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A method for modelling coastal erosion risk: the example of Scotland

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Abstract

It is thought that 70% ~~Seventy percentages~~ of beaches worldwide are experiencing erosion (Bird ~~in Coastline changes: a global review, Wiley, Hoboken~~, 1985), and as global sea levels are rising and expected to accelerate, the management of coastal erosion is now a shared global issue. This paper aims to demonstrate a method to robustly model both the incidence of the coastal erosion hazard, the vulnerability of the population, and the exposure of coastal assets to determine coastal erosion risk, using Scotland as a case study. In Scotland, the 2017 Climate Change Risk Assessment for Scotland highlights the threat posed by coastal erosion to coastal assets and the Climate Change (Scotland) Act 2009 requires an Adaptation Programme to address the risks posed by climate change. Internationally, an understanding and adaption to coastal hazards is imperative to people, infrastructure and economies, with Scotland being no exception. This paper uses a Coastal Erosion Susceptibility Model (CESM) (Fitton et al. ~~in Ocean Coast Manag 132:80 89. https://doi.org/10.1016/j.ocecoaman.2016.08.018~~, 2016) to establish the exposure to coastal erosion of residential dwellings, roads, and rail track in Scotland. In parallel, the vulnerability of the population to coastal erosion, using a suite of indicators and Experian Mosaic Scotland geodemographic classification, is also presented. The combined exposure and vulnerability data are then used to determine coastal erosion risk in Scotland. This paper identifies that 3310 dwellings (a value of £524 m) are exposed to erosion, and the Coastal Erosion Vulnerability Index (CEVI) identifies 1273 of these are also considered to be highly vulnerable to coastal erosion, i.e. at high risk. Additionally, the CESM classified 179 km (£1.2 bn worth) of road and 13 km of rail track (£93 m to £2 bn worth) to be exposed. Identifying locations and assets that are exposed and at risk from coastal erosion is crucial for effective management and enables proactive, rather that reactive, decisions to be made at the coast. Natural hazards and climate change are set to impact most on the vulnerable in society. It is therefore imperative that we begin to plan, manage, and support both people and the environment in a manner which is socially just and sustainable. We encourage a detailed vulnerability analysis, such as the CEVI demonstrated here for Scotland, to be included within future coastal erosion risk research. This approach would support a more sustainable and long-term approach to coastal management decisions.

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Keywords

Coastal erosion
Vulnerability
Geodemographic classification
Exposure
GIS

1. Introduction

Coastal erosion is thought to impact 70% of the Earth’s sandy beaches (Bird 1985) with climate change expected to exacerbate both the rates and extents of coastal erosion (Leatherman et al. 2000; Zhang et al. 2004; Masselink and Russell 2013). Coasts are attractive places to live and have average population densities three times the global average (Small and Nicholls 2003). It is therefore imperative that the risks of coastal erosion are understood to allow the impacts of the hazard to be minimised. There are numerous examples of local to regional scale approaches to assess coastal erosion, e.g. Alexandrakis and Poulos (2014), Bosom and Jiménez (2011), Mendoza and Jimenez (2006), Reeder et al. (2010) and Thieler and Hammar-Klose (1999). However, few also include socio-economic indicators to establish possible impacts of coastal erosion, e.g. Reeder et al. (2010), Mclaughlin and Cooper (2010), Martins et al. (2012) and Lins-de-Barros and Muehe (2011), with Boruff et al. (2005) conducting a more complete vulnerability analysis. Here we present an approach, using Scotland as a case study, to robustly model both the hazard of coastal erosion, the vulnerability of the population, and the exposure of coastal assets to determine coastal erosion risk.

Scotland’s coastline is dominated by hard rocky coast and other areas of mixed sediments (superficial consolidated sediments with limited erosion potential) that are largely resilient to coastal erosion, together making up a coastal length of 15,604 km or 78% of the shoreline by length (Hansom et al. 2017). The soft shoreline (beaches and dunes) covers 3812 km or 19% of the shoreline by length, extending 3812 km, with 590 km of artificial shoreline making up the remaining 3% (Hansom et al. 2017). The distribution of these coastal types varies spatially with the east coast having a larger proportion of soft and artificial coast and the north and west coasts being characterised by a long, rock-dominated and often fjord-like indented coast. Since much of the east coast is backed by low-lying land, it has experienced extensive urban and industrial development and, together with extensive transport infrastructure, the east coast is asset rich. On the other hand, the north, south and west coasts and their islands are dominated by rocky coastlines with more limited development and infrequent built assets. An exception to this general pattern in the west is the Firth of Clyde where extensive lengths of previously soft coast have been defended to protect asset-rich hinterlands that support infrastructure, industrial and housing development.

In Scotland, the 2017 UK Climate Change Risk Assessment (UK-CCRA-2017) served to highlight the growing threat posed by coastal erosion to Scottish coastal assets (ASC 2016). Approximately, 11% of dwellings (272,000), 25% of roads (10,700 km), and 14% of rail track (420 km) are situated within 500 m of the Mean High Water Springs (Hansom et al. 2017). The Climate Change (Scotland) Act 2009 requires development of an adaptation programme to address risks identified in the UK-CCRA-2017. One of the risks to be taken into account for all coastal management and planning decisions is coastal erosion, yet at that time no national-scale erosion data existed that allowed an accurate assessment of the current and potential future threats posed by coastal erosion in Scotland. In 2016 and 2017, two developments directly addressed this deficit: a pan-Scotland Coastal Erosion Susceptibility Model (CESM) (Fitton et al. 2016) provided a methodology to classify coastal areas susceptible to erosion, identifying 2100 km (approximately 11.5%) of the Scottish coastline as having very high susceptibility to coastal erosion and the Dynamic Coast project (www.dynamiccoast.com), an online national database and webmaps ~~in 2017~~ showing coastal changes and erosion rates over time (Hansom et al. 2017). Since the coastline supports communities, industry, and infrastructure, an understanding of any changes in coastal erosion extents and rates will inform assessments of coastal hazard and ~~must be a~~ is key to effective and proactive planning (Scottish Government 2014).

The assets exposed to coastal flooding have been assessed by the Scottish Environment Protection Agency (SEPA) (2016), as has the vulnerability of the coastal population to flooding (The Scottish Government 2015). In comparison, coastal erosion has been given minor attention and there exists only limited information on any assets that are, or could be, impacted by coastal erosion. Only four local authorities (LAs) have an operational Shoreline Management Plan that identifies erosional sites and proposed a policy approach (Angus, Dumfries and Galloway, East Lothian, and Fife) equating to only 7% of

Scotland's shoreline. A further two LAs (North Ayrshire and South Ayrshire) are currently developing an SMP which will cover a further 2% of the coast (Fitton et al. 2016). Natural hazards impact most on vulnerable people (Wisner et al. 2004); however, no assessment of the vulnerability of coastal populations to coastal erosion in Scotland as a consequence of their socio-economic circumstances had been conducted. In order for Scotland to adapt and manage present coastal hazards as well as any climate change-induced exacerbation of hazard, identifying the 'hot-spots' of coastal erosion risk was a strategic priority. Once identified, this should provide a more targeted management focus, enabling proactive rather that reactive decisions to be made, and encourage a more sustainable and long-term approach to coastal planning. The development of the CESM (Fitton et al. 2016) was the first step in the identification of these erosion hot-spots and provided the basis for identifying the exposure of people and assets located in areas with high susceptibility to coastal erosion.

Here we aim to:

1. Establish a robust methodology that allows coastal erosion risk to be modelled, using Scottish data as an example. This requires the identification of: key assets (residential dwellings, road and rail track) potentially exposed to coastal erosion, the socio-economic indicators required to model the vulnerability of the population to coastal erosion using a geodemographic classification, and combining the areas of high susceptibility to coastal erosion together with the vulnerability of the population to coastal erosion to identify the populations most at risk from coastal erosion.

2. Discuss the implications of coastal erosion risk modelling to inform vulnerability in the context of coastal management in Scotland and beyond.

1.1. Definitions

Numerous models and definitions of vulnerability and risk exist within the literature, so for clarity we define here the terms used within this paper. We accept that vulnerability is ultimately the result of large-scale, sometimes global processes, as identified within the 'Pressure and Release' model (Wisner et al. 2004); however, the working approach adopted within this paper is based on the 'Hazards of Place' model (Cutter 1996) in order to allow the physical and socio-economic components of the coastal erosion hazard to be more readily applied at the national scale.

We use the term vulnerability to represent '*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). People therefore have a sensitivity and resilience to a hazard. We define sensitivity as the degree to which an individual/household would be affected if they were exposed to a hazard, whereas we define resilience 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). Thus, vulnerability can be considered as a state that exists regardless of a person's exposure to a hazard (Allen 2003; Brooks 2003).

Throughout this paper we use the term *susceptible/susceptibility* when discussing the inherent properties of coastal geomorphological landforms, i.e. a stretch of coast may be highly susceptible to coastal erosion as a result of soft lithologies at low elevation. Only when an asset is involved is the term *exposure* used, i.e. a dwelling which is situated on land that is highly susceptible to coastal erosion would be described as exposed to coastal erosion. When the *vulnerability* (which in this paper refers only to residential populations) is combined with exposure of residential dwellings ~~is~~ coastal erosion risk established.

2. Methodology

2.1. The Coastal Erosion Susceptibility Model (CESM)

The CESM (Fitton et al. 2016) was developed to address a need to improve the understanding of coastal erosion within Scotland in order to assess the potential direct and indirect impacts on coastal populations and assets. A full explanation of the CESM, including methods, is available in Fitton et al. (2016), to which the reader is referred; however, a brief description is offered here.

