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# A methodology for urban micro-scale coastal flood vulnerability and risk assessment and mapping

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## Abstract

One of the most dangerous challenges to settlements in the UK comes from flooding. Currently, there is extensive map coverage of flood hazards zones in the UK; however, it is increasingly recognised that risk associated with natural hazards cannot be reduced solely by focussing on the hazard. There is also an urgent need for methods of evaluating and mapping flood vulnerability and risk in detail. Despite its significance, conventional flood risk assessment methodologies often underestimate likely levels of vulnerability in areas prone to hazards, yet it is the degree of vulnerability within a community that determines the consequences of any given hazard. The research presented proposes a general methodology to assess and map Coastal Flood Vulnerability and Risk at a detailed, micro-scale level. This captures aspects that are considered crucial and representative of reality (socio-economic, physical and resilient features). The methodology is then applied to a UK case study (city of Portsmouth). Environment Agency flood hazard data, National Census socio-economic data and Ordnance Survey topographic map data have been used to evaluate and map coastal flood vulnerability, examining neighbourhoods within census wards. This led to a subsequent analysis of Coastal Flood Risk, via the combination of a Coastal Flood Vulnerability Index and a Coastal Flood Hazard Index, for the Portsmouth ward Hilsea. This, consequently, identifies potential weaknesses that could lead to more effective targeting of interventions to improve resilience and reduce vulnerability in the long term and provides a basis for hazard and environmental managers/planners to generate comprehensive national/international vulnerability and risk assessments.

**Keywords** Coastal flooding · Vulnerability · Risk · Neighbourhood · GIS

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## 1 Introduction

Globally extreme floods are among the most destructive forces of nature (Rougier et al. 2013; Lamond 2012). In the UK, the UK Climate Change Risk Assessment (UKCCRA) has identified flooding as the greatest risk posed by a changing climate (DEFRA 2015). Currently, some 5.2 million properties in England and Wales are at risk of flooding (Environment Agency 2017), and less than 10% of those 5.2 million are aware of it. Furthermore, even fewer have flood response plans or understand the potentially devastating long-term consequences flooding can have.

Coastal areas are particularly susceptible to increases in frequency and magnitude of flood events via climate change (IPCC 2014; Chang et al. 2015). Coastal communities tend to rely on coastal ecosystems, seasonal employment related to high levels of tourism and other transient groups (students), infrastructure and communications, resulting in higher levels of vulnerability to major hazard (storms, coastal erosion, coastal flooding and sea-level rise) impacts (Benzie 2014). Added to this, coastal floods can lead to differential levels of impacts (e.g. loss of life, damage to the built and natural environments or extreme disruption to the lives of the population affected) on coastal communities due to varying extents of local vulnerability (physical and socio-economic). Coastal zones are socially, economically and environmentally important. They attract economic activity and settlements that lead to urbanisation, extension of infrastructure and other land use changes, ultimately resulting in further increases in flood vulnerability of coastal communities over time. This research has sought to assess and map UK Coastal Flood Vulnerability (CoFV) and Risk (CoFR) at a detailed, micro-scale level, examining neighbourhoods within census wards. This captures relevant features of coastal flood vulnerability (pre- and post-impact), assists our understanding of the reality of local vulnerability, in order to understand flood risk in detail, and results in an opportunity to prepare for and adapt to future flood events, at the level of detail necessary to deliver effective solutions.

Within this paper, *risk* is seen as an interaction of coastal flood hazard and vulnerability where risk refers to the interaction of hazards and areas/systems/communities' vulnerability, i.e. an outcome of exposure, susceptibility and resilience. Hazard refers to the possible future occurrence of natural events (e.g. storm surges) that could have serious adverse effects on vulnerable communities/areas (e.g. loss of life, injury, other health impacts, damage/loss to property, infrastructure, livelihoods, ecosystems and environmental resources) (Birkmann 2006; Ramieri et al. 2011; Cardona et al. 2012; IPCC 2014).

Yet to understand and assess flood risk in detail there needs to be an assessment of vulnerability and uncertainty. It has been increasingly recognised that risk associated with threats to human society cannot be reduced by solely focussing on the hazard component (Lindley et al. 2011; Birkmann et al. 2013). The concept of risk is a combination of the likely impacts/consequences from a hazardous event and the probability of that event (Ramieri et al. 2011; IPCC 2014). A flood risk assessment should therefore incorporate the interaction between the nature of the event (flood hazard) and the inherent characteristics of the area and population at risk (vulnerability) (Green et al. 2000; Cancado et al. 2008). This is crucial for natural hazard risk management, not only in the evaluation of strategies to increase resilience, but also in risk communication leading to successful mitigation (Rougier et al. 2013). Natural hazards, like the environmental systems in which they occur, are full of many interactions and nonlinearities: our understanding of their nature and our ability to predict their behaviour is therefore limited (Rougier et al. 2013). It is therefore vital to acquire and disseminate the most accurate information, where possible, in detail, of

the risk community's face, in order to inform flood risk and environmental managers where levels of underlying vulnerability ('pressure points') are at their highest, guide emergency planners where perils may arise, and assist creation of policies to utilise and target limited resources.

Understanding levels of flood vulnerability in an area is therefore a key step towards effective flood risk reduction and resilience. The concept of vulnerability underscores the social construction of risk and can be applied to assist understanding of risk of the disaster. Within flood affected communities, people and areas experience different levels of impacts according to their degrees of vulnerability (Birkmann et al. 2013). The hazard event is consequently no longer seen as the sole driver of risk. In fact, adverse effects are also determined by the vulnerability of societies and their systems, and this can be defined by three distinctive components—physical vulnerability (exposure), socio-economic vulnerability (susceptibility) and limited resilience (limited existing capacities, e.g. access to and mobilisation of resources). Therefore, in the methodology presented in this research, the traditional risk, hazard and vulnerability relationship has been modified to determine vulnerability and risk, by bringing together those three components (physical vulnerability, socio-economic vulnerability and limited resilience) into one measurement (see Sect. 2.1). This results in a formula that can cater for the assessment of vulnerability's many factors as vulnerability encompasses a variety of elements that are exposed, susceptible and unable to cope or adapt to harm.

A methodology to measure and map coastal flood vulnerability and risk in detail is presented within the remainder of this paper. This methodology can be used to identify those characteristics and individualities of coastal communities that enable them to cope, recover and respond to coastal flooding, crucially giving as detailed 'a picture' as possible. Within the format presented, no judgement was made on the relative importance of different vulnerability factors, i.e. equal weights were applied. The equations used in this analysis link the values of all the factors to their coastal flood vulnerability components and to coastal flood risk, with equal weighting. A similar approach was used by Balica et al. (2013) for the Flood Vulnerability Index (FVI), by Lindley et al. (2011) for the Flood Socio-spatial Vulnerability Index, by Peduzzi et al. (2001) for the River and Coastal Flood Disadvantage Index, by Briguglio (2004) for the GRAVITY index, and by Rygel et al. (2006) for the Economic Vulnerability Index. The methodology presented has been applied to the city of Portsmouth, UK, with results from the electoral ward of Hilsea (located on Portsea Island) shown as example. However, there is an opportunity for this methodology to be applied in other countries, where flood risk (particularly coastal) is prominent. And unlike others, this methodology offers an opportunity to alter the weights to all of the vulnerability factors, if so desired. The final part of this paper discusses the implications, applications, uncertainties and opportunities to improve this methodology.

