teenage children Well educated Professional/managers Technical occupations High incomes Well built stone houses Peaceful areas Well informed
4	Successful Managers	Older married couples Older children Well educated Directors/managers Good incomes Planning for future Comfortable lifestyle
5	White Collar Owners	Young full nest families Dual incomes Professional/managers Modern semis Two car household Careful with money Comfortable lifestyle
6	Emerging High Status	Young full nest families School age children Professional jobs Affluent lifestyle Detached houses
7	New Suburbanites	Young families Professional occupations Reasonable salaries Hard working Money conscious Semi-detached homes
8	Settling In	Young families Young singles & couples Professional jobs Ethical consumers Good incomes New properties
9	Military Might	Servicemen and family Military housing Married young Good incomes Work hard, play hard Good health
10	Songs of Praise	Older couples & families Some self-employed Some retired High savings Comfortable lifestyles Well built stone houses Community networks
11	Ageing in Suburbia	Middle-aged couples Empty nest families Semi-detached homes Savings & Investments Plenty of time Lively
12	Blue Collar Owners	Married couples School age children Technical/supervisory jobs Middle incomes Savings plans & pensions
13	Towns in Miniature	Older singles & couples Highlands & the coast Tight knit communities Low incomes & outgoings Some investments
14	Rural Playgrounds	Full nest families Farming communities Diverse cultures Some wealthy landowners Agricultural workers Desirable commuter areas
15	Agrarian Heartlands	Older families Large scale farming Skilled tradesmen Few prospects Few social problems High car ownership
16	Isolated Farmsteads	Scattered farmers Older working ages High incomes Traditional gender roles Detached rendered homes High car ownership No social problems
17	Scenic Wonderland	Empty nest families Small scale fishing Small scale farming Dramatic scenery Attractive housing High car ownership Few social problems
18	Far Away Islanders	Older families Children away at college Highlands & Islands Scattered communities Skilled trades Some second homes

Group	Name	Selected Characteristics
19	Prestige Tenements	Young singles & couples Who's Who of Scotland Top professionals No children High incomes Educated Intellectual Well informed
20	Studio Singles	Singles & co-habitees No children City tenements Bustle of city centre life Professional & service jobs Well informed
21	Rucksack and Bicycle	Young singles Four storey tenements Low incomes Freedom before careerdom Socialising with friends Liberal minded
22	College and Campus	Students (18-24) Intelligent Ambitious Low incomes Financially carefree Socially aware Politically aware
23	Inner City Transience	Young singles & couples Well educated Strong self-image Ambitious Career focused Hard working
24	Cosmopolitan Chic	West of Scotland Young singles Young co-habitees Few children Good education Pleasant tenements Professional occupations Cars not needed
25	Tenement Lifestyles	Singles & co-habitees Some very young children Ethnic mixture 4-storey tenements Routine work Low incomes Overcrowding Social deprivation Poor in every sense Life is tough
26	Downtown Flatlets	Young singles/co-habitees City and town centres Just left home, first job Routine occupations Low incomes Debt Modest outgoings Low car ownership Music and fashion Outer directed, content

Group	Name	Selected Characteristics
27	30 Something Singles	Older singles/co-habitees Well educated Well paid Professional/technical jobs Hard working Pleasant flats Respectable areas
28	Small Town Pride	Singles and co-habitees Some older people Few children Well educated Professionals/managers Converted flats
29	Dignified Seniors	Elderly people Some widowed No children Index linked pensions Small private flats Few social problems
30	Sought after Schemes	Older couples Exercised Right to Buy Intermediate jobs Strong work ethic Budget conscious
31	Rustbelt Renaissance	Older working ages Skilled trades/operators Hard working Exercised Right to Buy Generous plots Modest means Rooted in community
32	Planners Paradise	Families with children Modern spacious terraces Exercised Right to Buy Focus on family life Possibly overstretched
33	Smokestack Survivors	Families with children Some single parents Plant/machine operators Customer service High unemployment Low incomes Health problems
34	Quality City Schemes	Young families Some single parents School age children Vocational qualifications White collar workers Good incomes Pleasant homes Comfortable way of life

Group	Name	Selected Characteristics	Group	Name	Selected Characteristics
35	Lathe and Loom	Poorer families Single parents Routine work Low incomes Small town life Compact terraces Good council schemes Focussed on children	40	Families in the Sky	Single parents School age children Few qualifications High unemployment Purpose built flats State benefits Financial worries Long term sickness Alcohol and cigarettes
36	Indebted Families	Singles & co-habitees Many children Poor education High unemployment Low incomes Financial difficulties Deprivation Poor health Heavy smokers	41	Elders 4 in a Block	Pensioners Many widowed Rented flats & terraces Attractive areas State pension
37	Pockets of Poverty	Young parents Many children Flats in blocks Undesirable areas State dependency Debt problems Downtrodden, not down Alcohol & tobacco	42	Greys in Small Flats	Pensioners Some young families Blocks of flats Not desirable areas Poor education High unemployment Weak community ties Some long term illness
38	Mid Rise Breadline	Young single parents Many children 4 storey blocks Very poor areas Poor education Overcrowding Extreme deprivation Welfare dependency	43	Skyline Seniors	Poor singles Many pensioners Small council flats High rise blocks Unpleasant areas State benefits Health problems
39	Room and Kitchen	Single older adults Few children Small council flats City service jobs Low incomes Legacy of poor health	44	Twilight Infirmity	Pensioners Sheltered accommodation Residential homes Low incomes State pensions Few investments

To simplify analysis of the data, the data is standardised into an index value. The index value is calculated by Experian in the following manner:

Equation 3: Calculation of Index Value as used by Experian.

$$Index\ Value = \frac{Indicator\ Percentage}{Indicator\ Mean\ Percentage} \times 100$$

therefore an index of 100 means that an indicator variable value equals the mean. If we used the previous detached property example, the mean percentage across all 44 groups is 18.66%. For Group 1 (Captains of Industry) the index value equals 406, compared to a value of 101 for Group 18 (Far Away Islanders). Converting the percentages into index values allows the user to clearly see that the amount of detached dwellings in Group 1 is far above the national average, whereas the amount of detached dwellings in Group 18 is approximately average. The indicators that are significantly above and below a value of 100 are the most useful at discriminating between socioeconomic groups. However, not all the variables used with Mosaic Scotland are suitable for use within a coastal erosion vulnerability assessment. Hence, the literature was used (Table 2.18) to inform the selection of the most relevant variables to coastal erosion.

3.3.2 Selection of Socioeconomic Indicators

Using the information collated in the previous chapter a number of socioeconomic indicators were selected from the Grand Index that were regarded as being most applicable to coastal erosion vulnerability. The indicators chosen and the rationales behind their selection are shown in Table 3.16. For nine indicators, the relationship with vulnerability is positive, i.e. with an increase in the index score, vulnerability increases. For two indicators (dwelling density and property value) there is a negative relationship.

With the socioeconomic indicators selected, the Experian Mosaic Scotland data was processed in order to produce the vulnerability assessment. The data processing steps to do this are discussed in the following section.

Table 3.16: The indicators used within the Coastal Erosion Vulnerability Model and the rationale for their selection.

Indicator	Sensitivity	Resilience	Indicator & Vulnerability Relationship	Supporting Evidence for Use
Net Household Income	Those on a low income are likely to be already in financial difficulty and could easily be pushed into further problems. Financial difficulty can also severely impact upon mental health.	Those on low income will have little disposable income to use for recovery. Those on low income will suffer the most if days of work are missed in order to address problems at home.	Positive	(Burton et al., 1993; Cutter et al., 2000; Hewitt, 1997; Peacock et al., 1997; Platt, 1995; Puente, 1999)
Poor Health	Those in poor health may struggle with the mental impact of the hazard situation as they may be already physically or mentally stressed. Those in poor physical health may struggle if short term evacuation was required due to mobility and health complications.	Those in poor health may be unable to adapt to a new living situation, and may be moved away from a community support network. They will likely be reliant on others for help who may no longer be able to assist them.	Positive	(Dwyer et al., 2004; Morrow, 1999; Tobin and Ollenburger, 1993)
Elderly	The elderly may be heavily reliant on their homes as they are tailored to their needs. Loss of this home may have serious implications to quality of life. The elderly may struggle with mobility if required to evacuate a property at short notice.	The elderly are often reliant upon people within the local community, if the elderly person is repatriated elsewhere this may seriously impact on their mental and physical wellbeing	Positive	(Cutter et al., 2000; Hewitt, 1997; Ngo, 2001; O'Brien and Mileti, 1992)
Single Parents with Dependent children	Those with dependent children may find their finances are already stretched, and may be pushed into difficulty.	Recovery decisions have to be considered with the children's wellbeing in mind, therefore repatriation to a new area (either short or long term) may impact upon child's education and social wellbeing. A single parent would be put under considerable financial, physical and mental stress if having to deal with both recovery from property loss and taking responsibility for child care.	Positive	(Heinz Center for Science Economics and the Environment, 2000; Morrow, 1999; Puente, 1999; Wisner et al., 2004)
No Savings	-	A lack of savings hinders the ability of people to cope with short and long term financial pressures and adapting to a new living situation could be financially demanding.	Positive	(Burton et al., 1993; Cutter et al., 2000; Hewitt, 1997; Peacock et al., 1997; Platt, 1995; Puente, 1999)

Indicator	Sensitivity	Resilience	Indicator & Vulnerability Relationship	Supporting Evidence for Use
Secured/ Unsecured Loans	-	People with loans are required to make monthly payments, if the ability to pay these loans is hindered due to unexpected but necessary costs elsewhere, they may suffer short and/or long term financial difficulty.	Positive	(Burton et al., 1993; Cutter et al., 2000; Hewitt, 1997; Peacock et al., 1997; Platt, 1995; Puente, 1999)
No Access to a Vehicle	Without a car, short term evacuation of people and possessions is more difficult.	If a person is repatriated to a new location, without a car travelling between a work place or school may be problematic.	Positive	(Masozera et al., 2007; Morrow, 1997)
Homeowners	-	Those living in a mortgaged property may find themselves in negative equity, and may struggle financially as a result. Those who own their home outright lose a significant financial asset, which may impact upon their future finances.	Positive	(Felsenstein and Lichter, 2013)
Education	Lower education level hinders the ability to understand and interpret warning information.	Those with higher education levels have a greater range of potential job options and can therefore seek employment in a number of sectors. Those with higher education levels are more likely to have higher paid jobs.	Positive	(Heinz Center for Science Economics and the Environment, 2000; Howieson and Iannelli, 2008; Howieson, 2003)
Dwelling Density	A low dwelling density means that the cost/benefits of installing state funded defences are likely to be low and therefore not installed.	Areas with low dwelling densities will be more reliant on locally based resource extraction e.g. farming, which limits employment and housing options.	Negative	(Cova and Church, 1997; Cutter et al., 2000; Mitchell, 1999)
Property Value	Low value housing is often in more physically susceptible areas.	House price is an indication of wealth, and those with expensive houses are often economically well off and have a money invested in other assets, and hence more money available to enable recovery.	Negative	(Adger et al., 2004; Felsenstein and Lichter, 2013)

3.3.3 Data Processing

Once the indicators had been selected some of the original data (Table 3.17) required processing where a number of data variables needed to be amalgamated into a single indicator. Additionally, some indicators had to be adjusted so that the relationship between the indicator and vulnerability was compatible with the other indicators. The indicators requiring pre-processing and the methods used are listed below:

- *Income* - the income indicator is an aggregation of the income variables shown in Table 3.17. Therefore the final income indicator represents the proportion of people that have a net income of £399 or less per week. This value was chosen as the median weekly household income for 2011/12 in Scotland was £436 (Scottish Government, 2013). Therefore by selecting the data up to £399 it is possible to identify those on lower incomes relative to the Scottish population.

- *Education* – the education indicator is an aggregation of the education level variables shown in Table 3.17. The final education level indicator represents the proportion of people that left school at 16 or earlier. Scottish pupils who leave school at 16 or before are often those with low attainment and are likely to experience unemployment and unstable post-school careers (Howieson and Iannelli, 2008; Howieson, 2003). They are also unlikely to gain other qualifications and in employment have poorer prospects of training. Data that identifies those that leave school at 16 or before is therefore a useful socioeconomic indicator.

- *Elderly* – the elderly indicator is an aggregation of two data variables; households with 'Single Pensioners' and households that are 'Exclusively Pensioners'. The two data variables are added together to represent the total amount of households with resident pensioners.

- *Dwelling Density & Property Value* – both variables have an inverse relationship with vulnerability i.e. with an increase in their index value vulnerability decreases. For compatibility with the other indicators this relationship needs to be reversed. To do this the calculation in Equation 3 needs to be rearranged to equal:

$$Adjusted\ Index\ Value = \frac{Indicator\ Mean\ Percentage}{Indicator\ Percentage} \times 100$$

With this adjustment, an increase in housing density or property value will now result in a low index value and makes this compatible with all other indicators where an increase in index value signifies an increase in vulnerability.

Table 3.17: The raw data variables taken from the Experian Mosaic Grand Index to generate the socioeconomic indictors used within the Coastal Erosion Vulnerability Model.

Indicator	Data Source	Data Description	Data Level
Income	Yougov financial screener	Less than £100 a week £100 to £199 a week £200 to £299 a week £300 to £399 a week	Household (%)
Poor Health	Census CYE	Health - Poor health	Adult population (%)
Elderly	Census CYE	Single pensioner Exclusively pensioners	Households (%)
Single Parents with Dependent children	Census CYE	Lone parents with dependent children	Households (%)
No Savings	Yougov financial screener	Proportion with no savings	Adult population (%)
Secured/ Unsecured Loans	Yougov financial screener	Proportion with unsecured/secured loans	Adult population (%)
No Access to Vehicle	Yougov financial screener	None	Adult population (%)
Homeowners	UKCDD	Owner Occupied	Households (%)
Education Level	Research Now	Primary (left before 16, before finishing secondary school) Secondary (left at 16 or 'O' Levels or GCSE's)	Adult population (%)
Dwelling Density	Dwelling estimates + spatial analysis	Dwelling density (1km)	Dwellings
Property Value	UKCDD + Analysis	Postcode Average property value	Households

For a robust vulnerability assessment it is important that indictors have minimal statistical correlation. To ascertain if there are any interdependencies a Pearson correlation test was performed within Minitab. A value of ±1 indicates linear correlation between two indicators. Willis et al. (2010) use a correlation of ±0.85 as an indicator of high correlation within their work. The correlations for the socioeconomic indicators used are shown in Table 3.18. None of the correlations are greater than ±0.85, therefore all the proposed indicators can be used within the vulnerability model.

Table 3.18: Pearson Correlation values between the socioeconomic indicators used within the Coastal Erosion Vulnerability Model.

	Income	Poor Health	Elderly	Single Parents with Dependent Children	No Savings	Secured/Unsecured Loan	No Access to Vehicle	Home Owners	Education Level	Dwelling Density
Poor Health	0.744									
Elderly	0.437	0.562								
Single Parents with Dependent Children	0.408	0.456	-0.209							
No Savings	0.675	0.715	0.02	0.792						
Secured/ Unsecured Loan	-0.063	0.045	-0.196	0.253	0.312					
No Access to Vehicle	0.635	0.537	-0.07	0.428	0.614	-0.189				
Home Owners	-0.721	-0.683	-0.067	-0.554	-0.782	0.01	-0.735			
Education Level	-0.241	-0.317	0.066	-0.23	-0.347	0.286	-0.594	0.557		
Dwelling Density	-0.212	-0.169	0.216	-0.105	-0.231	0.277	-0.815	0.415	0.542	
Property Value	0.66	0.66	0.127	0.532	0.727	0.41	0.445	-0.643	-0.08	-0.083

3.3.3.1 Weighting using Lorenz Curves and Gini Coefficients

When combining the socioeconomic indicators together it is useful to include weightings to identify the most important indicators and this can be performed with a published methodology using Lorenz curves and Gini coefficients (Willis et al., 2010). Lorenz curves are a graphical representation of inequality, which are complemented by Gini coefficients that are a statistical measure of inequality (Black et al., 2009). Both these "devices" are routinely used within the field of economics. For example, using the personal income example used by Black et al. (2009), the axes of the Lorenz curve will be 'cumulative share of income' against 'cumulative share of population'. The resulting curve shows the distribution of income throughout the population, with a straight Lorenz curve indicating equal distribution, and a skewed curve indicating inequality. An example is shown in Figure 3.13.

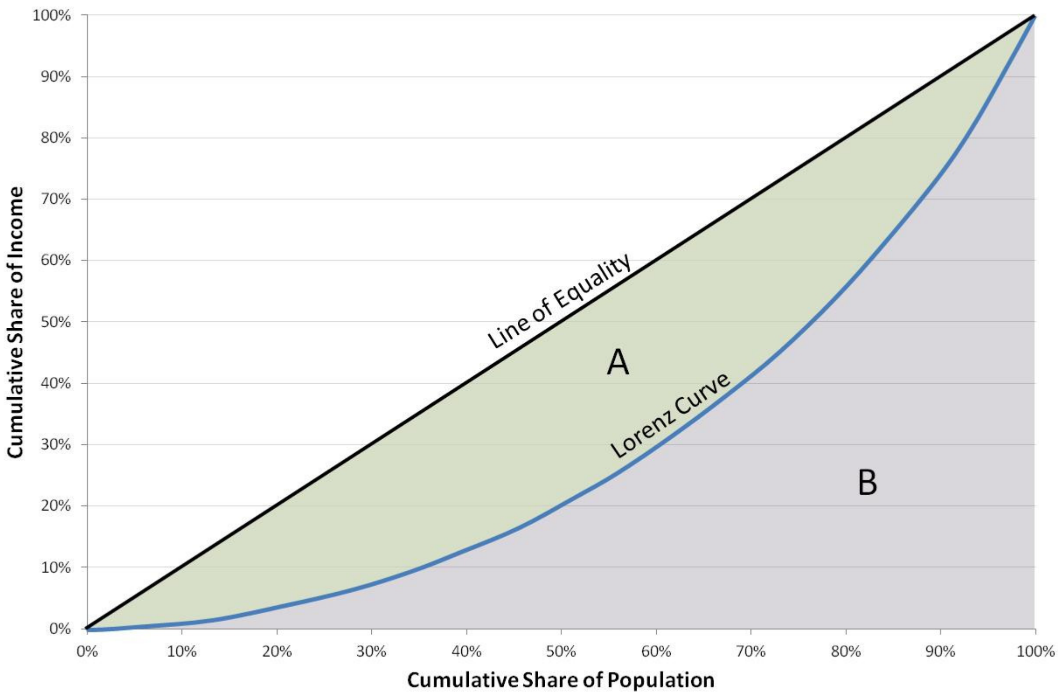

Figure 3.13: A hypothetical example of a Lorenz Curve. The Gini co-efficient is calculated using the areas of A and B.

The Gini coefficient can be calculated as a ratio between the areas of A and B shown in Figure 3.13. A Gini coefficient value of 0 indicates equality; whereas a value of 1 indicates maximum inequality. The calculation is as follows:

$$Gini\ coefficient = \frac{A}{A+B}$$

It is possible to weight individual indicators using the Lorenz curves and Gini coefficients as the "*discriminatory differences can be brought out by analysing population distribution*" (Willis et al., 2010, p. 7). The Lorenz Curves and Gini coefficients were calculated for each of the indicators listed in Table 3.17 as follows:

1. The first stage is to calculate the proportion of the total Scottish population and total dwellings represented in each of the 44 categories. This is calculated using data included in Mosaic Scotland which represents the percentage of the population allocated into each of the 44 groups, e.g. Group 1 has 2.25% of the Scottish population. Taking the total Scottish population as 5,194,000 in 2009 (General Register Office for Scotland, 2010), we can estimate that Group 1 represents 116,865 people (5,194,000 x 0.0225). Mosaic Scotland also supply data for the percentage of dwellings allocated to each group. The total number of dwellings in Scotland is 2,558,733 (derived from GIS analysis of OS Address MasterMap Layer 2 data). Group 1 represents 1.36% of dwellings, which equates to an estimated 34,799

dwellings. The output at this stage is the population or number of dwellings represented in each of the 44 categories. (See Columns A and B in Table 3.19);

2. The next stage is to multiply the indicator data for each group by either the dwelling or population that data represents (the Data Level column in Table 3.17). For example, for the Homeowners indicator Group 40 represents 26,355 dwellings and 1.53% of those are owned by the occupants (Column C in Table 3.19) which equates to approximatly 403 dwellings (Column D in Table 3.19). This is then repeated for each of the other 43 categories. The output of this stage is either the population or number of dwellings represented by nine indicators (out of 11) in each of the 44 classifications. The two exceptions are *Property Value* and *Dwelling Density* as these are the only data not represented by a percentage. The *Property Value* data at this stage represents the total value of dwellings within each of the groups, and the *Dwelling Density* data represents a dimensionless number (See Appendix Table C.2.1.1). For each indicator the groups are then sorted in ascending order based upon the data calculated at this stage (Column D);

3. This stage is the calculation of the X axis used for the Lorenz Curve. The X variable is the cumulative population which in this case is represented by the 44 categories. If data was evenly distributed between each group, each group should represent 1/44th of the data (Column E in Table 3.19). Hence, plotted on the X axis is the cumulative distribution, e.g. the lowest ranked group within the Homeowners indicator should represent 2.27%, the second to lowest ranked should represent 4.54% and so on resulting in the top ranked group represents a cumulative value of 100% (Column F in Table 3.19);

4. This stage is the calculation of the Y axis used for the Lorenz Curve. First, the sum of the data calculated in Stage 2 is calculated e.g. For the Homeowners indicator, there are 1,604,679 homeowners in Scotland (sum of the Column D data for each of the 44 categories). The proportion of each group compared to the total is calculated, e.g. Group 40 has 403 homeowners, and therefore represents 0.0003 of the total (Column G in Table 3.19). The proportions are then cumulatively aggregated, so that the top ranked category represents a cumulative value of 1 (Column H in Table 3.19);

5. The Gini coefficient can be calculated using the Lorenz curve graph or by using the following equation:

$$Gini\ coefficient = 1 - \sum_{i=1}^{n}(X_{i-1} - X_i)(Y_{i-1} + Y_i)$$

where X_i is the cumulated proportion of the population (Column F in Table 3.19), and Y_i is the cumulated indicator data (Column H in Table 3.19) and the data is sorted in ascending order according to Y_i. Columns I, J, K, and L in Table 3.19 show the Gini coefficient calculation. Hence, the Gini coefficient for the Homeowners Indicator is 0.445;

6. The Lorenze Curve can then be drawn by plotting the X axis data calculated in Stage 3 (Column F in Table 3.19), against the Y axis data calculated in Stage 4 (Column H in Table 3.19). See Figure 3.14.

Once the Gini coefficients for all 11 variables were calculated they were applied to the Mosaic Scotland Index Value data. To do this the following calculation is performed:

$$Weighted\ Index\ Value = Index\ Value\ x\ Gini\ Coefficent$$

For example, Group 40 has an index score of 2.4 for the Homeowner indicator. The score becomes 1.1 when weighted with a Gini coefficient of 0.455. This was repeated for each of the other 43 groups for each of the eleven indicators. The average weighted index value for the eleven indicators in each group is then calculated, and the groups are sorted in ascending order using this average. At this point, the relative vulnerability of each Mosaic Scotland group has been calculated, with groups with a high average weighted index value indicating the most vulnerable groups (See Appendix Table C.2.1.2). The Mosaic Scotland groups were than assigned a vulnerability rank from 1 to 44 based upon their average weighted index score (a rank of 1 was assigned to the least vulnerable group i.e. the lowest average weighted index score, and a rank of 44 to the most vulnerable group). In order to further support analysis of the vulnerability data, the cumulative percentage population and dwellings the groups represent was calculated.

Once the vulnerability was calculated it was necessary to import the data into the GIS. To do this a spatial parameter needs to be assigned to the Mosaic Scotland data. The Mosaic Scotland data was supplied for each postcode in Scotland assigned to one of the 44 groups. Therefore, to import the data into the GIS the spatial information of each postcode was required. The GIS data '*Code-point with Polygons*' (accessed via Edina Digimap) includes the boundaries of each postcode in Scotland and was therefore utilised. By joining the Mosaic Scotland data with the GIS postcode data, it was possible to translate the Mosaic

Scotland groups and their associated vulnerability data into the correct postcode boundaries within the GIS. This output can therefore be considered as the socioeconomic vulnerability model, and is termed the Coastal Erosion Vulnerability Model (CEVM).

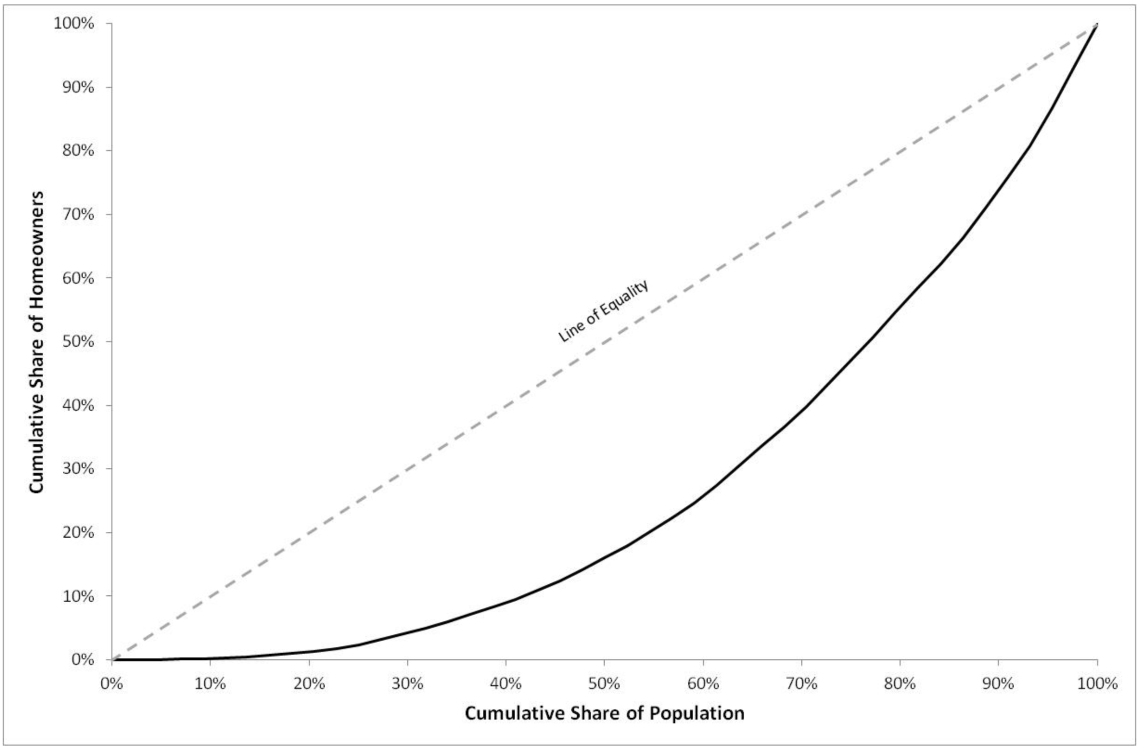

Figure 3.14: Lorenz Curve for the Homeowners indicator, which results in a Gini coefficient of 0.455. Dashed line represents line of equality.

Within the Mosaic Scotland data some postcodes are difficult to classify since they are dominated by non-residential buildings, such as hospitals. Experian designate such postcodes as 'Unclassified', representing 0.6% of Scottish postcodes. These postcodes may not be devoid of residential dwellings and so a conservative approach has been adopted to assign the maximum vulnerability score to unclassified postcodes (rather than exclude them from the analysis).

3.3.4 Model Validation

To validate the accuracy of the CEVM, the results are compared with the Output Area Classification 2011 (OAC2011). The OAC2011 is a geodemographic classification of the UK using 60 variables taken from the 2011 UK Census and uses the census output areas rather than postcodes as the spatial unit. The classification is hierarchical in structure and has Supergroup, Group and Subgroup tiers with 8, 26 and 76 classifications respectively (see Appendix C.2.2). The OAC2011 classification has been generated for general use and has not been specifically tailored for coastal erosion vulnerability. However, 'pen portraits' (descriptions of the classifications) and radial plots describing the characteristics of each classification group are provided and this allows qualitative assessment of the OAC2011 groups who may be vulnerable to coastal erosion (i.e. groups with above average levels of poor health would be considered vulnerable). The validation process was as follows:

1. The OAC2011 Subgroups were qualitatively assessed to determine their vulnerability to coastal erosion based upon the criteria set out in Table 3.16. Each Subgroup (76 classifications) was assigned a value of between 1 and 5, with 5 indicating very high vulnerability to coastal erosion and 1 indicating very low vulnerability to coastal erosion (see Appendix C.2.2).

2. As the OAC2011 used output areas rather than postcodes, each CEVM postcode was assigned an OAC2011 classification by converting the postcode unit areas into points at the polygon centroids. The points were then spatially joined to the OAC2011 output areas, along with the CEVM attribute data.

3. The data was then analysed by plotting the OAC2011 vulnerability rank against the CEVM rank.

Theoretically, areas that are identified as highly vulnerable in the CEVM should strongly correlate with the OAC2011 vulnerability rank. However, there are two key sources of potential error which could decrease the correlation. Firstly, the difference in spatial units used could be problematic: the OAC2011 uses Output Areas (OAs) and the CEVM uses postcodes. The OAs are in general larger in area than the postcode areas (See Table 3.14), and in some locations multiple postcodes are situated within one OA. Secondly, the OAC2011 was not created for applied vulnerability purposes, rather it is a general geodemographic classification and so does not fully represent coastal erosion vulnerability. The key vulnerability variables have been qualitatively identified for each classification however, but as other variables are used in the OAC2011 clustering process some OAs may not have been classified correctly in terms of coastal erosion vulnerability. Despite these potential sources of error, it was expected that a weak to moderate general correlation trend should be present. In the absence of any published alternative, the above approach was adopted to validate the coastal erosion vulnerability model.

3.4 Risk Analysis

Once the socioeconomic model had been produced it was then possible to assign the socioeconomic vulnerability score to individual dwellings using the OS Address MasterMap

Layer 2. The location of 'dwellings' (the term used within the OS data) were extracted and spatially joined to the CEVM allowing identification of the location of dwellings with high socioeconomic vulnerability to coastal erosion. These dwellings are then spatially joined to the CESM layer, so that dwellings have both a CEVM and CESM. This therefore allows identification of dwellings that are at high risk of coastal erosion i.e. have both a high physical exposure to coastal erosion (from the CESM) and high socioeconomic vulnerability (from the CEVM).

3.5 Chapter Summary

This chapter has described the proposed methodology to achieve the research aims. In brief:

- Coastal erosion susceptibility was modelled using datasets for ground elevation, rockhead elevation, wave exposure, proximity to the open coast, sediment supply and the presence of coastal defences. The outputs were a polyline representing the coast, along with a 50 m raster of national coverage;

- Asset data for dwellings, key assets, transport infrastructure, historic assets, and natural assets were used along with the UPSM and CESM to assess the level of exposure to coastal erosion. The economic value of the exposed assets was calculated where possible;

- The CEVM was produced using the Experian Mosaic Scotland classification to classify populations based upon 11 variables. These were weighted using Gini coefficients to determine socioeconomic vulnerability to coastal erosion i.e. the CEVM;

- Dwellings were then assigned both a CESM and CEVM score in order to establish coastal erosion risk.

The outputs and results of the above methods will be presented in the following chapter.

Table 3.19: Example homeowners data

	A	B	C	D	E	F	G	H	I	J	K	L
		Stage 1	**Stage 2**		**Stage 3**		**Stage 4**		**Stage 5**			
Calculation		**A** x 2,558,733		**B** x **C** Data is ranked in ascending order according to this value	1/44	Cumulative summation of **E**	**D** / Total of **D**	Cumulative summation of **F**	$F_{i-1} - F_i$	$H_{i-1} + H_i$	**I x J**	1 – Sum of **K**
Mosaic Scotland Group	% of Dwellings	Number of Dwellings	% Homeowners	Number of Homeowners	Gini X	σX	Gini Y	σY	$\sigma X_{i-1} - \sigma X_i$	$\sigma Y_{i-1} + \sigma Y_i$		Gini Coefficient
40	1.03%	26,355	1.53%	403	0.023	0.023	0.0003	0.0003	0.0227	0.0003	0.00001	
43	0.81%	20,726	1.97%	409	0.023	0.045	0.0003	0.0005	0.0227	0.0008	0.00002	
9	0.20%	5,117	16.62%	850	0.023	0.068	0.0005	0.001	0.0227	0.0015	0.00004	
22	0.24%	6,141	18.01%	1,106	0.023	0.091	0.0007	0.0017	0.0227	0.0028	0.00006	
44	1.28%	32,752	3.78%	1,239	0.023	0.114	0.0008	0.0025	0.0227	0.0042	0.0001	
37	3.23%	82,647	4.42%	3,656	0.023	0.136	0.0023	0.0048	0.0227	0.0073	0.00017	
38	1.61%	41,196	9.77%	4,024	0.023	0.159	0.0025	0.0073	0.0227	0.0121	0.00027	
21	0.67%	17,144	24.19%	4,146	0.023	0.182	0.0026	0.0099	0.0227	0.0172	0.00039	
42	3.47%	88,788	6.64%	5,893	0.023	0.205	0.0037	0.0135	0.0227	0.0234	0.00053	
39	1.57%	40,172	15.06%	6,050	0.023	0.227	0.0038	0.0173	0.0227	0.0309	0.0007	
8	0.50%	12,794	80.57%	10,308	0.023	0.25	0.0064	0.0237	0.0227	0.041	0.00093	
25	1.16%	29,681	43.54%	12,923	0.023	0.273	0.0081	0.0318	0.0227	0.0555	0.00126	
20	1.31%	33,519	41.70%	13,979	0.023	0.295	0.0087	0.0405	0.0227	0.0723	0.00164	
24	0.90%	23,029	65.38%	15,057	0.023	0.318	0.0094	0.0499	0.0227	0.0904	0.00205	
36	2.97%	75,994	21.70%	16,494	0.023	0.341	0.0103	0.0602	0.0227	0.11	0.0025	
41	3.92%	100,302	17.41%	17,461	0.023	0.364	0.0109	0.071	0.0227	0.1312	0.00298	
18	0.83%	21,237	85.49%	18,156	0.023	0.386	0.0113	0.0824	0.0227	0.1534	0.00349	
35	4.54%	116,166	17.33%	20,131	0.023	0.409	0.0125	0.0949	0.0227	0.1773	0.00403	
26	2.76%	70,621	31.91%	22,533	0.023	0.432	0.014	0.1089	0.0227	0.2038	0.00463	

	A	B	C	D	E	F	G	H	I	J	K	L
19	1.15%	29,425	85.45%	25,143	0.023	0.455	0.0157	0.1246	0.0227	0.2336	0.00531	
29	1.25%	31,984	82.34%	26,335	0.023	0.477	0.0164	0.141	0.0227	0.2656	0.00604	
16	1.32%	33,775	88.93%	30,036	0.023	0.5	0.0187	0.1597	0.0227	0.3008	0.00684	
23	2.13%	54,501	59.67%	32,519	0.023	0.523	0.0203	0.18	0.0227	0.3397	0.00772	
1	1.36%	34,799	98.72%	34,353	0.023	0.545	0.0214	0.2014	0.0227	0.3814	0.00867	
17	1.51%	38,637	92.71%	35,820	0.023	0.568	0.0223	0.2237	0.0227	0.4251	0.00966	
33	3.20%	81,879	45.69%	37,411	0.023	0.591	0.0233	0.247	0.0227	0.4708	0.0107	
27	2.03%	51,942	82.60%	42,902	0.023	0.614	0.0267	0.2738	0.0227	0.5208	0.01184	
6	1.92%	49,128	98.53%	48,406	0.023	0.636	0.0302	0.3039	0.0227	0.5777	0.01313	
34	3.18%	81,368	61.36%	49,930	0.023	0.659	0.0311	0.3351	0.0227	0.639	0.01452	
13	3.11%	79,577	62.96%	50,100	0.023	0.682	0.0312	0.3663	0.0227	0.7014	0.01594	
3	2.03%	51,942	97.89%	50,844	0.023	0.705	0.0317	0.398	0.0227	0.7643	0.01737	
15	2.49%	63,712	90.34%	57,556	0.023	0.727	0.0359	0.4338	0.0227	0.8318	0.0189	
4	2.34%	59,874	99.03%	59,296	0.023	0.75	0.037	0.4708	0.0227	0.9046	0.02056	
2	2.35%	60,130	99.31%	59,713	0.023	0.773	0.0372	0.508	0.0227	0.9788	0.02225	
14	2.46%	62,945	96.84%	60,958	0.023	0.795	0.038	0.546	0.0227	1.054	0.02395	
28	2.64%	67,551	90.37%	61,048	0.023	0.818	0.038	0.584	0.0227	1.13	0.02568	
7	2.47%	63,201	97.12%	61,380	0.023	0.841	0.0383	0.6223	0.0227	1.2063	0.02742	
10	2.69%	68,830	97.26%	66,947	0.023	0.864	0.0417	0.664	0.0227	1.2863	0.02923	
5	2.90%	74,203	98.74%	73,271	0.023	0.886	0.0457	0.7097	0.0227	1.3737	0.03122	
30	3.99%	102,093	76.40%	77,999	0.023	0.909	0.0486	0.7583	0.0227	1.4679	0.03336	
31	4.73%	121,028	64.86%	78,496	0.023	0.932	0.0489	0.8072	0.0227	1.5655	0.03558	
11	3.79%	96,976	99.17%	96,173	0.023	0.955	0.0599	0.8671	0.0227	1.6743	0.03805	
32	5.51%	140,986	74.63%	105,215	0.023	0.977	0.0656	0.9327	0.0227	1.7998	0.0409	
12	4.43%	113,352	95.29%	108,013	0.023	1	0.0673	1	0.0227	1.9327	0.04392	
Total		2,558,221		1,604,679							0.545	0.455

Chapter 4: Results

4.1 Physical Susceptibility to Coastal Erosion

The susceptibility of the coast to erosion was generated using a number of spatial datasets. The Underlying Physical Susceptibility Model (UPSM) used elevation, rockhead elevation, wave exposure, and proximity to the open coast. The Coastal Erosion Susceptibility Model (CESM) was generated with the addition of sediment accretion and coastal defence data to the UPSM. The following section uses the area around the Dornoch Firth as an exemplar to show the effect of each input dataset on the UPSM in turn, followed by the final CESM output. This location was chosen as it contains a number of different coastal settings within a small spatial extent, and therefore offers a good basis to demonstrate the results of the research approach. Included within Appendix C.1 are several examples of UPSM and CESM outputs for a number of locations around Scotland.

The UPSM and CESM are intended to be used within a GIS context and are therefore best observed in a GIS like environment. Consequently, both models and intermediate datasets have been made available via a web map: http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*) using GeoServer and OpenLayers 3 to allow the user to fully explore the data at various levels of detail in a similar manner to the online flood risk maps produced by SEPA (http://map.sepa.org.uk/floodmap/map.htm). Additionally, the ModelBuilder scripts, most of the datasets (the BGS Supreficial Thickness Model and Experian Mosaic Scotland data could not be included due to license restrictions), and outputs are included on a DVD within this thesis.

4.1.1 Elevation

Areas of low elevation have increased susceptibility to coastal erosion compared to higher elevations as a consequence of being closer to ongoing coastal process i.e. wave action and inundation. The source data for the elevation data was the OS Terrain 50, adjusted so that a 0 m elevation equated to the elevation of regional MHWS. Figure 4.1 shows the unadjusted OS Terrain 50 data i.e. relative to OD, for the area around the Dornoch Firth ranked in accordance with the categories outlined in Chapter 3 (Table 3.7). Areas of land that have a low ground elevation should have a rank of 5 since they are close to the MHWS elevation, and gradually descend in rank as elevation increases with distance inland. However, there are a number of areas which have a classification that appears too low for their elevation and therefore susceptibility is underestimated. For example, much of the Morrich More coastline (area within black box on Figure 4.1) has a rank of 4. However, Morrich More is at a low altitude relative to MHWS and expert knowledge suggests much of this area should have the highest susceptibility rank.

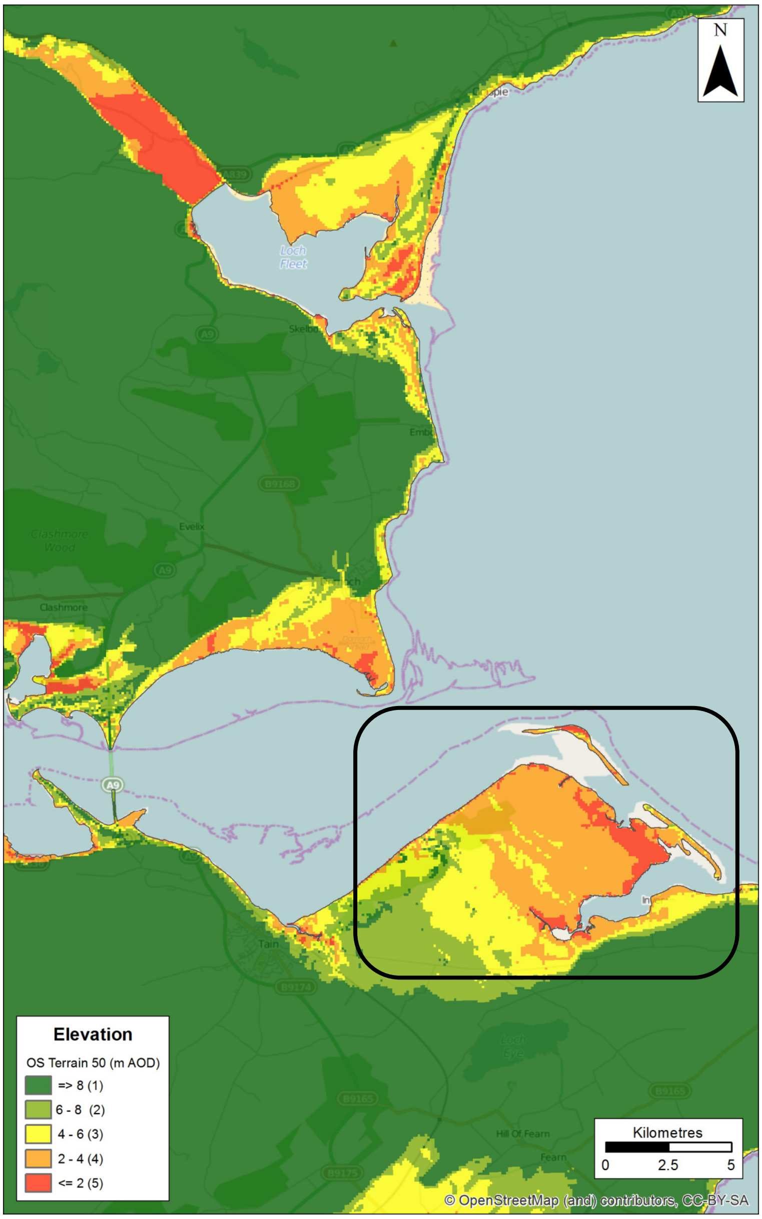

Figure 4.1: The OS Terrain 50 data for the Dornoch Firth ranked according with the categories outlined in the methodology. Note the elevation data unit is meters above OD. Green (rank of 1) to red (rank of 5) indicates low to high susceptibility. Morrich More is shown within the black box.

The reason for this misclassification is that the elevation data is relative to OD, and not relative to the MHWS elevation. Therefore, the MHWS elevation at Morrich More is below the elevation of OD (i.e. elevation of Newlyn) resulting in the misclassification. To adjust the elevation data, information from 133 tidal gauges was utilised. This adjustment transformed the OS Terrain 50 data so that is relative to the regional MHWS elevation i.e. the elevation of MHWS was equal to 0 m. Therefore, a rank of 5 corresponds to areas of land that are between 0 to 2 m above the elevation of MHWS (see Section 3.1.2.1 for the methodology used). Figure 4.2 shows the adjusted OS Terrain 50 data for the area around the Dornoch Firth. As a result of this adjustment much of Morrich More now has a classification of 5, in line with expert knowledge.

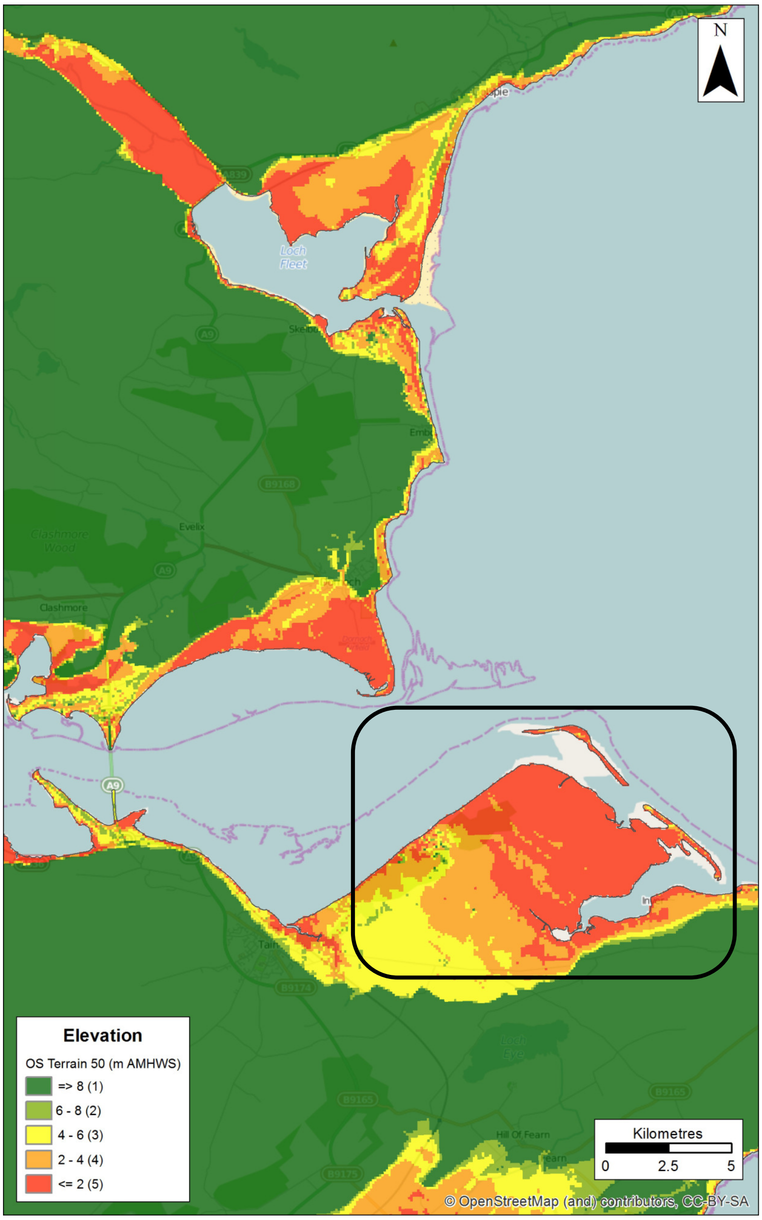

Figure 4.2: The OS Terrain 50 data for the Dornoch Firth adjusted to the MHWS datum using tidal gauge data and ranked according with the categories outlined in the methodology. Note the elevation data unit is meters above MHWS. Green (rank of 1) to red (rank of 5) indicates low to high susceptibility. Morrich More is shown within the black box. The data can be explored further on the web map - http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*).

4.1.2 Rockhead

The elevation of the rockhead greatly influences whether an area has superficial (i.e. erodible) deposits at or near MHWS which would increase susceptibility to coastal erosion. The rockhead elevation (which was originally relative to OD) was adjusted in the same way as the elevation data described above. Figure 4.3 shows the unadjusted rockhead data for areas around the Dornoch Firth. By adjusting the rockhead data for MHWS elevation (Figure 4.4), the hinterland extent of each classification increases and converts some areas that are close to MHWS from moderate susceptibility, to high. The area of Golspie is shown in the black box in Figure 4.3, which once adjusted to MHWS elevation, greatly increases in susceptibility. Conversely, Morrich More (area within blue box on Figure 4.4) shows very little change. This is due to the area having substantial thicknesses of superficial deposits (hence why much of the area has a rank of 5) and therefore a relatively small OD adjustment has little impact on the overall classification for the majority of the area. Additionally, the southwest boundary is constrained by a postglacial cliff line (approximate cliff position shown as dotted line on Figure 4.4) and therefore a rapid change in susceptibility rank is observed at the cliff.

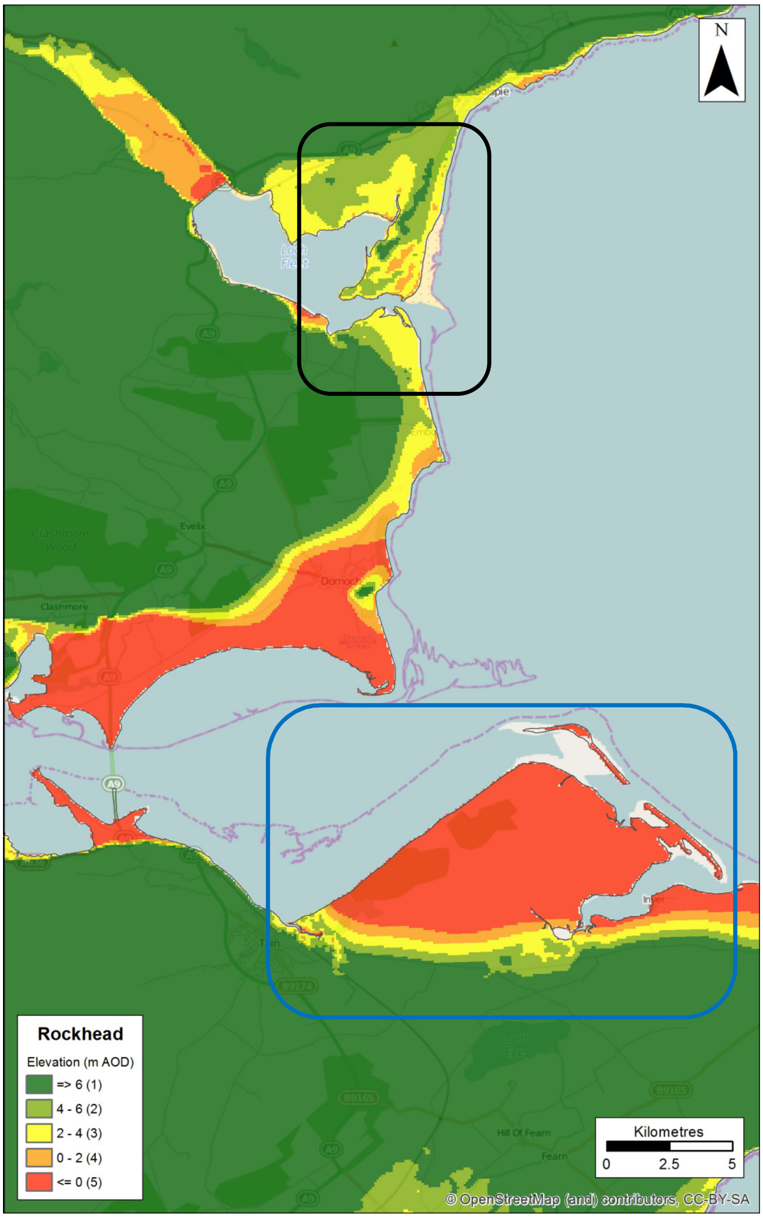

Figure 4.3: The rockhead elevation data for the Dornoch Firth ranked according with the categories outlined in the methodology. Note the elevation data unit is meters above OD. Green (rank of 1) to red (rank of 5) indicates low to high susceptibility. Golspie shown within the black box, and Morrich More shown within the blue box.

Due to the complexities of the relationship between rockhead elevation, ground elevation and past geological processes each area is impacted differently by the MHWS adjustment. Overall the adjusted data is more suitable for use in the model as the dataset is relative to the MHWS elevation and compatible with the Elevation data.

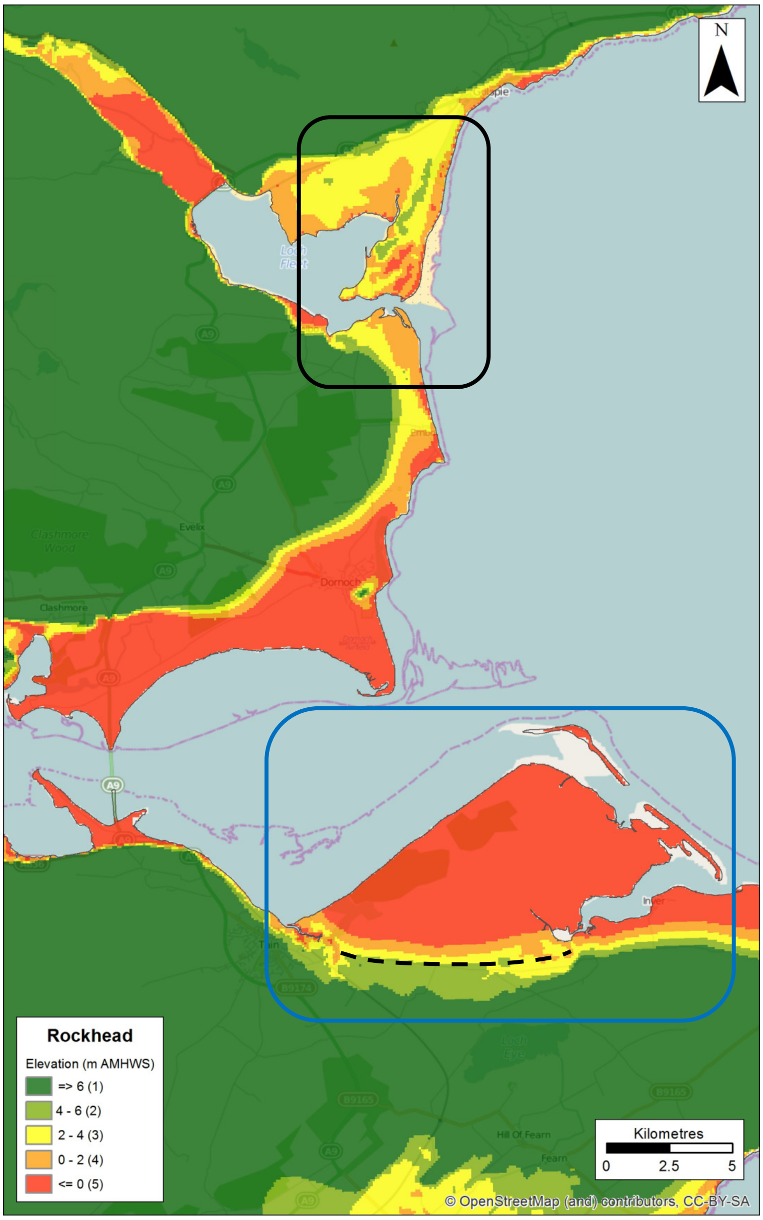

Figure 4.4: The rockhead elevation data for the Dornoch Firth adjusted to the MHWS datum using tidal gauge data and ranked according with the categories outlined in the methodology. Note the elevation data unit is meters above MHWS. Green (rank of 1) to red (rank of 5) indicates low to high susceptibility. Golspie shown within the black box, and Morrich More shown within the blue box. The data can be explored further on the web map - http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*).

4.1.3 Proximity to Open Coast

Coastal erosion occurs predominantly in energetic locations, which are unlikely to occur within inlets and estuaries. It was therefore necessary to remove inlets from the model where the inlet width was narrow and shallow enough to cause attenuation of wave activity and thus a reduction in coastal erosional susceptibility. The proximity to open coast data was produced by GIS processing of the OS MHWS data. The processing resulted in 'cutting-off' inlets that had a mouth less than 500 m wide. The effect of this can be seen at the sea loch of Loch Fleet in Figure 4.5 (black box) where the shoreline of Loch Fleet is ranked as 1. The mouth is approximately 200 m wide, hence, the coast within the loch is not classified as open coast, and is therefore assigned a low susceptibility category. Much of the coast around the Dornoch Firth is designated as open coast hence at the position of MHWS the susceptibility rank is 5, which decreases with distance inland. This dataset removes areas where coastal processes are limited compared to the open coast and is therefore a key component of the UPSM and CESM.

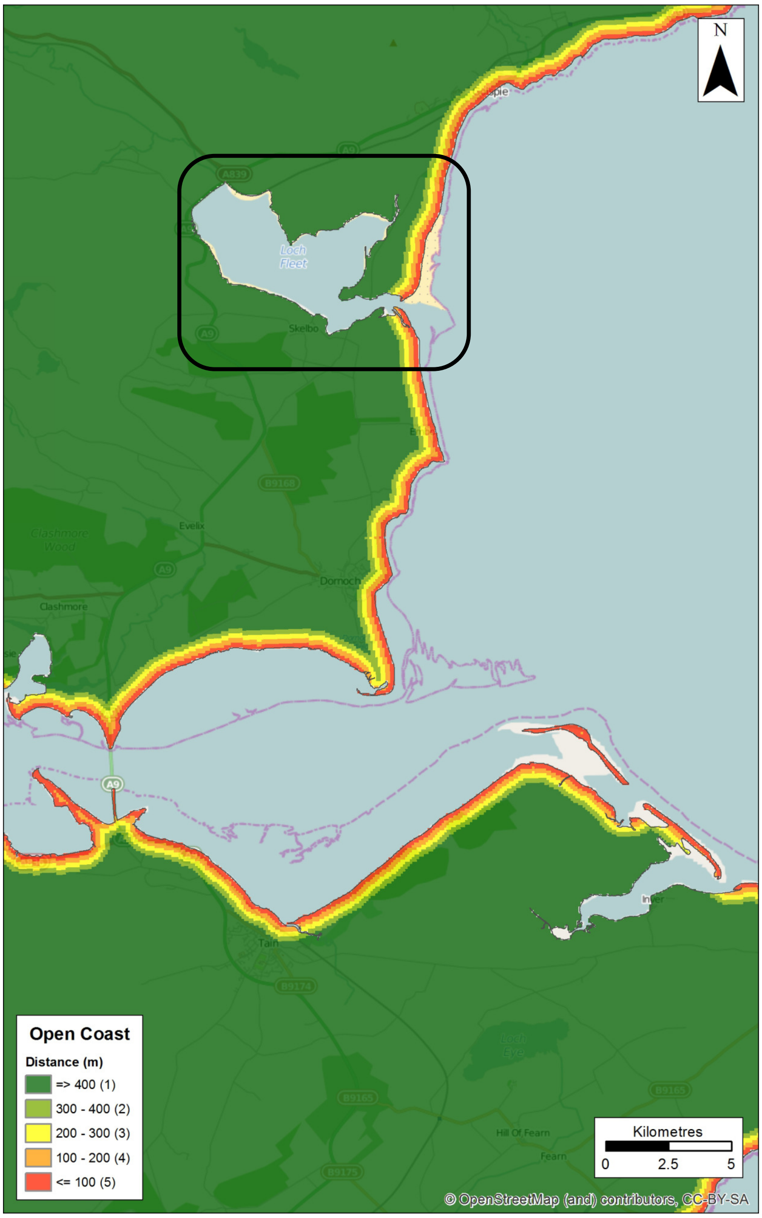

Figure 4.5: The proximity to open coast data for the Dornoch Firth. This data was produced using GIS processing and the OS MHWS data. This processing removed inlets that had a mouth of less than 500 m. Green (rank of 1) to red (rank of 5) indicates low to high susceptibility. Loch Fleet is shown within the black box. The data can be explored further on the web map - http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*).

4.1.4 Wave Exposure

As stated above, coastal erosion occurs in areas where coastal processes are highly energetic. Therefore, it was necessary to identify where the areas of high wave exposure occur, i.e. high energy environments, as these areas have potentially enhanced coastal erosion susceptibility. The wave exposure data was produced using the SNIFFER wave fetch data and processed within the GIS. Overall the data delineates the patterns of wave exposure (Figure 4.6) expected from expert knowledge i.e. areas that are sheltered or enclosed, such as Loch Fleet (black box in Figure 4.6) have a low wave exposure, whereas areas of open coast are predominantly classified with high wave exposure.

