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A probabilistic methodology to estimate future coastal flood risk due to sea level rise

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ABSTRACT

In this paper we present a methodology to estimate the probability of future coastal flooding given uncertainty over possible sea level rise. We take as an example the range of sea level rise magnitudes for 2100 contained in the IPCC Third Assessment Report [Church, J.A., Gregory, J.M., Huybrechts, P., Kuhn, M., Lambeck, K., Nhuan, M.T., Qin, D., Woodworth, P.L., Anisimov, O.A., Bryan, F.O., Cazenave, A., Dixon, K.W., Fitzharris, B.B., Flato, G.M., Ganopolski, A., Gornitz, V., Lowe, J.A., Noda, A., Oberhuber, J.M., O'Farrell, S.P., Ohmura, A., Oppenheimer, M., Peltier, W.R., Raper, S.C.B., Ritz, C., Russell, G.L., Schlosser, E., Shum, C.K., Stocker, T.F., Stouffer, R.J., van de Wal, R.S.W., Voss, R., Wiebe, E.C., Wild, M., Wingham, D.J. and Zwally, H.J., 2001. Changes in sea level. In Houghton, J.T. et al. (eds), Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom, 881pp.] and infer a plausible probability distribution for this range. We then use a Monte Carlo procedure to sample from this distribution and use the resulting values as an additional boundary forcing for a two-dimensional model of coastal inundation used to simulate a 1 in 200 year extreme water level event. This yields an ensemble of simulations for an event of this magnitude occurring in 2100, where each member represents a different possible scenario of sea level rise by this time. We then develop a methodology to approximate the probability of flooding in each model grid cell over the ensemble and by combining these hazards maps with maps of land use values (consequence) we are able to estimate spatial contributions to flood risk that can aid planning and investment decisions. The method is then applied to a 32 km section of the UK coast in Somerset, South-West England and used to estimate the monetary losses and risk due a 1 in 200 year recurrence interval event under: (a) current conditions; (b) with the IPCC's most plausible value for sea level rise by 2100 (0.48 m) and (c) using the above methodology to fully account for uncertainty over possible sea level rise. The analysis shows that undertaking a risk assessment using the most plausible sea level rise value may significantly underestimate monetary losses as it fails to account for the impact of low probability, high consequence events. The developed method provides an objective basis for decisions regarding future defence spending and can be easily extended to consider other sources of uncertainty such as changing event frequency–magnitude distribution, changing storm surge conditions or model structural uncertainty, either singly or in combination as joint probabilities.

1. Introduction

There are currently over 1.2 billion people living within 100 km of the coast and less than 100 m above sea level, the broad area that will be affected by global rising sea levels (Small and Nicholls, 2003). In England and Wales alone it is estimated that 5 million people and 2 million properties are currently at risk of flooding, and many of these are located in coastal floodplains. Over £500 million is spent each year on flood defence in the UK, and the total annual cost of flooding has been estimated at over £1 billion. Flood risk (defined as the product of event probability and consequence) may also change significantly in the future. Climate change, sea level rise, socio-economic change and defence degradation over time may all act to alter patterns of hazard and exposure, and hence risk. For example, the Intergovernmental Panel on Climate Change Third Assessment Report (Church et al., 2001) estimates that sea level rise over the 21st century will be between 9 and 88 cm. In addition, multi-model ensemble analysis of climate models (Palmer and Raisanen, 2002) suggests that the probability of extreme wet winters may increase fivefold by 2100 and that the climate will become significantly stormier. Typical storm tracks may also change, leading to a changing probability of tidal surge events (Lowe and Gregory, 2005). At the same time different possible socio-economic futures may lead to greater development in coastal floodplains (Nicholls and Tol, 2006) or change society's attitude to the multi-billion pound investment decisions needed to maintain or

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enhance flood defences in the face of changing threats (Myatt et al., 2003). For the UK, the first national-scale integrated assessment of such risks (Evans et al., 2004) has shown that under particular climate change and socio-economic scenarios the average annual cost of flooding in England and Wales could rise to £25 billion by 2080 and up to 3. 5 million people could be at risk from floods by this time.

Estimating the potential future exposure of coastal communities to flooding is therefore a critical task for long term planning and risk assessment given the typical design life of coastal defence structures of 50–100 years (see for example Winn et al., 2003; Walsh et al., 2004). To date methods for achieving this have been based on deterministic modelling of coastal inundation using hydrodynamic or GIS-based models of varying complexity (e.g. El-Raey, 1997; Liu, 1997; Hubbert and McInnes, 1999; Samuels and Burt, 2002; Wu et al., 2002; Ritchie et al., 2004; Dawson et al., 2005; Brown, 2005). In these studies particular sea level rise scenarios are used to increase the water levels used as boundary condition forcing for the inundation model and the consequent flooding compared to current day levels. However, estimates of future sea level rise are subject to considerable uncertainty as a result of assumptions made concerning future emission scenarios, the impact of this radiative forcing on the atmosphere, the rate of heat penetration into the oceans and uncertainty over the response of the ice caps and ice-sheets to climate change (Church et al., 2001). The use of deterministic scenarios masks this uncertainty and does not allow expert knowledge to be taken into account to weight the likelihood of particular sea level rise magnitudes.

In this paper we therefore present a methodology to estimate the probability of future coastal flooding given uncertainty over possible sea level rise. We take as an example the range of sea level rise magnitudes for 2100 contained in the IPCC Third Assessment Report (Church et al., 2001) and infer a plausible probability distribution for this range. We then use a Monte Carlo procedure to sample from this distribution and add the resulting sea level rise values to the water levels estimated for a particular recurrence interval event under current conditions. These dynamic water levels are then used as the boundary forcing for a large area, fine spatial resolution two-dimensional model of coastal floodplain inundation. This yields an ensemble of simulations for a given recurrence interval event, where each member represents a different possible scenario of sea level rise by 2100. For simplicity, we thus assume no change in the event frequency–magnitude distribution by this time. We then develop a methodology to weight the flood extent predicted in each realisation of the resulting simulation ensemble by the probability of the sea level rise magnitude used to generate it. By accumulating these weighted values we can approximate the probability of flooding in each model grid cell for a particular recurrence interval event given uncertainty over future sea level rise and produce maps of potential future flood hazard. By combining these maps of flood probability (hazard) with maps of land use values (consequence) we are able to estimate spatial contributions to flood risk that can aid planning and investment decisions. Full details of the methodology are given in Section 2, whilst Section 3 demonstrates its application to a 32 km section of the UK coast in Somerset, South-West England. The benefits of the methodology are that uncertainty over the magnitude of future sea level rise is explicitly addressed in a consistent framework that can be updated as new knowledge becomes available. Moreover, whilst we only deal here with uncertainty over sea level rise, the methodology can be easily extended to consider other sources of uncertainty such as changing event frequency–magnitude distribution, changing storm surge conditions or model structural uncertainty, either singly or in combination as joint probabilities.

