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A national coastal erosion susceptibility model for scotland

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ABSTRACT

The upland nature of the Scottish landscape means that much of the social and economic activity has a coastal bias. The importance of the coast is further highlighted by the wide range of ecosystem services that coastal habitats provide. It follows that the threat posed by coastal erosion and 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 and this serves to hinder the current and future management of the coast. To address this knowledge gap, two interrelated models have been developed and are presented here: the Underlying Physical Susceptibility Model (UPSM) and the Coastal Erosion Susceptibility Model (CESM). The UPSM is generated within a GIS at a 50 m^2 raster of national coverage, using data relating to ground elevation, rockhead elevation, wave exposure and proximity to the open coast. The CESM moderates the outputs of the UPSM to include the effects of sediment supply and coastal defence data. When validated against locations in Scotland that are currently experiencing coastal erosion, the CESM successfully identifies these areas as having high susceptibility. This allows the UPSM and CESM to be used as tools to identify assets inherently exposed to coastal erosion, areas where coastal erosion may exacerbate coastal flooding, and areas are inherently resilient to erosion, thus allow more efficient and effective management of the Scottish coast.

1. Introduction

Coastal areas have historically been utilised for human settlement on account of an abundance of the natural resources required for survival and development (Özyurt and Ergin, 2009). Within the UK, living close to the coast remains desirable today as a consequence of the vast range of ecosystem services and benefits that coasts provide. Jones et al. (2011) identify that even though coastal habitats occupy only 0.6% of the UK's land area, they account for approximately £48 bn (adjusted to 2003 values) of ecosystem benefits. Ecosystem service valuations for Scotland are not readily available, however with a coastline length of 18,670 km (Angus et al., 2011), (approximately 64% of UK's total coastline, and 12.5% of the European total according to Pranzini and Williams (2013)) the ecosystem services derived from Scottish coastal habitats are likely to be significant.

The geography of Scotland, with a highly undulating hinterland, long and indented coastline, together with a large number of islands (Fig. 1), means that much of the economic, social, and cultural assets within Scotland are largely located at the coast. Approximately 70% of the Scottish population (ca. 3.5 million people) live within 10 km of the coast (Scottish Executive, 2005). Coastal populations 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 (Zsamboky et al., 2011). Economically, the coast supports industries including oil and gas installations, ports, fishing, agriculture, aquaculture, links golf, and tourism (The James Hutton Institute, 2013). Consequently, coastal hazards such as flooding and erosion have the potential to substantially impact upon both people who live near the coast, and the Scottish economy. The Scottish coastal zone is therefore a resource which offers many opportunities, but also requires careful management to allow all stakeholders to benefit (Scottish Government, 2014).

Within Scotland, the risk posed by the hazard of flooding (both fluvial and coastal) has received much attention from the Scottish Environment Protection Agency (SEPA) yet, by comparison, coastal erosion has seen limited attention at a national level. This bias was noted by the Climate Change Risk Assessment (CCRA) for Scotland which states that “*maps of past erosion, current state and future*

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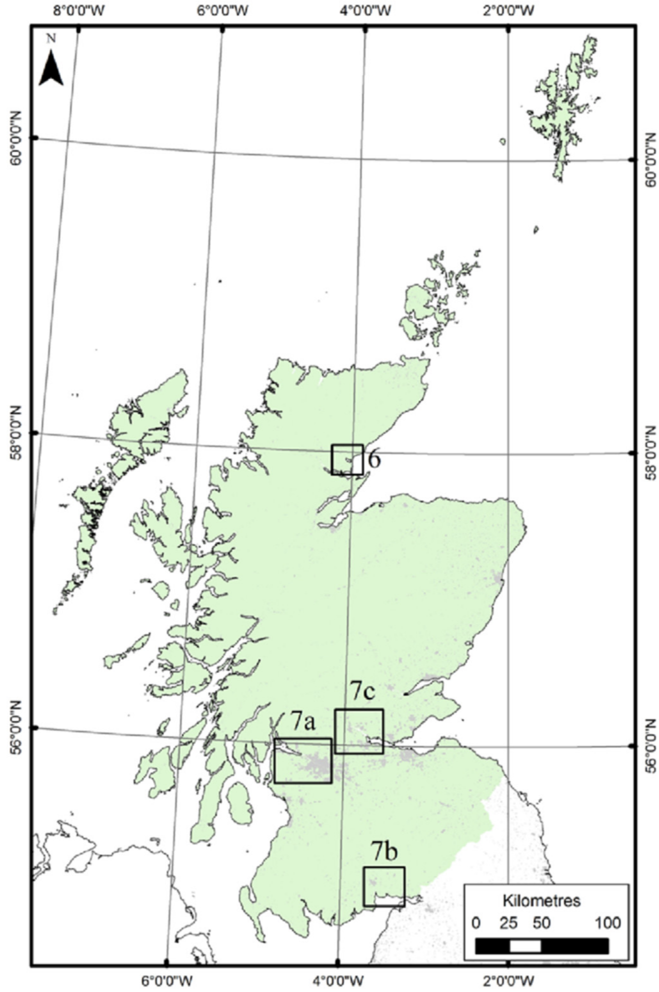

Fig. 1. Scotland's mainland and islands (shaded in green) which has an estimated coastal length of 18,670 km (Angus et al., 2011). Black boxes show the locations of the areas within Figs. 6, 7a–c. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

erosion conditions are required" (Defra, 2012, p.191). This was further highlighted by Dr. Aileen McLeod, the Scottish Minister for Environment, Climate Change and Land Reform, who in her Ministerial Address at the annual 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*". This is a potentially significant limitation considering that coastal erosion may exacerbate coastal flooding by removing the natural landforms and habitats (beaches, dunes and saltmarshes) which provide a coastal defence ecosystem service. In Scotland, sand dune, saltmarsh, and machair habitats are predicted to reduce by 36%, 25%, and 8% respectively by 2060 from 1900 levels (Beaumont et al., 2014). In Scotland, there is a paucity of information on the locations where coastal erosion is occurring and at what rate. Only four local authorities (LAs) have an operational Shoreline Management Plan that identifies erosional sites (Angus, Dumfries and Galloway, East Lothian, and Fife) equating to 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 (Hansom and Fitton, 2015). The remaining 91% of the coastline has yet to be assessed in detail in terms of coastal erosion.