## 2 Methods and data

### 2.1 Indexing, formation and compilation

The combination of all factors related to vulnerability can significantly increase or decrease the potential impacts for those at risk (England and Knox 2015). Flood risk is the product of the flood hazard and a community's vulnerability to it, with high levels of vulnerability combined with significant inundation, resulting in high levels of risk. Therefore, to reduce

flood vulnerability and risk, a key task is the definition of vulnerability and the mechanisms for its identification. It is therefore critical to understand flood vulnerability and the context in which it has evolved, including the scale needed for analysis in order to analyse and understand information that represents reality. For this research, Eq. 1 was developed to assess coastal flood vulnerability and risk, combining the different components and factors of vulnerability into one model.

$$R = H \times V(PV, SV, LR) \quad (1)$$

where  $V(PV, SV, LR) = PV + SV + LR$ .  $R$  is risk;  $H$  is hazard;  $V$  is vulnerability,  $PV$  is physical vulnerability;  $SV$  is socio-economic vulnerability; and  $LR$  is limited resilience.

However, several different data sources being incorporated into one model require a standardisation of the data, to ensure uniformity in scales and units (Cutter et al. 2003; Tapsell et al. 2010; Menoni et al. 2012). Therefore, an index approach was adopted to enable all the different vulnerability factors to be combined into their respective CoFV components: physical vulnerability, socio-economic vulnerability and limited resilience.

Index-based approaches have been developed and utilised in previous research in order to measure vulnerability (e.g. Sullivan and Meigh 2003; Connor and Hiroki 2005; Lindley et al. 2011), including several that specifically concentrate on the vulnerability of coastal communities (Balica et al. 2012; Chang et al. 2015). An index is made of a set of factors, which can be defined as inherent characteristics that quantitatively estimate the condition of a system, i.e. they usually focus on minor but telling pieces of that system that can give users a sense of the bigger picture (Balica 2012a, b). They are a tool that can guide decision-makers to a holistic understanding of the current states of a system, indicating areas that need the most attention with the often limited budgets available for flood management (Balica 2012b). When assessing CoFV, it is vital to create understandable links between the theoretical concepts of vulnerability and decision making processes, i.e. encapsulating that link in an accessible tool (Balica et al. 2012), e.g. a Coastal Flood Vulnerability Index (CoFVI).

The factors used in this research have been deduced through theoretical research (Cutter et al. 2003; Kaźmierczak and Cavan 2011; Lindley et al. 2011; Birkmann et al. 2013) where links have been derived from a theoretical framework, with proxies chosen based on those links (Damm 2010; Balica et al. 2012). The factors used were screened for their suitability, definition (or theoretical structure) and their data availability. Hazard and vulnerability indices were then created and finally combined in Eq. 2, to create a Coastal Flood Risk index (CoFRI).

$$\text{CoFRI} = \{\text{CoFHI} * \text{CoFVI}(\text{CoFPVI}, \text{CoFSVI}, \text{CoFLRI})\} \quad (2)$$

The result is a simple numerical basis for ranking sections of coastlines in terms of their potential for impact and change, identifying regions most at risk. For this study, 31 data variables were used for the CoFRI methodology; 29 of the variables were used for the CoFVI, split into three vulnerability component indexes: Coastal Flood Physical Vulnerability Index (CoFPVI), Coastal Socio-economic Vulnerability Index (CoFSVI), and Coastal Flood Limited Resilience Index (CoFLRI).

## 2.2 Coastal flood hazard and vulnerability: factors and data

Coastal vulnerability assessments still focus mainly on climate change aspects, such as sea-level rise, flooding potential and overall risk of flooding. To better support the development of coastal management policy and planning, integrated assessments of climatic change in

coastal areas are required, including the significant non-climatic aspects such as physical (the land), socio-economic and resilient indicators (Nicholls et al. 2008). When measuring coastal flood risk, it is essential to know where the potential flood zones could be situated. Whatever is situated in those zones will dictate the risk of those areas. Within this study, the hazard assessment involved the analysis of a neighbourhood's inundation (flood water) coverage from floods of different magnitudes. Flood hazard zones produced for the Solent Strategic Flood Risk Assessment (SFRA) were used within this study to measure coastal flood water surface area coverage, especially the 'Undefended Hazard' map set (Havant Borough Council per comms 2012; PUSH 2009). The SFRA Flood Zones are provided by the Environment Agency (EA) and present the hazard zones posed by flooding without consideration of the mitigating effect of existing flood defences (Atkins 2007). The 'Undefended Hazard' map layers gave examples of the hazard posed by the flood water within these zones, in the form of a hazard index. This set is a function of velocity and depth of the flood water, i.e. the indices within each EA Flood Zone, (2 (FZ2) (1 in 1000 year event) and 3 (FZ3) (1 in 200 year event)) have been estimated using assumptions and methods used in the best practice guidance (Defra/Environment Agency Flood and Coastal Defence R&D Document: Flood Risk to People 2006). For example, the FZ2 index data are based on what the potential depths and velocity flood water could be during a 1 in 1000 year event. These flood zones were clipped to each neighbourhood, and the total surface area ( $m^2$ ) each flood hazard zone covered was measured. As all neighbourhoods have different geographical areas, a ratio of the inundation area against the surface area for each neighbourhood was calculated, enabling a fair comparison of the flood hazard between each neighbourhood. These results populated the Coastal Flood Hazard Index for a Flood Zone 3 and 2 events. The data used in this study to populate the hazard index are available for England and Wales, but similar information is available worldwide.

Residential areas with an inadequate physical environment or inappropriate housing suffer the most in natural disasters (White et al. 2004; Wamsler 2006). To summarise, there is a close relationship between natural disasters and sustainable urban development (Ayala-Carcedo 2004; Wisner et al. 2004); in fact in recent years, floods in metropolitan areas have shown that environment-compatible urbanisation has not yet occurred (Başaran-Uysal et al. 2014). Therefore, in order for successful urban flood mitigation to occur, the degree of physical vulnerability in urbanised areas needs to be determined (Başaran-Uysal et al. 2014). Physical vulnerability includes the physical assets which are present at the location where floods can occur, i.e. buildings, roads, power stations, critical infrastructure, land, dwellings/households, individuals, and their proximity to the coastline, etc. (Każmierczak and Cavan 2011; Cardona et al. 2012; Menoni et al. 2012). I.e. it is the predisposition of the essential urban characteristics within an exposed community/area (Birkmann 2006; Każmierczak and Cavan 2011; Lindley et al. 2011; Birkmann et al. 2013; Cutter 2006) that will either exacerbate or reduce a floods impact (Cardona et al. 2012). To characterise an area's physical vulnerability, essential physical characteristics were identified through literature review, observation and evaluation. This results in the creation of a set of physical vulnerability factors to guide data selection and manipulation, including *population density, green areas, essential buildings, utilities, transport, dwellings, tenure, commercial and industrial areas* and *vulnerable buildings*. This ensues land use and population density geoinformatic variables needed to represent the physical factors. Within this study, the majority of the physical vulnerability factors required data not readily available. Initial investigations of the OS Mastermap Topography Layer and Mastermap Address Layer 2 datasets indicated that the data required were present (and available for other case studies) but concealed within many layers. A screening of the data for land use information

