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Quantified analysis of the probability of flooding in the Thames Estuary under imaginable worst case sea-level rise scenarios

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Abstract

This paper explores and quantifies the likely flood impacts in the Thames estuary for a number of plausible, but extreme sea level rise (SLR) scenarios. The collapse of the Western Antarctic Ice Sheet (WAIS) could cause global mean sea level to rise by 5-6m in 100 years. The worst case SLR scenario combined with the 1,000 storm surge event would result in 1000km$^2$ of land being inundated. This area currently contains 1 million properties and their inundation would result in direct damages of at least £150 billion at 2003 prices. However, the smaller SLR scenarios, resulting from only a partial collapse of the WAIS also have significant impacts demonstrating the vulnerability of the estuary to SLR. Construction of a new storm surge barrier in the outer Thames Estuary is shown to provide greater resilience to unexpectedly high sea level rise 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 recognised 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 100km distance and 100m elevation of the coastline) in 1990 at densities about three times the global mean (Small and Nicholls, 2003). Urbanisation is an important trend, including a high concentration of the world’s biggest cities (Nicholls, 1995) and a considerable portion of global GDP 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, construction of artificial barriers and development, is 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 sea level rise regardless of any other factors (Wigley, 1995; Nicholls and 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. The likely net future change in sea level from 1990 to 2080s is expected by the UK Climate Impacts Programme (UKCIP) to be between 0.26 and 0.86m in London, with an additional +50% uncertainty due to regional oceanographic effects (Hulme et al., 2002). This is based on the downscaling of the IPCC (2001) global mean SLR scenarios. In the extreme the total collapse of the Western Antarctic Ice Sheet (WAIS) would result in a SLR of 5-6m (Mercer, 1978;
Oppenheimer, 1998). The probability and associated time scale for such a collapse is highly uncertain. While significant collapse is considered highly unlikely to occur during the 21st century (Vaughan and Spouge, 2002), our limited scientific understanding of collapse does not allow us to discount total collapse over 100 years and hence this remains a plausible, albeit unlikely scenario.

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

“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 1m 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 CO₂ emissions (eg. Keller et al., 2000, Mastrandrea and Schneider, 2001) or global impacts on populations across sectors (eg. Arnell et al., 2002, Parry, 2004). Analysis at a more local level enables more specific quantification of impacts and consideration of possible responses. This paper presents an exploratory analysis of SLR in the range of 1 to 5m in the next 100 years. The analysis is based on a 2D 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 United Kingdom, is home to 7.5 million people and has an average population density of 4,500 people per square kilometre. It is estimated that currently one 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 southwest over the North Sea, which funnel a bulge of water into the confines of the
southern North Sea and hence Thames estuary. London is defended by a complex system involving
over 200km of embankments and floodwalls, the Thames Barrier and a suite of warning systems
(Environment Agency, 2003a, 2003b). While the possibility of a barrier was discussed earlier in the
twentieth century, the decision to build the present defences was made in direct response to the
1953 storm surge that killed 300 people and flooded 65,000 hectares of low lying land on Britain’s
east coast (Gilbert and 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 over the next 15-30 years (Office of the
Deputy Prime Minister, 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 (SoP) to below a 1 in 1,000
year standard (i.e. the barrier is expected to be overtopped by the 1 in 1,000 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, 2003b,
2003c) and ODPM (2004). These consider landward realignment of the flood defence line as a
complimentary 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 ~1m 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 and Le Hir, 2002) to models that treat flow as one-dimensional in the down-estuary direction only (Kashefi, 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 250m 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. We also assume that the large volume of saline water entering the estuary is such that density can be assumed constant. Lastly, we assume the flood wave propagation can be represented as an approximation to a 2D diffusive wave. Here the estuary and floodplain is 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:

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

\[ (1) \]
Change in water depth in a cell over time $t$ is then calculated by summing the fluxes over the four cell faces.

$$\frac{dh^{i,j}}{dt} = \frac{Q^{i+1,j}_x - Q^{i,j}_x + Q^{i,j+1}_y - Q^{i,j}_y}{\Delta x \Delta y}$$

(2)

where $h^{i,j}$ is the water free surface height in cell $(i,j)$, $\Delta x$ and $\Delta y$ 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 and 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 and De Roo, 2000, Horritt and Bates, 2001) for the case of fluvial flooding, whilst Dawson et al. (2003) 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. We hypothesise 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 routing of the correct volume of 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 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 sea level rise 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 DEM has been constructed from IFSAR (Interferometric Synthetic Aperture Radar) data (Colemand and Mercer, 2002) and has an r.m.s.e. of ±0.7m.