The CESM is generated by firstly creating an Underlying Susceptibility Model (UPSM) which represents the natural inherent erosion susceptibility of the coastline. The UPSM is GIS based and uses four data sets (ground elevation, rockhead elevation, wave exposure, and proximity to the open coast), each of which is ranked on a linear scale of 1–5 based on their relationship with erosion susceptibility (Table 1), similar to the methods used by Mclaughlin and Cooper (2010) and Thieler and Hammar-Klose (1999). The four ranked data layers are then summed (with weighting shown in Table 1), and those areas with a higher overall score are deemed to be more susceptible to coastal erosion.

Table 1 This spacing on this table can be improved.

The proximity to open coast row is omly single, compared to double for the other three rows. Could the single row be changed to double for uniformity.

Overview of categorisation and susceptibility rankings for each of the data layers used within the UPSM

	Very High 5	**High 4**	**Moderate 3**	**Low 2**	**Very Low 1**	**Weighting**
Ground elevation (m above MHWS)	< 2	2–4	4–6	6–8	> 8	1
Rockhead elevation (m above MHWS)	< 0	0–2	2–4	4–6	> 6	1
Proximity to open coast (m)	< 100	100–200	200–300	300–400	> 400	1
Wave exposure (non-dimensional)	> 300	225–300	150–225	75–150	< 75	0.5
The Wave Exposure data layer was given a weighting of 0.5 compared to the other three data sets due to data quality issues. A rank of 5 represents very high susceptibility, and a rank of 1 indicates very low susceptibility. See Fitton et al. (2016) for further detail						

The CESM is formed by adjusting the UPSM with the inclusion of artificial coastal defences and sediment accretion data which, where present, serve to reduce the UPSM score. Coastal defences, such as sea walls, hinder coastal erosion by providing an immobile hard engineered structure which maintains the position of the upper shoreline. The influence of sediment accretion is more complex; however, in summary, where there is a net accumulation of sediment (i.e. an accreting beach) sediment is deposited which replaces any sediment eroded and enables the growth of beach height and/or width. This sediment may supply sand dunes, creating habitat for stabilising vegetation, and a higher and/or wider beach is more effective at reducing wave energy, both of which mitigate the coastal processes that contribute to coastal erosion.

The final UPSM and CESM outputs are a national (pan-Scotland)-scale 50 m^2 resolution raster which represents coastal erosion susceptibility on a scale of 0–100. The model outputs from the UPSM and CESM are ranked into five equal interval classifications (Table 2) and can be viewed via a webmap at www.jmfitton.xyz/cer where it possible to interrogate the models. The UPSM and CESM are both used within the exposure analysis to allow the identification of assets benefiting from the protection offered by artificial defences and natural processes, and so provide the basis for a preliminary national-scale cost/benefit analysis. The UPSM and CESM have no temporal data included; therefore, they cannot be used to say that erosion will occur within a given time period; the models are only an indication of the potential for erosion to occur.

Table 2 **Table 2** In the uncorrected proof the width of the first column is excessively large, with the second column too small. Can this be adjusted so that the two columns are of equal width.

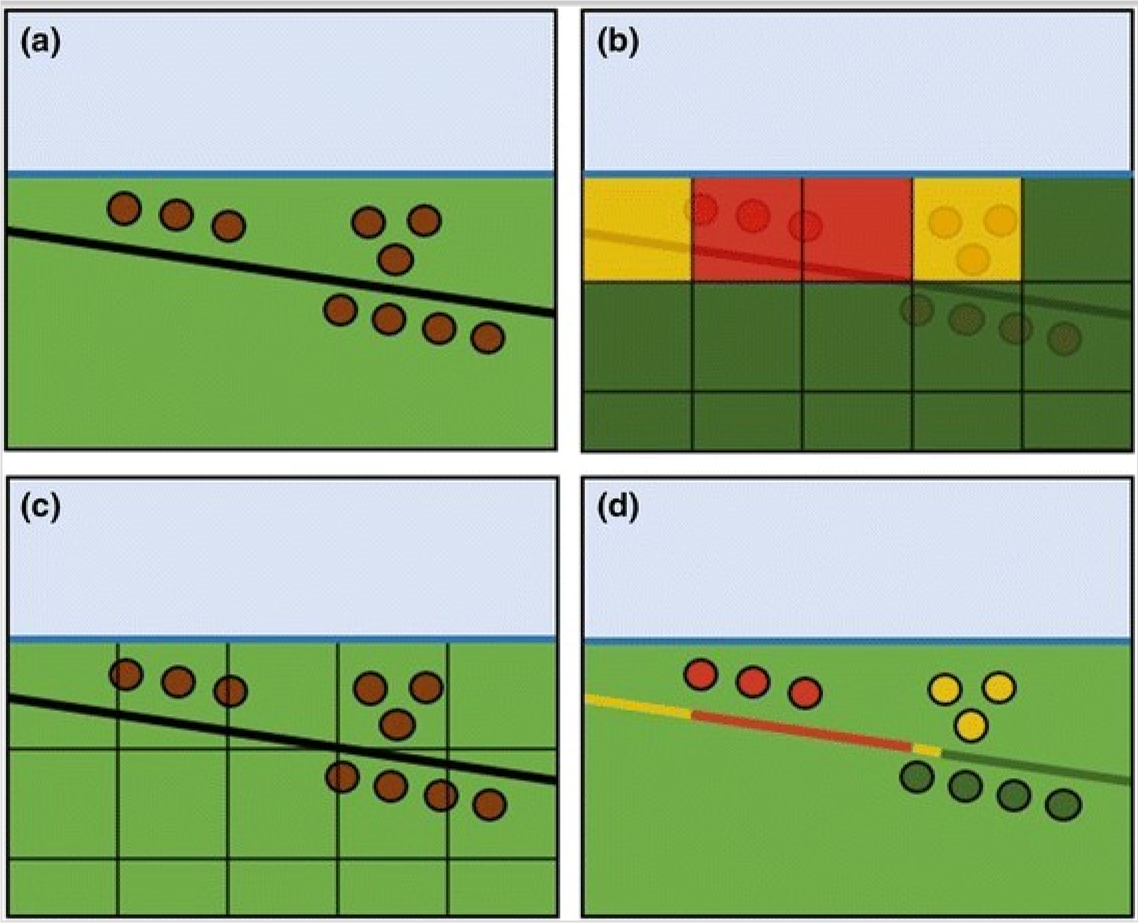
The description of coastal erosion susceptibility used within this research based upon the UPSM or CESM score

UPSM or CESM score	Susceptibility description
≥ 0 to ≤ 20	Very Low
> 20 to ≤ 40	Low
> 40 to ≤ 60	Medium
> 60 to ≤ 80	High
> 80 to ≤ 100	Very High

To identify the assets which may be impacted by coastal erosion, the CESM is converted from a 50 m^2 raster to a polygon. This polygon is then intersected with the asset data, which assigns a location-specific erosion susceptibility score to the asset (see Fig. 1 for a hypothetical example). Assets with a score of over 80 (very high susceptibility) are considered to be exposed, although we recognise that this cut-off value is arbitrary.

Fig. 1

A hypothetical coastal example of how the CESM score is assigned to asset data, **a** a rail track (black line), and dwellings (brown circles) are located at the coast, **b** the 50 m^2 CESM raster for the same area shows areas of very high susceptibility (red grid cells), high susceptibility (yellow grid cells), and very low susceptibility (green grid cells), **c** the raster is converted to a polygon, then intersected with the asset data which has the effect of assigning the values of the 50 m^2 raster grid to the asset data, **d** the CESM values have been assigned to the asset data with lengths of the rail track and dwellings classified as exposed (red lengths of rail track and red dwellings)



2.2. Coastal assets

The asset types used within the analysis (Table 3) have been selected due to their social and economic importance to society such as small individual assets and dwellings (‘point’ data) and transport infrastructure assets such as roads and rail track (‘polyline’ data). The assets assessed in this paper are restricted for brevity to the above two categories since they are often priority assets for management purposes, but others can be assessed (‘polygon data’ such as historic and environmental assets).

Table 3

The asset data used along with the CESM to determine the assets potentiall exposed to coastal erosion

Data type	Asset	Description	Source
Point	Dwellings	Residential properties	OS MasterMap Address Layer 2

Data type	Asset	Description	Source
Polyline	Roads	Motorways, A, B, and minor roads	OS Meridian 2
	Rail track	Location of rail track	OS Meridian 2

2.2.1. Urban/rural classification

The Scottish Government Urban/Rural classification (The Scottish Government 2014) was used to determine whether assets are located within either urban or rural environments (Table 4) and then to assess whether the assets exposed are likely to be locally important to community functioning. For example, a road closure in a remote area, with no alternative routes, will result in significant local disruption compared to in an urban situation where alternative routes may be available. The classification uses population and accessibility data (in the form of drive time analysis) to categorise areas into six urban/rural classes. The urban/rural classification is a polygon data set, which allowed the classifications to be assigned to the road and rail track data in the same manner as described in Fig. 1c, d.