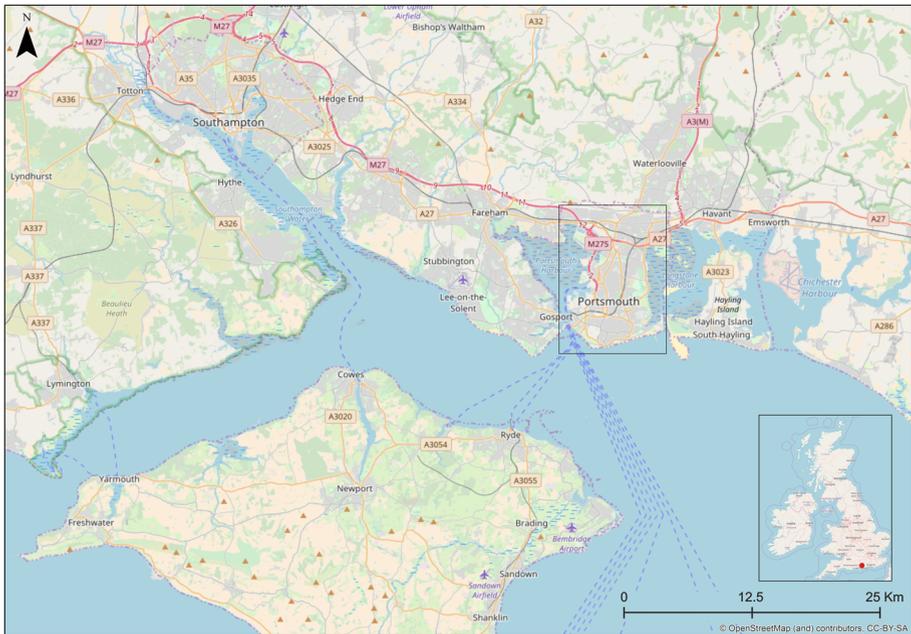
resulted in a process of elimination of certain OS data layers that did not assist the assessment of physical vulnerability. A new coastal vulnerability land use classification system was then created within ArcGIS software to aid extraction of OS data required to populate the selected physical vulnerability factors, resulting in an analysis of the built environment.

A vulnerability analysis involves the identification of conditions that make people and places vulnerable to extreme natural events (Cutter et al. 2003; Cardona et al. 2012; Birkmann et al. 2013). Flooding can particularly affect the day-to-day lives of receptors in the flood water pathway. Along with transport disruption and damage to buildings and infrastructure, flooding also impacts human lives, possibly fatally. Within this paper, the socio-economic component involves the issues (susceptibility) related to humans and economy, i.e. deficiencies in the mobility of humans due to age, gender, or general disabilities, and issues related to the income or other issues that are related to economics, which are predisposed before disaster occurs (Cutter et al. 2008). Essential socio-economic characteristics were identified through literature review, observation and evaluation. This results in the creation of a set of socio-economic vulnerability factors to guide data selection, these included *age, household structure, illness or disability, proficiency in local language, economic, providers of unpaid care, occupation, communal establishment residents, and home population*. For this study, the data available to populate all the assessed factors were collected from the 2011 UK National Census (January 2013 version), under the Open Government Licence v2.0, and estate agent websites (sold house prices via [www.rightmove.co.uk](http://www.rightmove.co.uk) and [www.zoopla.co.uk](http://www.zoopla.co.uk) for each post code present in each individual neighbourhood [Output Area (OA)] were collected from 2011 to 2014, providing a mean value that represented the economic factor for each neighbourhood in the Hilsea ward). These datasets are all freely available and can be used for other UK case studies.

Flood resilience can be seen as a community or system's ability to either defy or alter itself, so that the damage of floods is either mitigated or minimised. Within this research, resilience is analysed in a negative state as 'limited resilience', where resilience refers to the capacity of linked systems to absorb recurrent disturbances, such as storms or floods, so as to retain or adapt and mitigate or avoid harm, maintaining a significant/acceptable amount of processes, functioning and structure (Adger 2006; Balica 2012a). Limited resilience is determined by limitations, in terms of access to, and mobilisation of, the resources of a community or system in responding to a hazard (Birkmann et al. 2013). This includes pre-event risk reduction, in-time coping and post-event response measures (Birkmann et al. 2013). The essential limited resilience characteristics were identified through literature review, observation, evaluation and data availability. A set of resilience factors were created to guide data selection, including *socio-economic status, education, car ownership and emergency facilities*. Within this research, these factors were populated by 2011 UK National Census Datasets (January 2013 version) and certain OS Mastermap Topography Layers and Address Layer 2 data.

### 2.3 Case study: Portsmouth, UK

To test the CoFRI methodology, areas within the island city of Portsmouth were used (Fig. 1). Portsmouth lies within the Solent region, and the city is split between the mainland and Portsea Island with 45 km of open coastal frontage. Portsmouth's primary source of flood risk is from the sea (Portsmouth City Council 2011a, b, c; Wadey et al. 2012), as the majority of Portsea Island is less than 10 m above mean sea level, with approximately 47% of the city land area designated as within FZ2 and FZ3 (Atkins 2007, 2011). Were it not for the



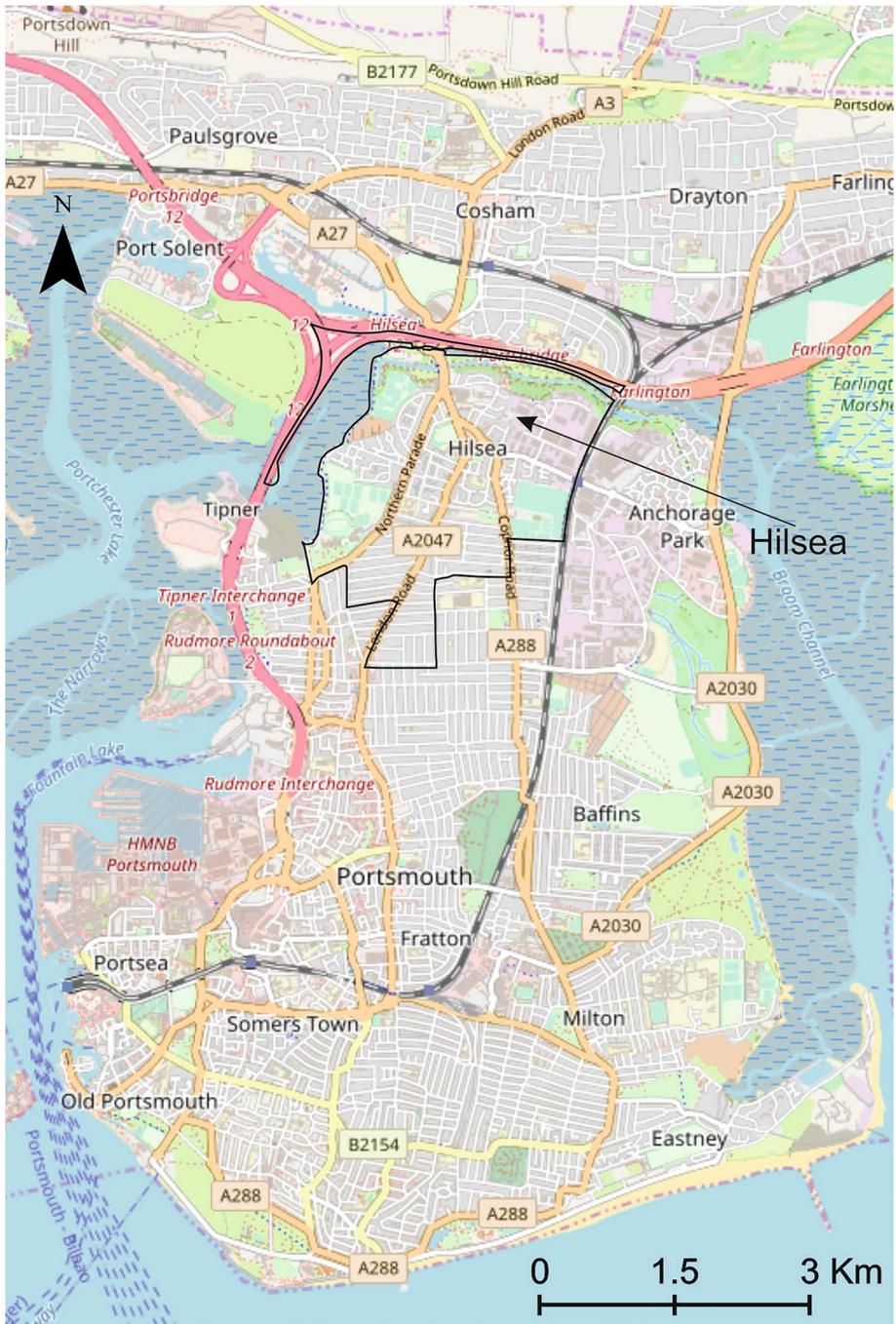
**Fig. 1** Location map of Portsmouth and the Solent within the UK Map data © OpenStreetMap contributors