2. Methodology

The first step in our flood risk assessment methodology is to assemble current best available evidence concerning possible future sea level rise for a given location and formalise this knowledge in terms of a probability distribution. As an example we here take the IPCC Third Assessment Report (Church et al., 2001) estimates of potential global mean sea level rise by the year 2100, although we could equally take any other assessment or combination of assessments. The IPCC Third Assessment Report (Church et al., 2001) considers available observational and modelling evidence to project forward the change in all components of sea level rise (thermal expansion of the oceans, changes in glacier and ice sheet water storage, changes in global terrestrial water storage) and determine the likely error in each component. By taking 1990 as the baseline and using 35 different future greenhouse gas emission scenarios the Third Assessment Report estimated that global mean sea level rise by 2100 was likely to be in the range from 0.09 to 0.88 m, with a central value of 0.48 m. However, no information is available to quantify the probability of any given sea level rise magnitude within this range. Despite this we can assign a probability of 0 to any sea level rise below 0.09 m or above 0.88 m. Whilst not strictly correct, as there is a low but poorly determined probability that ice sheet collapse may result in SLR of >0.88 m by 2100, this seems a reasonable way to proceed. The information in the IPCC report also allows us to state that a sea level rise in the range 0.09–0.48 m by 2100 has a probability of 0.5 and this is the same for a rise in the range 0.48–0.88 m. Logically, we can also state that the probability of a sea level rise between 0.09 and 0.88 m by 2100 is 1. In other words:

$$\begin{aligned}
&P_{\mathrm{SLR}}|\mathrm{SLR}<0.09 = 0\\
&P_{\mathrm{SLR}}|\mathrm{SLR}>0.88 = 0\\
&\sum_{P_{\mathrm{SLR}}=0.09}^{0.48} P_{\mathrm{SLR}} = \sum_{P_{\mathrm{SLR}}=0.48}^{0.88} P_{\mathrm{SLR}} = 0.5\\
&\sum_{P_{\mathrm{SLR}}=0.09}^{0.88} P_{\mathrm{SLR}} = 1
\end{aligned} \tag{1}$$

Where P_{SLR} is the probability of a given sea level rise and SLR is the sea level rise magnitude in metres. It is also plausible (although not essential) that the median value of 0.48 m is the most likely to be correct. If we assume the simplest distribution possible that fits these data we obtain an almost triangular function with a probability distribution as shown in Fig. 1. This represents our best interpretation of the Third Assessment Report's estimate of the uncertainty in global mean sea level rise by 2100. As new information becomes available (e.g. estimates of regional SLR or local subsidence which may cause significant deviations from global values) the distribution of P_{SLR} can be adjusted accordingly, and the methodology can even be adapted to account for low frequency, high magnitude events such as ice sheet collapse (e.g. Dawson et al., 2005) by including a long, low probability tail to the right hand side of the distribution.

Sampling from the distribution contained in Eq. (1) gives a range of different sea level rise scenarios and their associated probability. These can then be added to the dynamic water levels used as boundary condition

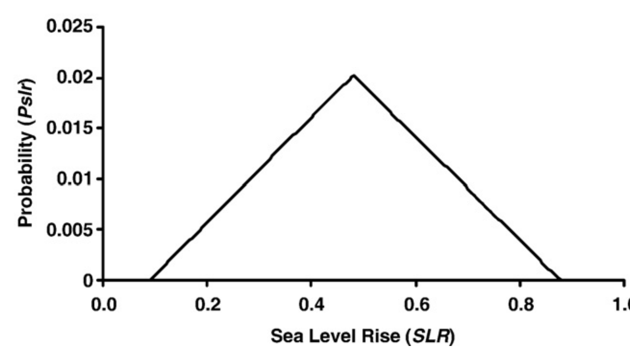

Fig. 1. Probability distribution for sea level rise by 2100 derived by formalising the qualitative information contained in the IPCC Third Assessment Report (Church et al., 2001).

forcing for numerical inundation models. This gives an ensemble of inundation model simulations for a given recurrence interval event at some future point which captures our uncertainty over the sea level rise that can be expected by this time. The outputs from each model realisation in the ensemble are maps of water height at each computational node in the model at each time step during the simulation. From these the maximum predicted flood depths over the simulation can be found and used as a measure of the flood hazard. To obtain a weighted map of the probability of inundation across the study domain given uncertainty over future sea level rise we here extend the methodology outlined by Aronica et al. (2002) and Bates et al. (2004) for mapping spatially distributed uncertainty. Accordingly, the probability of flooding in each model grid cell, i, over an ensemble of model realisations, j, is given by

$$P_i^{flood} = \frac{\sum_j f_{ij} P_{\mathrm{SLR}}}{\sum_j P_{\mathrm{SLR}}} \tag{2}$$

where P_i^{flood} is the probability of inundation in a particular cell of a model given a range of different scenarios with an associated range in probability of occurrence, f_{ij} is equal to 1 or 0 depending on whether cell i is flooded or dry in simulation j, and P_{SLR} is the probability of occurrence of simulation j taken from Fig. 1. By plotting P_i^{flood} over the model domain we obtain a map which approximates the probability of future flooding at that location for a particular recurrence interval event given uncertainty over future sea level rise.

3. Study site and data availability

We applied the methodology outlined in Section 2 to a 32 km stretch of coast along the estuary of the River Severn in Somerset, South-West England. The study area is 24 km by 24 km and is centred on the North Somerset Levels, south west of Bristol (see Fig. 2). This is an extensive area of low lying land containing a number of settlements (Avonmouth, Nailsea, Portishead, Clevedon and Weston Super-Mare), the M5 motorway and the mouths of three tidal rivers: the Axe, Yeo and Bristol Avon. The majority of the land area (154 km^2) is <10 m above mean sea level and is protected from flooding by a range of engineered defences with a standard of protection of approximately 200 years along the coast and 50 years along the main rivers. 145 km^2 of the area is below the level of the current 1 in 1000 year flood event and this gives an approximate value for the size of the present coastal floodplain. In addition, embankments along the M5 motorway may also act to restrict inland flooding. Behind these defences water levels are managed using an extensive system of lock gates, channels and ditches to balance farming and wildlife needs. Most of the farmland on the Levels is classified as "managed grassland" and is predominantly used for grazing sheep and cattle with smaller areas of arable land. The population living in coastal towns is approximately 100 000 and many of these urban areas would be susceptible to flooding if not protected by defences. In addition, there are major docks at Avonmouth and a number of large chemical manufacturing plants built on the coastal floodplain. The Severn Estuary also has the world's second highest tidal range (mean spring tidal range of ~15 m at Avonmouth) making it an extremely dynamic environment. The area therefore contains substantial assets at risk from flooding which make it a critical site for future flood risk assessment.

The key data requirements for a flood inundation model are an accurate Digital Elevation Model (DEM) and forcing data (time series of discharge or water level) at the model boundaries. For this site a DEM (in m above Ordnance Datum Newlyn) derived from airborne laser altimetry (LiDAR) was obtained from the Environment Agency of England and Wales. LiDAR data are now commonly used in flood inundation models (see Bates et al., 2006) and the data used in this study had a spatial resolution of 2 m and vertical accuracy of 10 cm root mean square error (rmse). This had previously been processed by the Environment Agency to remove surface objects, such as vegetation and buildings, to leave a 'bare earth' DEM down to approximately mean low tide level. Cells beyond this seaward limit were then masked to prevent the model undertaking calculations in this area thereby reducing the computational cost. A similar process was also followed for upland areas beyond the reach of any flooding towards the South-West of the domain.