Table 4

The six classes of the Scottish Government urban/rural classification 2013–2014

Class name	Description
Large urban areas	Settlements of 125,000 or more people
Other urban areas	Settlements of 10,000 to 124,999 people
Accessible small towns	Settlements of 3000–9999 people and within 30-min drive of a settlement of 10,000 or more
Remote small towns	Settlements of 3000–9999 people and with a drive time of over 30 min to a settlement of 10,000 or more
Accessible rural	Areas with a population of < 3000 people, and within a 30-min drive time of a settlement of 10,000 or more
Remote rural	Areas with a population of < 3000 people, and with a drive time of over 30 min to a settlement of 10,000 or more

2.3. Economic value of assets

To assign an economic value to the assets exposed to coastal erosion, each asset must be assigned a unit value. The economic values used here are based on the information below. However, it should be noted these economic values are only indicative, and a more complete methodology is required to fully assess both the direct and indirect costs of damage to and/or loss of an asset by coastal erosion.

2.3.1. Residential property values

The Register of Scotland produces a quarterly assessment of house prices in Scotland (Table 5) (Registers of Scotland 2017). The average house prices for the dwellings within each LA between April and June 2017 were used to estimate economic values, rather than a national average. 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 5

Average property prices in each local authority for quarter of April to June 2017. Taken from Registers of Scotland (2017)

Local authority	Number of dwellings	Average house price (£)
Aberdeen City	116,351	201,483
Aberdeenshire	113,335	215,592
Angus	54,916	158,631
Argyll and Bute	48,054	150,535
City of Edinburgh	242,095	247,618
Clackmannanshire	24,078	127,066
Dumfries and Galloway	74,311	131,822
Dundee ~~e~~City	74,768	133,546
East Ayrshire	57,951	121,738
East Dunbartonshire	44,863	228,746
East Lothian	45,940	213,908

Local authority	Number of dwellings	Average house price (£)
East Renfrewshire	37,777	250,129
Falkirk	72,628	133,156
Fife	173,844	149,929
Glasgow ~~c~~City	305,085	149,258
Highland	115,332	167,940
Inverclyde	39,278	128,885
Midlothian	37,682	195,739
Moray	43,666	159,132
Na h-Eileanan an Iar	14,921	97,351
North Ayrshire	68,070	122,312
North Lanarkshire	151,865	126,649
Orkney Islands	10,952	149,747
Perth and Kinross	70,761	195,288
Renfrewshire	84,223	139,155
Scottish Borders	57,712	173,344
Shetland Islands	11,104	158,685
South Ayrshire	55,442	148,601
South Lanarkshire	147,472	148,601
Stirling	40,756	189,685
West Dunbartonshire	45,023	106,301
West Lothian	77,005	157,196

2.3.2. Road and rail track values

Assigning a single value to erosion repairs to a coastal road or rail track is problematic since repair costs vary on a case-by-case basis depending on the type and severity of damage done and whether reinstatement includes a new coastal defence structure. However, a useful proxy to use is repair costs for road and rail track recently affected by coastal erosion. The coastal erosion damage caused to the A2 road in Northern

Ireland in January 2014 resulted in a 40-m-long collapse of the roadway. The reinstatement cost was £260,000, including the provision of rock armouring sea defences (Northern Ireland Executive 2014). Using this as an estimate then the repair cost for a section of road affected by coastal erosion averages approximately £6500 per metre.

It is also difficult to assign a value to rail track, as there is a marked difference between the costs associated with maintenance/repair work compared to reinstatement after a catastrophic failure. Using two examples from Scotland for repair/upgrading of crumbling coastal defences (Gourock and Helmsdale) estimated costs are on average £7000 per metre. This includes defences such as rock revetment and grouting and sloped concrete revetments (AECOM 2016a, b). However, if a significant and sudden event occurs, where more substantial reinstatement of rail track is required, costs can be considerably higher. For example, in Dawlish, England, during the winter storms of 2013/2014 can be used as a proxy for rail track reinstatement cost. Storm damage caused the sea wall protecting the rail track to fail, resulting in 100 m of rail track damage (Network Rail 2014) at a cost of £15 million (The Guardian 2014) or £150,000 per metre. Note these values do not include any wider economic losses associated with the loss of transport connectivity, which may in some cases be orders of magnitude larger than direct repair costs, dependent on the individual circumstances.

3. Vulnerability

The vulnerability of the Scottish population to coastal erosion is assessed using the Coastal Erosion Vulnerability Index (CEVI) which uses a postcode-level geodemographic classification tailored to the socio-economic characteristics of Scotland (Experian’s Mosaic Scotland). Experian’s Mosaic products have been used previously for vulnerability assessments by Tomlinson et al. (2011) and Willis et al. (2010). Census data have also been widely used, e.g. Cutter et al. (2003), to assess vulnerability to natural hazards. However, census data were rejected for use here since the output areas (OA) of the UK census for rural regions of Scotland can cover a large area. Use of UK postcodes allows socio-economic differentiation within smaller areas to be identified.

Experian's Mosaic Scotland classification is built upon 536 variables including data from the UK census, the Electoral Roll, Experian's 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 (Experian 2009). The data are clustered using k-means techniques to produce 44 classification types within Scotland and then validated by market research and fieldwork. These classification types ~~then need to be allocated~~ require the allocation of a vulnerability indicator value before they can be used in combination with the CESM.

3.1. Vulnerability indicators

Few examples exist of vulnerability assessments using indicators tailored specifically towards coastal erosion. The standard approach is to use population density, with increasing density resulting in increasing vulnerability to the hazard, e.g. Hegde and Reju (2007), Mclaughlin and Cooper (2010), Reeder et al. (2010) and Martins et al. (2012). A more in-depth approach to assessing the human dimension of coastal erosion vulnerability was used by Boruff et al. (2005), who used census data and the PCA-based method previously used by Cutter et al. (2003), who had identified a range of indicators relevant to environmental hazards in the USA, including socio-economic status, gender, race, ethnicity and age. However, Boruff et al. (2005) did not tailor the vulnerability indicators to the hazard of coastal erosion. This may not be appropriate, as the nature of coastal erosion has unique characteristics which require vulnerability indicators to be applied differently than when considering other hazards.

Using Cutter et al. (2003) as a basis, vulnerability indicators were selected that were judged to be the most appropriate to coastal erosion socio-economic vulnerability from Experian's Mosaic Scotland classification data. The indicators and selection rationale are shown in Table 6. For nine of these indicators, the relationship with vulnerability is positive, i.e. vulnerability increases with increasing indicator value. For two indicators (dwelling density and property value), there is a negative relationship.

Table 6

The indicators used within the Coastal Erosion Vulnerability Index (CEVI) and the rationale for their selection.

The indicators used within Cutter et al. (2003) were used as a basis for indicator selection

Indicator (vulnerability relationship)	**Rationale**
Net household income: Proportion of households with income of < £399 a week (Positive)	Those on a low income are likely to be already in financial difficulty and could easily be pushed into further problems, limiting their ability to recover. Financial difficulty can also severely impact upon mental health
Poor health: Proportion of adult population with poor health (Positive)	Those in poor physical health may struggle if short-term evacuation was required due to mobility and health complications. Adapting to a new living situation, and moving away from a community support network who they may be reliant upon may negatively impact those of poor health
Elderly: Proportion of households that entirely consist of pensioners (Positive)	The elderly may be heavily reliant on their homes as they are tailored to their needs; therefore, loss of their home may have serious implications to quality of life. The elderly may also 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 are repatriated elsewhere, this may seriously impact on their mental and physical well-being
Lone parents with dependent children: Proportion of households that consist of sole parents with dependent children (Positive)	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. Recovery decisions have to be considered with the children's well-being in mind; therefore, repatriation to a new area (either short or long term) may impact upon a child's education and social well-being
No savings: Proportion of adult population with no savings (Positive)	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
Secured or unsecured loans: Proportion of	People with loans are required to make monthly payments; if the ability to pay these loans is

Indicator (vulnerability relationship)	**Rationale**
adult population with secured or unsecured loans (Positive)	hindered due to unexpected but necessary costs elsewhere, they may suffer short- and/or long-term financial difficulty
No access to a vehicle: Proportion of adult population with no access to a vehicle (Positive)	Without a car, short-term evacuation of people and possessions is more difficult. Additionally, if a person is repatriated to a new location, without a car travelling between a work place and school without a car may be problematic
Homeowners: Proportion of households occupied by the homeowner (Positive)	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
Education: Proportion of adult population who left school before or at 16 (Positive)	Those with lower education attainment ~~lack~~ hinders the ability to understand and interpret warning information. Those with higher education levels have a greater range of potential job options and can potentially seek employment in a number of sectors and are more likely to have higher-paid jobs
Dwelling density: Density of dwellings per km^2 (Negative)	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 services and facilities which may also be exposed to erosion
Property value: Average postcode property value (Negative)	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

The indicators listed in Table 6 align with the suggestion that people who are socially and economically on the margins of society are likely to be the most vulnerable. However, two of the vulnerability indicators used here operate in an unlikely fashion in a coastal hazard context where they suggest a decrease in vulnerability. For example, living in an urban environment is ~~generally~~ thought to potentially complicate evacuation in the event of a hazard, yet with coastal erosion hazard large-scale evacuation is rare. Living in an urban environment likely decreases vulnerability to coastal erosion hazard as cost-effective management support and coastal defences are often targeted in locations where the concentration of people and infrastructure are greatest. Furthermore, p~~P~~eople who rent often do so because they lack the financial means to purchase a property, and are potentially ‘transient’ populations. If a renter’s home is threatened by coastal erosion they can~~, and will,~~ move to a new property and potentially reduce their vulnerability.