coastal defences, a 1 in 200 year event (FZ3) would inundate more than 24,000 properties in the Solent (Wadey et al. 2012, 2013; NFDC 2009), and over 15,000 of these properties are situated in Portsmouth alone, making Portsmouth the third most exposed (in terms of properties within the hazard zone) city to coastal flooding in the UK, after London and Hull (NFDC 2009; Building Futures 2009). 87% of Portsmouth is covered by existing development with a population density of 5141 individuals for each sq km. Of the remaining 13%, 8% of the city is within environmental protection areas (Atkins 2011). Future developments within Portsmouth will have to occur on brownfield sites, leading to likely intensification of dwelling density. The UK South East Plan (GOSE 2009) has allocated an additional 14,700 homes to be built in Portsmouth before 2026, further constraining development in the city and increasing pressure on flood risk management practices (Environment Agency 2010).

The Hilsea ward in Portsmouth was one of the wards chosen to develop and test the methodology (Fig. 2) (Hilsea is shown in this paper as an example). It is a ward within Flood Cell 4 of the local SFRA and has been identified by Portsmouth City Council (2011a) as a critical area, due to its high risk to life from inundation and high capital costs for flood defences. Hilsea is situated in the north-west corner of Portsea Island and is of low relief (less than 10 m above mean sea level). The land cover is mainly residential, although it has significant industrial/commercial areas, along with substantial open spaces in the form of parks and playing fields and ancient monuments.

## 2.4 Reducing the number of variables

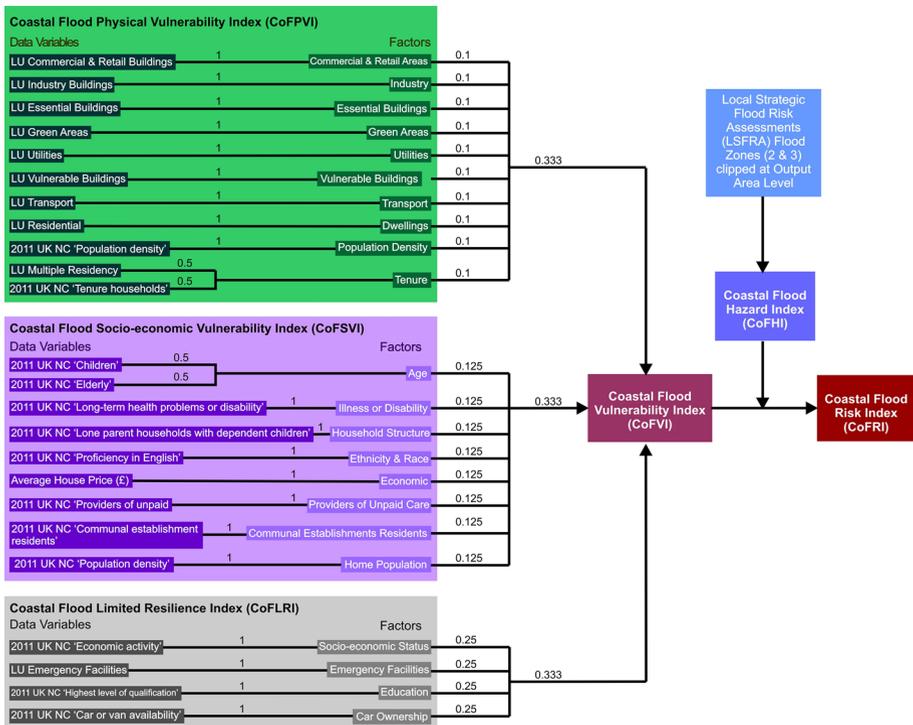
All Hilsea datasets were screened for singularity or multi-collinearity, which can cause significant problems when analysing large volumes of data. Large datasets can cause



**Fig. 2** City of Portsmouth ward boundaries. Hilsea ward highlighted. Map data © OpenStreetMap contributors

difficulties finding unique data contributions of the variables to the factors being determined, simply due to their size and the impracticality of the task. The data screening ensured that data which were very highly correlated were isolated from the model before indexing took place. Therefore, in order to identify the most significant vulnerability factors within the study (shown in Fig. 3), each data variable was re-analysed for relevance, i.e. did all the variables chosen portray the reality of coastal flood vulnerability (Każmierczak and Cavan 2011; Balica 2012b). This led to the removal of two CoFSV variables: *Country of Birth* and *Number of Students*. To screen the data further, a Pearson’s correlation test was applied to the remaining variables comparing the CoFV component factors against one another. If two factors had a strong correlation (i.e. > 0.75), this suggested they were too similar in type and could cause multi-collinearity, affecting the overall CoFVI results.

The strongest correlations were between the variables *Gender* and *Home Population*, and *Home Population* and *Part-time Workers*. This high correlation was understandable, as they are population datasets, and a majority of the *Home Population* would be women, and a vast majority of the population would work. Hence, this results in strong correlations between these particular variables. The *Gender* variable also had strong positive correlation results, with *Children* and *Part-time Worker* variables. After further scatter plot investigations, the *Home Population* variable was kept and *Gender* and *Part-time Workers* were removed. As *Home Population* contained the female population, the *Gender* variable was seen as an unnecessary duplicate. The scatter plots also displayed



**Fig. 3** Final model of CoFRI and CoFVI data variables and vulnerability factors, with added weights (*LU* New Land Use Classification and *NC* National Census)

a strong positive relationship between *Home Population* and *Part-time Workers*. As both of these variables are in the same vulnerability component (CoFSV), to avoid risk of bias within the CoFSVI, the *Part-time Workers* variable was removed. Sometimes causality can be the reason for positive trends (i.e. what connects one process, the cause, with another process, the effect, where the former is partly responsible for the latter and the second is partly dependent on the former), but in examples such as *Home Population*, *Gender*, and *Part-time Workers*, the datasets were too similar and likely to cause multi-collinearity altering the CoFVI results.

The final 27 data variables (see Fig. 3) were standardised before incorporation into the CoFRI in order to ensure uniformity in scales and units. In general, proportional normalisation was used, keeping the relative data ratios as they were, before standardisation (Balica et al. 2013), i.e. factors kept their relative proportions, but were dimensionless. Once the data variables functional relationship to vulnerability was known, i.e. it does that variable contribute negatively or positively to overall vulnerability. For example, higher numbers of the elderly will increase vulnerability (a positive contribution) due to their fragility, and larger areas of green spaces will reduce vulnerability (negative contribution) due to interception, storage and infiltration of flood water (Handley and Carter 2006; Kaźmierczak and Cavan 2011; Lindley et al. 2011; Climate Just 2014). A normalisation equation was computed to standardise each variable, for each neighbourhood within Hilsea. Equation 3 was used to normalise the different factors identified and involved using a predefined minimum and maximum (Connor and Hiroki 2005; Briguglio 2004; UNDP 2006).

$$Va = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (3a)$$

$$Va = 1 - \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (3b)$$

where  $Va$ =data variable;  $X_i$ =factor value;  $X_{\min}$ =factor value minimum;  $X_{\max}$ =factor value maximum.

