Water Resources Development,
Vol. 21, No. 4, 577–591, December 2005

Quantified Analysis of the Probability of Flooding in the Thames Estuary under Imaginable Worst-case Sea Level Rise Scenarios

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ABSTRACT *Most studies of the impacts of sea level rise (SLR) have explored scenarios of <1 m during the 21st century, even though larger rises are possible. This paper takes a different approach and explores and quantifies the likely flood impacts in the Thames estuary for a number of plausible, but unlikely, SLR scenarios. The collapse of the Western Antarctic Ice Sheet (WAIS) could cause global mean sea level to rise by 5–6 m; here a time-scale for such an event of 100 years is assumed to create a worst-case scenario. Combined with the 1 in 1000 storm surge event, this would result in 1000 km^2 of land being frequently inundated. This area currently contains 1 million properties and their inundation would result in direct damage of at least £97.8 billion at 2003 prices. Smaller SLR scenarios, resulting from a partial collapse of the WAIS over 100 years, also have significant potential impacts, demonstrating the vulnerability of the Thames estuary to SLR. Construction of a new storm surge barrier in the outer Thames estuary is shown to provide greater resilience to unexpectedly high SLR because of the additional large flood storage capacity that the barrier would provide. This analysis has, for the first time, connected mechanisms of abrupt climate change and SLR with hydrodynamic modelling used to quantify impacts. In particular, it is recognized that future management strategies need to be adaptive and robust in order to manage the uncertainty associated with climate change.*

Introduction

A significant proportion of the world's population reside in the coastal zone: 1.2 billion people lived in the near-coastal zone (the area within 100 km distance and 100 m elevation of the coastline) in 1990 at densities about 3 times the global mean (Small & Nicholls, 2003). Urbanization is an important trend, including a high concentration of the world's biggest cities (Nicholls, 1995), and a considerable portion of global gross domestic product (GDP)

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0790-0627 Print/1360-0648 Online/05/040577-15 © 2005 Taylor & Francis
DOI: 10.1080/07900620500258380

is also produced in coastal zones (Turner *et al.*, 1996). Coastal development is already threatened by a range of hazards. Moreover, human development and activity, such as the destruction of saltmarsh, the construction of artificial barriers and development, are impacting the natural behaviour of the coastal zone and changing the risk of flooding and storm damage. Climate change, in particular sea level rise (SLR), is an additional pressure that will greatly impact on developments in the coastal zone (Nicholls, 2002).

There is a great deal of uncertainty as to future changes in sea level. The rate of SLR is governed by many factors (in some cases opposing). The heavily dampened response of the ocean to atmospheric warming means society is committed to a certain amount of SLR regardless of any other factors (Wigley, 1995; Nicholls & Lowe, 2004). Thermal expansion and ice cap melting will result in increased SLR, whereas Antarctica's growth and increased terrestrial storage of water resources by humans could act to reduce SLR. Regional oceanographic and meteorological effects and vertical land movements further compound the uncertainty about future relative SLR at any site. For London, the UK Climate Impacts Programme (UKCIP) has downscaled the global mean SLR scenarios of the Intergovernmental Panel on Climate Change (IPCC) (2001), suggesting a rise of between 0.26 m and 0.86 m, with an additional +50% uncertainty due to regional oceanographic effects (Hulme *et al.*, 2002). If Antarctica were a positive contribution to SLR during the 21st century, the rise in sea level could be larger than the above scenarios. In the extreme, the total collapse of the Western Antarctic Ice Sheet (WAIS) would result in an SLR of 5–6 m (Mercer, 1978; Oppenheimer, 1998). The probability and associated time-scale for such a collapse are highly uncertain. While significant collapse is considered highly unlikely to occur during the 21st century (Vaughan & Sponge, 2002), our limited scientific understanding of collapse does not allow us to discount total collapse over 100 years, although such an event must have a low probability. It is noteworthy that since this research project finished recent observations by the British Antarctic Survey have cast further doubts on the stability of the WAIS (Tirpak *et al.*, 2005). These extreme WAIS collapse scenarios were explored in the Atlantis project, which was primarily a study of response to abrupt climate change (Tol *et al.*, forthcoming), and the present study supported this research with an analysis of possible impacts and potential responses for the Thames estuary.

Abrupt climate change is defined by the National Research Council (2002) thus:

> . . .from the point of view of societal and ecological impacts and adaptations, abrupt climate change can be viewed as a significant change in climate relative to the accustomed or background climate experienced by the economic or ecological system being subjected to the change, having sufficient impacts to make adaptation difficult.

Hulme (2003) suggests that SLR in excess of the maximum IPCC (2001) estimates of approximately 1 m per century may be considered as an example of abrupt climate change. Previous analyses of the impacts of climate change events have often focused on broad-brush estimates of loss of GDP for different global policy scenarios such as reducing CO_2 emissions (e.g. Keller *et al.*, 2000; Mastrandrea & Schneider, 2001) or global impacts on populations across sectors (e.g. Arnell *et al.*, 2002; Parry, 2004). Analysis at a more local level enables more specific quantification of the impacts and consideration of possible responses. This paper presents an exploratory analysis of SLR scenarios in the range of 1–5 m over the next 100 years. The analysis is based on a two-dimensional hydrodynamic storm surge model of the Thames estuary. The results of a limited number of plausible adaptation scenarios are also explored.