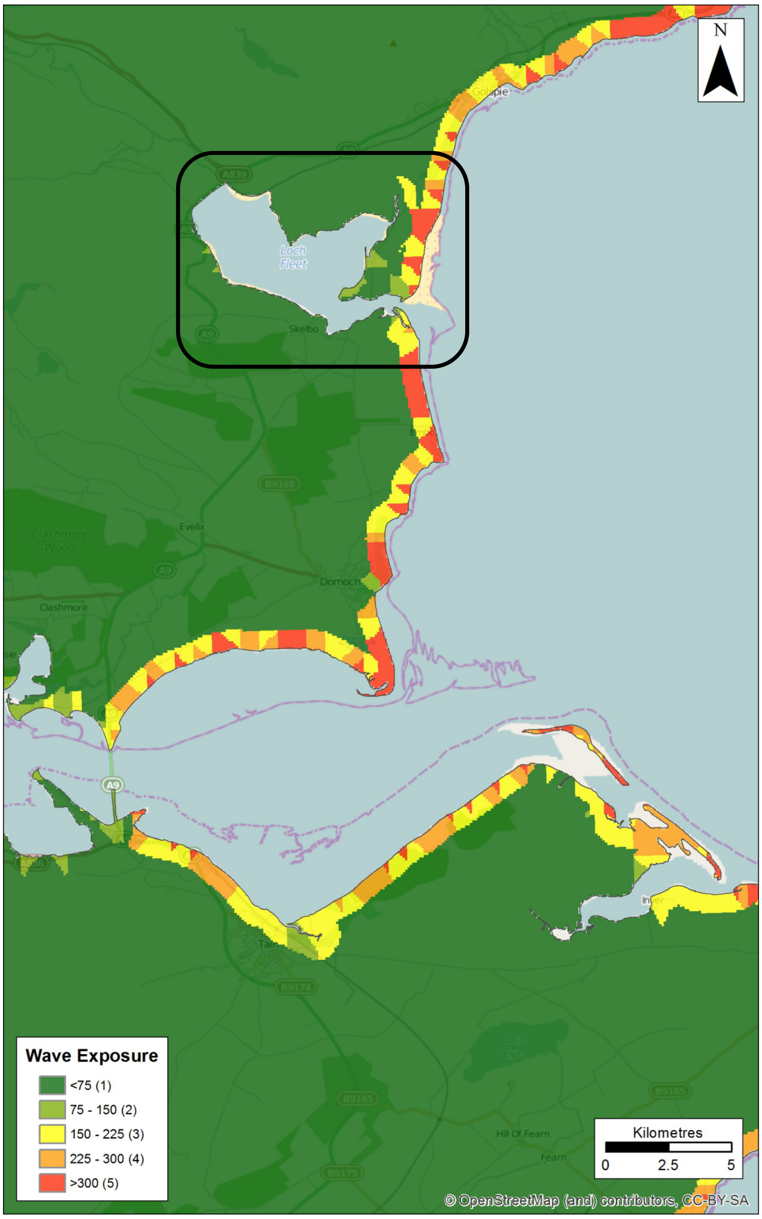

Figure 4.6: The wave exposure data for the Dornoch Firth. This data was produced using the SNIFFER wave fetch data and processed within GIS. The units of wave exposure are non-dimensional. Green (rank of 1) to red (rank of 5) indicates low to high susceptibility. Loch Fleet shown within the black box. The data can be explored further on the web map - http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*).

Nevertheless, the data remains highly variable even on straight lengths of the open coast where there seems to be no geomorphological reason for any variation in wave exposure (however, this variability is still reduced in comparison with the original data). Coastal processes are important to include in the model, yet a fetch-based method is not entirely satisfactory since local wave refraction patterns and wave directional landfall will control the effect of wave exposure. However, as no other national wave exposure data currently exists it was decided to use this data within the model as is, albeit with a weighting half of the other datasets in acknowledgment of its potential for inaccuracy. Furthermore, the coastline will have adjusted to the wave exposure during previous events, hence the areas of high wave exposure should be already somewhat resistant to coastal erosion.

4.1.5 UPSM

The datasets discussed above were aggregated resulting in the UPSM (Figure 4.7). The areas classified with high susceptibility all have low ground elevations, low rockhead elevations, are situated near the open coast, and have high wave exposure. The units of the UPSM are dimensionless, and range from 0 (very low susceptibility) to 100 (very high susceptibility). Within the Dornoch Firth area much of the open coast is classified with high susceptibility. However, variation occurs in the extent to which the high susceptibility extends into the hinterland. For example, most of the Morrich More's coastline (black box in Figure 4.7) is classified with a score of equal to or greater than 60, which extends approximately 400 m inland along all of its low and easily eroded beach and dune coastal frontage. In contrast, the area of Tain (blue box in Figure 4.7) has only a small distance inland classified as equal to or greater than 60 since the low lying sediments are backed by a high cliffline that lies close to the shore. However, in both these instances at the position of the MHWS the susceptibility is classified the same i.e. equal to or greater than 80.

4.1.6 CESM

With the addition of the sediment accretion and coastal defence handicap data to the UPSM, the CESM was produced (Figure 4.8). The units of the CESM are dimensionless, and range from 0 (very low susceptibility) to 100 (very high susceptibility). The area that shows the impact of the additional data within the Dornoch area is Golspie (black box in Figure 4.8). The coast in the north of the box is protected by a boulder revetment (riprap) and as a consequence reduces markedly in susceptibility from the UPSM to the CESM. Furthermore, the area in the south of the box at Golspie benefits from sediment transported from the north and accretion in the south and shows a decrease in susceptibility because of this supply of protective sediment. There is a very distinctive peak of high susceptibility between these two areas at the southern end of the boulder revetment protection that suffers from end scour and flanking as this area neither benefits from protection or accretion. Further examples of the UPSM and CESM are included within Appendix C.1.1.

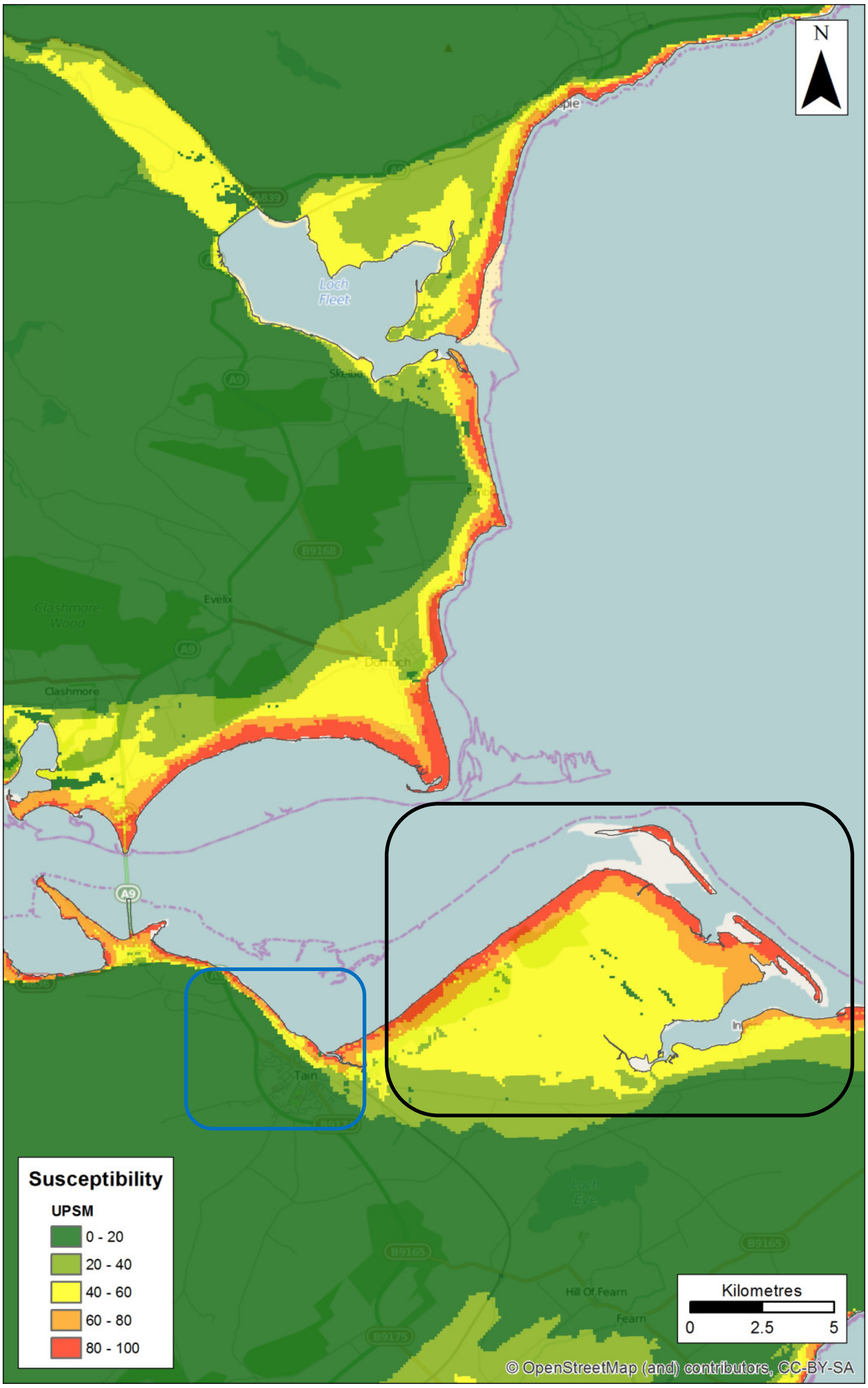

Figure 4.7: The Underlying Physical Susceptibility Model (UPSM) for the Dornoch Firth. Tain shown within the blue box. Morrich More shown within the black box. The data can be explored further on the web map - http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*). The units of the UPSM are dimensionless, and range from 0 (very low susceptibility) to 100 (very high susceptibility).

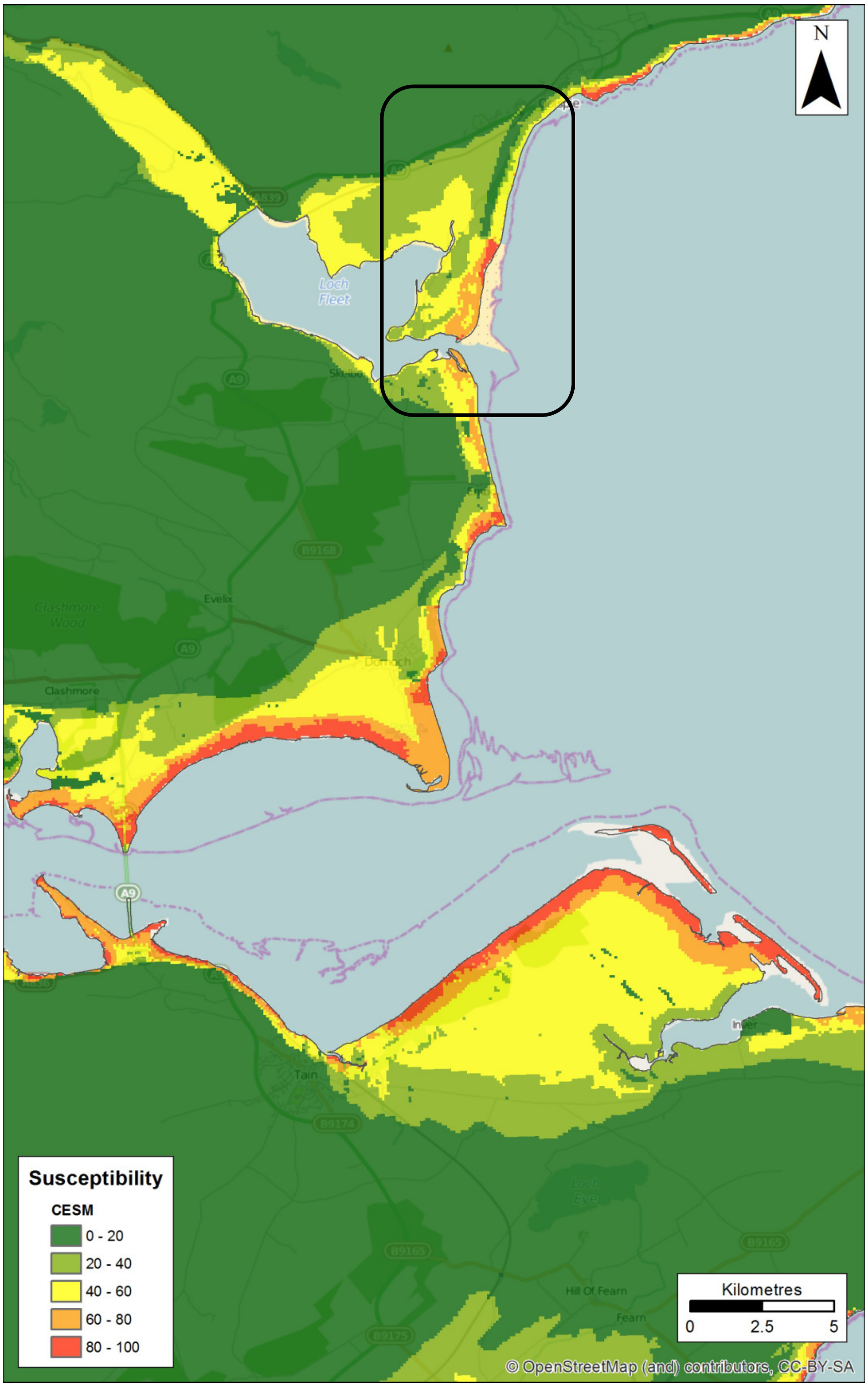

Figure 4.8: The Coastal Erosion Susceptibility Model (CESM) for the Dornoch Firth. Golspie shown within the black box. The data can be explored further on the web map - http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*). The units of the CESM are dimensionless, and range from 0 (very low susceptibility) to 100 (very high susceptibility).

4.1.7 CESM Validation

4.1.7.1 SNH Validation

The CESM was compared to the locations of SNH coastal erosion casework in order to assess the average CESM score at known erosion locations. The SNH data identifies 63 locations that are currently experiencing erosion (Figure 4.9), this equates to a coastal length of 94 km when transferred onto the UPSM/CESM coastline. When compared to the CESM for the same lengths of coast, 22 of the SNH confirmed erosion locations (or 44 km of coast) are found to have an average CESM score of between 80 and 100. A further 22 locations (equating to a length of 33.6 km) have an average CESM score of between 60 and 80. Therefore, 83% of coasts identified as eroding by SNH data are classified as highly or very highly susceptible to erosion by the CESM (additional results are found within Appendix C.1.2). There are 4 locations (1.8 km of coast) which are eroding but the CESM average score is less than 20, indicating a CESM underestimate of susceptibility in these locations. These locations are Melby Beach (Shetland), Sandness Coast (Shetland), Start Point (Sanday), and East Wemyss (Fife). Expert knowledge suggests that these locations are characteristic of a few intermediate sites where the known mix of extensive intertidal rock platform, sand and gravel beach (and derelict defences at East Wemyss) and the input data is not of sufficient resolution to identify these nuances, hence reduces the CESM score below what would be expected. However, overall the CESM performs well in comparison to the validation data and adds confidence to the accuracy of the model.

Table 4.1: Comparison of known erosion locations (SNH erosion casework) and the average CESM score for the same coastline. These results show that due to the high percentage of validation data that has a score over 60, the CESM performs well in comparison to the validation data, and suggests the model is accurate in the majority of locations.

Average CESM Score	**Number of Erosion Locations**	**Length of Eroding Coast (km)**	**Proportion of Eroding Coast (%)**
0-20	4	1.8	1.9
20-40	2	0.7	0.7
40-60	13	13.5	14.4
60-80	22	33.6	35.8
80-100	22	44.4	47.2
Total	63	93.97	100

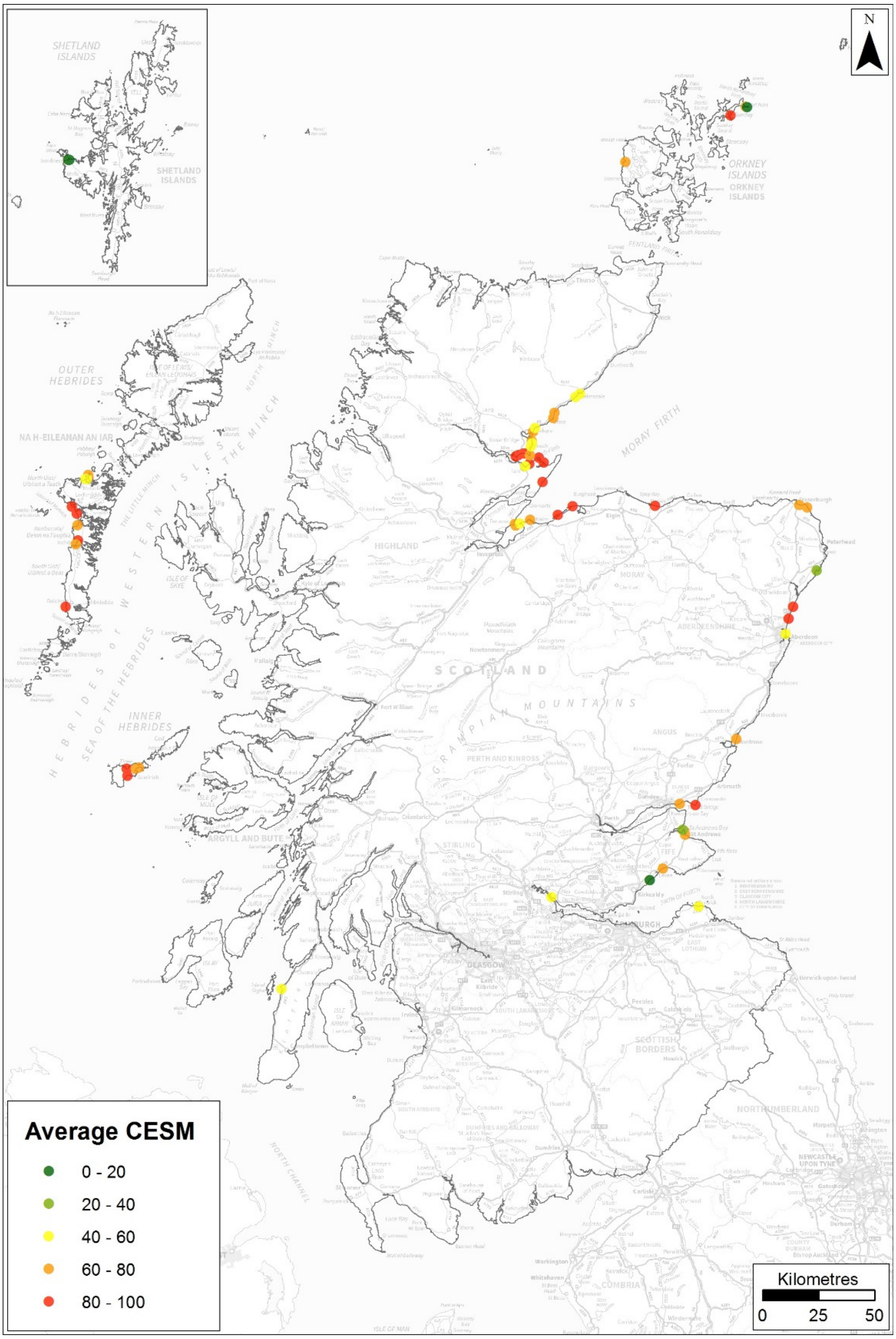

Figure 4.9: The average CESM score at the locations of SNH coastal erosion casework. Mapping courtesy of the OS.

4.1.7.2 Eurosion Validation

The CESM output was compared to the locations where the Eurosion coastal evolution data suggests that coastal erosion was occurring in 2004. In a similar manner to the SNH validation above, areas classified as eroding should have a high CESM score. The Eurosion data identifies 36 locations where coastal erosion is confirmed (Eurosion codes 50 and 51) which when translated onto the UPSM/CESM coastline equates to a coastal length of 125.9

km. There are an additional 440 locations where coastal erosion is probable but not confirmed (Eurosion code 4) which equates to a coastal length of 1,516.8 km. In total 1,724.3 km of coast is confirmed or probably eroding when the Eurosion data is translated onto the UPSM/CESM coastline (Table 4.2). The average score along the 1,724.3 km of coast is 60.4 for the UPSM and 56.8 for the CESM (Table 4.2 and Figure 4.10), however when coasts that have hard or soft defences are not considered the average UPSM score drops to 58.8 and the CESM score rises to 58.0. When only the locations that are confirmed as eroding are considered the average UPSM score rises to 81.2 and the CESM score rises to 69.0 (Figure 4.11). When just the locations where there are no defences are considered the UPSM score remains at 81.2 whereas the CESM score rises to 78.4. A summary of this data is shown in Table 4.3 with 11 (equating to 38.6 km) of the 32 locations have a CESM score equal to or greater than 80. A further 14 (39.2 km) have an average CESM score of between 60 and 80, and 7 (7.9 km) averaging between 40 and 60. There are no locations with an average score below 40. These results shows that in locations with no defences and confirmed erosion (according to Eurosion) the model performs well. The validation results for the Eurosion data and the SNH data strongly support the notion that the CESM accurately models coastal erosion susceptibility.

Table 4.2: Comparison of the locations the Eurosion data classify and the average UPSM and CESM score for these locations.

Eurosion Code	Eurosion Description	Coastline Type	Average UPSM	Average CESM	CESM Coastal Length (km)
4	Erosion probable but not documented	No Defences Present	57.2	56.6	1,516.8
		Hard Defences Present	75.0	41.6	78.8
		Soft Defences Present	78.5	57.8	2.7
		All	58.3	55.6	1,598.3
50	Erosion confirmed (available data), localised on parts of the segment	No Defences Present	81.8	76.3	35.6
		Hard Defences Present	75.6	36.8	9.2
		Soft Defences Present	-	-	-
		All	80.5	68.3	44.8
51	Erosion confirmed (available data), generalised to almost the whole segment	No Defences Present	80.8	80.0	50.1
		Hard Defences Present	80.7	46.7	21.5
		Soft Defences Present	88.0	66.5	9.5
		All	81.6	69.4	81.2
50 and 51	Data for all the Eurosion categories where erosion is confirmed	No Defences Present	81.2	78.4	85.8
		Hard Defences Present	79.1	43.6	30.7
		Soft Defences Present	88.0	66.5	9.5
		All	81.2	69.0	125.9
4, 50 and 51	Data for all three Eurosion categories where erosion is probable or confirmed	No Defences Present	58.8	58.0	1,602.6
		Hard Defences Present	76.2	42.1	109.5
		Soft Defences Present	85.6	64.3	12.2
		All	60.4	56.8	1,724.3

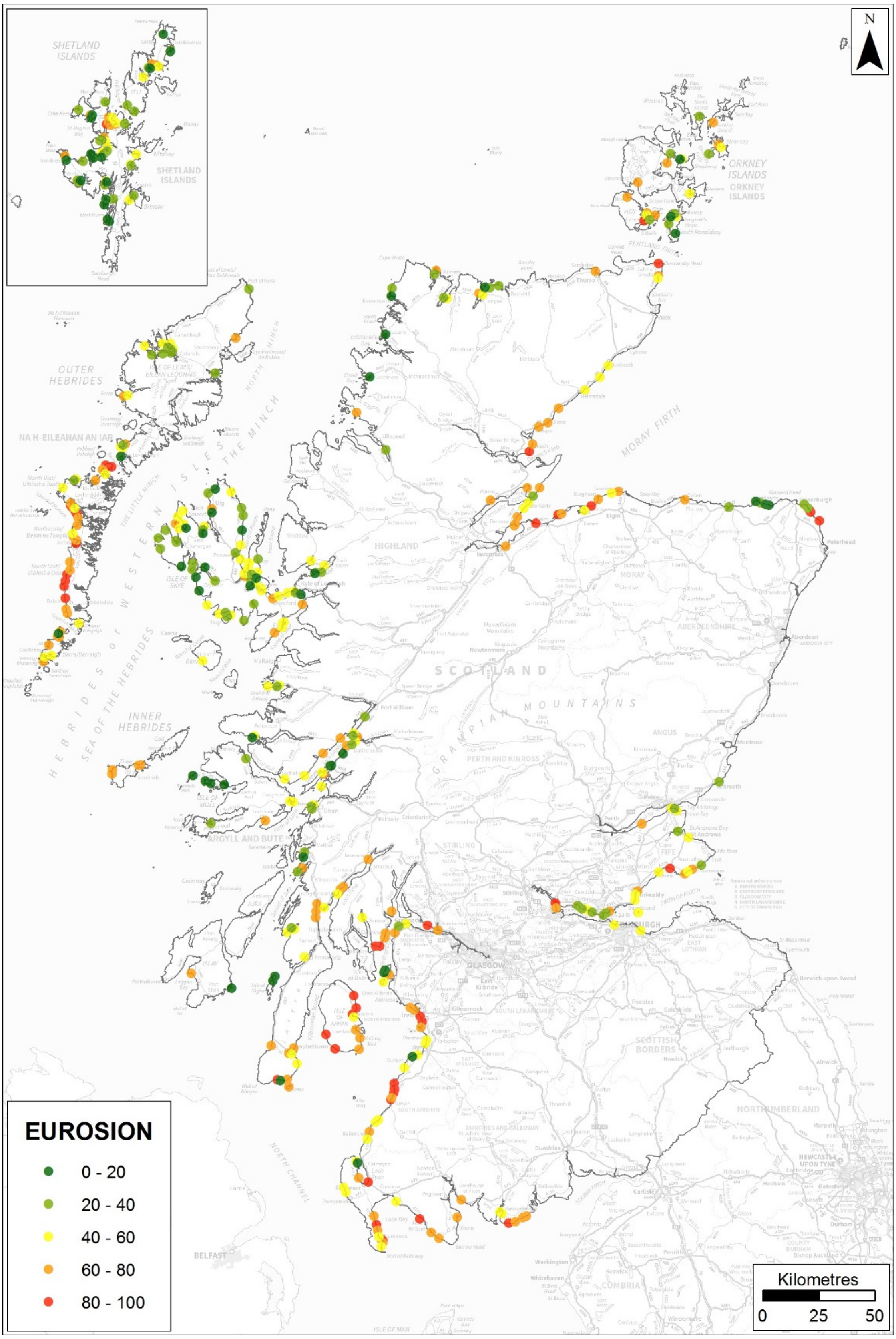

Figure 4.10: The average CESM score at the locations identified by Eurosion as "Erosion probable but not documented" (Eurosion code 4). Mapping courtesy of the OS.

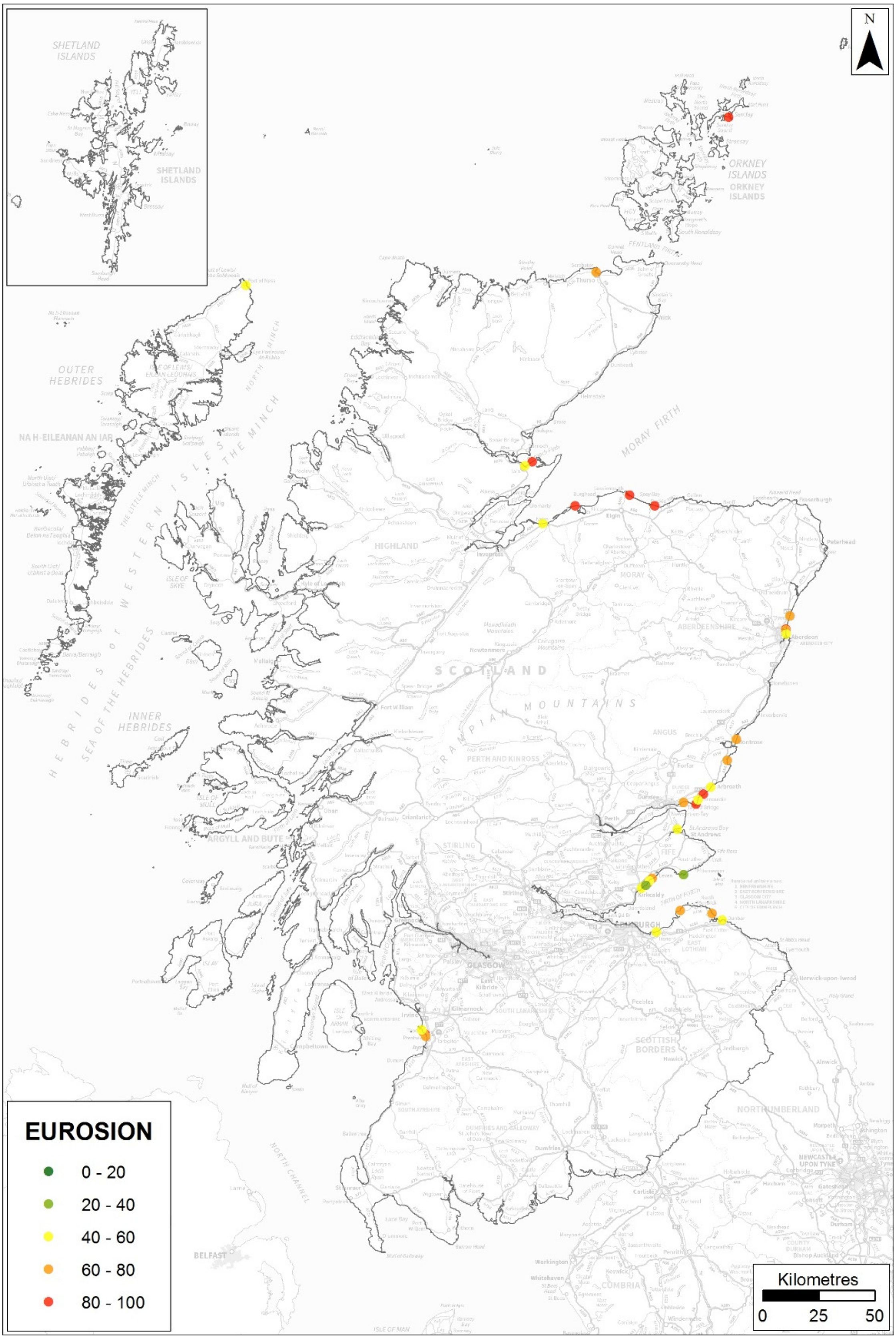

Figure 4.11: The average CESM score at the locations identified by Eurosion as "Erosion confirmed" (Eurosion codes 50 and 51). Mapping courtesy of the OS.

Table 4.3: Comparison of known erosion locations (Eurosion data) where no defences are present and the average CESM score for the same coastline.

CESM Score	Number of Erosion Locations	Length of Eroding Coast (km)	Proportion of Eroding Coast (%)
0-20	0	0	0
20-40	0	0	0
40-60	7	7.9	9.2
60-80	14	39.2	45.7
80-100	11	38.6	45.1
Total	32	85.8	100

4.1.7.3 Qualitative Validation

To get feedback from potential users of the model, two experts from SNH (Stewart Angus and George Lees) were asked to comment on the CESM output. For a number of key locations they were both asked to rate the model out of 5 (1 being low accuracy and 5 high accuracy), the results of which are shown in Table 4.4 (additional results are in Appendix C.1.2).

Table 4.4: Qualitative rating of the CESM at key locations by SNH (Stewart Angus and George Lees).

Location	CESM Accuracy 1 to 5 (1 = Low Accuracy, 5 = High Accuracy)	
	Stewart Angus	**George Lees**
Aberdeen	5	4
Largs	-	3
Dornoch & Morrich More / Tain	5	5
Dundee	5	3
Edinburgh	5	3
Glasgow	-	3
Inverness	3	4
Kirkwall	4 to 5	4
Stornoway	2	4
South Uist	4	5

Angus was positive about the model and in the majority of locations rated the model as 4 or greater. A few sites such as Inverness, where the model was thought to overestimate susceptibility, and Stornoway where susceptibility was thought to be both under and overestimated, were rated lower. Angus commented that "*overall I think this is a very valuable model*". Lees rated the model with a score of 4 or above in most locations. Coasts with substantial coastal defences were rated as a 3 e.g. Glasgow and Dundee. Lees identified three scenarios where the model generally underperforms; coastlines where extensive coastal defences exist, areas of saltmarsh, and low lying inland areas with shallow elevation gradients from MHWS. Overall Lees commented that the model was "*an exceptional and valuable piece of work, which works especially well on natural shorelines*".

4.1.8 CESM Statistics

Statistics for the UPSM and the CESM have been produced nationally, and separated by local authorities (LAs). The location of each LA is shown in Figure 4.12. LAs were chosen as a suitable unit for comparison of statistics as coastal management decisions are made on a LA basis rather than any other management unit or scientific basis.

A line which represents the coastline can be generated by taking the outer edge of the raster and converting it into a polyline. As the data was calculated from the outside edge of the UPSM/CESM raster the data contains no information on the hinterland. Table 4.5 shows the national summary for both the UPSM and CESM coastlines for the whole of Scotland. The spatial distribution is shown in Figure 4.13 and Figure 4.14.

Table 4.5: National statistics for the UPSM and CESM coastline in kilometres and percentage of the national coast. The susceptibility score is on a scale of 0 to 100, with 0 being the lowest, and 100 the highest.

	Susceptibility Score				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
UPSM (km)	10,239	555	2,691	2,028	2,719
UPSM (%)	56	3	15	11	15
CESM (km)	10,286	788	2,903	2,155	2,100
CESM (%)	56	4	16	12	12

Table 4.6 shows the length of the coast classified with very high (VH) susceptibility (a UPSM/CESM score >= 80). These are approximate lengths due to the rasterised form of the coastline. The total length of the Scottish coast was calculated as 18,232 km (with narrow inlets excluded), which is approximately 438 km shorter than the actual coastal length of 18,670 km (Angus et al., 2011). Nationally, 14.9% (or 2,719 km) of the Scottish coast is classified with VH susceptibility according to the UPSM, and 11.5% (or 2100 km) according to the CESM. For the UPSM, Na h-Eileanan an Iar has the longest lengths of coast with VH susceptibility within an LA, with 602 km of very highly susceptible coastline. However, this only makes up 17.3% of the Na h-Eileanan an Iar coastline, whereas 83.5% (or 15.9 km) of the Dundee City LA coastline is classified with VH susceptibility. For the CESM, Na h-Eileanan an Iar still has the longest length of coast classified with VH susceptibility with 561.5 km (or 16.1%). However, the proportion of the Dundee City coast classified with VH susceptibility has reduced to 6.3%. North Ayrshire has proportionally the longest length of coast classified with VH susceptibility with 32.5%.

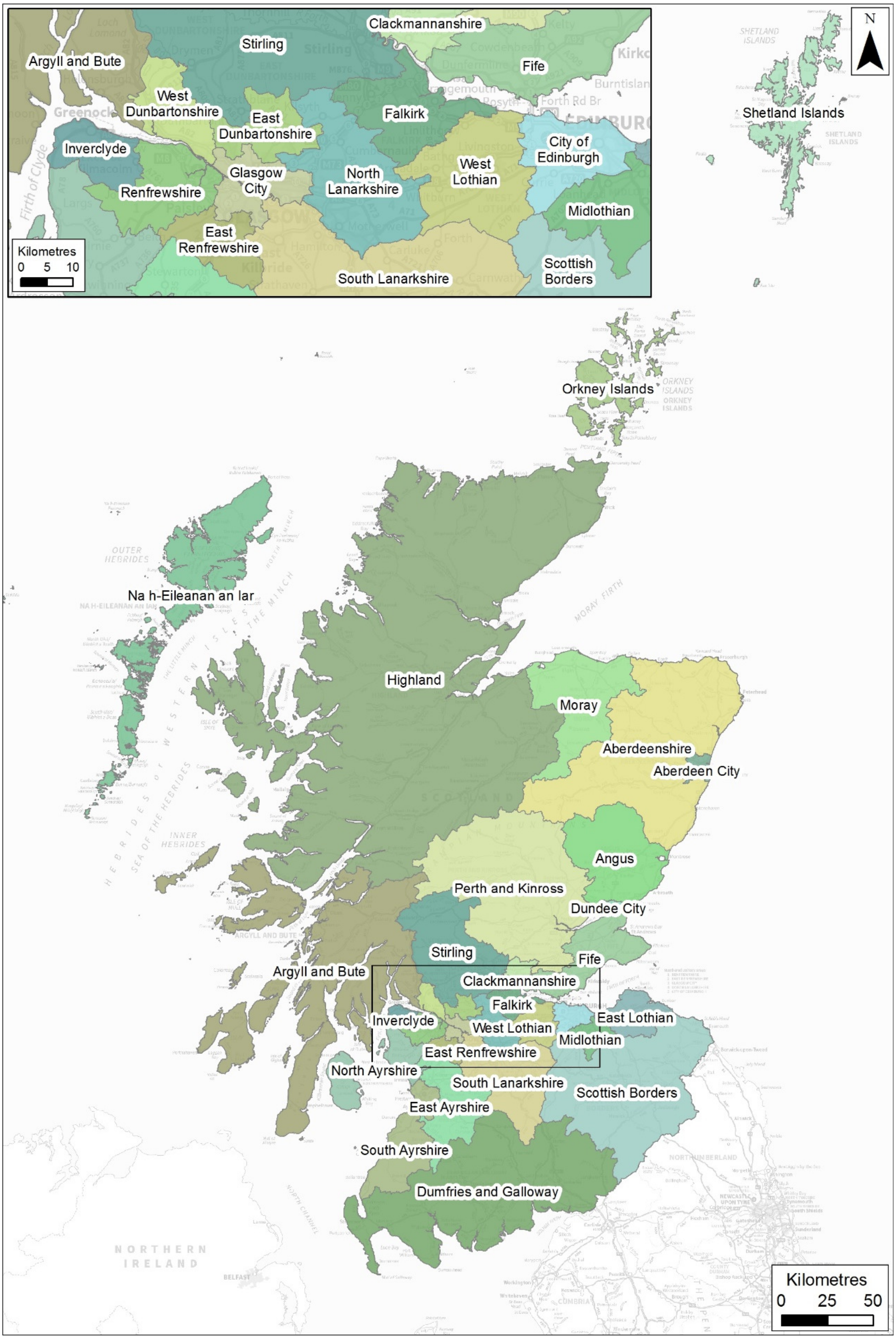

Figure 4.12: The location of Scottish local authorities. The area within the black box has been enlarged for ease of reading. Mapping courtesy of the OS.

Overall Dundee City had the largest decline in coast with VH susceptibility between the UPSM and CESM with a reduction of 92.5%, a function of its extensive seawall extent. Only the Renfrewshire and West Lothian LAs were completely unaffected by sediment accretion and coastal defence effects, with the Orkney and Shetland Island showing minor reductions of 1.0% and 0.6% respectively. Nationally, sediment accretion and coastal defences serve to reduce the length of very highly susceptible coast by 22.7%.

Table 4.6: Length of the coastline in each local authority classified with very high susceptibility (UPSM/CESM score =>80). Proportions are a percentage of the local authority coastline. Data is sorted by CESM proportion.

Local Authority	**Coastline Length (km)**	**UPSM**		**CESM**		**Reduction**	
		km	**%**	**km**	**%**	**km**	**%**
North Ayrshire	270.6	117.1	43.3	88.0	32.5	29.0	24.8
East Lothian	110.3	56.3	51.0	29.9	27.1	26.4	46.9
West Lothian	7.8	2.1	26.9	2.1	26.9	0.0	0.0
Moray	144.2	55.5	38.5	38.3	26.6	17.1	30.9
Angus	102.6	46.7	45.5	23.6	23.0	23.1	49.5
Perth and Kinross	116.2	24.6	21.2	23.8	20.5	0.9	3.4
Dumfries and Galloway	721.8	218.3	30.3	139.9	19.4	78.4	35.9
Falkirk	57.9	35.6	61.5	11.2	19.3	24.4	68.6
South Ayrshire	129.8	44.6	34.4	21.5	16.6	23.1	51.8
Na h-Eileanan an Iar	3,476.9	602.4	17.3	561.5	16.1	40.9	6.8
Orkney Islands	1,234.6	193.3	15.7	191.5	15.5	1.9	1.0
West Dunbartonshire	37.0	5.9	15.9	5.7	15.3	0.3	4.2
Fife	270.7	108.8	40.2	36.1	13.4	72.6	66.8
Aberdeenshire	336.5	69.7	20.7	44.8	13.3	24.9	35.7
Inverclyde	45.8	19.3	42.1	5.6	12.2	13.7	71.0
Argyll and Bute	3,609.5	439.1	12.2	377.9	10.5	61.2	13.9
Aberdeen City	46.5	6.1	13.2	4.3	9.2	1.9	30.1
City of Edinburgh	45.7	24.3	53.1	3.9	8.6	20.4	83.7
Highland	5,029.2	495.7	9.9	357.7	7.1	138.0	27.8
Clackmannanshire	27.6	6.5	23.4	1.8	6.4	4.7	72.9
Dundee City	19.0	15.9	83.5	1.2	6.3	14.7	92.5
Shetland Islands	2,206.2	127.8	5.8	127.0	5.8	0.8	0.6
Renfrewshire	54.0	2.1	3.9	2.1	3.9	0.0	0.0
Scottish Borders	54.5	1.0	1.7	0.9	1.6	0.1	10.5
Glasgow City	42.7	0.0	0.0	0.0	0.0	0.0	0.0
South Lanarkshire	4.7	0.0	0.0	0.0	0.0	0.0	0.0
Stirling	30.0	0.0	0.0	0.0	0.0	0.0	0.0
East Ayrshire	0.0	-	-	-	-	-	-
East Dunbartonshire	0.0	-	-	-	-	-	-
East Renfrewshire	0.0	-	-	-	-	-	-
Midlothian	0.0	-	-	-	-	-	-
North Lanarkshire	0.0	-	-	-	-	-	-
Total	18,232.3	2718.6	14.9	2100.3	11.5	618.3	22.7

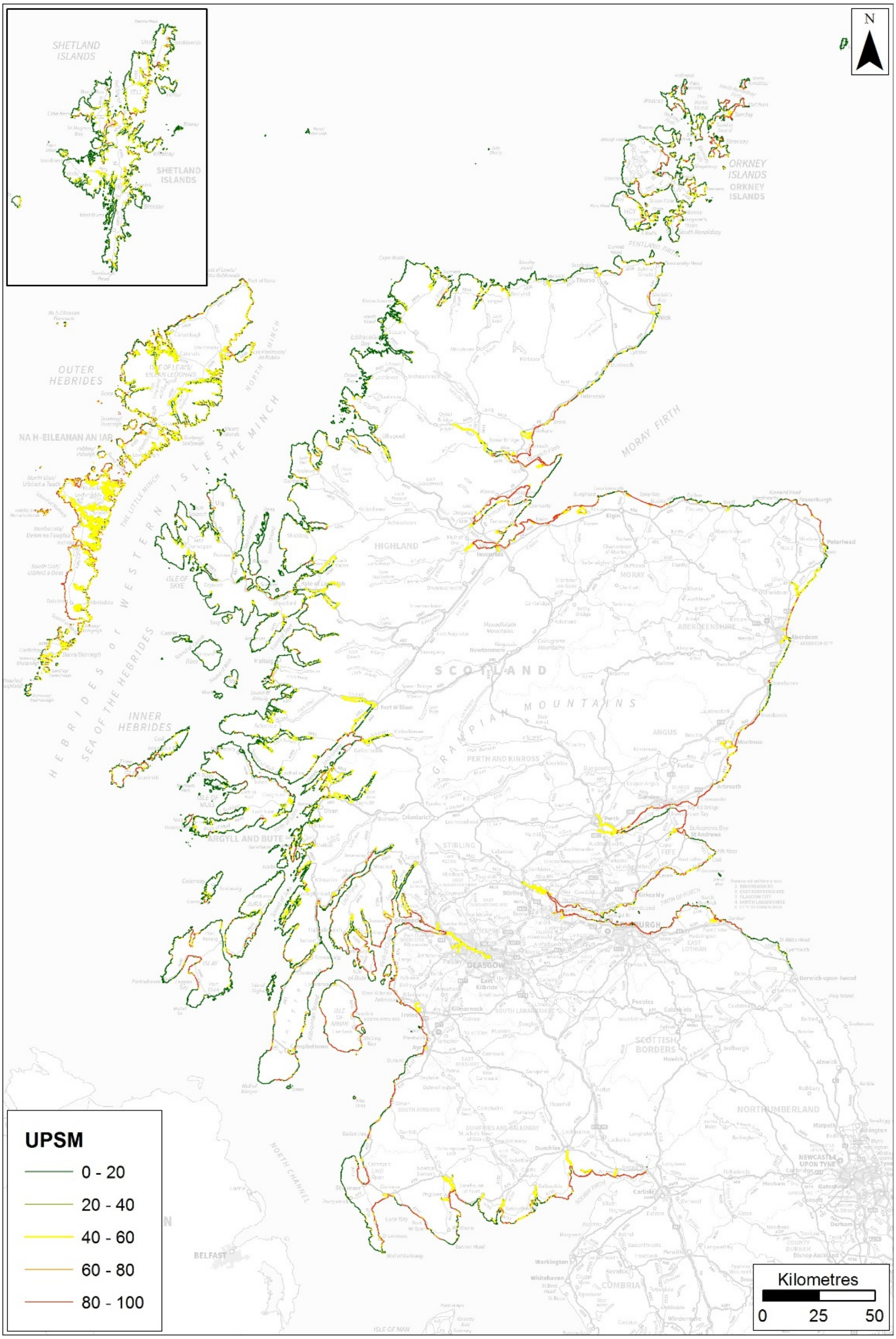

Figure 4.13: The outer edge of the UPSM raster, which can be considered as the UPSM coastline. Mapping courtesy of the OS.

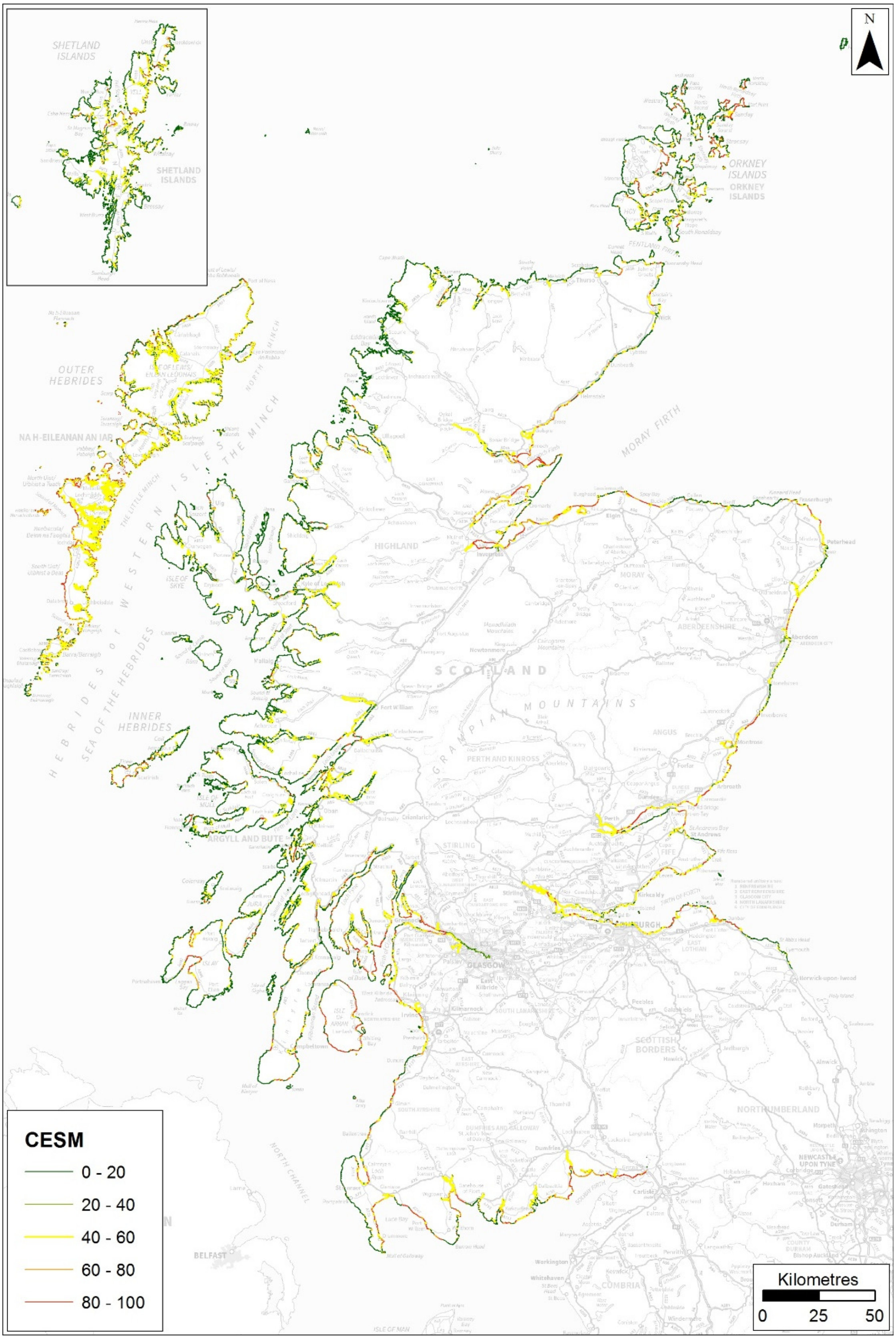

Figure 4.14: The outer edge of the CESM raster, which can be considered as the CESM coastline. Mapping courtesy of the OS.

Table 4.7: Land area in each local authority classified with very high susceptibility (UPSM/CESM score =>80).Table is sorted by CESM area proportion. Proportions are a percentage of the total (not coastal) local authority area.

Local Authority	Local Authority Area	UPSM		CESM		Difference	
		(km^2)	(%)	(km^2)	(%)	(km^2)	(%)
Orkney Islands	1,055.50	21.8	2.1	21.6	2.1	0.2	0.8
Na h-Eileanan an Iar	3,169.30	39.5	1.2	34.6	1.1	4.9	12.5
North Ayrshire	895.1	11	1.2	8.1	0.9	3	26.8
East Lothian	683.9	7.3	1.1	3.9	0.6	3.4	47
Shetland Islands	1,499.80	7.7	0.5	7.7	0.5	0	0.5
Falkirk	299.7	5.1	1.7	1.4	0.5	3.7	72.8
Argyll and Bute	7,098.90	36.4	0.5	30.3	0.4	6.2	16.9
West Dunbartonshire	178.8	0.6	0.4	0.6	0.3	0	5
Fife	1,336.00	14.7	1.1	4.6	0.3	10.1	68.8
Inverclyde	163.4	2.2	1.4	0.5	0.3	1.8	78.3
Moray	2,243.70	7.2	0.3	5.5	0.2	1.8	24.6
Dumfries and Galloway	6,463.60	25.7	0.4	14.5	0.2	11.3	43.7
Dundee City	60.3	2.3	3.8	0.1	0.2	2.2	94.4
Aberdeen City	187.4	1	0.5	0.4	0.2	0.6	62.8
South Ayrshire	1,229.10	5.4	0.4	2.1	0.2	3.3	61
City of Edinburgh	265	2.7	1	0.4	0.1	2.4	87.2
Highland	26,301.90	50.7	0.2	32.8	0.1	17.9	35.3
Clackmannanshire	159.9	0.7	0.4	0.2	0.1	0.5	73
Angus	2,189.50	5.9	0.3	2.4	0.1	3.6	59.9
Renfrewshire	264	0.3	0.1	0.3	0.1	0	0
Aberdeenshire	6,328.80	6.7	0.1	4.1	0.1	2.7	39.5
Perth and Kinross	5,388.40	3	0.1	2.9	0.1	0.1	3.2
West Lothian	429.1	0.2	0	0.2	0	0	0
Scottish Borders	4,741.30	0.1	0	0.1	0	0	7.1
East Ayrshire	1,270.30	0	0	0	0	0	0
East Dunbartonshire	174.5	0	0	0	0	0	0
East Renfrewshire	173.8	0	0	0	0	0	0
Glasgow City	176.2	0	0	0	0	0	0
Midlothian	355.3	0	0	0	0	0	0
North Lanarkshire	472.2	0	0	0	0	0	0
South Lanarkshire	1,774.10	0	0	0	0	0	0
Stirling	2,254.30	0	0	0	0	0	0
Total	79,283.20	258.4	0.3	178.9	0.2	79.5	30.8

Table 4.8: Very highly susceptible area to length ratios for the UPSM and CESM within each local authority, sorted by CESM area/length ratio.

Local Authority	UPSM (km^2)	CESM (km^2)	UPSM (km)	CESM (km)	UPSM Area/Length (km^2/km)	CESM Area/Length (km^2/km)
Moray	7.2	5.5	55.5	38.3	0.131	0.142
East Lothian	7.3	3.9	56.3	29.9	0.129	0.129
Fife	14.7	4.6	108.8	36.1	0.135	0.127
Falkirk	5.1	1.4	35.6	11.2	0.143	0.124
Renfrewshire	0.3	0.3	2.1	2.1	0.123	0.123
Perth and Kinross	3.0	2.9	24.6	23.8	0.121	0.121
Orkney Islands	21.8	21.6	193.3	191.5	0.113	0.113
West Dunbartonshire	0.6	0.6	5.9	5.7	0.110	0.109
Dundee City	2.3	0.1	15.9	1.2	0.146	0.108
Clackmannanshire	0.7	0.2	6.5	1.8	0.105	0.105
Dumfries and Galloway	25.7	14.5	218.3	139.9	0.118	0.104
Angus	5.9	2.4	46.7	23.6	0.127	0.101
South Ayrshire	5.4	2.1	44.6	21.5	0.120	0.097
West Lothian	0.2	0.2	2.1	2.1	0.095	0.095
North Ayrshire	11.0	8.1	117.1	88.0	0.094	0.092
Highland	50.7	32.8	495.7	357.7	0.102	0.092
Aberdeenshire	6.7	4.1	69.7	44.8	0.097	0.091
City of Edinburgh	2.7	0.4	24.3	3.9	0.112	0.089
Inverclyde	2.2	0.5	19.3	5.6	0.116	0.087
Aberdeen City	1.0	0.4	6.1	4.3	0.157	0.083
Argyll and Bute	36.4	30.3	439.1	377.9	0.083	0.080
Scottish Borders	0.1	0.1	1.0	0.9	0.074	0.077
Na h-Eileanan an Iar	39.5	34.6	602.4	561.5	0.066	0.062
Shetland Islands	7.7	7.7	127.8	127.0	0.060	0.060
East Ayrshire	0.0	0.0	0.0	0.0	0.000	0.000
East Dunbartonshire	0.0	0.0	0.0	0.0	0.000	0.000
East Renfrewshire	0.0	0.0	0.0	0.0	0.000	0.000
Glasgow City	0.0	0.0	0.0	0.0	0.000	0.000
Midlothian	0.0	0.0	0.0	0.0	0.000	0.000
North Lanarkshire	0.0	0.0	0.0	0.0	0.000	0.000
South Lanarkshire	0.0	0.0	0.0	0.0	0.000	0.000
Stirling	0.0	0.0	0.0	0.0	0.000	0.000
Total	258.4	178.9	2,718.6	2,100.3	0.095	0.085

Table 4.7 shows the area within each local authority classified with VH susceptibility. This differs from the coastal lengths statistics above as it takes into account both the amount of very highly susceptible land at the coast and the hinterland. The UPSM area statistics mirror the spatial distribution of the UPSM length statistics as the Na h-Eileanan an Iar LA (the Western Isles) has the greatest area of land classified with VH susceptibility with 39.5 km^2 (or 1.2% of the LA area). Dundee City remains proportionally the LA with the most very highly susceptible land with 3.8% (or 2.3 km^2 of LA area). The CESM area statistics do

show variation in comparison to the length statistics however. Na h-Eileanan an Iar has the most very highly susceptible area with 34.6 km^2 (1.1%), however proportionally the Orkney Islands has the most land with VH susceptibility with 2.1% (or 21.6 km^2). This differs from the length statistics above where North Ayrshire has proportionally the longest length of very highly susceptible coastline.

The length and area statistics can be explored further by combining them into a ratio. Table 4.8 shows the area of VH susceptibility to length of VH susceptibility ratio for the UPSM and CESM (data taken from Table 4.6 and Table 4.7). The ratio describes the area that is classified with VH susceptibility for every 1 km of the very highly susceptible coastline within each LA. Analysing this ratio, the amount of hinterland susceptibility behind the immediate coastline can be identified. Dundee City has the highest UPSM VH susceptibility area/length ratio with 0.146 indicating that for every 1 km of the coastline an area of 0.146 km^2 on average is classified as very highly susceptible. The Falkirk LA ratio is close to Dundee City with 0.143. The Moray LA has the highest CESM area/length ratio with 0.142, with East Lothian second highest with 0.129. Na h-Eileanan an Iar, which consistently ranked highest for the CESM area and length statistic, has one of the lowest ratios with 0.062. The area/length somewhat negates the issue of the length statistic skewing the data in favour of LAs with long coastlines, and the area statistic skewing the data in favour of small local authorities.

4.1.9 Section Summary

Section 4.1 has:

- demonstrated how the underlying datasets of UPSM and CESM have been combined in order to create an output which represent the erosional susceptibility of the coast. The UPSM and CESM are output via a 50 m^2 resolution raster and as a polyline that covers the whole of the Scottish coast;

- shown that in sections of coasts which are actively eroding (according to SNH and Eurosion data) the CESM produces a high to very high erosion susceptibility score in the majority of locations. Furthermore, a qualitative review by experts Stewart Angus and George Lees (both of SNH) suggests that the CESM represents a good indicator of coastal erosion susceptibility at a wide range of key selected locations. The CESM thus represents a robust pan-Scotland indicator of susceptibility to coastal erosion;

- established that nationally some 2,100 km of coastline can be classified with very high susceptibility according to the CESM, this equating to 11.5% of the Scottish coast. However, coastal erosion susceptibility varies significantly within the local authorities of Scotland. The North Ayrshire LA has proportionally the greatest length of very highly susceptible coast (32.5% or 88.0 km), whereas Na h-Eileanan an Iar has the longest total length (561.5 km or 16.1% of the LA coastline). The Orkney Islands has proportionally the largest area of very highly susceptible land (2.1% or 21.6 km^2), whereas Na h-Eileanan an Iar has the largest area in total (34.6 km^2 or 1.1%). When the length and area statistics are combined into an area to length ratio the LA of Moray has the highest ratio (0.142) indicating that for every 1 kilometre of very highly susceptible coastline there is a land area of 0.142 km^2 with very high susceptibility.

4.2 Exposure

From this point forward the term exposure/exposed is used to indicate where an asset is located and the UPSM or CESM score is equal to or greater than 80. A value of 80 and above was chosen as this represents the areas of very high erosion susceptibility. However, a threshold value of less than 80 could have been used, resulting in an increased number of assets exposed. A threshold of 80 was selected as it represents the assets relatively most exposed, and are therefore a priority for management. The results for the exposure analysis for dwellings, key assets, transport infrastructure, recreational assets, historic assets and natural assets, are examined in turn below. The economic values within the tables will be quoted within the text to three significant figures for ease of reading.

4.2.1 Residential Property

Nationally, 2,557,260 dwellings[14] were assessed to determine their exposure to coastal erosion. For the UPSM, 13,298 dwellings were located in areas deemed to have a VH susceptibility which represents 0.52% of all dwellings (Table 4.9). For the CESM, this number decreases to 3,310 (or 0.13%) demonstrating that 9,988 dwellings are removed from

[14] Within the OS MasterMap Address Layer 2 dataset residential properties they are termed ‘dwellings’. A dwelling is as a self-contained unit of accommodation. Self-containment is where all the rooms (including kitchen, bathroom and toilet) in a household’s accommodation are behind a single door which only that household can use. A household is one person or a group of people who have the accommodation as their only or main residence AND (for a group) either share at least one meal a day, or share the living accommodation, that is, a living room or sitting room (Department for Communities and Local Government, 2012)

the highest susceptibility category due to the benefits offered by sediment accretion and/or coastal defences.

Table 4.9: A national summary of the number and proportion of dwellings within each susceptibility category for the UPSM and CESM. The susceptibility score is on a scale of 0 to 100, with 0 being the lowest, and 100 the highest.

		Total Dwellings	0-20	20-40	40-60	60-80	80-100
UPSM	Total	2,557,260	2,137,114	241,726	128,982	36,140	13,298
	Total (%)	-	83.57	9.45	5.04	1.41	0.52
CESM	Total	2,557,260	2,219,776	246,685	77,881	9,608	3,310
	Total (%)	-	86.80	9.65	3.05	0.38	0.13
	UPSM/CESM Difference (Count)	-	82,662	4,959	-51,101	-26,532	-9,988

Using the LA average house price (for July to September 2014) the value of the dwellings within each susceptibility category was calculated (Table 4.10). This analysis shows that the dwellings classified as exposed according to the UPSM, which have a value equal to £2.21bn with CESM exposure amounting to £526m. This means that £1.68bn worth of property benefit from sediment accretion and/or coastal defences.

Table 4.10: National value of properties within each susceptibility category for the UPSM and CESM. The susceptibility score is on a scale of 0 to 100, with 0 being the lowest, and 100 the highest.

	0-20	20-40	40-60	60-80	80-100
UPSM Total	£349,501,650,768	£38,562,929,757	£20,331,360,566	£5,921,234,553	£2,210,653,845
CESM Total	£362,463,810,721	£39,917,818,512	£12,137,199,565	£1,483,028,603	£525,972,088
Difference	£12,962,159,953	£1,354,888,755	-£8,194,161,001	-£4,438,205,950	-£1,684,681,757

Table 4.11 shows the exposure of dwellings by local authority. The Fife and Highland LAs have the most dwellings exposed according to the UPSM with 1,646 (or 0.95% of Fife dwellings) and 1,606 (or 1.39% of Highland dwellings) respectively. However, East Lothian has the highest proportion of dwellings exposed to erosion according to the UPSM with 3.06% (or 1,407 dwellings). For the CESM, Highland has the most dwellings exposed with 961 (or 0.83% of LA dwellings). However, proportionally the Argyll and Bute LA has the highest percentage of dwellings with 1.25% (or 601 dwellings) highly exposed to coastal erosion.

The difference between the UPSM and CESM statistic is due to the inclusion of coastal defence and accretion data into the model. Table 4.12 shows the number of dwellings which benefit from coastal defences, accretion or both (i.e. where a sea wall is fronted by an accreting beach) within each LA. A total of 158,299 (or 6.2%) of dwellings benefit from coastal defences in this way. Fife has 29,677 dwellings which benefit from defences, with Glasgow second highest with 24,845. However, these numbers of dwellings represent only 8.5% and 8.1% respectively of the total dwellings within each LA. East Lothian proportionately the highest number of dwellings which benefit from defences with 28.9% (4,790 dwellings), closely followed by Argyll and Bute with 28.0% (13,446 dwellings).

Table 4.11: Number of dwellings in each local authority classified with very high susceptibility (UPSM/CESM score =>80). Table is sorted by CESM proportion. Proportions are a percentage of the local authority.