The resulting values ranged from 0 to 1, with 1 representing high vulnerability (Balica 2012b). To measure coastal flood vulnerability at the most detailed level possible, the maximum and minimum for each data variable were taken on an individual ward basis.

The final computed data variables and factors chosen for the CoFVI and CoFRI are displayed in Fig. 3. This figure visualises the final model of the CoFVI and CoFRI data variables, vulnerability factors and their added weights. All data variables, the factors they populate, and the vulnerability component index (CoFPVI, CoSVI and CoFLRI) to which they are situated are displayed in three light grey boxes to the left of the diagrammatic model.

The creation of the CoFVI and CoFRI for this research has been influenced by elements of many natural hazard index methodologies (specifically: Sullivan and Meigh 2003; Connor and Hiroki 2005; Lindley et al. 2011; Balica et al. 2012). To create the equally weighted CoFVI for Hilsea involved the combination of the CoFPVI, CoFSVI and CoFLRI in Eq. 4.

$$\text{CoFVI} = \frac{w_{\text{cofpvi}} \text{CoFPVI} + w_{\text{cofsvi}} \text{CoFSVI} + w_{\text{coflri}} \text{CoFLRI}}{w_{\text{cofpvi}} + w_{\text{cofsvi}} + w_{\text{coflri}}} \quad (4)$$

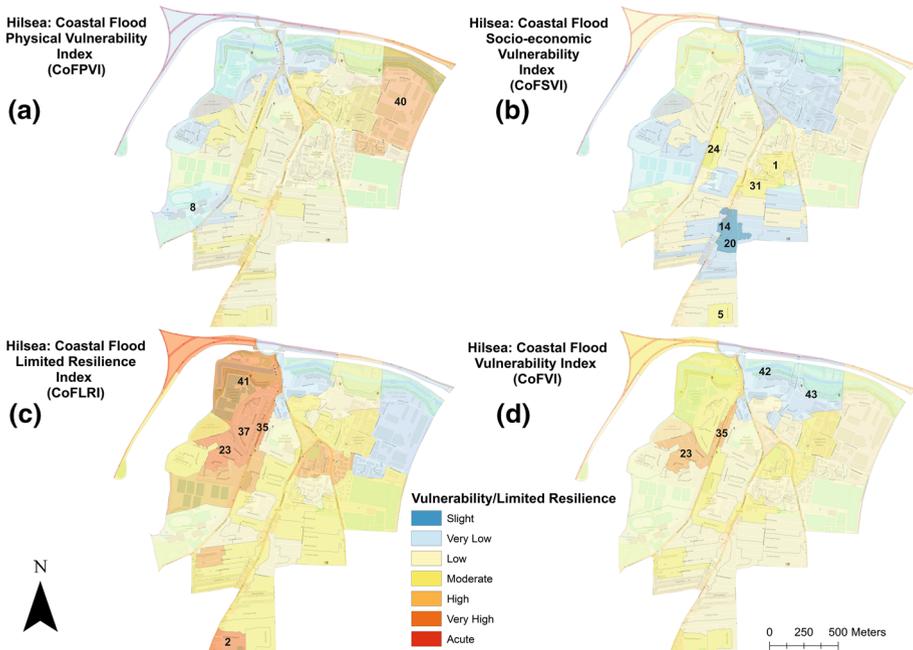
where  $w_{\text{cofpvi}}$ ,  $w_{\text{cofsvi}}$ ,  $w_{\text{coflri}}$ —weights of vulnerability component indexes.

The last stage of the analysis involved creating the equally weighted CoFRI. This involved combining the CoFVI results with the FZ3 or FZ2 CoFHI results in Eq. 5. This resulted in two different CoFRI for Hilsea—CoFRI (FZ3) and CoFRI (FZ2).

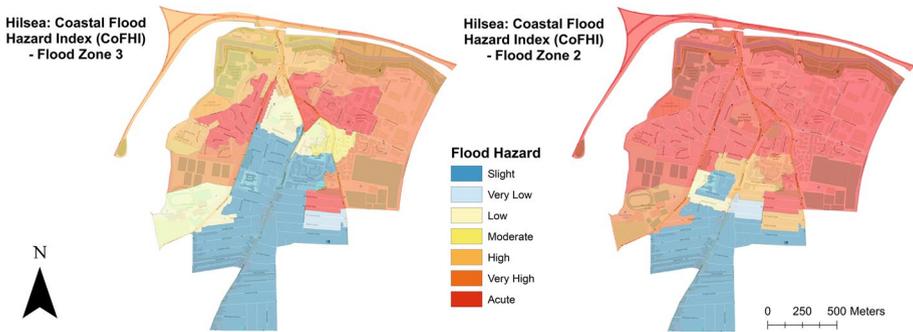
$$\text{Coastal Flood Risk (CoFRI)} = \text{CoFHI} * \text{CoFVI} \tag{5}$$

### 3 Results

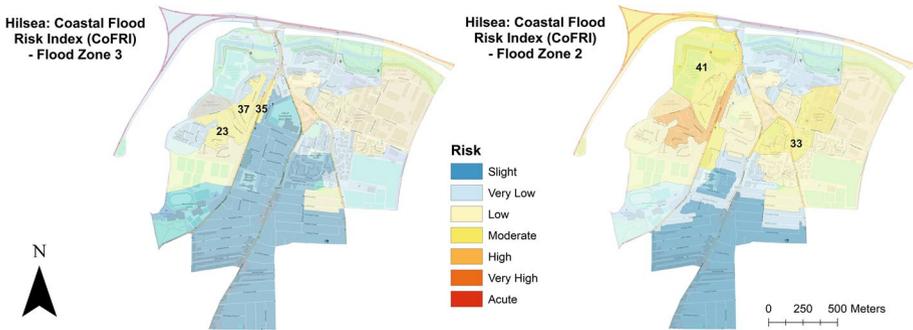
The Coastal Flood Physical Vulnerability Index (CoFPVI), Coastal Flood Socio-economic Vulnerability Index (CoFSVI), Coastal Flood Limited Resilience Index (CoFLRI), Coastal Flood Vulnerability Index (CoFVI), Coastal Flood Hazard Index (CoFHI) and Coastal Flood Risk Index (CoFRI) of each neighbourhood (OA) were joined to an OA coded polygon and displayed in ArcMap 10.3.1. All CoFVI, CoFHI and CoFRI results for Hilsea are presented in Figs. 4, 5 and 6. Vulnerability, limited resilience and risk levels are at 7 equal intervals (slight, very low, low, moderate, high, very high and acute) (Lindley et al. 2011; Climate Just 2014), between 0 and 1, allowing for numerical comparisons of vulnerability, hazard and risk between neighbourhoods within Hilsea. This produces a value to assist improved targeting of vulnerable and at-risk areas, crucial to prioritising interventions to improve resilience, reduce vulnerability and enhance recovery.



