

Adaptation thresholds and pathways for tidal flood risk management in London

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ABSTRACT

Protecting the UK's capital city from global mean sea level rise that the IPCC considers plausible over the next centuries would require a combination of a new tidal barrier, high volume pumping and incremental raising of the system of flood walls and embankments. Using a risk and decision analysis methodology that is transferable to other vulnerable coastal cities of high strategic economic and political importance, we quantify sequences of adaptations that would be needed to protect London from flooding by the sea to the year 2300. Two critical adaptation thresholds are identified: (i) when mechanical pumping has to be provided alongside the moveable tidal barrier in order to drain the River Thames and (ii) when a permanently closed barrier with pumping to remove all of the river flow becomes the only viable means of avoiding flooding. We test the sensitivity of the costs and benefits of alternative adaptation pathways to a wide range of sea level rise trajectories. The adaptation pathway that most cost-effectively and robustly maintains risk at a tolerable level involves moving the Thames Barrier 17 km towards the sea if mean sea level rises 2 m above present levels. Our methodology provides a quantitative risk-based implementation of an adaptation pathway.

1. Introduction

Adaptations to climate risk that involve major infrastructure investments pose difficult decisions. Infrastructure investments such as major flood defences involve high up-front costs, yet could be over-designed (and hence wasteful) or under-designed (leaving intolerable residual risk). Given the sensitivity of these decisions to future uncertainties, including about the scale and rate of climate change, the importance of robust methodology for adaptation to uncertainty is now widely recognised (Dessai et al., 2009; Hallegatte et al., 2012; Lempert et al., 2009; Weaver et al., 2013). These concepts have been operationalised in adaptation pathways approaches that involve planning for a range of scenarios, building in the capacity to change course depending on how the future materialises (Denton et al., 2014; Haasnoot et al., 2013; Haasnoot et al., 2012; Hermans et al., 2017; Kingsborough et al., 2017; Walker et al., 2013; Zandvoort et al., 2017).

The Thames Estuary 2100 (TE2100) project that analysed options for adapting London's tidal flood protection was one of the first applications of the adaptation pathways approach (Bloemen et al., 2018; Ranger et al., 2013; Reeder and Ranger, 2010; Stafford Smith et al., 2011). TE2100 developed a compelling narrative about how flood risk could be managed under a range of sea level rise scenarios into the 22nd century, including high end scenarios that involve accelerated ice sheet melting. Reeder et al. (2009)

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identified five adaptation thresholds in the Thames Estuary. Here we focus upon Thresholds 2 (raising the crest level of the defences), 3 (moving to an outer barrier) and 4 (modification of the barrier so that it operates as a barrage). Threshold 1 (extreme surge events) is implicit in our analysis, whilst our analysis explores engineering options for all rates of sea level rise considered so never reaches an overall engineering limit to adaptation (Threshold 5). Reporting on the TE2100 study, Penning-Rowsell et al. (2013) indicate that “both sensitivity and scenario analysis have little effect on option choice”, which is a conclusion that we explore thoroughly in this paper in order to expose critical sensitivities to sea level rise. By doing so we aim to (i) present in-depth quantified analysis of risk, scenario and decisions for adaptation to sea level rise in the Thames Estuary and (ii) advance methodology for quantification of adaptation tipping points, which can be used for analysis of other coastal adaptation challenges.