Two indicators required further refinement to support their use as vulnerability indicators. The ‘Income’ indicator represents the proportion of people with a net weekly income of £399 or less. The median weekly household income for 2011/2012 in Scotland was £436 (Scottish Government 2013) so £399 identifies those on lower incomes relative to the Scottish population (more recent data are available for average income; however, the value from 2011/2012 is commensurate with the age of the data within the Experian Mosaic Scotland classification).

The ‘Education Level’ indicator represents the proportion of people who left school at 16 or earlier. Scottish pupils who leave school at 16 or before often have low attainment, are likely to experience unemployment and unstable postschool careers (Howieson 2003; Howieson and Iannelli 2008), are unlikely to gain other qualifications, and have poorer prospects of employment training.

Robust vulnerability assessments require indicators to have minimal statistical correlation to ensure that multiple variables are not measuring the same aspects; thus, a test of statistical correlation was conducted to rule this out. The Pearson correlations for the socio-economic indicators used here are shown (Table 7) where a value of ± 1 indicates a direct linear correlation between two indicators. Willis et al. (2010) used a threshold correlation value of ± 0.85 to indicate high correlation within their research. However, none of the indicator correlations exceed this threshold and so they can all be utilised ~~used within the vulnerability index~~.

Table 7 **Table 7** In the uncorrected proof the row spacing is highly vaired. This spacing

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Pearson correlation values between the socio-economic indicators used within th

	Income	Poor health	Elderly	Single parents with dependent children	No savings	Secured or unsecured loans
Income	1					
Poor health	0.744	1				
Elderly	0.437	0.562	1			
Single parents with dependent children	0.408	0.456	− 0.209	1		
No savings	0.675	0.715	0.02	0.792	1	
Secured or unsecured loans	− 0.063	0.045	− 0.196	0.253	0.312	1
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
Education level	− 0.241	− 0.317	0.066	− 0.23	− 0.347	0.286
Dwelling density	− 0.212	− 0.169	0.216	− 0.105	− 0.231	0.277
Property value	0.66	0.66	0.127	0.532	0.727	0.41

A value of ± 1 indicates a direct linear correlation between two indicators. W of ± 0.85 to indicate high correlation. Here, none of the correlations exceed tl vulnerability index

To simplify the analysis, we standardised the data into an index value calculated as follows:

$$\text{Index value} = \frac{\text{Indicator value}}{\text{Mean indicator value}} \times 100 \tag{1}$$

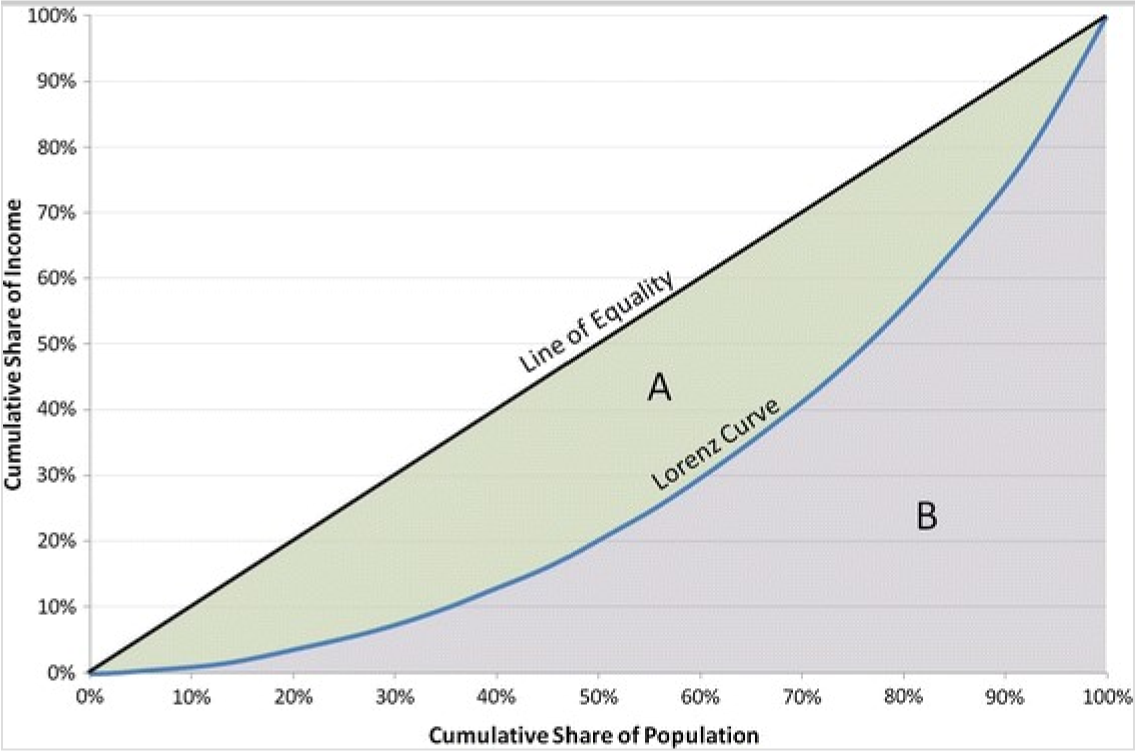
with the equation inverted for the indicators that have a negative relationship with vulnerability. An index value of 100 means that an indicator value equals the mean. The indicators that are substantially above or below a value of 100 are the most useful at discriminating between socio-economic groups.

3.1.1. Indicator weighting

When dealing with combinations of indicators it is useful to include weightings to highlight those indicators that contribute most to discrimination and this was accomplished here using Lorenz curves and Gini coefficients (Willis et al. 2010). A Lorenz curve provides a graphical representation of inequality and a Gini coefficient provides a statistical measure of that inequality, both are in routine use within ~~E~~economics (Black et al. 2009). Figure 2 shows the hypothetical Lorenz curve as a skewed curve (for example, showing the uneven distribution of income within a population) with the straight line indicating equality. The Gini coefficient can be calculated as a ratio between the areas of A and B shown in Fig. 2 (see Eq. 2), or by using Eq. (3) (using the example of Fig. 2, X equals the cumulative share of population, and Y equals the cumulative share of income).

Fig. 2

A hypothetical example of a Lorenz Curve. The Gini coefficient is calculated as a ratio of the areas of A and B



$$\text{Gini coefficient} = \frac{A}{A+B} \qquad (2)$$

$$\text{Gini Coefficient} = 1 - \sum_{i=1}^{n} (X_{i-1} - X_i)\,(Y_{i-1} + Y_i) \qquad (3)$$

A Gini coefficient of 0 indicates absolute equality, whereas, a value of 1 indicates maximum inequality. The calculated Gini coefficients for each indicator used here are shown in Table 8. The Gini coefficient for the ‘Education Level’ indicator had the highest coefficient with 0.60. This indicates that only a relativity small group of people in society left school at 16 or earlier; therefore, this indicator is more discriminating and will be isolated to a smaller number of Mosaic Scotland classifications. The Gini coefficients were then applied to the Coastal Erosion ~~Socioeconomic~~ Vulnerability Indicators (CEVI) using Eq. (4):

Table 8

Gini coefficients for the indicators used within the Coastal Erosion Vulnerability I

	Income	Poor health	Elderly	Single parents with dependent children	No savings	Secure or unsecu loans
Gini coefficient Can this be on a new line to prevent hypenation.	0.43	0.43	0.42	0.53	0.41	0.42

$$\text{Weighted index value} = \text{Indicator index value} \times \text{Gini coefficient} \quad 4$$

AQ2

In order to create a composite index of socio-economic vulnerability, the 11 weighted index values are calculated for each of the 44 classification types within Mosaic Scotland. The mean of the weighted index scores is calculated for each classification type, with a lower mean weighted index score equating to a lower vulnerability and vice versa. Mosaic Scotland assigns a classification type to each postcode, allowing the CEVI score to be assigned to a postcode and the vulnerability to acquire a spatial context within a GIS.

To simplify the outputs of the CEVI, the results were classified into five descriptive groups of vulnerability ordered by their average weighted index score and the percentage of dwellings within each to calculate a cumulative percentage to produce: Very Low, Low, Moderate, High and Very High groupings. Consequently, ‘Very Low’ vulnerability represents approximately the least vulnerable 20% of dwellings, and ‘Very High’ equates to the top 20% of vulnerable dwellings.

Within Mosaic Scotland 0.6% of postcodes are designated by Experian as unclassified, since they are dominated by non-residential buildings, such as hospitals. However, these postcodes may not be completely devoid of residential dwellings, and rather than excluding them from the analysis, a conservative approach has been adopted here and the maximum vulnerability descriptor assigned to unclassified postcodes.

4. Results

4.1. Exposure

From here onward, we use the term exposure/exposed to describe an asset located in an area with a UPSM or CESM score ≥ 80, representing an area with very high erosion susceptibility and a likely priority for management concern.

Nationally, there are 2,557,260 dwellings in Scotland which were assessed to determine their exposure to coastal erosion. The UPSM classified 13,298 of dwellings (0.52% of all dwellings) (Table 9) with very high susceptibility to coastal erosion, this number decreasing to 3310 (or 0.13%) using the CESM. This reduction is directly related to the inclusion of the protection offered by either artificial defences or sediment accretion to the UPSM. Sediment accretion increases the volume of any beach fronting the asset at risk of erosion, resulting in a reduction in the overall risk. This is the rationale behind beach nourishment schemes aiming to offer a wide beach to protect assets immediately inland, a good example being the artificial beach fronting Portobello, Musselburgh, a town to the east of the Scottish capital, Edinburgh. Due to this added protection, 9988 dwellings across Scotland can be removed from the highest susceptibility category. Using the average house price for April to June 2017 within each LA, some £2.2~~1~~ bn worth of dwellings are classified in the UPSM as exposed, this reducing to £524 m exposed when the protection offered by defences and accretion are included (Table 9). In all exposure categories, 158,229 dwellings (£24.5 bn worth) are estimated to benefit from defences, with 8387 dwellings (£1.2 bn worth) benefiting to some degree from sediment accretion.