Local Authority	Total Dwellings	UPSM		CESM	
		Count	%	Count	%
Argyll and Bute	48,054	1,355	2.82	601	1.25
Na h-Eileanan an Iar	14,921	149	1.00	143	0.96
Highland	115,332	1,606	1.39	961	0.83
Orkney Islands	10,952	72	0.66	72	0.66
South Ayrshire	55,442	1,362	2.46	267	0.48
North Ayrshire	68,070	773	1.14	316	0.46
East Lothian	45,940	1,407	3.06	207	0.45
Dumfries and Galloway	74,311	486	0.65	250	0.34
Aberdeenshire	113,335	849	0.75	244	0.22
Shetland Islands	11,104	20	0.18	15	0.14
Moray	43,666	128	0.29	29	0.07
Fife	173,844	1,646	0.95	108	0.06
Dundee City	74,768	798	1.07	39	0.05
Angus	54,916	308	0.56	22	0.04
Inverclyde	39,278	924	2.35	4	0.01
West Dunbartonshire	45,023	4	0.01	4	0.01
Perth and Kinross	70,761	33	0.05	6	0.01
City of Edinburgh	242,095	1,143	0.47	17	0.01
Falkirk	72,628	226	0.31	3	0.00
West Lothian	77,005	2	0.00	2	0.00
Aberdeen City	116,351	7	0.01	0	0.00
Clackmannanshire	24,078	0	0.00	0	0.00
East Ayrshire	57,951	0	0.00	0	0.00
East Dunbartonshire	44,863	0	0.00	0	0.00
East Renfrewshire	37,777	0	0.00	0	0.00
Glasgow City	305,085	0	0.00	0	0.00
Midlothian	37,682	0	0.00	0	0.00
North Lanarkshire	151,865	0	0.00	0	0.00
Renfrewshire	84,223	0	0.00	0	0.00
Scottish Borders	57,712	0	0.00	0	0.00
South Lanarkshire	147,472	0	0.00	0	0.00
Stirling	40,756	0	0.00	0	0.00

Table 4.12: Number of dwellings in each local authority that benefit from coastal defences, accretion or both. The data is sorted by the proportion of local authority dwellings benefitting from defences column.

Local Authority	Total Dwellings	Dwellings Benefitting from Defences		Dwellings Benefitting from Accretion		Dwellings Benefitting from both Accretion and Defences	
		Number	Proportion of LA Dwellings (%)	Number	Proportion of LA Dwellings (%)	Number	Proportion of LA Dwellings (%)
East Lothian	16,579	4,790	28.9	0	0.0	0	0.0
Argyll and Bute	48,054	13,446	28.0	1,981	4.1	1,696	3.5
Inverclyde	39,278	8,914	22.7	0	0.0	0	0.0
Orkney Islands	1,018	175	17.2	14	1.4	0	0.0
South Ayrshire	50,187	7,267	14.5	1,989	4.0	38	0.1
Highland	115,332	12,903	11.2	1,432	1.2	385	0.3
North Ayrshire	68,070	6,841	10.0	1,092	1.6	435	0.6
Angus	54,916	5,170	9.4	26	0.0	19	0.0
Moray	43,666	4,023	9.2	517	1.2	51	0.1
Fife	347,930	29,667	8.5	938	0.3	80	0.0
Glasgow City	305,085	24,845	8.1	0	0.0	0	0.0
Aberdeen City	116,351	8,985	7.7	0	0.0	0	0.0
Aberdeenshire	113,335	8,199	7.2	120	0.1	102	0.1
Dundee City	74,768	5,292	7.1	0	0.0	0	0.0
West Dunbartonshire	45,023	2,953	6.6	0	0.0	0	0.0
Na h-Eileanan an Iar	14,921	872	5.8	278	1.9	5	0.0
City of Edinburgh	242,095	10,140	4.2	0	0.0	0	0.0
Falkirk	72,628	1,778	2.4	0	0.0	0	0.0
Renfrewshire	84,223	1,126	1.3	0	0.0	0	0.0
Perth and Kinross	70,761	274	0.4	0	0.0	0	0.0
South Lanarkshire	147,472	566	0.4	0	0.0	0	0.0
Clackmannanshire	24,078	3	0.0	0	0.0	0	0.0
Dumfries and Galloway	3,973	0	0.0	0	0.0	0	0.0
East Ayrshire	57,933	0	0.0	0	0.0	0	0.0
East Dunbartonshire	44,863	0	0.0	0	0.0	0	0.0
East Renfrewshire	37,777	0	0.0	0	0.0	0	0.0
Midlothian	37,550	0	0.0	0	0.0	0	0.0
North Lanarkshire	151,865	0	0.0	0	0.0	0	0.0
Scottish Borders	9,738	0	0.0	0	0.0	0	0.0
Shetland Islands	30	0	0.0	0	0.0	0	0.0
Stirling	40,756	0	0.0	0	0.0	0	0.0
West Lothian	77,005	0	0.0	0	0.0	0	0.0
Total	2,557,260	158,229	6.2	8,387	0.3	2,811	0.1

Table 4.13: The total value of dwellings benefitting from coastal defences and accretion. Data is sorted by the total value of dwellings benefiting from defences column.

Local Authority	Average House Price	Total Value of Dwellings Benefitting from Defences	Total Value of Dwellings Benefitting from Accretion
Fife	£143,075	£4,244,606,025	£134,204,350
Glasgow City	£138,885	£3,450,597,825	£0
City of Edinburgh	£235,402	£2,386,976,280	£0
Highland	£165,519	£2,135,691,657	£237,023,208
Argyll and Bute	£149,928	£2,015,931,888	£297,007,368
Aberdeen City	£221,268	£1,988,092,980	£0
Aberdeenshire	£232,803	£1,908,751,797	£27,936,360
Inverclyde	£130,377	£1,162,180,578	£0
South Ayrshire	£152,219	£1,106,175,473	£302,763,591
East Lothian	£223,429	£1,070,224,910	£0
Angus	£162,354	£839,370,180	£4,221,204
North Ayrshire	£119,549	£817,834,709	£130,547,508
Dundee City	£128,901	£682,144,092	£0
Moray	£153,560	£617,771,880	£79,390,520
West Dunbartonshire	£115,299	£340,477,947	£0
Falkirk	£131,383	£233,598,974	£0
Renfrewshire	£137,072	£154,343,072	£0
Na h-Eileanan an Iar	£98,160	£85,595,520	£27,288,480
South Lanarkshire	£130,436	£73,826,776	£0
Perth and Kinross	£192,154	£52,650,196	£0
Orkney Islands	£129,075	£22,588,125	£1,807,050
Clackmannanshire	£140,162	£420,486	£0
Dumfries and Galloway	£139,054	£0	£0
East Ayrshire	£115,845	£0	£0
East Dunbartonshire	£217,596	£0	£0
East Renfrewshire	£234,651	£0	£0
Midlothian	£178,405	£0	£0
North Lanarkshire	£119,348	£0	£0
Scottish Borders	£164,448	£0	£0
Shetland Islands	£126,089	£0	£0
Stirling	£197,690	£0	£0
West Lothian	£153,458	£0	£0
Total		£25,389,851,370	£1,242,189,639

Nationally, a total of 8,387 (or 0.3%) of dwellings benefit from accretion. South Ayrshire and Argyll and Bute have the most dwellings benefiting from accretion with 1,989 (4.0% of LA dwellings) and 1,696 (4.1% LA dwellings) dwellings respectively. Highland (1,432 dwellings or 1.2% of LA dwellings) and North Ayrshire (1,092 dwellings or 1.6% of LA dwellings) are the only other LAs to have more than 1,000 dwellings benefiting from accretion.

A total of 2,811 (or 0.1%) of dwellings nationally benefit from both defences and accretion. However, 60% of these dwellings are in Argyll and Bute where 1,696 dwellings (or 3.5% of LA dwellings) benefit from both defences and accretion. The remaining 40% of dwellings are dispersed within nine LAs.

Using the average house prices within each LA the total value of the dwellings benefiting from coastal defences and accretion can be calculated. Dwellings worth a total of £25.4bn benefit from coastal defences. Fife has the highest value of property that benefits from coastal defences (£4.24bn), followed by Glasgow City (£3.45bn) and City of Edinburgh (£2.39bn) second and third respectively. A total of £1.24bn worth of property nationally benefits from accretion, with South Ayrshire benefitting the most in terms of value with £303m.

The coastal length of defences and accretion are shown in Table 4.14. Nationally, the length of coastal defences is 705.7 km. Fife has 106.2 km of coastal defences of which 29,667 dwellings benefit. This means that on average 279 dwellings benefit for every 1 km of coastal defences. This compares to a national ratio of 224. Highland has the second most coastal defences with 88.8 km, equating to 145 dwellings per km of defences. Glasgow City, despite having only 34.6 km of defences, has a dwelling to defence length ratio of 718, almost double the second highest ratio of 392 for Aberdeen City.

Nationally, 471.4 km of coast is classified as accreting by the data used within this research, from which 8,387 dwellings benefit. This equates to a national ratio of 17 dwellings per km of accreting coast. Highland has the longest length of accreting coast with 141.9 km, of which 1,432 dwellings benefit, equating to a ratio of 10.0. In comparison, North Ayrshire has only 4.4 km of accreting coastline, but 1,092 dwellings benefit, therefore the ratio equals 247. North Ayrshire is also the only LA where the defence ratio is higher for accretion than coastal defences, an aspect which may be useful in emphasising in their forthcoming SMP.

Table 4.14: The coastal length within each local authority and the number of dwellings benefiting from coastal defences and accretion. The ratio of length of number of dwellings benefiting from defences or accretion is also shown. Data for columns A and C are taken from Table 4.12. Data is sorted by the defence ratio column.

Local Authority	Dwellings Benefitting from Defences			Dwellings Benefitting from Accretion		
	Number (A)	Defence Coastal Length (km) (B)	Defence Ratio: Number of Dwellings per 1 km of Defences (A/B)	Number (C)	Accretion Coastal Length (km) (D)	Accretion Ratio: Number of Dwellings per 1 km of Accretion (C/D)
Glasgow City	24,845	34.6	718	0	0.0	-
Aberdeen City	8,985	22.9	392	0	0.1	0
City of Edinburgh	10,140	27.0	376	0	0.0	-
Dundee City	5,292	15.0	352	0	0.0	-
Inverclyde	8,914	26.5	337	0	0.0	-
South Ayrshire	7,267	22.4	325	1,989	10.0	199
Fife	29,667	106.2	279	938	17.5	54
East Lothian	4,790	20.5	233	0	13.1	0
Angus	5,170	22.6	229	26	7.5	3
Argyll and Bute	13,446	61.6	218	1,981	63.6	31
West Dunbartonshire	2,953	14.3	206	0	0.0	-
Perth and Kinross	274	1.3	205	0	0.0	-
Moray	4,023	20.5	196	517	17.9	29
Renfrewshire	1,126	5.9	190	0	0.0	-
Aberdeenshire	8,199	43.7	188	120	26.6	5
North Ayrshire	6,841	44.0	156	1,092	4.4	247
Highland	12,903	88.8	145	1,432	141.9	10
South Lanarkshire	566	4.9	116	0	0.0	-
Falkirk	1,778	35.5	50	0	0.0	-
Na h-Eileanan an Iar	872	26.6	33	278	79.4	4
Orkney Islands	175	10.3	17	14	3.7	4
Clackmannanshire	3	6.3	0.47	0	0.0	-
Dumfries and Galloway	0	25.8	0	0	84.1	0
Scottish Borders	0	5.4	0	0	0.0	-
Shetland Islands	0	13.3	0	0	1.6	0
East Ayrshire	0	-	-	0	-	-
East Dunbartonshire	0	-	-	0	-	-
East Renfrewshire	0	-	-	0	-	-
Midlothian	0	-	-	0	-	-
North Lanarkshire	0	-	-	0	-	-
Stirling	0	-	-	0	-	-
West Lothian	0	-	-	0	-	-
Total	158,229	705.7	224	8,387	471.4	17

Table 4.15: The total value of the dwellings benefiting from 1 km of coastal defences or accreting coastline within each local authority. This is calculated by multiplying the average dwelling price by the defence ratio in Table 4.14. The table is sorted by the value of dwellings benefiting from defences column.

Local Authority	Average House Price	Value of Dwellings Benefitting from Defences	Value of Dwellings Benefitting from Accretion
Glasgow City	£138,885	£99,702,022	-
City of Edinburgh	£235,402	£88,503,831	-
Aberdeen City	£221,268	£86,845,371	£0
East Lothian	£223,429	£52,079,587	£0
South Ayrshire	£152,219	£49,492,411	£30,218,352
Dundee City	£128,901	£45,421,319	-
Inverclyde	£130,377	£43,906,168	-
Aberdeenshire	£232,803	£43,695,682	£1,050,951
Fife	£143,075	£39,980,451	£7,660,303
Perth and Kinross	£192,154	£39,420,139	-
Angus	£162,354	£37,202,576	£565,373
Argyll and Bute	£149,928	£32,742,034	£4,668,675
Moray	£153,560	£30,130,894	£4,438,861
Renfrewshire	£137,072	£26,035,780	-
Highland	£165,519	£24,063,982	£1,670,653
West Dunbartonshire	£115,299	£23,795,159	-
North Ayrshire	£119,549	£18,592,106	£29,486,239
South Lanarkshire	£130,436	£15,069,888	-
Na h-Eileanan an Iar	£98,160	£3,215,938	£343,627
Falkirk	£131,383	£2,200,297	£0
Orkney Islands	£129,075	£2,192,594	£485,456
Clackmannanshire	£140,162	£66,945	-
Dumfries and Galloway	£139,054	£0	£0
Scottish Borders	£164,448	£0	-
Shetland Islands	£126,089	£0	£0
East Ayrshire	£115,845	-	-
East Dunbartonshire	£217,596	-	-
East Renfrewshire	£234,651	-	-
Midlothian	£178,405	-	-
North Lanarkshire	£119,348	-	-
Stirling	£197,690	-	-
West Lothian	£153,458	-	-
National Average	£170,190	£38,122,560	£2,893,230

Table 4.15 expands upon Table 4.14 further by calculating the total value of the dwellings using the defence ratio for each LA. This can be considered as a likely benefit value within a cost/benefit analysis for 1 km of coastal defences or accretion. Nationally, on average £38.1m worth of dwellings benefit for every kilometre of coastal defences. The sorted order of the LAs is similar to Table 4.14 for defences, with Glasgow City having a dwelling value of £99.7m per kilometre. Glasgow City has the highest total value despite having a relatively low average house price but a high defence ratio. However, some LAs have relatively high

house prices but low defence ratio yet have a high total value e.g. Aberdeenshire. Nationally, on average £2.89m worth of dwellings benefit for every kilometre of accretion. The LAs of South and North Ayrshire have the highest value of dwellings per kilometre of accretion with £30.2m and £29.5m values respectively. South Ayrshire has slightly higher value, despite having a lower defence ratio, due to the higher average house price than North Ayrshire.

4.2.2 Key Assets

In addition to the residential property reported above, there exist a number of other assets which are located at the coast that can be subjected to the same analysis to assess their exposure to coastal erosion. All of the OS Address MasterMap Layer 2 data has been assessed, however only a selection of the key assets are reported here for brevity (Table 4.16).

Table 4.16: Number of key assets classified as very highly exposed (UPSM/CESM score =>80) by asset type.

Asset Type	Asset	UPSM	CESM
Emergency Services	Ambulance Station	1	0
	Fire Station	3	2
	Police Station	1	0
Local Economy	Camping	5	3
	Caravanning	30	17
	Hotel	35	18
	Distillery	1	0
	General Commercial	437	73
	Shopping	132	25
Key Infrastructure	Oil Distribution	0	0
	Oil Refining	1	0
	Gas Production and Distribution	1	0
	Electricity Generating	4	2
	Electricity Sub Station	167	32
	Sewage Treatment	12	6
Education	Pre School Education	1	1
	Nursery	0	0
	Primary School	2	1
	Secondary School	0	0
	High School	0	0
	School	2	1
	Further Education	0	0
	Higher Education	1	0
	University	2	0
Health	Hospital	0	0
	Hospice	1	0
	Nursing Home	2	0
	Mental Health Centre	0	0
Transportation	Jetty	71	56
	Pier	112	50

Overall, there are very few Emergency Service assets which are exposed to coastal erosion, with only two fire stations exposed according to the CESM i.e. are located where the CESM has a score => 80. When assets that contribute to the local economy are considered, some 437 general commercial and 132 shopping assets are exposed according to the UPSM. These numbers reduce when the CESM is used to 73 and 25 respectively. In addition 17 caravanning and 18 hotel assets are also exposed according to the CESM. There are 167 electric substations and 12 sewage treatment plants are exposed nationally according to the UPSM, decreasing to 32 and six respectively with the CESM. For education assets eight schools are exposed according to the UPSM with only three schools exposed with the CESM. A hospice and two nursing homes are categorised as exposed by the UPSM, but no health assets are exposed according to the CESM. In terms of key transport assets, 71 jetties and 112 piers are exposed with the UPSM, which is reduced to 56 and 50 respectively with the CESM.

4.2.3 Transport Infrastructure

4.2.3.1 Roads

A total length of 54,245 km of roads were analysed to assess the length of the road network exposed to coastal erosion. Using the UPSM a total of 314 km of roads (Table 4.17) are classified as being exposed, with the majority of this length (165 km) attributed to the minor road type. No motorways were classified as exposed. Using a repair cost of £6,500 per metre (Section 2.2.42), the current liability of roads which are exposed using the UPSM is £2.04bn. Argyll and Bute has the greatest length of roads exposed with 74.5 km (Table 4.18), which equates to 23.8% of the exposed roads in Scotland.

Table 4.17: A national summary of the length of roads within each susceptibility category for the UPSM and the current financial liability of the roads classified with high susceptibility (UPSM score => 80) by road type.

Road Type	UPSM (km)					Current Liability
	0-20	20-40	40-60	60-80	80-100	
A Road	9,165.5	446.5	313.1	160.0	97.0	£630,514,187
B Road	6,789.3	206.3	140.7	82.2	51.3	£333,286,229
Minor	33,141.4	1,667.9	1,025.6	358.5	165.4	£1,074,873,091
Motorway	382.4	33.4	17.2	1.7	0.0	£0
Total	49,478.7	2,354.1	1,496.6	602.4	313.6	£2,038,673,506

When the CESM is brought into play then a total of 178 km of roads (Table 4.19) are classified as exposed, with the majority of this length (82.6 km) again represented by minor roads. Thus, the length of exposed minor roads benefitting from defence and accretion reduces by 50% in the CESM, with A and B roads reduced by only 37% and 33% respectively. The current liability of roads which are highly exposed using the CESM is £1.16bn. Argyll and Bute remains the LA with the greatest length of roads exposed (Table 4.20) with 57.5 km (£374m) or 32.2% of the national length of exposed roads. Highland has the second most length of exposed roads with 36.2 km (£235m) exposed which equates to 20.2% of the national length of exposed roads.

Table 4.18: The length of roads within each susceptibility category for the UPSM and the current financial liability of the roads classified with high susceptibility (i.e. a UPSM score => 80) by local authority. Table sorted by current liability.

Local Authority	**UPSM (km)**					**Current Liability (£)**
	0-20	**20-40**	**40-60**	**60-80**	**80-100**	
Argyll and Bute	2,318.0	78.7	106.3	111.7	74.5	484,445,279
Highland	7,020.6	280.0	240.4	105.1	59.4	386,223,759
North Ayrshire	726.5	160.8	47.4	42.2	29.4	191,185,216
Dumfries and Galloway	4,282.6	184.8	65.5	39.5	27.5	178,427,600
Fife	2,249.6	50.6	52.3	36.2	19.7	128,051,729
South Ayrshire	1,036.9	100.3	40.3	39.6	17.5	113,768,488
Orkney Islands	898.9	62.9	40.2	32.1	12.8	83,238,352
Na h-Eileanan an Iar	930.3	134.2	137.8	34.2	12.6	81,743,481
Inverclyde	316.8	5.0	9.5	14.1	11.7	75,909,713
East Lothian	900.3	28.9	28.0	23.2	10.2	66,083,665
Aberdeenshire	5,927.8	65.7	38.2	26.2	8.9	57,984,477
Dundee City	437.3	9.0	8.5	10.3	7.8	50,544,899
City of Edinburgh	1,129.8	55.6	29.2	13.4	4.9	31,534,432
Angus	1,657.2	76.3	54.0	19.0	4.4	28,583,447
Moray	1,495.0	108.0	78.4	16.2	3.4	22,244,952
Falkirk	557.5	103.1	115.8	12.6	2.8	18,123,207
Shetland Islands	923.1	30.5	30.9	9.8	2.6	16,939,289
Aberdeen City	728.1	66.0	26.5	7.7	1.4	9,142,219
Perth and Kinross	2,636.3	119.7	28.6	2.0	1.2	8,076,933
West Dunbartonshire	224.9	63.1	44.8	2.0	0.4	2,879,947
West Lothian	899.6	0.1	0.1	0.4	0.3	1,644,711
Renfrewshire	568.0	88.0	113.9	4.6	0.2	1,597,077
Scottish Borders	3,116.1	12.0	1.0	0.3	0.0	300,635
Glasgow City	1,198.0	266.5	99.1	0.0	0.0	0
Stirling	937.6	130.0	42.4	0.0	0.0	0
Clackmannanshire	197.2	43.7	13.7	0.0	0.0	0
South Lanarkshire	2,147.7	22.8	3.9	0.0	0.0	0
East Dunbartonshire	433.4	7.7	0.0	0.0	0.0	0
East Ayrshire	1,209.9	0.0	0.0	0.0	0.0	0
North Lanarkshire	1,376.8	0.0	0.0	0.0	0.0	0
Midlothian	564.4	0.0	0.0	0.0	0.0	0
East Renfrewshire	432.5	0.0	0.0	0.0	0.0	0
Total	49,478.7	2,354.1	1,496.6	602.4	313.6	2,038,673,506

Table 4.19: A national summary of the length of roads within each susceptibility category for the CESM and the current financial liability classified with high susceptibility (i.e. a CESM score => 80) by road type.

Road Type	CESM (km)					Current Liability
	0-20	20-40	40-60	60-80	80-100	
A Road	9,262.9	470.4	278.6	108.6	61.6	£400,251,879
B Road	6,816.3	216.1	139.0	63.9	34.5	£224,044,683
Minor	33,520.5	1,742.2	815.9	197.7	82.6	£537,006,925
Motorway	391.3	27.2	14.7	1.5	0.0	£0
Total	49,991.0	2,455.9	1,248.2	371.7	178.7	£1,161,303,487

Table 4.20: The length of roads within each susceptibility category for the CESM and the current financial liability classified with high susceptibility (i.e. a CESM score => 80) by local authority. Table sorted by current liability.

Local Authority	CESM (km)					Current Liability (£)
	0-20	20-40	40-60	60-80	80-100	
Argyll and Bute	2,346.4	92.1	101.9	91.3	57.5	373,866,022
Highland	7,068.9	321.3	199.7	79.4	36.2	235,248,709
North Ayrshire	740.6	171.6	46.7	25.2	22.1	143,884,014
Dumfries and Galloway	4,289.6	193.1	70.7	25.7	20.7	134,290,957
Orkney Islands	901.0	67.5	35.8	29.9	12.6	81,666,879
Na h-Eileanan an Iar	939.7	137.6	134.5	28.5	8.8	57,232,303
East Lothian	909.4	42.7	25.5	7.9	5.0	32,340,434
Aberdeenshire	5,952.0	67.2	30.9	13.3	3.5	22,953,703
South Ayrshire	1,055.7	112.6	42.4	20.8	3.1	19,958,191
Shetland Islands	924.7	30.7	30.0	9.1	2.4	15,583,046
Fife	2,275.6	75.5	45.6	9.4	2.2	14,615,879
Dundee City	447.9	13.5	7.6	2.9	1.0	6,219,718
Moray	1,500.8	117.4	74.5	7.5	0.9	5,728,557
Inverclyde	325.7	13.3	13.8	3.7	0.6	3,754,287
Perth and Kinross	2,636.4	120.0	29.3	1.6	0.5	3,226,042
West Dunbartonshire	240.9	66.0	26.0	2.0	0.4	2,879,947
Falkirk	562.2	114.9	111.9	2.4	0.4	2,579,620
West Lothian	899.6	0.1	0.1	0.4	0.3	1,644,711
Renfrewshire	573.4	89.9	106.7	4.6	0.2	1,597,077
City of Edinburgh	1,157.6	68.2	6.7	0.2	0.1	894,994
Angus	1,674.9	87.4	43.7	4.8	0.1	709,607
Aberdeen City	762.7	58.6	7.6	0.8	0.1	428,790
Scottish Borders	3,117.2	12.1	0.1	0.2	0.0	0
Stirling	937.6	130.0	42.4	0.0	0.0	0
Clackmannanshire	197.2	43.7	13.7	0.0	0.0	0
Glasgow City	1,362.8	200.4	0.4	0.0	0.0	0
East Dunbartonshire	433.4	7.7	0.0	0.0	0.0	0
South Lanarkshire	2,173.7	0.8	0.0	0.0	0.0	0
East Ayrshire	1,209.9	0.0	0.0	0.0	0.0	0
North Lanarkshire	1,376.8	0.0	0.0	0.0	0.0	0
Midlothian	564.4	0.0	0.0	0.0	0.0	0
East Renfrewshire	432.5	0.0	0.0	0.0	0.0	0
Total	49,991.0	2,455.9	1,248.2	371.7	178.7	1,161,303,487

The roads classified by the CESM as exposed were compared to the urban/rural classification to identify the rurality of the exposed roads. The results in Table 4.21 indicate that for all road types, the majority of exposed roads are found within the urban/rural classification "accessible rural" or "remote rural" (94.7% of exposed A Roads, 94.5% of exposed B Roads, and 87.8% of exposed Minor Roads). This analysis is important, as it assesses whether the assets that are exposed are likely to be locally important to the community i.e. if a road is lost in a more remote area, that road may be the only road available with no alternative routes, and therefore the disruption to the local community would be significant.

Table 4.21: Analysis of the roads with a CESM =>80 by their respective urban/rural classification.

Road Type	Urban/Rural Classification	CESM Length of road with score of 80-100 (km)	CESM Proportion of road with score of 80-100 (%)
A Road	Large Urban Areas (1)	0.6	0.0
	Other Urban Areas (2)	1.7	2.7
	Accessible Small Towns (3)	0.0	0.1
	Remote Rural Small Towns (4)	0.9	1.5
	Accessible Rural (5)	14.8	24.0
	Remote Rural (6)	43.5	70.7
B Road	Large Urban Areas (1)	0.0	0.0
	Other Urban Areas (2)	0.3	0.9
	Accessible Small Towns (3)	0.6	1.6
	Remote Rural Small Towns (4)	1.0	3.0
	Accessible Rural (5)	5.5	15.9
	Remote Rural (6)	27.1	78.6
Minor Road	Large Urban Areas (1)	1.4	1.7
	Other Urban Areas (2)	3.3	4.0
	Accessible Small Towns (3)	2.8	3.3
	Remote Rural Small Towns (4)	2.6	3.2
	Accessible Rural (5)	16.7	20.2
	Remote Rural (6)	55.9	67.6

4.2.3.2 Rail Track

A total length of 2,512 km of rail track was assessed for exposure to coastal erosion. Using the UPSM a length of 26.4 km of rail track is classed as exposed (Table 4.22). With one metre of rail track equating to £150,000 to repair (Section 2.2.4.3), the national liability of rail track is £3.97bn. Eleven LAs have rail track exposed, with Highland with the most exposed length of rail track with 10.4 km (a liability of £1.55bn) which is over twice the length of rail track exposed in the second highest LA, Argyll and Bute, which has 4.6 km.

Using the CESM a total of 13.3 km of rail track is exposed equating to a national liability of £2.0bn. Eight LAs have rail track exposed, a reduction of three from the UPSM, with Highland remaining with the most exposure with 6.2 km. This equates to a liability of £927m, and is a reduction of 4.2 km from the UPSM. Argyll and Bute remains second highest with 4.4 km, however this is only a reduction of 0.2 km from the UPSM.

Table 4.22: The length of rail track within each susceptibility category for the UPSM and the current financial liability classified with high susceptibility (i.e. a UPSM score => 80) by local authority. Table sorted by current liability.

Local Authority	**UPSM (km)**					**Current Liability (£)**
	0-20	**20-40**	**40-60**	**60-80**	**80-100**	
Highland	519.4	49.2	32.7	14.3	10.4	1,553,366,798
Argyll and Bute	129.4	0.9	3.1	3.2	4.6	694,580,981
Dundee City	2.8	0.8	2.0	5.3	3.7	555,498,733
Angus	22.6	5.2	7.7	10.6	3.0	446,654,960
North Ayrshire	34.8	7.7	6.2	5.5	1.4	203,435,939
Fife	108.5	3.4	2.0	2.5	1.0	154,908,952
Inverclyde	24.7	0.7	2.0	2.0	0.8	123,082,854
West Dunbartonshire	7.7	9.4	6.6	1.4	0.6	88,465,555
Perth and Kinross	141.6	26.8	8.7	0.9	0.5	76,641,086
Dumfries and Galloway	175.1	11.1	0.4	0.3	0.4	56,361,489
Renfrewshire	26.8	7.0	4.7	0.8	0.1	13,651,855
South Ayrshire	67.3	9.8	4.2	3.0	0.0	0
Stirling	45.8	8.6	4.4	0.0	0.0	0
Clackmannanshire	0.9	1.1	4.1	0.0	0.0	0
Glasgow City	71.9	22.1	3.7	0.0	0.0	0
Moray	55.6	5.0	3.4	0.0	0.0	0
Aberdeen City	23.3	1.7	0.9	0.0	0.0	0
South Lanarkshire	115.7	5.1	0.1	0.0	0.0	0
East Lothian	55.1	1.9	0.0	0.0	0.0	0
Falkirk	36.4	6.9	0.0	0.0	0.0	0
City of Edinburgh	55.1	1.3	0.0	0.0	0.0	0
East Dunbartonshire	19.3	1.0	0.0	0.0	0.0	0
North Lanarkshire	109.7	0.0	0.0	0.0	0.0	0
Aberdeenshire	108.4	0.0	0.0	0.0	0.0	0
West Lothian	77.3	0.0	0.0	0.0	0.0	0
East Ayrshire	60.2	0.0	0.0	0.0	0.0	0
Scottish Borders	29.9	0.0	0.0	0.0	0.0	0
East Renfrewshire	27.3	0.0	0.0	0.0	0.0	0
Midlothian	0.0	0.0	0.0	0.0	0.0	0
Total	2,152.4	186.8	97.0	49.8	26.4	3,966,649,203

Table 4.23: The length of rail track within each susceptibility category for the CESM and the current financial liability classified with high susceptibility (i.e. a CESM score => 80) by local authority.

Local Authority	CESM (km)					Current Liability (£)
	0-20	20-40	40-60	60-80	80-100	
Highland	523.1	54.0	29.7	12.9	6.2	926,694,379
Argyll and Bute	131.2	1.4	1.7	2.6	4.4	661,367,012
Angus	24.0	9.3	8.5	6.1	1.2	178,591,925
Fife	109.1	5.2	2.2	0.5	0.6	91,022,429
West Dunbartonshire	11.2	9.8	2.8	1.4	0.6	88,465,555
Perth and Kinross	141.7	27.1	8.9	0.6	0.3	39,588,556
Renfrewshire	26.8	7.0	4.7	0.8	0.1	13,651,855
Inverclyde	26.1	1.0	2.3	0.8	0.0	2,338,527
Dundee City	4.7	4.4	4.0	1.4	0.0	0
North Ayrshire	36.6	11.8	6.2	0.7	0.0	0
South Ayrshire	68.9	11.4	3.8	0.1	0.0	0
Stirling	45.8	8.6	4.4	0.0	0.0	0
Clackmannanshire	0.9	1.1	4.1	0.0	0.0	0
Moray	55.6	5.0	3.4	0.0	0.0	0
Dumfries and Galloway	175.1	11.4	0.7	0.0	0.0	0
East Lothian	55.1	1.9	0.0	0.0	0.0	0
Glasgow City	83.3	14.4	0.0	0.0	0.0	0
Falkirk	36.4	6.9	0.0	0.0	0.0	0
East Dunbartonshire	19.3	1.0	0.0	0.0	0.0	0
Aberdeen City	25.2	0.7	0.0	0.0	0.0	0
South Lanarkshire	120.4	0.5	0.0	0.0	0.0	0
North Lanarkshire	109.7	0.0	0.0	0.0	0.0	0
Aberdeenshire	108.4	0.0	0.0	0.0	0.0	0
West Lothian	77.3	0.0	0.0	0.0	0.0	0
East Ayrshire	60.2	0.0	0.0	0.0	0.0	0
City of Edinburgh	56.4	0.0	0.0	0.0	0.0	0
Scottish Borders	29.9	0.0	0.0	0.0	0.0	0
East Renfrewshire	27.3	0.0	0.0	0.0	0.0	0
Midlothian	0.0	0.0	0.0	0.0	0.0	0
Total	2,189.6	194.0	87.5	27.9	13.3	2,001,720,238

Table 4.24: Analysis of the rail track with a CESM =>80 by their respective urban/rural classification.

Urban/Rural Classification	CESM	
	Length of rail track with score of 80-100 (km)	Proportion of road with score of 80-100 (%)
Large Urban Areas (1)	0.3	2.3
Other Urban Areas (2)	1.6	12.0
Accessible Small Towns (3)	0.0	0.0
Remote Rural Small Towns (4)	0.0	0.0
Accessible Rural (5)	8.3	62.4
Remote Rural (6)	3.2	24.1
Total	13.3	100.0

The rail track that were classified by the CESM as exposed were compared to the urban/rural classification to identify the rurality of the exposed rail track. The results are shown in Table 4.24, which indicates that the majority of exposed rail track are found within the urban/rural classification of "accessible rural" (62.4% of potentially exposed rail track). A further 24.1% of exposed rail track are within the "remote rural" category.

4.2.4 Recreational Assets

A total area of 176 km^2 of golf course was assessed to determine the exposure of courses to coastal erosion. According to the UPSM (Table 4.25) a total area of 5.3 km^2 is exposed equating to a total liability of £9.66m per year when using the economic value of £1.81 per year per m^2 (the value of running of the golf course facilities i.e. green fees, membership fees etc. This value would be considerably higher if all the economic benefits (direct and indirect) that the golf industry provide were taken into account.) Highland, Fife and East Lothian all have liabilities above £1 million with areas of 1.0 km^2, 0.9 km^2, and 0.7 km^2 exposed respectively.

When the CESM is used (Table 4.26) a total area of 2.3 km^2 is deemed exposed to erosion, equating to a liability of £4.2m per year. This is a reduction of 3.0 km^2 or 56.6% from the UPSM. Only one LA has liability over £1 million, East Lothian, which has an area of 0.6 km^2 exposed.

Table 4.25: The area of golf courses within each susceptibility category for the UPSM and the current financial liability classified with high susceptibility (i.e. a UPSM score => 80) by local authority.

Local Authority	**UPSM (km^2)**					**Current Liability (£ per year)**
	0-20	**20-40**	**40-60**	**60-80**	**80-100**	
Highland	4.6	0.7	1.5	2.0	1.0	1,846,196
Fife	14.4	0.3	1.3	1.5	0.9	1,550,643
East Lothian	8.2	0.7	0.8	0.8	0.7	1,245,001
Moray	2.4	0.1	0.7	0.7	0.5	868,054
Angus	1.1	0.5	2.0	0.9	0.4	807,957
South Ayrshire	1.9	2.0	1.2	1.2	0.4	789,528
Aberdeen City	3.2	0.9	0.9	0.4	0.4	694,313
Dumfries and Galloway	4.6	0.8	0.4	0.7	0.4	666,277
North Ayrshire	2.1	1.4	0.5	0.6	0.3	566,562
Orkney Islands	0.7	0.0	0.0	0.1	0.2	282,954
Aberdeenshire	8.2	1.0	1.6	0.9	0.1	174,387
Argyll and Bute	2.8	0.6	0.9	0.7	0.1	172,914
City of Edinburgh	10.3	0.1	0.0	0.0	0.0	0
Clackmannanshire	2.0	0.4	0.0	0.0	0.0	0
Dundee City	2.1	0.0	0.0	0.0	0.0	0
East Ayrshire	1.1	0.0	0.0	0.0	0.0	0
East Dunbartonshire	6.6	0.0	0.0	0.0	0.0	0
East Renfrewshire	3.8	0.0	0.0	0.0	0.0	0
Falkirk	2.7	0.7	0.0	0.0	0.0	0
Glasgow City	3.5	0.3	0.0	0.0	0.0	0
Inverclyde	1.3	0.0	0.0	0.0	0.0	0
Midlothian	2.0	0.0	0.0	0.0	0.0	0
Na h-Eileanan an Iar	0.4	0.0	0.1	0.0	0.0	0
North Lanarkshire	6.9	0.0	0.0	0.0	0.0	0
Perth and Kinross	11.8	0.0	0.7	0.0	0.0	0
Renfrewshire	5.2	0.2	0.8	0.0	0.0	0
Scottish Borders	7.1	0.0	0.0	0.0	0.0	0
Shetland Islands	0.5	0.0	0.0	0.0	0.0	0
South Lanarkshire	6.7	0.1	0.0	0.0	0.0	0
Stirling	2.3	0.0	0.0	0.0	0.0	0
West Dunbartonshire	0.9	0.0	0.3	0.0	0.0	0
West Lothian	3.8	0.0	0.0	0.0	0.0	0
Total	135.3	10.9	13.9	10.5	5.3	9,664,787

Table 4.26: The area of golf courses within each susceptibility category for the CESM and the current financial liability classified with high susceptibility (i.e. a CESM score => 80) by local authority.

Local Authority	**CESM (km^2)**					**Current Liability (£ per year)**
	0-20	**20-40**	**40-60**	**60-80**	**80-100**	
East Lothian	8.3	0.9	0.8	0.7	0.6	1,066,574
Moray	2.4	0.1	0.7	0.7	0.5	868,054
Fife	14.5	1.0	1.4	1.2	0.3	521,533
North Ayrshire	2.1	1.6	0.6	0.4	0.2	399,468
Highland	4.9	1.4	2.0	1.3	0.2	336,105
Orkney Islands	0.7	0.0	0.0	0.1	0.2	282,954
Dumfries and Galloway	4.6	1.0	0.6	0.5	0.1	224,936
South Ayrshire	1.9	2.2	1.4	1.0	0.1	221,621
Aberdeenshire	8.2	1.5	1.5	0.5	0.1	125,366
Argyll and Bute	2.8	0.6	1.0	0.5	0.1	121,522
Aberdeen City	3.5	0.8	1.2	0.3	0.0	27,198
Angus	1.1	0.8	2.7	0.3	0.0	0
City of Edinburgh	10.3	0.1	0.0	0.0	0.0	0
Clackmannanshire	2.0	0.4	0.0	0.0	0.0	0
Dundee City	2.1	0.0	0.0	0.0	0.0	0
East Ayrshire	1.1	0.0	0.0	0.0	0.0	0
East Dunbartonshire	6.6	0.0	0.0	0.0	0.0	0
East Renfrewshire	3.8	0.0	0.0	0.0	0.0	0
Falkirk	2.7	0.7	0.0	0.0	0.0	0
Glasgow City	3.5	0.2	0.0	0.0	0.0	0
Inverclyde	1.3	0.0	0.0	0.0	0.0	0
Midlothian	2.0	0.0	0.0	0.0	0.0	0
Na h-Eileanan an Iar	0.4	0.1	0.1	0.0	0.0	0
North Lanarkshire	6.9	0.0	0.0	0.0	0.0	0
Perth and Kinross	11.8	0.0	0.7	0.0	0.0	0
Renfrewshire	5.3	0.3	0.6	0.0	0.0	0
Scottish Borders	7.1	0.0	0.0	0.0	0.0	0
Shetland Islands	0.5	0.0	0.0	0.0	0.0	0
South Lanarkshire	6.8	0.0	0.0	0.0	0.0	0
Stirling	2.3	0.0	0.0	0.0	0.0	0
West Dunbartonshire	0.9	0.0	0.3	0.0	0.0	0
West Lothian	3.8	0.0	0.0	0.0	0.0	0
Total	136.5	13.9	15.7	7.5	2.3	4,195,331

4.2.6 Historic Assets

4.2.6.1 Listed Buildings

A total of 68,113 listed buildings were assessed for coastal erosion exposure from the Historic Scotland dataset. According to the UPSM (Table 4.27) a total of 1,145 listed buildings are exposed nationally with the majority of buildings in the B and C categories. Argyll and Bute has the most listed buildings exposed with 205, which is equal to 7.27% of the listed buildings within the LA (Table 4.28). Fife has the second highest exposed listed buildings in regards to total number with 195 (3.14%), however Falkirk is second highest in regards to proportion with 6.68% (30 listed buildings).

According to the CESM (Table 4.29) a total of 316 listed buildings are highly exposed nationally with the majority of buildings in the B and C categories which mirrors the UPSM. Based on the CESM the number of exposed listed buildings has reduced by 829, which is a reduction of 72.4%. The LA analysis (Table 4.30) shows that Argyll and Bute has the most listed buildings exposed with 94, which is equal to 3.34% of the listed buildings within the LA. Aberdeenshire has the second highest exposed listed buildings in regards to total numbers with 77 (1.76%), however North Ayrshire is second highest in regards to proportion with 2.69% (28 listed buildings).

Table 4.27: A national summary of the number of listed buildings within each susceptibility category for the UPSM by listed building category.

Listed Building Category	UPSM				
	0-20	20-40	40-60	60-80	80-100
A	5,587	570	299	122	64
B	27,120	3,558	2,647	1,184	540
C	20,139	2,078	2,214	1,450	541
Total	52,846	6,206	5,160	2,756	1,145

Table 4.28: The number of listed buildings within each susceptibility category for the UPSM by local authority. Table sorted by UPSM proportion. Proportions are a percentage of the total number of listed buildings within each local authority.

Local Authority	UPSM					Proportion
	0-20	20-40	40-60	60-80	80-100	%
Argyll and Bute	1,800	131	368	314	205	7.27
Falkirk	226	103	38	52	30	6.68
Inverclyde	223	5	28	30	15	4.98
Dundee City	876	156	180	132	68	4.82
North Ayrshire	545	176	114	158	49	4.70
Aberdeenshire	3,414	233	370	222	144	3.29
Fife	4,723	295	455	540	195	3.14
Highland	2,652	415	598	300	126	3.08
South Ayrshire	567	318	304	119	34	2.53
Na h-Eileanan an Iar	185	41	76	21	7	2.12
Shetland Islands	402	18	56	30	10	1.94
Angus	1,917	240	234	57	42	1.69
East Lothian	1,884	150	383	212	38	1.42
Orkney Islands	636	72	137	55	11	1.21
Moray	1,469	299	116	137	23	1.13
City of Edinburgh	8,459	954	470	243	107	1.05
Dumfries and Galloway	3,361	534	321	78	34	0.79
Aberdeen City	1,155	759	97	20	5	0.25
West Lothian	556	0	0	1	1	0.18
Perth and Kinross	3,086	169	356	12	1	0.03
Clackmannanshire	346	31	5	4	0	0.00
East Ayrshire	1,024	0	0	0	0	0.00
East Dunbartonshire	278	4	0	0	0	0.00
East Renfrewshire	204	0	0	0	0	0.00
Glasgow City	3,704	744	253	0	0	0.00
Midlothian	993	0	0	0	0	0.00
North Lanarkshire	399	0	0	0	0	0.00
Renfrewshire	512	156	77	0	0	0.00
Scottish Borders	3,978	33	40	18	0	0.00
South Lanarkshire	1,401	26	2	0	0	0.00
Stirling	1,728	114	35	0	0	0.00
West Dunbartonshire	143	30	47	1	0	0.00
Total	52,846	6,206	5,160	2,756	1,145	1.68

Table 4.29: A national summary of the number of listed buildings within each susceptibility category for the CESM by listed building category.

Listed Building Category	CESM				
	0-20	20-40	40-60	60-80	80-100
A	5,894	478	184	66	20
B	29,043	3,848	1,627	382	149
C	21,488	2,996	1,427	364	147
Total	56,425	7,322	3,238	812	316

Table 4.30: The number of listed buildings within each susceptibility category for the CESM by local authority. Table sorted by CESM proportion. Proportions are a percentage of the total number of listed buildings within each local authority.

Local Authority	CESM					Proportion
	0-20	20-40	40-60	60-80	80-100	%
Argyll and Bute	2,014	297	290	123	94	3.34
North Ayrshire	570	271	105	68	28	2.69
Aberdeenshire	3,776	209	214	107	77	1.76
Shetland Islands	402	25	54	27	8	1.55
Na h-Eileanan an Iar	207	39	60	19	5	1.52
Orkney Islands	691	141	30	39	10	1.10
Highland	3,011	456	411	171	42	1.03
Dundee City	1,011	297	63	35	6	0.42
East Lothian	1,961	480	191	24	11	0.41
Inverclyde	249	32	17	2	1	0.33
Dumfries and Galloway	3,411	567	295	41	14	0.32
West Lothian	556	0	0	1	1	0.18
Fife	5,099	709	316	73	11	0.18
Moray	1,542	375	97	28	2	0.10
South Ayrshire	897	269	163	12	1	0.07
Angus	2,028	257	196	8	1	0.04
City of Edinburgh	8,734	1,370	115	11	3	0.03
Perth and Kinross	3,088	172	355	8	1	0.03
Aberdeen City	1,406	609	21	0	0	0.00
Clackmannanshire	346	31	5	4	0	0.00
East Ayrshire	1,024	0	0	0	0	0.00
East Dunbartonshire	278	4	0	0	0	0.00
East Renfrewshire	204	0	0	0	0	0.00
Falkirk	228	122	92	7	0	0.00
Glasgow City	4,469	232	0	0	0	0.00
Midlothian	993	0	0	0	0	0.00
North Lanarkshire	399	0	0	0	0	0.00
Renfrewshire	512	159	74	0	0	0.00
Scottish Borders	4,000	63	3	3	0	0.00
South Lanarkshire	1,429	0	0	0	0	0.00
Stirling	1,728	114	35	0	0	0.00
West Dunbartonshire	162	22	36	1	0	0.00
Total	56,425	7,322	3,238	812	316	0.46

4.2.6.2 Scheduled Monuments

In total, an area of 174 km^2 was assessed for coastal erosion susceptibility equating to 8,144 separate sites. A further area of 8.0 km^2 (21 sites) is located below MHWS and therefore not analysed here. For the UPSM 2.52% of the scheduled monument area is classified as exposed nationally (Table 4.31), which equates to an area of 4.37 km^2. The LAs of Clackmannanshire, Fife and Moray all have over 20% of their scheduled monument area exposed to coastal erosion.

Table 4.31: The area of scheduled monuments within each susceptibility category for the UPSM by local authority. Table sorted by UPSM proportion. Proportions are a percentage of the total scheduled monument area within each local authority.

	UPSM (km^2)					Proportion
	0-20	**20-40**	**40-60**	**60-80**	**80-100**	**%**
Clackmannanshire	0.03	0.00	0.00	0.00	0.02	34.33
Fife	3.49	1.05	0.55	0.79	2.96	33.47
Moray	0.46	0.16	0.28	0.32	0.33	21.40
Orkney Islands	1.89	0.17	0.11	0.27	0.17	6.41
Inverclyde	0.43	0.00	0.00	0.02	0.02	5.13
Na h-Eileanan an Iar	1.26	0.07	0.11	0.05	0.04	2.79
Highland	20.98	0.25	0.40	0.65	0.60	2.61
Renfrewshire	0.33	0.00	0.02	0.04	0.01	1.75
Argyll and Bute	5.63	0.11	0.19	0.06	0.10	1.62
Falkirk	2.49	0.41	0.09	0.04	0.04	1.34
Dundee City	0.05	0.00	0.00	0.00	0.00	1.18
Shetland Islands	4.70	0.10	0.16	0.05	0.03	0.51
East Lothian	7.89	0.22	0.04	0.04	0.02	0.30
South Ayrshire	0.96	0.06	0.10	0.03	0.00	0.10
City of Edinburgh	3.94	0.04	0.02	0.01	0.00	0.10
North Ayrshire	3.10	0.01	0.00	0.02	0.00	0.06
Angus	8.53	0.37	0.10	0.01	0.01	0.06
Aberdeenshire	10.21	0.17	0.05	0.02	0.01	0.05
Dumfries and Galloway	15.73	0.57	0.08	0.09	0.01	0.03
West Dunbartonshire	0.38	0.19	0.10	0.00	0.00	0.00
West Lothian	1.79	0.00	0.00	0.00	0.00	0.00
Perth and Kinross	26.60	0.24	0.06	0.00	0.00	0.00
Aberdeen City	0.78	0.02	0.01	0.00	0.00	0.00
Stirling	3.34	0.00	0.02	0.00	0.00	0.00
Glasgow City	0.94	0.05	0.01	0.00	0.00	0.00
Scottish Borders	18.70	0.00	0.00	0.00	0.00	0.00
East Dunbartonshire	1.85	0.00	0.00	0.00	0.00	0.00
South Lanarkshire	8.11	0.00	0.00	0.00	0.00	0.00
North Lanarkshire	2.08	0.00	0.00	0.00	0.00	0.00
Midlothian	1.69	0.00	0.00	0.00	0.00	0.00
East Ayrshire	1.50	0.00	0.00	0.00	0.00	0.00
East Renfrewshire	0.09	0.00	0.00	0.00	0.00	0.00
Total	159.96	4.28	2.49	2.51	4.37	2.52

Table 4.32: The area of scheduled monuments within each susceptibility category for the CESM by local authority. Table sorted by CESM proportion. Proportions are a percentage of the total scheduled monument area within each local authority.

	CESM (km^2)					Proportion
	0-20	20-40	40-60	60-80	80-100	%
Clackmannanshire	0.03	0.00	0.00	0.00	0.02	34.33
Fife	3.52	1.07	0.65	2.27	1.34	15.12
Orkney Islands	1.89	0.17	0.11	0.27	0.17	6.41
Moray	0.47	0.20	0.45	0.35	0.10	6.19
Inverclyde	0.43	0.00	0.00	0.02	0.02	4.86
Na h-Eileanan an Iar	1.26	0.07	0.11	0.05	0.04	2.79
Renfrewshire	0.33	0.00	0.02	0.04	0.01	1.75
Argyll and Bute	5.65	0.12	0.17	0.06	0.10	1.56
Dundee City	0.06	0.00	0.00	0.00	0.00	1.18
Falkirk	2.51	0.44	0.07	0.03	0.03	1.09
Highland	21.00	0.41	0.61	0.72	0.13	0.59
Shetland Islands	4.70	0.10	0.16	0.05	0.03	0.51
East Lothian	7.90	0.26	0.03	0.01	0.02	0.29
South Ayrshire	0.96	0.06	0.11	0.02	0.00	0.10
City of Edinburgh	3.97	0.03	0.00	0.00	0.00	0.09
North Ayrshire	3.10	0.01	0.00	0.02	0.00	0.06
Angus	8.53	0.37	0.10	0.01	0.01	0.06
Aberdeenshire	10.21	0.17	0.05	0.02	0.01	0.05
Dumfries and Galloway	15.73	0.57	0.08	0.09	0.01	0.03
West Dunbartonshire	0.50	0.17	0.00	0.00	0.00	0.00
West Lothian	1.79	0.00	0.00	0.00	0.00	0.00
Aberdeen City	0.80	0.01	0.00	0.00	0.00	0.00
East Ayrshire	1.50	0.00	0.00	0.00	0.00	0.00
East Dunbartonshire	1.85	0.00	0.00	0.00	0.00	0.00
East Renfrewshire	0.09	0.00	0.00	0.00	0.00	0.00
Glasgow City	0.95	0.05	0.00	0.00	0.00	0.00
Midlothian	1.69	0.00	0.00	0.00	0.00	0.00
North Lanarkshire	2.08	0.00	0.00	0.00	0.00	0.00
Perth and Kinross	26.60	0.24	0.06	0.00	0.00	0.00
Scottish Borders	18.70	0.00	0.00	0.00	0.00	0.00
South Lanarkshire	8.11	0.00	0.00	0.00	0.00	0.00
Stirling	3.34	0.00	0.02	0.00	0.00	0.00
Total	160.24	4.51	2.82	4.02	2.03	1.17

4.2.1 Natural Assets

Four types of nature conservation designations (SSSIs, GCRs, SACs and SPAs) were assessed for coastal erosion exposure. For SSSIs, a total supratidal area of 9,428 km^2 (93% of total SSSI area) was assessed equating to 1,421 sites with 42.5 km^2 (258 sites) classified as exposed according to the UPSM, and 25.6 km^2 (248 sites) for the CESM. Highland has the largest extent exposed in the UPSM with 8.6 km^2 (70 sites). Dumfries and Galloway is the second highest with 8.50 km^2 (14 sites). Na h-Eileanan an Iar has the most area exposed when the CESM is used with 5.89 km^2 (26 sites).

Table 4.33: Area of SSSI, GCR, SAC, and SPA conservation designations classified with very high susceptibility (i.e. a UPSM/CESM score =>80) by local authority.

Local Authority	SSSI		GCR		SAC		SPA	
	UPSM	CESM	UPSM	CESM	UPSM	CESM	UPSM	CESM
	(km^2)							
Aberdeen City	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Aberdeenshire	0.95	0.59	0.72	0.49	0.13	0.09	0.22	0.09
Angus	1.54	0.62	0.65	0.40	0.90	0.35	0.12	0.05
Argyll and Bute	4.36	3.38	1.11	0.86	0.81	0.64	3.08	2.27
City of Edinburgh	0.12	0.03	0.03	0.01	0.00	0.00	0.12	0.03
Clackmannanshire	0.02	0.01	0.00	0.00	0.00	0.00	0.02	0.01
Dumfries and Galloway	8.50	2.32	5.85	0.77	6.40	1.88	6.21	1.67
Dundee City	0.04	0.01	0.00	0.00	0.05	0.01	0.04	0.01
East Ayrshire	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
East Dunbartonshire	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
East Lothian	1.76	0.66	0.11	0.09	0.00	0.00	0.55	0.10
East Renfrewshire	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Falkirk	0.59	0.15	0.00	0.00	0.00	0.00	0.57	0.13
Fife	2.24	0.91	1.06	0.16	1.02	0.26	1.26	0.34
Glasgow City	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Highland	8.61	4.94	8.11	5.27	4.91	3.54	8.01	4.35
Inverclyde	0.03	0.01	0.00	0.00	0.00	0.00	0.02	0.01
Midlothian	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Moray	1.79	1.31	2.43	1.76	1.03	0.72	0.34	0.13
Na h-Eileanan an Iar	6.81	5.92	2.90	2.40	5.13	4.87	6.10	5.53
North Ayrshire	0.62	0.47	0.36	0.31	0.00	0.00	0.00	0.00
North Lanarkshire	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Orkney Islands	2.26	2.21	0.55	0.50	0.24	0.24	1.28	1.28
Perth and Kinross	0.87	0.86	0.00	0.00	0.77	0.76	0.88	0.87
Renfrewshire	0.04	0.04	0.00	0.00	0.00	0.00	0.04	0.04
Scottish Borders	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Shetland Islands	0.74	0.73	0.17	0.17	0.50	0.50	0.16	0.16
South Ayrshire	0.38	0.23	0.03	0.03	0.00	0.00	0.01	0.01
South Lanarkshire	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stirling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
West Dunbartonshire	0.17	0.17	0.00	0.00	0.00	0.00	0.16	0.16
West Lothian	0.02	0.02	0.00	0.00	0.00	0.00	0.01	0.01
Total	42.48	25.61	24.08	13.24	21.90	13.86	29.22	17.26

For GCR sites a total supratidal area of 2,246 km^2 (81% of total GCR area) was assessed equating to 888 sites with 24.1 km^2 (218 sites) classified as highly exposed according to the UPSM, and 13.2 km^2 (218 sites) for the CESM. Highland has the most area exposed in the

UPSM with 8.11 km^2 (76 sites). Dumfries and Galloway second highest with 5.85 km^2 (10 sites). Highland remains the most exposed when the CESM is used with 5.27 km^2 (75 sites).

For Special Area of Conservation (SAC) sites a total area of 6,069 km^2 (15% of total SAC area) was assessed equating to 239 sites with 21.9 km^2 (66 sites) classified as highly exposed according to the UPSM and 13.9 km^2 (65 sites) for the CESM. Dumfries and Galloway has the most area exposed in the UPSM with 6.40 km^2 (3 sites). Na h-Eileanan an Iar is second highest with 5.13 km^2 (8 sites). When the CESM is used Na h-Eileanan an Iar has the most area exposed with 4.87 km^2 (8 sites), a reduction of 0.26 km^2. The Dumfries and Galloway has 1.88 km^2 (3 sites) exposed with the CESM, a reduction of 4.52 km^2. The second highest LA when the CESM used is the Highland LA with 3.54 km^2 (23 sites).

For Special Protection Area (SPA) sites a total area of 10,084 km^2 (77% of total SPA area) was assessed equating to 151 sites with 29.2 km^2 (67 sites) classified as highly exposed according to the UPSM, and 17.3 km^2 (67 sites) for the CESM. Highland has the most area exposed in the UPSM with 8.01 km^2 (15 sites). Dumfries and Galloway second highest with 6.21 km^2 (2 sites). Highland drops to the second most exposed when the CESM is used with 4.35 km^2 (15 sites), with Na h-Eileanan an Iar the most exposed with 5.50 km^2 (10 sites).

4.2.2 Section Summary

Section 4.2 has:

- demonstrated that by mapping the CESM with the location of a range of coastal asset types, the potential exposure to coastal erosion of various assets can be identified irrespective of whether these asset data are point, line or areal in nature;

- identified that the following assets are exposed to coastal erosion according to the CESM:

  - 3,310 dwellings, equating to a liability of £526m;

  - 287 key assets. Including 73 general commercial buildings, 25 shopping buildings, 18 hotels, 17 caravanning sites, 32 electricity substations, and 6 sewage treatment plants, of considerable but indeterminate economic value;

  - 178.7 km of roads, equating to a liability of £1.16bn and 13.3 km of rail track, equating to a liability of £2.0bn;

- 2.3 km^2 of golf courses, equating to a liability of £4.2 m per year;

- 316 listed buildings and 2.03 km^2 stretched across 150 separate sites of scheduled monuments, of considerable but indeterminate historical and economic value;

- 25.61 km^2 of land assigned an SSSI designation (248 sites), 13.24 km^2 of land assigned a GCR designation (218 sites), 13.86 km^2 of land assigned an SAC designation (65 sites) and 17.26 km^2 of land assigned an SPA designation (67 sites) of considerable but indeterminate economic value.

4.3 Coastal Erosion Vulnerability Model

4.3.1 Socioeconomic Vulnerability

The CEVM used the Experian Mosaic Scotland geodemographic classification to assess postcodes for socioeconomic vulnerability to coastal erosion. The first stage was to calculate the Gini coefficients for the chosen indicators (Table 4.34).The Gini coefficient for the Education Level indictor had the highest coefficient with 0.60. This indicates that the distribution of people who left school at 16 or earlier is narrower than the other indictors and will therefore be isolated to a smaller number of Experian Mosaic groups.

Table 4.34: Gini coefficients for the indicators used within the CEVM.

Experian Mosaic Group	**Income**	**Poor Health**	**Elderly**	**Single Parents with Dependent Children**	**No Savings**	**Secured/Unsecured Loans**	**No Access to Vehicle**	**Homeowners**	**Education Level**	**Dwelling Density**	**Property Value**
Gini Coefficient	0.43	0.43	0.42	0.53	0.41	0.42	0.49	0.46	0.60	0.36	0.33

The Gini coefficients are used to weight the index scores for each indicator. The raw index scores and the weighted index scores can be found in Appendix Tables A.2.1.1 and A.2.1.2. Table 4.35 shows the average weighted index score for each Experian Mosaic Type. The scores range from 29.9 to 237.7, with a low score indicating relatively low vulnerability, and a high score relatively high vulnerability. In order for users to more easily understand the outputs of the CEVM the Experian Mosaic groups were classified into five descriptive classifications. The quintiles were calculated by ordering the groups by their average weighted index score then using the percentage of dwellings within each to calculate the cumulative percentage. This means that "Very Low" vulnerability represents the least vulnerable 20% of dwellings, and "Very High" equates to the top 20% of vulnerable dwellings.

The lowest average weighted score, i.e. relatively least vulnerable, was obtained by the "Military Might" (Type 9) classification (generally healthy service personnel and families, with good incomes and living in military housing. The Experian Mosaic Types, numbered between 4 and 9, are all classified within the group of "Families on the Move" by Experian. "Families on the Move" are generally young couples with young families, modern homes and good career prospects. Out of the 12 Mosaic Types classified within 'Very Low' vulnerability, three are from within this group (Military Might (9), Successful Managers (4) and New Suburbanites (7)). Also in the very low vulnerability category are Types 1 to 3, which constitute the group "Upper Echelons". People within this group are typically top professionals, with expensive homes in desirable locations and well qualified. All of the Experian Mosaic types numbered between 19 and 24 are within the group named "Urban Sophisticates" and are categorised with very low vulnerability. These are people who are mostly young, well-educated singles who live in apartments in the older, inner areas of large cities.

The Experian Mosaic Type with the highest weighted index score, i.e. relatively most vulnerable, is "Isolated Farmstead" (Type 16) who are generally scattered farmers with older working ages who live in detached homes. The four Mosaic types with the highest average weighted index scores are part of the "Country Lifestyles". In addition to "Isolated Farmstead", there is "Scenic Wonderland" (Type 17), "Far Away Islanders" (Type 18) and "Agrarian Heartlands" (Type 15). People within the Country Lifestyles Group tend to be older working couples who are farm owners or workers, crofters or self-employed hill farmers on low wages and generally based in scattered, rural communities or on isolated farms and crofts.