**Fig. 4** CoFPVI (a), CoFSVI (b), CoFLRI (c) and CoFVI (d) for Hilsea ward at neighbourhood (OA) level, with added transparency and base maps. Numbers (Tables 1, 2) highlight certain neighbourhoods due to notable vulnerability/resilience levels. Base maps are © Crown Copyright/database right supplied by Ordnance Survey and Contains National Statistics data © Crown copyright and database right [2017] (for ONS) and Map data © OpenStreetMap contributors



**Fig. 5** CoFHI for Hilsea ward at neighbourhood level. CoFHI FZ3 and FZ2 for Hilsea ward (acute means almost, to complete surface area coverage by the flood zone, and slight represents none, to very little surface area coverage by the flood zone). Base maps are © Crown Copyright/database right supplied by Ordnance Survey © Crown copyright and database right [2017] (for ONS) and Map data © OpenStreetMap contributors



**Fig. 6** CoFRI for Hilsea ward at neighbourhood level—FZ3 and FZ2. Numbers (Table 2) highlight certain neighbourhoods due to notable risk levels. Base maps are © Crown Copyright/database right supplied by Ordnance Survey and Contains National Statistics data © Crown copyright and database right [2017] (for ONS) and Map data © OpenStreetMap contributors

All CoFVI components (CoFPVI, CoFSVI and CoFLRI) results for the ward of Hilsea are presented in Table 1 and Fig. 4. Highlighted neighbourhoods (in bold in Table 1 or numbered in Fig. 4) correspond to the area’s significant vulnerability or limited resilience levels. The majority of Hilsea has low physical vulnerability (Fig. 4a). Neighbourhood 8 has very low levels of physical vulnerability due to very few dwellings, renters, commercial and industry buildings and multiple residency buildings, whereas neighbourhood 40 has the highest level of physical vulnerability in the ward, due to a combination of having the highest numbers of industrial, commercial and utility buildings in Hilsea. The majority of neighbourhoods in Hilsea have either very low or low levels of socio-economic vulnerability (Fig. 4b). However, neighbourhoods 14 and 20 have slight levels of socio-economic vulnerability due to very few numbers of elderly, young children, lone parents, residents with long-term illnesses, providers of unpaid care, non-English speakers and very small populations in these areas. Neighbourhoods 24, 31 and 5 all have moderate levels of socio-economic vulnerability, due to a mixture of substantial numbers of elderly, residents with long-term illnesses, communal establishment residents, providers of unpaid care, many

**Table 1** CoFPVI, CoFSVI and CoFLRI results for each neighbourhood (OA) within Hilslea

Hilslea neighbour- hoods	Coastal flood physical vulner- ability levels	Coastal flood socio-economic vulnerability levels	Coastal flood limited resilience levels
<b>1</b>	0.37	<b>0.44</b>	0.39
<b>2</b>	0.46	0.41	<b>0.77</b>
3	0.34	0.38	0.52
4	0.39	0.34	0.50
<b>5</b>	0.44	<b>0.48</b>	0.52
6	0.42	0.36	0.44
7	0.43	0.17	0.43
<b>8</b>	<b>0.18</b>	0.34	0.41
9	0.44	0.30	0.54
10	0.42	0.25	0.47
11	0.48	0.22	0.56
12	0.40	0.25	0.44
13	0.42	0.29	0.57
<b>14</b>	0.41	<b>0.11</b>	0.49
15	0.41	0.30	0.39
16	0.42	0.21	0.52
17	0.34	0.21	0.39
18	0.43	0.36	0.51
19	0.38	0.17	0.38
<b>20</b>	0.38	<b>0.13</b>	0.36
21	0.44	0.29	0.44
22	0.39	0.19	0.62
<b>23</b>	0.56	0.42	<b>0.81</b>
<b>24</b>	0.52	<b>0.48</b>	0.65
25	0.38	0.35	0.44
26	0.38	0.38	0.51
27	0.29	0.29	0.44
28	0.39	0.33	0.44
29	0.35	0.27	0.48
30	0.38	0.24	0.45
<b>31</b>	0.38	<b>0.50</b>	0.48
32	0.39	0.31	0.59
33	0.37	0.41	0.64
34	0.25	0.22	0.44
<b>35</b>	0.51	0.39	<b>0.83</b>
36	0.33	0.32	0.33
<b>37</b>	0.40	0.35	<b>0.82</b>
38	0.46	0.20	0.44
39	0.52	0.22	0.55
<b>40</b>	<b>0.60</b>	0.31	0.27
<b>41</b>	0.20	0.36	<b>0.81</b>
42	0.27	0.19	0.27
43	0.30	0.21	0.31

Numbers highlighted in bold indicate neighbourhoods with notable vulnerability and/or resilience levels

valuable properties and larger populations. Neighbourhood 31 also has the highest level of socio-economic vulnerability in Hilsea. Limited resilience levels in Hilsea are mostly moderate (Fig. 4c); however, four neighbourhoods in the north-west of the ward (41, 23, 37 and 35) and one in the south (2) have very high levels of limited resilience. This is due to a mixture of no emergency facilities, very high numbers of unemployed, many residents with low education levels and low numbers of residents with available transport. Neighbourhood 37 has the highest numbers of unemployed and those with a lack of education in Hilsea. Overall neighbourhood 35 has the highest levels of limited resilience in Hilsea, due to a combination of low resilience levels for each CoFLR factor.

All CoFVI, CoFHI and CoFRI results are presented in Table 2 and Figs. 4, 5 and 6. Neighbourhoods highlighted (in bold in Table 2 or numbered in Figs. 4 and 6) correspond to the area's significant vulnerability or risk levels. For Hilsea, the majority of neighbourhoods have low vulnerability levels (Fig. 4d). Two neighbourhoods (23 and 35, situated adjacent to each other at the north-west end of the ward) in particular have the highest vulnerability levels in Hilsea, whereas neighbourhoods 42 and 43 (situated on the coastline to the north) have the lowest. The former is due to moderate levels of physical vulnerability, very high levels of limited resilience, but low levels of socio-economic vulnerability in both neighbourhoods (23 and 35). Neighbourhood 23 has the highest amount of children, lone parents with dependent children, dwellings and renters. It also has very high numbers of unemployed, a large population, very little green space or transport links and no essential buildings. Neighbourhood 35 has little to no transport links and small amounts of green space compared to other neighbourhoods in Hilsea. It also has high numbers of renters, multiple residency buildings, unemployed and the highest number of households with no car availability within the ward. The latter is due to very low physical (neighbourhood 42) and socio-economic vulnerability (both neighbourhoods), and substantial resilience present (particularly neighbourhood 42).

For a Flood Zone 3 (FZ3) event (Fig. 5), flood water will inundate a majority of the ward, particularly the northern end. Due to the topography (considered in the FZ3 and FZ2 models) in Hilsea, it is in fact neighbourhoods not directly on the coastline that are the most at risk of being completely covered in flood water, for a flood FZ3 event. For a Flood Zone 2 (FZ2) event (Fig. 5), over half of Hilsea will be inundated, with complete surface area coverage by flood water for many more neighbourhoods. The southern end of Hilsea will not be inundated for either a FZ3 or FZ2 event.

For a FZ3 event, coastal flood risk in Hilsea is predominantly low or zero (Fig. 6). This is due to a combination of mostly low levels of underlying vulnerability in Hilsea and low levels of flood water spatial coverage. Hilsea has three neighbourhoods that are most at risk for a FZ3 event—37, 35 and 23. Neighbourhoods 23, 35 and 37 have moderate levels of coastal flood risk due to acute inundation and significant levels of vulnerability (either moderate or high). These three neighbourhoods have higher levels of physical and socio-economic vulnerability and limited resilience compared to other neighbourhoods in the ward (Fig. 4). Compared to the remaining neighbourhoods in Hilsea, that either have low, very low risk or in fact no risk at all (zero). For a flood of this magnitude (FZ3), the centre and southern end of Hilsea are very safe. Despite underlying vulnerability, no flood water is predicted to inundate these areas, resulting in little to no flood risk.