Additionally, there is an absence of information concerning where coastal erosion could potentially occur in the future i.e. the inherent susceptibility of the coast to erosion. This is of particular relevance when considering the potential impacts of future climate change. The CCRA for Scotland (Defra, 2012) states that more frequent extreme weather and rising sea levels will instigate changes in coastal evolution as a result of climate change (further supported by Masselink and Russell, 2013; Ramieri et al., 2011 Zhang et al., 2004). The Climate Change (Scotland) Act 2009 requires Scottish Ministers to develop a Scottish Climate Change Adaptation Programme, which addresses the identified risks. Coastal erosion has implications for agriculture, tourism industry, transport sector, infrastructure, buildings, urban environment along with cultural and natural heritage interests. Government, Agencies and Local Authorities have obligations to incorporate coastal erosion within their work. Therefore, a pressing need exists to improve the understanding of coastal erosion within Scotland at a national scale, so that the potential direct and indirect impacts on coastal populations and assets can be fully assessed and so to better inform sustainable coastal management. This paper aims to introduce two interrelated models that aim to address the above need in Scotland: the Underlying Physical Susceptibility Model (UPSM) and Coastal Erosion Susceptibility Model (CESM). Below we detail the methodology and validation of the model and discuss the potential applications of its outputs for coastal management in Scotland. Forthcoming linked papers will detail a) the application of the CESM to identify the socioeconomically vulnerable population and key assets that are potentially exposed to coastal erosion and b) how the CESM will support the current and future approach to coastal management in Scotland.

2. Methodology

Large spatial scale erosion assessments are difficult to produce because coastal processes are complex, locally nuanced and require significant amounts of data to model. As a result there are few examples of national scale coastal erosion models within the literature, with much research focussing primarily either on local or regional scale erosion models e.g. Alves et al. (2011), Fernandez-Nunez et al. (2015), Lins-de-Barros and Muehe (2011), Reeder-Myers (2015). However, two studies, Eurosion (2004) and Mclaughlin and Cooper (2010), attempt to produce coastal erosion assessments that can be used at a national scale. Eurosion (2004) was an EU-wide project across 20 countries (including Scotland) aimed at understanding and quantifying coastal erosion 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 lacked detail (the coastal polyline outputs were at 1:100,000 scale) 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). An alternative method was developed by Mclaughlin and Cooper (2010) who produced a coastal erosion assessment for Northern Ireland at various different spatial scales: national (500 m^2 raster), regional (25 m^2 raster) and local (1 m^2 raster). This 'nested' method allows consistent management decision-making across a range of spatial scales. Additionally, Eurosion and many other studies portrayed erosion data as a line (a vector output) with various classifications according to the methodology of the assessment e.g. Harvey and Woodroffe (2008), Lins-de-Barros and Muehe (2011), Reeder et al. (2010). This line normally represents erosion data that occurs along the coastline but it may also include data representing offshore or inland conditions. On the other hand, instead of plotting a line Mclaughlin and Cooper (2010), Hegde and Reju (2007), and Alves et al. (2011) use a cell based or raster output which represents the information contained within the raster cell for the coastal area overlain by that cell as well as adjacent cells. The raster output can then be considered to produce a more flexible and easier to interpret output since it allows the identification of changes in erosional characteristics at, and along, the coast. With the potential for erosion to move inland over time then the raster information held in adjacent inland cells may become relevant as the coastline relocates landward.

The research methodology used here builds and extends the method used by Mclaughlin and Cooper (2010) by employing a number of raster datasets, which are ranked, and then combined to produce two national scale coastal erosion susceptibility models with outputs as a 50 m raster and a coastal polyline: the Underlying Physical Susceptibility Model (UPSM) which represents the natural inherent erosion susceptibility of the coastline and; the Coastal Erosion Susceptibility Model (CESM) which is the UPSM output moderated by the addition of artificial coastal defences and sediment accretion.

The UPSM was generated from four GIS datasets: ground elevation, rockhead elevation, proximity to the open coast, and exposure to wave activity. These datasets were chosen for inclusion within the model due to their high relevance when assessing coastal erosion susceptibility in Scotland (Table 1) and, crucially were all readily available at a national scale and at high resolution (Table 2). The strength of the rock type was not considered within this model as the bedrock in Scotland is highly resistant to erosion, with very few instances of soft bedrock (May and Hansom, 2003). Consequently, the relative strength difference between the soft superficial deposits (fluvial/glacial) and hard bedrock is high. Therefore, the model is designed to identify the areas of soft superficial deposits situated above rockhead. Where bedrock is present at the surface minimal erosion is expected to occur. A summary of the methods is shown in Fig. 2. All GIS processing was conducted within ArcMap 10.2.