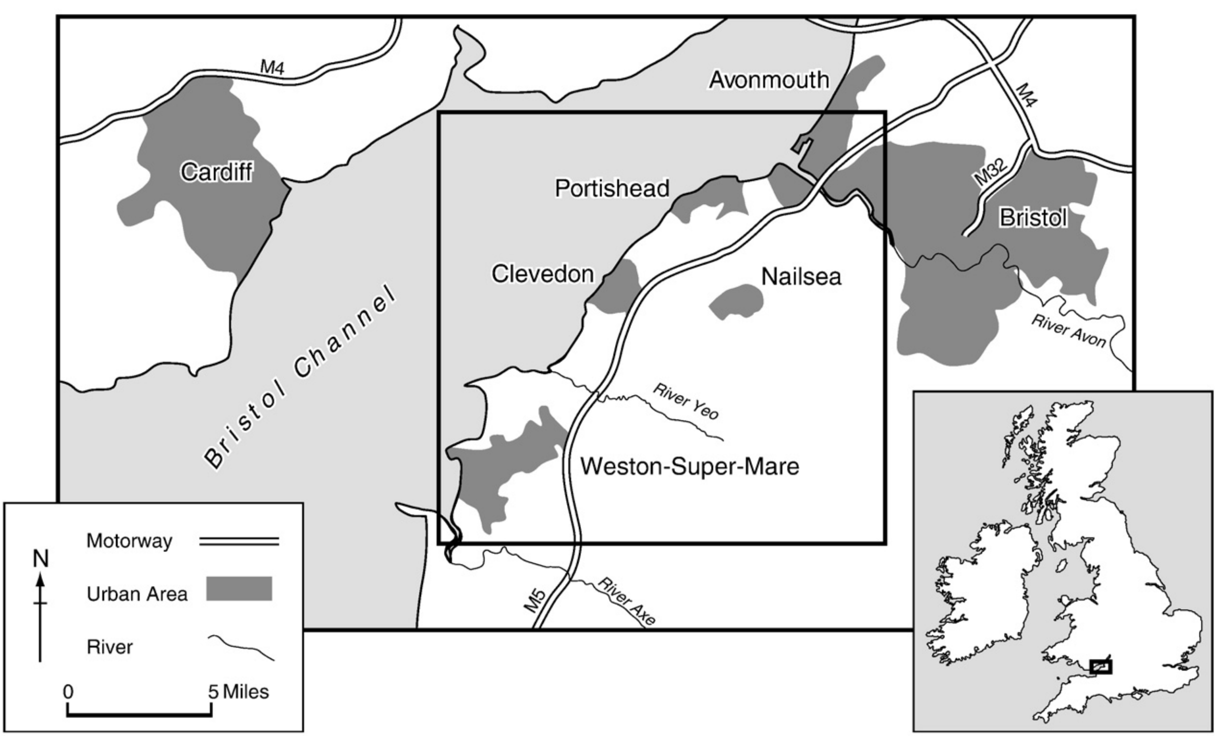

Fig. 2. Map of the study area showing principal communication links and settlements. The extent of the modelled domain is indicated by the inner box.

Previous studies (e.g. Horritt and Bates, 2002) have shown that such high resolution DEM data may not be necessary to successfully predict floodplain inundation in flat areas such as the North Somerset Levels and therefore to reduce the computational cost of the simulation ensemble the LiDAR data was aggregated to 50 m resolution. This spatial averaging may, however, 'smear out' out topographic features such as embankments and flood defences that are critical to inundation development. The location of these features was digitised by hand from information on UK Ordnance Survey maps and their crest elevations were then re-inserted back into the 50 m aggregated DEM using the maximum heights recorded in the 2 m LiDAR data set. The LiDAR crest elevations for known flood defences were also cross-checked against the values in the UK's National Flood and Coastal Defence Database (DEFRA, 2006). This process resulted in a model grid of 480×480 (or 230,400) cells containing the best available information on defence and embankment crest elevations (see Fig. 3). Whilst this aggregation process overestimates the widths of flood defences, it should be a reasonable compromise between topographic fidelity and computational efficiency for this proof-of-concept experiment.

To simulate flooding over this DEM we used the LISFLOOD-FP inundation model as this has been shown to be computationally efficient (e.g. Aronica et al., 2002) and to yield good predictions of maximum inundation extent for fluvial (e.g. Bates and De Roo, 2000) and coastal (e.g. Bates et al., 2005) flooding problems. However it should be noted that the analysis derived above is model independent. In LISFLOOD-FP floodplain flows are treated using a storage cell approach first developed by Cunge et al. (1980) and implemented for a raster grid to allow an approximation to a 2D diffusive wave. Here we solve a continuity equation relating flow into a cell and its change in volume:

$$\frac{\partial h^{i,j}}{\partial t} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y} \tag{3}$$

and a momentum equation for each direction where flow between cells is calculated according to Manning's law (only the x direction is given here):

$$Q_x^{i,j} = \frac{h_{\text{flow}}^{5/3}}{n}\left(\frac{h^{i-1,j} - h^{i,j}}{\Delta x}\right)^{1/2}\Delta y \tag{4}$$

where $h^{i,\,j}$ is the water free surface height at the node (i, j), Δx and Δy are the cell dimensions, n is the Manning's friction coefficient, and Q_x and Q_y describe the volumetric flow rates between floodplain cells. Q_y is defined analogously to Eq. (2). The flow depth, h_{flow}, represents the depth through which water can flow between two cells, and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation. These equations are solved explicitly using a finite difference discretization of the time derivative term:

$$\frac{{}^{t+\Delta t}\,h^{i,j} - {}^{t}\,h^{i,j}}{\Delta t} = \frac{{}^{t}\,Q_x^{i-1,j} - {}^{t}\,Q_x^{i,j} + {}^{t}\,Q_y^{i,j-1} - {}^{t}\,Q_y^{i,j}}{\Delta x \Delta y} \tag{5}$$

where ${}^{t}h$ and ${}^{t}Q$ represent depth and volumetric flow rate at time t respectively, and Δt is the model time step. The maximum stable

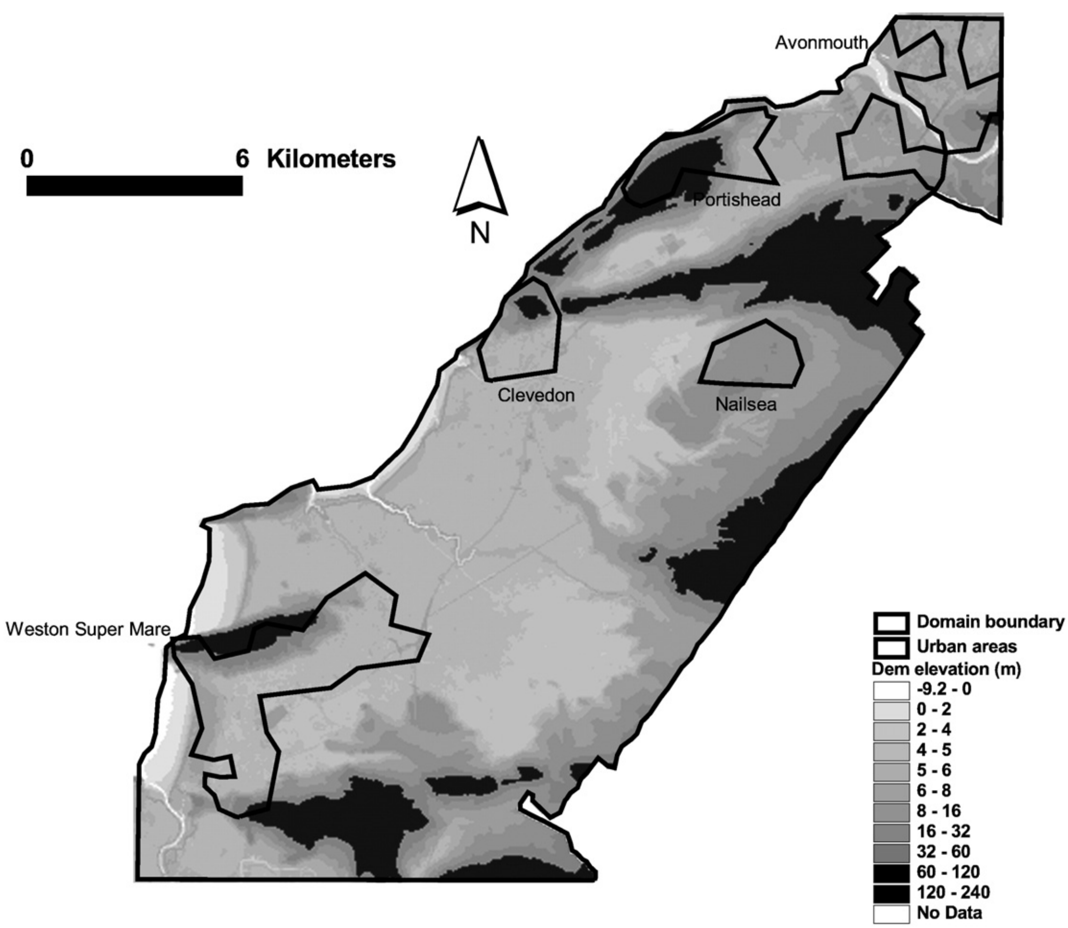

Fig. 3. 50 m spatial resolution DEM (in m above Ordnance Datum Newlyn) of the model domain (as defined by the bounding box in Fig. 2) derived from 2 m spatial resolution airborne laser altimetry (LiDAR) data supplemented by defence crest and embankment elevations derived from various sources as detailed in the text.