Table 9

Summary of the assets exposed to coastal erosion and the associated value

	UPSM	Value	CESM	Value
Dwellings	13,298	£2.2 bn	3310	£524 m
Roads (km)				

Exposed is defined as assets situated in areas of the UPSM and CESM which have a score of ≥ 80

	UPSM	Value	CESM	Value
Motorway	0.0	–	0.0	–
A Road	97.0	£631 m	61.6	£400 m
B Road	51.3	£333 m	34.5	£224 m
Minor Road	165.4	£1.0 bn	82.6	£537 m
	313.7	£2.0 bn	178.7	£1.2 bn
Rail (km)	26.4	£185 m to £4.0 bn	13.3	£93 m to £2.0 bn
Exposed is defined as assets situated in areas of the UPSM and CESM which have a score of ≥ 80				

Nationally, out of 54,245 km of roads analysed, a total of 314 km (Table 9) is classified by the UPSM as exposed, of which 165 km is minor roads. Using the CESM, this reduces to 178 km of exposed roads (Table 9), of which 83 km is minor roads. The value of exposed roads using the UPSM and CESM is £2.0 bn, and £1.2 bn, respectively (using a repair estimate of £6500 per metre). Overall, 1227 km of roads benefits from coastal defences, and 190 km (£1.2 bn) benefits to some degree from sediment accretion.

Out of a total of 2512 km of coastal rail track, 26.4 km is classified as exposed by the UPSM, with a value of £185 m for repair and maintenance (estimate of £7000 per metre) to £4.0 bn in the event of reinstatement of rail track (estimate of £150,000 per metre) (Table 9). According to the CESM, 13.3 km (£93 m to £2.0 bn) of rail track is classified as exposed. Coastal defences offer protection to 88 km of rail track, with 16 km (£616 m to £2.4 bn) benefiting from sediment accretion.

In order to identify whether the road and rail track classified by the CESM as exposed are rural or urban, their locations were compared within the urban/rural classification (Table 4). The results indicate that the 95% of exposed A roads, 95% of exposed B roads, 88% of exposed minor roads, and 87% of exposed rail track are found within the two most rural classifications of ‘accessible rural’ or ‘remote rural’.

4.2. Vulnerability

Table 10 shows the results of the CEVI, with Fig. 3 showing the spatial distribution of vulnerability (a webmap version is available at www.jmfitton.xyz/cer, which allows interaction and interrogation of the CEVI).

Table 10 **Table 10** A line should be drawn across each of the rows at the base of the vulnerability description, i.e. a line should run between the rows with the Rank of 12 and 13.

The text in the vulnerabiltiy description should also be vertically centered.

Summary of the Experian Mosaic Groups and their CEVI weighted index score, their vulnerability rank, and their cumulative dwelling percentage

Rank	Mosaic Scotland classification type	Mean weighted index score	Cumulative proportion of dwellings (%)	Vulnerability description
1	Military Might	29.9	0.2	Very Low
2	Captains of Industry	30.7	1.6	
3	Rucksack and Bicycle	31.1	2.2	
4	Prestige Tenements	31.2	3.4	
5	Wealth of Experience	33.3	5.7	
6	College and Campus	34.8	6.0	
7	New Influentials	35.1	8.0	
8	Successful Managers	35.9	10.3	
9	Ageing in Suburbia	36.0	14.1	
10	New Suburbanites	36.0	16.6	
11	Cosmopolitan Chic	36.8	17.5	

Table sorted by mean weighted index score

Rank	Mosaic Scotland classification type	Mean weighted index score	Cumulative proportion of dwellings (%)	Vulnerability description
12	Studio Singles	37.3	18.8	
13	Inner City Transience	37.4	20.9	Low
14	White Collar Owners	38.2	23.8	
15	Emerging High Status	38.4	25.8	
16	Blue Collar Owners	39.3	30.2	
17	Songs of Praise	39.3	32.9	
18	Settling In	42.6	33.4	
19	Small Town Pride	43.4	36.0	
20	Elders 4 in a Block	49.9	40.0	
21	Downtown Flatlets	50.1	42.7	Moderate
22	Quality City Schemes	50.3	45.9	
23	30 Something Singles	50.6	47.9	
24	Skyline Seniors	51.5	48.7	
25	Twilight Infirmity	52.2	50.0	
26	Lathe and Loom	53.2	54.5	
27	Towns in Miniature	53.5	57.7	
28	Rural Playgrounds	53.9	60.1	High
29	Planners Paradise	54.6	65.6	
30	Greys in Small Flats	54.6	69.1	

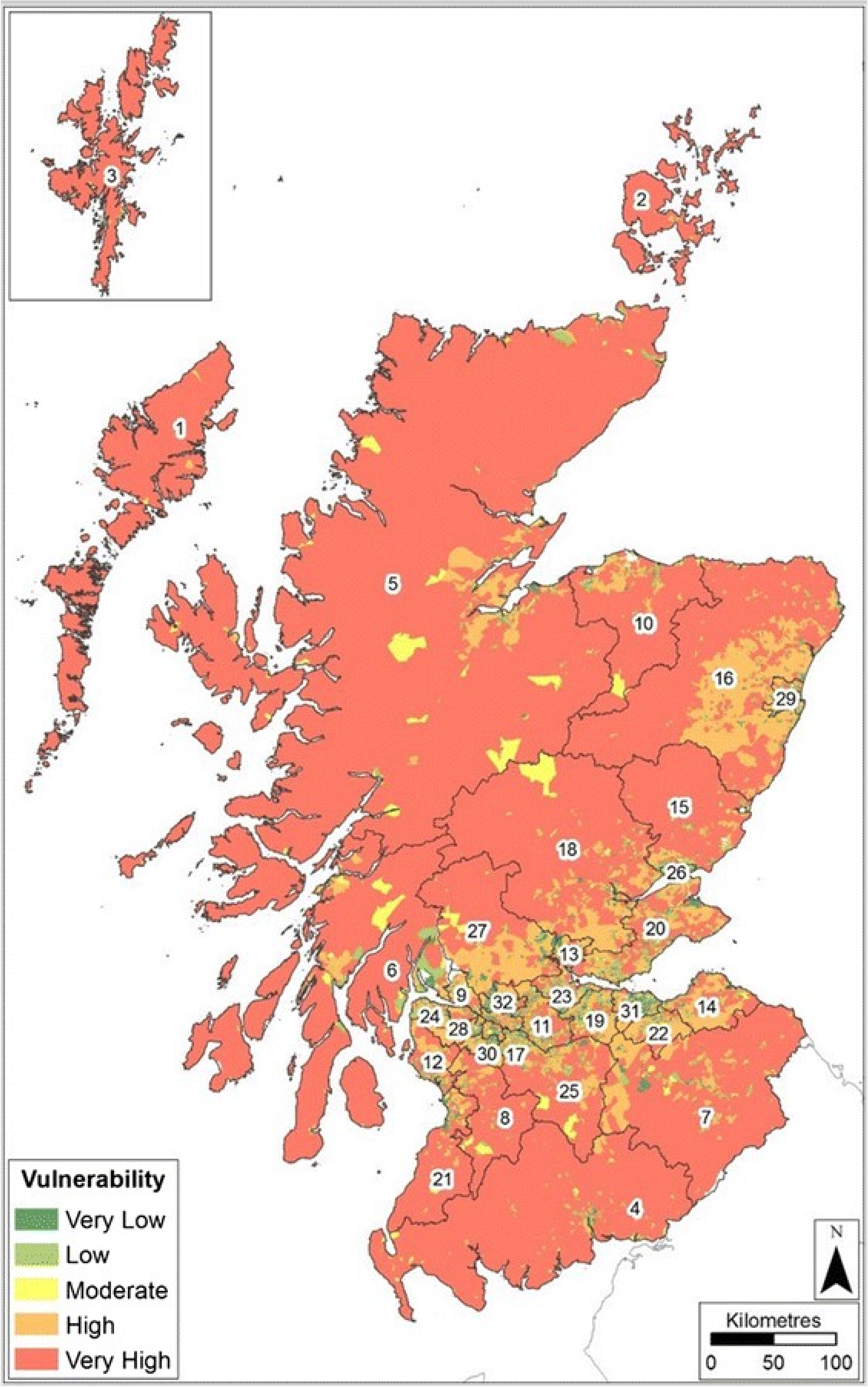
Table sorted by mean weighted index score

Rank	Mosaic Scotland classification type	Mean weighted index score	Cumulative proportion of dwellings (%)	Vulnerability description
31	Dignified Seniors	54.8	70.3	
32	Families in the Sky	56.9	71.4	
33	Smokestack Survivors	57.4	74.6	
34	Room and Kitchen	57.6	76.1	
35	Sought after Schemes	57.9	80.1	Very High
36	Rustbelt Renaissance	58.2	84.9	
37	Tenement Lifestyles	58.6	86.0	
38	Indebted Families	60.6	89.0	
39	Mid Rise Breadline	60.6	90.6	
40	Pockets of Poverty	61.0	93.8	
41	Agrarian Heartlands	65.3	96.3	
42	Far Away Islanders	72.2	97.2	
43	Scenic Wonderland	77.8	98.7	
44	Isolated Farmsteads	237.7	100	
Table sorted by mean weighted index score				