All the original datasets required pre-processing from different formats before integrating into the UPSM. The elevation data for the ground and rockhead were relative to ordnance datum (OD) Newlyn. However, mean high water springs (MHWS) elevation varies markedly around Scotland (from 5.44 m above OD (mAOD) in Solway to −0.78 mAOD in St. Kilda), consequently a value of 0 mOAD, may represent an elevation above or below actual MHWS (see Fig. 3a for a hypothetical example). The ground and rockhead elevation data was therefore adjusted to be relative to the regional MHWS elevation. To adjust the data, a raster surface representing the regional MHWS elevation was generated using data from 133 tide gauges around the Scottish coast. This raster surface was translated inland and using the raster calculator the MHWS elevation raster surface was subtracted from the ground and rockhead elevation data. This resulted in the ground and rockhead elevation data being adjusted so that a value of 0 m now represents the elevation of regional MHWS (Fig. 3b).

The proximity to open coast source data included inlets and estuaries that are primarily dominated by fluvial, rather than coastal processes. Hence, the polyline data was processed to remove any inlet with a mouth of 500 m wide or less to generate a line more representative of the ‘open coast’. A 50 m raster of straight line distance from the ‘open coast’ was then generated. The wave exposure data was supplied as a 200 m raster, and was therefore not compatible with the other datasets. To correct this, a 50 m raster was created which allocated the data from the nearest wave exposure data point using the cost allocation tool (ESRI, 2016a).

The four datasets were ranked on a one to five scale (with a range of 5 representing very high susceptibility to 1 indicating very low susceptibility) (Table 3). These ranks were established through extensive testing of different rank thresholds at locations of already known to be of high and low erosion susceptibility within a range of coastal habitats e.g. cliffs, saltmarsh, machair, and beaches. To generate the UPSM the four ranked raster scores were aggregated in order to assess which areas were most susceptible to erosion overall. The wave exposure data was weighted at 50% of the value relative to the other data parameters, as the quality of the dataset as a result of the 200 m–50 m conversion was potentially diminished, and 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. The data was included since it was deemed important to include a parameter that accommodates coastal processes, but the influence of this dataset in the final model output has been deliberately reduced. The UPSM output was a 50 m raster with scores ranging from 3.5 to 17.5. Locations that have high aggregate scores were deemed to be have high natural susceptibility to coastal erosion as they represent areas with attributes that are the most similar to category ‘5’ of the susceptibility ranking i.e. low ground elevation, low rockhead

Table 1
Rationale for using the chosen parameters within the UPSM. MHWS = Mean High Water Springs.

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, and have potentially less volumes of sediment.	**Yes** (Alves et al., 2011; Arun Kumar and Kunte, 2012; Eurosion, 2004; 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)

Table 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 (OS)	Open
Rockhead Elevation	Superficial Deposit Thickness Model	Raster: 50 m	British Geological Survey (BGS)	Closed (Licensed)
Proximity to 'Open Coast'	Mean High Water Springs (MHWS)	Polyline: 1:10,000	Ordnance Survey (OS)	Open
Wave Exposure	Wave Fetch Model	Raster: 200 m	Scotland & Northern Island Forum for Environmental Research (SNIFFER)	Open

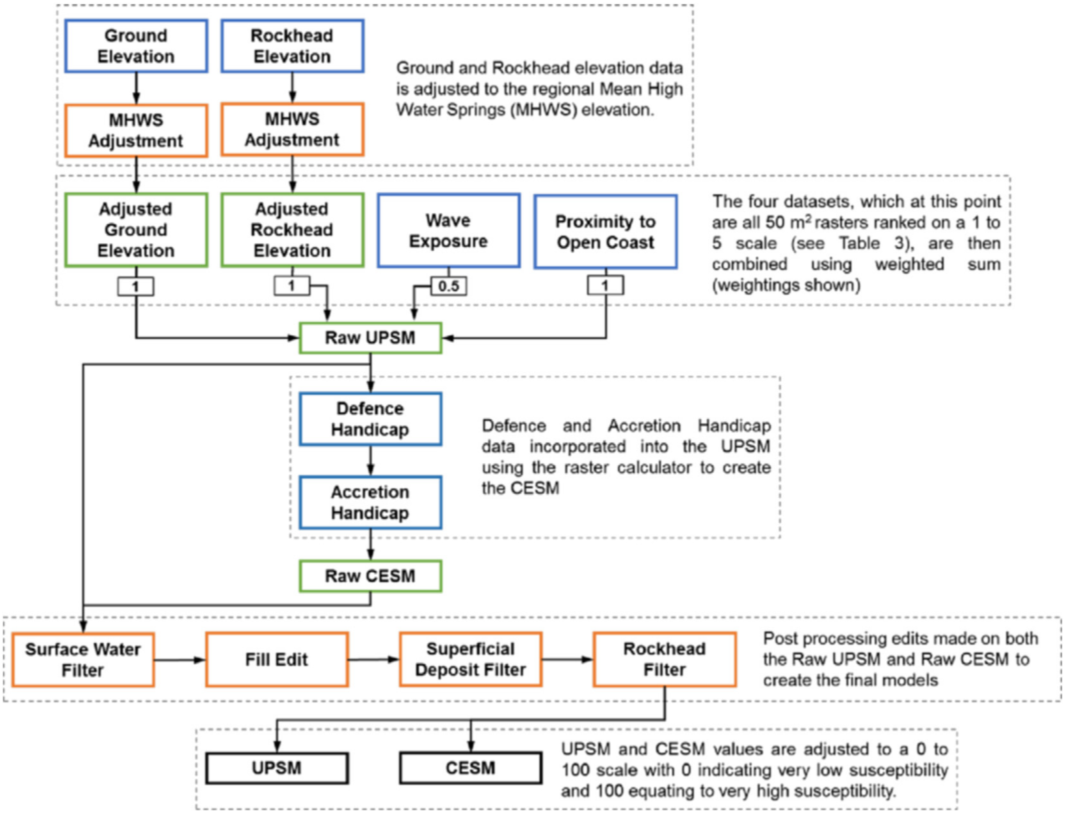

Fig. 2. A simplified methodology workflow to create the Underlying Physical Susceptibility Model (UPSM) and the Coastal Erosion Susceptibility Model (CESM). See Table 3 for the ranking used within the input datasets. Blue boxes correspond with input data, orange boxes are GIS processing steps, green boxes are intermediate data, and black boxes are the final outputs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

elevation, very close to the open coast, and with high wave exposure.