London, the capital of the UK, is home to 7.5 million people and has an average population density of 4500 people/km^2. It is estimated that currently 1 million people (London Assembly, 2002) and 300 000 properties are in the (present day) tidal flood risk area. The dominant flood threat comes from surge tides, caused by areas of low pressure travelling south or south-west over the North Sea which funnel a bulge of water into the confines of the southern North Sea and hence the Thames estuary. London is defended by a complex system involving over 200 km of embankments and floodwalls, the Thames Barrier and a suite of warning systems (Environment Agency, 2003a, b). While the possibility of a barrier was discussed earlier in the 20th century, the decision to build the present defences was made in direct response to the 1953 storm surge, which killed 300 people and flooded 65 000 ha of low-lying land on the UK's east coast (Gilbert & Horner, 1984). A full 30 years (only 8 years of which were construction time) after this event, the barrier was completed. Since the construction of the Thames Barrier, London's previously derelict docklands have been regenerated with new homes and businesses, including the new financial district around Canary Wharf. Significant future development is planned in flood-prone zones alongside the tidal Thames in London, Kent and Essex over the next 15–30 years (Office of the Deputy Prime Minister (ODPM), 2004).

The design life of the Thames Barrier and associated defence system is until 2030, by which time it is expected that rising sea levels will reduce the standard of protection to below a 1:1000 year standard (i.e. the barrier is expected to be overtopped by the 1 in 1000 year event if it were to occur). Given the long lead-time required to upgrade the defences, planning of the flood risk management strategy until 2100 is already in its early stages. A number of possible management strategies in the Thames estuary are being considered by the Environment Agency (2003a, b, c) and the ODPM (2004). These consider landward realignment of the flood defence line as a complementary strategy to raising defences and the generation of wetlands, thereby reversing a long-term trend of encroachment and land claim into the tidal Thames. It is likely that the current defence system will be raised by ~1 m at a cost of roughly £4 billion (London Assembly, 2002), although much more analysis is required before detailed options and their costings become available.

Inundation Modelling of the Thames Tidal Floodplain

Tidal circulation, and hence inundation resulting from a storm surge, is driven by a number of physical processes including gravitational forcing, density variations due to salinity, turbulence and surface wind stress. Numerical models of such flows range in complexity from fully three-dimensional solutions of some derivative of the Navier–Stokes equations (Cugier & Le Hir, 2002) to models that treat flow as one-dimensional in the down-estuary direction only (Kashefipour *et al.*, 2002). Choice of model depends on the morphology of the estuary and the hydrodynamics of the flow to be simulated. The tidal Thames is a drowned river valley with morphology typical of coastal plain estuaries (Dyer, 1973) with extensive tidal mudflats. Simulation of inundation over low-gradient tidal floodplains with significant flood defence structures (embankments, etc.) requires at least a two-dimensional modelling approach with relatively high spatial resolution (grid scales 250 m or less) to represent the complex geometry. However, full two-dimensional modelling of the whole Thames estuary remains computationally prohibitive at this scale, particularly if one wishes to simulate multiple scenarios associated with different potential futures.

To reduce the computational burden of the hydrodynamic calculations for this study it was assumed that for very large storm surge events the gravitational forcing at the estuary mouth is the dominant driving process. The authors also assume that the large volume of saline water entering the estuary is such that density can be assumed to be constant. Lastly, the authors assume the flood wave propagation can be represented as an approximation to a two-dimensional diffusive wave. Here the estuary and floodplain are discretized as a grid of rectangular cells. Flow between cells is then calculated simply (Figure 1) as a function of the free surface height difference across each cell face:

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

Change in water depth in a cell over time t is then calculated by summing the fluxes over the four cell faces:

$$\frac{\mathrm{d}h^{i,j}}{\mathrm{d}t} = \frac{Q_x^{i-1,j} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y} \tag{2}$$

where $h^{i,j}$ is the water free surface height in cell (i,j), .Δx and Δy are the cell dimensions, n is a friction coefficient and Q_x and Q_y describe the volumetric flow rates between floodplain cells. Equations (1) and (2) give similar results to a more accurate finite difference discretization of the diffusive wave equation (Horritt & Bates, 2001) but with much reduced computational cost. This model, LISFLOOD-FP, has been shown to perform as well as full two-dimensional codes (Bates & De Roo, 2000; Horritt & Bates, 2001) for the case of fluvial flooding, whilst Dawson *et al.* (2003) and Bates *et al*. (2005) have achieved good performance for coastal flood modelling. This research has suggested that model resolution and topographic data quality are stronger controls on the ability to simulate flood inundation than model physics. The authors hypothesize that this representation of flooding as a volume-filling problem is also true for estuaries, and that a good first order model therefore only requires the simple routeing of the correct volume of