Table 1
Heights of extreme water levels in metres above Ordnance Datum Newlyn (ODN) for particular recurrence interval events at Weston Super-Mare and Avonmouth

	1 in 1 year	1 in 100 years	1 in 200 years	1 in 1000 years
Weston Super-Mare	7.29	8.03	8.13	8.40
Avonmouth	8.18	8.98	9.09	9.37

time step at each iteration is then calculated after Hunter et al. (2005) as:

$$\Delta t = \frac{\Delta x^2}{4} \qquad \min \left(\frac{2n}{h_{\text{flow}}^{5/3}} \left| \frac{\partial h}{\partial x} \right|^{1/2}, \frac{2n}{h_{\text{flow}}^{5/3}} \left| \frac{\partial h}{\partial y} \right|^{1/2} \right) \tag{6}$$

which allows the model to adapt Δt in time according to the flow conditions. Use of this adaptive time step has been shown (Hunter et al., 2005) to be essential in order to achieve correct simulations of wave propagation with this class of model.

4. Model set up and simulations

Boundary conditions for LISFLOOD-FP consisted of time series of water levels through a tidal cycle in each of the 607 cells marking the seaward edge of the computational domain. To define these we took the peak levels (also in m above Ordnance Datum Newlyn) for 1 in 1, 1 in 100, 1 in 200 and 1 in 1000 year extreme water levels (astronomic tide plus surge) determined for current conditions using the methodology of Dixon and Tawn (1997) for Avonmouth, Portishead, Clevedon and Weston Super-Mare (see Environment Agency, 2003). We then interpolated these along the coast to obtain a maximum tide height in each of the 607 seaward edge cells. Table 1 shows the maximum water levels for each recurrence interval event at Weston Super-Mare and Avonmouth (the limits of the model) and also indicates the funnelling effect of the estuary with water levels progressively increasing as the water propagates inland. We then

Table 2
Friction and monetary loss values for the 5 land use classes shown in Fig. 4

Land use	Manning's n	Damage (in £) resulting from inundation of a 50 m×50 m cell
Arable	0.04	375
Managed Grassland	0.03	14
Forest	0.1	0
Bare Earth	0.022	0
Urban	0.018	750 000

represented the water level variation for 3 h either side of the peak down to mean sea level using a simple triangular function. It was unnecessary to simulate water levels below mean sea level as these do not result in any coastal inundation. Under normal conditions the tidal curve in the estuary is broadly sinusoidal, but during extreme events this can be affected by storm surge and wind conditions. Making assumptions regarding these effects is difficult, so here we have used a triangular function as the simplest distribution that fits the peak water levels derived from the event frequency analysis. The triangular hydrograph is therefore a simple approximation to a real extreme event tide curve for the Severn Estuary, but one which is sufficient to demonstrate the ability of the flood risk mapping methodology developed in this paper. It should also be noted that we do not simulate inundation resulting from waves overtopping the coastal defences (although this is possible with the model) and we assume that the tidal range is independent of any sea level rise. Using these boundary conditions we ran two control simulations for each recurrence interval event assuming: (a) no sea level rise and (b) the median sea level rise by 2100 predicted in the IPCC Third Assessment Report (0.48 m).

For the 1 in 200 year event we also developed an ensemble of simulations to represent the effect of uncertainty in sea level rise by 2100 based on Fig. 1. Given the simple probability distribution in Fig. 1

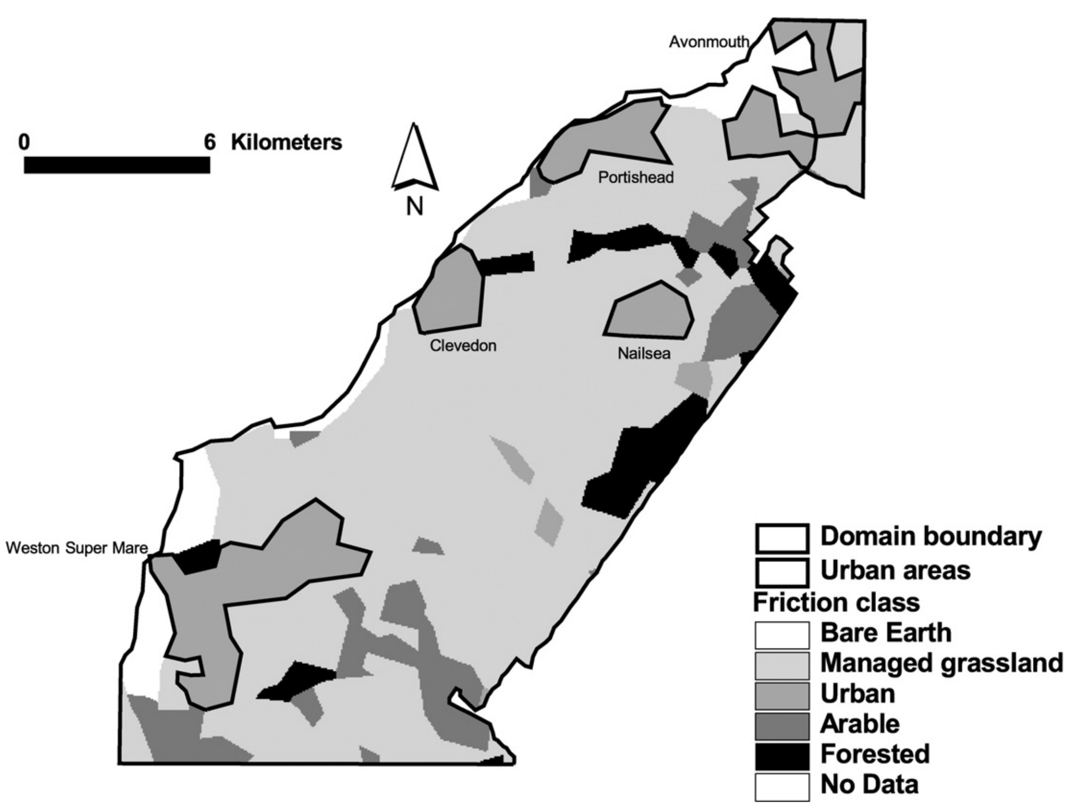

Fig. 4. Land use map derived from the Land Cover Map of Great Britain 2000 used to set friction values for the numerical simulations.

we used a regular sampling interval of 7.9 mm to cover the distribution from 0.09 to 0.88 m of sea level rise. This gives a total of 101 simulations which were run on a cluster of 40 single core 2.0 Ghz computers. The computational cost of any given simulation was primarily a function of the number of wet cells and the adaptive time step determined by Eq. (6). Optimum time steps varied between 0.1