The UPSM model defines the inherent susceptibility of the coastal zone, and excludes the influence of coastal defences and the dynamic supply of sediment to, and within, soft shorelines, both of which reduce coastal erosion susceptibility. To take account of these two factors data on coastal defence structures was acquired from Halcrow (2011) and accretion data taken from the Eurosion (2005) dataset and the Coastal Cells in Scotland reports (Ramsay and Brampton, 2000), which were updated where necessary using expert knowledge and aerial photography. To integrate this data into the UPSM, a 'handicap' value was assigned to these two datasets. 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 (an example is shown in Fig. 4a). The accretion handicap has been applied with a series of buffers as the boundaries of accretion zones are difficult to define. Therefore, the seaward 200 m of cells with accretion received a handicap of −3 and the next 100 m of cells inland received a handicap of −2, followed by the next 100 m of cells inland which had a handicap of −1 (Fig. 4b). These buffers also grade along the coast at the end of the accretion zones. This results in a more realistic and less abrupt output, whilst emphasising the protective function the sediment

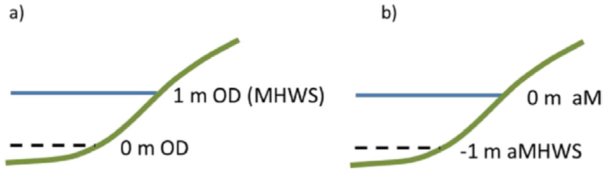

Fig. 3. A hypothetical example showing how the OS Terrain 50 (ground elevation data) was adjusted to MHWS a) The raw OS Terrain 50 DTM is relative to ordnance datum (OD), with MHWS elevation at 1 m above OD b) Shows the OS Terrain 50 after adjustment for the elevation of MHWS (DTM − MHWS elevation), hence elevations above 0 m represent elevations above MHWS. m aMHWS = metres above MHWS.

Table 3
Overview of categorisation and susceptibility rankings for each of 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. A rank of 5 represents very high susceptibility, with a rank of 1 indicating very low susceptibility.

	Susceptibility classification					
	Very high	High	Moderate	Low	Very low	Weighting
	5	4	3	2	1	
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

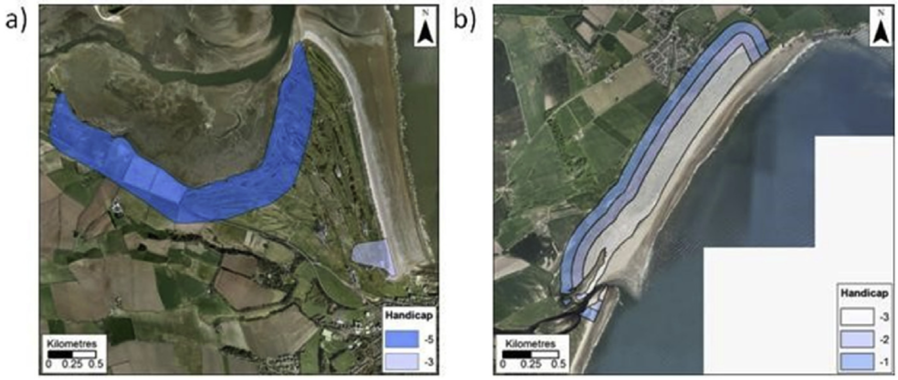

Fig. 4. Examples of the data format used to integrate (a) defence and (b) accretion handicap data into the CESM. Aerial photography supplied by the Ordnance Survey.

supply has on the immediate interior. Both the coastal defence and accretion handicaps were stopped at 400 m inland.

Using the raster calculator, the defence and accretion handicaps were subtracted from the UPSM. Where areas benefit from both coastal defences and accretion then the two handicap values were added together. Therefore, it is possible for areas of the UPSM to be reduced by a maximum handicap value of −8 (Defence Handicap (−5) + Accretion Handicap (−3) = −8). Following this calculation some raster values of less than 3.5 were created. In order to maintain the UPSM range of 14 (3.5–17.5), values of less than 3.5 were reclassified to 3.5. With the inclusion of coastal defences and accretion data, the model then became the Coastal Erosion Susceptibility Model (CESM).

Due to the processing methodologies applied to create the UPSM and CESM, there was some areas where coastal erosion susceptibility were overestimated. Therefore, a number of post-processing adjustments were made to improve the final outputs and to remove anomalous results. These include areas of inland water i.e. lochs, which are unlikely to be susceptible to coastal erosion and were therefore removed from the UPSM and CESM model by assigning a value of 3.5 to areas of inland water. Locations where the rockhead elevation was greater than 6 m above MHWS are unlikely to erode significantly, even in areas close to the coast and where wave exposure might be high. Therefore, the UPSM and CESM were reclassified to 3.5 in areas where the rockhead elevation was 6 m above MHWS. Areas where bedrock, rather than superficial deposits, was located at the surface level are unlikely to erode due to the generally hard and resistant nature of the bedrock geologies in Scotland. Due to their relative strength compared to superficial deposits, the different bedrock lithologies were treated equally. Where no superficial deposits exist and bedrock was at the surface, the UPSM and CESM were reclassified to 3.5. This post-processing step was not applied to the Outer Hebrides because this area was mapped by the British Geological Survey (BGS) at the same scale as the rest of Scotland. The UPSM and CESM identified some areas of elevated susceptibility relative to the surrounding area that were hydrologically disconnected from the coast. In reality, these areas were effectively protected by land that was unlikely to erode. An example is shown in Fig. 5a. These ‘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 (ESRI, 2016b), with the peaks reduced to match the surrounding cell values (Fig. 5b).