Table 4.35: Summary of the Experian Mosaic Groups and their CEVM weighted index score, their vulnerability rank, and their cumulative dwelling percentage. Table sorted by average weighted index.

Experian Mosaic Type	Experian Mosaic Description	Average Weighted Index Score	Vulnerability Rank	Percentage of National Dwellings in Experian Group	Cumulative Percentage of National Dwellings in Experian Group	Socioeconomic Vulnerability Description
9	Military Might	29.9	1	0.2	0.2	Very Low
1	Captains of Industry	30.7	2	1.36	1.56	
21	Rucksack and Bicycle	31.1	3	0.67	2.23	
19	Prestige Tenements	31.2	4	1.15	3.38	
2	Wealth of Experience	33.3	5	2.35	5.73	
22	College and Campus	34.8	6	0.24	5.97	
3	New Influentials	35.1	7	2.03	8	
4	Successful Managers	35.9	8	2.34	10.34	
11	Ageing in Suburbia	36.0	9	3.79	14.13	
7	New Suburbanites	36.0	10	2.47	16.6	
24	Cosmopolitan Chic	36.8	11	0.9	17.5	
20	Studio Singles	37.3	12	1.31	18.81	
23	Inner City Transience	37.4	13	2.13	20.94	Low
5	White Collar Owners	38.2	14	2.9	23.84	
6	Emerging High Status	38.4	15	1.92	25.76	
12	Blue Collar Owners	39.3	16	4.43	30.19	
10	Songs of Praise	39.3	17	2.69	32.88	
8	Settling In	42.6	18	0.5	33.38	
28	Small Town Pride	43.4	19	2.64	36.02	
41	Elders 4 in a Block	49.9	20	3.92	39.94	
26	Downtown Flatlets	50.1	21	2.76	42.7	Moderate
34	Quality City Schemes	50.3	22	3.18	45.88	
27	30 Something Singles	50.6	23	2.03	47.91	
43	Skyline Seniors	51.5	24	0.81	48.72	
44	Twilight Infirmity	52.2	25	1.28	50	
35	Lathe and Loom	53.2	26	4.54	54.54	
13	Towns in Miniature	53.5	27	3.11	57.65	
14	Rural Playgrounds	53.9	28	2.46	60.11	High
32	Planners Paradise	54.6	29	5.51	65.62	
42	Greys in Small Flats	54.6	30	3.47	69.09	
29	Dignified Seniors	54.8	31	1.25	70.34	
40	Families in the Sky	56.9	32	1.03	71.37	
33	Smokestack Survivors	57.4	33	3.2	74.57	
39	Room and Kitchen	57.6	34	1.57	76.14	
30	Sought after Schemes	57.9	35	3.99	80.13	Very High
31	Rustbelt Renaissance	58.2	36	4.73	84.86	
25	Tenement Lifestyles	58.6	37	1.16	86.02	
36	Indebted Families	60.6	38	2.97	88.99	
38	Mid Rise Breadline	60.6	39	1.61	90.6	
37	Pockets of Poverty	61.0	40	3.23	93.83	
15	Agrarian Heartlands	65.3	41	2.49	96.32	
18	Far Away Islanders	72.2	42	0.83	97.15	
17	Scenic Wonderland	77.8	43	1.51	98.66	
16	Isolated Farmsteads	237.7	44	1.32	99.98	

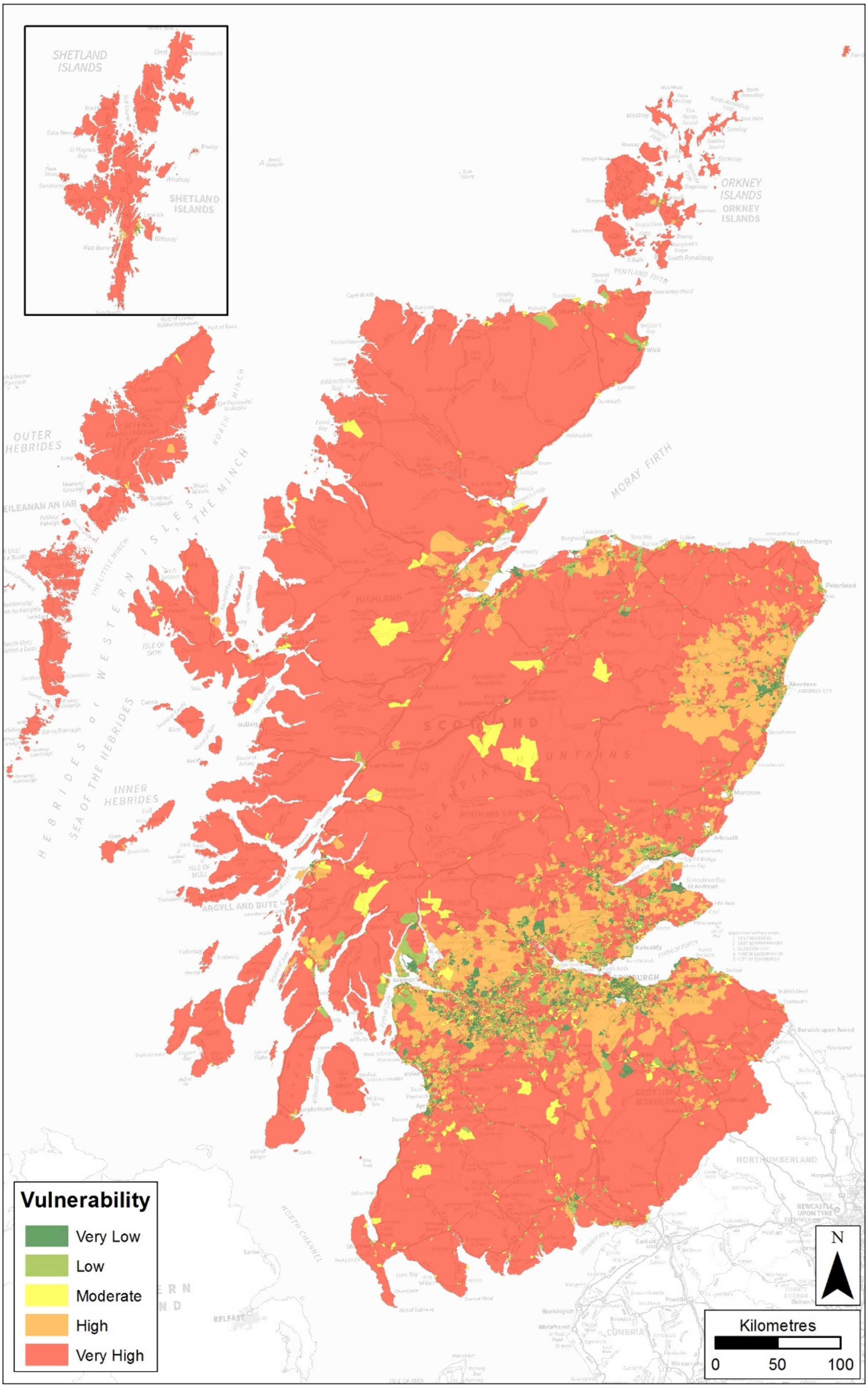

Figure 4.15: Socioeconomic vulnerability to coastal erosion in Scotland. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage. Mapping courtesy of the OS.

Table 4.36: Proportion of dwellings within each vulnerability category by local authority. Sorted by percentage of dwellings in the very high vulnerability category.

Local Authority	Total Dwellings	Proportion of dwellings within each vulnerability category per local authority (%)				
		Very Low	Low	Moderate	High	Very High
Na h-Eileanan an Iar	14,921	0.4	4.5	8.2	3.2	83.7
Orkney Islands	10,952	0.8	8.3	18.8	5.1	66.9
Shetland Islands	11,104	3.7	7.7	14.8	8.9	64.9
Dumfries and Galloway	74,311	5.2	18.1	21.9	10.9	43.9
Highland	115,332	6.3	17.3	22.9	12.5	40.9
Argyll and Bute	48,054	11.3	16.6	20.9	15.6	35.6
Scottish Borders	57,712	7.3	17.9	26.6	16.4	31.8
East Ayrshire	57,951	8.0	23.6	20.9	16.7	30.8
West Dunbartonshire	45,023	8.8	20.6	18.8	23.2	28.6
Moray	43,666	11.4	24.1	23.5	12.9	28.1
North Lanarkshire	151,865	10.8	20.1	16.8	24.5	27.8
North Ayrshire	68,070	10.6	21.6	19.1	21.7	27.0
Clackmannanshire	24,078	12.6	23.8	21.9	15.7	26.0
East Lothian	45,940	14.9	23.4	15.1	20.8	25.8
Angus	54,916	12.1	26.1	23.2	12.8	25.8
Aberdeenshire	113,335	11.7	25.0	17.2	20.4	25.6
Glasgow City	305,085	20.4	13.7	14.5	26.1	25.4
Perth and Kinross	70,761	13.3	21.8	23.6	16.2	25.1
West Lothian	77,005	13.1	23.6	18.6	20.1	24.6
Fife	173,844	16.3	23.8	20.1	16.5	23.3
South Ayrshire	55,442	21.3	22.3	16.4	16.8	23.1
Midlothian	37,682	15.9	21.2	13.5	26.3	23.1
Falkirk	72,628	12.7	25.8	19.9	18.9	22.8
Inverclyde	39,278	12.2	19.6	21.7	24.0	22.5
South Lanarkshire	147,472	15.5	23.7	16.3	22.9	21.6
Dundee City	74,768	24.3	17.4	19.7	17.2	21.4
Stirling	40,756	29.0	18.7	14.3	17.4	20.6
Renfrewshire	84,223	18.7	23.1	19.9	18.1	20.1
Aberdeen City	116,351	34.9	17.1	19.0	13.2	15.9
East Renfrewshire	37,777	42.6	24.5	7.8	14.2	11.0
City of Edinburgh	242,095	35.5	27.1	17.0	10.0	10.4
East Dunbartonshire	44,863	44.9	22.3	9.2	14.1	9.5

Figure 4.15 shows the spatial distribution of socioeconomic vulnerability which reveals that postcodes with very high vulnerability are predominantly found in rural locations. The CEVM is also hosted on a web map (accessible via http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*). In general, vulnerability decreases close to urban centres, however due to the socioeconomic variations within towns/cities, there are postcodes which have very high vulnerability in urban locations. Large scale maps for a number of different towns/cities can be found in the Appendix C.2.1.

With the socioeconomic vulnerability of each postcode identified, the classification was assigned to individual dwellings. A total of 2,557,260 dwellings were assessed. Table 4.36 shows the proportion of dwellings in each vulnerability classification by LA. Na h-Eileanan an Iar has the highest proportion of dwellings classified with very high socioeconomic vulnerability with 83.7% (or 12,486 dwellings). The Orkney and Shetland Islands also have high proportions of socioeconomically vulnerable dwellings with 66.9% (7,323 dwellings) and 64.9% (7,207 dwellings) respectively. East Dunbartonshire has proportionally the least amount of dwellings classified with VH vulnerability with 9.5% (4,258 dwellings). However, City of Edinburgh has slightly higher proportions that are classed with VH vulnerability with 10.4%, however this equates to 25,172 dwellings, 20,914 more than East Dunbartonshire.

4.3.2 CEVM Validation

To validate the CEVM the model was compared to the OAC2011 geodemographic classification. The OAC2011 is a geodemographic classification of the UK using the 60 variables taken from the 2011 UK Census. The classification is hierarchical in structure and has Supergroup, Group and Subgroup tiers with 8, 26 and 76 classifications respectively (see Appendix C.2.2).

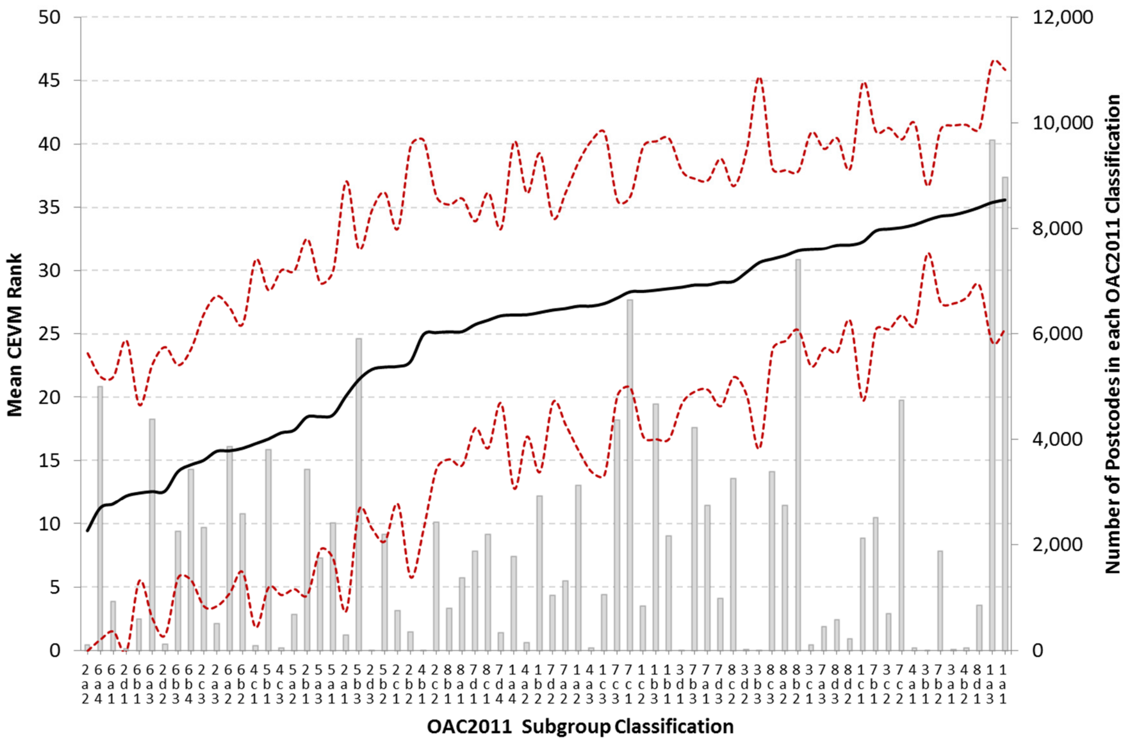

Figure 4.16: The OAC2011 Subgroup classification with the associated mean CEVM rank (black line, and left vertical axis). The standard deviation is also shown (red line). Vulnerabiltiy increases with an increase in CEVM rank.The bars show the number of postcodes within each of the OAC2011 Classifications (right vertical axis).

Figure 4.16 shows the OAC2011 Subgroup classification and the mean CEVM vulnerability rank (Table 4.35) of the postcodes within each of the census output areas. The comparison shows that the OAC2011 Subgroup 1a1, described as "Rural Workers and Families" is generally located in the same area as highly vulnerable postcodes derived from the CEVM. The OAC2011 classification with the lowest mean CEVM rank was 2a2, which is described as "Student Digs", which is within the Supergroup of "Cosmopolitans". Many of the OAC2011 classifications with low mean CEVM ranks are within this Supergroup, which predominantly includes students and the "Aspiring and Affluent". "Suburbanites" (Supergroup 6) also have low mean CEVM ranks. Subgroups 3a2, 8b1, and 8d3 were excluded from the analysis as only one postcode was located within these groups resulting in low confidence in the results.

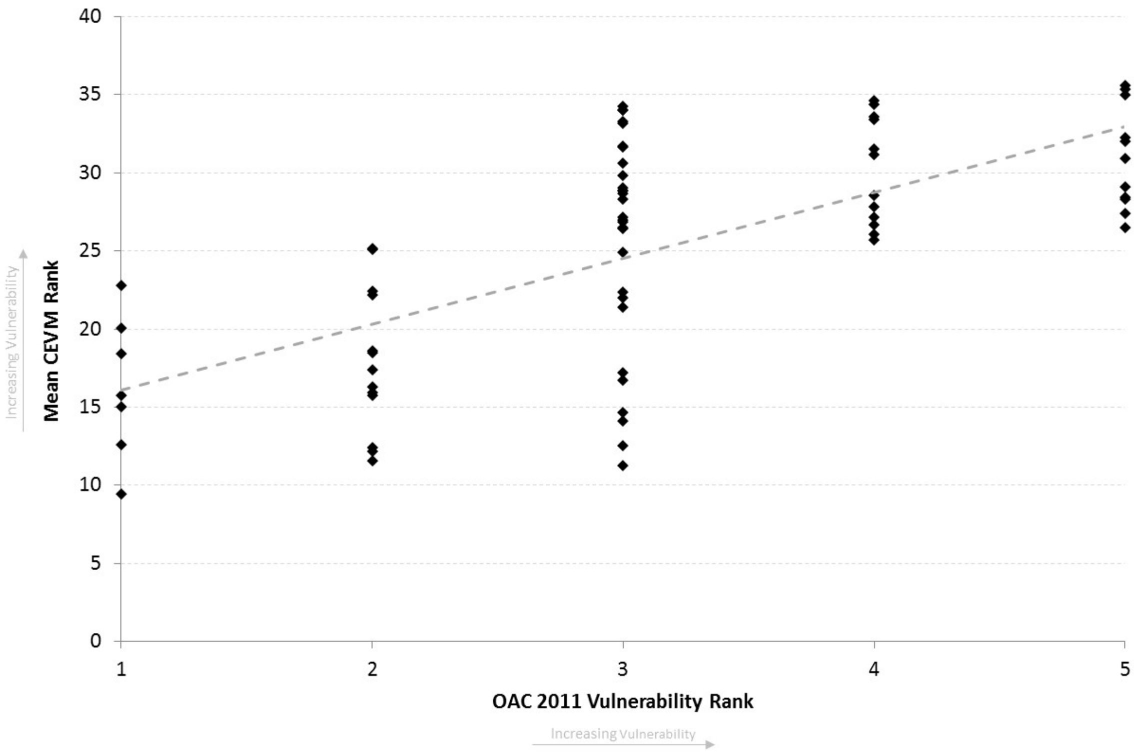

Figure 4.17: The qualitative OAC2011 sub-group classification vulnerability rank compared to the mean CEVM rank. The general trend is that the CEVM and the OAC2011 vulnerability assessment show a direct relationship. However, there is some scatter within the data, particularly in the OAC2011 Vulnerability Rank 3 group. This is discussed further in 5.3.1.

When a qualitative assessment of socioeconomic vulnerability is assigned to each OAC2011 subgroup the CEVM can be validated. Figure 4.17 shows the relationship between the qualitative vulnerability of the OAC2011 output areas and the mean CEVM rank. The figure shows that OAC2011 classifications there were qualitatively ranked as 5 (high vulnerability), were spatially located in the same location as postcodes that had a generally high mean CEVM rank. There is a general trend that the CEVM and the OAC2011 vulnerability assessment show a direct relationship. However, there is some scatter within the data, particularly in the OAC2011 Vulnerability Rank 3 group, with the mean CEVM rank varying from 11.2 to 34.3. The other four classifications have ranges which are much more constrained. This validation shows relative accuracy at the end members of the vulnerability spectrum i.e. the very low and very high vulnerable classifications, but is slightly less reliable in the middle groups.

4.3.3 Section Summary

Section 4.3 has:

- shown that the coastal erosion vulnerability, derived from a range of socioeconomic indicators and weighted using a Gini coefficient approach, varies considerably around Scotland. Nationally, 633,977 dwellings are classified with very high vulnerability. Proportionately the Na h-Eileanan an Iar LA has the most dwellings with very high vulnerability (83.7% or 12,486 dwellings), with Glasgow City having the highest number of dwellings (77,501 or 25.4% of the LA dwellings);

- demonstrated that there is agreement between the CEVM and the OAC2011 data. For example, the areas the CEVM classifies with very low vulnerability are typically areas where students live, areas that are also classified as student areas in the OAC2011 data. The qualitative vulnerability assessment using the OAC2011 data also agrees with the CEVM classification of high and low vulnerability, and adds confidences that the CEVM adequately identifies areas of high socioeconomic vulnerability.

4.4 Coastal Erosion Risk

In Figure 4.15, the whole land area of Scotland has a vulnerability classification despite the hazard of coastal erosion only occurring at the coast. This can be explained by the socioeconomic vulnerability within a postcode is independent of its spatial location, i.e. vulnerability is based solely on socioeconomic indicators. When the dwelling exposure data is combined with CEVM the coastal erosion risk can be established.

Coastal erosion risk, with physical exposure derived from the UPSM and socioeconomic vulnerability derived from the CEVM, is shown in Table 4.37. The table illustrates that 2,036 dwellings show very high levels of both physical exposure and socioeconomic vulnerability to coastal erosion. This means that if these dwellings were impacted by coastal erosion they would severely struggle both with the initial impact, and recovery from the hazard. Conversely, 1,681 dwellings lie in the category most exposed to coastal erosion, however their socioeconomic circumstances mean that their vulnerability is very low and so may cope more easily if they were impacted by this hazard. The coastal erosion exposure derived from using the CESM and then combined with the CEVM is also shown in Table 4.38. This analysis shows that 1,273 dwellings have very high risk to coastal erosion, a reduction of some 695 dwellings from the UPSM exposure risk assessment.

Table 4.37: Coastal erosion risk of dwellings with exposure derived from the UPSM.

		UPSM					
		0-20	**20-40**	**40-60**	**60-80**	**80-100**	**Total**
CEVM	**Very Low**	402,955	38,568	13,992	4,134	1,681	461,330
	Low	445,658	50,306	26,450	9,342	3,674	535,430
	Moderate	359,973	51,934	38,936	11,137	3,898	465,878
	High	387,584	45,409	20,830	4,813	2,009	460,645
	Very High	540,944	55,509	28,774	6,714	2,036	633,977
	Total	2,137,114	241,726	128,982	36,140	13,298	

Table 4.38: Coastal erosion risk of dwellings with exposure derived from the CESM.

		CESM					
		0-20	**20-40**	**40-60**	**60-80**	**80-100**	**Total**
CEVM	**Very Low**	414,507	35,707	9,711	1,181	224	461,330
	Low	461,124	54,599	16,835	2,267	605	535,430
	Moderate	382,406	57,081	23,215	2,336	840	465,878
	High	405,902	43,228	10,491	656	368	460,645
	Very High	555,837	56,070	17,629	3,168	1,273	633,977
	Total	2,219,776	246,685	77,881	9,608	3,310	

The spatial distribution of the dwellings which are classified with VH coastal erosion risk are shown in Table 4.39. The most dwellings in the VH risk category according to the UPSM are found within Highland with 377 houses. Argyll and Bute, and Dumfries and Galloway, have 318 and 308 VH risk dwellings. When the CESM is used Argyll and Bute has the most VH risk dwellings with 286, while Highland, and Dumfries and Galloway, have 255 and 205 respectively. A total of 14 LAs have no dwellings classified within the VH coastal erosion risk category. Highland has the largest reduction in dwellings from the UPSM to the CESM with 122 dwellings benefitting from coastal defences and/or sediment accretion.

The 1,273 dwellings were classified as high risk were then compared against the urban/rural classification to ascertain the level of rurality of at risk dwellings. The results are shown in Table 4.40. Just over two-thirds (66.1% or 842 dwellings) of VH risk dwellings are located within the remote rural category, with a further 26.1% (or 332 dwellings) deemed to be within the accessible rural category.

Table 4.39: Number of high risk dwellings in each local authority with exposure derived from the UPSM and CESM. Data is sorted by the CESM Very High Risk column.

Local Authority	Very High Risk		Reduction
	UPSM	CESM	
Argyll and Bute	318	286	32
Highland	377	255	122
Dumfries and Galloway	308	205	103
North Ayrshire	185	177	8
Na h-Eileanan an Iar	94	88	6
Orkney Islands	66	66	0
Aberdeenshire	135	62	73
Fife	142	58	84
Moray	53	19	34
South Ayrshire	24	19	5
Shetland Islands	20	15	5
East Lothian	72	10	62
City of Edinburgh	71	4	67
Angus	59	4	55
Perth and Kinross	15	3	12
Inverclyde	69	0	69
Falkirk	26	0	26
West Lothian	2	0	2
Aberdeen City	0	0	0
Clackmannanshire	0	0	0
Dundee City	0	0	0
East Ayrshire	0	0	0
East Dunbartonshire	0	0	0
East Renfrewshire	0	0	0
Glasgow City	0	0	0
Midlothian	0	0	0
North Lanarkshire	0	0	0
Renfrewshire	0	0	0
Scottish Borders	0	0	0
South Lanarkshire	0	0	0
Stirling	0	0	0
West Dunbartonshire	0	0	0

Table 4.40: Urban/Rural Classification of very high risk dwellings.

Urban/Rural Classification	Number of Very High Risk Dwellings	Percentage of Very High Risk Dwellings
Large Urban Areas (1)	0	0
Other Urban Areas (2)	27	2.1
Accessible Small Towns (3)	42	3.3
Remote Rural Small Towns (4)	30	2.4
Accessible Rural (5)	332	26.1
Remote Rural (6)	842	66.1
Total	1,273	100.0

4.4.1 Section Summary

Section 4.4 has:

- shown that combining the CESM and the CEVM to estimate coastal erosion risk reveals 1,273 dwellings to be both exposed and very highly vulnerable to coastal erosion i.e very high risk. Argyll and Bute has the most at risk dwellings with 286. Nationally, a further 224 dwellings are very highly exposed to coastal erosion, but have very low vulnerability, significantly reducing the impact coastal erosion would have upon these people.

4.5 Chapter Summary

Within this chapter the results of modelling physical susceptibility and socioeconomic vulnerability to erosion have been reported. The modelling produced the UPSM and CESM, both of which are a national 50 m^2 raster and polyline output. Confidence in the CESM is high as within sections of coasts which are known to be actively eroding, the CESM produces a high to very high erosion susceptibility. When subject to a qualitative review by coastal experts they reported high levels of confidence in the output of the CESM. The CESM classifies 2,100 km of the Scottish coast with very high erosion susceptibility, equating to 11.5% of the coast. A range of assets were examined to identify the assets potentially most exposed to coastal erosion. This analysis identified 3,310 dwellings (a liability of £526m), 287 key assets, 179 km of roads (a liability of £1.16bn), 13 km of rail track (a liability of £2.0bn), 2 km^2 of golf courses (a liability of £4.2m per year), 316 listed buildings and 2 km^2 of scheduled monuments; 26 km^2 of SSSI land, 15 km^2 of GCR, 14 km^2 of SAC land and 17 km^2 of SPA land exposed to coastal erosion.

To identify the dwellings that were vulnerable to coastal erosion the CEVM was generated. The CEVM was derived from a range of socioeconomic indicators and weighted using a Gini coefficient approach. The CEVM was compared to the OAC2011 to validate the model. The results of the qualitative vulnerability assessment show that the areas classified with high and low vulnerability by the CEVM directly correlate with the areas of high and low vulnerability according to the qualitative OAC2011 assessment. Nationally, 633,977 dwellings are classified with very high vulnerability. To estimate the risk of coastal erosion the CESM and CEVM were combined. In total 1,273 dwellings are both exposed and very highly vulnerable to coastal erosion. Chapter 5 will discuss these results and consider the wider implications of this research.

Chapter 5: Discussion

In Chapter 3 the key research aims of this research were stated as:

- generate a coastal erosion physical susceptibility model;
- identify the assets which are exposed to coastal erosion, and determine their economic value where possible;
- generate a coastal erosion socioeconomic vulnerability model;
- utilise both the physical susceptibility and socioeconomic vulnerability models to produce a coastal erosion risk assessment.

This chapter aims to interpret and discuss the results reported in Chapter 4 and to discuss the wider implications of this research.

5.1 Physical Susceptibility to Erosion

5.1.1 CESM Validation

The first research aim stated in Chapter 3 was to model coastal erosion susceptibility on a high resolution national scale to establish the areas where coastal erosion has the potential to occur. Achieving this will better inform government, agencies, and coastal managers about the extent and hazard of coastal erosion. This has been achieved by generating the UPSM and CESM models, which utilised a total of six national datasets. The datasets were ranked and aggregated within a raster output (Figure 4.1 to Figure 4.8 and Appendix C.1.1). This approach is similar to that used by McLaughlin & Cooper (2010), an approach identified in Chapter 2 as an appropriate and suitable methodology to adopt for the purposes of this research.

However, in order for the CESM to be a practical tool for government, agencies, and coastal managers it has to be robust and reliable. Using SNH data, there are 63 locations (a coastal length of 94 km) where erosion is known to be currently ongoing (Table 4.1). This means that the CESM should classify these areas with very high susceptibility. Of the 94 km of eroding coast, 78 km (or 83%) were classified as highly or very highly susceptible to erosion by the CESM. There was 1.83 km (or 3%), at four separate locations (Figure 4.9) were classified with very low susceptibility by the CESM. These four locations were classified as such because of the post processing step of removing locations where no drift deposits occur. Before the post processing steps are applied these locations were classified with a much higher susceptibility. As erosion is known to be occurring at these sites, drift deposits are thus likely to exist at these locations, indicating that the source mapping of drift deposits is the root of inaccuracy rather than the modelling methodology. Expert knowledge checks confirm that these locations are characterised by a mix of extensive intertidal rock platform, backed by sand and gravel beach deposits contributing to the classification error within the BGS drift data. The SNH validation results show that the model is robust and can be relied upon with confidence.

A second validation test was performed using the Eurosion (2004) data where 1,298 km of coastline were claimed to be actively eroding in 2004. This becomes 1,724 km when translated on to the CESM coastline, some 418 km of additional eroding coast (Table 4.2). The reason almost certainly for this lies in the Eurosion (2004) polyline being much more generalised (due to smaller scale mapping) in comparison with the detail and complexity of the CESM coastline, and this increases the length of the coastline.

Along the 1,724 km Eurosion coastline, the average UPSM score is 60.4, and the average CESM score is 56.8, somewhat lower than the scores obtained in the SNH validation. However, of the 1,724 km Eurosion data only 126 km (99 km in the original Eurosion data) is confirmed as actively eroding (Eurosion codes 50 and 51). There are 1,598 km classified with the code ‘4’ or “Erosion probable but not documented” (Figure 4.10). When analysis is limited to the areas that have definite and confirmed erosion (Table 4.2 and Figure 4.11) the average UPSM score rises to 81.2, and the average CESM score to 69.0. The high average UPSM score confirms that the areas that have been confirmed as eroding also have high susceptibility. Nevertheless, the average CESM score is slightly lower than expected. Further investigation shows that the Eurosion data classifies 110 km of hard defences and 12 km of soft defences as eroding. Within the confirmed erosion areas, there are 31 km and 10 km of hard and soft defences respectively. This is unlikely to be accurate, and suggests misclassification within the Eurosion data. Therefore, comparing the Eurosion data to areas where defences are present will result in a lower than expected CESM score. Hence, a more representative comparison would be to compare the coastlines where there are no defences present. On an undefended coast where erosion is confirmed, the average UPSM score is 81.2 and the average CESM 78.4 and shows that areas classified as eroding by Eurosion where no defences are present, have relatively high susceptibility. This validation test of the UPSM and CESM further adds confidence to the robustness of the model outputs.

The qualitative feedback from Angus and Lees (Table 4.4) highlights a tendency within the model to overemphasise the susceptibility in areas characterised by the presence of extensive coastal defences. It is acknowledged that the manner in which the defences are modelled within the CESM may not fully represent the complex nature of the coast where defences exist. However, at a national level, the lack of reliable datasets from the Local Authorities on the extent and nature of their existing coastal defences meant there was little option other than to use the methods described in this research. This is clearly an area where the model can be improved greatly once the supporting data is acquired. This is discussed further in Section 6.2. Overall, the QA comments from Angus and Lees were very positive about the robustness of the CESM and support the quantitative assessment that the model outputs can be accepted with confidence.

5.1.2 CESM Statistics

Using Eurosion data it was calculated that 11.6% (or 1,298 km) of coastline is confirmed or probably eroding (Eurosion, 2004). However, this data was produced when it was thought that the length of the Scottish coastline was 11,154 km, whereas the coastal length is now estimated to be 18,670 km (Angus et al., 2011). This newer estimate is in broad agreement, but 438 km longer than the CESM coastal length of 18,232 km (Table 4.6). The disparity is likely a function of the 50 m raster grid from which the CESM coastline has been generated. This allows the coast to move only in an east-west or north-south direction every 50 m and produces a coastline that is less crenulated and shorter than the actual coastline. Within this length, the CESM classifies 2,100 km or 11.5% of the coast with VH susceptibility (Table 4.6 and Figure 4.14) whereas Eurosion classified 11.6% of the Scottish coast as eroding. This research has highlighted that the Eurosion data should be used with caution since of the 11.6% classified by Eurosion as eroding, only 1.1% (126 km) is confirmed.

The length (Table 4.6) and area statistics (Table 4.7) have also been analysed at a local authority (LA) scale in order to replicate the actions of a national coastal manager who might attempt to identify the LAs where coastal erosion has the potential to be an issue. Information such as the length of coast subject to erosion (or proportion of either a country or a management unit) is often cited within reports and the literature. It is apparent that this statistic may not always be the most appropriate method by which to identify areas with the most severe erosion issues. For example, the CESM classifies North Ayrshire as having the greatest percentage of very highly susceptible coast with 32.5% (or 88.0 km). However, in terms of total length the Na h-Eileanan an Iar local authority has the greatest length of very highly susceptible coast with 561.5 km but only accounts for 16.1% of LA coastline. When attempting to identify the LAs that potentially have the most eroding coast, the total length and percentage statistic can be misleading. For example, Na h-Eileanan an Iar consists of a number of rocky, crenulated islands, resulting in a long total coastline length (3,477 km or 18.6% of the Scottish coast). Therefore, even with 561.5 km of very highly susceptible coastline (26.7% of the total very highly susceptible national coastline), proportionally the LA is ranked only 10^{th} out of 27. The same issue occurs in the Shetland Islands, Orkney Islands, Highland, and Argyll and Bute. Therefore in LAs with longer coastlines the erosion susceptibility may be seen as less severe with a small proportion of the LA length classified as very highly susceptible. The percentage statistic is often used as a method to normalise the difference in length statistics as a result of highly crenulated versus straight coastlines. Conversely, by using the length of coastline as an indicator, LAs with long coastlines are more likely to have long lengths of coast with VH susceptibility and appear to have relatively severe coastal erosion susceptibility compared to the shorter coastline LAs. Therefore, neither approach is ideal.

However, as the CESM uses a raster based approach, it is possible to identify not just the length, but also the area of the hinterland that is classified with VH susceptibility. This statistic is not calculable when just a 'line' approach is used, and hence there has been little opportunity to test whether area is a more reliable statistic to identify management units (LAs in this case) of most concern with regards to coastal erosion than length of percentage statistics. In terms of the CESM results, the area statistics somewhat mirror the length statistics, in Na h-Eileanan an Iar (34.6 km^2 or 1.1% of the total LA area) and North Ayrshire (8.1 km^2 or 0.9%) and are ranked as some of the LAs with the most area with VH susceptibility as a proportion of the LA area. The Orkney Islands has proportionally the most amount of land classified as very highly susceptible with 2.1% (or 21.6 km^2). The length versus proportion statistic issue described above (this time, with total area or the proportion of the LA area statistic) is again prevalent, but it is not as evident compared to the length statistics. The large LAs that consist of a high number of islands and whose potential erosion severity was potentially over or underestimated using a length statistic (i.e. Argyll and Bute, Na h-Eileanan an Iar, Orkney Islands and Shetland Islands) are highly ranked in terms of both total area and proportion of very highly susceptible area. Highland has large land mass with large islands (Highland is second only to Na h-Eileanan an Iar in terms of total area) and a large area of land classified with VH susceptibility (32.8 km^2). However, as a proportion of the total land area this only equates to 0.1% of the LA and is ranked 17^{th} out of 27. Therefore, the area statistic is preferable where the length statistic is skewed as a result of a high number of islands increasing the coastal length. Nevertheless, where a long coastal length is due to a LA covering a large geographic area, with few islands the problem persists.

An alternative is possible here since both the length and area statistics are available. By using both these sets of data it is possible to calculate the ratio of the area of very highly susceptible land that is situated landward of the very highly susceptible coast and the length of coast classified with VH susceptibility (Table 4.8).

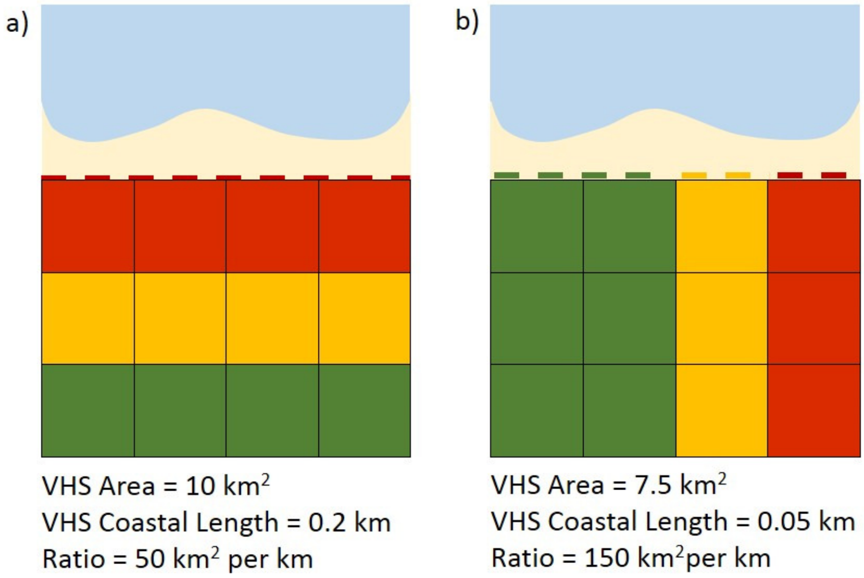

Figure 5.1: A hypothetical scenario demonstrating the area to length ratio metric with 50 m grid cells, with areas in red indicating very high susceptibility (VHS), with areas of yellow moderate susceptibility, and green equates to very low susceptibility a) where very high coastal erosion susceptibility is limited to a strip along the coast the length ratio is smaller compared to scenario b) where despite being only a short length of coast susceptible to erosion, this susceptibility extends inland, resulting in a high ratio.

Figure 5.1 shows two hypothetical scenarios for calculating the area to length ratio. In scenario A, the high susceptibility to erosion is confined to a strip along a long length of coast. If this were to erode, erosion would be limited to only a small area of the hinterland. In scenario B, susceptibility is confined to a short coastal length, however if this were to erode, erosion could potentially continue some distance in land. This statistic is therefore a metric that is able to differentiate between coasts where coastal erosion is possible on a long narrow strip and where coastal erosion could potentially impact on areas further in land. With regards to the CESM, the length statistics can be considered as the current coastal erosion susceptibility, as these are the locations where coastal processes are currently active. However, the area and the area to length ratio can be thought of as metrics that indicate where coastal erosion might be a problem in the future. Therefore, a coastal manager may conclude from the CESM that North Ayrshire or Na h-Eileanan an Iar potentially have a significant length of coast susceptible to erosion currently, whereas Moray is likely to be the most impacted by coastal erosion in the future due to the greater extent of hinterland susceptible to erosion. The use of this metric has not been previously used within coastal management as the 'smartline' approach (Harvey and Woodroffe, 2008; Lins-de-Barros and Muehe, 2011) used extensively within the literature (see Table 2.12) does not allow calculation of areas. Using a line to represent the coast generally indicates that the data only assess the current, rather than future, susceptibility of the coast to erosion. However, even the researchers who have used a raster based approach (Alves et al., 2011; McLaughlin and Cooper, 2010; Vittal and Reju, 2007) did not produce a ratio to describe the hinterland's susceptibility to erosion despite having the option to do so, demonstrating that the concept of future susceptibility in terms of hinterland susceptibility has often been neglected in the literature. The ability of this research to produce area statistics offers a further information source, in addition to length, that may assist coastal managers. Supporting future decision making is vital, considering the climate change induced impact on sea level rise and extreme storm events which are likely to increase coastal erosion (Masselink and Russell, 2013; Zhang et al., 2004). The potential hindrance to using the CESM methodology in other regions is the availability of national raster datasets (this is discussed further in Section 6.2). However, where possible a raster, rather than a line, based approach should be used as it provides a more robust and complete output.

5.1.1 Section Summary

Section 5.1 has:

- shown that the validation results support the notion that the CESM accurately models the susceptibility of the coast. This is important since the CESM has to be robust and reliable in order to be a usable tool for government, agencies, and coastal managers;
- demonstrated the use of coastal length and area statistics for management units (in this case local authorities) to support decision making. However, due to the variation between LAs in coastal length and area these statistics can be skewed. As the CESM is output in a raster format, it was possible to create area to length ratios, a statistic that has not been used previously within coastal management, but which represents another metric that could be used to inform coastal managers;
- determined that the line approach often used within the literature does not offer as much information to the end user as a raster based approach. Using a raster allows a more robust output to be derived and information for both current and future erosion susceptibility of the coast and hinterland to be established.

5.2 Using the CESM for Coastal Management

5.2.1 Potential Applications

The CESM has not been tailored for a specific application other than to model coastal erosion susceptibility. This was a conscious decision made at the outset of this research. The advantage of this approach is that the CESM can be used for a range of different end uses. For example, an earlier version of the UPSM and CESM model is currently in use by the Scottish Environment Protection Agency (SEPA) to assist in their flood risk management assessments (Hansom et al., 2013a, 2013b). The CESM is used by SEPA to identify areas where coastal erosion may exacerbate coastal flooding. SEPA have identified potentially vulnerable areas (PVAs) to fluvial and coastal flooding. By identifying lengths of coast within PVAs with high coastal flooding risk, the PVAs where coastal erosion may remove natural flood defence assets e.g. sand dune, salt marsh, and exacerbate coastal flooding can be identified (Figure 5.2). SEPA have chosen to use a version of the UPSM where only sediment supply, and not the coastal defence data is used to reduce the susceptibility. The decision to exclude the coastal defences reflects an intentionally pessimistic view of the assets and the level of protection (and the quality of the defence dataset) at the coast, therefore assumes a 'worst case' scenario. An example of this version of the model being used by SEPA for Benbecula, South Uist and Barra, Outer Hebrides is shown in Figure 5.3. The impact of coastal erosion on coastal flooding had not been considered by SEPA before the use of the UPSM and CESM. These models allow those planning coastal flood protection option to consider the erosion implications of their approaches. The inability of SEPA's flood maps to consider the compound impact of storms, coastal erosion, and coastal and fluvial flooding is a known weakness that could and should be a subject of further research, particularly given the increase in coastal flooding already anticipated (Pettit, 2015).

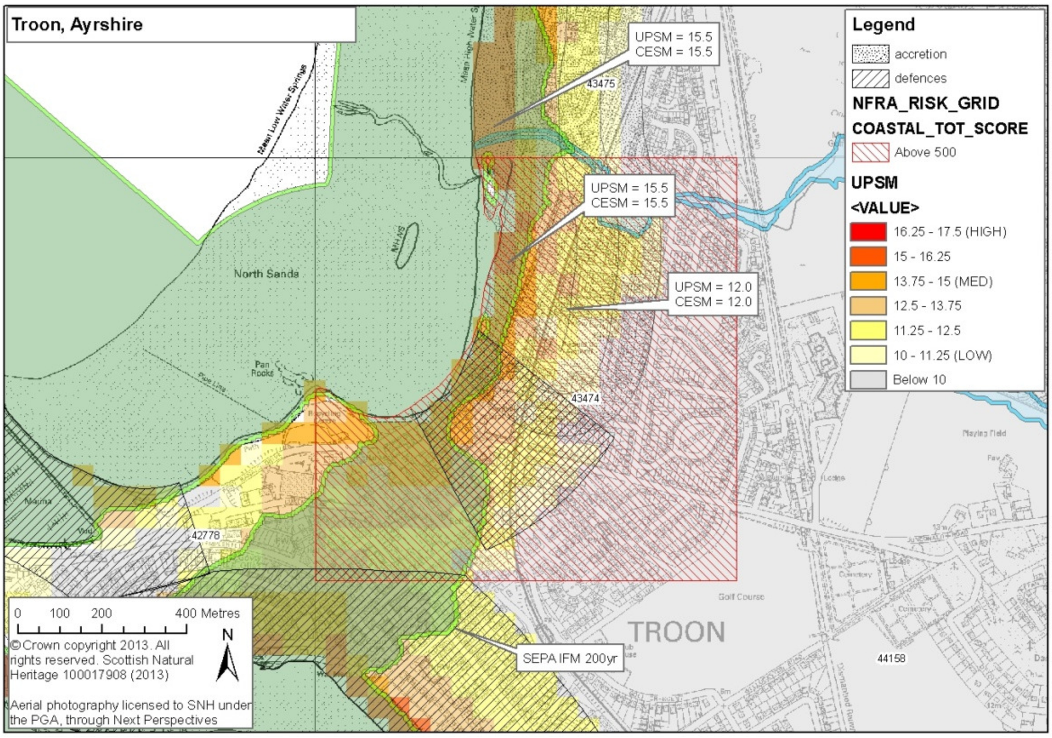

Figure 5.2: An example for Troon, Ayshire, showing how the CESM can be used to inform flood risk management by identifying coast within potentially vulnerable areas (PVAs) that have high erosion susceptibility which may exacerabte coastal flooding by removing natural flood defence assets. Taken from Hansom et al. (2013b)

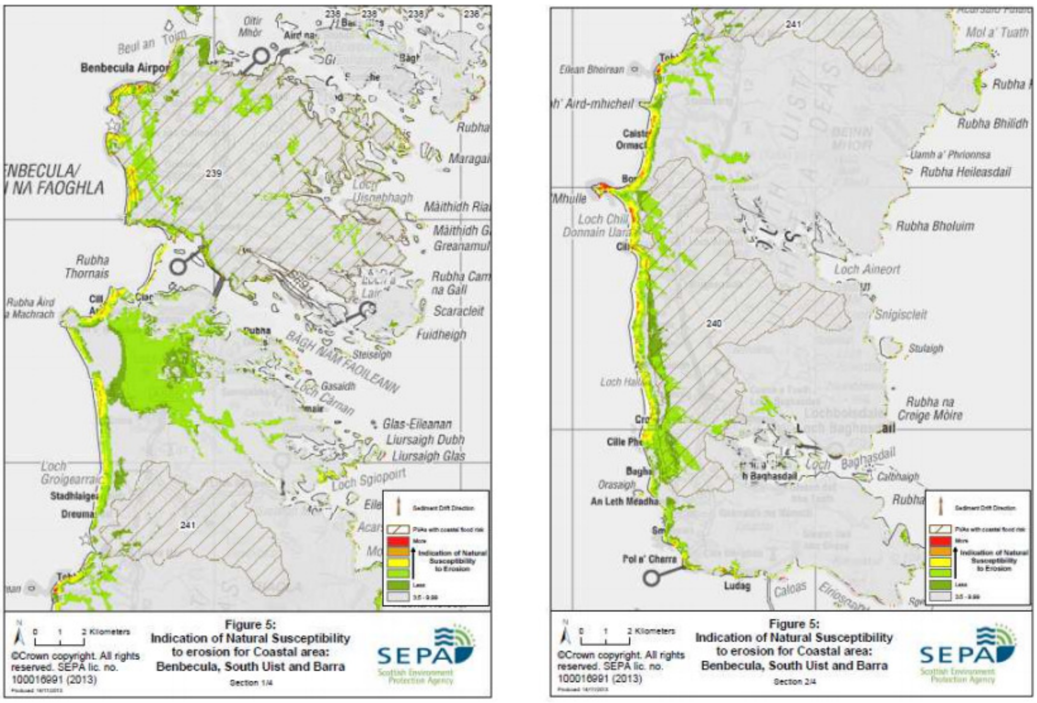

Figure 5.3: The UPSM with sediment supply model used by SEPA within their flood risk management appraisals for Benbecula, South Uist and Barra. Taken from SEPA (2013a).

With the changes that are predicted with climate change (see Section 2.2) there is often a necessity to extrapolate current trends into the future. The CESM currently does not offer any insight into *when* erosion might occur in the future as the data to support such information either does not exist or has high uncertainty. Due to the potential future changes that could occur with regards increased storm occurrence/severity, sea level rise, and wave climate as a result of climate change (Stocker et al., 2013) any prediction about future coastal erosion rates/location would potentially have a large amount of error. The CESM is a tool for coastal managers, but by making predictions that have low confidence, decisions could be made that potentially do more harm than good.

For the CESM, an approach has been taken that means that no future predictions are necessarily needed. The approach is similar to how the National Oceanic and Atmospheric Administration (NOAA) in the US manage the threat of hurricanes. NOAA do not devote time and resource to predicting where individual hurricanes over a hurricane season are most likely to hit the coast (NOAA, 2014a). They forecast the long term trends (NOAA, 2014b) and ensure that the whole coastline that is potentially exposed to hurricanes is adequately prepared for a hurricane if one does occur. Only when an individual hurricane forms, and additional data are collected and analysed, is the path of the hurricane predicted (NOAA, 2014a). Similarly, the CESM allows coastal managers to take the necessary precautions for coastal erosion in the areas that could potentially be affected. Hence, it is a proactive, rather than reactive, tool.

In the locations where coastal erosion is occurring, the CESM could aid predictions of future coastal erosion. This would work best where historic analysis of the coastline position was available in order to calculate the current coastal change rate (erosion or accretion). As a result of the success of applying the UPSM and CESM to the SEPA flood risk assessments, and an increase in the need for further information on coastal erosion in Scotland, the Scottish Government commissioned the National Coastal Change Assessment (NCCA) in 2014. The NCCA is a major policy-driven pan-government research project collating information on coastal change and susceptibility to future coastal erosion and aims to create a shared evidence base to support more sustainable coastal and terrestrial planning decisions in the light of a changing climate[15].

The NCCA methodology to establish historic coastal change is to extract the georectified coastline position from three time periods: OS 2nd Edition Country Series maps (1892-1905), the 1970s (approximately – the data for this time period spans 1956 to 1996) and current coastal position (updated by LiDAR datasets where available). These time series will be then compared in order to estimate past erosion and accretion rates. An example taken from the NCCA pilot web map showing the amount of coastal change from the 1984 to the 2013

[15] This research is being undertaken as an extension of this PhD at the University of Glasgow and project managed by SNH and the Scottish Government.

MHWS position derived from LiDAR is shown in Figure 5.4 (the pilot web maps were used to demonstrate the NCCA outputs to the Scottish Government, SNH and the OS, and due to their success have been developed by SNH using their ArcGIS Online system (Figure 5.5). Using the historic coastal change rates the coastline position can then be projected into the future. Where erosion is occurring the future coastline position projection will be mediated by the CESM in order to limit erosion only to the areas where the hinterland is susceptible to further erosion. Using the erosion rates combined with a number of socioeconomic datasets, key assets potentially exposed to future coastal erosion can be identified, similar to the approach used within this thesis. The NCCA thus aims to inform existing strategic planning (Shoreline Management Plans, Flood Risk Management Planning, Strategic and Local Plans, National and Regional Marine Planning etc.) and to identify those areas which may remain vulnerable in the coming decades and require supplementary support. A national scale assessment of coastal change such as the NCCA has not been undertaken previously and would have been difficult to establish without the CESM and the availability of supporting national data.

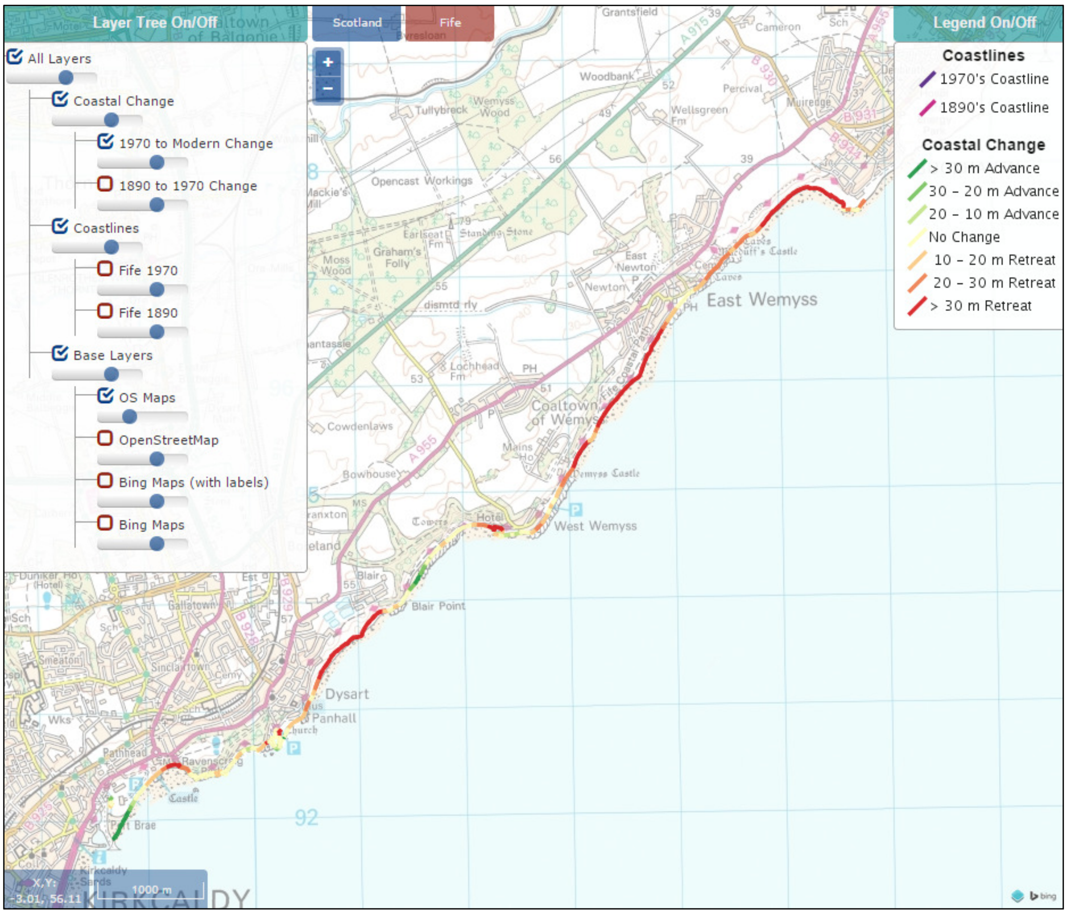

Figure 5.4: An example of the amount of coastal change at East Wemyss, Fife, between 1984 and 2013. Taken from the NCCA web map, currently unavailable to the public.

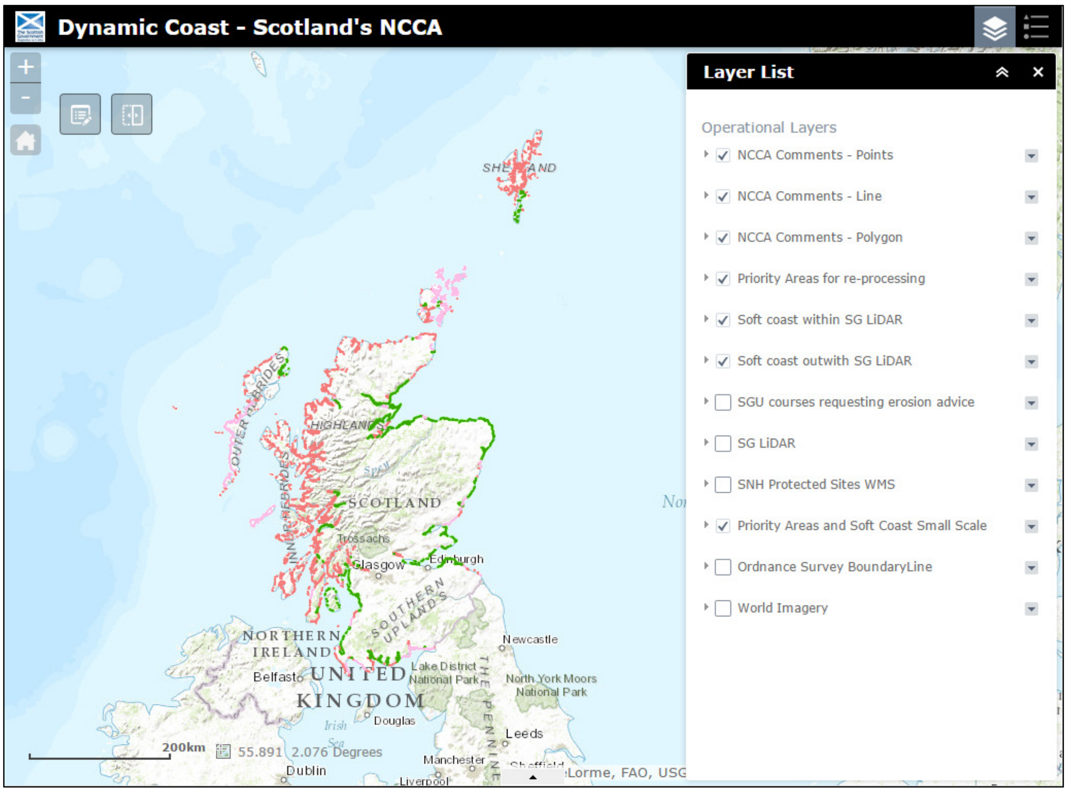

Figure 5.5: An example of the web map on the SNH ArcOnline system which was developed from the NCCA pilot web maps. This version allows users to insert points, polylines and polygons including comments on to the map.

As part of the NCCA, it was identified that the OS MHWS position was out of date and required updating. The CESM was used, along with the rockhead data layer and aerial photography to create a ‘Soft Coast’ dataset i.e. the lengths of coast that could be considered highly dynamic. The stretches of soft coast are likely to be the areas that have had the most change, and therefore have the largest errors in the position of the OS MHWS line. Due to the time constraints within the NCCA, the soft coast data was used to prioritise the areas to update the MHWS position. As a result, an updated MHWS line for the key areas of coastal change will be available for analysis within the NCCA project, adding accuracy and confidence to the project outputs. Key to this was deployment of the CESM to guide the soft coast delineation.

Although the discussion thus far has focussed upon the problem of coastal erosion, coastal erosion is not necessarily negative, as for coastal accretion to take place (which in the model is valued and used to reduce susceptibility) coastal erosion has to occur somewhere else along the coast. Coastal erosion is therefore only considered a problem where it impacts upon assets: hence the exposure assessments within this research. However, knowing where erosional sources (or potential sources) of sediment actually are, is a key piece of information for coastal management. For example, if a sea wall was planned to be installed at a location for either coastal erosion or coastal flooding purposes, the CESM allows the user to identify if any sediment sources will be removed, potentially 'switching off' accretion at adjacent sites. Alternatively, building a seawall may 'switch on' erosion down drift (potentially creating an on-site problem if assets are impacted), but which may generate sediment to fuel accretion somewhere else. Therefore coastal erosion processes can be seen to be an ecosystem service of great value, and one that can be investigated and potentially managed by the CESM.

5.2.2 Exposure of Assets

The second research objective in Chapter 3 was to determine the economic value of assets that are likely to be exposed to coastal erosion. Exposure was calculated by intersecting the location of assets with the UPSM and CESM. As the CESM output can either be a polyline or a raster, this allows greater flexibility when users wish to integrate other datasets with the CESM. This has been demonstrated in Chapter 4 when identifying assets which are potentially exposed to coastal erosion such as the exposure of point (e.g. dwellings), linear (e.g. road) and areal assets (e.g. golf courses), the last category represents a task that is problematic with the linear outputs produced by Reeder et al. (2010), Harvey & Woodroffe, (2008), Thieler & Hammar-Klose, (1999) and many others.

However, the assets which are located within areas of VH susceptibility (UPSM/CESM =>80), and are therefore potentially exposed to coastal erosion have been identified here. Calculating the exposure and the economic value of the exposed assets serves to highlight to coastal managers the impacts of coastal erosion. It can also assist with the siting of new assets by avoiding areas that are not currently eroding, but are highly susceptible, therefore avoiding potential coastal erosion problems in the future. This analysis uses the raster UPSM and CESM output, rather than the line output. Again, this analysis would not be possible if the model was based solely upon a line based approach (e.g. Alexandrakis & Poulos, (2014), Alves et al. (2011), Lins-de-Barros & Muehe, (2011).

5.2.2.1 Residential Property

Dwellings are a key assets to assess as it directly impacts upon people. Nationally, there are 3,310 dwellings (or 0.13%; see Table 4.9) with a total value of £526m (Table 4.10) exposed to coastal erosion. It is thought that approximately 5% of dwellings in Scotland are at risk from a 1 in 200 year coastal or fluvial flood event (SEPA, 2009). This equates to approximately 127,000 dwellings. The number of exposed dwellings to erosion could be considered minor in comparison to flooding. However, the value of the dwellings exposed remains considerable and should not be ignored. Whilst it is necessary to consider erosion and flood risk in turn, the reality in many cases is that they are often inherently linked. At present this linkage has not been acknowledged sufficiently within modelling but is anticipated to have a growing importance in the coming decades, hence the use of the UPSM and CESM by SEPA to investigate this issue. Hansom & Fitton (2013) have identified the interlinking aspect of this at Golspie, where the £1 million contribution to the local economy per year (in the form of a golf course, caravan park, and go-kart track) is being threatened by the combined problem of erosion induced coastal flooding. The CESM, flood risk maps, and time series aerial and ground surveys have proven invaluable in informing the Highland Council, tenants, and landowners, not only of the short term risks but also the broader strategic aspects of future management, including adaptation options.