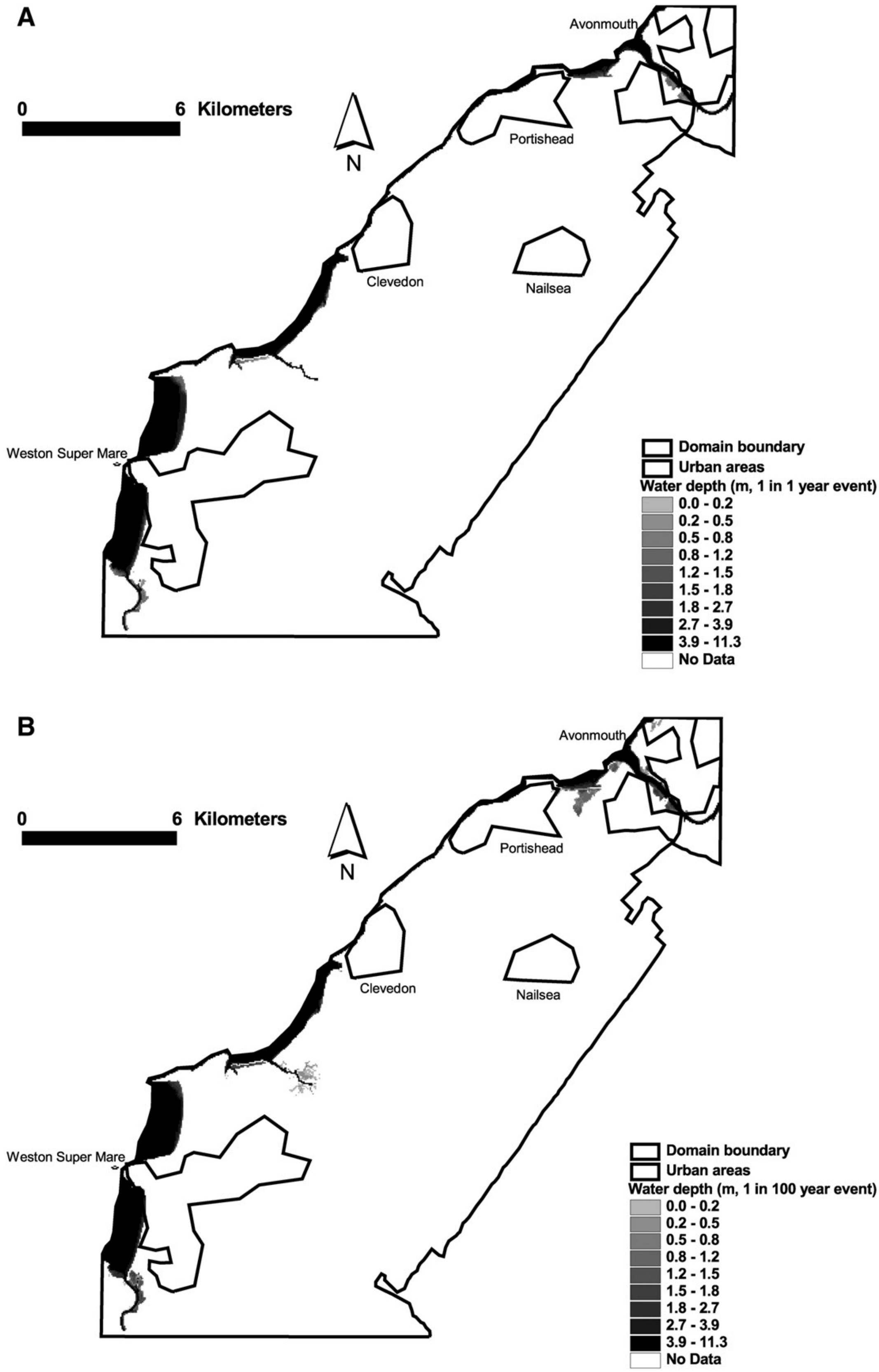

Fig. 5. Flood depths predicted by the LISFLOOD-FP model for 1 in 1, 1 in 100, 1in 200 and 1 in 1000 year recurrence interval events assuming no sea level rise.

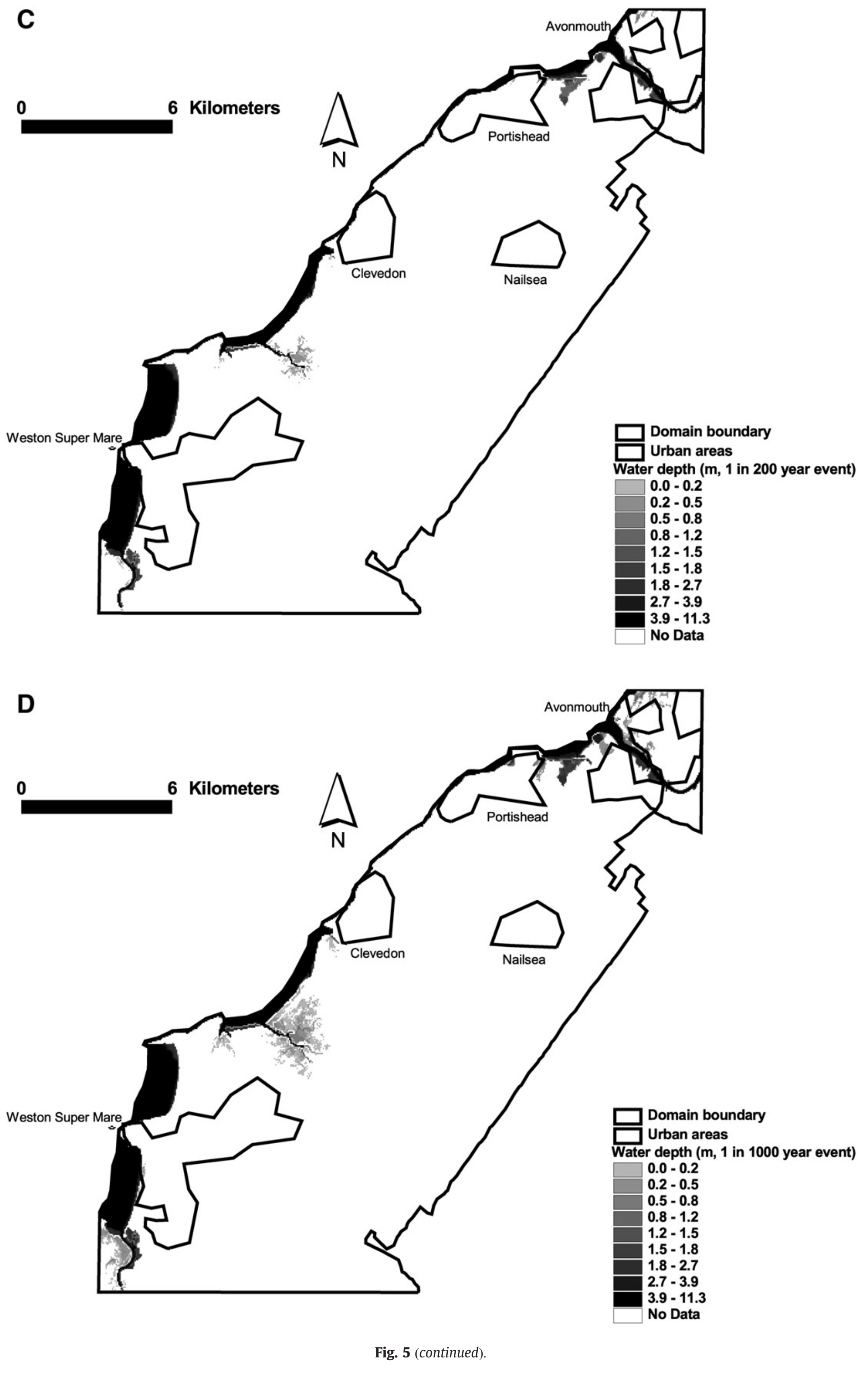

Fig. 5 (*continued*).

and 0.01 s during each simulation depending on the flow depth and water surface slopes, and showed relatively little variability between events. Computational costs was therefore largely a function of the number of wet cells (i.e. event magnitude) and the length of time taken to complete an individual simulation varied between 20 h and 7 days. For these simulations mass balance errors per time step were

Table 3
Total inundated area for various recurrence interval events predicted by the LISFLOOD-FP model assuming current conditions and 0.48 m of sea level rise

Event	Area inundated (in km^2) with no sea level rise	Area inundated (in km^2) with 0.48 m of sea level rise
1 in 1 year	0.0	1.0
1 in 100 years	1.1	11.3
1 in 200 years	1.8	14.0
1 in 1000 years	5.7	24.6

always <0.003% of the total volume of water in the domain, and typically were 1–2 orders of magnitude less than this.