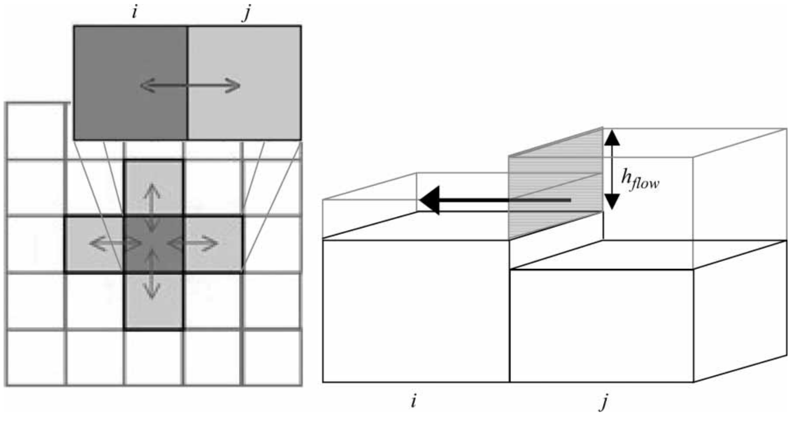

Figure 1. Representation of flow between raster cells in LISFLOOD-FP.

Table 1 Predicted water levels measured in metres above Ordnance Datum for given return periods along the Thames in 2030; sites are represented by triangles in Figure 3

	Return period (years)								
Site	2	5	10	20	50	100	200	500	1000
Silvertown (Thames Barrier)	5.21	5.44	5.61	5.77	5.95	6.11	6.29	6.51	6.70
Erith	5.10	5.33	5.50	5.66	5.87	6.02	6.21	6.43	6.62
Tilbury	4.66	4.89	5.03	5.19	5.37	5.53	5.70	5.91	6.09
Sheerness	3.89	4.08	4.20	4.33	4.49	4.62	4.77	4.96	5.12

Source: Jones (2001) and Environment Agency (2003a).

water over a detailed representation of the estuarine topography and flood defences. Effects such as wind shear, turbulence and density currents are, for very large storm surges at least, assumed to be secondary. While this simple model may not simulate fine details of the wave propagation (e.g. the timing of flood onset at a particular point), it will capture the maximum flood extent sufficiently well to evaluate the impact of different future SLR and defence scenarios.

Model boundary conditions are derived from statistical analysis of water levels in the estuary, shown in Table 1, and a typical storm surge history as shown in Figure 2. Therefore it is assumed that the storm surge characteristics captured in Table 1 and Figure 2 are constant over time, which, given the large magnitude of the SLR scenarios being considered, is a reasonable first assumption. The digital elevation map has been constructed from interferometric synthetic aperture radar data (Colemand & Mercer, 2002) and has a root mean square error of ± 0.7 m.

Flood risk in estuaries is dominated by two mechanisms: defence overflow and defence breaching (Hall *et al.*, 2003a). Overflow volumes of flood defences can be calculated using standard weir equations (e.g. see Chadwick & Morfett, 1993). Consideration of defence breach scenarios adds a further computational burden on the assessment of inundation probabilities (Hall *et al.*, 2003a) and requires the (often controversial) assessment of failure probabilities and breach widths to flood defence structures. The assessment of the

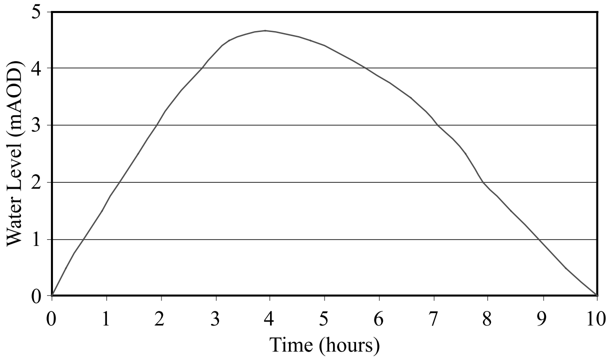

Figure 2. The 1953 storm surge as measured at Sheerness. *Source*: Rossiter (1954) and Smith & Ward (1998).