For a FZ2 event (Fig. 6), however, risk levels in Hilsea significantly alter, particularly in the northern and central parts of the ward. Many more neighbourhoods are now at risk compared to the smaller, yet more likely FZ3 event. In fact 20 neighbourhoods that had no risk for a FZ3 event were reduced to 15 for a FZ2 event (see Table 2 and Fig. 6). This is due to floodwater potentially inundating more areas in the ward, spreading southwards,

**Table 2** Coastal Flood Vulnerability Index (CoFVI), Coastal Flood Hazard Index (CoFHI) and Coastal Flood Risk Index (CoFRI) results for each neighbourhood (OA) within Hilsa, for floods of different magnitudes (FZ3 and FZ2)

Hilsa neighbourhoods	Coastal flood vulnerability levels	Coastal flood hazard levels—Flood Zone 3	Coastal flood hazard levels—Flood Zone 2	Coastal flood risk levels—Flood Zone 3	Coastal flood risk levels—Flood Zone 2
1	0.40	0.05	0.84	0.02	0.34
2	0.55	0	0	0	0
3	0.41	0	0	0	0
4	0.41	0	0	0	0
5	0.48	0	0	0	0
6	0.40	0	0	0	0
7	0.34	0	0	0	0
8	0.31	0.32	0.85	0.10	0.26
9	0.43	0	0	0	0
10	0.38	0	0	0	0
11	0.42	0	0	0	0
12	0.36	0	0	0	0
13	0.43	0	0	0	0
14	0.34	0	0	0	0
15	0.37	0	0	0	0
16	0.38	0	0	0	0
17	0.32	0	0.04	0	0.01
18	0.44	0	0.35	0	0.15
19	0.31	0	0	0	0
20	0.29	0	0	0	0
21	0.39	0	0.16	0	0.06
22	0.40	0.77	0.99	0.31	0.40
<b>23</b>	<b>0.59</b>	<b>0.89</b>	<b>1</b>	<b>0.53</b>	<b>0.59</b>
24	0.55	0.09	0.92	0.05	0.51

**Table 2** (continued)

Hilsea neighbour- hoods	Coastal flood vulnerability levels	Coastal flood hazard levels— Flood Zone 3	Coastal flood hazard levels— Flood Zone 2	Coastal flood risk levels— Flood Zone 3	Coastal flood risk levels— Zone 2
25	0.39	0	0.63	0	0.25
26	0.42	0.11	1	0.04	0.42
27	0.34	0.77	0.99	0.27	0.34
28	0.39	0.22	0.64	0.08	0.25
29	0.37	0	0.06	0	0.02
30	0.36	0.92	1	0.33	0.36
31	0.45	0	0.62	0	0.28
32	0.43	0.39	1	0.16	0.43
<b>33</b>	<b>0.48</b>	<b>0.53</b>	<b>0.99</b>	<b>0.25</b>	<b>0.48</b>
34	0.30	0.69	1	0.21	0.30
<b>35</b>	<b>0.58</b>	<b>0.93</b>	<b>0.99</b>	<b>0.54</b>	<b>0.58</b>
36	0.33	0.41	0.99	0.13	0.33
<b>37</b>	<b>0.52</b>	<b>0.96</b>	<b>1</b>	<b>0.51</b>	<b>0.52</b>
38	0.37	0.89	0.99	0.33	0.37
39	0.43	0.98	1	0.42	0.43
40	0.39	0.84	1	0.33	0.39
<b>41</b>	<b>0.46</b>	<b>0.60</b>	<b>0.97</b>	<b>0.27</b>	<b>0.44</b>
<b>42</b>	<b>0.24</b>	<b>0.69</b>	<b>0.99</b>	<b>0.17</b>	<b>0.24</b>
<b>43</b>	<b>0.28</b>	<b>0.83</b>	<b>1</b>	<b>0.23</b>	<b>0.28</b>

Numbers highlighted in bold indicate neighbourhoods with notable vulnerability and/or risk levels

affecting more neighbourhoods in the centre and further south. The southern end of the ward still has little to no risk due to flood water not travelling this far, making this part of the ward the safest with regard to coastal flooding. Overall more neighbourhoods have moderate levels of coastal flood risk, and two in particular (23 and 35) have high levels of coastal flood risk, due to acute inundation and high levels of underlying vulnerability.

## 4 Discussion

Analysing the ‘physical’, ‘socio-economic’ and ‘resilient’ composition of an area at neighbourhood scale produces an opportunity to unearth the principle factors and dimensions of vulnerability. By deciphering, assessing and illustrating key local contexts that formulate the local flood risk problem (Maskrey et al. 2016), we can venture towards flood risk management practices that are successful and embed resilience into a community. To strive towards this, a suitable flood vulnerability and risk analysis is needed, an example of which has been presented in this article.

The coastal flood vulnerability and risk model presented in this paper (Fig. 3) combine the vital components of vulnerability (physical, social and resilient elements) into one framework at neighbourhood level, confirming that vulnerability can be analysed as an element of physical vulnerability, socio-economic vulnerability and resilience of a system affected by hazards (Lindley et al. 2011; Balica 2012a; Birkmann et al. 2013). Highlighting that by defining vulnerability in this way, a very detailed evaluation of vulnerability can ensue (Cutter et al. 2003). For example, what vital characteristics within communities/ areas need to be assessed to understand the reality of vulnerability in order to truly pinpoint areas of high flood risk?

This study has also assessed coastal flood vulnerability and risk at a micro-level: neighbourhood scale. By assessing at a higher resolution combined with analysing the physical, socio-economic and resilient components of vulnerability, a thorough analysis of coastal flood vulnerability and risk could be carried out. This produces indexes and corresponding maps identifying previously undetected vulnerable and at-risk neighbourhoods within the ward of Hilsea in Portsmouth. This methodology identified vulnerable and at-risk areas (particularly neighbourhoods 23, 35 and 37) that have not been highlighted as needing particular attention by previous Portsmouth flood risk assessments. This includes the Local Strategic Flood Risk Assessment (LSFRA) (2007) and the national Flood Vulnerability and River and Coastal Flood Disadvantage Indexes (Lindley et al. 2011; Climate Just 2014). This is due to the former using only a limited number of number social vulnerability factors, and the latter analysing at a much coarser scale (Middle Super Output Area).

To reduce vulnerability and the potential for flood related impacts, the scale and physical, social, and resilience-related components of vulnerability need to be considered; otherwise, crucial features are missed and at-risk areas are unidentified. However, the limitation of a detailed assessment at micro-scale, as used in this study, is the time required to acquire and process the datasets. Nevertheless, vulnerability cannot merely be limited to the identification of deficiencies (Birkmann et al. 2013). In the context of specific local problems and limited budgets, the specific local contexts (physical, socio-economic and resilient) that frame a local flood risk problem must be fully understood (Johnston and Soulsby 2006; Prell et al. 2007; Maskrey et al. 2016), in order to enable the correct identification of priorities, scale of intervention and stakeholders to be involved. For instance, more neighbourhoods in Hilsea are at risk if floods of higher magnitudes were to occur

(i.e. FZ2 rather than a FZ3), as more of Hilsea would be inundated. However, it may be presumed that these areas at high risk are directly along the coastline, due to sheer proximity. Yet, the results presented in this paper show that in the case of Hilsea, neighbourhoods further inland were actually the most at risk, due to underlying vulnerability levels that have been previously undetected. In fact, neighbourhood 23 is the most vulnerable area in Hilsea, and neighbourhood 42 is the least vulnerable area in Hilsea, despite the latter's proximity to the coastline. These results provide as clear a picture as possible of the reality of coastal flood risk within the Hilsea area, leading to better understanding and guidance for future flood risk management activities in Hilsea and Portsmouth.