To address these questions we adopt a multi-layered simulation framework (Harvey et al., 2012), at the heart of which is a model of water levels in the Thames Estuary and flood damage in the tidal Thames floodplain where London is located. The boundary conditions for this model (surge tide water levels in the outer estuary and fluvial flows in the River Thames) are sampled statistically from a joint extreme value distribution. Integration over that distribution provides an estimate of risk. The next layer simulates long term change in the factors that influence risk, e.g. sea level rise. Adaptation actions (e.g. raising of flood dikes or moving the Thames Barrier) are triggered in response to changing risk. The simulation framework calculates the costs and residual risk associated with all possible adaptation pathways. Finally, the sensitivity of those estimates to exogenous uncertainties (e.g. the rate of sea level rise) is systematically explored. We apply this framework to quantify the effectiveness of alternative adaptation strategies, in order to identify adaptation thresholds i.e. critical thresholds of sea level rise when the approach to management of tidal flood risk has to fundamentally change, by some combination of relocating the Thames Barrier, installing pumps to assist the gravity drainage of the River Thames, and finally abandoning gravity drainage with opening sluice gates altogether. We conclude with reflections on what this work implies for the concepts of ‘adaptation thresholds’ and ‘adaptation tipping points’.

1.1. Adaptation to sea level rise in the Thames Estuary

London is currently protected from flooding by the sea by the Thames Barrier at Silvertown and a series of embankments, walls and barriers on either side of the estuary from Silvertown towards the sea (Fig. 1) (Lavery and Donovan, 2005). The Thames Barrier, which consists of a system of 10 mechanical gates, is closed when a surge tide is forecast. Surge tides occur when cyclonic conditions propagate southwards across the North Sea, raising tide levels in the southern North Sea. If it were not for the Thames Barrier, the centre of London would be flooded by extreme surge tides. This system of protection was planned following the 1953 surge, when 307 people lost their lives in London and along the North Sea coast of England. In the same surge 1836 people perished in the Netherlands.

The Thames Barrier was completed in 1982 and is able to protect London from storm surges with an annual exceedance probability (AEP) of less than 0.001. The frequency of closure has increased from an average of once a year during its first ten years of operation to a record of 50 closures in 2013/14. In part this increase is due to a change in mode of operation of the Thames Barrier, so that it is now sometimes closed to prevent the rising tide from propagating up-river, which enhances drainage of the River Thames, thus helping to alleviate fluvial flood risk in west London. However the number of closures attributable to surge tides is also increasing. Relative sea level is increasing in London at a rate of 1.8–3.3 mm/year because of a combination of subsidence (1.09 mm/year) and eustatic sea level rise (Bingley et al., 2007).

The possible effects of accelerating sea level rise in London during the 21st Century have been extensively studied (Dawson et al., 2005; Reeder et al., 2009), notably in the Thames Estuary 2100 (TE2100) study, which concluded that the Thames Barrier and associated flood dikes could, with fairly modest modification, be expected to provide a good standard of flood protection through to 2070, based on best estimates of sea level rise (Penning-Rowsell et al., 2013). TE2100 proposed a strategy for a series of adaptations whose timing would depend upon the rate of sea level rise (Environment Agency, 2009). The main adaptation options that TE2100 considered were:

- Option 1. Improve the existing defences
- Option 2. Tidal flood storage
- Option 3. New Barrier
- Option 4. Barrier with locks

However, flood storage was eliminated from consideration because of questions of reliability and risks to health and safety (Environment Agency, 2009), so in this paper we consider various combinations of Options 1, 2 and 4.

The TE2100 study considered the possibility of global mean sea level rise that exceeded the upper bound of IPCC projections (1.0 m mean sea level (MSL) rise by 2100 (Stocker et al., 2013)) due to increased ice discharge from the Greenland and Antarctic ice sheets, using a so-called High ++ scenario of 2 m of mean sea level rise (MSLR) by 2100 (Howard et al., 2008).

2. Material and methods

The integrated simulation and adaptation assessment methodology that we have developed (Harvey et al., 2012) combines: flood hazard analysis, flood damage assessment, flood risk assessment, the implications of long term change, adaptation options and sensitivity analysis to key uncertainties.