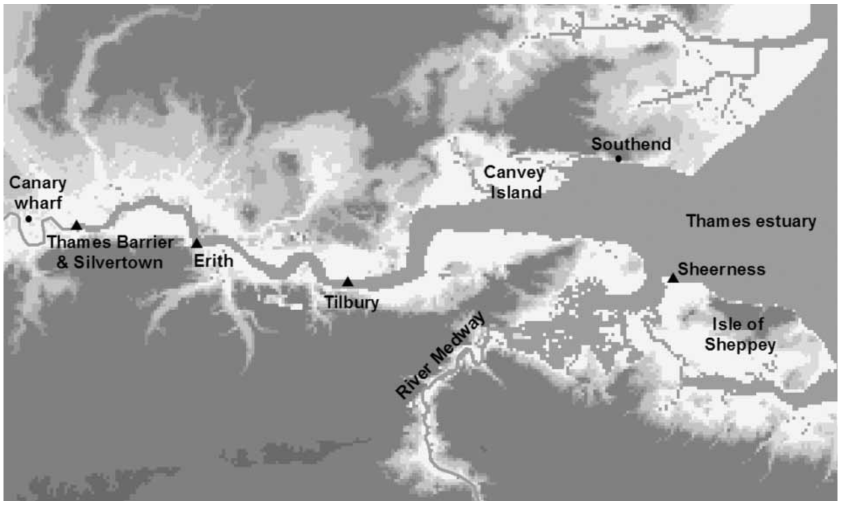

Figure 3. Map of Thames estuary showing the floodplain relief (lighter shades mean lower ground), the four tidal gauges (triangles), the Isle of Sheppey, Canvey Island and the River Medway.

flood risk contribution from defence breaching can be efficiently assessed using methods outlined by Dawson (2003). However, the good present condition of the barrier and defences downstream of it (Environment Agency, 2003a) (and the likelihood of significant upgrade in the next few decades) means that failure is unlikely except under extreme conditions of defence overflow. Due to the extreme nature of the SLR scenarios being considered in the modelling, the additional contribution to the total inundation volume from breaching is negligible when compared to the inundation volume from extreme overflow events.

A number of potential adaptation scenarios are considered in the hydrodynamic model. The first, a *status quo* scenario, gives a baseline for comparison against other possible intervention scenarios. This represents a policy of maintaining the strength of the defences at the 2003 crest level. This scenario is a baseline and it should be noted that significant upgrades to the current defence system are planned in line with the high-end UKCIP scenarios for SLR (~1 m crest level rise) (Hulme *et al.*, 2002). Another adaptation scenario is to raise the current defence system: in this case the defences are assumed to maintain the same relative levels of protection. The construction of new alternative downstream tidal barriers is also considered: the first is upstream of the Medway estuary at Canvey Island (E: 581250, shown in Figure 4); and the second is downstream of the Medway at the Isle of Sheppey (E: 593250, shown in Figure 5), a location first suggested by Gilbert & Horner (1984), who contributed substantially to the design and construction of the current Thames Barrier. When implementing the possibility of constructing an outer barrier, it was assumed that the other estuary defences would be upgraded to reflect the increased standard of protection offered by the new barrier.

Key results from the hydrodynamic model are presented. Figures 6–8 show the flood outline for the 1:1000 year flood event, assuming that no defences are constructed or raised, for 1 m, 3 m and 5 m net SLR scenarios. The topography of the Thames estuary floodplain is such that the area at risk from flooding increases most rapidly for the first 1 m

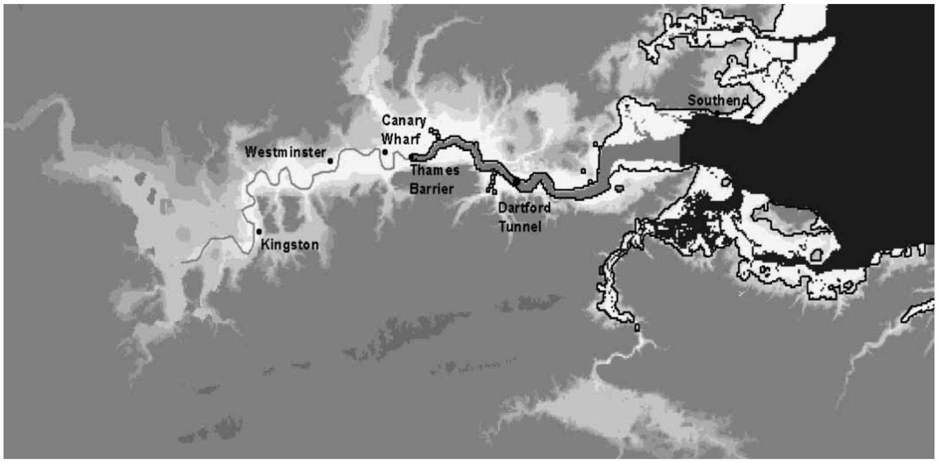

Figure 4. The 1:1000 year flood after 1 m net SLR assuming the Canvey Island Barrier is designed to a standard of protection of 1:1000 in 2030.

of SLR. Each additional 1 m of SLR produces a smaller increase in the inundated area. In the worst-case scenario of 5 m net SLR (equivalent to a 5 m SLR and no intervention, or a 6 m SLR and 1 m raise in crest defence level), approximately 1000 km^2 of land and 1 million properties would be at risk from flooding during the 1000 year event (Figure 8). The approximate area inundated for the 1 m and 3 m SLR scenarios is 650 km^2 and 850 km^2, respectively, whilst the current area at risk from the 1000 year event is $\sim$400 km^2. The number of properties likely to be inundated for different return periods and SLR scenarios is summarized in Figure 9. The most dramatic result is that even with a 2 m net SLR, 200 000 properties (assuming no further development) would be flooded annually assuming no adaptation response.