Finally, to allow the UPSM and CESM outputs to be more easily interpreted the aggregated scores were converted to a non-dimensional scale of 0–100 using the following method:

$$\frac{(UPSM\ or\ CESM\ Score - 3.5)}{14} \times 100$$

To further ease understanding the score within the UPSM and CESM is converted to a description (Table 4). Both the UPSM and CESM were output as a national 50 m raster. In addition, 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 respectively.

To determine whether the CESM accurately represents coastal erosion susceptibility the model was quantitatively validated using other datasets: Scottish Natural Heritage (SNH) coastal erosion case work data and Eurosion (2004) data. Both the SNH and Eurosion datasets highlighted where erosion was occurring and so the CESM should ideally classify these areas with a high susceptibility score. The model therefore could only be validated in locations where erosion was known to be active. Both the SNH and Eurosion data were translated onto the CESM coastline, and the average CESM score was then calculated for each stretch of coast identified as eroding.

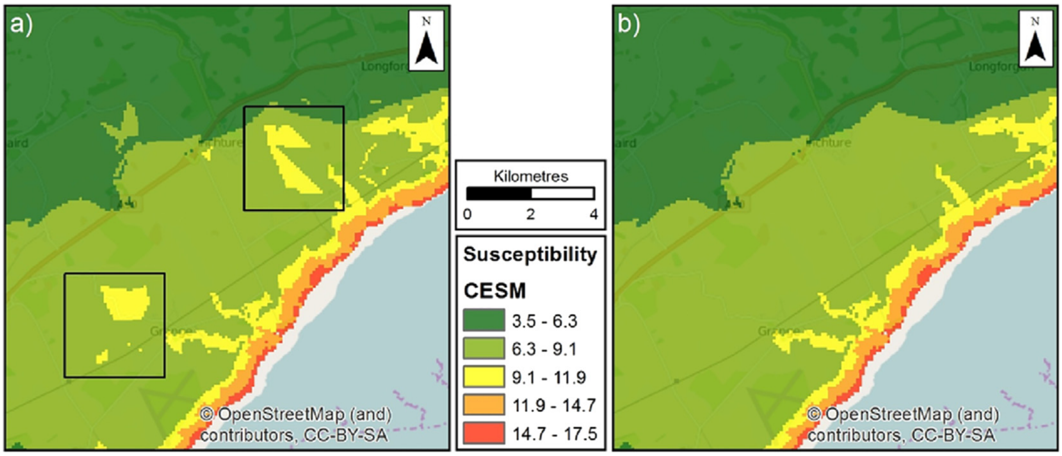

Fig. 5. a) areas of elevated erosion susceptibility relative to the surrounding area on the north side of the Firth of Tay can be seen (highlighted within black boxes) b) these areas have been removed using the 'Fill' tool in ArcGIS.

3. Results

To demonstrate the UPSM and CESM output, the area around Golspie, Highland Region, is used below as an exemplar (Fig. 6). The areas classified with very high susceptibility (red) have low ground elevations, low rockhead elevations, are situated near the open coast, and have high wave exposure. The influence that the presence of coastal defence and sediment accretion has on coastal susceptibility can be isolated by comparing the UPSM and CESM inset boxes in Fig. 6. The coast in the north of the inset boxes is protected by a boulder revetment and this allows a susceptibility reduction from the UPSM to the CESM. Furthermore, the area in the south of the box at Golspie benefits from sediment transported from the north to fuel accretion in the south and is reflected in a decrease in susceptibility due to this supply of sediment. Susceptibility peaks between these two areas at the southern end of the boulder revetment protection where end scour and flanking occurs as this area neither benefits from protection or accretion.

The UPSM and CESM are best observed in a GIS environment. Consequently, both models have been made available via a web map: http://www.jmfitton.xyz/cesm_scotland using GeoServer and OpenLayers 3 to allow the user to fully explore the data at various levels of detail. Table 5 provides a summary of the national statistics for the UPSM and CESM.

3.1. *CESM validation*

In order to validate the outputs of the CESM, the average CESM score at its erosion locations was compared to locations of known coastal erosion reported from SNH case work records and Eurosion (2004) data. The SNH data identified 63 locations currently experiencing erosion (Table 6), and the Eurosion data identified 32 locations with confirmed coastal erosion (Eurosion codes 50 and 51) (Table 7).

Table 4
The description of coastal erosion susceptibility used within this research based upon the UPSM or CESM score.

UPSM or CESM score	Coastal erosion susceptibility description
0 to $\leq$ 20	Very Low
>20 to $\leq$ 40	Low
>40 to $\leq$ 60	Medium
>60 to $\leq$ 80	High
>80 to $\leq$ 100	Very High

The SNH casework data shows that 83% of coasts identified as eroding by the SNH data are classified as highly or very highly susceptible to erosion (a score of greater than 60) by the CESM. There are 4 locations (1.8 km of coast) which are eroding but the CESM average score is less than 20, indicating that the CESM underestimates the susceptibility in these locations. Through the author's knowledge of these locations, these sites are known to be a combination of extensive intertidal rock platform, sand and gravel beaches. The input data is not of sufficient resolution to identify these nuances, hence reduces the CESM score below what would be expected at such sites. Of the locations confirmed as eroding by the Eurosion data, 91% were classified by the CESM as highly or very highly susceptible to erosion (score of greater than 60). There were no locations that achieved an average score of less than 40. The validation results for the both the SNH and Eurosion data strongly support the notion that the CESM accurately models coastal erosion susceptibility.