Fig. 3

The Coastal Erosion Vulnerability Index (CEVI) for Scotland. Although the CEVI has been tailored for coastal erosion, areas of the hinterland that are some distance from the coast are classified with very high vulnerability, which may appear counter-intuitive. However, as stated in

Sect. 1.1, vulnerability is defined as being independent of the geographical extent of the coastal erosion hazard; therefore, it is only when the CESM is used along with the CEVI (as shown in Fig. 4) is risk confined to the coast. Numbering refers to the local authorities in Table 11. This map is viewable in greater detail via a webmap at www.jmfitton.xyz/cer


Vulnerability
Very Low
Low
Moderate
High
Very High
N
Kilometres
0
50
100
1
2
3
4
5
6
7
8
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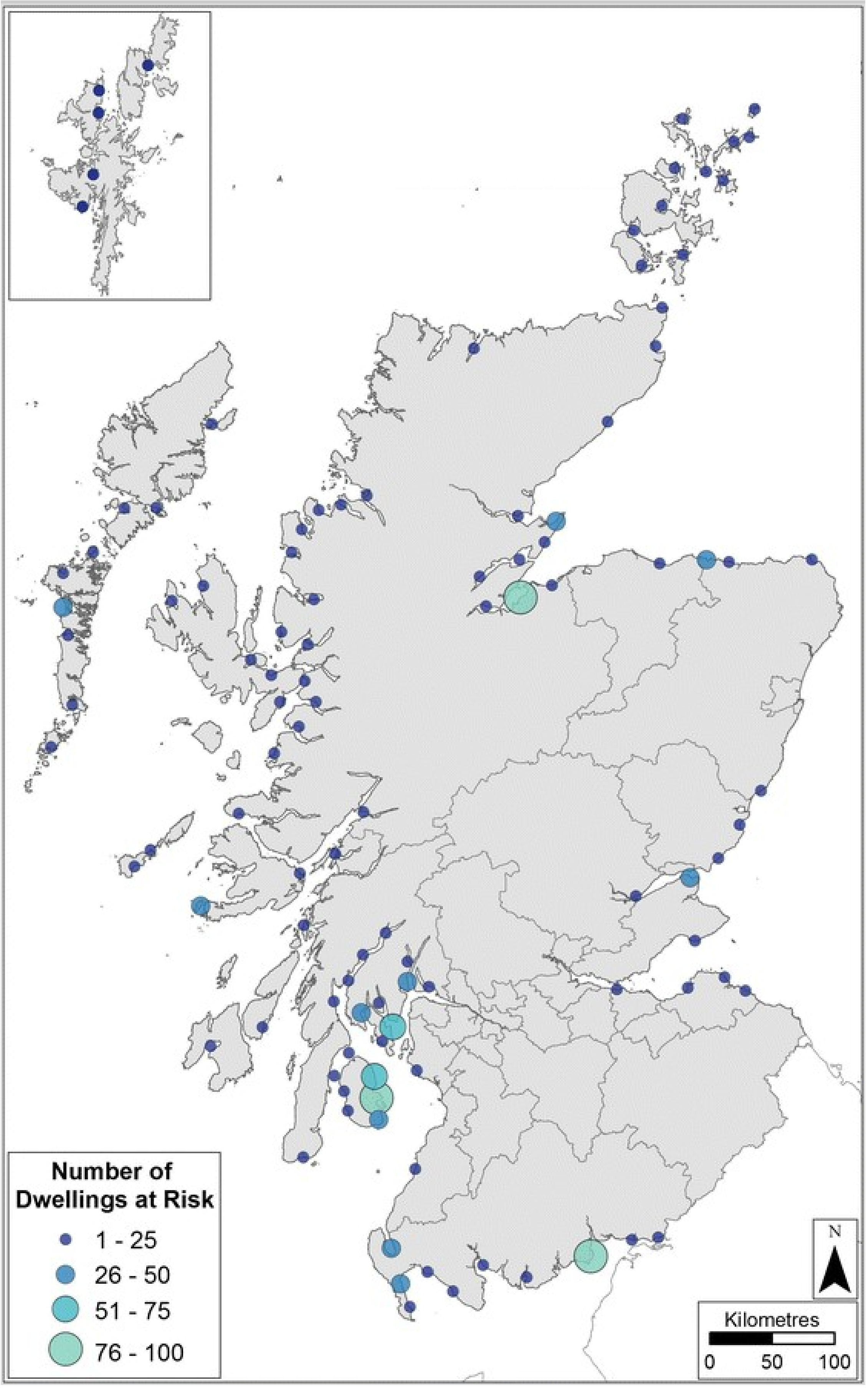
30
31
32

Fig. 4

The location of the 1273 high-risk dwellings which are classified as exposed (CESM $\geq$ 80) and have very high vulnerability according to the CEVI [Very High (red) areas in Fig. 3]. In contrast to Fig. 3, where the entirety of Scotland was classified with a degree of vulnerability, the addition of the CESM has confined the risk to dwellings at the coast


Number of Dwellings at Risk
1 - 25
26 - 50
51 - 75
76 - 100
N
Kilometres
0
50
100

A national total of 633,977 dwellings were identified as having ‘Very High’ vulnerability. The Mosaic Scotland classification types within this group include ‘Isolated Farmsteads’, ‘Scenic Wonderland’, ‘Far Away Islanders’, and ‘Agrarian Heartlands’. These classifications generally consist of older couples who are farm owners or workers, self-employed hill farmers, on low wages, and are generally based in scattered, rural communities or on isolated farms. The Mosaic Scotland classifications within the ‘Very Low’ vulnerability group are a mix of young couples with young families, modern homes and good career prospects (‘Successful Managers’, ‘New Suburbanites’, and ‘Military Might’), or top professionals, with expensive homes in desirable locations and well qualified (‘Captains of Industry’, ‘Wealth of Experience’, and ‘New Influentials’). These are also people who are mostly young, well-educated singles who live in apartments in the older, inner areas of large cities (‘Prestige Tenements’, ‘Studio Singles’, ‘Rucksack and Bicycle’, ‘College and Campus’, and ‘Cosmopolitan Chic’). For more information on the classification types see Experian (2009).

With the vulnerability of each postcode identified, the classification was assigned to individual dwellings. As coastal management is administered at the LA level in Scotland (i.e. regional government), Table 11 shows the proportion of dwellings in each vulnerability classification by LA. Na h-Eileanan an Iar (The Western Isles) has the highest proportion of dwellings classified with ‘Very High’ vulnerability with 83.7% (or 12,486 dwellings) followed by the Orkney Islands (66.9%, 7323 dwellings) and the Shetland Islands 64.9% (7207 dwellings). The City of Edinburgh has 10.4% classified as ‘Very High’ vulnerability, equating to 25,172 dwellings. East Dunbartonshire has proportionally the least amount of dwellings classified with ‘Very High’ vulnerability (9.5%, 4258 dwellings).

Table 11

Proportion of dwellings within each socio-economic vulnerability category by local authority

Local authority	Total dwellings	Proportion of dwellings within each vulnerability category (%)				
		Very Low	Low	Moderate	High	Very High
Na h-Eileanan an Iar (1)	14,921	0.4	4.5	8.2	3.2	83.7
Orkney Islands (2)	10,952	0.8	8.3	18.8	5.1	66.9
Shetland Islands (3)	11,104	3.7	7.7	14.8	8.9	64.9
Dumfries and Galloway (4)	74,311	5.2	18.1	21.9	10.9	43.9
Highland (5)	115,332	6.3	17.3	22.9	12.5	40.9
Argyll and Bute (6)	48,054	11.3	16.6	20.9	15.6	35.6
Scottish Borders (7)	57,712	7.3	17.9	26.6	16.4	31.8
East Ayrshire (8)	57,951	8.0	23.6	20.9	16.7	30.8
West Dunbartonshire (9)	45,023	8.8	20.6	18.8	23.2	28.6
Moray (10)	43,666	11.4	24.1	23.5	12.9	28.1
North Lanarkshire (11)	151,865	10.8	20.1	16.8	24.5	27.8
North Ayrshire (12)	68,070	10.6	21.6	19.1	21.7	27.0
Clackmannanshire (13)	24,078	12.6	23.8	21.9	15.7	26.0
East Lothian (14)	45,940	14.9	23.4	15.1	20.8	25.8
Angus (15)	54,916	12.1	26.1	23.2	12.8	25.8
Aberdeenshire (16)	113,335	11.7	25.0	17.2	20.4	25.6
Glasgow City (17)	305,085	20.4	13.7	14.5	26.1	25.4
Perth and Kinross (18)	70,761	13.3	21.8	23.6	16.2	25.1
West Lothian (19)	77,005	13.1	23.6	18.6	20.1	24.6

Sorted by percentage of dwellings in the very high vulnerability category. Local authority numbering refers to Fig. 3