Friction values were assigned separately for each 50 m cell in the model domain based on the Land Cover Map of Great Britain 2000. This data set was derived from an automatic classification of Landsat Thematic Mapper data (Fuller et al., 1994) and is available for the whole of the UK. Land use for the study area is shown in Fig. 4, and the five categories of Arable, Managed Grassland, Forest, Bare Earth and Urban were associated with corresponding values of Manning's n friction parameter of 0.04, 0.03, 0.1, 0.022 and 0.018 based on the tables contained in standard literature sources (Chow, 1959; Acrement and Schneider, 1984). The land cover data were also used to set values for the monetary damage that would occur through inundation of that particular cell. The values used were modified from those in Penning-Rowsell et al. (2003) which provides depth–damage curves for particular land use types. For simplicity we averaged these depth–damage curves to determine a single loss value that would occur given inundation of a particular cell, however using a full depth–damage curve is a relatively simple extension of the methodology described here. These friction and land use value for each land use type are summarised in Table 2.

5. Results and discussion

Fig. 5 shows the maximum flood depths predicted by the LISFLOOD-FP model for various recurrence interval events assuming no sea level rise (i.e. under current conditions). Cells with maximum predicted depths of <0.1 m are excluded from these plots as: (a) this is below the accuracy level of the LiDAR data and (b) is unlikely to lead to significant and unpreventable flood damage. The total area inundated on the landward side of the sea defences by each of these events is summarised in Table 3. The 1 in 1 year, 1 in 100 year and 1 in 200 year high tide events did not lead to any overtopping of the coastal defences for this site (as one would hope given their design criteria). For the 1 in 100 year and 1 in 200 year high tide events, a small amount of flooding is present at the mouth of the Gordano Valley between Portishead and Avonmouth where the fluvial defences in this area have been overtopped. The coastal defences also appear to cope with a 1 in 1000 year high tide event, protecting the coastal towns of Weston Super-Mare and Clevedon from flooding. Flooding, to a greater or lesser extent, also occurs on the Somerset Levels after breaching the river defences on the Yeo and Axe for the 1 in 100 year, 1 in 200 year and 1 in 1000 year high tide events. However, this flooding only affects 2 types of land use: arable land proximal to the River Axe, and managed grassland on the Somerset Levels surrounding the River Yeo.

Fig. 6 shows the impact on flooding of a sea level rise of 0.48 m. The total area inundated by these events on the landward side of the sea defences is again summarised in Table 3. The 1 in 1 year high tide event with an additional 0.48 m of sea level rise causes no flooding apart from slight inundation in the Gordano Valley. This is unsurprising as the maximum water elevation during a 1 in 1 year event with 0.48 m of sea level rise is still less than that during a 1 in 100 year high tide event under current conditions and therefore is below current defence crest elevations. However, when 0.48 m of sea level rise is added to the 1 in 100 year and 1 in 200 year events, flooding occurs on the Levels over areas of 11.3 km^2 and 14 km^2 respectively (see Table 3). In both cases the floodwaters progress far enough across the Somerset Levels to reach the M5 motorway embankment, which contains the flood at this point. In reality, numerous culverts and bridges running underneath this road (but not represented in the model) will allow some of this water to progress further eastward. Small amounts of flooding are present on the outskirts of Portishead, Clevedon and Weston Super-Mare although the resolution of the DEM and land use map makes it difficult to ascertain the precise extent of flooding that would occur. 0.48 m of sea level rise added to the 1 in 1000 year high tide event leads to a significant amount of flooding. Over 24 km^2 of land is inundated in this scenario, most of which is on the low lying, agricultural land of the Somerset Levels but some of the urban areas in the region are also affected. The majority of flooding is sourced from the tidal section of the River Yeo and, after overtopping the defences, flooding has been forced away from the river channel and across the Levels by the M5 motorway embankment. About a quarter of Clevedon is flooded to a depth of between 0.l and 0.5 m. The sea has also overtopped the coastal defences of Weston Super-Mare and led to a flood progressing through the central part of the town.

Whilst Fig. 6 represents the most plausible estimate of the area at risk of flooding by 2100 (*c.f.* Fig. 1), the use of any particular deterministic scenario masks uncertainty over possible future conditions. In this case the IPCC Third Assessment Report estimates that sea level rise by 2100 will be in the range from 0.09 to 0.88 m and this range is sufficiently wide to lead to major differences in predicted losses depending on which scenario is used in decision making. For example, Fig. 7 shows the risk (in terms of the annualised monetary loss, £ yr^{-1}) resulting from a 1 in 200 year event over this sea level rise range. This was obtained by taking the maximum flood extent predicted for a 1 in 200 year event assuming sea level rises of 0.09, 0.28, 0.48, 0.68 and 0.88 m and for each flooded cell on the landward side of the sea defences summing the per cell monetary losses given in Table 2. This gives the total loss for the event which is then converted into a simple risk value for this single event by multiplying by the event annual probability (in this case 0.005). In other words, the risk R (in £ yr^{-1}) for a given recurrence interval event (T) is given by:

$$R_T = \left(\sum_i f_i L_i\right) P_T \tag{7}$$

where for each model pixel, i, the variable f takes a value of 1 if the cell is inundated and is zero otherwise and L is the monetary loss caused by inundation of that cell to greater than 0.1 m. All monetary values are given at current levels with no allowance made for inflation by 2100.

Fig. 7 shows that a 0.09 m rise added to the 1 in 200 year high tide event would lead to an R_{200} of just over £250 yr^{-1} (total event losses of ~£50 k). This is purely agricultural loss because the coastal defences protecting the urban areas are not overtopped with this sea level rise. At the more extreme end of the IPCC projection, a sea level rise of 0.88 m on a 1 in 200 year event would lead to an R_{200} of £4.75 M yr^{-1} (total monetary loss of ~£950 M) due to flooding of parts of the urban areas. Uncertainty over scenario selection can therefore make a major difference to arguments over which defence spending decisions are, or are not, justified.

A more robust way to proceed is to take into account the uncertainty over future sea level rise when calculating R_T. In Eq. (7) f is equivalent to the probability that a particular cell is flooded in a given event, and for a single deterministic simulation this can only be 1 or 0. In reality the probability of flooding in any model grid cell for a 200 year event occurring in 2100 is uncertain because of uncertainty over sea level rise. This probability (here termed P_i^{flood}) can be calculated from an ensemble of model realisations using Eq. (2) so a better formulation for $R_T$given this uncertainty is therefore:

$$R_T = \left(\sum_i P_i^{\text{flood}} L_i\right) P_T \tag{8}$$

P_i^{flood} for the 1 in 200 year event was therefore calculated for each pixel using the ensemble approach described in Section 0. These values of P_i^{flood} can then be mapped across the model domain and used to calculate a value for the risk due to a 1 in 200 year event in 2100 weighted according to spatial variations in the probability of flooding. P_i^{flood} values are shown in Fig. 8 and this figure indicates that there is a 25% probability that parts of Clevedon, Portishead and Weston Super-Mare will be inundated by a 1 in 200 year event occurring in 2100 given uncertain sea