4. Evaluation

In the majority of locations the CESM appears to produce an accurate representation of erosional susceptibility as demonstrated by the validation results. However, there are three scenarios where the model potentially misrepresents susceptibility. 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 those actually at the coast, for example along the River Clyde at Renfrew (Fig. 7a). 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 could be generated which more accurately reflects individual coastal defences.

The second scenario where the model can be considered to

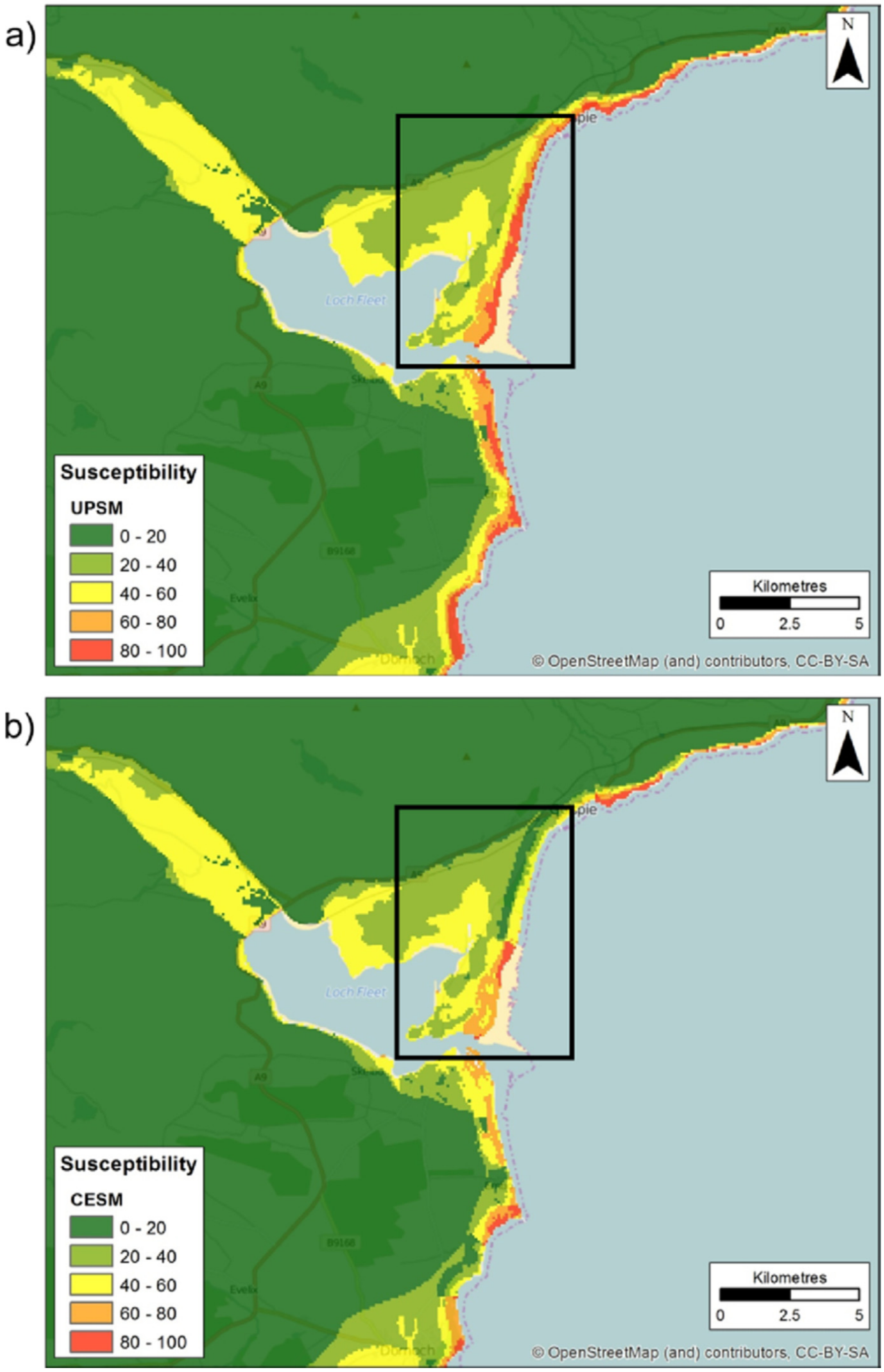

Fig. 6. Example of (a) the UPSM and (b) the CESM for the area surrounding Golspie, Highland Region. The UPSM and CESM can be accessed at http://www.jmfitton.xyz/cesm_scotland.

misrepresent susceptibility is in areas of saltmarsh. The CESM highlights the fact that saltmarsh possesses attributes to suggest that it is erodible (Fig. 7b), however this may be overestimated. Areas of saltmarsh offer the ecosystem service of coastal protection by attenuating wave energy as the marsh is traversed. 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. The inclusion of additional ecosystem services within the model and beyond sediment accretion is worthy of further consideration in future iterations.