Local authority	Total dwellings	Proportion of dwellings within each vulnerability category (%)				
		Very Low	Low	Moderate	High	Very High
Fife (20)	173,844	16.3	23.8	20.1	16.5	23.3
South Ayrshire (21)	55,442	21.3	22.3	16.4	16.8	23.1
Midlothian (22)	37,682	15.9	21.2	13.5	26.3	23.1
Falkirk (23)	72,628	12.7	25.8	19.9	18.9	22.8
Inverclyde (24)	39,278	12.2	19.6	21.7	24.0	22.5
South Lanarkshire (25)	147,472	15.5	23.7	16.3	22.9	21.6
Dundee City (26)	74,768	24.3	17.4	19.7	17.2	21.4
Stirling (27)	40,756	29.0	18.7	14.3	17.4	20.6
Renfrewshire (28)	84,223	18.7	23.1	19.9	18.1	20.1
Aberdeen City (29)	116,351	34.9	17.1	19.0	13.2	15.9
East Renfrewshire (30)	37,777	42.6	24.5	7.8	14.2	11.0
City of Edinburgh (31)	242,095	35.5	27.1	17.0	10.0	10.4
East Dunbartonshire (32)	44,863	44.9	22.3	9.2	14.1	9.5
Sorted by percentage of dwellings in the very high vulnerability category. Local authority numbering refers to Fig. 3						

4.3. Risk

Figure 3 shows the whole land area of Scotland classified by the CEVI, despite the hazard of coastal erosion only occurring at the coast. This apparent paradox follows from definition of vulnerability used here, i.e. vulnerability is based on socio-economic factors within a postcode and independent of its spatial location. Only when the CEVI is combined with the CESM is coastal erosion risk established (Table 12 and Fig. 4). Reference to Figure 4 inserted. A total of 1273 dwellings have a very high risk of coastal erosion, a reduction of some 695 dwellings from the UPSM risk assessment due to the influence of defences and/or sediment accretion. At 286, Argyll and Bute has the highest number of dwellings classed as being at very high risk of coastal erosion, with 255 at similar risk in Highland and 205 in Dumfries and Galloway (‘Appendix 1’ section). A total of 14 LAs have no dwellings classified within the very high coastal erosion risk category. Highland has the largest number of dwellings (122) benefiting from coastal defences and/or sediment accretion.

Table 12

Coastal erosion risk of dwellings with exposure derived from the CESM and vulnerability from the CEVI

CEVI	CESM					
	Very Low	Low	Moderate	High	Very High	Total
Very Low	414,507	35,707	9711	1181	224	461,330
Low	461,124	54,599	16,835	2267	605	535,430
Moderate	382,406	57,081	23,215	2336	840	465,878
High	405,902	43,228	10,491	656	368	460,645
Very High	555,837	56,070	17,629	3168	1273	633,977
Total	2,219,776	246,685	77,881	9608	3310	

The locations of the 1273 dwellings classified with very high exposure and vulnerability are shown in Fig. 4

5. Discussion

5.1. Dwellings

Nationally, 3310 dwellings (or 0.13% of the total), with a value of £524 m at 2017 values are inherently exposed to coastal erosion. For context, approximately 5% of all dwellings are currently at risk from a 1 in 200-year coastal or fluvial flood event (SEPA 2009), equating to approximately 127,000 dwellings. Despite the number of dwellings exposed to coastal erosion being considerably less than from flooding, the value of the dwellings exposed remains considerable. Additionally, the costs of repairing a dwelling impacted by coastal erosion will likely far exceed costs associated with flooding. In addition, coastal erosion and flood risk are generally treated independently, but the reality is that they are often inherently linked, with the erosional loss of a protective structure (e.g. a beach or dune cordon) greatly exacerbating the extent of coastal flooding. To date this linkage has not been sufficiently acknowledged within modelling but is anticipated to grow in importance over the coming decades. As a result, the UPSM and CESM are now incorporated into SEPA's flood risk assessments and updates for Scotland (http://map.sepa.org.uk/floodmap/map.htm). A subsequent project, Dynamic Coast, has identified the extents and rates of coastal erosion in Scotland and assessed the coastal assets affected now and as far into the future as 2050 (www.dynamiccoast.com).

The UPSM and CESM comparisons have identified that a significant number of areas and assets benefit from coastal defences, confirming the need for an ongoing reliance on coastal defences as a management strategy (Cooper and McKenna 2008; Potts 1999). However, this itself raises questions about how these areas are to be managed in the future since such defence infrastructure will require maintenance or replacement in order to effectively protect the coast. Whether this strategy is financially efficient and sustainable, in comparison with alternative routes and in every situation, is a moot point. Clearly, to resolve all problems where coastal erosion negatively impacts assets anywhere, Scotland included, would be prohibitively costly and so prioritisation is needed. Coastal managers usually prioritise resources on a market value basis to achieve the best cost/benefit ratio for a coastal erosion management project. Areas of high housing density and/or high property values (e.g. East Lothian and the City of Edinburgh LAs) are where coastal defences have resulted in large reductions between the UPSM and CESM analysis ('Appendix 2' section). However, in rural LAs the cost efficiency of any defence structure is much less. For example, the Western Isles (Na h-Eileanan an Iar) and the Orkney Islands have a high proportion of dwellings potentially exposed to erosion, likely due to a poor cost/benefit ratio in areas of low population density, preventing management intervention.

However, seldom is the vulnerability of the people most impacted by such decisions taken into consideration. For example, in relation to 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*' (England and Knox 2015, p. 7), i.e. the vulnerability of the people likely to be impacted seems to have little bearing on spending decisions. A similar conclusion can be arrived at here since rural populations are amongst the most vulnerable yet rural areas are where coastal intervention will be the least cost-effective, resulting in a reduced justification for resource allocation.

The CEVI can be used as a management tool capable of identifying those sections of society who would suffer most if they were impacted by coastal erosion loss. Combining the CESM with the CEVI established that 1273 dwellings are both highly exposed (CESM) and their occupants highly vulnerable (CEVI) to coastal erosion, i.e. high risk. Cooper and McKenna (2008) argued that 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. However, the reality (in Scotland and probably elsewhere) is that a policy of equal sharing of benefits/burdens across the whole of society has not been previously used for coastal erosion management decisions. Using tools such as the CESM/CEVI allows a 'needs' approach (prioritise the most vulnerable) to be available to coastal managers who, theoretically at least, may not have to align with 'market value' approaches to coastal erosion risk reduction strategies. As the most vulnerable in Scotland tend to be in rural locations, space is often available inland to utilise more sustainable management approaches, such as managed realignment or relocation of assets inland (adaptation). Nevertheless, many aspects of social justice are considered and supported by the current Scottish Government, and therefore, the approach developed here may prove useful in extending these concepts into coastal zone management.

The research reported here highlights some of potential impacts of coastal erosion in Scotland. However, unrepresented in this analysis are the intangible impacts of coastal erosion and any associated flooding upon the physical and mental well-being of those affected. Depression and other mental disorders are commonly reported consequences of flooding (Kirch et al. 2005; Reacher et al. 2004) and similar effects are likely to be associated with the stresses associated with loss from coastal erosion, although the impact of coastal erosion on health and well-being is poorly documented.

5.2. Transport infrastructure

The coastal fringe often offers convenient and cost-effective locations to route roads and rail track, but this leads to potential exposure to coastal erosion. The analysis above identifies the extent of the road and the rail track network in Scotland potentially exposed to erosion. However, the cost of maintenance/repair and direct replacement as a metric for liability produces a range of results which are an order of magnitude different for rail track. Uncosted is the fact coastal erosion may also result in the loss of land and may render it impossible for a like-for-like reinstatement. New routes may be required, dramatically increasing the cost of reconnecting the eroded road or rail section to the network. Also excluded from these valuations are the implications of damage to a key transport connection with no alternative, and there may be significant loss to the local economy. In 2013–2014, 80 m of the main line rail track at Dawlish in Southwest England suffered storm damage, resulting in a 60-day closure, 7500 service cancellations, and an estimated loss of between £60 million to £1.2 bn to the local economy (Devon Maritime Forum 2015); however, Dawson et al. (2016) advises that these figures are used with caution. This demonstrates the difficulty in assigning a single generic cost metric to these types of assets and limits their potential use for decision-making. This is therefore an area requiring further research, such as developing scenario-based costs for the individual exposed rail track sites, to enable and support more informed decision-making at the coast.

Loss of road or rail track is likely to be worst felt in rural areas where a single road or rail track may well be a social, economic and safety lifeline route. Tragically demonstrated in 2005, five people drowned on a causeway in the Western Isles (Na h-Eileanan an Iar), whilst fleeing from rising flood waters in an area with no officially recognised hazard escape route (BBC 2005). Urban areas have more roads and rail track options, and so alternative routes are often available. Comparison of the exposed roads and rail track in both urban and rural settings shows the majority (at least 87%) to be located in rural areas, where any loss of connectivity is likely to have greater impact on local people and their economy. Such situations should be high priority for managers when assessing local transport infrastructure needs and risks at the coast, a nuance potentially obscured if the analysis is nationally based.

5.3. CEVI evaluation

As a multi-indicator vulnerability index specific to coastal erosion the CEVI is novel. It was generated using a 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), but the two methods produce similar vulnerability indices (Willis and Fitton 2016). However, there are a number of aspects to consider when using geodemographic/census data, which are outlined below.

5.3.1. Temporal currency

A potential issue with vulnerability assessments, such as the CEVI, 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 socio-economic type, e.g. gentrification. The commercial geodemographic products are kept up to date as their clients require the most accurate and current information as possible. However, these products are still mainly built upon census data which are collected at time intervals that can span many years, e.g. every 10 years in the UK. For assessing the vulnerability of a population to a hazard, it is essential that vulnerability should be assessed regularly in order to keep the modelling relevant and up to date, and ensures decisions made with the best available evidence. Furthermore, the vulnerability assessments in general are limited by the fact that it is problematic to extrapolate vulnerability into the future to predict future risk; therefore, vulnerability analyses are generally only available to assess current risks.