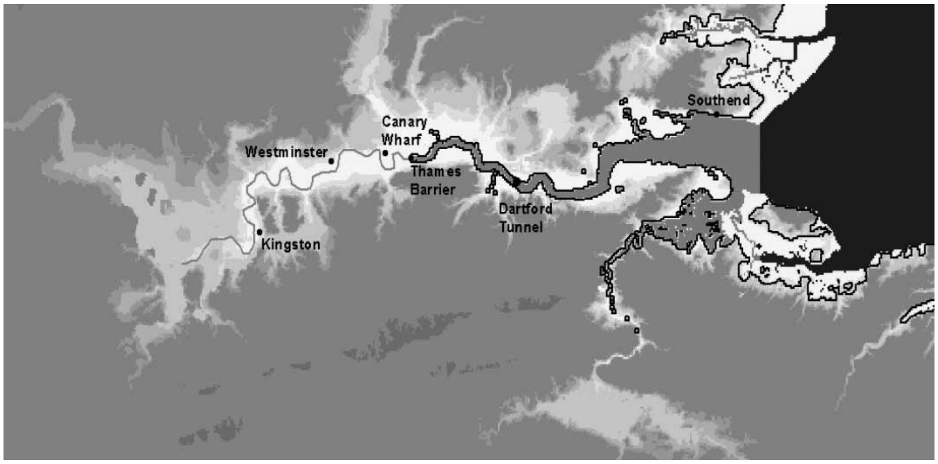

Figure 5. The 1:1000 year flood after 1 m net SLR assuming the Sheppey Barrier is designed to a standard of protection of 1:1000 in 2030.

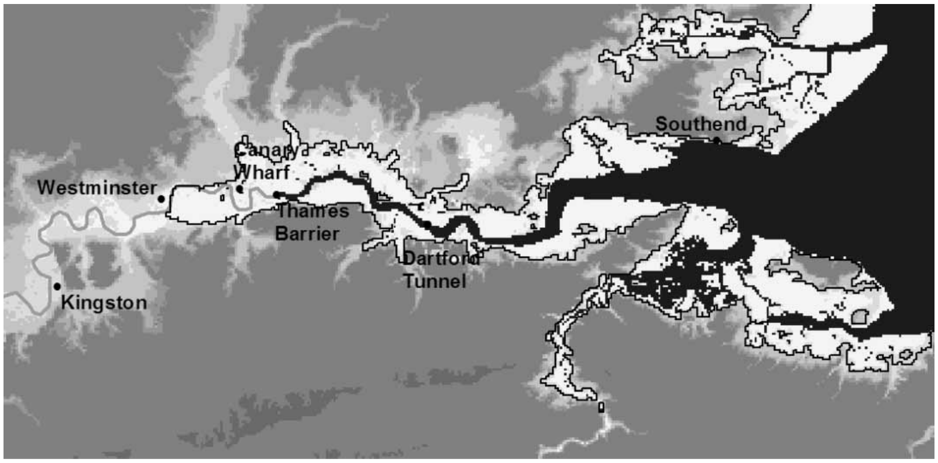

Figure 6. The 1:1000 year flood outline after 1 m net SLR (lighter grey shades in the floodplain represent lower ground, the estuary very dark).

Clearly, each flood outline can equate to a number of SLR and defence-raising scenario combinations. For example, the flood outline given by Figure 6 can represent a 1 m SLR with no defence raise, or a 2 m SLR and defences raised by 1 m or any other combination of defence-raising and SLR scenario that gives a net 1 m SLR. A total of 30 hydrodynamic simulations were performed for each scenario at net SLR increments of 0.2 m. By plotting contours of storm surge return period and net SLR, the appropriate flood outline can be selected; this is shown for Figures 6–8 in Figure 10. This figure also shows how even a 0.5 m SLR can significantly increase the probability of flooding. Thus, a rate of SLR of 1 m every 20 years will result in a significant increase in inundation probability for large areas of the Thames estuary after only 20–30 years, which is likely to pose significant challenges in terms of developing rapid adaptation strategies.