The third scenario where the model underperforms is where areas of low elevation extend substantial distances inland. This is demonstrated in the upper Forth and Carse of Stirling (Fig. 7c), where the valley extending inland has only a shallow elevation gradient from MHWS. As a result, the model classifies these areas with heightened susceptibility. The CESM score for these types of areas is usually below a score of 60, as the increasing distance from the coast and wave exposure parameters serves to reduce susceptibility and the CESM classifies accordingly. However, it may be unrealistic to expect these areas to be exposed to coastal erosion at all in the medium term and a correction for future iterations could

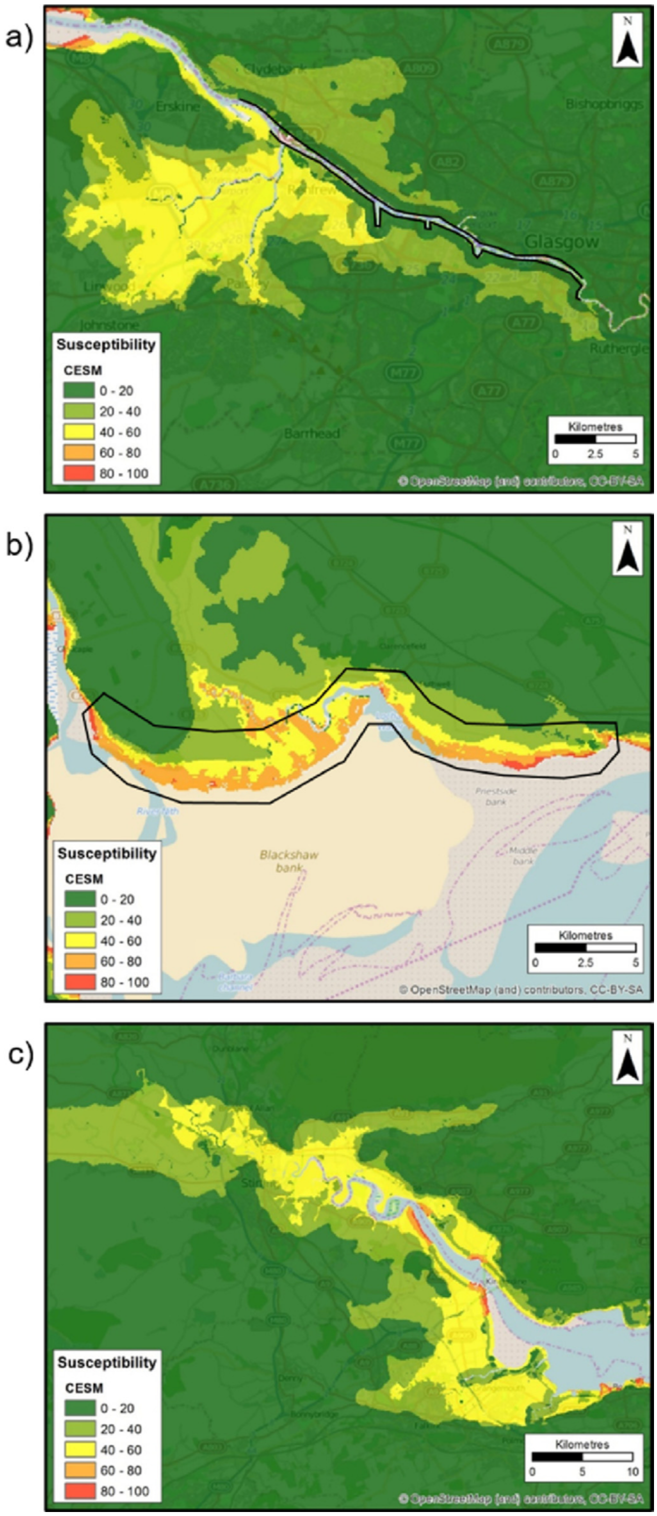

Fig. 7. a) CESM for the River Clyde at Renfrew near Glasgow showing the model overestimation of susceptibility behind defences (highlighted in black), b) Example of saltmarsh (within the black box) classified with high susceptibility at Clarencefield in the Solway Firth, c) Example of the model classifying areas far inland with heightened susceptibility due to the shallow elevation gradient from MHWS in the inner Firth of Forth and Carse of Stirling. The UPSM and CESM can be accessed at http://www.jmfitton.xyz/cesm_scotland.

limit the distance to coast parameter to exclude areas beyond a specific distance as having no susceptibility (e.g. areas greater than 400 m from the coast are removed from the analysis).

The influence of tidal range was not considered within this model due to the relatively consistent mean spring tidal range of between 4 and 5 m around the Scottish coast (Scottish Government, 2011). However, the tidal range can locally narrow, such as the amphidromic point between Islay and the Mull (1–2 m), and widen, as seen within the Solway Firth (7–8 m). As the CESM was focussed primarily at the national scale, the influence of the local tidal range upon coastal erosion susceptibility were not incorporated within the CESM. The inclusion of this data will be explored in future iterations of the model.

5. Discussion

It is important to state that the CESM does not identify areas where erosion *is* ongoing, nor where erosion *will* occur in the future. The CESM identifies locations where erosion *can* occur. Nevertheless, the CESM can be used in conjunction with a wide range of coastal asset data to identify those assets that are currently inherently exposed to coastal erosion and are therefore a priority for targeted coastal management effort. Examples include the locations of residential property, roads, railtrack, sewage pipes and works and a wide variety of coastal infrastructure and industrial sites. The CESM can also be used together with an assessment of socioeconomic vulnerability of the population resident at the coast in order to determine their exposure to coastal erosion risk. The methodological approach used here produced the UPSM as an intermediate dataset, however the UPSM can also be regarded as a valuable output as it represents the physical properties of the natural coast without the influence of coastal defence or sediment accretion. The CESM can therefore be compared to the UPSM to assess the value/benefit of existing or planned defences, the benefit of maintaining existing defences at their current level into the future, and the ecosystem service benefit of natural landforms and accretion.