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 (see for example Chadwick and 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 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) mean that failure is unlikely except under extreme conditions of defence overflow. Due to the extreme nature of the sea level rise 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, represents 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 UKCIP (Hulme et al., 2002) predictions for SLR (~1m crest level rise). Another 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 alternative tidal barriers is also considered; the first is upstream of the Medway estuary at Canvey Island (E: 581250
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– shown in Figure 6), the second is downstream of the Medway at the Isle of Sheppey (E: 593250 – shown in Figure 7) a location first suggested by Gilbert and Horner (1984) who worked on the current Thames barrier. For the outer barrier scenarios, other estuary defences are upgraded appropriately to reflect the standard of protection offered by the new barrier.

Key results from the hydrodynamic model are presented. Figures 3 to 6 show the flood outline for the 1:1000 year flood event, assuming that no defences are constructed or raised, for 1m, 3m and 5m 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 1m of SLR. Each additional 1m of SLR produces a smaller increase in the inundated area. In the worst case scenario of 5m net SLR (equivalent to a 5m SLR and no intervention – or a 6m SLR and 1m raise of crest defence level), approximately 1000km$^2$ of land and 1million properties would be at risk from flooding from the 1000 year event (Figure 5). The approximate area inundated for the 1m and 3m SLR scenarios is 650 and 850km$^2$ respectively, whilst the current area at risk from the 1000 year event in the model domain is ~400km$^2$. The number of properties likely to be inundated for different return periods and SLR scenarios is summarised in Figure 8. The most dramatic result is that even with a 2m net SLR, 200,000 properties (assuming no further development) would be flooded annually assuming no adaptation response.

Clearly each flood outline can equate to a number of SLR and defence raising scenarios. For example, the flood outline given by Figure 3 can represent a 1m SLR with no defence raise, or a 2m SLR and defences raised by 1m or any other combination of defence raising and SLR scenario that gives a net 1m SLR. A total of 30 hydrodynamic simulations were performed for each scenario at net SLR increments of 0.2m. By plotting contours of storm surge return period and net SLR, the appropriate flood outline can be selected - this is shown for Figures 3 to 6 in Figure 9.
Figure 6 and Figure 7 show flood outlines for the Canvey Island and Sheppey barrier. The flood outlines are for 1:1000 year flood event assuming 1m SLR after the construction of barriers to a 1000 year SoP. The areas inundated for the outer barrier scenarios are $450\text{km}^2$ for a barrier located at Canvey Island and $350\text{km}^2$ for a barrier located at Sheppey Island, as compared with $650\text{km}^2$ 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 position in the estuary means that even for 5m net SLR catastrophic flooding would be avoided in central London (i.e. Westminster) although East London (including Canary Wharf) would still be at risk (albeit considerably reduced).

**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:

$$R = \int_0^{y_{\text{max}}} p(y)D(y)dy$$  \hspace{1cm} (3)

where $y_{\text{max}}$ 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 damages for each inundated raster cell. For the most extreme net SLR scenario of 5m (Figure 5), during the 1,000 year event, the economic damages are estimated (in terms of 2003 prices) at £50 billion for residential property approximately £100 billion for non-residential property. These estimates do not include the economic damage to infrastructure and because they are based on national averages, may require weighting to account for higher 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 (~1m net) increase in sea level. Whilst the direct damages to infrastructure would undoubtedly be large, the potential impact on the UK economy in the long term may be disastrous. The loss of working hours and trading etc. during the inundation and subsequent clean up could run into billions. Given the dynamic nature of financial businesses located in London they could rapidly relocate to other financial districts in Europe such as Frankfurt. The global nature of many businesses in London would mean the impact of a serious flood event is likely to be felt worldwide.