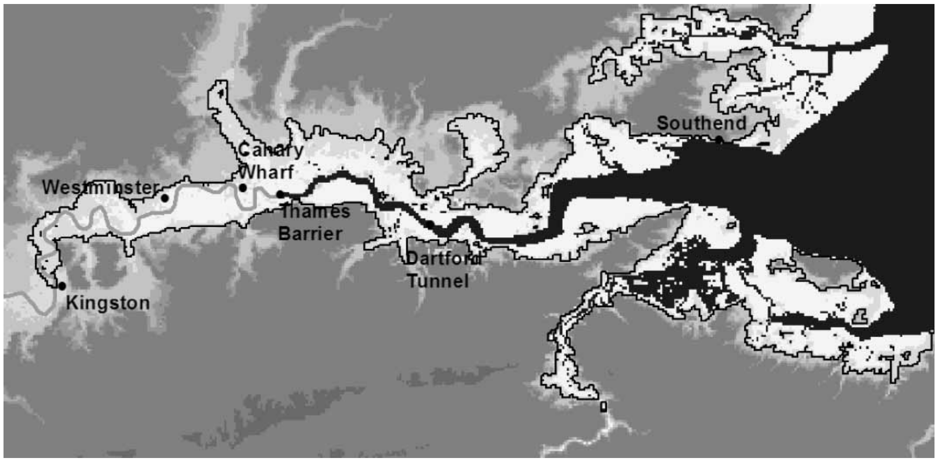

Figure 7. The 1:1000 year flood after 3 m net SLR.

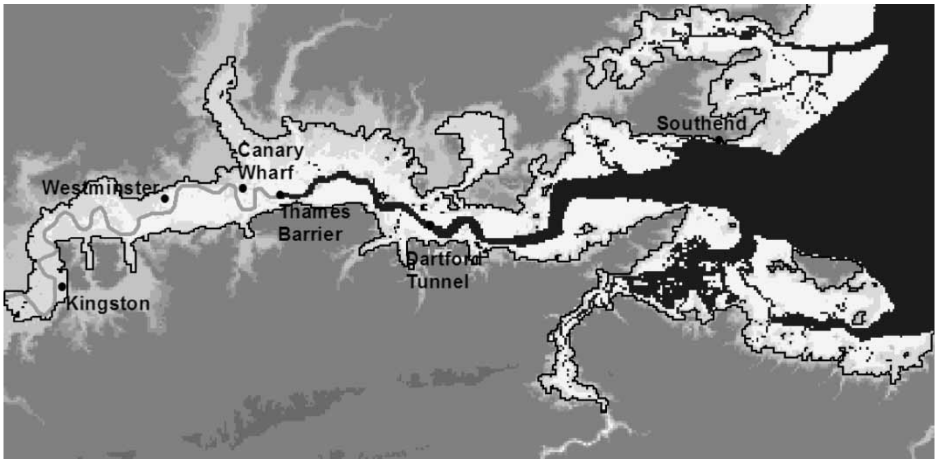

Figure 8. The 1:1000 year flood after 5 m net SLR, or 6 m SLR and 1 m defence upgrade (worst-case flood extent modelled).

Figures 4 and 5 show flood outlines for the Canvey Island and Sheppey barriers, respectively. The flood outlines are for a 1:1000 year flood event assuming 1 m SLR after the construction of barriers to a 1000 year standard of protection. The areas inundated for the outer barrier scenarios are 450 km^2 for a barrier located at Canvey Island and 350 km^2 for a barrier located at Sheppey Island, as compared with 650 km^2 for the existing Thames Barrier. Hence, construction of the outer barriers significantly reduces inundation probabilities in the floodplain. Their resilience to storm surges and high river flows is a result of the increased storage potential behind the barrier. This resilience, combined with their downstream position in the estuary, means that inundation of central London (i.e. Westminster) is much less likely, although East London (including Canary Wharf) would still be at risk (albeit considerably reduced).

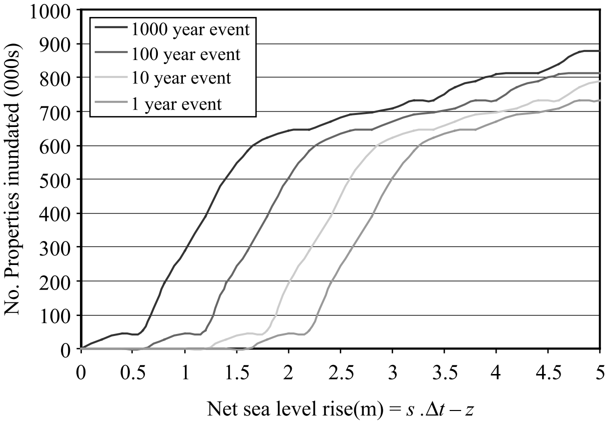

Figure 9. Number of properties inundated for different return periods and net SLR (= rate of SLR × Δt − Δz where Δt equals SLR duration and Δz is the change in crest level height) based on current defence system and assuming no development in the floodplain after 2003.

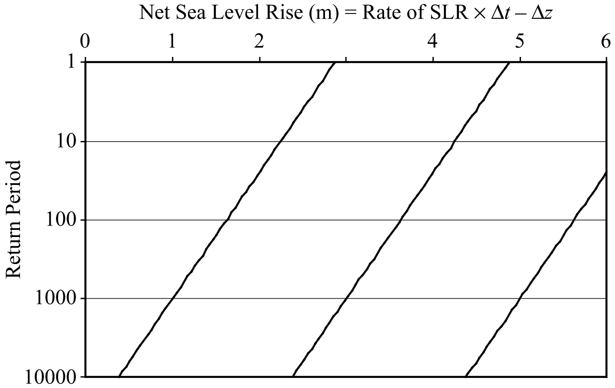

Figure 10. Contour lines showing how Figures 6–8 equate to a multitude of flood events and crest level-raising scenarios depending on the net SLR ($=$ rate of SLR $\times$ Δt $-$ Δz where Δt equals SLR duration and Δz is the change in crest level height).