With the changes that are predicted due to climate change, there is often a necessity to extrapolate current trends into the future. The CESM currently does not offer any insight into *when* erosion may occur in the future. Due to the potential future changes that could occur with regards to human interference, and 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 as they vary across locations is problematic. For the CESM, an approach has been taken that means that no future predictions are necessarily needed. The approach is similar to the way in which the National Oceanic and Atmospheric Administration (NOAA) in the United States manages the threat of hurricanes. NOAA does not devote time and resources to predicting where individual hurricanes over a hurricane season are most likely to hit the coast (NOAA, 2014a). Instead, they forecast the long-term trends (NOAA, 2014b) and attempt to ensure that the coastline potentially exposed to hurricanes is adequately prepared if one does occur. Only when an individual hurricane forms, and additional data are collected and analysed, can the path of the hurricane be 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, the utility of the CESM lies in its early deployment as a proactive, rather than a reactive, tool.

The CESM has not been tailored for a specific application other than to model coastal erosion susceptibility. The advantage of this approach is that the CESM can be used for a range of different end uses. For example, a version of the CESM is currently in use by the Scottish Environment Protection Agency (SEPA) to assist in their flood risk management assessments (Hansom et al., 2013a; 2013b, see http://map.sepa.org.uk/floodmap/map.htm) The CESM is used

Table 5
National statistics for the UPSM and CESM.

Model format	Model statistic	Susceptibility score				
		0–20	20–40	40–60	60–80	80–100
		Very low	Low	Moderate	High	Very high
Coastline Polyline (outer edge of raster)	UPSM (km)	10,239	555	2691	2028	2719
	UPSM (%)	56.2	3.0	14.8	11.1	14.9
	CESM (km)	10,286	788	2903	2155	2100
	CESM (%)	56.4	4.3	15.9	11.8	11.5
	Difference between CESM and UPSM (km)	47	233	212	127	−619
Raster	UPSM (km^2)	76,894	962	830	339	258
	CESM (km^2)	76,959	1008	829	309	179
	Difference between CESM and UPSM (km^2)	65	46	−1	−30	−79

Table 6
Comparison of known erosion locations (SNH coastal erosion casework) and the average CESM score for the same coastline.

Average CESM score	SNH erosion locations		
	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

Table 7
Comparison of known erosion locations (Eurosion codes 50 and 51 data) where no defences are present and the average CESM score for the same coastline.

Average CESM score	Eurosion erosion locations		
	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

by SEPA to identify areas where coastal erosion may exacerbate coastal flooding by removing natural flood defence assets e.g. beach ridges, sand dunes, salt marsh. As a result of the success of applying the CESM to the SEPA flood risk assessments, and a realisation for the need for further information on coastal erosion in Scotland identified by the CCRA for Scotland (Defra, 2012), the Scottish Government commissioned the National Coastal Change Assessment (NCCA) in 2014 (see http://www.dynamiccoast.com). The NCCA seeks to use past coastal change rates to allow estimates of the coastline position to be projected into the future. Where erosion can be demonstrated to be occurring then the future coastline position projection can be mediated by the CESM in order to limit erosion only to the areas where the hinterland is susceptible to coastal erosion. 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 identify areas that are currently erosional or may become susceptible to erosion in the coming decades and require management action. The NCCA national scale assessment of coastal change has not been undertaken previously and its utility would have been very restricted without the CESM and the availability of supporting national datasets.

Although the discussion thus far has focussed upon coastal erosion as a problem, coastal erosion is not necessarily negative. The absence of substantial supplies of sediment from elsewhere on the Scottish coast (Hansom, 1999) means that coastal accretion depends upon coastal erosion occurring somewhere else along the coast. Such sediment accretion is allocated an implicit value within the CESM since it reduces susceptibility. Coastal erosion is only considered a problem where it impacts upon assets, yet knowing where erosional sources (or potential sources) of sediment actually are (or will be), 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. Conversely, construction of the same seawall may ‘switch on’ erosion in front of the defence and down drift (potentially creating an on-site problem if assets become impacted), but which itself may release sediment to fuel accretion elsewhere. Therefore *both* coastal erosion and accretion processes can be seen to be ecosystem services of great value, and ones that can be investigated and proactively managed by the CESM.

6. Conclusion

This paper has set out to introduce two interrelated models that aim to directly address a pressing need to improve the national scale understanding of coastal erosion within Scotland, in order that the potential direct and indirect impacts on coastal communities and assets can be fully assessed and better inform sustainable coastal management. The Underlying Physical Susceptibility Model (UPSM) and a Coastal Erosion Susceptibility Model (CESM) have national 50 m^2 raster and polyline outputs and respectively classify 2718 km (14.9%) and 2100 km (11.5%) of the Scottish coastline as having very high erosion susceptibility. The models are already in use in improving SEPA's flood risk management assessments, as well as highlighting the potential impacts of coastal erosion at a national level within Scotland. This has led to the development of the historic and forward-looking NCCA project that aims to support multiple statutory and non-statutory policy areas (e.g. Scottish Planning Policy, Flood Risk Management Strategies, Strategic and Local Development Plans, the Climate Change Adaptation Programme and National and Regional Marine Plans). Future research aims to apply the UPSM, CESM and NCCA to assess the key assets, communities and socioeconomically vulnerable elements of the population that may be exposed or potentially become exposed to coastal erosion in Scotland. The models and the associated research outputs will empower government and local authorities to proactively develop effective and sustainable management of the current and future coast.

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