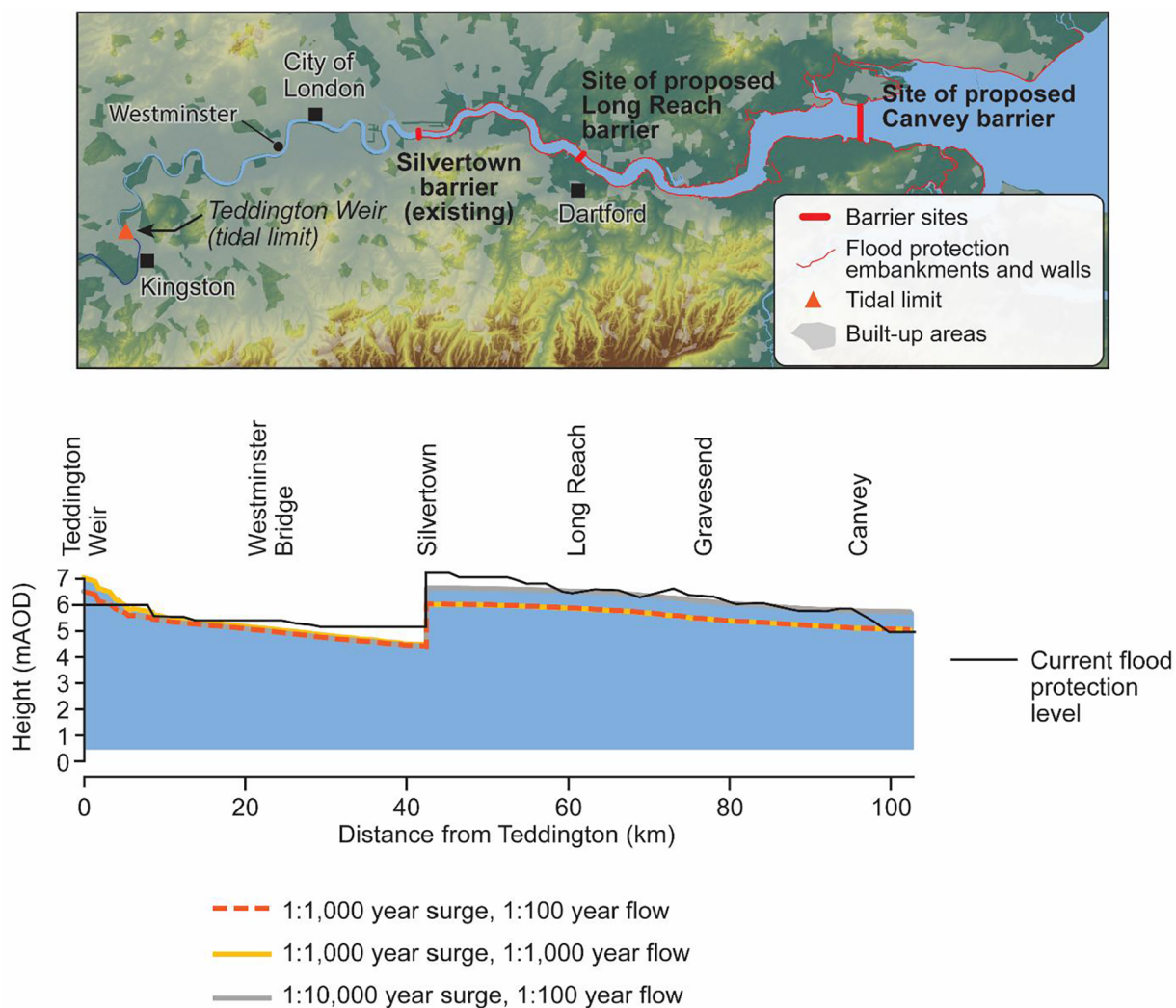


Fig. 1. The Thames Estuary and London's system of protection against tidal flooding.