Taking the value of a dwelling as an indicator of the economic liability is likely to be an underestimate of the true cost if a person were to lose their home due to coastal erosion. The house would be lost, but with that there would be knock-on effects in securing a new place to live, potentially replacing possessions etc., in order to fully recover. Unrepresented in these figures are the intangible impacts upon physical and mental wellbeing and the stress placed upon those impacted by the loss. People may develop depression and other mental disorders as a consequence of being flooded (Kirch et al., 2005; Reacher et al., 2004). Additionally, there are costs for the taxpayer in terms of emergency services and ongoing costs associated with social and health services. Therefore the values quoted within this research are an absolute minimum of what could be expected. More research into the direct and indirect economic costs associated with home loss to coastal erosion is therefore needed to more accurately estimate its economic impact.

As discussed in Section 5.2.1 the advantage of having both a UPSM and CESM output is that comparisons can be made to allow estimates of the assets that benefit from defences or accretion. Nationally, 158,229 dwellings benefit from defences (Table 4.12), which equates to a property value of approximately £25.4bn (Table 4.13). In comparison, only 8,387 dwellings benefit from accretion, equating to £1.2bn worth of property. Therefore, it can be inferred that coastal defences are heavily relied upon as a management strategy at the coast. As expected, areas of high housing density and/or high property values e.g. Glasgow, Edinburgh, and Aberdeen, are the areas where coastal defences are at their most cost effective (Table 4.14 and Table 4.15). However, in LAs such as Na h-Eileanan an Iar, and the Orkney Islands the cost efficiency of any defence structure is much less. Both of these LAs have a high proportion of dwellings potentially exposed to erosion (Table 4.11), perhaps influenced by the fact that funding individual defences in these areas of low population density is difficult.

However, in LAs with a high value of property protected by defences there is also a future liability issue that needs to be addressed. With defences already in place, there is pressure to maintain, and perhaps upgrade and extend, these defences in the future. In a number of locations the very existence of defences may be supporting the value of the properties defended (McLaughlin et al., 2002), and removing or not upgrading defences may result in negative equity for homeowners, creating socioeconomic problems. In LAs such as North and South Ayrshire, Argyll and Bute and Highland there are over 1,000 properties benefitting from natural accretion (Table 4.14). This is an ecosystem service that is currently uncosted and potentially masks an underlying issue. A reliance on natural accretion to prevent erosion depends on the maintenance of accretion into the future, a situation that may be reversed as a result of natural or anthropogenic actions, with erosion potentially occurring, threatening residential properties. Hence, it is imperative that coastal accretion, and coastal processes as a whole, are well understood to ensure management decisions do not inadvertently create erosion problems (Pilkey and Cooper, 2014; Pilkey and Wright, 1988; Pranzini and Williams, 2013; Taylor et al., 2004).

Maintaining and upgrading defences may not be possible in every location due to economic constraints and this will potentially increase the number of properties exposed to coastal erosion. Additionally, more properties may become exposed in areas where the coast becomes erosional due to the loss of accretion. In both these cases, decisions will have to be made as to whether to intervene (via defences or beach nourishment) or to allow natural processes to continue without human interference regardless of the consequences. In areas where nature is left to continue unhindered, there may be people who lose their land and properties. Usually these decisions are heavily based upon the financial costs and benefits of intervention. However, seldom is the socioeconomic vulnerability of the people who will be most impacted by these decisions taken into consideration. For example, England & Knox (2015, p, 7) show that for flood risk management in England *"levels of planned expenditure in flood risk management to 2021 do not appear to align with areas of significant flood disadvantage, or with wider deprivation"* i.e. the vulnerability of the people likely to be impacted has no bearing on spending decisions. By utilising the CEVM, an alternative tool becomes available to managers to allow a method capable of identifying the sections of society who would suffer the most if they were to lose their properties. This means that decisions that make the highly vulnerable people more exposed to coastal erosion can be avoided. The CEVM will be discussed further in Section 5.3.

Releasing information to the public, needs to be well managed in order to avoid any negative outcomes. Therefore when releasing the CESM and CEVM into the public domain, the potential damaging consequences of releasing this type of information should be considered. Taussik et al. (2006) state that those threatened by coastal erosion face financial hardship, stress and other health issues, social blight, loss of community spirit, and mistrust of authorities. By making the CESM and CEVM accessible to the public, people who were unaware of their coastal erosion exposure previously, may then find themselves being classified as exposed. This could result in one or a combination of the problems stated by Taussik et al. (2006) affecting an individual/community. The release of such information should therefore be managed correctly to achieve the objective of informing the population, with minimal negative consequences. However, the research output implications here are no different to the publication of an SMP where people are negatively impacted by a length of coast being categorised as areas of 'no active intervention' or 'managed realignment' management strategies. The public access of the outputs from this research could in fact be considered a means to reduce vulnerability by providing those at risk with ample warning to take action. The CESM highlights areas that are susceptible to erosion but may not be currently eroding, and residents may be unware of the threat. By providing the public with more information, regardless of the potential negative impacts highlighted by Taussik et al. (2006), the risk of coastal erosion could be reduced for current and future generations. On the other hand, a compromise can be reached when releasing this type of information by reducing the resolution of information available to the public. For example, not allowing the public to view the model at a scale where individual properties can be identified. This is the approach used by SEPA (http://map.sepa.org.uk/floodmap/map.htm) and the Environment Agency (http://maps.environment-agency.gov.uk/) for their online flood maps, where the map does not allow the user to zoom in beyond a certain scale. This method allows the risk information to be published, whilst minimising the potential negative impacts described above. If the CESM and CEVM were to be made public in an online map format the same approach of restricting the scales visible to the user would be taken to ensure individual properties could not be identified.

5.2.2.2 Key Assets

As discussed in Section 2.1.1 the coast is key to the local economy due to the number of assets which utilise the coast to derive economic and/or cultural benefits. By assessing the number of these assets that are exposed to erosion decisions can be made to manage the coast in a way that benefits all stakeholders. This research has shown that there is a mixture of asset types exposed to coastal erosion (Table 4.16), however the CESM suggests that low numbers of assets are currently exposed to coastal erosion. Comparison of the CESM with the UPSM, shows that the reason so few assets appear as exposed is because they are benefiting from defence structures or accretion. Therefore in the future, if defences are breached or not maintained, or accretion ceases, there could be a substantial increase in the number of assets exposed. For example, some 32 electricity substations are potentially exposed. However, the UPSM analysis shows that there would 167 potentially exposed if defences and accretion were not present. Factoring in any potential future changes in sea level and extreme storm events will likely enhance the numbers of exposed assets. Currently, it could be argued that coastal assets are well managed in terms of coastal erosion exposure in Scotland, however with changes in nature of coastal erosion and flooding, and potentially a lack of funding for either new or upgrading of defences decisions about the location of coastal assets will need to be addressed by coastal managers in the near future. It is unknown whether organisations who manage key assets, such as the National Grid (who manage the electricity substations), are aware of the impacts coastal erosion could have. Much of the funding and resources is spent addressing the problem of flooding, with the impacts of coastal erosion being realised after an event, i.e. management is reactive, rather than proactive to coastal erosion. The management of coastal assets has been the subject of research by the Resilience-Increasing Strategies for Coasts – toolKIT (RISC-KIT) who take a nodal approach to assess the importance and the potential direct and in-direct consequences of losing an asset (van Dongeren et al., 2014). For example, if an electricity substation is lost, there be will be costs to replace the substation, but there will also be people and businesses without power for a period of time, which may further impact upon the local economy. For many assets this research is the first time their exposure to coastal erosion has been assessed, and is the first stage of further research in this area. Therefore, key assets require further analysis to determine the full extent of the direct and indirect impact of asset loss.

5.2.2.3 Transport Infrastructure

Due to the hilly topography of the hinterland of Scotland, it is often difficult to find suitable routes for transportation infrastructure. The coast has provided the easiest location to site roads and rail track and has led to potential exposure to coastal erosion. The analysis of the road network shows that currently 179 km of Scotland's roads are exposed to coastal erosion, equating to a liability of almost £1.2bn (Table 4.17 and Table 4.19). For rail track some 13 km are classified as exposed, equating to a liability of £2.0bn (Table 4.22 and Table 4.23). The liability for both the road and the rail network are substantial. However, using just the cost of replacement as a metric for liability is again an underestimate. With coastal erosion, there is a direct loss of land, this means that in some cases it might not be possible to replace the road or rail track on a like-for-like basis and new routes may be required, which could dramatically increase the cost of repairing the network. Furthermore, if the route that is damaged is a life-line transport connection, there may be significant loss to the local economy as a consequence of the lack of alternative. For example, in the winter of 2013-2014, 80 m of the South West Main line rail track was damaged at Dawlish, Devon resulting in a 60 day closure of the line while repairs were undertaken. Consequently, there were 7,500 service cancellations which resulted in an estimated loss of between £60 million to £1.2 bn to the local economy (Devon Maritime Forum, 2015). Therefore, even if a road or rail track is repaired fully, disruption during the repair phase can still impact upon the local economy.

The loss of road or rail track is likely to be worst felt in rural areas where a single road or rail track can be of great importance. This is demonstrated by the deaths of five people in the Outer Hebrides, who drowned while escaping rising flood waters via a causeway (the only route available to them) during a storm in 2005 (BBC, 2005). In urban areas there are more roads and rail track, and therefore a higher likelihood that alternative routes are available. In rural areas the loss of a road or rail track that links two communities may severely disrupt transportation as it may be unlikely that there are alternative routes. Comparison of the exposed roads and rail track between urban and rural locations shows the majority to be located in rural areas (Table 4.21 and Table 4.24). Such exposed rural roads and rail track are likely to be crucial to local people and the economy, and should therefore be of greater priority for coastal managers. This research shows that when assessing transport infrastructure, it is better to analyse transport infrastructure assets based on local, rather than national importance, i.e. analysing roads based on type (Motorway, A Road, B Road, Minor Road etc.) can mask the identification of key transport routes.

5.2.2.4 Recreational Assets

Using the golf industry in Scotland as an exemplar for recreational assets is instructive. Golf generates an estimated £1.2bn in revenues for the wider Scottish economy per year which supports approximately 20,000 people in employment (KPMG, 2013). Many links golf courses within Scotland, such as St. Andrews, have historic and cultural value, in addition to the recreational aspect of the course. This research has identified that there is 2.3 km^2 of golf course area exposed to coastal erosion equating to a value of almost £4.2 million per year. (Table 4.25 and Table 4.26).

Golf courses often look to limit coastal erosion by using defences, such as at Golspie and Tain golf courses. However, by their very nature golf courses could be adapted to the changing coast by moving tees and greens and effectively creating new holes as time progresses. This is the policy adopted at the new course at Machrihanish Dunes golf course where the entire course can be shifted inland if erosion becomes an issue in the future. This is recommended practice by SNH (2000). However, there is reluctance to take this approach as some golf courses famously attract golfers due to the layout of specific holes. If defences are the desired management approach favoured by the golf club, the club needs to prove that defending the courses is economic/social and environmental benefit to the local community (Scottish Golf Environment Group, 2014). Due to the importance of golf to the local and national economy defences are relatively easy to justify, but this means that an asset which could be very adaptable, is in reality, very rigid. If it is proving difficult to adapt at golf courses, it would follow that adaptation in more 'controversial' situations, such as urban areas, is likely to be even more problematic.

There are a number of recreational activities that use the coast, but the activity takes place in the marine environment e.g. yachting, boating, swimming etc. The types of activities use the coast as access, and require the coast to remain relatively stable. It was not possible to assess the impact upon these activities within this research due to a lack of adequate data. However, they should be considered in future recreational and economic assessments as activities that could be impacted by coastal erosion.

5.2.2.5 Historic Assets

The historic assets of Scotland are categorised using the listed building and scheduled monuments system provided by Historic Scotland. Buildings are listed based upon their age and rarity, architectural or historic interest and/or close historical association (Historic Scotland, 2011). Scheduled monuments are of national importance and are protected legally under the Ancient Monuments and Archaeological Areas Act 1979. Historic assets are highly valued (but their *value* is incalculable) and their loss due to coastal erosion is of concern and already a priority for research (Historic Scotland (2012) and the Scottish Coastal Archaeology and the Problem of Erosion (SCAPE); see http://www.scapetrust.org). The CESM analysis shows that 316 listed buildings (Table 4.29 and Table 4.30) and an area of 2.03 km^2 scheduled monuments (Table 4.31 and Table 4.32) are exposed to coastal erosion.

For both listed buildings and scheduled monuments the proportion that is exposed is relativity minor (0.46% and 0.01% respectively). However, by their very nature, the buildings and monuments are unique and therefore irreplaceable. There is a strong argument that buildings and monuments should be protected from erosion, for example the sea wall at the World Heritage Site of Skara Brae, a Neolithic settlement in Orkney. However, sites that are deemed 'more important' will be more likely to be subject to this approach, but classifying which sites are more important is open to debate, and calculating the economic benefit of defending these sites is challenging, if not impossible. Defending an historic asset is therefore difficult and sometimes unfeasible. In areas where defences are not possible, managed realignment is the preferred approach (Dawson, 2006). This can likely be done for archaeological sites, but moving buildings or large monuments will not be possible (economically or technically) in most instances, and therefore some assets will eventually be lost to erosion. Conservation now looks to alternatives other than protection or preservation and one approach may be digital recording. This has been the approach used at Wemyss Caves in Fife, a series of caves which contain rock carvings from approximately 600-700 AD which are now threatened by coastal erosion. Using a combination of techniques such as laser scanning and photography the caves have been digitally recorded (The SCAPE Trust, 2014). By creating a digital record the information is available long after the site may have been destroyed and therefore offers a sustainable (by reducing the need for coastal defences) and cost-effective approach to managing historic heritage threatened by coastal erosion.

5.2.2.1 Natural Assets

The ecosystem services that are derived from the coast were discussed in Chapter 2 (Table 2.1). Areas assigned a conservation designation have been deemed to be important to society as we derive one or multiple ecosystem services (provisional, regulating and cultural services) from these areas. By determining the coastal erosion exposure of areas assigned a conservation designation, the loss of ecosystem services due to erosion can be estimated. Note that if the erosion is natural, then erosion is considered acceptable, concern for these assets only occurs when the erosion is human induced. Analysis of four types of conservation designations (SSSI, GCR, SAC, and SPA) in this research has shown that there is a large area exposed to coastal erosion (Table 4.33[16]). There is no simple method to determine which of the natural assets are of most importance as comparing between sites of the same or

[16] This table uses the local authority boundaries as a unit for this analysis. It should be noted that does not necessarily indicate the local authority has the management responsibility for these natural assets. The responsibility will most likely lie with either SNH, the local authority, or the land owner.

different conservation designation types is problematic. For example, it is difficult to compare a 1 km^2 area of one SSSI with another 1 km^2 of SSSI in a different location as different services can be derived at each location. The comparison is complicated further if a SSSI is compared with an SPA. Within this research the aim was to determine the economic liability of the exposed assets if possible. Using ecosystem services and the economic value of these is the usual method to assess importance of natural assets. With natural assets, however, the cultural services (e.g. recreation, tourism, education etc.) can be significant, the most difficult service for which to estimate an economic value. This is further complicated since the type of ecosystem/habitat exposed to erosion may not necessarily be negatively impacted (from a human perspective) by erosion. For example, the loss of saltmarsh is most likely perceived as negative as there is loss of the carbon sequestration and coastal defence ecosystem services. However, a coastal rock outcrop that is important for its scientific merit may benefit from erosion which maintains a clear rock face that is accessible. Therefore, whether coastal erosion is positive or negative from a human perspective needs to be determined on a site by site basis by expert judgement. However, this needs to be balanced against whether the erosion benefits the coastal environment as a whole.

5.2.3 Section Summary

Section 5.2 has:

- shown that the UPSM and CESM have been applied to the problem of coastal flooding by SEPA, and coastal change as part of the NCCA project. The CESM allows coastal managers to take the necessary precautions for coastal erosion in the areas that it could potentially occur, negating the need to make predictions about exactly *when* and *where* erosion *will* take place. The CESM is therefore a proactive rather than a reactive tool;

- shown that calculating the exposure and (where possible) the economic value of the exposed assets can highlight the potential impacts of coastal erosion. The CESM can further assist coastal managers looking to site new assets at the coast by identifying areas that are not currently eroding, but that are highly susceptible. Therefore development can avoid these areas and avert potential coastal erosion problems in the future;

- established that there are fewer dwellings potentially exposed to coastal erosion compared to flooding. However, there are 158,229 dwellings that currently benefit from defences (a property value of approximately £25.4bn). If these defences were not maintained or upgraded then coastal erosion (and associated coastal flooding) could become more of an issue in the future;

- shown that there are only a limited number of key assets that are potentially exposed to coastal erosion currently. This is due to the presence of coastal defences rather than assets being located on coasts with low susceptibility. This means that in the future, the coastal defences protecting these assets will have to be maintained or upgraded. This might not always be feasible, and therefore coastal managers may have to look toward the future repositioning a large number of key assets to sites with low susceptibility;

- demonstrated that the economic liability of erosion for both the road and the rail network are substantial. The impact will be worst felt in rural areas where a single road or rail track is of great importance as a lifeline route. Coastal managers are better to analyse transport infrastructure based on local importance, rather than national importance;

- shown that golf courses can be adapted to the changing coast. This is suggested practice by SNH (2000). However, there is reluctance to adopt adaptation approaches at golf courses in spite of these assets being highly suited to this type of management. Using adaptation in potentially more 'controversial' situations, such as urban areas, is likely to be even more problematic.

- established that historic assets are highly valued and their loss due to coastal erosion is already the subject of research within Scotland. Protecting the important historic assets is difficult as there is no objective measure to decide which historic assets are the most important. Alternatives such as using digital archiving is one route to record historical assets without the need for coastal defences.

- demonstrated that the impact of coastal erosion upon natural assets is not necessarily negative. Whether coastal erosion is positive or negative needs to be determined on a site by site basis by experts within their field. However, this needs to be balanced against whether the erosion benefits the coastal environment as a whole.

5.3 Risk

5.3.1 Vulnerability

The third aim highlighted within Chapter 3 was to generate a model that could identify socioeconomic vulnerability to coastal erosion. A total of 11 socioeconomic indicators were selected from the Experian Mosaic Scotland geodemographic classification and weighted using Gini coefficients (Table 4.34) to make a single vulnerability measure based upon the methods of Willis et al. (2010). The CEVM shows that there is a large variation in the socioeconomic vulnerability within Scotland (Table 4.35) with rural areas highlighted as being particularly vulnerable (Figure 4.15). The CEVM was validated against the OAC2011 classification (Figure 4.16 and Figure 4.17) which indicated that there can be confidence in the CEVM outputs. The scatter seen within Figure 4.17 can be explained by the fact that the OAC and CEVM use different output areas with the OAC using census output areas, whereas the CEVM uses postcodes. This means that the borders between units are not the same in both datasets, potentially adding an element of error in the results. This is unavoidable as the OAC2011 data is not available at postcode level, hence no direct comparison with the CEVM exists. Nevertheless, the general trend is positive and adds to the confidence of the CEVM. As vulnerability and risk are closely linked, the following section examines vulnerability and risk in the context of the CESM and CEVM.

5.3.2 Risk

The final overall aim of this research was to develop a risk assessment for coastal erosion. As outlined in Figure 2.24 this is achieved by combining the CESM with the CEVM, which, amongst other outputs, established that 1,273 dwellings are both exposed and vulnerable to coastal erosion. As discussed in Section 5.2.2.1 estimation of coastal erosion risk allows coastal managers to assess those sectors of society most likely to be impacted and suffer most from coastal erosion at specific locations. This is a metric that has not been previously used for coastal erosion management within Scotland. The analysis shows that risk is not distributed equally amongst the Scottish population, either as a consequence of location (and therefore exposure), or due to the imbalance of socioeconomic attributes. By combining the CESM and CEVM, it becomes clear that there are two routes to reduced risk: either reduce exposure or reduce vulnerability. Whichever method (or combination) is used an initial decision has to be made about whether coastal managers (at LA or central government level) should intervene to reduce the coastal erosion risk to property. This will be discussed in the following section.

5.3.2.1 Social Justice

For the management of any environment, the concepts of social justice (defined as the manner by which benefits and costs are distributed through society) should be a key component (Cooper and McKenna, 2008). Hence, coastal managers have a responsibility to manage the coast in a way that the benefits/burdens are shared equally between the whole of society. With regards to coastal erosion a legitimate social justice question to ask is '*Should society (the government) intervene to reduce the risk of those exposed to coastal erosion?*' To address this question the following discussion draws upon the work of Dobson (1998), who explores the generic concepts of social justice and the principles by which justice is distributed, as well as Cooper & McKenna's (2008) discussion of social justice specifically in relation to coastal erosion.

If the answer to the above question is '*yes*', then it may well be unlikely that coastal managers will have access to sufficient resources to reduce the risk of everyone exposed now or in the future. Managers therefore will need to prioritise, in a socially justifiable manner, the areas where reduction of coastal erosion risk is best targeted. There are a number of ways that coastal managers can contribute to solutions that favour social justice (Table 5.1).

Table 5.1: The principles of social justice distribution and their application to coastal erosion management in Scotland. Based upon Dobson (1998).

	Principle of Distribution				
	Market Value	**Utility**	**Desert**	**Equality**	**Need**
What is it?	Maximise the value of property defended	Maximise the number of properties defended	Prioritise areas that are most deserving	Redistribute the risk	Prioritise the most vulnerable people
Currently used in coastal management?	Yes	Yes	No	No	No
Why is it used/not used?	Analysis and economic cost/benefit methods are a well-established technique and uses readily available data		Difficult to apply	No coastal erosion insurance	No data available
How does this research contribute?	Offers additionally information on the value and number of properties exposed to coastal erosion.		N/A	N/A	Offers information on the vulnerability of people offering an alternative to market value or utility approaches.

Using Dobson's conceptualisation as a foundation[17], coastal erosion risk is currently reduced on a 'market value' basis, i.e. coastal erosion risk will be reduced in areas that achieve the best cost/benefit ratio (Cooper and McKenna, 2008; Potts, 1999). In some situations, decisions could be made on a 'utility' basis, where the highest number of dwellings are

[17] The terms market value, utility, desert, equality, and need are taken from and defined further in Dobson (1998).

protected, but these scenarios are likely to achieve a high cost/benefit ratio. There are three other principles that could be used as alternatives to a market value or utility approach; desert, equality, and need.

A 'desert' based approach prioritises those who are most deserving of assistance. If a local community who are threatened by coastal erosion form a group that has campaigned for assistance, it could be argued they are more deserving than others. As an overall approach however, this is a difficult concept to apply to coastal erosion as deciding who is 'deserving' of assistance adds another layer of complication to the issue. The concept of 'equality' means that the risk is redistributed as evenly as possible throughout society. An example of this is the recent flood insurance policies (Flood Re) in the UK currently being developed. The premiums for households within high flood risk are capped (at various levels dependent upon council tax banding), so that the premiums do not become unaffordable, with the cost of this policy being paid for by a levy on premiums of all households (Association of British Insurers, 2015). However, there is currently no insurance available for coastal erosion, so a subsidised insurance scheme is not currently an option. Furthermore the changes in the future flood insurance scheme mean that those with effectively zero risk will no longer support to the same degree those with high risk. Allowing access to insurance effectively decreases vulnerability, rather than exposure. Other approaches could be used to reduce exposure, for example improving education and raising awareness of coastal erosion exposure, or offering funds and expertise to create adaptation plans that allow coastal assets to be more easily relocated. The final distribution approach is on a 'needs' basis, which means that those who are most vulnerable should be prioritised. The sectors of society and indeed individual dwellings that are most vulnerable to coastal erosion have been identified for this first time in this study by the generating the CEVM. The 'needs' approach is now available to coastal managers who, theoretically at least, do not have to be aligned with the 'market value' or 'utility' approach to prioritise coastal erosion risk reduction.

The discussion about methods of distribution above assumes that intervention should occur. Cooper & McKenna (2008) offer an interpretation of social justice which strongly favours the route of non-intervention when looking at the longer-term and national scales (Figure 5.6). Coastal managers within Scotland typically work at a local authority level (regional level), where reasoning for short-term and local scale intervention can be strong (blue area on Figure 5.6). Social justice is better achieved if coastal management adheres to a long term and national approach (green area on Figure 5.6). This view is based upon the fact that intervention (whether hard or soft) is detrimental to the coast in both financial and environmental aspects to some degree (e.g. loss of a beach due to a sea wall) and this is a cost that the whole of society must pay. However, only relatively small numbers of people may benefit from this intervention, therefore the benefits are more difficult to justify when the costs are distributed amongst non-coastal residents. Justification is made even more problematic when the social justice of future generations is considered: climate change and sea level rise will likely increase the amount of coastal erosion and coastal environmental assets may be lost before future generations gain the benefit. Cooper & McKenna (2008)state that in areas that are already defended, any decision to not maintain or upgrade these defences can be justified on the basis that these properties should not have been defended at the taxpayers' expense in the first place. In this way, social injustice for those that have not benefited from public money is being rebalanced. Cooper & McKenna (2008) conclude that difficult decisions with regards intervention should occur at national scales rather than local, i.e. intervention would only occur if the benefits are national and relate to current and future society. It therefore follows that to aid this decision-making the data and information supplied to coastal managers should be at a national scale.

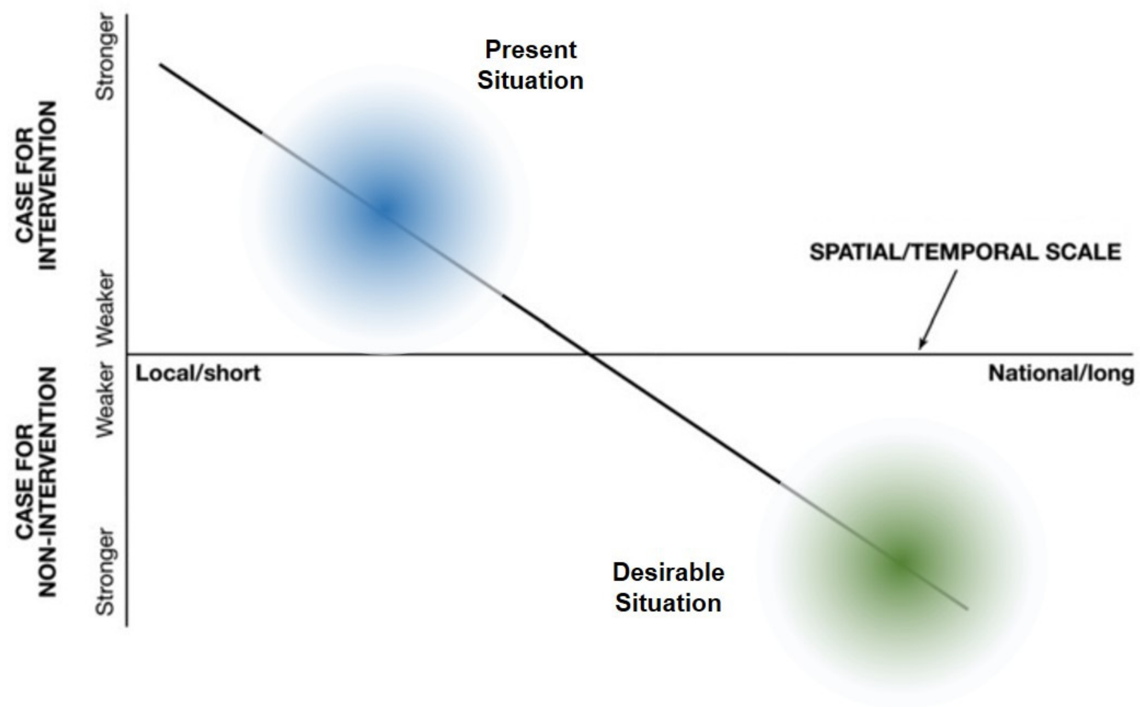

Figure 5.6: Relationship between the case for public intervention in coastal erosion management and scale, both spatial and temporal. The gradient is likely to differ depending on the form of intervention, but the trend will remain the same. The blue area represents the present situation of coastal management within Scotland, with the green area representing the desirable position coastal management should work towards in the future. Adapted from Cooper and McKenna (2008).

Within Scotland, coastal erosion management and the supporting data is too disparate, as evidenced both by the lack of nationwide SMPs and national coastal datasets (physical and socioeconomic). This is further compounded by the devolution of coastal management decisions which take place at local authority level and focussed on local/regional issues. The data used within the CESM and the CEVM are all relevant at a national scale, and when combined can highlight the national scale risk. Since, many of the dwellings at most risk are located in rural areas, intervention is unlikely to occur if decided on a market value or utility approach. This could therefore be considered the more socially justifiable approach at a national level. If a needs-based approach is used, there is a case that intervention for the rural dwellings is initially justified. However, the degree of social justice will depend on the type of intervention implemented. For example, using hard or soft defences will come at a financial and environmental cost to society, whereas an adaptation approach i.e. assisting people by moving to a new location, may have a financial cost but an environmental gain. Theoretically, if the people in dwellings that are at risk from coastal erosion are moved to less exposed locations, the ‘problem’ of coastal erosion is significantly reduced. This will involve a substantial financial outlay initially, but costs could be offset against the reduced costs of installing and maintaining defences and the fact that there will be no negative impacts upon coastal processes (initially and in the future). Research has yet to explore whether intervention in the form of adaptation is a more socially justifiable method (on national and long term scales) to deal with coastal erosion than the insertion of hard or soft defences in the coastal environment.

5.3.3 Section Summary

Section 5.3 has:

- demonstrated that in spite of confidence with the outputs of the CEVM, the validation data used are not ideal due to the mismatch in output area (postcodes versus census output area). Unfortunately, this is unavoidable as the OAC2011 data is not available at postcode level and no direct comparison with the CEVM is currently available;

- established that coastal erosion risk is not equally distributed amongst the Scottish population, as a consequence of location (and therefore exposure), or due to the imbalance of socioeconomic attributes. The research highlights that there are two methods to reduce risk of coastal erosion; either reduce exposure or reduce vulnerability;

- discussed the principles of distribution with regards social justice and coastal erosion. The CEVM allows coastal managers to take a needs based approach to coastal management, rather than a market value or utility approach;

- shown that a long term and national approach to coastal management is more socially justifiable. In Scotland, decisions are made at the local/regional scale and this favours intervention in the form of coastal defences. A national based approach may offer more opportunity to use adaptational approaches. However, at present research has yet to explore whether this is a more socially justifiable method.

5.4 Chapter Summary

This chapter has discussed a number of implications for coastal management that have arisen due to the outputs of this research. The CESM has the potential to be a robust and reliable tool for coastal managers to inform decision making. This is supported by the validation tests performed on the model. However, this research highlighted that the common metrics used to describe coastal erosion statistics may misrepresent the amount of coast susceptible to erosion. This research offers an alternative in the form of an area to length ratio that allows the coastal manager to determine the local authority (or any management unit) that has potentially the most amount of land susceptible to erosion, both currently and in the future.

It was established within this chapter that the issue of coastal erosion will directly impact on a relatively low number of properties compared to those impacted by flooding (both coastal and fluvial). However, this is only because many dwellings are already protected by coastal defences, and there are still many properties that are situated on land that is highly susceptible to erosion. The situation is the same for a number of key assets. There is therefore a considerable future liability for Scotland that means there will be great pressure for coastal defences to be maintained and upgraded in their current form. This is without taking into account the coastal flooding protection also offered by these defences, which will make the case even stronger.

There are a range of assets that are potentially exposed to coastal erosion, that all face different management challenges. The impact of losing part of the transport network (even for just a short amount of time) will be most keenly felt in rural areas where a single road or rail track can be of great importance as a lifeline route. The difference in national versus local importance of transport infrastructure means that the importance of assets at the local scale should be assessed as a way to prioritise the assets most in need of potential management actions e.g. adaptation. However, there appears to be reluctance to use adaptational approaches with some assets which would otherwise be ideal for adaptation, such as golf courses. The reluctance to use adaptation approaches at golf courses suggests that adaptation in urban areas is going to be highly complex and very difficult to implement. Management of natural assets is problematic as coastal erosion at a site can be both viewed as positive and negative. This judgement needs to be determined by experts. However, the unescapable fact that erosion release sediments to the benefit of the wider coastal environment is often overlooked and needs to be considered.

The use of the CEVM is a novel inclusion within a coastal erosion assessment for Scotland. The validation of the CEVM proved valuable, but was not without issue due to the mismatch in output areas used. Use of the CEVM established that coastal erosion risk is not distributed equally amongst the Scottish coastal population and highlighted that risk can be reduced by either reducing exposure or reducing vulnerability. In terms of social justice the CEVM will allow coastal managers to take a needs-based approach rather than a market value or utility approach. This will assist in making decisions based on the long-term and national approach to coastal management which is proven to be a more socially justifiable approach. In Scotland decisions are made at the local/regional scale and therefore the case for intervention in the form of coastal defences becomes stronger. However, at present research has yet to fully explore whether adaptational approaches represent a more socially justifiable method.

Chapter 6: Conclusion

This thesis set out to achieve four aims, which are summarised along with the accomplished outputs within Table 6.1. Within this chapter, the key outcomes are discussed, and the research outputs and methods are critiqued and evaluated. Finally, the potential direction of future research is detailed.

Table 6.1: Summary of the aims and the outcomes of this thesis.

Aim	Output
Physical Susceptibility - model coastal erosion susceptibility on a high resolution national scale to establish the areas where coastal erosion may occur;	The UPSM and CESM were produced, which models coastal erosion susceptibility on a 50 m raster for the whole of the Scottish coast. The input datasets were ground elevation, rockhead elevation, wave exposure, proximity to the open coast, sediment supply and the presence of coastal defences. The model was validated with SNH and Eurosion data, proving confidence in the model is high.
Exposure - determine the assets that are likely to be exposed to coastal erosion, and their economic value;	The UPSM and CESM were used in combination with other GIS datasets to establish the levels of exposure for dwellings, key assets, transport infrastructure, historic assets, and natural assets. The economic liability of the exposed assets was also calculated where possible. The UPSM and CESM are compatible with assets data that are either point, line or areal in nature.
Vulnerability - explore the use of geodemographies in order to produce a coastal erosion socioeconomic vulnerability model to identify the people that will suffer most if exposed to coastal erosion;	The CEVM used the Experian Mosaic Scotland classification to identify 11 variables (weighted using Gini coefficients) to determine socioeconomic vulnerability to coastal erosion. Nationally, 633,977 dwellings were classified with very high vulnerability according to the CEVM.
Risk - combine the physical susceptibility and socioeconomic vulnerability models to establish coastal erosion risk.	Both the CESM and CEVM were used in order to estimate coastal erosion risk. In total 1,273 dwellings were both exposed and very highly vulnerable to coastal erosion.

6.1 Key Outcomes

The modelling of coastal erosion susceptibility has produced the UPSM and the CESM, both of which are a national 50 m^2 raster and polyline output. The models use either four or six datasets which produced robust and reliable outputs. Approximately, 2,718 km (14.9%) and 2,100 km (11.5%) of the Scottish coastline were classified with very high erosion susceptibility according to the UPSM and CESM respectively. Both these models have been applied outwith of this project to the problem of coastal flooding by SEPA, and coastal change as part of the NCCA. The models and intermediate datasets can be seen via a web map: http://www.jmfitton.xyz/phd (Login: *user* Password: *4g7a9f*). To extract more information from these models, they were compared with the location of a number of different assets to determine coastal erosion exposure. This analysis identified the following assets were exposed to coastal erosion:

- 3,310 dwellings, equating to a liability of £526m;
- 287 key assets. Including 73 general commercial buildings, 25 shopping buildings, 18 hotels, 17 caravanning sites, 32 electricity substations, and 6 sewage treatment plants, of considerable but indeterminate economic value;
- 179 km of roads, equating to a liability of £1.16bn and 13.3 km of rail track, equating to a liability of £2.0bn;
- 2.3 km^2 of golf courses, equating to a liability of £4.2m per year;
- 316 listed buildings and 2.03 km^2 stretched across 150 separate sites of scheduled monuments, of considerable but indeterminate historical and economic value;
- 25.6 km^2 of land assigned an SSSI designation (248 sites), 13.2 km^2 of land assigned a GCR designation (218 sites), 13.9 km^2 of land assigned an SAC designation (65 sites) and 17.3 km^2 of land assigned an SPA designation (67 sites) of considerable but indeterminate economic value.

The identification of the people who are socioeconomically vulnerable to coastal erosion was deemed an important output of this research, as it would allow the government and coastal managers to take a needs-based approach to coastal management, rather than a market value or utility approach. The CEVM was derived from 11 socioeconomic indicators derived from the Experian Mosaic Scotland geodemographic classification. Nationally, 633,977 dwellings were classified with very high vulnerability, which when combined with the CESM identified a total of 1,273 dwellings with both exposure and very high vulnerability to coastal erosion. As a consequence of this research coastal managers are now more informed about where coastal erosion has the potential to occur, and the impact that this may have on a range of assets located within the coastal zone. They can therefore make more cost-effective and sustainable decisions for the coast. The previous resource used to accomplish this was the Eurosion data, which is only available as polyline output, is of smaller scale (1:100,000, compared to the CESM which is a 50 m raster and used the 1:10,000 MHWS polyline), and highly inaccurate in substantial areas of Scotland (only 1.1% of the coast classified as eroding by Eurosion was confirmed, with many of the locations classified as “Erosion probable but not documented’ showing low erosion susceptibility scores according to the CESM). Furthermore, the outputs of this research have directly contributed to improving SEPA's flood risk management assessments, as well as highlight the potential impacts of coastal erosion within Scotland, leading to the development of the National Coastal Change Assessment project.

All the aims set out in Chapter 2 have been accomplished (Table 6.1). However, in Figure 2.24, this thesis outlined a working approach to modelling both the geomorphological and socioeconomic of a hazard. All the stages within the workflow have been explicitly covered within this thesis except the 'mitigation/adaptation' stage. The reason for this is that the 'mitigation/adaptation' stage can be seen as start point of this research, as coastal erosion has previously been managed in Scotland (predominantly in the form of hard coastal defences). Therefore, this research assesses the current hazard potential with the mitigation measures in place. As stated in Section 2.4.3 in reference to the work flow:

> "*The model is cyclical, demonstrating that once mitigation has taken place, the hazard potential is continually reassessed to take into account the temporal and spatial change in susceptibility and vulnerability.*"

The utility of this research is best gauged to inform the future mitigation and adaption implemented by coastal managers e.g. SMPs. Furthermore, in order to account for changes in both the geomorphological and socioeconomic systems the modelling should be repeated at regular intervals. An update every five years is recommended to mirror the approximate update frequency of the IPCC reports and OS mapping data and allows for any advances in the quality and quantity of the input datasets.

However, for this approach to be efficient and effective as possible, coastal management in Scotland needs to be implemented at a national scale. As discussed previously, social justice is achieved more readily when decisions are made at this scale. Currently, coastal management in Scotland is effectively devolved by central government into the hands of the LAs, with management units clearly incongruent with coastal process boundaries (e.g. coastal cells). The current state of coastal management in Scotland therefore encourages LAs to respond to coastal issues in a manner than benefits the LA, with little consideration for the coast as a whole. Centralising coastal management in Scotland is a long-term recommendation, although there are many barriers to accomplishing this. A more achievable short-term recommendation is that the evidence base on which coastal management decisions are made is on a national scale. At least this approach allows coastal managers to consider the impacts, both positive and negative, of their actions upon adjacent lengths of coast outwith of their immediate responsibility, ensuring a more holistic approach to coastal management. The CESM and CEVM performs this function.

6.2 Critique and Evaluation

The research outputs ought to be critiqued with regard to the international literature highlighted within Chapter 2 to determine how the research outputs of this thesis compare with other approaches. Furthermore, the research outputs should be evaluated to better understand the strengths and weaknesses within the CESM and CEVM in order to identify potential future improvements. This section will critique and evaluate the CESM and CEVM in turn.

6.2.1 Critique

The CESM used a novel approach to assist the management of coastal erosion risk in Scotland. The CESM was developed predominantly from the work of McLaughlin & Cooper, (2010), and Thieler & Hammar-Klose (1999). These methods had to be adapted to a Scottish context as crucial national scale datasets that were needed for their approaches were absent. Consequently, a method had to be developed that used the available datasets, which resulted in the use of the rockhead elevation dataset; a data type that has not been used previously within a national coastal erosion susceptibility assessment. Rockhead data is particularly useful as it effectively allows the geology of the coast to be assessed in three dimensions, i.e. the height of the rockhead is known in relation to sea level, not just the spatial extent. To apply the CESM methodology to areas outwith of Scotland, rockhead data is required. As the BGS have modelled rockhead for Great Britain, it would be possible for the CESM to be generated for England and Wales (although some adjustments of the ranking classifications may be required). However, it would appear that Great Britain is unique, as evidence of other national scale rockhead models cannot be found. The other datasets used with the CESM would be relatively easy to obtain. Therefore, the application of the CESM to other countries may be limited (rockhead models could be generated using the methodologies used by the BGS, if sufficient borehole data exists). Ideally, a modelling methodology should allow for its application in a range of different locations, on the other hand the CESM was developed due to the lack of data available to use the current methodologies within the literature. Consequently, the CESM methodology is an additional optional route that parallels the methods of McLaughlin & Cooper (2010), and Thieler and Hammar-Klose (1999).

Within Scotland, four LAs have operational SMPs, with a further two LAs with SMPs currently under development (Hansom & Fitton, 2015). As stated in Chapter 2, the lack of SMP pan-Scotland coverage means that existing SMPs are best used to support, rather than inform a national coastal erosion model. However, as the CESM output has been validated and proven to be a robust and reliable model, the UPSM and CESM could be used to inform the development of new SMPs. Neither the UPSM nor CESM identify areas where erosion *is* ongoing nor where erosion *will* occur in the future; the models identify locations where erosion *can* occur. The UPSM is a valuable output in its own right since it represents the physical properties of the natural coast without any defence or accretion influences. The UPSM therefore can also be regarded as the erosion susceptibility if coastal defences were removed (either as a result of a management decision or if there was a defence failure) or in the event of a cessation of natural accretion. Hence, the UPSM can assess the possible implications of the management approaches suggested with an SMP. The CESM models the current state of the coast and therefore the areas of high erosion susceptibility will be locations that are undefended/not accreting. Both the UPSM and CESM models can be used individually or by comparing the value/benefit of existing or planned defences, and the ecosystem service benefit of natural accretion can be evaluated. This information can be used to inform the SMP management approach adopted for a length of coast. The potential implications of SMP management approaches, particularly no active intervention and managed realignment approaches, could not have been fully interrogated at national scales prior to this research.

Previous to this research the main source of information on coastal erosion within Scotland was the Eurosion (2004) data. However, as this was an EU wide project the scale of the assessment was too small to inform decision-making at national levels. In addition, as this research has highlighted, there were substantial lengths of coast where erosion was unconfirmed yet was used within national statistics. To improve coastal management in Scotland, a new source of data is required that succeeds Eurosion. The NCCA project currently under way, which was partly developed as a result of the issues highlighted by the CESM, is able to do this. Furthermore, the CESM will be used as part of the NCCA, and subsequently the CESM will be updated with some of the data produced as part of the NCCA analysis. Therefore, jointly the CESM and NCCA will supersede the Eurosion data with higher resolution, more up to date, and more accurate data.

Prior to this project there existed no published research that used a coastal erosion specific vulnerability model within a risk assessment. The socioeconomic vulnerability model used within this research has been specifically tailored to the hazard of coastal erosion. The CEVM was generated using the Experian Mosaic Scotland geodemographic classification, similar to the work of Tomlinson et al. (2011) and Willis et al. (2010), as opposed to the PCA approach used by Cutter et al. (2003) and Lindley et al. (2011). The use of geodemographics for vulnerability assessments is thus far limited within the literature and the CEVM used here can be used to promote the use (and methods) of geodemographics in such applications. The Mosaic geodemographic classification is available for 29 countries yet thus far has been used only in Italy, England and Scotland. The methodology applied here has currency to identify relevant indicators and generate vulnerability models for any hazard(s) of interest. The limited use of geodemographies for vulnerability within the literature is possibly due to their commercial and expensive nature. The largest and most reliable geodemographic classifications also bring an improvement in the spatial unit of assessment. The Experian Mosaic used within this thesis, was at the smaller postcode level, rather than census output area level, meaning there was potential to identify more spatial differentiation. If need be, the Mosaic geodemographic classification can be accessed at individual household level, allowing vulnerability to be assessed at a very fine resolution. This may raise some ethical concerns as to whether this level assessment could be done without the permission of the household.

The alternative to using the commercial geodemographic classification is to use census data and build a non-commercial alternative, such as the OAC2011 classification. This is an option that is not often available to researchers due to the level of skill and time required to generate a national classification. However, databases such as the Index of Multiple Deprivation (IMD) which is managed and updated by the UK government, using a combination of data sources, may be a reliable non-commercial alternative (this is discussed further in Section 6.2.2.3). An updated IMD will be published in 2016, which using some of the knowledge and methodologies applied within this thesis could be compared with the CEVM to test its applicability to vulnerability assessments.

6.2.2 Evaluation

6.2.2.1 CESM Evaluation

In the majority of locations the CESM is an accurate representation of erosional susceptibility as demonstrated by the CESM validation results in Section 4.1.7. However, there are three scenarios where the model underperforms, as highlighted by George Lees' comments. The first of these is in areas of hard defences where the model classifies areas landward of coastal defences to have a higher susceptibility than at the coast, for example along the River Clyde in Figure 6.1. The figure shows that the area of Renfrew which is behind a sea wall has a susceptibility of 40-60 (the yellow areas on the figure). In reality these areas are highly unlikely to erode due to the distance inland and the presence of the sea wall. The ‘fill’ post processing step should remove much of these instances, however when these areas of higher susceptibility are not completely surrounded by lower susceptibility, the fill processing does not function as desired. This could be overcome with an improvement in the defence dataset to allow areas that benefit from coastal defences to be more accurately calculated. Currently, throughout the CESM the area of benefit of coastal defences extends a standard 400 m inland. If data on defence design life, elevation, condition, age, and the previous erosion rate prior to installation of defences was known (such data does not currently exist), an area of benefit can be generated which more accurately reflects individual coastal defences. This would address the concern that the susceptibility of areas behind defended coasts is overestimated.

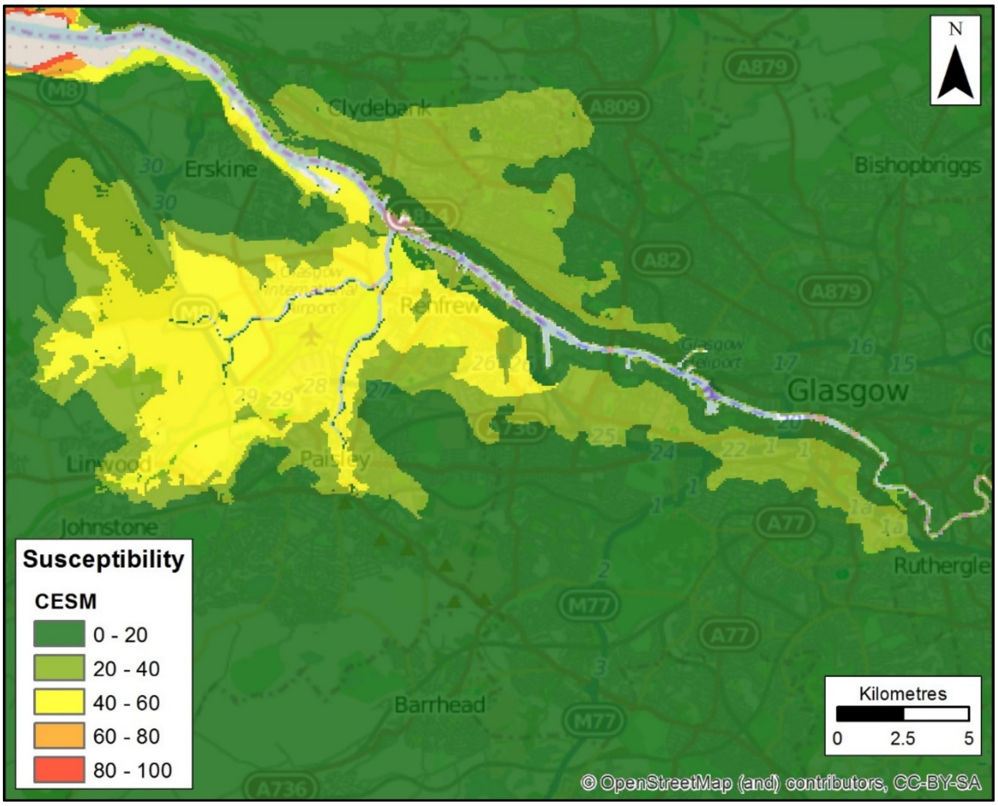

Figure 6.1: CESM for the River Clyde showing the weakness in modelling susceptibility behind defences.

The second scenario where the model can be considered to underperform is areas of saltmarsh. As discussed in Chapter 2 areas of saltmarsh offer the ecosystem service of coastal protection by attenuating wave energy as the marsh is traversed. The CESM highlights the fact that saltmarsh possesses attributes to suggest that it is erodible (Figure 6.2), however this may be overestimated. Areas that are accreting are accounted for within the model as an ecosystem service that prevents erosion, however the influence of saltmarsh on the coast and hinterland was not included as a similar parameter. Although there are extensive areas of saltmarsh habitats in Scotland (see Table 2.2) these are largely confined to a small number of localities. Nevertheless it is clear that where other habitats exist susceptibility may decrease. For example, wide beaches offer more wave energy attenuation than do narrow beaches, so therefore the hinterland of a narrow beach may have increased susceptibility, although might be moderated by grain size (gravel beaches are narrower than sandy beaches but may offer as much protection). The inclusion of more subtle ecosystem services within the model is worthy of further consideration in future iterations.

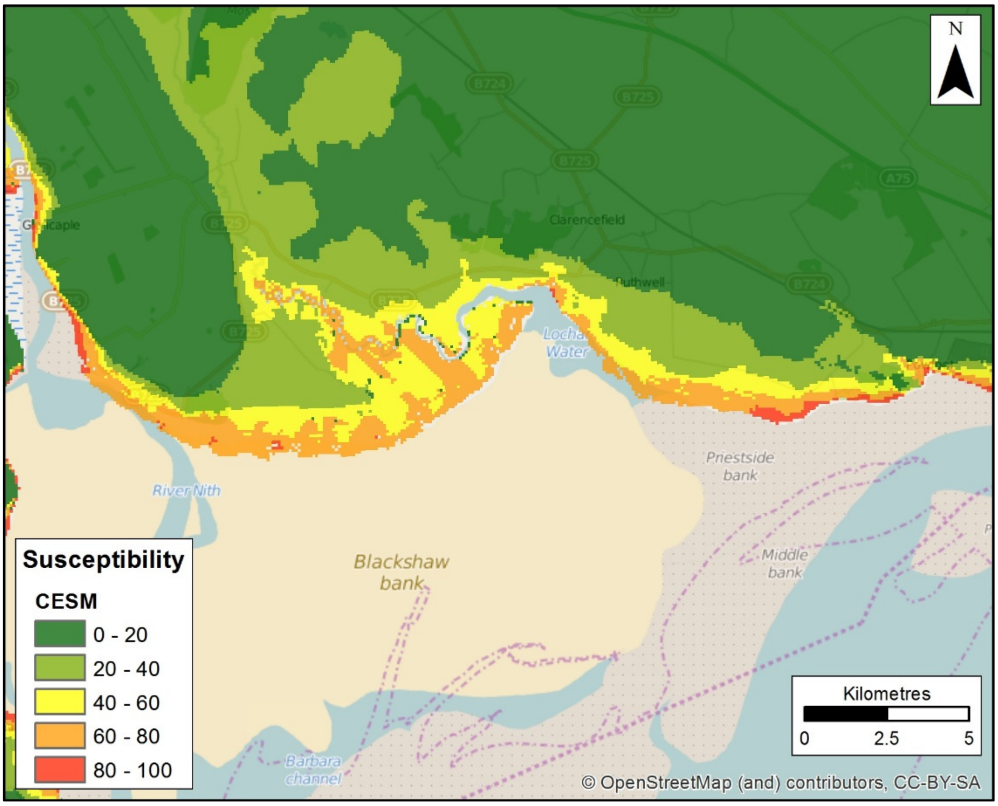

Figure 6.2: Example of saltmarsh classified with high susceptibility at Clarencefield in the Solway Firth.

The third scenario where the model underperforms is where areas of low elevation extend substantial distances inland. This is demonstrated in the upper Forth (Figure 6.3), where the valley has a shallow elevation gradient from MHWS. As a result, the model classifies these areas with heightened susceptibility. However, the CESM score for these types of areas is usually below a score of 60, as the distance to coast and wave exposure parameters in these locations reduce the susceptibility. Therefore the CESM will not classify these areas to have high levels of susceptibility. However, it is unrealistic to expect these areas to be exposed to coastal erosion at all. This could be corrected in future iterations by altering the distance to coast parameter to exclude areas beyond a specific distance as having no susceptibility i.e.

instead of areas greater than 400 m from the coast being assigned a rank of 1, the areas can be removed from the analysis completely.

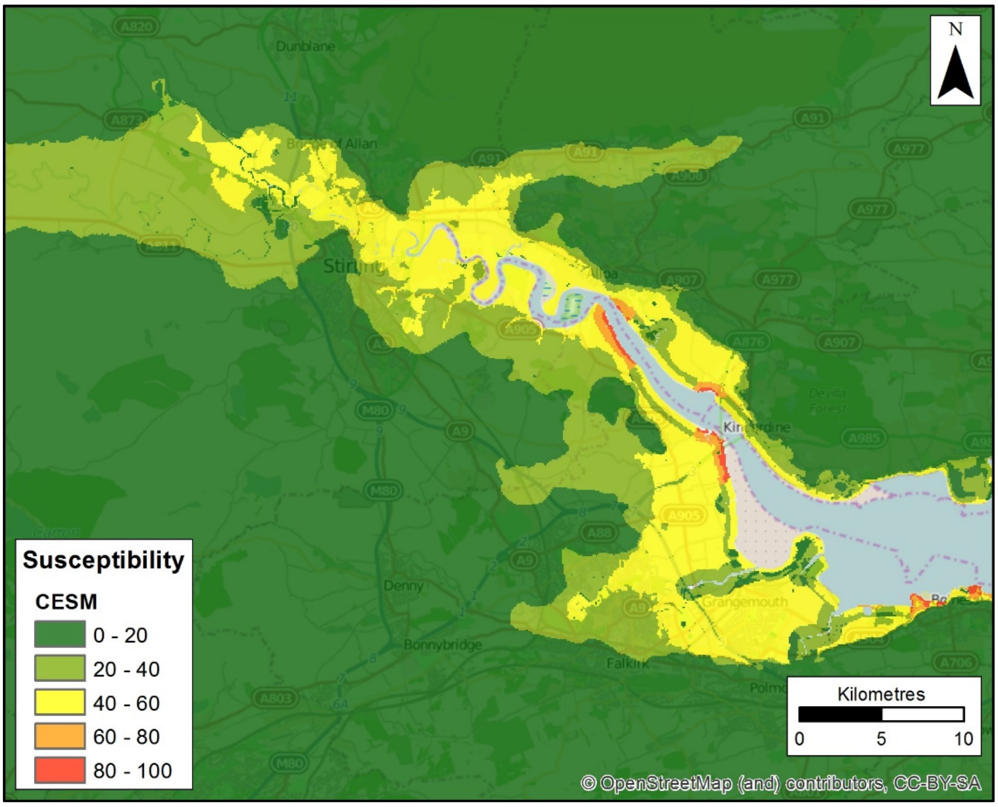

Figure 6.3: Example of the model classifying areas far inland with heightened susceptibility due to the shallow elevation gradient from MHWS.

6.2.2.2 CESM Datasets

The datasets selected for use within this research were on a national scale and generally of high quality. The only datasets where quality was not as high was the wave exposure data and the defence data. With wave exposure, the data was of national scale, but the resolution of the raster was 200 m, compared to 50 m for the other raster data. As discussed within Chapter 3 the data required extensive processing with GIS to convert the data into a form that was compatible with the other dataset. To improve the model it is clear that the wave exposure (and coastal processes data in general) should be improved. The wave exposure data used was the best available at the time of the research, this was due to the lack of more nuanced published approaches available, however recent improvements in coastal wave exposure data (e.g. ERA_INTERIM database (European Centre for Medium-Range Weather, 2009) will be explored in future iterations of the CESM.

The defence source data was also not of the highest quality, and could be improved. The data lacked any information other than location and a general defence type (hard or soft). This was a consequence of the additional data not yet being collected, and beyond the scope of this project. With more information about each defence (condition, height, design life etc.), the model can become more nuanced in locations where defences exist. The model works well on natural coastlines, but can under or over estimate susceptibility in locations of defences. In the near future, a project aiming to collect such national data for both anthropogenic and natural defences is likely to be commissioned as an output recommendation from the NCAA, which would then allow it to be retrofitted to the CESM. With improvements with the wave exposure and defence data, confidence in future iterations of the CESM would be enhanced.

The UPSM and CESM method used the MHWS OD Adjustment Raster (Section 3.1.2.1 and Figure 3.1) to adjust the elevation and rockhead datasets to be relative to MHWS. However, the adjustment raster did not interpolate values between tidal gauges. The raster was a relativity simple output using the cost allocation technique which resulted in minor ‘steps’ at the boundaries of regional MHWS elevations. Following discussions with the OS and the National Oceanography Centre (NOC) access to a more detailed point dataset of MHWS elevations at 2 km intervals around the Scottish coast has been granted. In future iterations this will be used to smooth the MHWS OD Adjustment raster and provide a more accurate adjustment to the elevation and rockhead datasets.

Compared to the previous coastal erosion assessments within the literature, the CESM uses comparatively few datasets. Within almost all of the assessments in Table 2.12 for other locations, there is data on the current shoreline evolution rate yet this does not currently exist for Scotland, and may be difficult to produce for the length of coast within Scotland. The CESM has been produced in the absence of such data. Of the six datasets used in the CESM, three are specifically coastal datasets, and without charge for research purposes. This demonstrates three key points:

- that it is possible to create a robust model even when access to a range of data types is limited, if the data selected is of relatively high quality;

- that data originally created to be generic is of high value, as it allows the end use to be tailored by the researcher;

- that research greatly benefits from data that is easily accessible, without complex license agreements.

The last of these three points could be seen as the most important for researchers. The ability to access data without cost and with only minor licensing requirements allows research to request and experiment using the data within a project. If there is a significant cost and licensing requirement merely to access the data, there is less chance the data will actually be used and so any further research produced as an outcome of the original project is lost. Additionally, if research makes use of data that is easily accessible, it allows for the outputs of this research to be more easily disseminated, as no further licences are required. The CESM uses this type of data and so its outputs can be used by a wider range of users without the problems associated with complex licensing (e.g. BGS allows use of the Superficial Thickness Model for research purposes for UK institutions at no cost). Producing research that can only be accessed by a limited number of users can stifle further research and limits the impact the outputs can have on the general public good.

6.2.2.3 CEVM Evaluation

The methodology used to generate the CEVM has been previously used by Willis et al. (2010). However, these methods have not been applied to coastal erosion vulnerability. The use of geodemographic classifications to identify vulnerability has seldom been used in Scotland. The Experian Mosaic Scotland classification offers a high level of detail at postcode level that is unavailable in non-commercial data. The Mosaic Scotland data is available at dwelling level. Therefore, if required the level of vulnerability assessment can be more detailed than assessed within this research. The potential issue with the type of vulnerability assessment, such as the CEVM, is that the model will become less accurate over time. This is a consequence of both people moving to a new property and invalidating the original data, and the fact that places evolve and attract a different socioeconomic type e.g. gentrification. The commercial geodemographic products are kept up to date as their clients require the most accurate information as possible. However, these products are still mainly built upon census data which is collected every 10 years in the UK. This research started in 2011, a few months after the collection of the 2011 census. Due to the time lag between collection of the census and output of the results, this meant that the Experian Mosaic Scotland classification was based upon the 2001 data. Thus the data used within the vulnerability analysis was at least 10 years old (the 2011 census data only started to be published for use until 2014 and its phased output is still ongoing at the time of writing). Commercial geodemographic products use more recent data to supplement census data, reducing the overall influence of the census data, however the age of the data should be of consideration to the end user.

The OAC2011 is a potentially powerful alternative to using commercial geodemographic products, however it uses solely census data. This means that it is most accurate, at the time of creation and the accuracy will degrade overtime as it is not supplemented by other data. As vulnerability is highly linked to access to resources, the Scottish Index of Multiple Deprivation (SIMD) could potentially be used as an alternative to a vulnerability assessment. Within Scotland this has been updated on a regular basis (first published in 2004, and updated in 2006, 2009, and 2012, with the next update expected in 2016) and can therefore offer a more up to date data on deprivation. The reason the SIMD was not used initially within this research was the difficulty in tailoring the data to a specific hazard due to the multiple sets of data and weighting used within the SIMD. Furthermore, both the OAC2011 and the SIMD data are at a scale of census OA, and therefore for coastal erosion where rurality is a key indicator, a large area of rural locations will be classed with the same vulnerability.

The Experian Mosaic Scotland data was the best data to use for the vulnerability assessment despite the potential issue over the date of the census data used. As it has previously not been used for vulnerability assessments in Scotland, it has been a useful exercise to investigate the potential pros and cons of using such data. As a commercial product, the cost of acquisition is a factor in its use. The data for this research was kindly supplied free of charge by Experian, but this is unlikely to be a universal option. However, a key strength of using geodemographic data (commercial or non-commercial) is that the type of people living within an area is known from the geodemographic database and so any mitigation measures can be tailored depending upon the target audience (personal communication, Iain Willis, Technical Director at JBA Risk Management December 2014). For example, publishing data on an online portal to assist users may be ineffectual for people without the computer skills to make use of the information e.g. the elderly. Using geodemographic classifications allows the assessment of the vulnerability of an area, however it has further value in that it allows better planning, and therefore improves the likelihood of success, of possible mitigation measures.