Preliminary Consideration of Socio-economic Impacts

Grids providing spatial information of flood depth from the inundation modelling can be combined with flood depth–damage curves (e.g. Penning-Rowsell *et al.*, 2003) to estimate expected primary direct damages from flooding. For a given grid cell the expected annual damage, R, is given by:

$$R = \int_0^{y_{\max}} p(y)D(y)\mathrm{d}y \tag{3}$$

where $y_{\max}$ is the flood depth that results in maximum possible damage to a property, $p(y)$ is the probability density function for flood depth and $D(y)$ is the damage at depth y. The total expected annual damage for the Thames estuary floodplain is obtained by summing the expected annual damage for each inundated raster cell. For the most extreme net SLR scenario of 5 m (Figure 8), during the 1000 year event, the economic damage is estimated (in terms of 2003 prices) at £39.6 billion for residential property and approximately £58.2 billion for non-residential property. These estimates do not include the economic damage to infrastructure such as the Underground rail system and, because they are based on national averages, may require weighting to account for higher property prices in the London region.

The high property density in the area will result in very high primary direct damages from such flood events. However, important commercial districts such as Canary Wharf are in the higher-risk zones—being placed under threat from only a small (~1 m net) increase in sea level. Whilst the direct damage to infrastructure would undoubtedly be large, the potential impact on the London and UK economy in the long term might be disastrous. The interruption to transport and communication links and the loss of working hours and trading, etc. during the inundation and subsequent clean-up could run into billions of pounds sterling. Given the dynamic nature of financial businesses located in London they might rapidly relocate to other financial districts in Europe, such as Frankfurt, that are perceived to be ‘safer’ in the long term. The international nature of business would mean the impact of a serious flood event is likely to have global economic repercussions (Munich Re, 2004).

Due to the extreme nature of the scenarios being considered it is likely that large areas of land are likely to be inundated rapidly. Water velocities cannot be reliably extracted from the inundation model, although rates of rise can be estimated and the model shows rates of rise in central London of up to 2 m/h for the 1:1000 year event after just 1 m net SLR. This rate of rise poses a serious threat to human life, particularly when considering that the high population density of the Thames estuary means that evacuation of large areas of floodplain poses a serious problem for the emergency services. The risk of inundation of a large number of London hospitals (and more elsewhere along the estuary) adds further to this strain. Supplies of drinking water, gas and electricity might be interrupted. Furthermore, inundation of heavy industry at Canvey Island and elsewhere could result in the spreading of contaminants and consequential environmental damage or conflagration as imagined by Doyle (2003).

These impacts are estimated based on the assumption that the socio-economic *status quo* is maintained and there is no further development in the floodplain. This scenario is unrealistic. First, significant development is already planned in the estuary, meaning impacts are likely to increase (ODPM, 2004). Secondly, the impact assessment is heavily simplified as it only considers direct damage resulting from independent flood events. Figure 9 demonstrates that even for small increases in net sea level, a large number of properties rapidly become susceptible to high probabilities of flooding. This increased flood frequency associated with the extreme SLR would result in more complex socio-economic feedbacks: society is likely to try and adapt to the SLR perhaps through increased provision of physical defences or even abandonment of frequently flooded areas. Consideration of these detailed socio-economic issues is outside the scope of this paper, but is reported by Lonsdale *et al*. (forthcoming). However, this preliminary analysis is useful because it highlights the magnitude of the challenge that such an extreme SLR would pose to flood risk managers.

Limitations and Directions for Further Research

The current model has been implemented with relatively limited data. This is a major advantage of using LISFLOOD-FP and a key reason in its selection for this study. The model has demonstrated its power as an exploratory tool to assess flood impacts, including the benefits of possible interventions on flood risk. As well as defence-raising scenarios, two possible outer barrier sites have been tested—at Canvey Island and Sheppey—to provide an indication of how two alternative barrier positions, when compared to the present barrier, might reduce flood risk along the estuary. These demonstrate increased effectiveness at reducing flood risk. However, it should be noted that not all flood risk management adaptations have been tested and the authors do not wish the analysis of only ‘hard’ adaptation options in this paper to be misinterpreted as an expression of support for the construction of an outer barrier. Future developments of the analysis should consider managed realignment within the estuary, and other ‘soft’ flood management solutions such as those proposed by Hall *et al.*, (2003b), which include flood resilient development, public education and flood warning. Additional modelling would be required in order to simulate the effectiveness of an integrated portfolio of responses. Fluvial flood events are also likely to become more important given the possibility of a 30% increase in winter precipitation by 2080 (Hulme *et al.*, 2002), and the consequent increase in water run-off in the Thames (Reynard *et al.*, 2001). Further enhancement of the model would enable the flood risk associated with joint fluvial and tidal events to be considered.