This study also verifies that the physical, socio-economic and resilient components of vulnerability (as used in this research) can be brought together into one model (Eq. 1), and one methodological framework (Fig. 3) can be used to encapsulate that model. There are many flood vulnerability assessments that have concentrated on social aspects (e.g. Cutter et al. 2003; Atkins 2007; Kaźmierczak and Cavan 2011; Lindley et al. 2011; Balica et al. 2012; Birkmann et al. 2013), or the environmental component of vulnerability (e.g. Gornitz 1991; Balica 2012b; Menoni et al. 2012). Yet, little research has occurred to analyse the built environment, specifically the building make-up of the urban environment, despite its significance. Liverman (1990), Bogardi and Birkmann (2004), Birkmann (2006), Menoni et al. (2012) and Birkmann et al. (2013) state that vulnerability refers to the propensity of exposed elements including our assets to suffer adverse effects when impacted by hazard events. Yet very few examples exist of studies analysing our built environment (urbanisation), when faced with flood hazards. Lindley et al. (2011) and Climate Just (2014) have highlighted physical exposure as a component of vulnerability; however, only two factors were measured by them to analyse the whole component: green spaces and building level (i.e. basement level). The Hilsea study presented in this paper has analysed eight physical vulnerability factors, some of which were made up of more than one data variable, leading to a more detailed analysis of the urban environment.

This was all possible due to the great volume and breadth of data available in the UK. This research incorporated hazard projection data, socio-economic data and physical/topographic data into one framework, demonstrating the ability to bring these different geoinformatic datasets together to achieve one goal. OS Mastermap and the 2011 UK National Census contain a vast amount of information that can be used to measure different attributes of vulnerability. For the majority of the physical vulnerability factors chosen for this project, the data were available, but required new approaches to calculate relevant information. For example, the creation of the coastal flood vulnerability themed land use re-classification system, which included the creation and population (via OS Mastermap data) of unique flood vulnerability layers for Hilsea, e.g. Multiple Residency and Vulnerable Buildings within ArcMap 10.3.1.

This research has utilised the vast network of available UK geoinformatic knowledge, demonstrating its potential between different institutions, universities and non-governmental organisations; hopefully encouraging collaborations between stakeholders that have a vested interest in managing coastal flooding. However, there are opportunities to further develop this methodology. The wealth of data available in the UK demonstrates the potential for other data variables to be utilised to populate new physical and socio-economic vulnerability factors, as well as resilience factors in future. A limitation of this research is the small number of factors used to measure the resilience component, relative to the other vulnerability components, due to its sheer complexity. Understanding how a community can adapt, respond or recover from flood events (their resilience) is a critical element of determining vulnerability. Yet currently there is no single UK flood resilience index to

establish the potential efficacy of flood risk management strategies, including community flood resilience. Despite the likelihood that large numbers of communities within high flood risk areas in the UK will have to rely on community flood resilience as their key strategy in future. Finding effective metrics to assess resilience in detail will be very challenging, as the data needed to understand community resilience might not be available in a geoinformatic format. However, examples of factors that could be considered to assess limited resilience further include; *flood insurance*, *flood awareness* and *building adaptation measures*. *Flood insurance* would be a very useful measurement of limited resilience in a neighbourhood. If many dwellings in the area do not possess insurance, then limited resilience would be higher, as residents would not have the documentation necessary to assist with their personal and financial recovery from the damage caused by a flood event. *Flood awareness* would give a good indication of the local levels of flood preparation, i.e. if they are high, increasing resilience levels in that neighbourhood. This factor could be measured by the numbers of residents who have ‘grab bags’ (bags ready for emergencies containing key documentation, clothing, water, some food and money), how many residents had flood experience (i.e. had experienced flooding), or the number of residents aware of where to go and what to do if an emergency occurs. *Building adaptation measures* is something that is being brought more into building plans and construction (Hafen City, Germany and Dordrecht, Netherlands). Adaptation examples include wet-proofing, floatable buildings, dry proofing, raising floor levels, one-way valves, or building regulations. It is seen as a sustainable form of improving resilience for communities in flood zones, and is a practice that is becoming well established in European coastal communities that have high coastal flood risk.

## 5 Conclusion

Flood risk assessments are more than simply analysing the hazard. Understanding the physical, socio-economic and resilient drivers in societies and their systems is just as vital, as these elements determine levels of underlying vulnerability which in turn can dictate the levels of severity of impacts. Climate change looks set to increase the number and severity of future coastal hazard events. It is therefore vital to measure and map coastal flood vulnerability, highlighting areas of high risk, facilitating better mitigation and adaptation. To address this complex challenge, this paper has presented research that has concentrated on the characteristics and demands of vulnerability assessments, when analysing coastal community flood risk at a detailed level of study. This results in a framework that brought the socio-economic, physical and limited resilience components of vulnerability together into one model. This produces a unique framework for measuring coastal flood vulnerability that operates at the level of detail necessary to deliver effective solutions (neighbourhood level) for flood management and environmental planning. Two detailed, micro-scale indices have been developed via this model: a coastal flood vulnerability index and a coastal flood risk index. These indexes have been tested on the city of Portsmouth, UK, with results for one of Portsmouth’s electoral wards (Hilsea) shown as an example. These indexes (between 0 and 1) and corresponding maps allow numerical comparisons to be made between neighbourhoods within Hilsea. The results indicate one neighbourhood in particular (23—north-west of the ward) has the highest vulnerability level in the ward and three particular neighbourhoods (35, 37, and 23—again all located in the north-west of the ward) dominantly have the highest coastal flood risk levels (for a 1 in 200 or 1 in 1000 year

event). Other neighbourhoods in the south of the ward collectively have substantial vulnerability levels compared to others. However, flood water is not predicted to inundate these areas, resulting in slight or no risk levels. In summary, there is a notable, visible difference in risk levels between FZ3 (1 in 200 year) and FZ2 (1 in 1000 year) events. More neighbourhoods in Hilsea are at risk if a flood of a FZ2's magnitude was to occur, as a greater expanse of Hilsea would be inundated by coastal flood water. Neighbourhoods in the centre of the ward that have little to no levels of coastal flood risk for a FZ3 event will be at risk for a FZ2 event. In fact coastal flood risk levels increase for over half of Hilsea's neighbourhoods if a flood of a FZ2's magnitude was to occur. Coastal flood risk levels for two neighbourhoods in particular (23 and 35) increase from moderate to high due to acute levels of inundation and substantial levels of underlying vulnerability. However, the southern end of the Hilsea ward remains safe for either of these flood events (FZ3/2), as coastal flood water would not spread that far inland.

The conceptual framework presented in this article, although complex, provides a valuable basis for national or international vulnerability factor development and vulnerability index creation. By analysing so many vulnerability factors and at a 'realistic' level (neighbourhood—a scale not previously used in other coastal flood vulnerability and risk assessments), this methodology has led to a more comprehensive vulnerability and risk assessment for Hilsea and identified key vulnerable and at-risk areas. This level of detail is necessary to assist our ability to inform decision-makers, deliver effective policies, and make sound investments. Vulnerability cannot be represented by a single statistic or a few socio-economic characteristics. There are factors identified within this research that can be replicated within other natural hazard vulnerability assessments. Specifically, many of the factors used in this project's methodology can be used for vulnerability assessments associated with other types of flooding (fluvial and pluvial) including Dwellings, Vulnerable Buildings, Tenure, Multiple Residency Buildings, Utilities, Population Density, Green Areas, Age, or Home Population. This methodology and the factors used can be utilised by hazard managers (particularly flood managers in the UK), emergency and environmental planners, and members of Resilience Forums, for more effective hazard risk management.

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## Compliance with ethical standards

**Conflict of interest** No potential conflict of interest was reported by the authors.

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