6.2.3 Section Summary

Section 6.2 has:

- shown that the UPSM is a valuable output in its own right. Both the UPSM and CESM models can be used individually or together to determine the value/benefit of defences that are in place;

- established that the Eurosion data is insufficient for the current needs of coastal managers in Scotland and can be replaced by the CESM and NCCA with higher resolution, more up to date, and more accurate data;

- highlighted that the use of commercial geodemographic classifications is limited within the literature, most likely due to expense. Within the UK, the IMD classifications may be an alternative to the commercial classifications, however this needs to be explored further;

- demonstrated that the CESM could be considered to underperform in three coastal scenarios; areas of hard defences, areas of saltmarsh and areas of low elevation that extend substantial distances inland, but means to correct these issues have been identified;

- highlighted that the wave exposure and defences dataset are not of comparable quality when compared with the other datasets within the CESM. If improvements to the wave exposure and defence data are implemented, the confidence in future iterations of the CESM can be greatly enhanced;

- established that it is possible to create a robust model even when access to a range of data types is limited, that generic data outputs are of high value as it allows the end use to be tailored by the researcher, and that research benefits from data that is easily accessible;

- shown that the CEVM will become less accurate over time as consequence of people moving and places evolving and so being classified as a different socioeconomic type. The commercial geodemographic products are kept up to date but OAC2011 is a potential alternative to using commercial geodemographic products, however its census data will degrade in accuracy overtime. As vulnerability is linked to access to resources, the regularly updated Scottish Index of Multiple Deprivation may be an option to assess vulnerability long term.

6.3 Future Research

This thesis has highlighted the existing data gaps that should be addressed by future research in order to further improve coastal management in Scotland. The areas of future research are:

- to establish historical coastal change rates on a national scale - this will allow the sediment supply handicap used within the CESM to be more nuanced. Furthermore, the nature and extent of future erosion can also be established. These are the proposed outputs from the NCCA project that is currently underway, which will be used to further develop the CESM;

- to improve the modelling of national scale wave exposure - the wave exposure dataset used within the CESM was not weighted equal to the other datasets due to concerns about the quality of the data. This data should be improved so that there is more confidence with regards to coastal processes within the CESM. It is acknowledged that there will always be detailed wave refraction effects at a local scale that may confound any regional analysis;

- to enhance the information held about the current coastal defences in place - information such as type, height, condition, design life, and cost etc. are needed to so that when used in combination with the historical change rate the areas that benefit from the defences can be calculated. This will greatly improve the cost/benefit calculations used to assess the viability of installing coastal defences;

- to develop the handicap system within the CESM to include other ecosystem services - currently only the ecosystem service of sediment accretion is used as a handicap to reduce susceptibility, however ecosystems such as saltmarsh can also reduce susceptibility. The degree to which other ecosystem services reduce susceptibility should be explored further, and if possible included within the CESM methodology;

- to determine the direct and indirect economic cost associated with the loss of an asset - more information is needed to more accurately estimate the economic liability (both direct and indirect) of losing an asset to coastal erosion (or hazards in general). This research was only able to assess direct economic liability for dwellings, transport and golf courses, using average economic values. To fully assess the impacts of climate change full economic analysis of these assets and historic and natural assets needs to be available to researchers;

- to clarify the social justice implications of using adaptation approaches to manage coastal erosion - the social justice implications of installing coastal defences has been addressed, however adaptation approaches such as using government funding to move people away from areas experiencing or expecting to experience coastal erosion problems has not been fully investigated;

- to establish a method to communicate the susceptibility, exposure, vulnerability and risk aspects of a hazard that informs the general public while minimising the potential negative impacts (e.g. property blight) of releasing such information.

The research required to address these knowledge gaps should be started as soon as possible to ensure that the coastal erosion hazard (and associated coastal flooding) can be better understood, allowing effective, efficient and socially just management to take place now, and in the future. One of the key threats to achieving this is the lack of a national approach to coastal management to collate, disseminate data and information, and inform and influence policy. This needs to be rectified quickly, otherwise we are likely to repeat the management mistakes of the past, which when the potential impacts of climate change are considered, could have significant consequences for the environment, society, and the economy in Scotland.

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Appendix A: Methodology Python Code

A.1 Datum Adjustment

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Local variables:
UK_inv_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\UK_inv.shp"
ports_tide_data_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input
data\\Supporting Data\\ports_tide_data.shp"
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\scotland"
uk_inv_100_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\uk_inv_100.shp"
uk_inv_100_shp__2_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\uk_inv_100.shp"
uk_inv_100_shp__3_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\uk_inv_100.shp"
uk_ib_100 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\uk_ib_100"
uk_tid_cost = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\uk_tid_cost"
Output_distance_raster = ""
Output_backlink_raster = ""
uk_tid_inland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\uk_tid_inland"
Output_distance_raster__2_ = ""
Output_backlink_raster__2_ = ""
uk_tid_in_pol_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\uk_tid_in_pol.shp"
tid_pol_join_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\tid_pol_join.shp"
mhws_od_adj = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\mhws_od_adj"

# Process: Buffer
arcpy.Buffer_analysis(UK_inv_shp, uk_inv_100_shp, "100 Meters", "FULL", "ROUND", "NONE", "")

# Process: Add Field
arcpy.AddField_management(uk_inv_100_shp, "ras", "SHORT", "", "", "", "", "NULLABLE",
"NON_REQUIRED", "")

# Process: Calculate Field
arcpy.CalculateField_management(uk_inv_100_shp__2_, "ras", "1", "VB", "")

# Process: Polygon to Raster (2)
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\GIS Data\\Classification\\Models\\Version
5.0.1\\1_Raw Input Data\\Supporting Data\\scotland"
arcpy.PolygonToRaster_conversion(uk_inv_100_shp__3_, "ras", uk_ib_100, "CELL_CENTER", "NONE",
"50")
arcpy.env.snapRaster = tempEnvironment0

# Process: Cost Allocation
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input
data\\Supporting Data\\uk_ib_100"
tempEnvironment1 = arcpy.env.extent
arcpy.env.extent = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\uk_inv_100.shp"
```

```
arcpy.gp.CostAllocation_sa(ports_tide_data_shp, uk_ib_100, uk_tid_cost, "", "", "FID",
Output_distance_raster, Output_backlink_raster)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.extent = tempEnvironment1

# Process: Cost Allocation (2)
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input
data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.extent
arcpy.env.extent = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\scotland"
arcpy.gp.CostAllocation_sa(uk_tid_cost, scotland, uk_tid_inland, "", "", "VALUE",
Output_distance_raster__2_, Output_backlink_raster__2_)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.extent = tempEnvironment1

# Process: Raster to Polygon
arcpy.RasterToPolygon_conversion(uk_tid_inland, uk_tid_in_pol_shp, "NO_SIMPLIFY", "VALUE")

# Process: Spatial Join
arcpy.SpatialJoin_analysis(uk_tid_in_pol_shp, ports_tide_data_shp, tid_pol_join_shp,
"JOIN_ONE_TO_ONE", "KEEP_ALL", "ID \"ID\" true true false 10 Double 0 10
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\uk_tid_in_pol.shp,ID,-1,-
1;Gauge_ID \"Gauge_ID\" true true false 254 Text 0 0
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,Gauge_ID,-1,-1;Name \"Name\" true true false 254 Text 0 0
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,Name,-1,-1;OD_Local \"OD_Local\" true true false 254 Text 0 0
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,OD_Local,-1,-1;OD_Newlyn \"OD_Newlyn\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,OD_Newlyn,-1,-1;OD_Loc_New \"OD_Loc_New\" true true false 16 Double 6
15 ,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,OD_Loc_New,-1,-1;HAT__CD \"HAT__CD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,HAT__CD,-1,-1;MHWS_CD \"MHWS_CD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,MHWS_CD,-1,-1;MSL_CD \"MSL_CD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,MSL_CD,-1,-1;MLWS_CD \"MLWS_CD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,MLWS_CD,-1,-1;LAT_CD \"LAT_CD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,LAT_CD,-1,-1;HAT__OD \"HAT__OD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,HAT__OD,-1,-1;MHWS_OD \"MHWS_OD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,MHWS_OD,-1,-1;MSL_OD \"MSL_OD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,MSL_OD,-1,-1;MLWS_OD \"MLWS_OD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,MLWS_OD,-1,-1;LAT_OD \"LAT_OD\" true true false 16 Double 6 15
,First,#,C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\ports_tide_data.shp,LAT_OD,-1,-1", "INTERSECT", "", "")

# Process: Polygon to Raster
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input
data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.extent
arcpy.env.extent = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_raw input data\\Supporting
Data\\scotland"
```

```
arcpy.PolygonToRaster_conversion(tid_pol_join_shp, "MHWS_OD", mhws_od_adj, "CELL_CENTER",
"NONE", scotland)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.extent = tempEnvironment1
```

A.2 Elevation

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting Data\\scotland"

# Script arguments
Raw_Elevation__50_m_Raster_ = arcpy.GetParameterAsText(0)
if Raw_Elevation__50_m_Raster_ == '#' or not Raw_Elevation__50_m_Raster_:
    Raw_Elevation__50_m_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\raw_elevation" # provide a default value if unspecified

OD_Adjustment__50_m_Raster_ = arcpy.GetParameterAsText(1)
if OD_Adjustment__50_m_Raster_ == '#' or not OD_Adjustment__50_m_Raster_:
    OD_Adjustment__50_m_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting Data\\mhws_od_adj" # provide a default value if unspecified

# Local variables:
elev_adj = Raw_Elevation__50_m_Raster_
elev_rank = elev_adj
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting Data\\scotland"

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("\"%raw_elevation%\" - \"%mhws_od_adj%\"", elev_adj)

# Process: Reclassify
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting Data\\scotland"
arcpy.gp.Reclassify_sa(elev_adj, "Value", "-19.25 2 5;2 4 4;4 6 3;6 8 2;8 1337.538318589154 1", elev_rank, "DATA")
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.mask = tempEnvironment1
```

A.3 Rockhead

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"

# Script arguments
OD_Adjustment__50_m_Raster_ = arcpy.GetParameterAsText(0)
if OD_Adjustment__50_m_Raster_ == '#' or not OD_Adjustment__50_m_Raster_:
    OD_Adjustment__50_m_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\mhws_od_adj" # provide a default value if unspecified

Raw_Rockhead_Elevation__50_m_Raster_ = arcpy.GetParameterAsText(1)
if Raw_Rockhead_Elevation__50_m_Raster_ == '#' or not Raw_Rockhead_Elevation__50_m_Raster_:
    Raw_Rockhead_Elevation__50_m_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version
5.1\\1_Raw Input Data\\raw_rockhead" # provide a default value if unspecified

# Local variables:
rockhead_adj = OD_Adjustment__50_m_Raster_
rockhead_rank = rockhead_adj
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("\"%Raw Rockhead Elevation (50 m Raster)%\" - \"%OD Adjustment (50 m
Raster)%\"", rockhead_adj)

# Process: Reclassify
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"
arcpy.gp.Reclassify_sa(rockhead_adj, "Value", "-136 0 5;0 2 4;2 4 3;4 6 2;6 1400 1", rockhead_rank,
"DATA")
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.mask = tempEnvironment1
```

A.4 Proximity to Open Coast

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Script arguments
MHWS_with_border__Polygon_ = arcpy.GetParameterAsText(0)
if MHWS_with_border__Polygon_ == '#' or not MHWS_with_border__Polygon_:
    MHWS_with_border__Polygon_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\MHWS_polygon.shp" # provide a default value if unspecified

# Local variables:
mhws_buf_250_shp = MHWS_with_border__Polygon_
v250_buf_poly_shp = mhws_buf_250_shp
v250_buf_poly_dis_shp = v250_buf_poly_shp
mhw_neg_buf_shp = v250_buf_poly_dis_shp
open_coast_bor_shp = mhw_neg_buf_shp
Open_coastline_shp = open_coast_bor_shp
euc_dis_oc = Open_coastline_shp
ocoast_rank = euc_dis_oc
Output_direction_raster = Open_coastline_shp
Border_clip_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\Border_clip.shp"
scot_ob_400 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scot_ob_400"
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"

# Process: Buffer
arcpy.Buffer_analysis(MHWS_with_border__Polygon_, mhws_buf_250_shp, "250 Meters", "FULL",
"ROUND", "ALL", "")

# Process: Feature To Polygon
arcpy.FeatureToPolygon_management("'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\mhws_buf_250.shp'", v250_buf_poly_shp, "", "ATTRIBUTES", "")

# Process: Dissolve
arcpy.Dissolve_management(v250_buf_poly_shp, v250_buf_poly_dis_shp, "Id", "", "MULTI_PART",
"DISSOLVE_LINES")

# Process: Buffer (2)
arcpy.Buffer_analysis(v250_buf_poly_dis_shp, mhw_neg_buf_shp, "-250 Meters", "FULL", "ROUND",
"NONE", "")

# Process: Feature To Line
arcpy.FeatureToLine_management("'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\mhw_neg_buf.shp'", open_coast_bor_shp, "", "NO_ATTRIBUTES")

# Process: Erase
arcpy.Erase_analysis(open_coast_bor_shp, Border_clip_shp, Open_coastline_shp, "")

# Process: Euclidean Distance
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scot_ob_400"
tempEnvironment1 = arcpy.env.extent
arcpy.env.extent = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scot_ob_400"
tempEnvironment2 = arcpy.env.mask
```

```
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scot_ob_400"
arcpy.gp.EucDistance_sa(Open_coastline_shp, euc_dis_oc, "", scot_ob_400, Output_direction_raster)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.extent = tempEnvironment1
arcpy.env.mask = tempEnvironment2

# Process: Reclassify
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.extent
arcpy.env.extent = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
tempEnvironment2 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"
arcpy.gp.Reclassify_sa(euc_dis_oc, "Value", "0 100 5;100 200 4;200 300 3;300 400 2;400 75000 1",
ocoast_rank, "DATA")
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.extent = tempEnvironment1
arcpy.env.mask = tempEnvironment2
```

A.5 Wave Exposure

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"

# Script arguments
Raw_Wave_Exposure__Raster_ = arcpy.GetParameterAsText(0)
if Raw_Wave_Exposure__Raster_ == '#' or not Raw_Wave_Exposure__Raster_:
    Raw_Wave_Exposure__Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\raw_wave" # provide a default value if unspecified

# Local variables:
wave_shift = Raw_Wave_Exposure__Raster_
wave_50 = wave_shift
wave_cost = wave_50
wave_400 = wave_cost
wave_expo = wave_400
wave_exp_rank = wave_expo
Output_distance_raster = wave_50
Output_backlink_raster = wave_50
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"
scot_ob_400 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scot_ob_400"
MHWS_B_400_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\MHWS_B_400.shp"

# Process: Shift
arcpy.Shift_management(Raw_Wave_Exposure__Raster_, wave_shift, "200", "200", scotland)

# Process: Resample
arcpy.Resample_management(wave_shift, wave_50, scotland, "NEAREST")

# Process: Cost Allocation
arcpy.gp.CostAllocation_sa(wave_50, scot_ob_400, wave_cost, "", "", "Value", Output_distance_raster,
Output_backlink_raster)

# Process: Clip
arcpy.Clip_management(wave_cost, "5113.10012322012 529852.840051295 470723.000000002
1220701.47034859", wave_400, MHWS_B_400_shp, "", "ClippingGeometry",
"NO_MAINTAIN_EXTENT")

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%wave_400%\"),1,\"%wave_400%\")", wave_expo)

# Process: Reclassify
arcpy.gp.Reclassify_sa(wave_expo, "Value", "1 75 1;75 150 2;150 225 3;225 300 4;300 800 5",
wave_exp_rank, "DATA")
```

A.6 Raw UPSM and CESM

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Script arguments
Defence_Handicap = arcpy.GetParameterAsText(0)
if Defence_Handicap == '#' or not Defence_Handicap:
    Defence_Handicap = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\def_hc" # provide a default value if unspecified

Elevation___Ranked_Raster_ = arcpy.GetParameterAsText(1)
if Elevation___Ranked_Raster_ == '#' or not Elevation___Ranked_Raster_:
    Elevation___Ranked_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\elev_rank" # provide a default value if unspecified

Outer_Coast__Ranked_Raster_ = arcpy.GetParameterAsText(2)
if Outer_Coast__Ranked_Raster_ == '#' or not Outer_Coast__Ranked_Raster_:
    Outer_Coast__Ranked_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\ocoast_rank" # provide a default value if unspecified

Rockhead__Ranked_Raster_ = arcpy.GetParameterAsText(3)
if Rockhead__Ranked_Raster_ == '#' or not Rockhead__Ranked_Raster_:
    Rockhead__Ranked_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\rockhead_rank" # provide a default value if unspecified

Sediment_Supply_Handicap = arcpy.GetParameterAsText(4)
if Sediment_Supply_Handicap == '#' or not Sediment_Supply_Handicap:
    Sediment_Supply_Handicap = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\sedsup_hc" # provide a default value if unspecified

Wave_Exposure__Ranked_Raster_ = arcpy.GetParameterAsText(5)
if Wave_Exposure__Ranked_Raster_ == '#' or not Wave_Exposure__Ranked_Raster_:
    Wave_Exposure__Ranked_Raster_ = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\wave_exp_rank" # provide a default value if unspecified

# Local variables:
cesm_def_acc = Defence_Handicap
cesm_175 = cesm_def_acc
raw_cesm = cesm_175
UPSM_175 = Elevation___Ranked_Raster_
raw_upsm = UPSM_175
Maximum = UPSM_175
Minimum = UPSM_175
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"

# Process: Weighted Sum
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input Data\\Supporting
Data\\scotland"
arcpy.gp.WeightedSum_sa("'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\elev_rank' VALUE 1;'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\rockhead_rank' VALUE 1;'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\wave_exp_rank' VALUE 0.5;'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\ocoast_rank' VALUE 1", UPSM_175)
```

```
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.mask = tempEnvironment1

# Process: Get Raster Properties (2)
arcpy.GetRasterProperties_management(UPSM_175, "MINIMUM", "")

# Process: Get Raster Properties
arcpy.GetRasterProperties_management(UPSM_175, "MAXIMUM", "")

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("(\"%UPSM_175%\"-float(%Minimum%)) / (float(%Maximum%) -
float(%Minimum%)) * 100", raw_upsm)

# Process: Raster Calculator (2)
arcpy.gp.RasterCalculator_sa("\"%UPSM_175%\" + \"%Defence Handicap%\"+ \"%Sediment Supply
Handicap%\"", cesm_def_acc)

# Process: Raster Calculator (3)
arcpy.gp.RasterCalculator_sa("Con(\"%cesm_def_acc%\", %Minimum%, \"%cesm_def_acc%\", \"value
<= %Minimum%\")", cesm_175)

# Process: Raster Calculator (4)
arcpy.gp.RasterCalculator_sa("(\"%cesm_175%\"-float(%Minimum%)) / (float(%Maximum%) -
float(%Minimum%)) * 100", raw_cesm)
```

A.7 Sediment Supply

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\scotland"

# Script arguments
Raw_Sediment_Supply_Data__Polyline_ = arcpy.GetParameterAsText(0)
if Raw_Sediment_Supply_Data__Polyline_ == '#' or not
Raw_Sediment_Supply_Data__Polyline_:
    Raw_Sediment_Supply_Data__Polyline_ =
"C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Raw_Sediment_Supply.shp" # provide a default value if unspecified

# Local variables:
scot_ob_400 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scot_ob_400"
acc_3 = Raw_Sediment_Supply_Data__Polyline_
sed_sup_200 = acc_3
accr_200_mask = sed_sup_200
acc_200_null = accr_200_mask
acc_300 = acc_200_null
acc_2 = acc_300
acc_hand = acc_2
SedSup_HC = acc_hand
Output_distance_raster__2_ = acc_200_null
Output_backlink_raster__2_ = acc_200_null
acc_400 = acc_200_null
acc_1 = acc_400
Output_distance_raster__3_ = acc_200_null
Output_backlink_raster__3_ = acc_200_null
Output_distance_raster = Raw_Sediment_Supply_Data__Polyline_
Output_backlink_raster = Raw_Sediment_Supply_Data__Polyline_
MHWS_B_200_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\MHWS_B_200.shp"
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
Temp_Files = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files"

# Process: Cost Allocation
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\scot_ob_400"
arcpy.gp.CostAllocation_sa(Raw_Sediment_Supply_Data__Polyline_, scot_ob_400,
acc_3, "", "", "handicap", Output_distance_raster, Output_backlink_raster)
arcpy.env.snapRaster = tempEnvironment0
```

```
# Process: Clip
arcpy.Clip_management(acc_3, "5313.00000000092 530052.800000003 470523
1220501.50690907", sed_sup_200, MHWS_B_200_shp, "", "ClippingGeometry",
"NO_MAINTAIN_EXTENT")

# Process: Raster Calculator
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
arcpy.gp.RasterCalculator_sa("\"%sed_sup_200%\"", accr_200_mask)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.mask = tempEnvironment1

# Process: Set Null
arcpy.gp.SetNull_sa(accr_200_mask, accr_200_mask, acc_200_null, "\"VALUE\" = 0")

# Process: Cost Allocation (2)
arcpy.gp.CostAllocation_sa(acc_200_null, scotland, acc_300, "100", "", "VALUE",
Output_distance_raster__2_, Output_backlink_raster__2_)

# Process: Cost Allocation (3)
arcpy.gp.CostAllocation_sa(acc_200_null, scotland, acc_400, "200", "", "VALUE",
Output_distance_raster__3_, Output_backlink_raster__3_)

# Process: Reclassify
arcpy.gp.Reclassify_sa(acc_300, "VALUE", "-3 -2", acc_2, "DATA")

# Process: Reclassify (2)
arcpy.gp.Reclassify_sa(acc_400, "VALUE", "-3 -1", acc_1, "DATA")

# Process: Mosaic To New Raster
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
arcpy.MosaicToNewRaster_management("'C:\\Users\\James\\Documents\\PhD\\Models\\V
ersion 5.1\\Temp
Files\\acc_200_null';'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\acc_2';'C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp
Files\\acc_1'", Temp_Files, "acc_hand", "", "8_BIT_SIGNED", "", "1", "MINIMUM",
"FIRST")
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.mask = tempEnvironment1

# Process: Raster Calculator (2)
tempEnvironment0 = arcpy.env.snapRaster
```

```
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\scotland"
tempEnvironment1 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%acc_hand%\"),0,\"%acc_hand%\")",
SedSup_HC)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.mask = tempEnvironment1
```

A.8 Coastal Defences

```
# Import arcpy module

import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw
Input Data\\Supporting Data\\scotland"

# Script arguments
Raw_Coastal_Defences__Polyline_ = arcpy.GetParameterAsText(0)
if Raw_Coastal_Defences__Polyline_ == '#' or not Raw_Coastal_Defences__Polyline_:
    Raw_Coastal_Defences__Polyline_ =
"C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Raw_Defences.shp" # provide a default value if unspecified

# Local variables:
def_cost = Raw_Coastal_Defences__Polyline_
def_hc = def_cost
Output_distance_raster = Raw_Coastal_Defences__Polyline_
Output_backlink_raster = Raw_Coastal_Defences__Polyline_
scot_ob_400 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scot_ob_400"
scotland = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"

# Process: Cost Allocation
arcpy.gp.CostAllocation_sa(Raw_Coastal_Defences__Polyline_, scot_ob_400, def_cost,
"400", "", "handicap", Output_distance_raster, Output_backlink_raster)

# Process: Raster Calculator
tempEnvironment0 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\1_Raw Input
Data\\Supporting Data\\scotland"
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%def_cost%\"),0,\"%def_cost%\")",
def_hc)
arcpy.env.mask = tempEnvironment0
```

A.9 Surface Water Filter

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Set Geoprocessing environments
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version
5.1\\3_UPSM_CESM\\raw_cesm"

# Script arguments
raw_upsm = arcpy.GetParameterAsText(0)
if raw_upsm == '#' or not raw_upsm:
    raw_upsm = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_UPSM_CESM\\raw_upsm" #
provide a default value if unspecified

raw_cesm = arcpy.GetParameterAsText(1)
if raw_cesm == '#' or not raw_cesm:
    raw_cesm = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_UPSM_CESM\\raw_cesm" #
provide a default value if unspecified

# Local variables:
sw_ras = raw_cesm
upsm_sw = sw_ras
cesm_sw = sw_ras
SurfaceWater_shp = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post
processing\\1_Surface Water\\Supporting Data\\SurfaceWater.shp"

# Process: Polygon to Raster
tempEnvironment0 = arcpy.env.snapRaster
arcpy.env.snapRaster = "C:\\Users\\James\\Documents\\PhD\\Models\\Version
5.1\\3_UPSM_CESM\\raw_cesm"
tempEnvironment1 = arcpy.env.extent
arcpy.env.extent = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_UPSM_CESM\\raw_cesm"
arcpy.PolygonToRaster_conversion(SurfaceWater_shp, "FEATCODE", sw_ras, "MAXIMUM_AREA",
"NONE", raw_cesm)
arcpy.env.snapRaster = tempEnvironment0
arcpy.env.extent = tempEnvironment1

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%sw_ras%\"),\"%raw_upsm%\",\"%sw_ras%\")", upsm_sw)

# Process: Raster Calculator (3)
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%sw_ras%\"),\"%raw_cesm%\",\"%sw_ras%\")", cesm_sw)
```

A.10 Rockhead Filter

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Script arguments
upsm_sw = arcpy.GetParameterAsText(0)
if upsm_sw == '#' or not upsm_sw:
    upsm_sw = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post processing\\1_Surface
Water\\upsm_sw" # provide a default value if unspecified

cesm_sw = arcpy.GetParameterAsText(1)
if cesm_sw == '#' or not cesm_sw:
    cesm_sw = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post processing\\1_Surface
Water\\cesm_sw" # provide a default value if unspecified

# Local variables:
rockhead_rank = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\2_Pre
Processing\\rockhead_rank"
upsm_sw_rh = upsm_sw
cesm_sw_rh = cesm_sw
rh_6 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\rh_6"
rh_6_0 = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\Temp Files\\rh_6_0"

# Process: Extract by Attributes
arcpy.gp.ExtractByAttributes_sa(rockhead_rank, "\"VALUE\" = 1", rh_6)

# Process: Reclassify
arcpy.gp.Reclassify_sa(rh_6, "VALUE", "1 0", rh_6_0, "DATA")

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%rh_6_0%\"),\"%upsm_sw%\",\"%rh_6_0%\")",
upsm_sw_rh)

# Process: Raster Calculator (2)
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%rh_6_0%\"),\"%cesm_sw%\",\"%rh_6_0%\")",
cesm_sw_rh)
```

A.11 Superficial Deposit Filter

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Script arguments
upsm_sw_rh = arcpy.GetParameterAsText(0)
if upsm_sw_rh == '#' or not upsm_sw_rh:
    upsm_sw_rh = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post processing\\2_Rockhead
Filter\\upsm_sw_rh" # provide a default value if unspecified

cesm_sw_rh = arcpy.GetParameterAsText(1)
if cesm_sw_rh == '#' or not cesm_sw_rh:
    cesm_sw_rh = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post processing\\2_Rockhead
Filter\\cesm_sw_rh" # provide a default value if unspecified

# Local variables:
cesm_sw_rh_s = cesm_sw_rh
upsm_sw_rh_s = upsm_sw_rh
sup_null = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post processing\\3_Superfical
Filter\\Supporting Data\\sup_null"

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%sup_null%\"),\"%upsm_sw_rh%\",\"%sup_null%\")",
upsm_sw_rh_s)

# Process: Raster Calculator (2)
arcpy.gp.RasterCalculator_sa("Con(IsNull(\"%sup_null%\"),\"%cesm_sw_rh%\",\"%sup_null%\")",
cesm_sw_rh_s)
```

A.12 Fill Edit

```
# Import arcpy module
import arcpy

# Check out any necessary licenses
arcpy.CheckOutExtension("spatial")

# Script arguments
cesm_sw_rh_s = arcpy.GetParameterAsText(0)
if cesm_sw_rh_s == '#' or not cesm_sw_rh_s:
    cesm_sw_rh_s = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post
processing\\3_Superfical Filter\\cesm_sw_rh_s" # provide a default value if unspecified

upsm_sw_rh_s = arcpy.GetParameterAsText(1)
if upsm_sw_rh_s == '#' or not upsm_sw_rh_s:
    upsm_sw_rh_s = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\4_post
processing\\3_Superfical Filter\\upsm_sw_rh_s" # provide a default value if unspecified

raw_cesm = arcpy.GetParameterAsText(2)
if raw_cesm == '#' or not raw_cesm:
    raw_cesm = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_upsm_cesm\\raw_cesm" #
provide a default value if unspecified

raw_upsm = arcpy.GetParameterAsText(3)
if raw_upsm == '#' or not raw_upsm:
    raw_upsm = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_upsm_cesm\\raw_upsm" #
provide a default value if unspecified

# Local variables:
upsm_neg = upsm_sw_rh_s
upsm_fill = upsm_neg
UPSM = upsm_fill
cesm_neg = cesm_sw_rh_s
cesm_fill = cesm_neg
CESM = cesm_fill

# Process: Raster Calculator (2)
arcpy.gp.RasterCalculator_sa("\"%cesm_sw_rh_s%\"  *  - 1", cesm_neg)

# Process: Fill
arcpy.gp.Fill_sa(cesm_neg, cesm_fill, "")

# Process: Raster Calculator (3)
tempEnvironment0 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_upsm_cesm\\raw_cesm"
arcpy.gp.RasterCalculator_sa("\"%cesm_fill%\" *  - 1", CESM)
arcpy.env.mask = tempEnvironment0

# Process: Raster Calculator
arcpy.gp.RasterCalculator_sa("\"%upsm_sw_rh_s%\" * -1", upsm_neg)

# Process: Fill (2)
arcpy.gp.Fill_sa(upsm_neg, upsm_fill, "")

# Process: Raster Calculator (4)
tempEnvironment0 = arcpy.env.mask
arcpy.env.mask = "C:\\Users\\James\\Documents\\PhD\\Models\\Version 5.1\\3_upsm_cesm\\raw_upsm"
arcpy.gp.RasterCalculator_sa("\"%upsm_fill%\" *  - 1", UPSM)
arcpy.env.mask = tempEnvironment0
```

Appendix B: Defence Type Descriptions

The following descriptions are based on Hill (2004).

'Hard' defences: management schemes that put hardware in place to slow down natural processes or prevent them from happening

'Soft' defences: management schemes that use natural processes and work with them

B.1 Hard Defence Types

Sea Walls: Concrete or masonry structures designed to resist wave action and protect the coast**.** They can be vertical, curved or stepped (Figure B1.1).

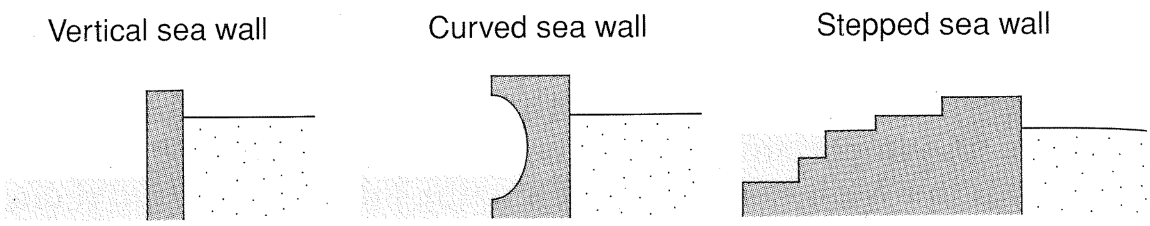

Figure B1.1: Examples of sea wall types. Taken from Hill (2004).

Revetments: Sloping aprons which encase sections of beach of low-angle cliffs. They are often made from concrete slabs or timber frames. They are generally made with rough surfaces or holes in order to dissipate wave energy (Figure B1.2).

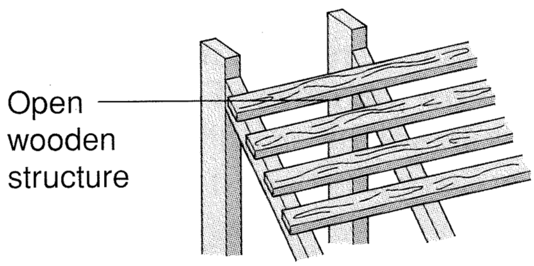

Figure B1.2: Example of a revetment. Taken from Hill (2004).

Breakwaters: These are structures built offshore in order to dissipate wave energy and/or contain sediment.

Rock Armour/Rip Rap: Large boulders placed in front of the area to be protected to dissipate wave energy and prevent erosion.

Gabion Baskets: These are wire cages filled with stones of a range of sizes (boulders to pebbles), but as they have a uniform size can be used to construct defences of various shapes (Figure B1.3).

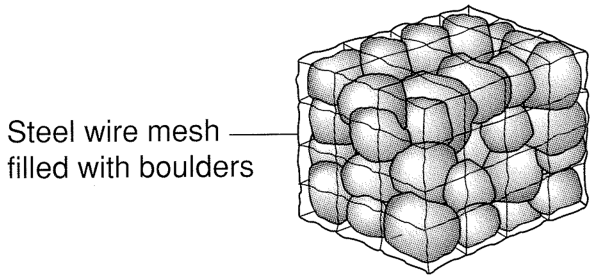

Figure B1.3: A Gabion Basket. Taken from Hill (2004).

B.2 Soft Defence Types

Groynes: These are sets of shore-perpendicular structures (usually wooden) which slow down the rate of longshore drift, and contain sediment on the beach (Figure B1.4).

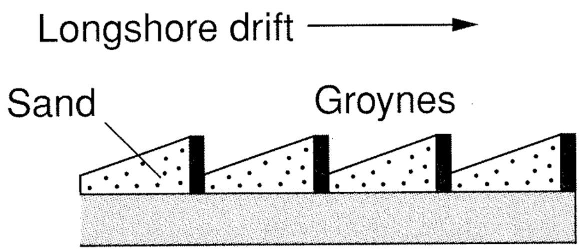

Figure B1.3: Example of a set of groynes used to capture sediment along a beach. Taken from Hill (2004).

Beach Nourishment: This is the process of quarrying sediment from one location and depositing it on an eroding beach to replenish the sediment supply to slow the rate of erosion.

Sand Dune Stabilisation: Sands dunes are a key natural coastal defence, hence they are often managed by using fencing and/or planting of vegetation such as marram grass to enhance the dune or stabilise the positon.

Appendix C: Additional Results

C.1 Physical Susceptibility

C.1.1 UPSM and CESM Outputs

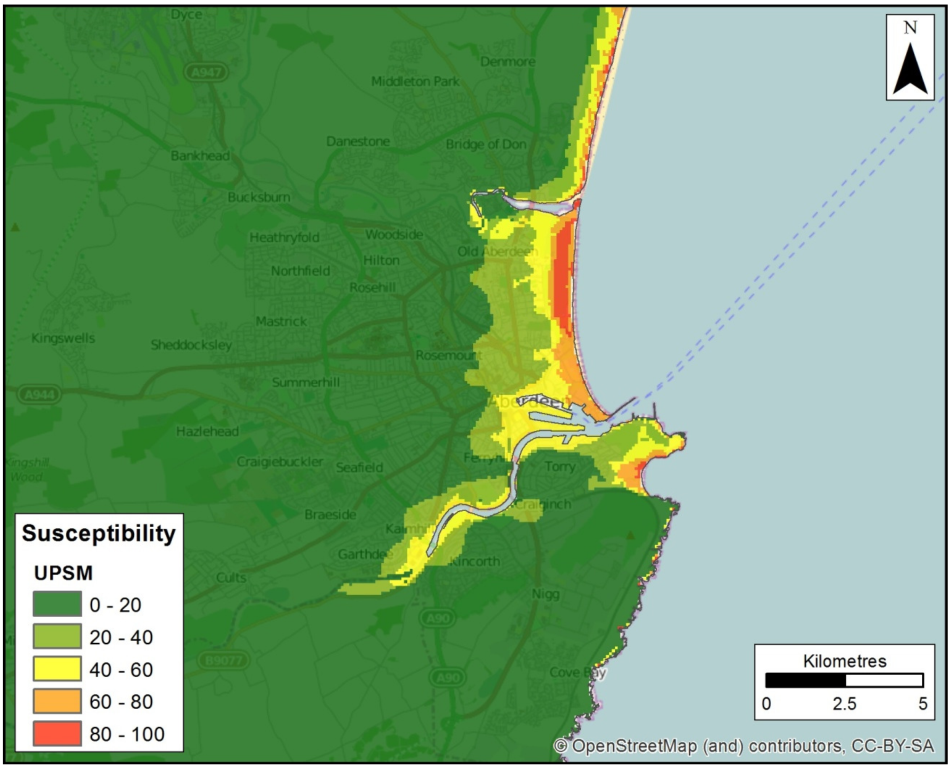

Figure C1.1.1: The Underlying Physical Susceptibility Model (UPSM) for Aberdeen.

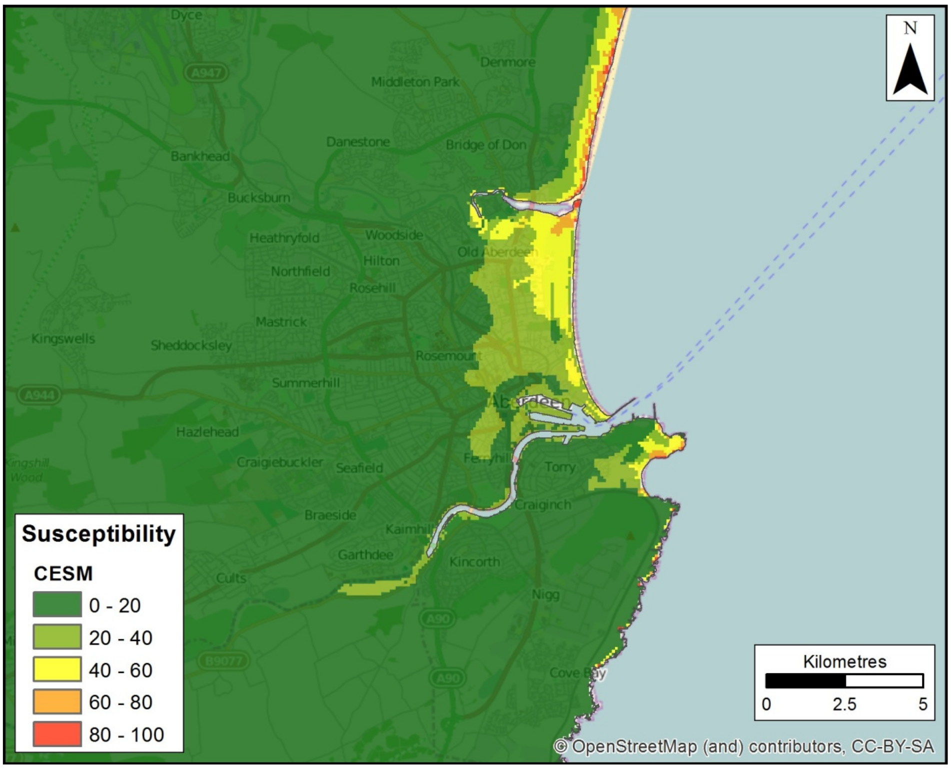

Figure C1.1.2: The Coastal Erosion Susceptibility Model (CESM) for Aberdeen.

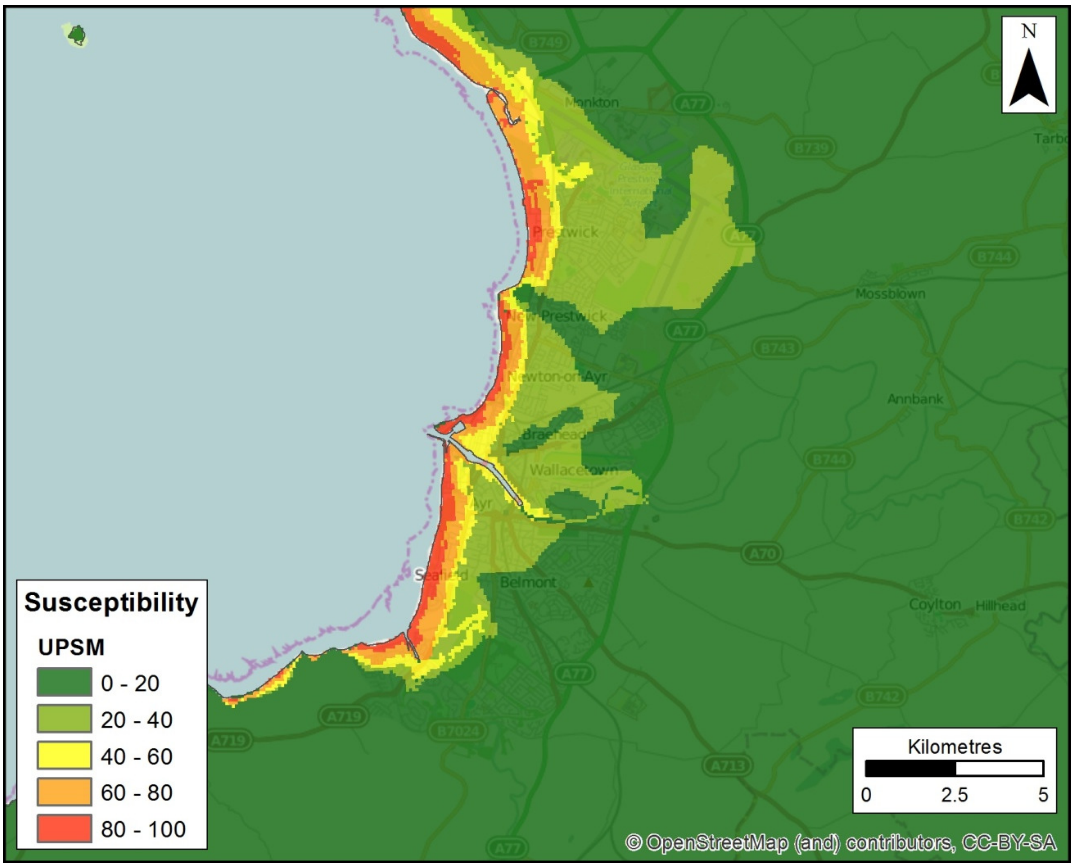

Figure C1.1.3: The Underlying Physical Susceptibility Model (UPSM) for Ayr.

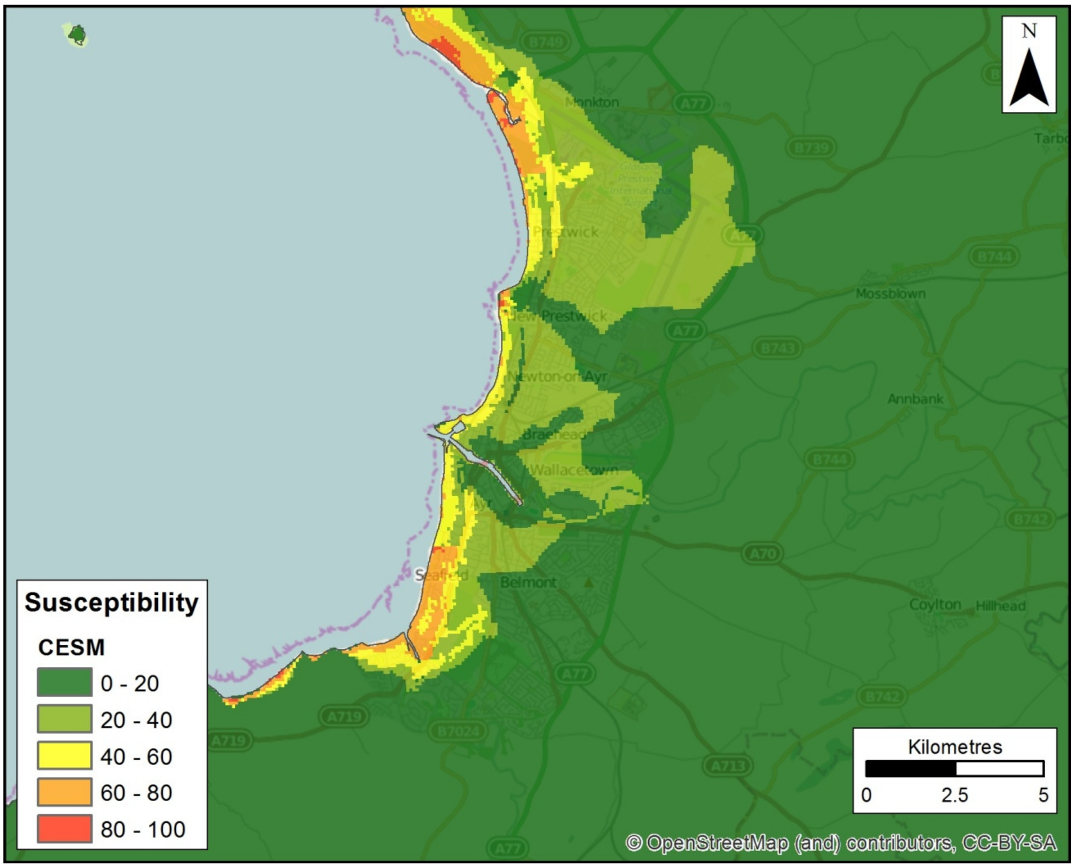

Figure C1.1.4: The Coastal Erosion Susceptibility Model (CESM) for Ayr.

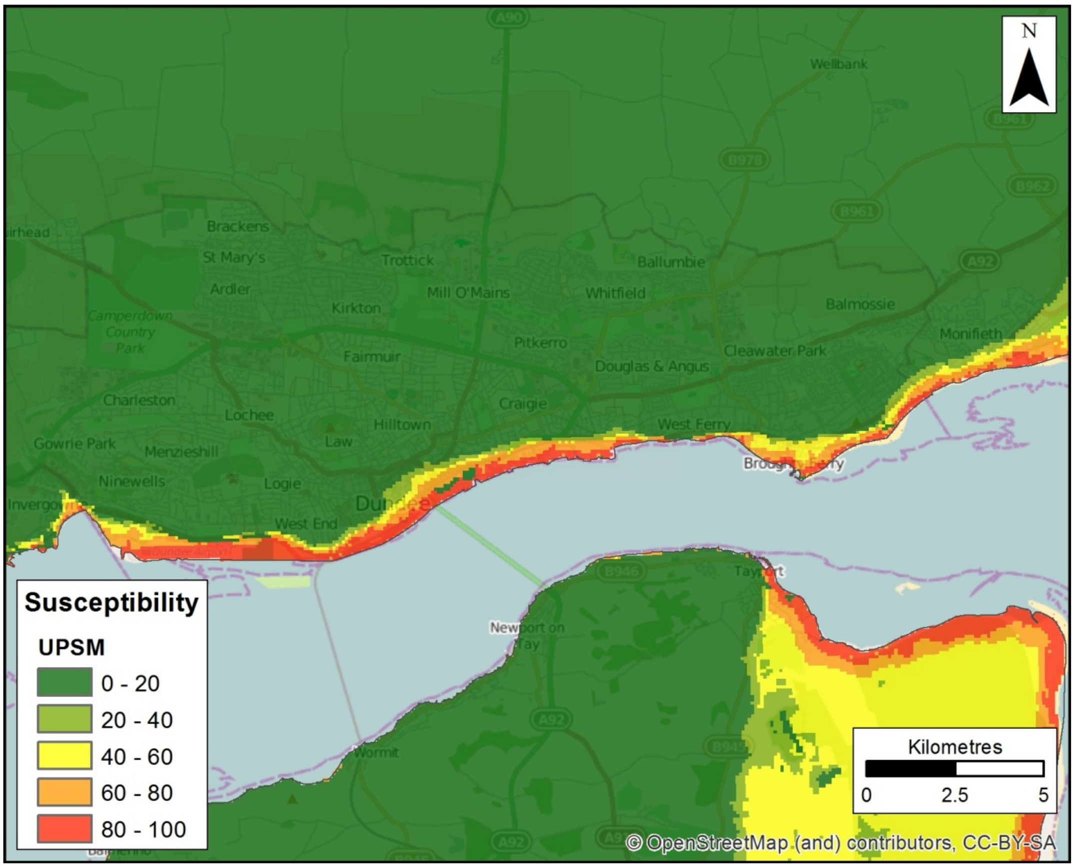

Figure C1.1.5: The Underlying Physical Susceptibility Model (UPSM) for Dundee.

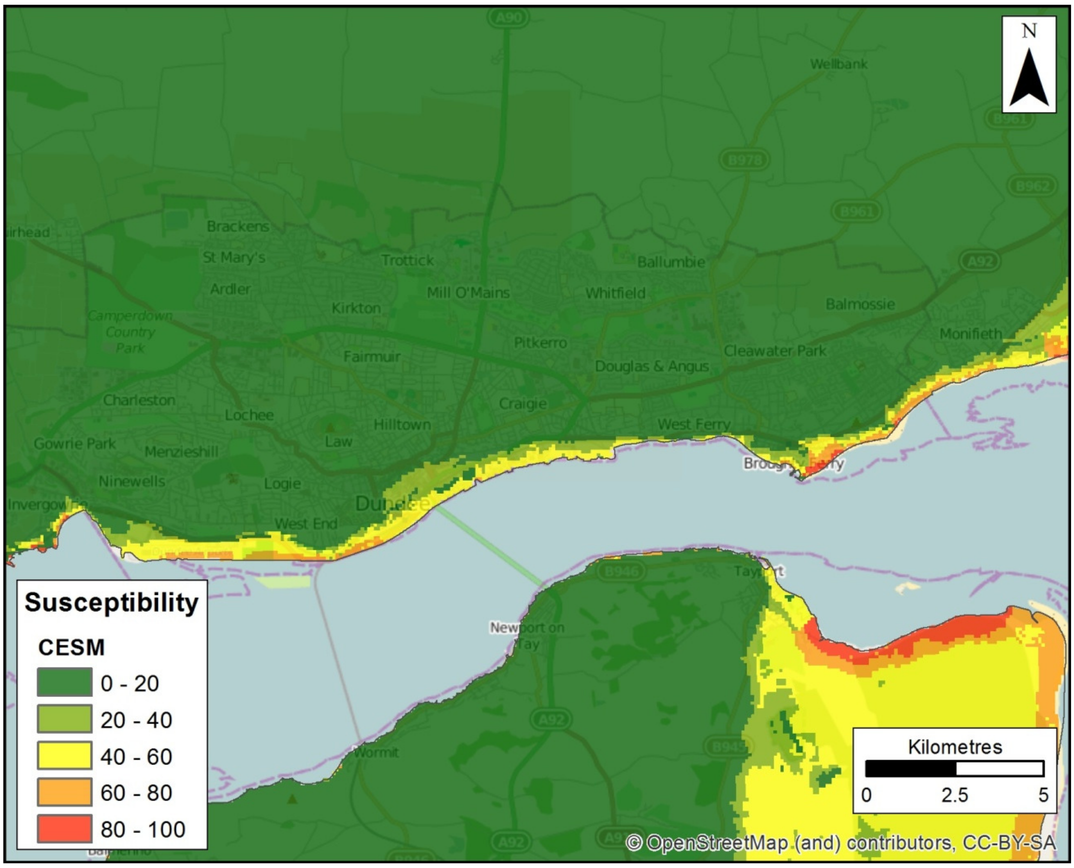

Figure C1.1.6: The Coastal Erosion Susceptibility Model (CESM) for Dundee.

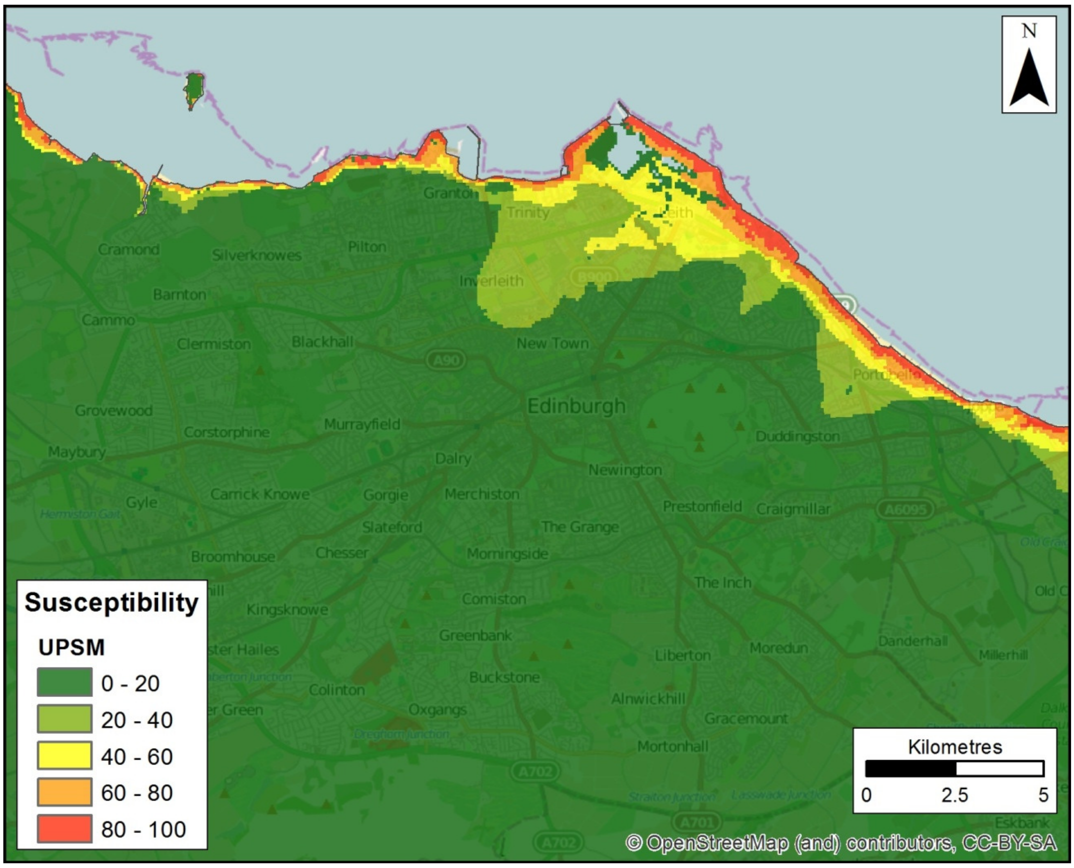

Figure C1.1.7: The Underlying Physical Susceptibility Model (UPSM) for Edinburgh.

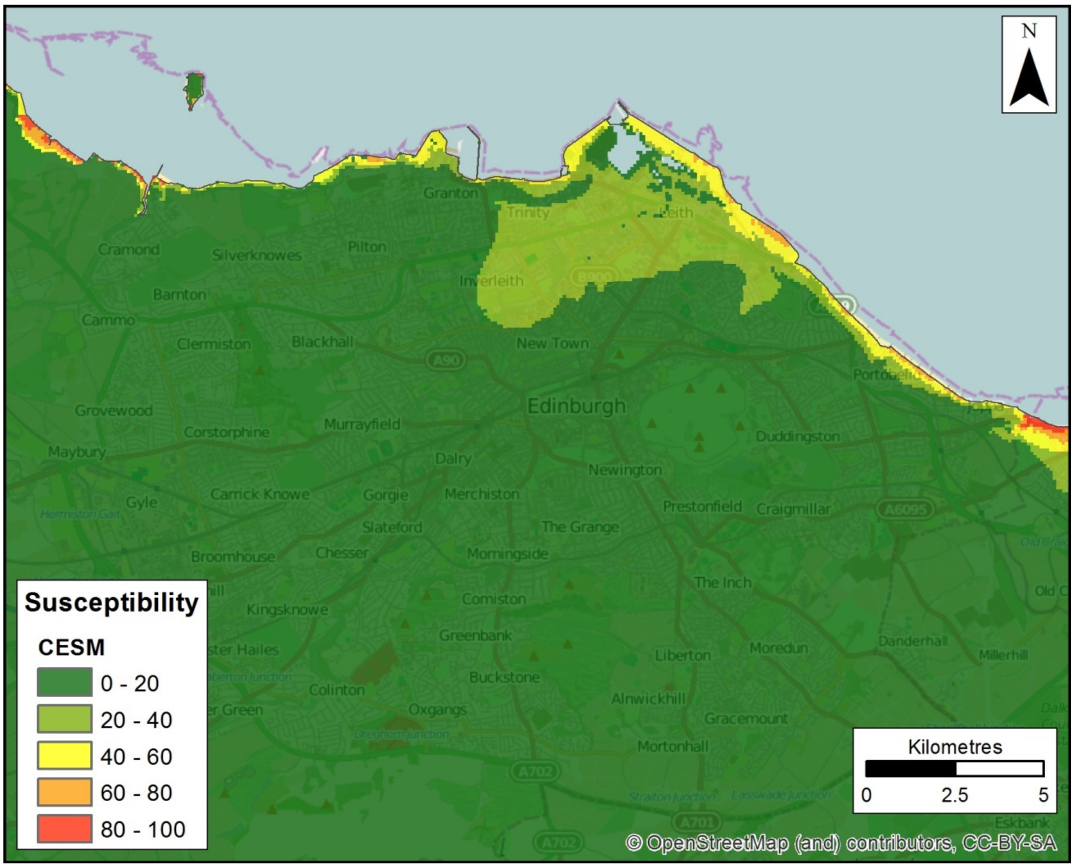

Figure C1.1.8: The Coastal Erosion Susceptibility Model (CESM) for Edinburgh.

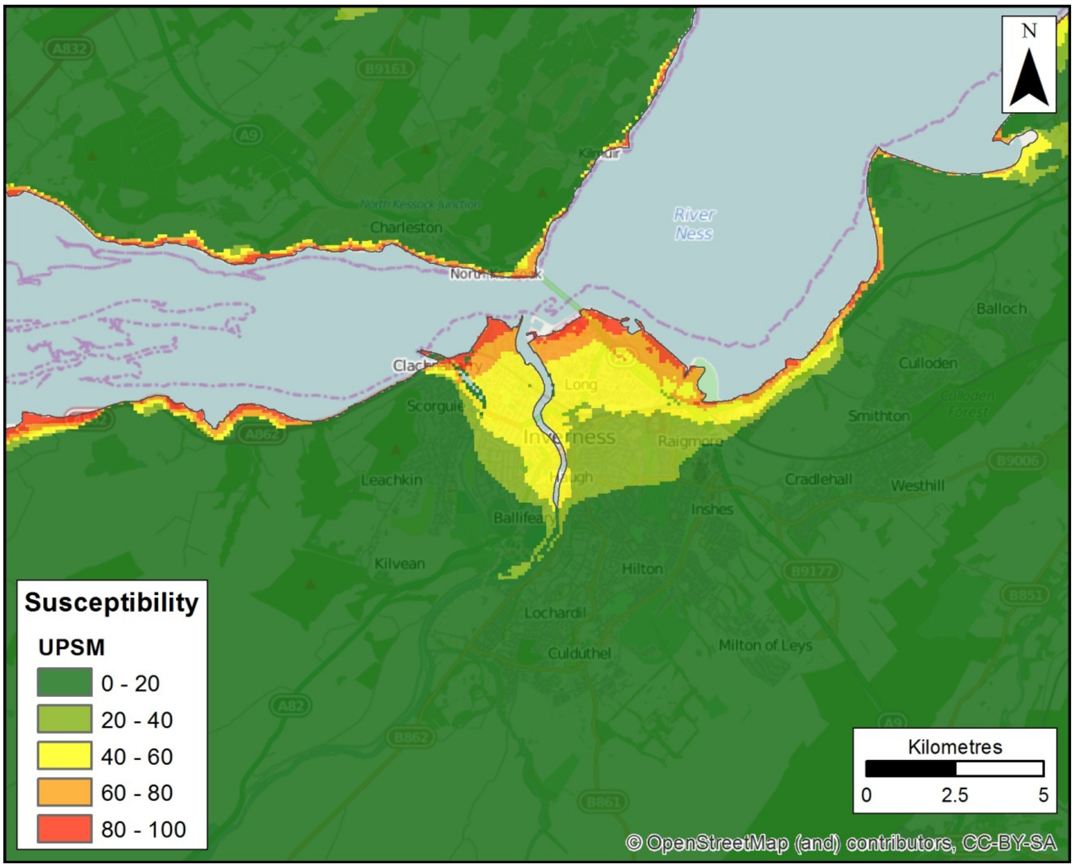

Figure C1.1.9: The Underlying Physical Susceptibility Model (UPSM) for Inverness.