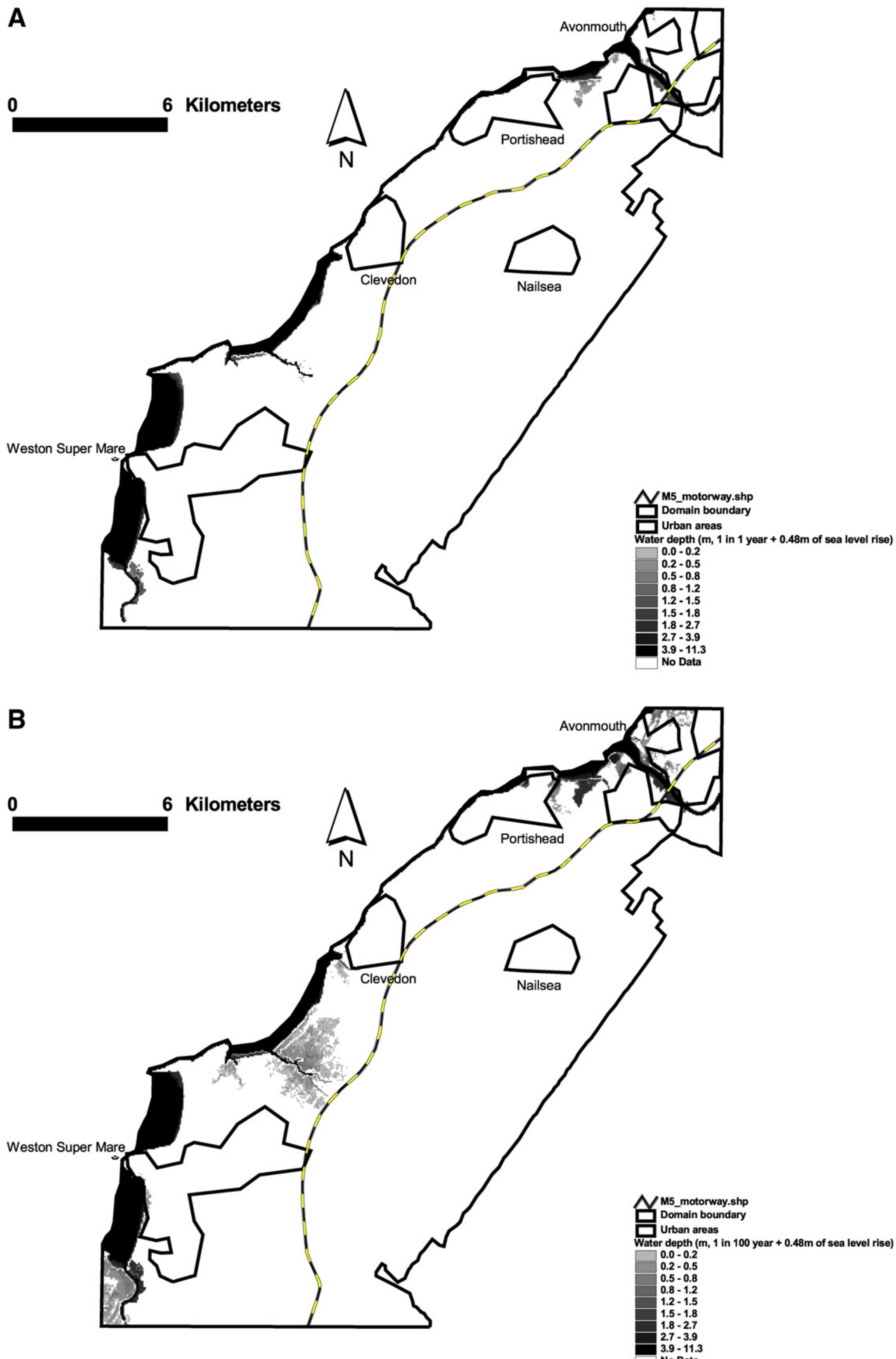

Fig. 6. Flood depths predicted by the LISFLOOD-FP model for 1 in 1, 1 in 100, 1in 200 and 1 in 1000 year recurrence interval events assuming the median sea level rise by 2100 (0.48 m) stated in the IPCC Third Assessment Report.

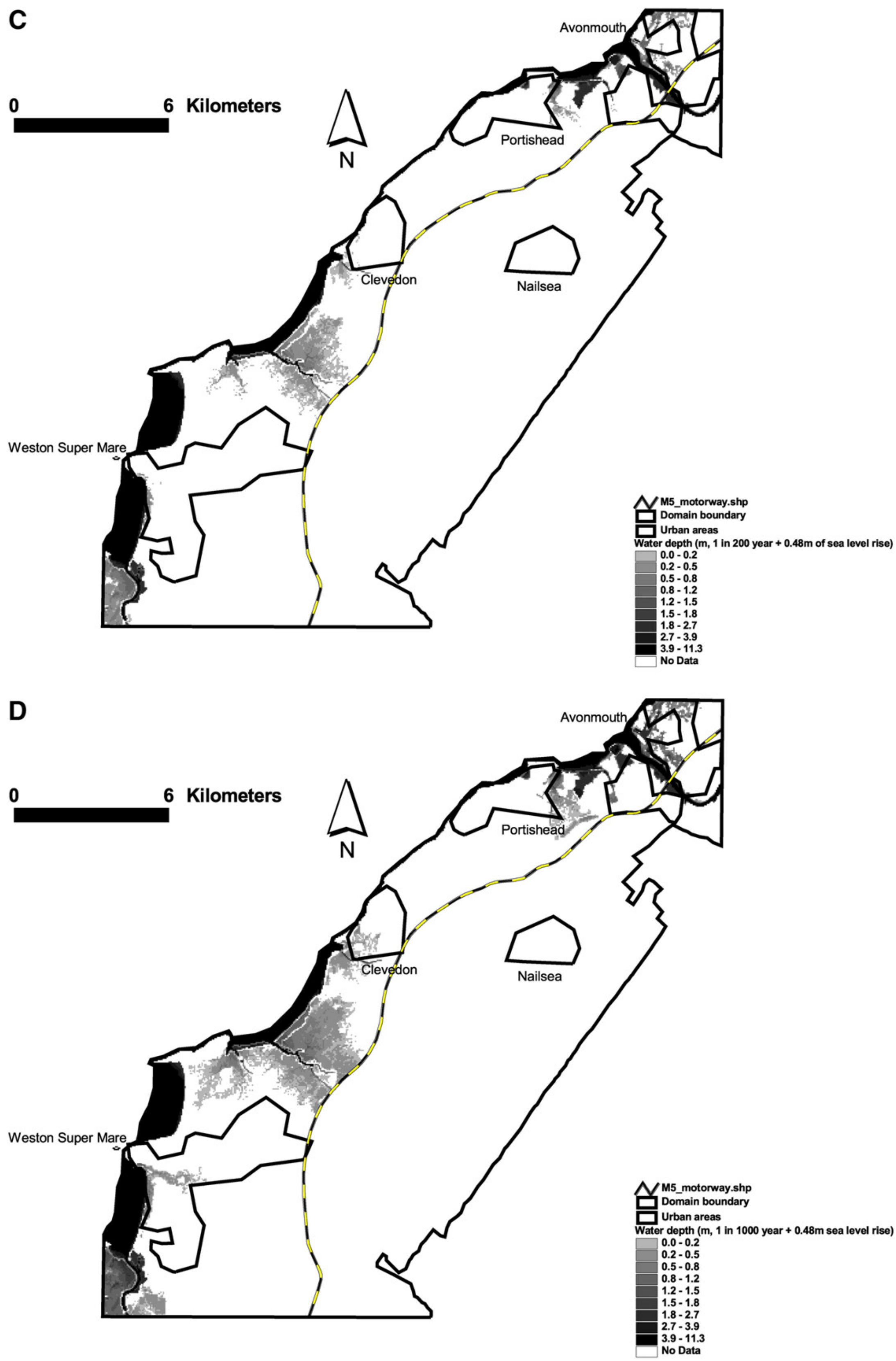

Fig. 6. (*continued*).

level rise. Application of Eq. (8) gives an ensemble R_{200} of £4.06 M yr^{-1}, which is significantly greater than the value of £0.9 M yr^{-1}calculated for the most plausible sea level rise scenario of 0.48 m. The reason for this is that even though the probability of flooding in urban areas over the whole ensemble is low, the consequences of this in terms of monetary losses per pixel are high (£750 k per 50 m×50 m cell). The contribution of small amounts of urban area flooding in the higher sea level rise scenarios to the total risk is therefore large and this dominates the

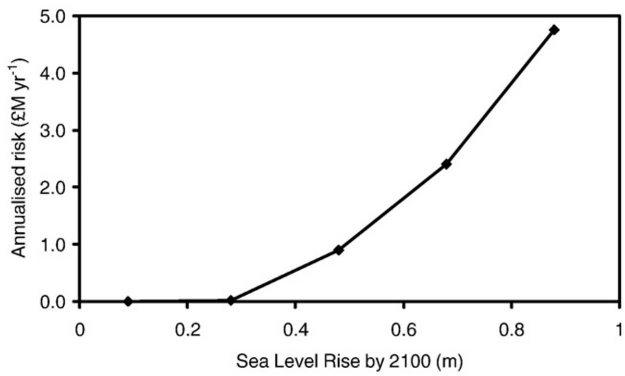

Fig. 7. Risk (in terms of annualised monetary losses in £ yr^{-1}) associated with a 1 in 200 year flood event over the range of sea level rise by 2100 stated in the IPCC Third Assessment Report.

calculation of the ensemble-based R_{200}. Use of the median sea level rise value in a deterministic risk analysis therefore underestimates total losses and would only justify significantly reduced (and possibly insufficient) spending on defences. Maps of the spatial contributions to risk (see Fig. 9) in the form of the risk per pixel may also very useful in prioritizing locations for defence spending and testing the impact of particular defence scenarios as part of objective, risk-based management.