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 can not be reliably extracted from the inundation model, although rates of rise can be extracted and the model shows rates of rise in central London of up to 2m per hour for the 1:1000 year event after just 1m net SLR. This rate of rise poses a serious threat to human life, particularly when considering the heavy 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 many major central London hospitals adds further to this strain. Furthermore, inundation of heavy industry at Canvey Island and elsewhere could result in the spreading of contaminants and consequential environmental damage.

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 (Office of the Deputy Prime Minister, 2004). Secondly, the impact assessment is heavily simplified
as it only considers direct damages resulting from independent flood events. Figure 8 demonstrates that even for small increases in net sea level, 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 scenarios; society is likely to respond to the SLR either through increased provision of physical defences, abandonment of flooded areas or (in the worst case) by falling into chaos. Consideration of these detailed socio-economic issues is outside the scope of this paper, but is reported by Lonsdale et al. (2004). 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 with which the impact of possible interventions on flood risk can be assessed. 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 very different barrier positions may impact on 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 retreat in 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. Further enhancement of the model would enable the flood risk associated with joint fluvial and tidal events to be considered.
These events are likely to become more important given the possibility of 30% increase in winter precipitation by 2080 (Hulme et al., 2002).

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 (Openheimer, 1998, Vaughn and Sponge, 2002), or North Atlantic Thermohaline Circulation (Clark et al., 2002)) but our poor understanding of the climate system and its sensitivity to anthropogenic forcing precludes the 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 1m net SLR. In order to respond to this effectively, future flood management strategies need to be robust.

This becomes increasingly important when the duration of such a change is considered. Should 1m net SLR occur over a long duration, society is likely to be able to respond on an ad hoc basis. However, the collapse (partial or complete) 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 take place over a similar timescale. In a SLR scenario of 5m over 100 years – even including the proposed upgrade of 1m to the defence system – within 40 years central London will be threatened by the 1 in 10 year flood (Figure 8). Given that it may also take a number of years before data collection and analysis
confirms 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 the large scale abandonment, may be forced upon the inhabitants of the Thames estuary. This is echoed by Mastrandrea and Schneider (2001) who state that the advent of abrupt climate changes would reduce adaptability and thus increase climate damages. They are supported in arguing for stronger and earlier mitigation action by Perrings (2003) who believes that such mitigation can be justified economically. 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 high UKCIP scenario for SLR of about 1m over the 21st Century. However, while the probability is certainly low, the collapse of the WAIS would force a stepped change in the rate of SLR which in the extreme could be as rapid as 5-6m over the same time period. Even partial collapse over the next 100 years would significantly increase flood risk in the Thames estuary.

Modelling presented in this paper has for the first time linked a possible mechanism for abrupt climate change and SLR to a 2D 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. Most importantly, the results show the need for future flood management to be both robust and adaptive so that it can better respond to unexpected changes, such as rapid SLR.

This paper has provided a quantified analysis of a small subset of possible responses under idealised 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 other parts of the Atlantis research project (Lonsdale et al., 2004).

ACKNOWLEDGEMENTS

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REFERENCES


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Captions for Tables and Figures

Table 1 Predicted water levels for given return periods along the Thames at 2030 (Jones, 2001, Environment Agency, 2003a), represented by triangles in Figure 3

Figure 1 Representation of flow between raster cells in LISFLOOD-FP
Figure 2 The 1953 storm surge as measured at Sheerness (Rossiter, 1954, Smith and Ward, 1998)
Figure 3 The 1:1000 year flood outline after 1m net SLR (lighter grey shades in the floodplain represent lower ground, the estuary very dark) also showing the four tidal points named in Table 1 (from West to East: Silvertown at the Thames Barrier, Erith, Tilbury and Sheerness)
Figure 4 The 1:1000 year flood after 3m net SLR
Figure 5 The 1:1000 year flood after 5m net SLR, or 6m SLR and 1m defence upgrade (worst case flood extent modelled)
Figure 6 The 1:1000 year flood after 1m net SLR assuming the Canvey Island barrier is designed to a SoP of 1:1000 in 2030
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Figure 8 No of properties inundated for different return periods and net sea level rise (relative to dyke crest level) based on current defence system
Figure 9 Contour lines showing how Figures 3 to 5 equate to a multitude of flood events and crest level raising scenarios depending on the net sea level rise (= Rate of SLR × Δt – Δz where Δt equals SLR duration and Δz is the change in crest level height).
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