5.3.2. Costs

If there is a need to keep vulnerability assessments updated, using potentially expense commercial classifications may be a barrier. However, freely available non-commercial alternatives are available, such as the UK 2011 Output Area Classification (OAC2011), a geodemographic classification based on the 2011 UK census. In addition, a number of countries are producing indices of multiple deprivation, such as the Scottish Index of Multiple Deprivation (SIMD) (Scottish Government 2017), which also exist for England (Department for Communities and Local Government 2015), Wales (Welsh Government 2015), and New Zealand (Exeter et al. 2017). Indices of multiple deprivation are often based on a range of government statistics that are collected more frequently than census data. This means these indices are updated every few years (e.g. Scotland has an index from 2006, 2009, 2012, and 2016). Whilst these indices do not have as many data parameters as a geodemographic calculation, due to the strong correlation between deprivation and vulnerability, and a regular update frequency, indices of multiple deprivation may well offer a cost-effective data source for assessing vulnerability to a hazard where available.

5.3.3. Coverage and spatial resolution

The advantage of using a commercial geodemographic classification is that products often cover multiple countries, e.g. Experian's Mosaic product is available in 23 countries. This means that a methodology that uses these products can be easily exported and applied to another location. Furthermore, products are available at a smaller spatial output unit, such as postcodes. Non-commercial products are often limited to census output units. This was a major consideration during the development of the CEVI, as many parts of Scotland are very rural, and as the census outputs units require a minimum population, very large census output areas were produced, especially in the north west of the country. Therefore, in order to more accurately differentiate and classify vulnerability in these rural areas, the small output areas offered by commercial products are desirable. In terms of area, Scottish postcodes have a mean area of 0.6 km^2 compared to OAs at 1.8 km^2. However, if risk is more focussed on urban populations, such as an assessment of vulnerability to urban heat island effects, census output units are likely to have a smaller area, and the smaller output areas offered by the commercial products may not be a significant improvement on the census output area units.

5.4. Decision support

As a result of the CESM and CEVI, data sets that support a more sustainable and socially just approach to ~~making~~ decision~~s~~ making at ~~that~~ the coast are now availible. There are two types of decisions these data will inform: firstly, the planning of new developments; for example, when developers and planners are building new housing, sites that are susceptible to erosion can be avoided and therefore limit potential future erosion problems. Secondly, when coastal managers are required to intervene to protect dwellings, the vulnerability of the occupants can be considered, rather than solely relying on economic cost/benefit analysis. By offering an alternative or supplementary evidence base for management intervention, there is potentially greater political, financial, and community support to consider more sustainable adaptation approaches, such as managed realignment. As the information and awareness of coastal erosion risk develops in the future, the number of people and assets located within areas of high coastal erosion susceptibility should reduce, therefore minimising the costs associated with coastal management in the long term.

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Raising awareness of coastal erosion risks is not without problems. The way in which the susceptibility, exposure, vulnerability, and risk aspects of the coastal erosion hazard are communicated both to the coastal manager and to the public needs to be managed sensitively, since there are dangers in releasing information about erosion-prone assets and areas without appropriate guidance. Whilst any such assessment is aimed at providing strategic information to assist future planning at the coast, there are also potential negative impacts (e.g.

property and community blight) to be addressed and managed. Additionally, whilst coastal management needs to assess potential erosion risk in the future, it also needs to better identify and prioritise those locations where erosion is currently a problem. For Scotland, this is now being delivered as part of the Dynamic Coast project (www.dynamiccoast.com).

The research reported here also enables a review of the contribution made by sediment supply to the defence of society's assets at the coast. Such a consideration is valuable when considering and articulating the benefits of natural capital. The Dynamic Coast project (www.dynamiccoast.com) has identified that £13 billion of assets are located closely behind natural defences (such as sand dunes), compared with £5 billion behind engineered sea walls. This assessment identifies that £2.5 to £4 billion worth of assets are not only protected by nature but are also more resilient being behind accreting beaches. When considering approaches to improve the sustainable management of coastlines, such economic valuations are important to ensure society places value on natural capital within these natural defences. This is important today, but it will be increasinlg so as climate change impacts increase.

6. Conclusion

The research presented here combines a model of the physical environment (CESM) and a model of the vulnerability of the population (CEVI) in order to assess the assets and people that are potentially exposed, and at risk, from coastal erosion in Scotland. Such a holistic approach represents a novel method to nationally assess coastal erosion risk as well as being also interrogable at the local postcode level. Such an approach is suitable to be exported to similar situations worldwide.

The exposure analysis identified 179 km of road, 13 km of rail track, and 3310 dwellings to be at risk from coastal erosion. In total this equates to an asset value of approximately £1.8–£3.7 bn. The Dynamic Coast project www.dynamiccoast.com will be able to determine lengths and number of these assets that will be impacted by coastal erosion in 2050. This research has also demonstrated that within the 3310 of exposed dwellings, 1273 are occupied by people that have very high vulnerability and would therefore be disproportionately impacted if their homes were to be lost to coastal erosion.

Natural hazards and climate change are set to impact most on the vulnerable in society. It is therefore imperative that we begin to plan, manage, and support both people and the environment in a manner which is socially just and sustainable. Therefore, it is no longer sufficient for coastal hazard risk analysis to focus on the physical aspects of erosion and to then utilise only limited socio-economic data, e.g. using solely population density. What is required is an evidence base that can robustly support coastal management decisions that are not based on economic cost/benefit alone. We encourage a detailed vulnerability analysis, such as the CEVI demonstrated here for Scotland, to be included within future coastal erosion risk research.

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7. Appendix 1

See Table 13.

Table 13

The number and proportion of high-risk dwellings within each local authority based on the CESM and CEVI, and the reduction (UPSM CESM) in dwellings a risk as a result of coastal defences and sediment accretion

Local authority	Very High Risk		Reduction
	UPSM	CESM	
Argyll and Bute	318	286	32 (10%)
Highland	377	255	122 (32%)

Local authority	Very High Risk		Reduction
	UPSM	CESM	
Dumfries and Galloway	308	205	103 (33%)
North Ayrshire	185	177	8 (4%)
Na h-Eileanan an Iar	94	88	6 (6%)
Orkney Islands	66	66	0 (0%)
Aberdeenshire	135	62	73 (54%)
Fife	142	58	84 (59%)
Moray	53	19	34 (64%)
South Ayrshire	24	19	5 (21%)
Shetland Islands	20	15	5 (25%)
East Lothian	72	10	62 (68%)
City of Edinburgh	71	4	67 (94%)
Angus	59	4	55 (93%)
Perth and Kinross	15	3	12 (80%)
Inverclyde	69	0	69 (100%)
Falkirk	26	0	26 (100%)
West Lothian	2	0	2 (100%)

8. Appendix 2

See Table 14.

Table 14

Assets classified as exposed by the UPSM and CESM in each local authority, a
in assets exposed as a result of coastal defences and sediment accretion

Local authority	UPSM			CESM		
	Dwellings	Roads	Rail track	Dwellings	Roads	Rail trac
	Number	km	km	Number	km	km
Aberdeen City	7	1.4	–	–	0.1	–

Local authority	UPSM			CESM		
	Dwellings	Roads	Rail track	Dwellings	Roads	Rail track
	Number	km	km	Number	km	km
Aberdeenshire	849	8.9	–	244	3.5	–
Angus	308	4.4	3	22	0.1	1.2
Argyll and Bute	1355	74.5	4.6	601	57.5	4.4
City of Edinburgh	1143	4.9	–	17	0.1	–
Clackmannanshire	–	–	–	–	–	–
Dumfries and Galloway	486	27.5	0.4	250	20.7	–
Dundee City	798	7.8	3.7	39	1	–
East Ayrshire	–	–	–	–	–	–
East Dunbartonshire	–	–	–	–	–	–
East Lothian	1407	10.2	–	207	5	–
East Renfrewshire	–	–	–	–	–	–
Falkirk	226	2.8	–	3	0.4	–
Fife	1646	19.7	1	108	2.2	0.6
Glasgow City	–	–	–	–	–	–
Highland	1606	59.4	10.4	961	36.2	6.2
Inverclyde	924	11.7	0.8	4	0.6	–
Midlothian	–	–	–	–	–	–
Moray	128	3.4	–	29	0.9	–
Na h-Eileanan an Iar	149	12.6	–	143	8.8	–
North Ayrshire	773	29.4	1.4	316	22.1	–
North Lanarkshire	–	–	–	–	–	–
Orkney Islands	72	12.8	–	72	12.6	–
Perth and Kinross	33	1.2	0.5	6	0.5	0.3
Renfrewshire	–	0.2	0.1	–	0.2	0.1

Local authority	UPSM			CESM		
	Dwellings	Roads	Rail track	Dwellings	Roads	Rail track
	Number	km	km	Number	km	km
Scottish Borders	–	–	–	–	–	–
Shetland Islands	20	2.6	–	15	2.4	–
South Ayrshire	1362	17.5	–	267	3.1	–
South Lanarkshire	–	–	–	–	–	–
Stirling	–	–	–	–	–	–
West Dunbartonshire	4	0.4	0.6	4	0.4	0.6
West Lothian	2	0.3	–	2	0.3	–
Total	13,298	313.6	26.5	3310	178.7	13.4

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