Uncertainties in the inundation modelling can be quantified (Aronica *et al.*, 2002), although in this study, due to the extreme nature of the events being considered, uncertainties in the flood outline and depth will be dominated by the inaccuracies of the DEM. However, these are likely to be insignificant by comparison to uncertainties related to our poor understanding of the underlying climate processes. A number of possible mechanisms for abrupt climate change have been identified (e.g. collapse of the WAIS (Oppenheimer, 1998; Vaughan & Sponge, 2002), or collapse of the North Atlantic Thermohaline Circulation (Clark *et al.*, 2002)) but our poor understanding of the climate system and its sensitivity to anthropogenic forcing presently precludes the detailed estimation of scenario probability. Whilst the authors are not suggesting that the full range of modelled scenarios need to be explicitly considered in future design, the model results highlight the vulnerability of the Thames estuary floodplain to even 1 m net SLR. In order to respond to these poorly defined risks effectively, future flood management strategies need to be robust and consist of a portfolio of possible adaptation options so that they can respond to a range of events, including those induced by abrupt or large climate change. In the case of London, it can be argued that this range extends to a 2 m SLR during the 21st century (Arnell *et al.*, 2005).

This becomes increasingly important when the rate of change is considered. Should 1 m net SLR occur over a long duration, society is likely to be able to respond on an *ad hoc* basis. However, rapid change such as the partial or complete collapse of the WAIS would force a step change in the rate of SLR. Based on the experience of constructing the current Thames Barrier and the Eastern Schelde Barrier in the Netherlands, it is unlikely that a new outer barrier could be designed and built in less than 20 years. Indeed, even an upgrade of the current defence system is likely to require a similar time-scale. In an SLR scenario of 5 m over 100 years—even including the proposed upgrade of 1 m to the defence system—within 40 years central London will be threatened by the 1 in 10 year flood (Figure 9). Given that it may also take a number of years before data collection and analysis confirm that a step change in the rate of SLR has occurred, rather than it being identified as natural variability, it is possible that radical non-structural solutions, such as large scale abandonment, might be forced upon the inhabitants of the Thames estuary. This is echoed by Mastrandrea & Schneider (2001), who state that the advent of abrupt climate changes would reduce adaptability and thus increase climate damage. They are supported in arguing for stronger and earlier climate mitigation action by Perrings (2003), who believes that such mitigation can be justified economically by the risks of abrupt change. Given the great uncertainty in our understanding of human and climate related processes, future decisions on flood management need to be flexible in the long term in order to effectively manage this uncertainty (cf. Evans *et al.*, 2004).

Conclusions

The Environment Agency and other stakeholders are currently reviewing the long-term strategy for managing the Thames estuary with the aim of protecting London into the next century. This plan is based around preparing for the high-end UKCIP scenario for SLR of about 1 m over the 21st century. However, a greater rise in SLR is certainly possible: the collapse of the WAIS is one causal mechanism which might force a stepped change in the rate of SLR. While this paper has explored a range of extreme SLR scenarios, an important result is that a net SLR as low as 1 m would significantly increase flood risk in the Thames estuary. Given the likely 1 m upgrade of the defences, this translates into a 2 m rise in sea level. This could be produced by a variety of combinations of sea level sources during the 21st century, such as (1) the high-end IPCC (2001) scenarios (~0.9 m), (2) positive regional changes in the north-west Atlantic (~0.4 m) and (3) the balance from Antarctica (~0.7 m) (see Arnell *et al.*, 2005).

Modelling presented in this paper has for the first time linked a possible mechanism for abrupt climate change and SLR to a two-dimensional hydrodynamic model that can be used to support quantified impacts assessment. The model demonstrated that a stepped change in SLR could have disastrous consequences along the Thames estuary, including scenarios of partial collapse of the WAIS. A limited number of adaptations were tested and this demonstrated the effectiveness of an outer barrier as one approach to reduce flood risk under these conditions. A number of further improvements to the model have been identified, in particular the need to model non-structural solutions and consider fluvial–marine interactions. Most importantly, the results show the need for future flood management to be both robust and adaptive so that it can better respond to the range of possible changes, such as rapid SLR.

This paper has provided a quantified analysis of a small subset of possible responses under idealized conditions to extreme SLR scenarios, providing an important baseline for flood risk managers. The model results can be used to support detailed consideration of societal response. Although outside the scope of this paper, this is being investigated in a series of other papers from the Atlantis research project, including Lonsdale *et al.* (forthcoming).

Acknowledgements

The research in this paper was funded through the European Commission FP5: EVK2-CT-2002-00138 as the Atlantis project (Atlantis: North Atlantic Sea-level Rise: Adaptation to Imaginable Worst Case Climate Change). The DEM was provided by the Environment Agency of England and Wales.

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