Clearly, much of the above analysis is dependent on the particular assumptions made regarding monetary loss values, the probability distribution inferred for future sea level rise and the way this is sampled, the choice of inundation model and some of the analysis conditions (e.g. using a single loss value for each cell rather than a full depth–damage curve). However, the intention here is not to over-analyse the specific numerical values obtained, but rather: (1) to demonstrate a more robust methodology for estimating coastal flood risk under uncertainty and (2) to illustrate the potential for bias resulting from a deterministic approach in a proof-of-concept experiment. Whilst, the risk values obtained will change with different models and assumptions, the conclusion that one needs to evaluate uncertainty fully in order to avoid bias is likely to be a general one.

6. Conclusions

This paper has presented a methodology to estimate the probability of future coastal flooding given uncertainty over possible sea level rise. This has been used to estimate the risk for a 1 in 200 year event and has been compared to the estimates of the risk that would be obtained if a single deterministic scenario for future sea level rise were to be assumed. The analysis shows that undertaking a risk assessment using the most plausible sea level rise scenario may significantly underestimate monetary losses as it fails to account for the impact of low probability, high consequence events. The developed method can also easily be extended to consider other sources of uncertainty such as changing event frequency–magnitude distribution, changing storm surge conditions or model structural uncertainty, either singly or in combination as joint probabilities.

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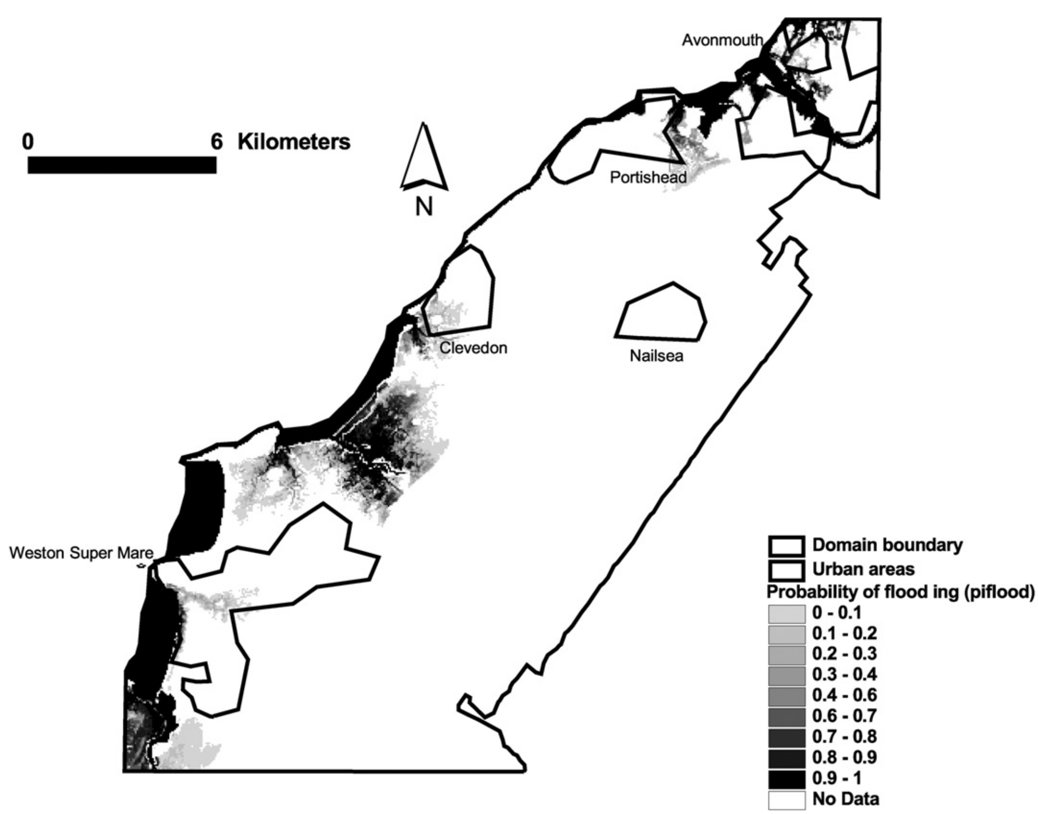

Fig. 8. Probability of inundation (P_i^{flood}) predicted by the LISFLOOD-FP model for a 1 in 200 year recurrence interval event given the uncertainty in sea level rise by 2100 stated in the IPCC Third Assessment Report.

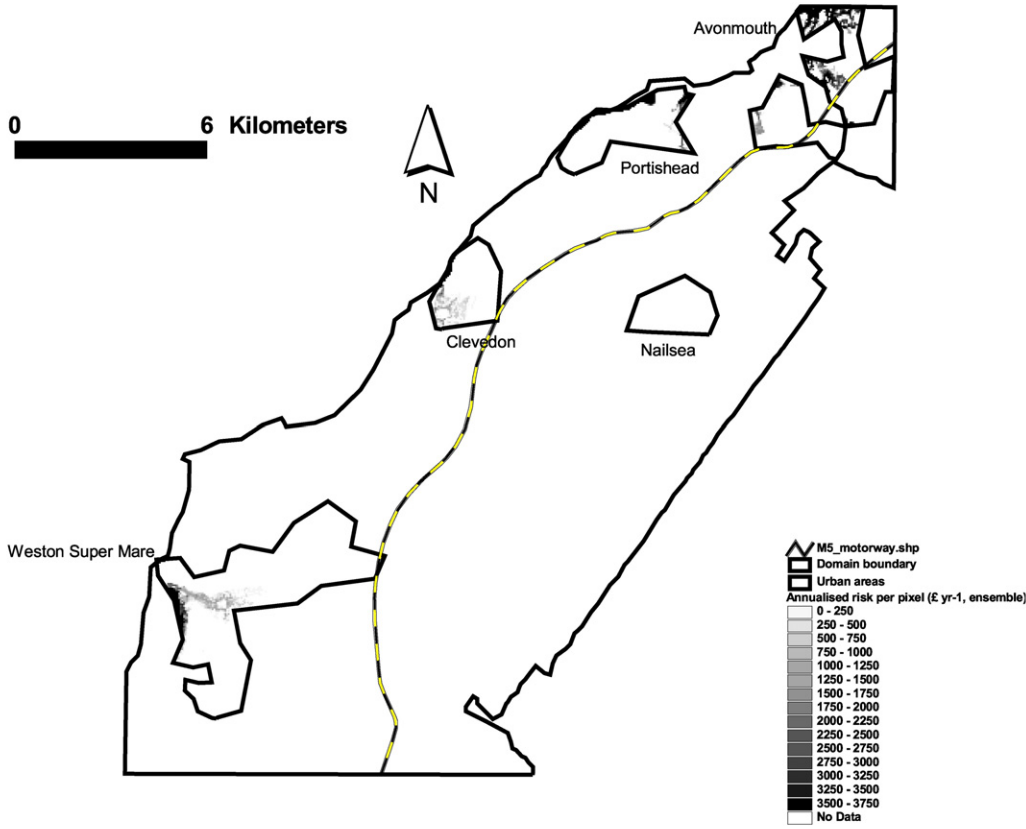

Fig. 9. Spatial variation of risk (in £ yr^{-1} per 50 m×50 m model cell) over the domain for a 1 in 200 year recurrence interval event given the uncertainty in sea level rise by 2100 stated in the IPCC Third Assessment Report.

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