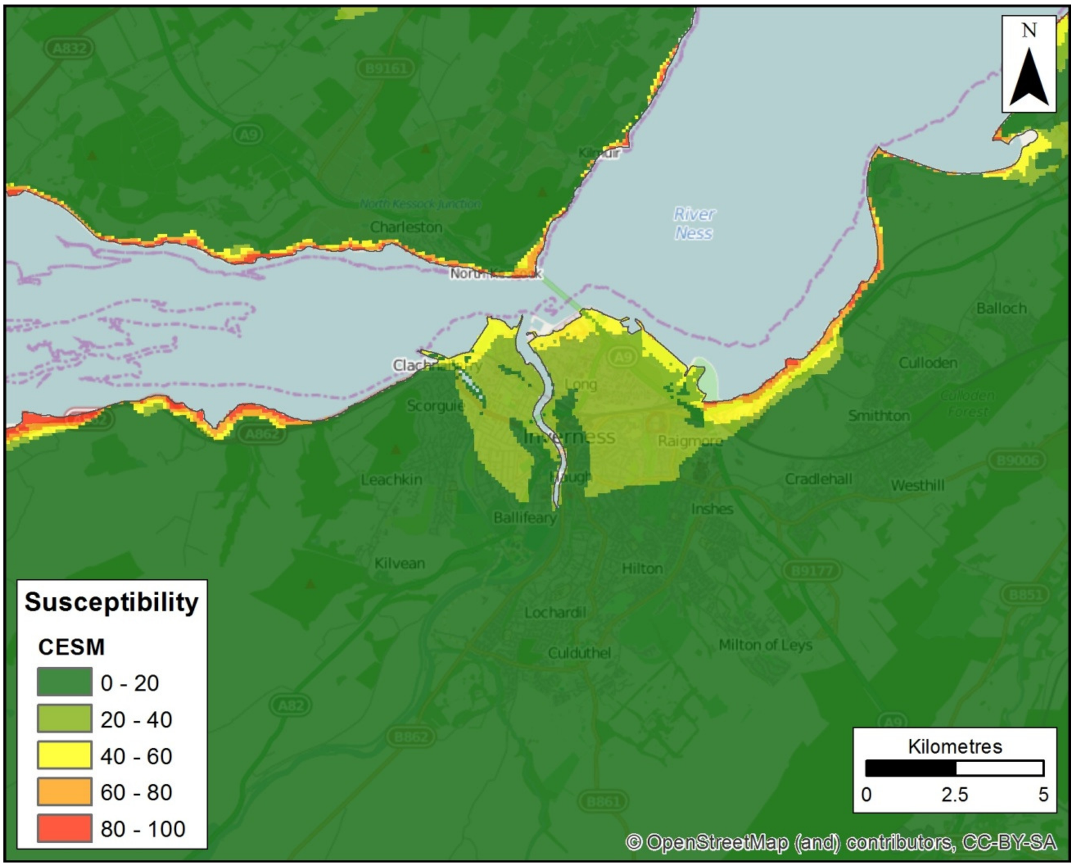

Figure C1.1.10: The Coastal Erosion Susceptibility Model (CESM) for Inverness.

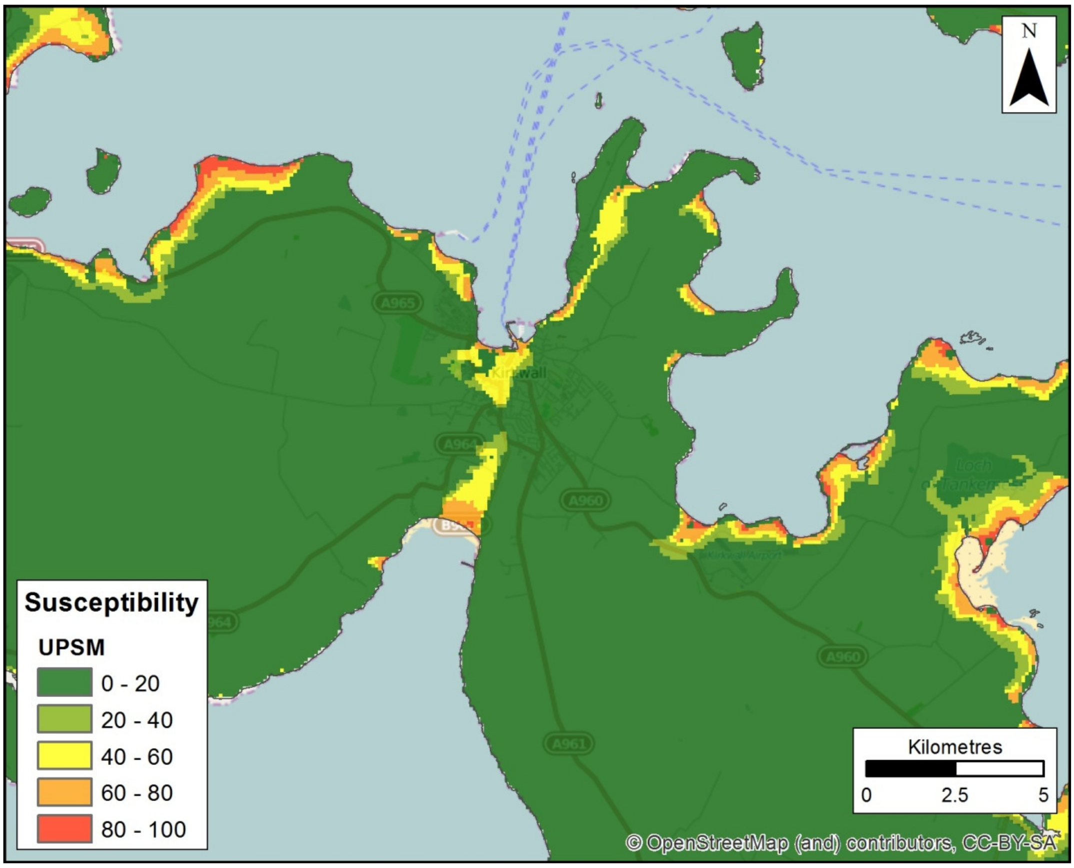

Figure C1.1.11: The Underlying Physical Susceptibility Model (UPSM) for Kirkwall.

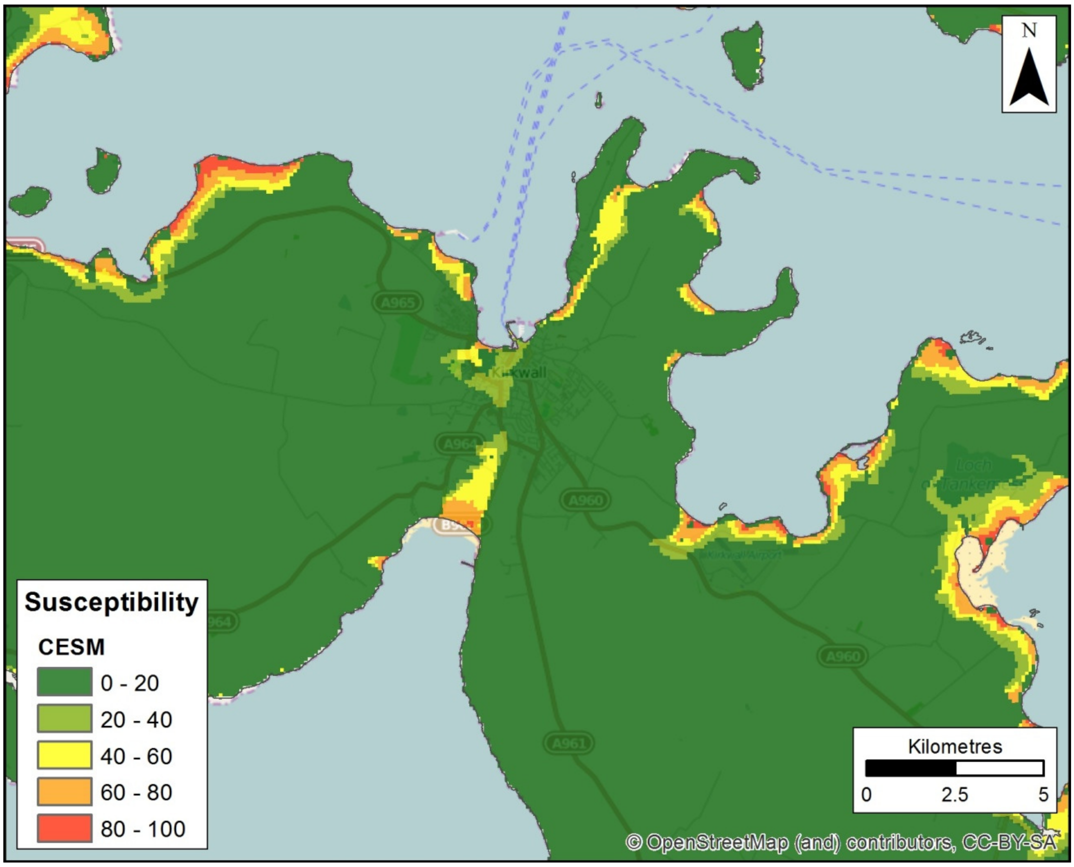

Figure C1.1.12: The Coastal Erosion Susceptibility Model (CESM) for Kirkwall.

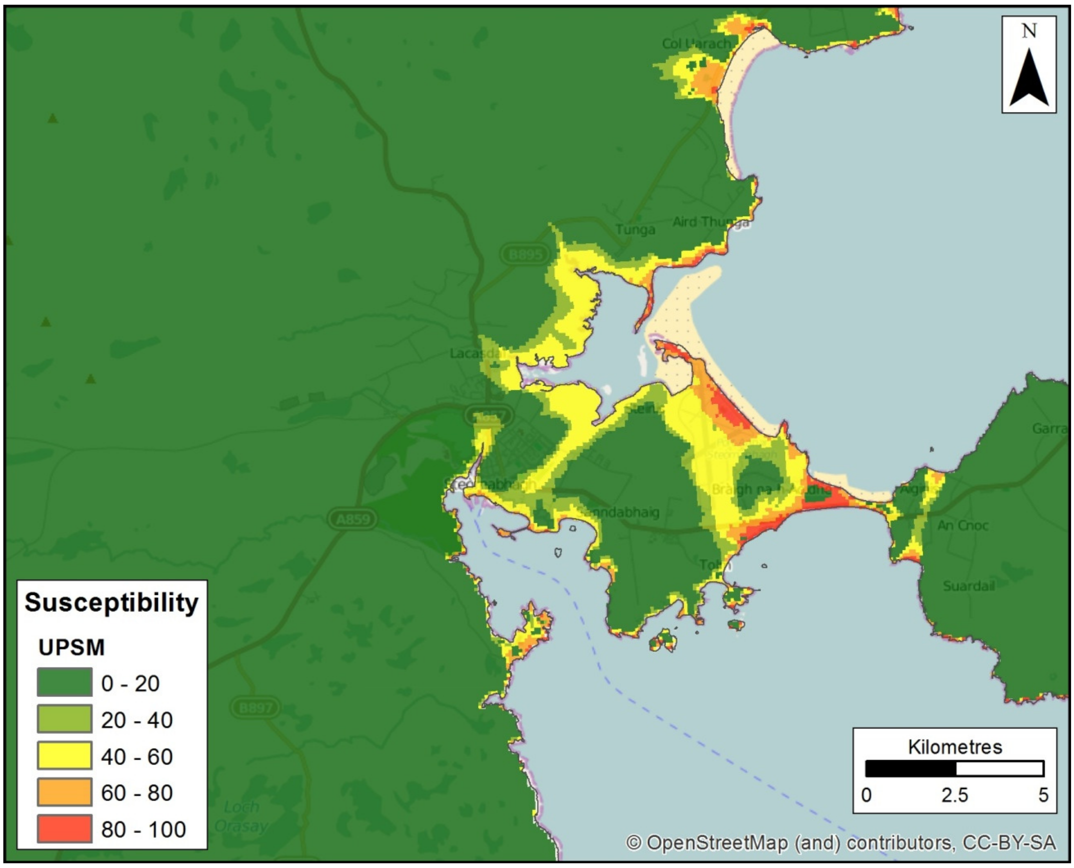

Figure C1.1.13: The Underlying Physical Susceptibility Model (UPSM) for Stornoway.

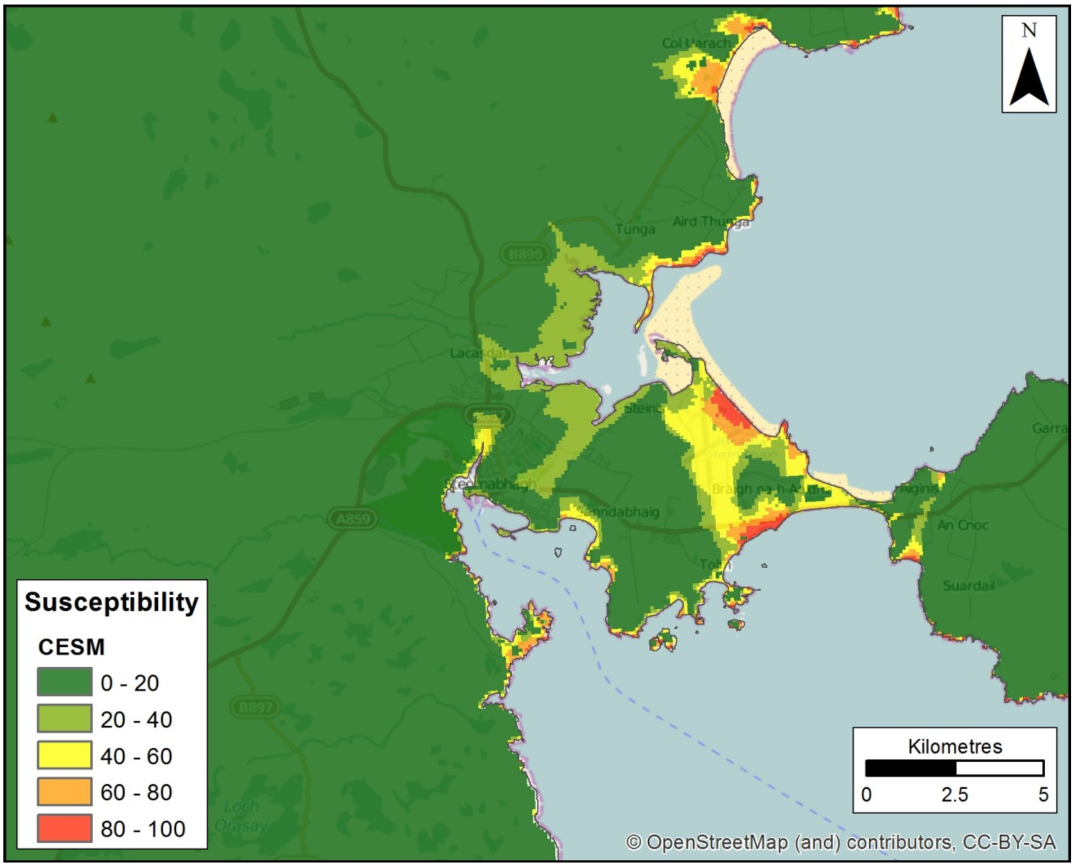

Figure C1.1.14: The Coastal Erosion Susceptibility Model (CESM) for Stornoway

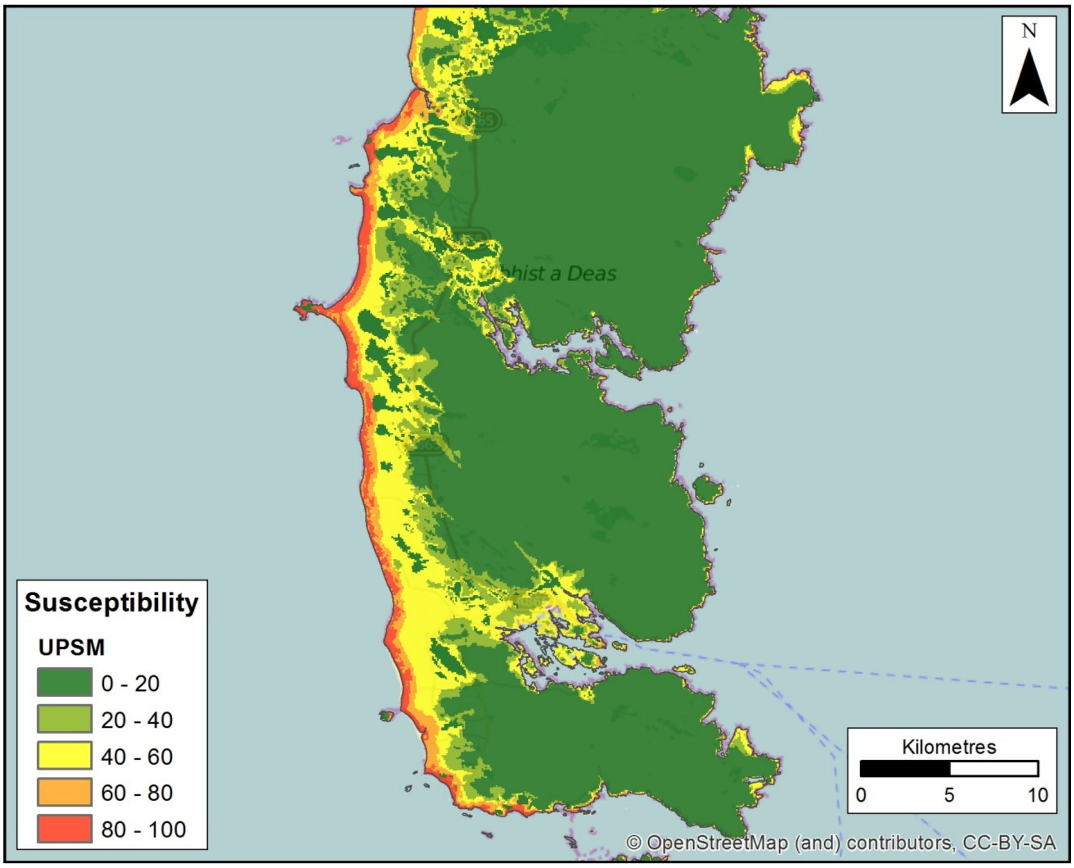

Figure C1.1.15: The Underlying Physical Susceptibility Model (UPSM) for South Uist.

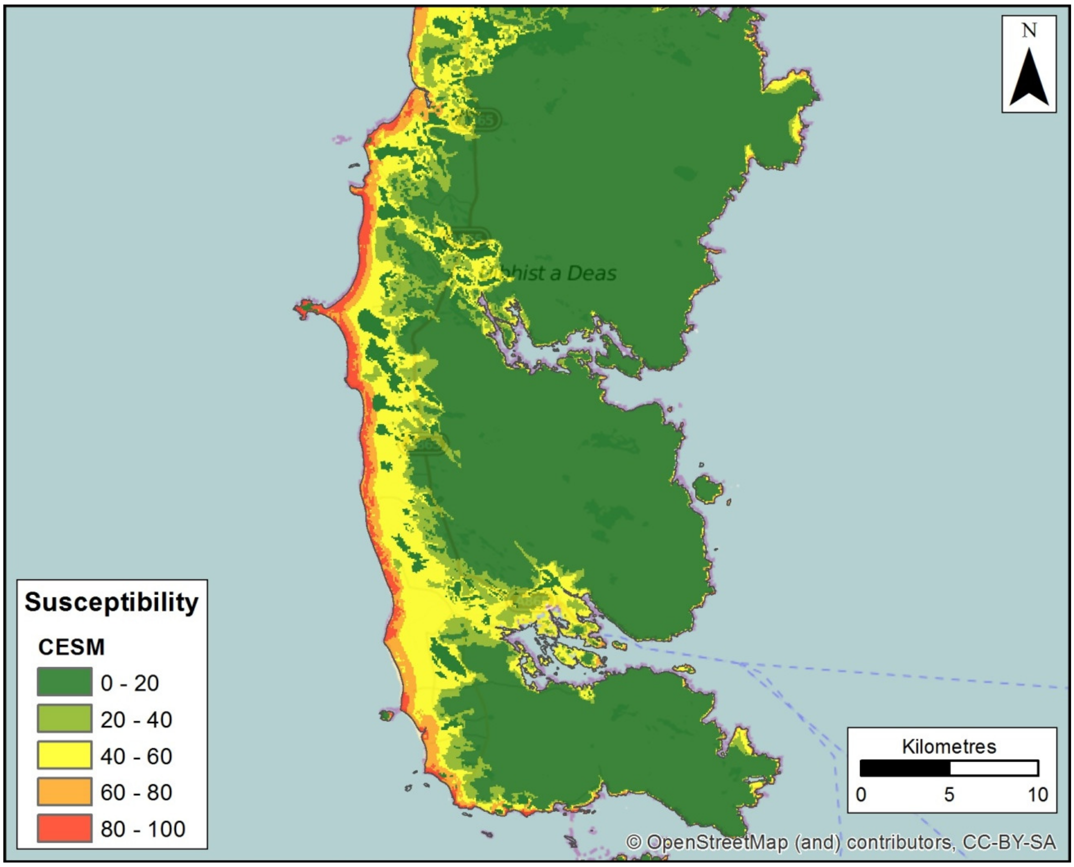

Figure C1.1.16: The Coastal Erosion Susceptibility Model (CESM) for South Uist.

C.1.2 Validation

Table C1.2.1: Validation results comparing the SNH erosion data to the UPSM and CESM coastline

Location	Length of Eroding Coast (km)	Average UPSM Score along Eroding Coast	Average CESM Score along Eroding Coast	Length of Eroding Coast (km)	Proportion of Eroding Coast (%)
Dornoch, Sutherland	0.28	100.0	100.0	44.4	47
Blairton Burn, Menie Links, Aberdeen	0.25	97.6	97.6		
Morrich More, Sutherland	2.45	95.7	95.7		
Dornoch, Sutherland	1.46	95.7	95.7		
Morrich More, Sutherland	3.05	94.6	94.6		
Buddon Links, Tayside	1.68	93.3	93.3		
Spey Bay (east), Moray	5.12	94.2	92.2		
Dornoch, Sutherland	1.70	91.7	91.7		
Morrich More, Sutherland	2.60	91.2	91.2		
Kirkibost, WI	3.36	88.6	88.6		
Bay of Newark, Sanday	1.51	85.7	85.7		
Balintore, Black Isle	0.24	85.7	85.7		
Crossapol, Tiree	1.20	85.1	85.1		
Kilpheder, WI	0.76	96.4	84.5		
Udal, WI	2.51	88.6	84.5		
Liniclate, WI	0.39	84.2	84.2		
Culbin Sands, Highland	2.28	93.8	84.1		
Cuthill Links, Sutherland	1.02	82.6	82.6		
Culbin Sands, Highland	2.70	82.5	82.5		
Balephetrish Bay, Tiree	1.29	82.3	82.3		
Blackdog, Aberdeenshire	0.47	82.1	82.1		
Baleshare, WI	8.04	84.0	80.1		
Broughty Ferry, Tayside	0.73	92.8	79.4	33.6	36
Brora, Sutherland	0.06	82.1	78.5		
Whiteness Head, Highland	0.56	100.0	78.5		
Bay of Skaill, Orkney	1.20	77.8	77.8		
Gualan, WI	3.26	76.4	76.4		
Lundin Links, Fife	1.86	81.0	76.4		
Fortrose & Rosemarkie GC, Black Isle	1.00	83.5	76.3		
West Sands, St Andrews, Fife	0.29	96.4	75.0		
Udal, WI	0.92	83.7	74.4		

Location	Length of Eroding Coast (km)	Average UPSM Score along Eroding Coast	Average CESM Score along Eroding Coast	Length of Eroding Coast (km)	Proportion of Eroding Coast (%)
Fraserburgh Bay, Aberdeenshire	2.85	80.0	71.5		
Swilcan Burn, St Andrews, Fife	0.14	89.3	71.4		
Brora, Sutherland	0.11	92.8	71.4		
Dornoch, Sutherland	0.10	92.8	71.3		
Scuthvie Bay, Sanday	0.80	68.7	68.7		
Inverallochy GC, Aberdeens.	0.84	77.1	68.1		
Gott Bay, Tiree	1.24	89.2	67.8		
Gott Bay, Tiree	0.79	89.2	67.8		
Benbecula, WI	2.43	77.9	67.2		
Kinnaber Links - Montrose	7.18	89.1	67.1		
Fortrose & Rosemarkie GC, Black Isle	0.75	84.3	62.9		
Golspie, Sutherland	4.52	91.1	62.1		
Coul Links, Embo, Sutherland	2.00	82.8	62.0		
Udal, WI	2.34	59.8	59.8		
Udal, WI	4.44	73.7	57.6		
Helmsdale, Sutherland	0.11	57.1	57.1		
Embo, Sutherland	0.41	83.9	57.1		
Portgower	0.69	55.1	55.1		
Rhunahaorin, Argyl	0.65	51.8	51.8		
Tain, Sutherland	0.18	86.9	51.2		
Golspie, Sutherland	0.62	86.8	51.1	13.5	14
Inch of Ferryton, Alloa / Firth of Forth	0.66	85.7	50.0		
Dornoch, Sutherland	0.64	80.5	48.0		
North Berwick, E. Lothain	0.34	47.6	47.6		
Aberdeen City, Aberdeenshire	1.57	78.2	42.5		
Fort George, Highland	0.84	74.3	42.1		
Cruden Bay, Aberdeenshire	0.34	58.9	32.1	0.7	1
Eden Estuary - Fife	0.33	82.1	24.9		
Melby Beach, Shetland	0.90	14.3	14.3		
East Wemyss, Fife	0.51	10.7	10.7	1.8	2
Start Point, Sanday	0.35	0.0	0.0		
Sandness Coast, Shetland	0.07	0.0	0.0		
Total	**93.97**	**82.95**	**72.71**	**93.97**	**100**

Table C1.2.2: Qualitative validation comments from Stewart Angus and George Lees. Note that Susceptibility To Erosion is abbreviated to STE.

Location	CESM Accuracy 1 to 5 (1 = Low Accuracy, 5 = High Accuracy)		Which areas were modelled well? Which areas need to be improved? Comments	
	Stewart Angus	George Lees	Stewart Angus	George Lees
Aberdeen	5	4	-	Distinguishes increased susceptibility of unprotected dunes flanking Don estuary, relative to protected shores to the south. Also, the relatively high STE of the dunes to the north of the Don. Good too around Nigg Bay, discriminating more erodible shores from resilient rockier coasts to the south. Unclear though why heavily defended seawall along Aberdeen seafront comes out as Med / Low STE, rather than V Low (but see comments below).
Largs	-	3	-	Not familiar with Ayr, but know Largs well. As above relative STE is discriminated well but, again, whether the Med STE for Largs seafront is correct is debatable. Shoreline further south from Hunterston to Portencross does have v low relief but is, in practice, dominated by bedrock at and immediately above the intertidal. CESM flags up as V High STE whereas in practice is Low or V Low.
Dornoch, Morrich More & Tain	5	5	After discussion with Ali Rennie.	Good. Largely natural, undefended coastline. CESM discriminates STE well.
Dundee	5	3	Comments refer to Tenstsmuir area	As earlier, heavily defended, built up coastlines coming out as of Med STE, which seems anomalous (but see general comments below). Also, note large areas of saltmarsh upstream come out as V High STE which, given *relatively* sheltered location am not sure about. Again, see below.
Edinburgh	5	3	-	As with other built up areas, the relative STE is good, but same questions about whether a heavily defended shoreline has anything but V Low STE. Also questionable whether large tracts of low-lying land far upstream and distant from the Forth itself should be showing up on model as anything other than V Low STE.
Glasgow	-	3	Not enough knowledge to comment	Same as for Edinburgh. Relative STE good, but eye is drawn to extensive inland areas around Glasgow airport, Clydebank and Dumbarton flagged up as having Med or Low STE despite distance from the sea / Clyde.
Inverness	3	4	Red areas overstate susceptibility?	As with other built up areas, though relatively more limited shoreline development here, and CESM good and fairly accurate as far as I can tell along adjacent shores.
Kirkwall	4 to 5	4	Perhaps Ferry Pt should be downgraded?	As Inverness
Stornoway	2	4	NB553585 fairly robust – high cliffs with geo NB536498 very vulnerable (resolution issue?) Area east of Stornoway itself score 4	As Inverness. Good discrimination between rocky coasts, defended land and soft erodible shores.
South Uist	4	5	Understates risk to dune ridge and interior but complex system (Angus, forthcoming)	Largely natural shore; CESM works well.

C.1.2.1 George Lees Overall Comments

Overall the CESM seems to give good discrimination of relative susceptibility to erosion (STE) at national and regional scales; that in itself is a major achievement. It also works well in most instances right down to a local level (at least to the 200/500m resolution of the input data), particularly on 'natural' coastlines. But outputs seem anomalous at a local scale in 3 specific situations:

- **Where coastal defences exist, typically in urban areas with proms and seawalls**. In most cities and towns considered above, seafronts show up as having Med or Low STE when, intuitively, one might anticipate that the presence of (typically major) defences might render STE as being V Low. Of course, one might argue that such locations are still, inherently, more STE than are rocky shores elsewhere which do map out as V Low, and that to map these defended shores as V Low might give a false sense of security. However it does appear anomalous. This could easily be addressed, if desired, by assigning a greater 'handicap' to defended shores than is currently done (e.g. -10 instead of -5).

- **Areas of saltmarsh** (e.g. Forth Estuary; Tay Estuary; Fairlie on the Clyde coast) come up as of V High STE. From a sedimentological / topographic perspective this is understandable. However the presence of saltmarsh typically reflects (among other things) relatively low wave exposure, so I wonder if they are as STE as indicated (i.e. doesn't their presence tend to indicate limited historical erosion?). Is a difficult one and I suppose they are still prone to frequent submersion, even if not so prone to erosion, so would probably leave as is.

- **Low lying inland areas around, but often many km distant from, estuaries**. (e.g. upper Forth Estuary; Abbotsinch; Clydebank; Dumbarton). Again it is understandable why the model might flag these up as of Med / Low STE, rather than V Low but STE per se at anything more than a few hundred metres (or, indeed, a few tens of metres) in such locations must be considered exceptionally low, especially where the nearest shores are also defended, as will tend to be the case in these situations. Perhaps just set a buffer beyond which STE is not displayed. Alternatively, as earlier, maybe want to retain these as is as, I assume, most are areas of former land claim which would be STE and flooding should defences fail.

So, overall, an exceptional and valuable piece of work, which works especially well on natural shorelines but is, perhaps, just confounded at a local scale where defences exists. Even if no changes are made, it may be worth having a few caveats in any accompanying text, to explain why 'defended' shorelines don't tend to show up as V Low STE.

C.1.3 UPSM and CESM Statistics

Table C1.3.1: Summary of UPSM coastline length classification by local authority.

Local Authority	Local Authority Coastline Length (km)	UPSM (km)				
		0-20	20-40	40-60	60-80	80-100
Aberdeen City	46.5	11.9	1.2	19.1	8.2	6.1
Aberdeenshire	336.5	169.2	4.1	43.8	49.9	69.7
Angus	102.6	6.4	1.8	20.9	26.8	46.7
Argyll and Bute	3,609.5	2,492.5	46.7	260.0	371.1	439.1
City of Edinburgh	45.7	13.0	0.3	0.8	7.5	24.3
Clackmannanshire	27.6	0.2	0.0	18.5	2.5	6.5
Dumfries and Galloway	721.8	246.6	10.0	141.9	105.0	218.3
Dundee City	19.0	0.9	0.0	0.2	2.0	15.9
East Ayrshire	0.0	0.0	0.0	0.0	0.0	0.0
East Dunbartonshire	0.0	0.0	0.0	0.0	0.0	0.0
East Lothian	110.3	25.1	0.1	12.0	16.9	56.3
East Renfrewshire	0.0	0.0	0.0	0.0	0.0	0.0
Falkirk	57.9	1.0	0.0	9.3	12.0	35.6
Fife	270.7	96.9	2.3	22.3	40.3	108.8
Glasgow City	42.7	6.9	0.4	35.4	0.0	0.0
Highland	5,029.2	3,527.4	103.1	512.9	390.2	495.7
Inverclyde	45.8	17.3	0.0	0.7	8.5	19.3
Midlothian	0.0	0.0	0.0	0.0	0.0	0.0
Moray	144.2	30.6	0.5	21.7	36.0	55.5
Na h-Eileanan an Iar	3,476.9	902.5	297.4	1,122.7	552.0	602.4
North Ayrshire	270.6	85.2	0.7	24.0	43.6	117.1
North Lanarkshire	0.0	0.0	0.0	0.0	0.0	0.0
Orkney Islands	1,234.6	813.3	7.5	61.7	158.8	193.3
Perth and Kinross	116.2	13.4	4.9	65.5	7.8	24.6
Renfrewshire	54.0	10.9	0.2	35.3	5.6	2.1
Scottish Borders	54.5	49.4	0.2	1.7	2.3	1.0
Shetland Islands	2,206.2	1,650.5	72.5	200.1	155.4	127.8
South Ayrshire	129.8	60.0	0.1	5.5	19.7	44.6
South Lanarkshire	4.7	0.5	0.5	3.7	0.0	0.0
Stirling	30.0	0.8	0.6	28.6	0.0	0.0
West Dunbartonshire	37.0	3.6	0.2	22.7	4.6	5.9
West Lothian	7.8	3.4	0.1	0.5	1.8	2.1
Total	18,232.3	10,239.2	555.3	2,691.1	2,028.1	2,718.6

Table C1.3.2: Summary of UPSM coastline percentage classification by local authority.

Local Authority	Local Authority Coastline Length (km)	UPSM (%)				
		0-20	20-40	40-60	60-80	80-100
Aberdeen City	46.5	25.6	2.6	41.1	17.5	13.2
Aberdeenshire	336.5	50.3	1.2	13.0	14.8	20.7
Angus	102.6	6.2	1.7	20.4	26.1	45.5
Argyll and Bute	3,609.5	69.1	1.3	7.2	10.3	12.2
City of Edinburgh	45.7	28.3	0.7	1.6	16.3	53.1
Clackmannanshire	27.6	0.5	0.0	67.0	9.1	23.4
Dumfries and Galloway	721.8	34.2	1.4	19.7	14.5	30.3
Dundee City	19.0	5.0	0.0	1.0	10.5	83.5
East Ayrshire	0.0	-	-	-	-	-
East Dunbartonshire	0.0	-	-	-	-	-
East Lothian	110.3	22.8	0.1	10.8	15.3	51.0
East Renfrewshire	0.0	-	-	-	-	-
Falkirk	57.9	1.7	0.0	16.1	20.7	61.5
Fife	270.7	35.8	0.9	8.3	14.9	40.2
Glasgow City	42.7	16.1	0.9	83.0	0.0	0.0
Highland	5,029.2	70.1	2.1	10.2	7.8	9.9
Inverclyde	45.8	37.8	0.0	1.5	18.6	42.1
Midlothian	0.0	-	-	-	-	-
Moray	144.2	21.2	0.3	15.0	24.9	38.5
Na h-Eileanan an Iar	3,476.9	26.0	8.6	32.3	15.9	17.3
North Ayrshire	270.6	31.5	0.2	8.9	16.1	43.3
North Lanarkshire	0.0	-	-	-	-	-
Orkney Islands	1,234.6	65.9	0.6	5.0	12.9	15.7
Perth and Kinross	116.2	11.5	4.2	56.4	6.7	21.2
Renfrewshire	54.0	20.1	0.4	65.3	10.3	3.9
Scottish Borders	54.5	90.6	0.4	3.1	4.2	1.7
Shetland Islands	2,206.2	74.8	3.3	9.1	7.0	5.8
South Ayrshire	129.8	46.2	0.1	4.2	15.2	34.4
South Lanarkshire	4.7	10.6	10.6	78.7	0.0	0.0
Stirling	30.0	2.5	2.0	95.5	0.0	0.0
West Dunbartonshire	37.0	9.7	0.5	61.4	12.4	15.9
West Lothian	7.8	43.6	0.6	6.4	22.4	26.9
Total	18,232.3	56.2	3.0	14.8	11.1	14.9

Table C1.3.3: Summary of CESM coastline length classification by local authority.

Local Authority	**Local Authority Coastline Length (km)**	**CESM (km)**				
		0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	46.5	15.6	16.3	6.6	3.7	4.3
Aberdeenshire	336.5	171.0	11.8	60.8	48.1	44.8
Angus	102.6	6.9	8.9	29.7	33.5	23.6
Argyll and Bute	3,609.5	2,495.8	61.2	289.7	384.9	377.9
City of Edinburgh	45.7	13.2	4.4	16.5	7.8	3.9
Clackmannanshire	27.6	0.2	2.2	22.5	1.0	1.8
Dumfries and Galloway	721.8	247.7	14.8	166.8	152.5	139.9
Dundee City	19.0	1.1	1.7	9.5	5.5	1.2
East Ayrshire	0.0	0.0	0.0	0.0	0.0	0.0
East Dunbartonshire	0.0	0.0	0.0	0.0	0.0	0.0
East Lothian	110.3	25.1	2.5	23.8	29.1	29.9
East Renfrewshire	0.0	0.0	0.0	0.0	0.0	0.0
Falkirk	57.9	2.5	13.2	24.7	6.4	11.2
Fife	270.7	100.7	22.8	68.7	42.4	36.1
Glasgow City	42.7	17.9	24.8	0.0	0.0	0.0
Highland	5,029.2	3,533.9	140.3	545.6	451.8	357.7
Inverclyde	45.8	17.9	4.4	10.2	7.7	5.6
Midlothian	0.0	0.0	0.0	0.0	0.0	0.0
Moray	144.2	30.6	5.2	33.2	36.9	38.3
Na h-Eileanan an Iar	3,476.9	909.1	328.6	1,130.1	547.6	561.5
North Ayrshire	270.6	86.0	9.2	48.9	38.4	88.0
North Lanarkshire	0.0	0.0	0.0	0.0	0.0	0.0
Orkney Islands	1,234.6	813.9	9.5	63.5	156.3	191.5
Perth and Kinross	116.2	13.4	4.9	66.3	7.9	23.8
Renfrewshire	54.0	11.2	5.3	29.9	5.6	2.1
Scottish Borders	54.5	49.4	0.8	1.5	2.0	0.9
Shetland Islands	2,206.2	1,650.9	75.9	200.8	151.6	127.0
South Ayrshire	129.8	61.1	4.5	14.4	28.4	21.5
South Lanarkshire	4.7	1.8	2.9	0.0	0.0	0.0
Stirling	30.0	0.8	0.6	28.6	0.0	0.0
West Dunbartonshire	37.0	5.2	11.5	10.5	4.2	5.7
West Lothian	7.8	3.4	0.1	0.5	1.8	2.1
Total	18,232.3	10,286.3	787.9	2,902.8	2,155.0	2,100.3

Table C1.3.3: Summary of CESM coastline percentage classification by local authority.

Local Authority	Local Authority Coastline Length (km)	CESM (%)				
		0-20	20-40	40-60	60-80	80-100
Aberdeen City	46.5	33.7	35.1	14.1	8.0	9.2
Aberdeenshire	336.5	50.8	3.5	18.1	14.3	13.3
Angus	102.6	6.7	8.7	28.9	32.7	23.0
Argyll and Bute	3,609.5	69.1	1.7	8.0	10.7	10.5
City of Edinburgh	45.7	28.7	9.5	36.1	17.0	8.6
Clackmannanshire	27.6	0.7	7.8	81.5	3.6	6.4
Dumfries and Galloway	721.8	34.3	2.1	23.1	21.1	19.4
Dundee City	19.0	6.0	8.7	50.1	28.9	6.3
East Ayrshire	0.0	-	-	-	-	-
East Dunbartonshire	0.0	-	-	-	-	-
East Lothian	110.3	22.8	2.2	21.5	26.4	27.1
East Renfrewshire	0.0	-	-	-	-	-
Falkirk	57.9	4.3	22.8	42.6	11.0	19.3
Fife	270.7	37.2	8.4	25.4	15.7	13.4
Glasgow City	42.7	42.0	58.0	0.0	0.0	0.0
Highland	5,029.2	70.3	2.8	10.8	9.0	7.1
Inverclyde	45.8	39.0	9.7	22.3	16.8	12.2
Midlothian	0.0	-	-	-	-	-
Moray	144.2	21.2	3.6	23.0	25.6	26.6
Na h-Eileanan an Iar	3,476.9	26.1	9.5	32.5	15.8	16.1
North Ayrshire	270.6	31.8	3.4	18.1	14.2	32.5
North Lanarkshire	0.0	-	-	-	-	-
Orkney Islands	1,234.6	65.9	0.8	5.1	12.7	15.5
Perth and Kinross	116.2	11.6	4.2	57.0	6.8	20.5
Renfrewshire	54.0	20.7	9.8	55.3	10.3	3.9
Scottish Borders	54.5	90.6	1.5	2.8	3.6	1.6
Shetland Islands	2,206.2	74.8	3.4	9.1	6.9	5.8
South Ayrshire	129.8	47.0	3.4	11.1	21.9	16.6
South Lanarkshire	4.7	38.3	61.7	0.0	0.0	0.0
Stirling	30.0	2.5	2.0	95.5	0.0	0.0
West Dunbartonshire	37.0	14.1	30.9	28.4	11.4	15.3
West Lothian	7.8	43.6	0.6	6.4	22.4	26.9
Total	18,232.3	56.4	4.3	15.9	11.8	11.5

Table C1.3.4: Summary of UPSM area classification by local authority.

Local Authority	**UPSM (km^2)**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	173.9	6.3	4.6	1.7	1.0
Aberdeenshire	6263.6	25.8	21.0	11.7	6.7
Angus	2128.8	21.7	24.6	8.5	5.9
Argyll and Bute	6890.0	58.6	63.0	51.0	36.4
City of Edinburgh	250.5	6.4	3.2	2.3	2.7
Clackmannanshire	133.4	11.3	13.1	1.4	0.7
Dumfries and Galloway	6233.0	115.2	59.8	29.9	25.7
Dundee City	55.1	0.7	0.8	1.5	2.3
East Ayrshire	1270.3	0.1	0.0	0.0	0.0
East Dunbartonshire	173.7	0.8	0.0	0.0	0.0
East Lothian	646.5	13.0	10.5	6.6	7.3
East Renfrewshire	173.8	0.0	0.0	0.0	0.0
Falkirk	233.5	22.5	32.1	6.5	5.1
Fife	1251.0	18.3	38.2	13.7	14.7
Glasgow City	139.4	25.4	11.4	0.0	0.0
Highland	25910.3	138.1	143.1	59.7	50.7
Inverclyde	157.4	0.8	1.0	2.1	2.2
Midlothian	355.3	0.0	0.0	0.0	0.0
Moray	2074.3	75.1	75.3	11.7	7.2
Na h-Eileanan an Iar	2778.8	124.3	166.8	59.9	39.5
North Ayrshire	824.1	34.3	15.3	10.5	11.0
North Lanarkshire	472.2	0.0	0.0	0.0	0.0
Orkney Islands	928.8	40.3	32.0	32.6	21.8
Perth and Kinross	5306.2	57.9	18.0	3.4	3.0
Renfrewshire	212.5	18.4	31.9	0.9	0.3
Scottish Borders	4731.2	8.9	0.4	0.7	0.1
Shetland Islands	1425.8	24.9	27.4	14.0	7.7
South Ayrshire	1193.1	17.6	5.9	7.1	5.4
South Lanarkshire	1769.2	4.1	0.7	0.0	0.0
Stirling	2149.3	84.5	20.5	0.0	0.0
West Dunbartonshire	161.3	6.7	9.1	1.2	0.6
West Lothian	428.5	0.0	0.2	0.2	0.2
Total	76894.5	962.0	829.7	338.6	258.4

Table C1.3.5: Summary of CESM area classification by local authority.

Local Authority	**CESM (km²)**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	177.3	6.5	2.7	0.6	0.4
Aberdeenshire	6265.7	27.7	23.3	8.1	4.1
Angus	2130.7	23.8	26.2	6.4	2.4
Argyll and Bute	6892.9	61.7	65.0	49.0	30.3
City of Edinburgh	253.1	8.3	2.5	0.8	0.4
Clackmannanshire	133.5	12.5	13.2	0.5	0.2
Dumfries and Galloway	6235.1	116.7	65.0	32.3	14.5
Dundee City	55.9	1.6	2.0	0.7	0.1
East Ayrshire	1270.3	0.1	0.0	0.0	0.0
East Dunbartonshire	173.7	0.8	0.0	0.0	0.0
East Lothian	647.9	14.9	11.3	6.0	3.9
East Renfrewshire	173.8	0.0	0.0	0.0	0.0
Falkirk	234.9	28.7	32.6	2.1	1.4
Fife	1255.4	25.6	41.3	9.1	4.6
Glasgow City	156.7	19.4	0.1	0.0	0.0
Highland	25916.8	151.7	140.5	60.2	32.8
Inverclyde	158.6	1.4	2.0	1.0	0.5
Midlothian	355.3	0.0	0.0	0.0	0.0
Moray	2074.7	76.1	76.3	11.0	5.5
Na h-Eileanan an Iar	2781.3	129.7	167.9	56.0	34.6
North Ayrshire	827.0	36.3	17.0	6.7	8.1
North Lanarkshire	472.2	0.0	0.0	0.0	0.0
Orkney Islands	929.1	40.7	31.8	32.3	21.6
Perth and Kinross	5306.3	57.9	18.0	3.4	2.9
Renfrewshire	213.6	19.4	29.8	0.9	0.3
Scottish Borders	4731.3	8.9	0.3	0.6	0.1
Shetland Islands	1426.2	25.1	27.2	13.7	7.7
South Ayrshire	1194.8	19.1	7.4	5.7	2.1
South Lanarkshire	1773.7	0.4	0.0	0.0	0.0
Stirling	2149.3	84.5	20.5	0.0	0.0
West Dunbartonshire	163.8	8.2	5.2	1.1	0.6
West Lothian	428.5	0.0	0.2	0.2	0.2
Total	76959.1	1007.6	829.1	308.6	178.9

C.1.3.1 Exposure

Table C.1.3.1.1: Numbers of dwellings within each susceptibility category by local authority according to the UPSM.

Local Authority	Total Dwellings	UPSM				
		0-20	20-40	40-60	60-80	80-100
Aberdeen City	116,351	94,429	17,966	3,717	232	7
Aberdeenshire	113,335	102,254	5,368	3,124	1,740	849
Angus	54,916	38,340	8,720	6,002	1,546	308
Argyll and Bute	48,054	35,806	2,882	4,063	3,948	1,355
City of Edinburgh	242,095	211,625	17,559	8,638	3,130	1,143
Clackmannanshire	24,078	17,006	5,797	1,246	29	0
Dumfries and Galloway	74,311	59,405	9,548	3,301	1,571	486
Dundee City	74,768	69,855	1,281	1,472	1,362	798
East Ayrshire	57,951	57,951	0	0	0	0
East Dunbartonshire	44,863	43,826	1,037	0	0	0
East Lothian	45,940	33,709	3,129	4,423	3,272	1,407
East Renfrewshire	37,777	37,777	0	0	0	0
Falkirk	72,628	46,692	12,276	12,487	947	226
Fife	173,844	158,117	6,064	4,384	3,633	1,646
Glasgow City	305,085	231,824	51,500	21,761	0	0
Highland	115,332	87,733	11,249	11,563	3,181	1,606
Inverclyde	39,278	34,708	851	1,210	1,585	924
Midlothian	37,682	37,682	0	0	0	0
Moray	43,666	35,568	4,322	2,743	905	128
Na h-Eileanan an Iar	14,921	11,644	1,525	1,255	348	149
North Ayrshire	68,070	40,407	18,954	4,682	3,254	773
North Lanarkshire	151,865	151,865	0	0	0	0
Orkney Islands	10,952	9,230	574	796	280	72
Perth and Kinross	70,761	55,103	10,308	5,212	105	33
Renfrewshire	84,223	60,238	13,961	10,009	15	0
Scottish Borders	57,712	57,229	196	145	142	0
Shetland Islands	11,104	10,286	366	333	99	20
South Ayrshire	55,442	29,935	15,129	4,494	4,522	1,362
South Lanarkshire	147,472	144,306	2,871	295	0	0
Stirling	40,756	29,955	7,379	3,422	0	0
West Dunbartonshire	45,023	25,606	10,914	8,205	294	4
West Lothian	77,005	77,003	0	0	0	2
Total	2,557,260	2,137,114	241,726	128,982	36,140	13,298

Table C.1.3.2: Percentage of dwellings within each susceptibility category by local authority according to the UPSM.

Local Authority	Total Dwellings	UPSM (%)				
		0-20	20-40	40-60	60-80	80-100
Aberdeen City	116,351	81.2	15.4	3.2	0.2	0.0
Aberdeenshire	113,335	90.2	4.7	2.8	1.5	0.7
Angus	54,916	69.8	15.9	10.9	2.8	0.6
Argyll and Bute	48,054	74.5	6.0	8.5	8.2	2.8
City of Edinburgh	242,095	87.4	7.3	3.6	1.3	0.5
Clackmannanshire	24,078	70.6	24.1	5.2	0.1	0.0
Dumfries and Galloway	74,311	79.9	12.8	4.4	2.1	0.7
Dundee City	74,768	93.4	1.7	2.0	1.8	1.1
East Ayrshire	57,951	100.0	0.0	0.0	0.0	0.0
East Dunbartonshire	44,863	97.7	2.3	0.0	0.0	0.0
East Lothian	45,940	73.4	6.8	9.6	7.1	3.1
East Renfrewshire	37,777	100.0	0.0	0.0	0.0	0.0
Falkirk	72,628	64.3	16.9	17.2	1.3	0.3
Fife	173,844	91.0	3.5	2.5	2.1	0.9
Glasgow City	305,085	76.0	16.9	7.1	0.0	0.0
Highland	115,332	76.1	9.8	10.0	2.8	1.4
Inverclyde	39,278	88.4	2.2	3.1	4.0	2.4
Midlothian	37,682	100.0	0.0	0.0	0.0	0.0
Moray	43,666	81.5	9.9	6.3	2.1	0.3
Na h-Eileanan an Iar	14,921	78.0	10.2	8.4	2.3	1.0
North Ayrshire	68,070	59.4	27.8	6.9	4.8	1.1
North Lanarkshire	151,865	100.0	0.0	0.0	0.0	0.0
Orkney Islands	10,952	84.3	5.2	7.3	2.6	0.7
Perth and Kinross	70,761	77.9	14.6	7.4	0.1	0.0
Renfrewshire	84,223	71.5	16.6	11.9	0.0	0.0
Scottish Borders	57,712	99.2	0.3	0.3	0.2	0.0
Shetland Islands	11,104	92.6	3.3	3.0	0.9	0.2
South Ayrshire	55,442	54.0	27.3	8.1	8.2	2.5
South Lanarkshire	147,472	97.9	1.9	0.2	0.0	0.0
Stirling	40,756	73.5	18.1	8.4	0.0	0.0
West Dunbartonshire	45,023	56.9	24.2	18.2	0.7	0.0
West Lothian	77,005	100.0	0.0	0.0	0.0	0.0

Table C.1.3.1.3: Numbers of dwellings within each susceptibility category by local authority according to the CESM.

Local Authority	Total Dwellings	CESM				
		0-20	20-40	40-60	60-80	80-100
Aberdeen City	116,351	100,203	14,792	1,356	0	0
Aberdeenshire	113,335	105,313	5,096	2,158	524	244
Angus	54,916	40,906	9,124	4,691	173	22
Argyll and Bute	48,054	39,728	3,740	2,443	1,542	601
City of Edinburgh	242,095	216,040	24,165	1,798	75	17
Clackmannanshire	24,078	17,006	5,800	1,244	28	0
Dumfries and Galloway	74,311	60,144	10,398	2,968	551	250
Dundee City	74,768	71,283	2,086	1,063	297	39
East Ayrshire	57,951	57,951	0	0	0	0
East Dunbartonshire	44,863	43,826	1,037	0	0	0
East Lothian	45,940	35,361	6,048	3,854	470	207
East Renfrewshire	37,777	37,777	0	0	0	0
Falkirk	72,628	46,759	13,089	12,741	36	3
Fife	173,844	161,772	8,260	3,138	566	108
Glasgow City	305,085	267,547	37,538	0	0	0
Highland	115,332	92,695	14,267	5,598	1,811	961
Inverclyde	39,278	35,875	2,096	1,261	42	4
Midlothian	37,682	37,682	0	0	0	0
Moray	43,666	36,080	4,952	2,377	228	29
Na h-Eileanan an Iar	14,921	11,925	1,504	1,064	285	143
North Ayrshire	68,070	42,448	20,658	3,756	892	316
North Lanarkshire	151,865	151,865	0	0	0	0
Orkney Islands	10,952	9,376	955	299	250	72
Perth and Kinross	70,761	55,160	10,344	5,220	31	6
Renfrewshire	84,223	60,935	14,382	8,891	15	0
Scottish Borders	57,712	57,401	302	4	5	0
Shetland Islands	11,104	10,291	369	331	98	15
South Ayrshire	55,442	33,842	16,121	3,817	1,395	267
South Lanarkshire	147,472	147,468	4	0	0	0
Stirling	40,756	29,955	7,379	3,422	0	0
West Dunbartonshire	45,023	28,159	12,179	4,387	294	4
West Lothian	77,005	77,003	0	0	0	2
Total	2,557,260	2,219,776	246,685	77,881	9,608	3,310

Table C.1.3.1.4: Percentage of dwellings within each susceptibility category by local authority according to the CESM.

Local Authority	**Total Dwellings**	**CESM (%)**				
		0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	116,351	86.1	12.7	1.2	0.0	0.0
Aberdeenshire	113,335	92.9	4.5	1.9	0.5	0.2
Angus	54,916	74.5	16.6	8.5	0.3	0.0
Argyll and Bute	48,054	82.7	7.8	5.1	3.2	1.3
City of Edinburgh	242,095	89.2	10.0	0.7	0.0	0.0
Clackmannanshire	24,078	70.6	24.1	5.2	0.1	0.0
Dumfries and Galloway	74,311	80.9	14.0	4.0	0.7	0.3
Dundee City	74,768	95.3	2.8	1.4	0.4	0.1
East Ayrshire	57,951	100.0	0.0	0.0	0.0	0.0
East Dunbartonshire	44,863	97.7	2.3	0.0	0.0	0.0
East Lothian	45,940	77.0	13.2	8.4	1.0	0.5
East Renfrewshire	37,777	100.0	0.0	0.0	0.0	0.0
Falkirk	72,628	64.4	18.0	17.5	0.0	0.0
Fife	173,844	93.1	4.8	1.8	0.3	0.1
Glasgow City	305,085	87.7	12.3	0.0	0.0	0.0
Highland	115,332	80.4	12.4	4.9	1.6	0.8
Inverclyde	39,278	91.3	5.3	3.2	0.1	0.0
Midlothian	37,682	100.0	0.0	0.0	0.0	0.0
Moray	43,666	82.6	11.3	5.4	0.5	0.1
Na h-Eileanan an Iar	14,921	79.9	10.1	7.1	1.9	1.0
North Ayrshire	68,070	62.4	30.3	5.5	1.3	0.5
North Lanarkshire	151,865	100.0	0.0	0.0	0.0	0.0
Orkney Islands	10,952	85.6	8.7	2.7	2.3	0.7
Perth and Kinross	70,761	78.0	14.6	7.4	0.0	0.0
Renfrewshire	84,223	72.3	17.1	10.6	0.0	0.0
Scottish Borders	57,712	99.5	0.5	0.0	0.0	0.0
Shetland Islands	11,104	92.7	3.3	3.0	0.9	0.1
South Ayrshire	55,442	61.0	29.1	6.9	2.5	0.5
South Lanarkshire	147,472	100.0	0.0	0.0	0.0	0.0
Stirling	40,756	73.5	18.1	8.4	0.0	0.0
West Dunbartonshire	45,023	62.5	27.1	9.7	0.7	0.0
West Lothian	77,005	100.0	0.0	0.0	0.0	0.0

Table C.1.3.1.5: Value of properties classified with very high susceptibility (UPSM/CESM score =>80) within each local authority.

Local Authority	Average House Price	UPSM	CESM
Aberdeen City	£221,268	£1,548,876	£0
Aberdeenshire	£232,803	£197,649,747	£56,803,932
Angus	£162,354	£50,005,032	£3,571,788
Argyll and Bute	£149,928	£203,152,440	£90,106,728
City of Edinburgh	£235,402	£269,064,486	£4,001,834
Clackmannanshire	£140,162	£0	£0
Dumfries and Galloway	£139,054	£67,580,244	£34,763,500
Dundee City	£128,901	£102,862,998	£5,027,139
East Ayrshire	£115,845	£0	£0
East Dunbartonshire	£217,596	£0	£0
East Lothian	£223,429	£314,364,603	£46,249,803
East Renfrewshire	£234,651	£0	£0
Falkirk	£131,383	£29,692,558	£394,149
Fife	£143,075	£235,501,450	£15,452,100
Glasgow City	£138,885	£0	£0
Highland	£165,519	£265,823,514	£159,063,759
Inverclyde	£130,377	£120,468,348	£521,508
Midlothian	£178,405	£0	£0
Moray	£153,560	£19,655,680	£4,453,240
Na h-Eileanan an Iar	£98,160	£14,625,840	£14,036,880
North Ayrshire	£119,549	£92,411,377	£37,777,484
North Lanarkshire	£119,348	£0	£0
Orkney Islands	£129,075	£9,293,400	£9,293,400
Perth and Kinross	£192,154	£6,341,082	£1,152,924
Renfrewshire	£137,072	£0	£0
Scottish Borders	£164,448	£0	£0
Shetland Islands	£126,089	£2,521,780	£1,891,335
South Ayrshire	£152,219	£207,322,278	£40,642,473
South Lanarkshire	£130,436	£0	£0
Stirling	£197,690	£0	£0
West Dunbartonshire	£115,299	£461,196	£461,196
West Lothian	£153,458	£306,916	£306,916

Table C.1.3.1.6: Value of dwellings within each susceptibility category by local authority according to the UPSM.

Local Authority	**UPSM**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	£20,894,115,972	£3,975,300,888	£822,453,156	£51,334,176	£1,548,876
Aberdeenshire	£23,805,037,962	£1,249,686,504	£727,276,572	£405,077,220	£197,649,747
Angus	£6,224,652,360	£1,415,726,880	£974,448,708	£250,999,284	£50,005,032
Argyll and Bute	£5,368,321,968	£432,092,496	£609,157,464	£591,915,744	£203,152,440
City of Edinburgh	£49,816,948,250	£4,133,423,718	£2,033,402,476	£736,808,260	£269,064,486
Clackmannanshire	£2,383,594,972	£812,519,114	£174,641,852	£4,064,698	£0
Dumfries and Galloway	£8,260,502,870	£1,327,687,592	£459,017,254	£218,453,834	£67,580,244
Dundee City	£9,004,379,355	£165,122,181	£189,742,272	£175,563,162	£102,862,998
East Ayrshire	£6,713,333,595	£0	£0	£0	£0
East Dunbartonshire	£9,536,362,296	£225,647,052	£0	£0	£0
East Lothian	£7,531,568,161	£699,109,341	£988,226,467	£731,059,688	£314,364,603
East Renfrewshire	£8,864,410,827	£0	£0	£0	£0
Falkirk	£6,134,535,036	£1,612,857,708	£1,640,579,521	£124,419,701	£29,692,558
Fife	£22,622,589,775	£867,606,800	£627,240,800	£519,791,475	£235,501,450
Glasgow City	£32,196,876,240	£7,152,577,500	£3,022,276,485	£0	£0
Highland	£14,521,478,427	£1,861,923,231	£1,913,896,197	£526,515,939	£265,823,514
Inverclyde	£4,525,124,916	£110,950,827	£157,756,170	£206,647,545	£120,468,348
Midlothian	£6,722,657,210	£0	£0	£0	£0
Moray	£5,461,822,080	£663,686,320	£421,215,080	£138,971,800	£19,655,680
Na h-Eileanan an Iar	£1,142,975,040	£149,694,000	£123,190,800	£34,159,680	£14,625,840
North Ayrshire	£4,830,616,443	£2,265,931,746	£559,728,418	£389,012,446	£92,411,377
North Lanarkshire	£18,124,784,020	£0	£0	£0	£0
Orkney Islands	£1,191,362,250	£74,089,050	£102,743,700	£36,141,000	£9,293,400
Perth and Kinross	£10,588,261,862	£1,980,723,432	£1,001,506,648	£20,176,170	£6,341,082
Renfrewshire	£8,256,943,136	£1,913,662,192	£1,371,953,648	£2,056,080	£0
Scottish Borders	£9,411,194,592	£32,231,808	£23,844,960	£23,351,616	£0
Shetland Islands	£1,296,951,454	£46,148,574	£41,987,637	£12,482,811	£2,521,780
South Ayrshire	£4,556,675,765	£2,302,921,251	£684,072,186	£688,334,318	£207,322,278
South Lanarkshire	£18,822,697,416	£374,481,756	£38,478,620	£0	£0
Stirling	£5,921,803,950	£1,458,754,510	£676,495,180	£0	£0
West Dunbartonshire	£2,952,346,194	£1,258,373,286	£946,028,295	£33,897,906	£461,196
West Lothian	£11,816,726,374	£0	£0	£0	£306,916

Table C.1.3.1.7: Value of dwellings within each susceptibility category by local authority according to the CESM.

Local Authority	CESM				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	£22,171,717,404	£3,272,996,256	£300,039,408	£0	£0
Aberdeenshire	£24,517,182,339	£1,186,364,088	£502,388,874	£121,988,772	£56,803,932
Angus	£6,641,252,724	£1,481,317,896	£761,602,614	£28,087,242	£3,571,788
Argyll and Bute	£5,956,339,584	£560,730,720	£366,274,104	£231,188,976	£90,106,728
City of Edinburgh	£50,856,248,080	£5,688,489,330	£423,252,796	£17,655,150	£4,001,834
Clackmannanshire	£2,383,594,972	£812,939,600	£174,361,528	£3,924,536	£0
Dumfries and Galloway	£8,363,263,776	£1,445,883,492	£412,712,272	£76,618,754	£34,763,500
Dundee City	£9,188,449,983	£268,887,486	£137,021,763	£38,283,597	£5,027,139
East Ayrshire	£6,713,333,595	£0	£0	£0	£0
East Dunbartonshire	£9,536,362,296	£225,647,052	£0	£0	£0
East Lothian	£7,900,672,869	£1,351,298,592	£861,095,366	£105,011,630	£46,249,803
East Renfrewshire	£8,864,410,827	£0	£0	£0	£0
Falkirk	£6,143,337,697	£1,719,672,087	£1,673,950,803	£4,729,788	£394,149
Fife	£23,145,528,900	£1,181,799,500	£448,969,350	£80,980,450	£15,452,100
Glasgow City	£37,158,265,095	£5,213,465,130	£0	£0	£0
Highland	£15,342,783,705	£2,361,459,573	£926,575,362	£299,754,909	£159,063,759
Inverclyde	£4,677,274,875	£273,270,192	£164,405,397	£5,475,834	£521,508
Midlothian	£6,722,657,210	£0	£0	£0	£0
Moray	£5,540,444,800	£760,429,120	£365,012,120	£35,011,680	£4,453,240
Na h-Eileanan an Iar	£1,170,558,000	£147,632,640	£104,442,240	£27,975,600	£14,036,880
North Ayrshire	£5,074,615,952	£2,469,643,242	£449,026,044	£106,637,708	£37,777,484
North Lanarkshire	£18,124,784,020	£0	£0	£0	£0
Orkney Islands	£1,210,207,200	£123,266,625	£38,593,425	£32,268,750	£9,293,400
Perth and Kinross	£10,599,214,640	£1,987,640,976	£1,003,043,880	£5,956,774	£1,152,924
Renfrewshire	£8,352,482,320	£1,971,369,504	£1,218,707,152	£2,056,080	£0
Scottish Borders	£9,439,479,648	£49,663,296	£657,792	£822,240	£0
Shetland Islands	£1,297,581,899	£46,526,841	£41,735,459	£12,356,722	£1,891,335
South Ayrshire	£5,151,395,398	£2,453,922,499	£581,019,923	£212,345,505	£40,642,473
South Lanarkshire	£19,235,136,048	£521,744	£0	£0	£0
Stirling	£5,921,803,950	£1,458,754,510	£676,495,180	£0	£0
West Dunbartonshire	£3,246,704,541	£1,404,226,521	£505,816,713	£33,897,906	£461,196
West Lothian	£11,816,726,374	£0	£0	£0	£306,916

Table C.1.3.1.8: Area of SSSI within each susceptibility category by local authority according to the UPSM.

Local Authority	**SSSI UPSM (km^2)**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	0.36	0.00	0.00	0.01	0.00
Aberdeenshire	398.53	1.79	4.97	2.55	0.95
Angus	60.53	1.12	5.67	2.64	1.54
Argyll and Bute	547.51	15.60	18.34	9.70	4.36
City of Edinburgh	3.17	0.00	0.00	0.03	0.12
Clackmannanshire	5.18	0.00	0.04	0.01	0.02
Dumfries and Galloway	379.41	8.03	7.92	8.59	8.50
Dundee City	0.00	0.00	0.00	0.01	0.04
East Ayrshire	195.32	0.00	0.00	0.00	0.00
East Dunbartonshire	1.36	0.00	0.00	0.00	0.00
East Lothian	21.72	0.50	1.06	1.31	1.76
East Renfrewshire	0.91	0.00	0.00	0.00	0.00
Falkirk	4.56	0.16	0.17	0.37	0.59
Fife	12.95	2.16	4.09	1.47	2.24
Glasgow City	1.48	0.00	0.00	0.00	0.00
Highland	5,121.45	8.81	24.73	8.28	8.61
Inverclyde	39.43	0.00	0.00	0.00	0.03
Midlothian	11.87	0.00	0.00	0.00	0.00
Moray	154.71	13.68	7.73	2.82	1.79
Na h-Eileanan an Iar	226.07	21.78	39.89	14.74	6.78
North Ayrshire	251.49	0.01	1.27	0.37	0.62
North Lanarkshire	9.99	0.00	0.00	0.00	0.00
Orkney Islands	211.24	0.62	2.12	2.05	2.26
Perth and Kinross	640.28	0.01	0.02	0.22	0.87
Renfrewshire	23.82	0.00	0.85	0.07	0.04
Scottish Borders	281.23	0.15	0.07	0.13	0.01
Shetland Islands	182.68	2.32	3.10	1.70	0.74
South Ayrshire	48.34	0.06	0.26	0.54	0.38
South Lanarkshire	91.59	0.00	0.00	0.00	0.00
Stirling	176.37	6.29	0.14	0.00	0.00
West Dunbartonshire	7.40	0.00	0.03	0.06	0.17
West Lothian	11.36	0.00	0.00	0.00	0.02
Total	9,122.3	83.1	122.5	57.7	42.4

Table C.1.3.1.9: Area of SSSI within each susceptibility category by local authority according to the CESM.

Local Authority	SSSI CESM (km^2)				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	0.36	0.00	0.00	0.01	0.00
Aberdeenshire	398.65	2.26	5.62	1.66	0.59
Angus	60.57	1.36	6.62	2.33	0.62
Argyll and Bute	547.79	16.53	18.44	9.37	3.38
City of Edinburgh	3.17	0.02	0.07	0.04	0.03
Clackmannanshire	5.18	0.00	0.04	0.01	0.01
Dumfries and Galloway	379.41	8.20	10.92	11.59	2.32
Dundee City	0.00	0.01	0.02	0.02	0.01
East Ayrshire	195.32	0.00	0.00	0.00	0.00
East Dunbartonshire	1.36	0.00	0.00	0.00	0.00
East Lothian	21.73	0.82	1.46	1.68	0.66
East Renfrewshire	0.91	0.00	0.00	0.00	0.00
Falkirk	4.56	0.43	0.66	0.05	0.15
Fife	13.13	2.67	4.49	1.71	0.91
Glasgow City	1.48	0.00	0.00	0.00	0.00
Highland	5,121.55	10.21	25.17	10.02	4.94
Inverclyde	39.43	0.00	0.00	0.01	0.01
Midlothian	11.87	0.00	0.00	0.00	0.00
Moray	154.80	14.02	7.77	2.82	1.31
Na h-Eileanan an Iar	226.20	23.05	40.95	13.17	5.89
North Ayrshire	251.49	0.10	1.42	0.28	0.47
North Lanarkshire	9.99	0.00	0.00	0.00	0.00
Orkney Islands	211.24	0.63	2.22	1.99	2.21
Perth and Kinross	640.28	0.01	0.04	0.23	0.86
Renfrewshire	23.82	0.00	0.85	0.07	0.04
Scottish Borders	281.24	0.15	0.07	0.13	0.01
Shetland Islands	182.69	2.41	3.03	1.66	0.73
South Ayrshire	48.38	0.10	0.25	0.62	0.23
South Lanarkshire	91.59	0.00	0.00	0.00	0.00
Stirling	176.37	6.29	0.14	0.00	0.00
West Dunbartonshire	7.41	0.03	0.00	0.06	0.17
West Lothian	11.36	0.00	0.00	0.00	0.02
Total	9,123.3	89.3	130.2	59.5	25.6

Table C.1.3.1.10: Area of GCR within each susceptibility category by local authority according to the UPSM.

Local Authority	GCR UPSM (km^2)				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	0.01	0.00	0.00	0.01	0.00
Aberdeenshire	231.78	1.41	3.46	1.98	0.72
Angus	9.46	0.30	2.30	0.96	0.65
Argyll and Bute	171.53	4.20	5.06	3.03	1.11
City of Edinburgh	2.40	0.00	0.00	0.02	0.03
Clackmannanshire	0.33	0.00	0.00	0.00	0.00
Dumfries and Galloway	48.05	5.70	7.77	7.72	5.85
Dundee City	0.00	0.00	0.00	0.00	0.00
East Ayrshire	3.18	0.00	0.00	0.00	0.00
East Dunbartonshire	0.22	0.00	0.00	0.00	0.00
East Lothian	8.29	0.02	0.07	0.08	0.11
East Renfrewshire	0.13	0.00	0.00	0.00	0.00
Falkirk	0.00	0.00	0.00	0.00	0.00
Fife	10.95	0.50	0.23	0.48	1.06
Glasgow City	0.02	0.00	0.00	0.00	0.00
Highland	1,217.94	6.57	27.61	8.32	8.11
Inverclyde	2.38	0.00	0.00	0.00	0.00
Midlothian	2.43	0.00	0.00	0.00	0.00
Moray	114.13	23.73	8.30	3.49	2.43
Na h-Eileanan an Iar	31.81	10.72	18.22	7.65	2.90
North Ayrshire	23.98	0.01	0.05	0.10	0.36
North Lanarkshire	0.13	0.00	0.00	0.00	0.00
Orkney Islands	15.45	0.12	0.79	0.71	0.55
Perth and Kinross	54.52	0.01	0.00	0.00	0.00
Renfrewshire	0.08	0.00	0.00	0.00	0.00
Scottish Borders	7.83	0.00	0.02	0.02	0.01
Shetland Islands	57.92	0.18	0.52	0.33	0.17
South Ayrshire	2.02	0.00	0.03	0.06	0.03
South Lanarkshire	4.89	0.00	0.00	0.00	0.00
Stirling	35.07	1.00	0.00	0.00	0.00
West Dunbartonshire	0.70	0.00	0.00	0.00	0.00
West Lothian	0.17	0.00	0.00	0.00	0.00
Total	2,057.8	54.5	74.4	34.9	24.1

Table C.1.3.1.11: Area of GCR within each susceptibility category by local authority according to the CESM.

Local Authority	GCR CESM (km^2)				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	0.01	0.00	0.00	0.01	0.09
Aberdeenshire	231.86	1.90	3.80	1.31	0.44
Angus	9.49	0.57	2.55	0.65	0.31
Argyll and Bute	171.76	4.65	4.81	2.85	0.85
City of Edinburgh	2.40	0.00	0.02	0.02	0.07
Clackmannanshire	0.33	0.00	0.00	0.00	0.00
Dumfries and Galloway	48.05	5.94	10.80	9.53	0.71
Dundee City	0.00	0.00	0.00	0.00	0.00
East Ayrshire	3.18	0.00	0.00	0.00	0.01
East Dunbartonshire	0.22	0.00	0.00	0.00	0.00
East Lothian	8.29	0.02	0.07	0.08	0.13
East Renfrewshire	0.13	0.00	0.00	0.00	0.00
Fife	0.00	0.00	0.00	0.00	0.00
Fife	10.96	0.51	0.33	1.27	0.73
Glasgow City	0.02	0.00	0.00	0.00	0.00
Highland	1,218.04	8.91	26.93	9.40	4.66
Inverclyde	2.38	0.00	0.00	0.00	0.49
Midlothian	2.43	0.00	0.00	0.00	0.14
Moray	114.31	24.39	8.35	3.26	1.40
Na h-Eileanan an Iar	31.87	11.15	19.12	6.75	2.26
North Ayrshire	23.98	0.04	0.07	0.10	0.19
North Lanarkshire	0.13	0.00	0.00	0.00	0.00
Orkney Islands	15.45	0.14	0.88	0.66	0.49
Perth and Kinross	54.52	0.01	0.00	0.00	0.01
Renfrewshire	0.08	0.00	0.00	0.00	0.02
Scottish Borders	7.83	0.00	0.02	0.02	0.00
Shetland Islands	57.92	0.18	0.52	0.33	0.15
South Ayrshire	2.02	0.00	0.03	0.06	0.03
South Lanarkshire	4.89	0.00	0.00	0.00	0.00
Stirling	35.07	1.00	0.00	0.00	0.00
West Dunbartonshire	0.70	0.00	0.00	0.00	1.68
West Lothian	0.17	0.00	0.00	0.00	0.00
Total	2,058.5	59.4	78.3	36.3	14.9

Table C.1.3.1.12: Area of SAC within each susceptibility category by local authority according to the UPSM.

Local Authority	SAC UPSM (km^2)				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	0.75	0.01	0.13	0.00	0.00
Aberdeenshire	349.23	0.45	0.51	0.25	0.13
Angus	47.97	1.11	4.42	1.48	0.90
Argyll and Bute	148.35	4.69	8.43	3.15	0.81
City of Edinburgh	0.00	0.00	0.00	0.00	0.00
Clackmannanshire	0.00	0.00	0.00	0.00	0.00
Dumfries and Galloway	128.94	6.03	4.79	5.51	6.40
Dundee City	0.00	0.00	0.00	0.00	0.05
East Ayrshire	27.41	0.00	0.00	0.00	0.00
East Dunbartonshire	0.00	0.00	0.00	0.00	0.00
East Lothian	0.00	0.00	0.00	0.00	0.00
East Renfrewshire	0.00	0.00	0.00	0.00	0.00
Falkirk	0.03	0.00	0.00	0.00	0.00
Fife	0.38	0.03	0.34	0.38	1.02
Glasgow City	0.00	0.00	0.00	0.00	0.00
Highland	3,813.59	3.87	16.07	5.02	4.91
Inverclyde	0.00	0.00	0.00	0.00	0.00
Midlothian	0.57	0.00	0.00	0.00	0.00
Moray	142.95	2.48	2.51	0.83	1.03
Na h-Eileanan an Iar	470.11	13.89	26.43	10.04	5.13
North Ayrshire	1.43	0.00	0.00	0.00	0.00
North Lanarkshire	2.10	0.00	0.00	0.00	0.00
Orkney Islands	109.08	0.18	0.22	0.16	0.24
Perth and Kinross	347.52	0.14	0.49	0.19	0.77
Renfrewshire	0.00	0.00	0.00	0.00	0.00
Scottish Borders	122.35	0.15	0.05	0.12	0.01
Shetland Islands	85.66	1.72	1.80	1.11	0.50
South Ayrshire	15.73	0.00	0.00	0.00	0.00
South Lanarkshire	10.97	0.00	0.00	0.00	0.00
Stirling	84.98	5.64	0.44	0.00	0.00
West Dunbartonshire	0.47	0.00	0.00	0.00	0.00
West Lothian	1.46	0.00	0.00	0.00	0.00
Total	5,912.0	40.4	66.6	28.2	21.9

Table C.1.3.1.13: Area of SAC within each susceptibility category by local authority according to the CESM.

Local Authority	SAC CESM (km^2)				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	0.78	0.11	0.00	0.00	0.00
Aberdeenshire	349.31	0.58	0.46	0.14	0.09
Angus	48.00	1.33	5.14	1.07	0.35
Argyll and Bute	148.40	4.89	8.72	2.78	0.64
City of Edinburgh	0.00	0.00	0.00	0.00	0.00
Clackmannanshire	0.00	0.00	0.00	0.00	0.00
Dumfries and Galloway	128.94	6.20	6.90	7.75	1.88
Dundee City	0.00	0.00	0.03	0.01	0.01
East Ayrshire	27.41	0.00	0.00	0.00	0.00
East Dunbartonshire	0.00	0.00	0.00	0.00	0.00
East Lothian	0.00	0.00	0.00	0.00	0.00
East Renfrewshire	0.00	0.00	0.00	0.00	0.00
Falkirk	0.03	0.00	0.00	0.00	0.00
Fife	0.40	0.12	0.44	0.92	0.26
Glasgow City	0.00	0.00	0.00	0.00	0.00
Highland	3,813.62	5.00	15.50	5.79	3.54
Inverclyde	0.00	0.00	0.00	0.00	0.00
Midlothian	0.57	0.00	0.00	0.00	0.00
Moray	142.95	2.52	2.60	1.00	0.72
Na h-Eileanan an Iar	470.14	14.24	27.06	9.29	4.87
North Ayrshire	1.43	0.00	0.00	0.00	0.00
North Lanarkshire	2.10	0.00	0.00	0.00	0.00
Orkney Islands	109.08	0.18	0.22	0.16	0.24
Perth and Kinross	347.52	0.14	0.50	0.20	0.76
Renfrewshire	0.00	0.00	0.00	0.00	0.00
Scottish Borders	122.35	0.15	0.05	0.12	0.01
Shetland Islands	85.66	1.72	1.80	1.11	0.50
South Ayrshire	15.73	0.00	0.00	0.00	0.00
South Lanarkshire	10.97	0.00	0.00	0.00	0.00
Stirling	84.98	5.64	0.44	0.00	0.00
West Dunbartonshire	0.47	0.00	0.00	0.00	0.00
West Lothian	1.46	0.00	0.00	0.00	0.00
Total	5,912.3	42.8	69.9	30.3	13.9

Table C.1.3.1.14: Area of SPA within each susceptibility category by local authority according to the UPSM.

Local Authority	SPA UPSM (km^2)				
	0-20	20-40	40-60	60-80	80-100
Aberdeen City	0.00	0.00	0.00	0.00	0.00
Aberdeenshire	1,030.83	1.37	3.26	0.62	0.22
Angus	349.57	0.04	1.07	0.61	0.12
Argyll and Bute	1,325.80	12.44	11.10	5.91	3.08
City of Edinburgh	0.03	0.00	0.00	0.03	0.12
Clackmannanshire	0.00	0.00	0.04	0.01	0.02
Dumfries and Galloway	167.72	3.94	4.45	5.47	6.21
Dundee City	0.00	0.00	0.00	0.01	0.04
East Ayrshire	166.17	0.00	0.00	0.00	0.00
East Dunbartonshire	0.00	0.00	0.00	0.00	0.00
East Lothian	0.29	0.02	0.42	0.43	0.55
East Renfrewshire	0.00	0.00	0.00	0.00	0.00
Falkirk	0.97	0.00	0.03	0.25	0.57
Fife	1.44	0.04	0.46	0.48	1.26
Glasgow City	0.00	0.00	0.00	0.00	0.00
Highland	4,491.05	2.09	16.05	6.49	8.01
Inverclyde	36.58	0.00	0.00	0.00	0.02
Midlothian	5.04	0.00	0.00	0.00	0.00
Moray	221.55	1.02	2.79	1.10	0.34
Na h-Eileanan an Iar	795.84	20.22	33.12	13.86	6.07
North Ayrshire	139.63	0.00	0.00	0.00	0.00
North Lanarkshire	5.09	0.00	0.00	0.00	0.00
Orkney Islands	163.04	0.30	0.81	0.72	1.28
Perth and Kinross	668.65	0.00	0.03	0.23	0.88
Renfrewshire	20.67	0.00	0.86	0.07	0.04
Scottish Borders	40.13	0.00	0.00	0.01	0.01
Shetland Islands	145.86	0.47	0.73	0.32	0.16
South Ayrshire	26.98	0.00	0.00	0.01	0.01
South Lanarkshire	44.56	0.00	0.00	0.00	0.00
Stirling	51.75	0.00	0.07	0.00	0.00
West Dunbartonshire	2.04	0.00	0.03	0.05	0.16
West Lothian	0.00	0.00	0.00	0.00	0.01
Total	9,901.3	41.9	75.3	36.7	29.2

Table C.1.3.1.15: Area of SPA within each susceptibility category by local authority according to the CESM.

Local Authority	**SPA CESM (km^2)**				
	0-20	**20-40**	**40-60**	**60-80**	**80-100**
Aberdeen City	0.00	0.00	0.00	0.00	0.00
Aberdeenshire	1,030.91	1.59	3.23	0.49	0.09
Angus	349.57	0.04	1.08	0.67	0.05
Argyll and Bute	1,326.03	13.17	10.91	5.96	2.27
City of Edinburgh	0.03	0.01	0.06	0.04	0.03
Clackmannanshire	0.00	0.00	0.05	0.01	0.01
Dumfries and Galloway	167.72	4.10	6.55	7.74	1.67
Dundee City	0.00	0.01	0.02	0.01	0.01
East Ayrshire	166.17	0.00	0.00	0.00	0.00
East Dunbartonshire	0.00	0.00	0.00	0.00	0.00
East Lothian	0.29	0.12	0.74	0.45	0.10
East Renfrewshire	0.00	0.00	0.00	0.00	0.00
Falkirk	0.97	0.16	0.51	0.05	0.13
Fife	1.46	0.18	0.66	1.04	0.34
Glasgow City	0.00	0.00	0.00	0.00	0.00
Highland	4,491.14	3.31	16.37	8.52	4.35
Inverclyde	36.58	0.00	0.00	0.01	0.01
Midlothian	5.04	0.00	0.00	0.00	0.00
Moray	221.55	1.06	2.92	1.14	0.13
Na h-Eileanan an Iar	796.04	20.93	33.97	12.68	5.50
North Ayrshire	139.63	0.00	0.00	0.00	0.00
North Lanarkshire	5.09	0.00	0.00	0.00	0.00
Orkney Islands	163.04	0.30	0.82	0.73	1.28
Perth and Kinross	668.65	0.00	0.04	0.24	0.87
Renfrewshire	20.67	0.00	0.86	0.07	0.04
Scottish Borders	40.13	0.00	0.00	0.01	0.01
Shetland Islands	145.86	0.47	0.73	0.32	0.16
South Ayrshire	26.98	0.00	0.00	0.01	0.01
South Lanarkshire	44.56	0.00	0.00	0.00	0.00
Stirling	51.75	0.00	0.07	0.00	0.00
West Dunbartonshire	2.04	0.03	0.00	0.05	0.16
West Lothian	0.00	0.00	0.00	0.00	0.01
Total	9,901.9	45.5	79.6	40.2	17.2

Table C.1.3.1.16: Number of key assets within each susceptibility category according to the UPSM.

Asset Type	Asset	UPSM				
		0-20	20-40	40-60	60-80	80-100
Emergency Services	Ambulance Station	100	8	5	2	1
	Fire Station	206	25	29	8	3
	Police Station	36	10	6	2	1
Local Economy	Camping	74	5	8	6	5
	Caravanning	414	34	44	59	30
	Hotel	1402	171	146	103	35
	Distillery	113	9	11	1	1
	General Commercial	38805	8905	6404	1654	437
	Shopping	9782	2386	1765	461	132
Key Infrastructure	Oil Distribution	11	1	2	1	0
	Oil Refining	39	5	5	2	1
	Gas Production and Distribution	30	8	4	0	1
	Electricity Generating	1850	35	14	10	4
	Electricity Sub Station	15627	1871	1340	386	167
	Sewage Treatment	456	25	45	16	12
Education	Pre School Education	495	55	35	5	1
	Nursery	152	16	4	2	0
	Primary School	1556	136	59	20	2
	Secondary School	33	5	2	0	0
	High School	173	10	8	0	0
	School	472	39	24	8	2
	Further Education	1	1	0	0	0
	Higher Education	165	30	17	4	1
	University	221	30	6	0	2
Health	Hospital	144	11	5	2	0
	Hospice	44	9	9	2	1
	Nursing Home	436	56	35	13	2
	Mental Health Centre	20	6	6	0	0
Transportation	Jetty	768	47	112	70	71
	Pier	471	17	72	63	112

Table C.1.3.1.17: Number of key assets within each susceptibility category according to the CESM

Asset Type	Asset	CESM				
		0-20	20-40	40-60	60-80	80-100
Emergency Services	Ambulance Station	101	11	4	0	0
	Fire Station	218	30	17	4	2
	Police Station	42	8	2	3	0
Local Economy	Camping	75	4	9	7	3
	Caravanning	424	37	56	47	17
	Hotel	1501	207	94	37	18
	Distillery	117	10	6	2	0
	General Commercial	44265	8373	3247	247	73
	Shopping	11220	2381	840	60	25
Key Infrastructure	Oil Distribution	11	2	1	1	0
	Oil Refining	39	9	4	0	0
	Gas Production and Distribution	33	8	2	0	0
	Electricity Generating	1856	33	13	9	2
	Electricity Sub Station	16311	2001	924	123	32
	Sewage Treatment	462	28	43	15	6
Education	Pre School Education	515	50	24	1	1
	Nursery	155	16	2	1	0
	Primary School	1585	140	39	8	1
	Secondary School	34	6	0	0	0
	High School	174	10	7	0	0
	School	484	40	18	2	1
	Further Education	1	1	0	0	0
	Higher Education	179	26	11	1	0
	University	223	29	7	0	0
Health	Hospital	147	14	0	1	0
	Hospice	51	11	3	0	0
	Nursing Home	458	57	24	3	0
	Mental Health Centre	21	7	4	0	0
Transportation	Jetty	773	68	121	50	56
	Pier	473	33	119	60	50

C.2 Socioeconomic Vulnerability

C.2.1 CEVM Outputs

Table C.2.1.1: The raw socioeconomic vulnerability index scores for the 11 indictors used within the CEVM.

Experian Group	Income	Poor Health	Elderly	Single Parents with Dependent Children	No Savings	Secured/Unsecured Loans	No Access to Vehicle	Homeowners	Education Level	Dwelling Density	Property Value
1	29.1	46.7	114.1	33.7	58.2	59.6	33.8	164.3	90.7	135.3	34.2
2	58.1	57.5	148.8	30.7	57.5	62.0	18.6	165.3	94.5	134.8	56.6
3	33.2	58.2	109.8	46.6	71.3	77.5	25.8	162.9	155.0	105.6	53.7
4	36.5	50.9	83.0	42.3	76.1	113.9	33.9	164.9	110.4	162.0	72.8
5	39.4	52.9	59.7	65.5	88.9	111.6	22.6	164.4	159.2	136.1	95.9
6	20.4	41.0	30.5	49.2	85.1	139.0	25.8	164.0	190.0	191.8	63.3
7	26.9	57.7	38.2	94.2	78.2	137.2	12.1	161.7	104.5	147.2	96.3
8	49.8	100.1	75.0	98.6	120.5	121.9	41.7	134.1	132.3	140.6	82.7
9	33.2	32.6	17.2	37.2	74.7	109.7	15.0	27.7	139.3	213.6	119.0
10	64.5	75.7	144.4	38.3	75.9	78.0	36.0	161.9	77.0	231.6	80.2
11	69.5	65.5	128.5	44.2	61.9	72.0	35.8	165.1	95.9	121.8	83.8
12	79.2	76.6	92.9	70.2	94.7	105.6	36.7	158.6	70.2	149.4	110.7
13	153.7	87.4	129.6	60.6	90.2	98.9	57.2	104.8	189.0	331.0	127.9
14	45.3	55.8	81.4	38.7	63.1	77.8	19.2	161.2	143.7	834.9	56.7
15	77.5	68.8	86.0	51.6	84.3	95.0	9.4	150.4	158.8	1076.0	82.5
16	89.0	68.3	88.6	38.4	78.0	118.8	25.5	148.0	143.7	7007.0	78.3
17	136.0	77.7	142.1	44.4	83.5	83.4	42.5	154.3	143.7	1336.2	72.3
18	89.0	72.1	110.7	51.8	83.5	95.8	23.1	142.3	128.5	1248.8	132.3
19	62.8	54.4	71.8	42.3	78.6	71.7	132.9	142.2	0.0	47.7	47.8
20	105.8	77.3	34.6	70.8	86.5	26.6	237.7	69.4	0.0	42.6	103.2
21	133.5	44.9	34.6	36.3	97.4	30.5	188.3	40.3	0.0	44.2	71.8
22	111.4	45.1	58.2	80.3	105.9	92.9	171.5	30.0	0.0	55.4	78.3
23	79.7	69.7	36.8	52.0	82.8	103.3	214.7	99.3	0.0	40.3	96.1
24	71.3	67.5	36.8	45.0	92.9	118.1	190.2	108.8	0.0	41.9	106.3
25	156.1	130.9	69.7	164.3	135.1	121.8	181.2	72.5	177.9	55.0	139.2
26	104.7	125.6	73.4	124.1	118.3	112.4	162.7	53.1	124.5	65.0	158.3
27	85.5	74.6	59.9	93.3	97.7	153.7	121.0	137.5	189.0	106.1	137.0
28	63.9	83.6	110.2	63.4	84.6	116.1	66.8	150.4	171.2	93.4	92.3
29	158.3	117.1	240.5	36.4	72.7	59.0	124.9	137.1	226.8	91.3	89.9
30	127.4	115.6	147.5	87.4	82.8	93.5	87.4	127.2	311.2	119.5	146.5
31	124.3	119.2	132.6	92.6	105.6	124.5	63.4	108.0	283.5	153.0	186.9
32	97.7	96.1	93.6	135.3	113.8	128.8	56.8	124.2	240.6	139.9	167.6
33	136.9	167.7	123.7	189.0	126.2	105.4	154.9	76.1	65.4	97.6	195.4
34	94.3	112.3	100.1	155.1	117.5	149.0	102.9	102.1	98.9	90.5	143.0
35	145.3	113.7	98.2	151.0	140.2	121.3	121.0	28.8	81.4	156.0	212.8
36	145.4	114.0	61.0	338.6	147.3	125.6	115.0	36.1	103.2	127.5	202.3

Experian Group	Income	Poor Health	Elderly	Single Parents with Dependent Children	No Savings	Secured/Unsecured Loans	No Access to Vehicle	Homeowners	Education Level	Dwelling Density	Property Value
37	175.6	126.9	53.7	353.6	160.8	117.5	179.3	7.4	0.0	105.9	231.2
38	94.2	165.4	60.2	438.0	151.4	99.5	168.2	16.3	0.0	80.1	203.1
39	155.0	230.7	154.0	144.9	145.5	78.4	227.3	25.1	0.0	63.2	189.2
40	171.3	195.6	75.8	238.7	135.9	70.7	222.0	2.5	0.0	67.3	202.1
41	172.8	166.8	178.5	84.6	113.8	146.4	116.6	29.0	0.0	106.5	191.6
42	170.6	167.8	116.2	128.3	140.6	100.2	205.6	11.0	0.0	99.8	231.7
43	158.7	233.9	183.8	84.9	107.6	91.3	152.6	3.3	0.0	75.3	236.9
44	167.1	237.8	314.1	33.2	132.8	84.3	120.2	6.3	0.0	90.8	185.3

Table C.2.1.2: The index scores weighted using Gini coefficients and the average index score for each Experian Mosaic Group. Socioeconomic vulnerability increases with an increase in index score.

Experian Group	Income	Poor Health	Elderly	Single Parents with Dependent Children	No Savings	Secured/Unsecured Loans	No Access to Vehicle	Homeowners	Education Level	Dwelling Density	Property Value	Average Weighted Index Score
1	12.2	46.9	19.9	45.6	16.9	25.2	24.0	22.8	70.7	43.1	10.5	30.7
2	24.4	48.9	24.5	59.4	15.4	24.9	25.0	12.5	71.1	42.9	17.4	33.3
3	13.9	80.1	24.8	43.8	23.3	30.9	31.3	17.4	70.1	33.7	16.5	35.1
4	15.3	57.1	21.7	33.1	21.1	32.9	46.0	22.9	70.9	51.6	22.4	35.9
5	16.5	82.3	22.6	23.8	32.7	38.5	45.1	15.2	70.7	43.4	29.5	38.2
6	8.5	98.3	17.5	12.2	24.6	36.8	56.1	17.4	70.5	61.1	19.5	38.4
7	11.3	54.0	24.6	15.3	47.1	33.9	55.4	8.2	69.5	46.9	29.6	36.0
8	20.9	68.4	42.7	30.0	49.3	52.2	49.2	28.1	57.7	44.8	25.4	42.6
9	13.9	72.0	13.9	6.9	18.6	32.3	44.3	10.1	11.9	68.1	36.6	29.9
10	27.0	39.8	32.3	57.6	19.1	32.9	31.5	24.3	69.6	73.8	24.6	39.3
11	29.1	49.6	27.9	51.3	22.1	26.8	29.1	24.1	71.0	38.8	25.8	36.0
12	33.2	36.3	32.6	37.1	35.1	41.0	42.6	24.7	68.2	47.6	34.0	39.3
13	64.4	97.7	37.2	51.7	30.3	39.1	39.9	38.5	45.1	105.5	39.3	53.5
14	19.0	74.3	23.8	32.5	19.3	27.3	31.4	12.9	69.3	266.0	17.4	53.9
15	32.5	82.1	29.3	34.3	25.8	36.5	38.4	6.3	64.7	342.9	25.3	65.3
16	37.3	74.3	29.1	35.4	19.2	33.8	48.0	17.2	63.7	2232.8	24.1	237.7
17	57.0	74.3	33.1	56.7	22.2	36.1	33.7	28.6	66.4	425.8	22.2	77.8
18	37.3	66.5	30.7	44.2	25.9	36.1	38.7	15.5	61.2	397.9	40.7	72.2
19	26.3	0.0	23.2	28.7	21.1	34.0	29.0	89.5	61.2	15.2	14.7	31.2
20	44.3	0.0	32.9	13.8	35.4	37.4	10.7	160.1	29.9	13.6	31.7	37.3
21	55.9	0.0	19.1	13.8	18.2	42.1	12.3	126.8	17.3	14.1	22.1	31.1
22	46.7	0.0	19.2	23.2	40.1	45.8	37.5	115.5	12.9	17.7	24.1	34.8
23	33.4	0.0	29.7	14.7	26.0	35.8	41.7	144.6	42.7	12.8	29.5	37.4
24	29.9	0.0	28.8	14.7	22.5	40.2	47.7	128.1	46.8	13.3	32.7	36.8
25	65.4	92.0	55.8	27.8	82.1	58.5	49.2	122.1	31.2	17.5	42.8	58.6
26	43.9	64.4	53.5	29.3	62.0	51.2	45.4	109.6	22.8	20.7	48.6	50.1
27	35.8	97.7	31.8	23.9	46.6	42.3	62.0	81.5	59.1	33.8	42.1	50.6
28	26.8	88.5	35.6	44.0	31.7	36.6	46.9	45.0	64.7	29.8	28.4	43.4
29	66.3	117.3	49.9	96.0	18.2	31.5	23.8	84.2	59.0	29.1	27.6	54.8
30	53.4	160.9	49.2	58.9	43.7	35.9	37.8	58.8	54.7	38.1	45.0	57.9
31	52.1	146.6	50.8	52.9	46.3	45.7	50.2	42.7	46.4	48.8	57.4	58.2
32	40.9	124.4	40.9	37.4	67.6	49.3	52.0	38.3	53.4	44.6	51.5	54.6
33	57.3	33.8	71.4	49.4	94.4	54.6	42.5	104.4	32.7	31.1	60.0	57.4
34	39.5	51.1	47.8	40.0	77.5	50.8	60.2	69.3	43.9	28.9	43.9	50.3
35	60.9	42.1	48.5	39.2	75.4	60.7	49.0	81.5	12.4	49.7	65.4	53.2
36	60.9	53.4	48.6	24.4	169.2	63.7	50.7	77.5	15.5	40.6	62.2	60.6
37	73.6	0.0	54.1	21.4	176.7	69.6	47.4	120.8	3.2	33.8	71.0	61.0
38	39.4	0.0	70.5	24.0	218.8	65.5	40.2	113.3	7.0	25.5	62.4	60.6
39	65.0	0.0	98.3	61.5	72.4	63.0	31.7	153.1	10.8	20.2	58.1	57.6
40	71.8	0.0	83.3	30.3	119.2	58.8	28.5	149.5	1.1	21.4	62.1	56.9

Experian Group	Income	Poor Health	Elderly	Single Parents with Dependent Children	No Savings	Secured/Unsecured Loans	No Access to Vehicle	Homeowners	Education Level	Dwelling Density	Property Value	Average Weighted Index Score
41	72.4	0.0	71.1	71.3	42.3	49.3	59.1	78.5	12.5	33.9	58.9	49.9
42	71.5	0.0	71.5	46.4	64.1	60.9	40.5	138.5	4.8	31.8	71.2	54.6
43	66.5	0.0	99.7	73.4	42.4	46.6	36.9	102.8	1.4	24.0	72.8	51.5
44	70.0	0.0	101.3	125.4	16.6	57.5	34.0	80.9	2.7	28.9	56.9	52.2

Table C.2.1.3: Number of dwellings within each vulnerability category per local authority.

Local Authority	Total Dwellings	Vulnerability				
		Very Low	Low	Moderate	High	Very High
Glasgow City	305,085	62,099	41,763	44,101	79,621	77,501
Highland	115,332	7,246	20,004	26,434	14,459	47,189
North Lanarkshire	151,865	16,430	30,569	25,502	37,194	42,170
Fife	173,844	28,299	41,426	34,953	28,689	40,477
Dumfries and Galloway	74,311	3,848	13,471	16,279	8,073	32,640
South Lanarkshire	147,472	22,828	34,935	24,104	33,759	31,846
Aberdeenshire	113,335	13,305	28,294	19,516	23,165	29,055
City of Edinburgh	242,095	85,972	65,553	41,155	24,243	25,172
West Lothian	77,005	10,060	18,180	14,324	15,468	18,973
Aberdeen City	116,351	40,559	19,902	22,103	15,343	18,444
North Ayrshire	68,070	7,191	14,722	12,981	14,792	18,384
Scottish Borders	57,712	4,235	10,350	15,357	9,439	18,331
East Ayrshire	57,951	4,621	13,678	12,119	9,697	17,836
Perth and Kinross	70,761	9,404	15,461	16,705	11,435	17,756
Argyll and Bute	48,054	5,420	7,965	10,055	7,502	17,112
Renfrewshire	84,223	15,779	19,479	16,793	15,219	16,953
Falkirk	72,628	9,254	18,705	14,420	13,720	16,529
Dundee City	74,768	18,156	13,006	14,729	12,896	15,981
Angus	54,916	6,630	14,360	12,729	7,029	14,168
West Dunbartonshire	45,023	3,948	9,253	8,475	10,452	12,895
South Ayrshire	55,442	11,787	12,384	9,120	9,328	12,823
Na h-Eileanan an Iar	14,921	58	672	1,225	480	12,486
Moray	43,666	4,964	10,512	10,254	5,645	12,291
East Lothian	45,940	6,861	10,729	6,953	9,542	11,855
Inverclyde	39,278	4,773	7,704	8,538	9,427	8,836
Midlothian	37,682	6,000	7,992	5,082	9,917	8,691
Stirling	40,756	11,806	7,621	5,845	7,081	8,403
Orkney Islands	10,952	92	914	2,063	560	7,323
Shetland Islands	11,104	406	856	1,645	990	7,207
Clackmannanshire	24,078	3,045	5,719	5,271	3,789	6,254
East Dunbartonshire	44,863	20,146	10,005	4,120	6,334	4,258
East Renfrewshire	37,777	16,108	9,246	2,928	5,357	4,138
Total	2,557,260	461,330	535,430	465,878	460,645	633,977

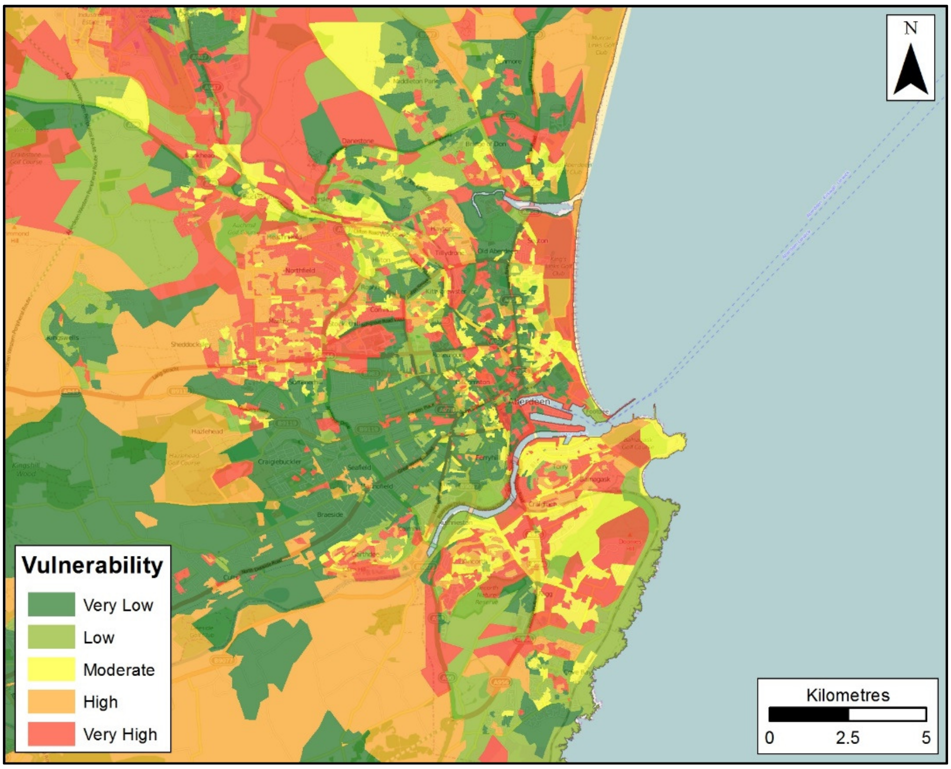

Figure C.2.1.1: Socioeconomic vulnerability to coastal erosion in Aberdeen. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

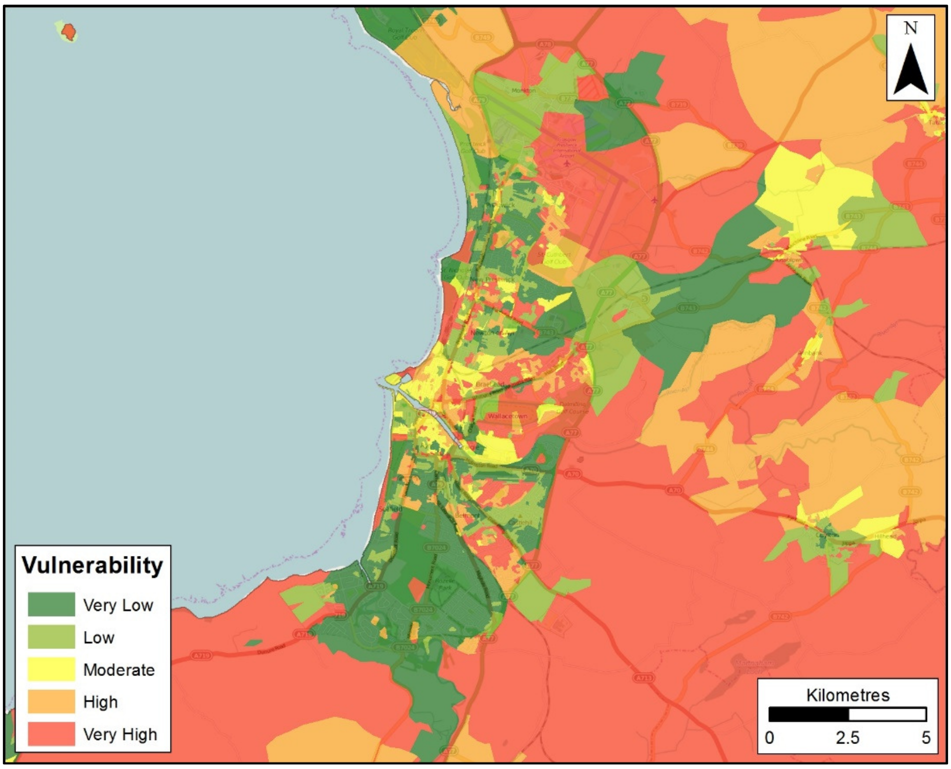

Figure C.2.1.2: Socioeconomic vulnerability to coastal erosion in Ayr. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

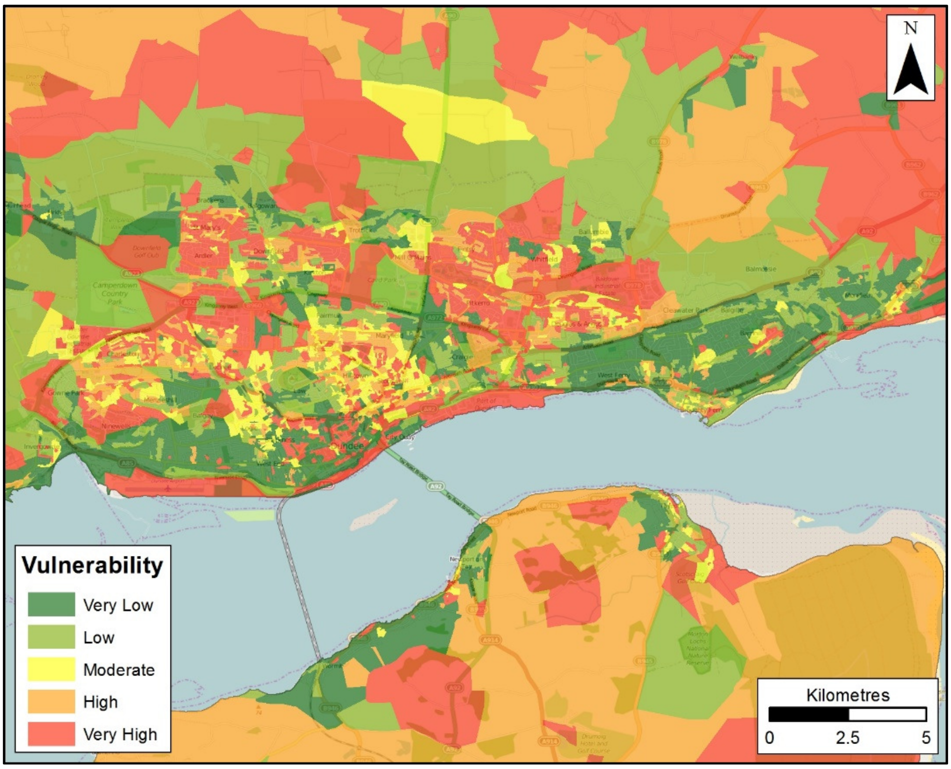

Figure C2.1.3: Socioeconomic vulnerability to coastal erosion in Dundee. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

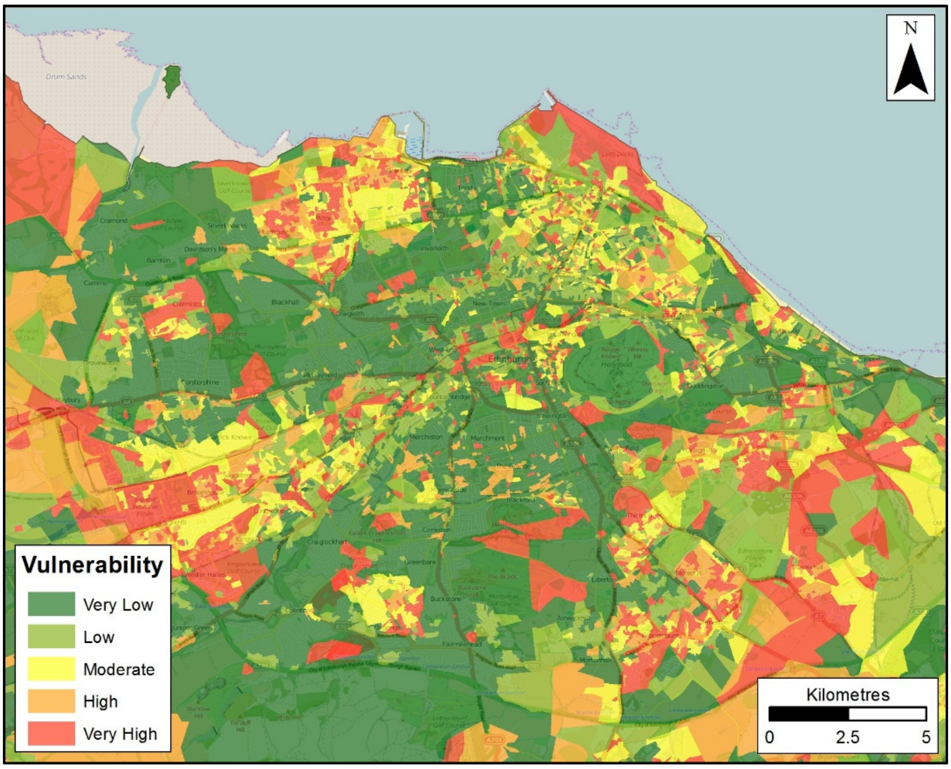

Figure C2.1.4: Socioeconomic vulnerability to coastal erosion in Edinburgh. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

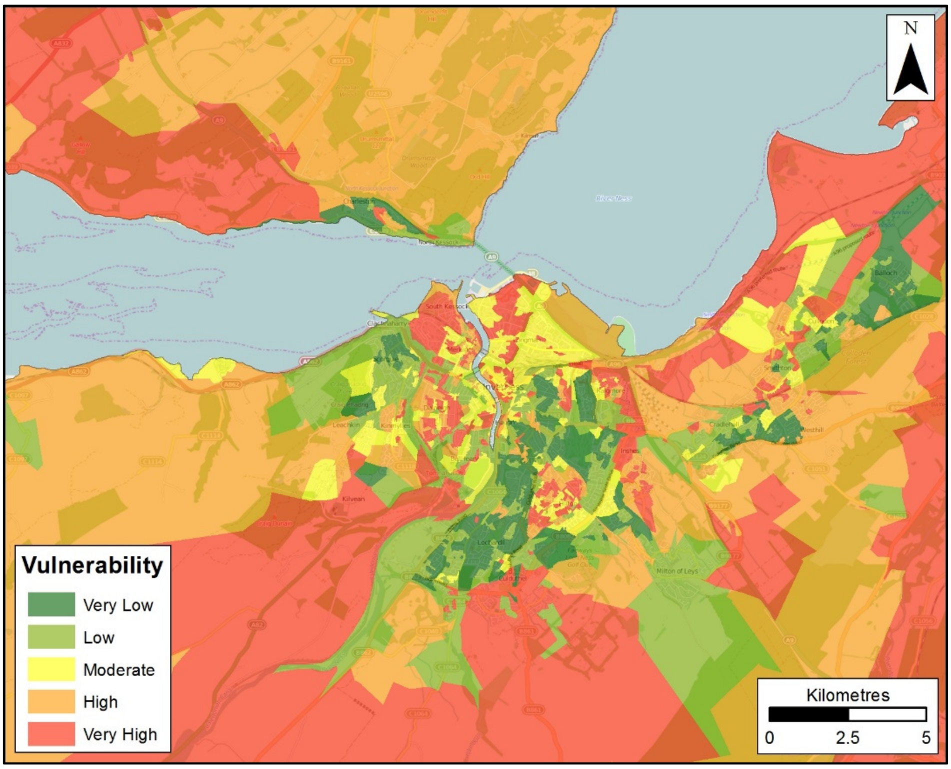

Figure C2.1.5: Socioeconomic vulnerability to coastal erosion in Inverness. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

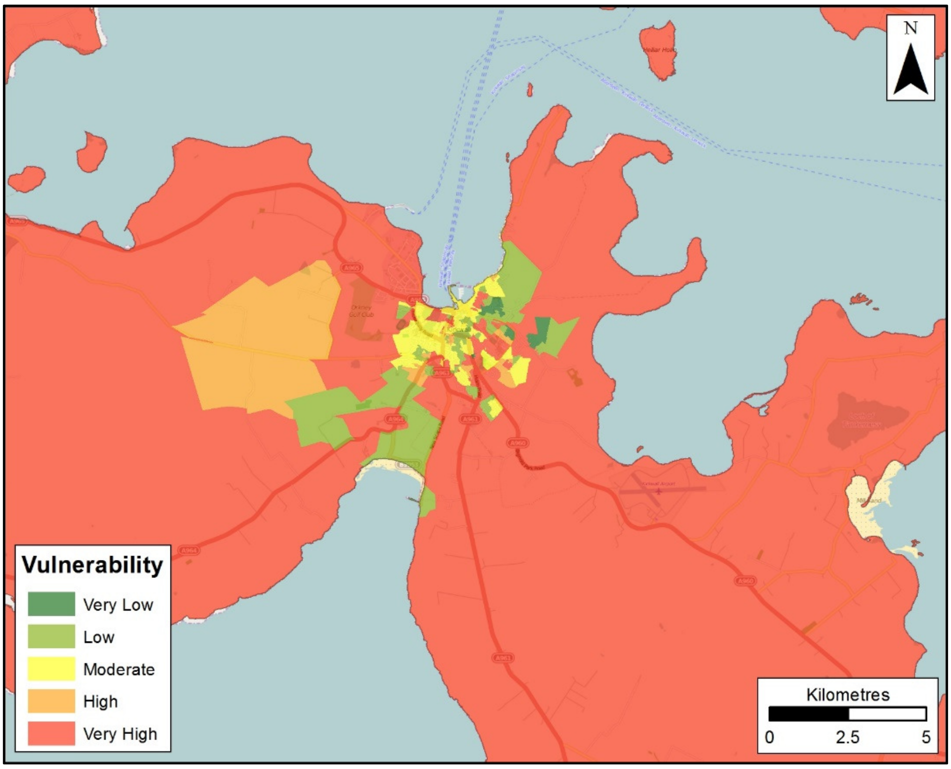

Figure C2.1.6: Socioeconomic vulnerability to coastal erosion in Kirkwall. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

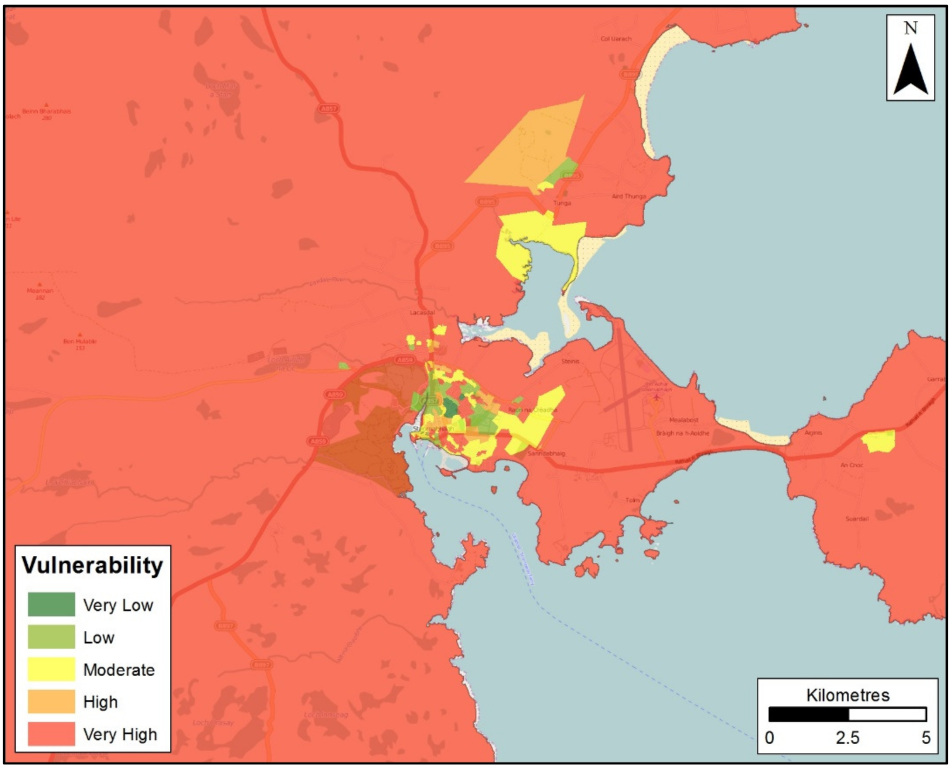

Figure C2.1.7: Socioeconomic vulnerability to coastal erosion in Stornoway. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

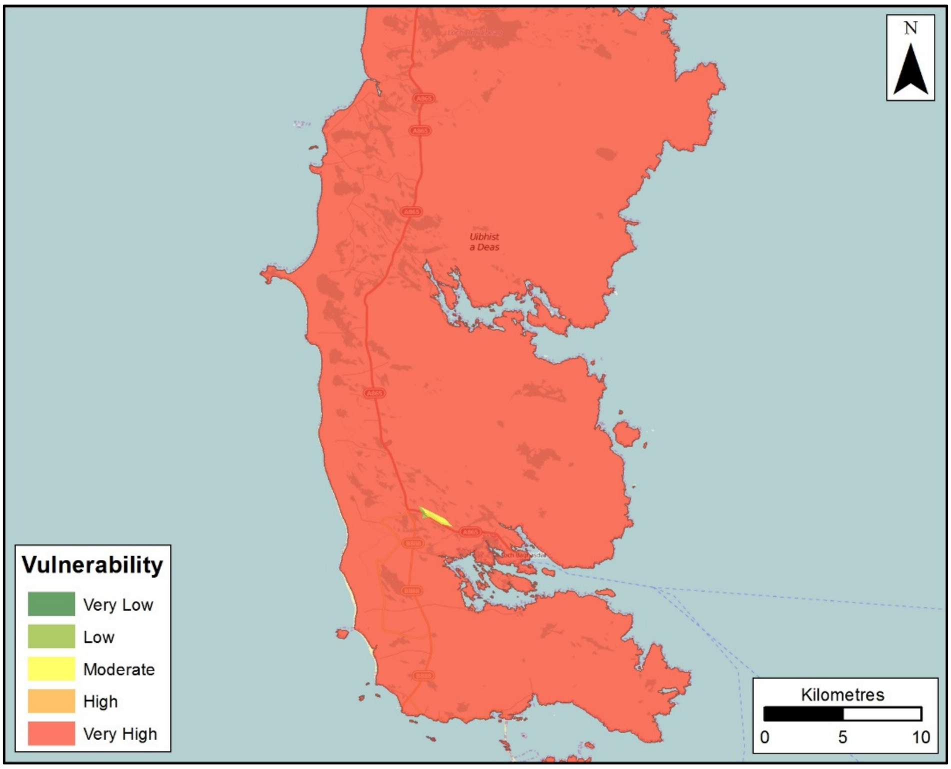

Figure C2.1.8: Socioeconomic vulnerability to coastal erosion in South Uist. Note that vulnerability is independent of the geographical extent of the coastal erosion hazard at this stage.

C.2.2 CEVM Validation

Table C2.2.1: The OAC2011 geodemographic classifications with the qualitatively assigned vulnerability rank. 1 = Very Low Vulnerability, 5 = Very High Vulnerability.

Supergroup		Group		Subgroup		Vulnerability
1	Rural Residents	1a	Farming Communities	1a1	Rural Workers and Families	5
				1a2	Established Farming Communities	4
				1a3	Agricultural Communities	5
				1a4	Older Farming Communities	5
		1b	Rural Tenants	1b1	Rural Life	4
				1b2	Rural White-Collar Workers	4
				1b3	Ageing Rural Flat Tenants	5
		1c	Ageing Rural Dwellers	1c1	Rural Employment and Retirees	5
				1c2	Renting Rural Retirement	5
				1c3	Detached Rural Retirement	5
2	Cosmopolitans	2a	Students Around Campus	2a1	Student Communal Living	1
				2a2	Student Digs	1
				2a3	Students and Professionals	1
		2b	Inner-City Students	2b1	Students and Commuters	1
				2b2	Multicultural Student Neighbourhoods	1
		2c	Comfortable Cosmopolitans	2c1	Migrant Families	2
				2c2	Migrant Commuters	2
				2c3	Professional Service Cosmopolitans	2
		2d	Aspiring and Affluent	2d1	Urban Cultural Mix	2
				2d2	Highly-Qualified Quaternary Workers	1
				2d3	EU White-Collar Workers	2
3	Ethnicity Central	3a	Ethnic Family Life	3a1	Established Renting Families	3
				3a2	Young Families and Students	3
		3b	Endeavouring Ethnic Mix	3b1	Striving Service Workers	3
				3b2	Bangladeshi Mixed Employment	3
				3b3	Multi-Ethnic Professional Service Workers	3
		3c	Ethnic Dynamics	3c1	Constrained Neighbourhoods	3
				3c2	Constrained Commuters	3
		3d	Aspirational Techies	3d1	New EU Tech Workers	3
				3d2	Established Tech Workers	3
				3d3	Old EU Tech Workers	3
4	Multicultural Metropolitans	4a	Rented Family Living	4a1	Social Renting Young Families	3
				4a2	Private Renting New Arrivals	3
				4a3	Commuters with Young Families	3
		4b	Challenged Asian Terraces	4b1	Asian Terraces and Flats	3
				4b2	Pakistani Communities	3
		4c	Asian Traits	4c1	Achieving Minorities	3
				4c2	Multicultural New Arrivals	3
				4c3	Inner City Ethnic Mix	3

Supergroup		Group		Subgroup		Vulnerability
5	Urbanites	5a	Urban Professionals and Families	5a1	White Professionals	2
				5a2	Multi-Ethnic Professionals with Families	2
				5a3	Families in Terraces and Flats	2
		5b	Ageing Urban Living	5b1	Delayed Retirement	3
				5b2	Communal Retirement	3
				5b3	Self-Sufficient Retirement	3
6	Suburbanites	6a	Suburban Achievers	6a1	Indian Tech Achievers	2
				6a2	Comfortable Suburbia	2
				6a3	Detached Retirement Living	3
				6a4	Ageing in Suburbia	3
		6b	Semi-Detached Suburbia	6b1	Multi-Ethnic Suburbia	2
				6b2	White Suburban Communities	2
				6b3	Semi-Detached Ageing	3
				6b4	Older Workers and Retirement	3
7	Constrained City Dwellers	7a	Challenged Diversity	7a1	Transitional Eastern European Neighbourhoods	3
				7a2	Hampered Aspiration	3
				7a3	Multi-Ethnic Hardship	3
		7b	Constrained Flat Dwellers	7b1	Eastern European Communities	3
				7b2	Deprived Neighbourhoods	3
				7b3	Endeavouring Flat Dwellers	3
		7c	White Communities	7c1	Challenged Transitionaries	3
				7c2	Constrained Young Families	4
				7c3	Outer City Hardship	4
		7d	Ageing City Dwellers	7d1	Ageing Communities and Families	4
				7d2	Retired Independent City Dwellers	3
				7d3	Retired Communal City Dwellers	3
				7d4	Retired City Hardship	3
8	Hard-Pressed Living	8a	Industrious Communities	8a1	Industrious Transitions	3
				8a2	Industrious Hardship	4
		8b	Challenged Terraced Workers	8b1	Deprived Blue-Collar Terraces	3
				8b2	Hard-Pressed Rented Terraces	4
		8c	Hard-Pressed Ageing Workers	8c1	Ageing Industrious Workers	4
				8c2	Ageing Rural Industry Workers	5
				8c3	Renting Hard-Pressed Workers	5
		8d	Migration and Churn	8d1	Young Hard-Pressed Families	5
				8d2	Hard-Pressed Ethnic Mix	5
				8d3	Hard-Pressed European Settlers	5