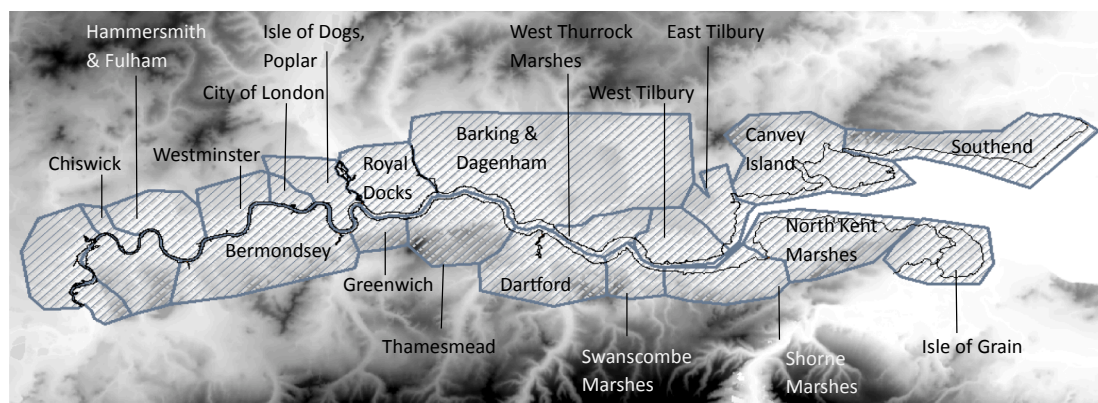


Fig. 2. Embayments in the Thames Estuary.

2.1. Flood hazard analysis

A one-dimensional hydrodynamic model was used to simulate water levels in the tidal Thames for given water level boundary condition in the outer estuary and inflow from the River Thames at the upper tidal limit. The floodplain of the Thames Estuary was subdivided into a series of areas of potential inundation, known as ‘embayments’ (Fig. 2) which are separated by physical features. Ground elevation in the embayments was obtained from a lidar-based digital elevation model. Flood depths in the tidal flood plain were estimated using a volume-filling method (see Theory and Calculation).

2.2. Flood damage assessment

Direct economic damage of flooding was estimated using depth-damage functions (Penning-Rowsell et al., 2005) for every building in the tidal floodplain. Functions were computed to convert the volume of water entering the floodplain into an estimate of damage to property in each embayment (Fig. 3). The relationship between the depth of water and the flood volume was estimated from the DEM, leading to a direct relationship between flood volume and damage for each embayment, shown in Fig. 3.

2.3. Storm surges and flood risk assessment

Horsburgh and Wilson (2007) have analysed the historical data for tidal surges in the outer Thames Estuary at Sheerness, southeast of Canvey Island. This analysis indicates that extreme surge events are predominantly associated with the rising tide. Following Halcrow (2005) we adopted a smoothed trapezoidal storm surge profile derived from the averaging of water levels observed during storm surges (Fig. 4). The height of the surge shape was scaled according to the observed distribution of high water level at Sheerness.

A Generalised Extreme Value distribution was fitted to the annual sea level maxima at Southend (Table 1; cf. (Dixon and Tawn, 1994) resulting location, scale and shape parameters of 3.738, 0.141 and 0.092 respectively. The predicted astronomical Spring high tide at Southend was subtracted from this, giving an estimate of the distribution of maxima, separate from mean sea level, which could then be adjusted for mean sea level rise.

The probability of breaching the flood walls and embankments is a significant determinant of flood risk, so reliability analysis of these structures was included in the probabilistic analysis of the flood volumes flowing from the estuary into the floodplain (Harvey et al., 2014). These volumes were then used as the basis for estimating the potential economic flood damage (see Theory and Calculation). The statistical expectation of the annual flood damage was obtained by numerical integration of the joint probability distribution of the hazard, the probability of flood dike failure and the consequential economic damage (see Theory and Calculation).

2.4. Mean sea level rise

Mean sea level rise (MSLR) scenarios were represented as a parametrised family of curves from the present day to 2300, which span the range of MSLR in IPCC AR5 (Stocker et al., 2013) for the years 2100 and 2300. The IPCC projections contain contributions from thermal expansion, glacier melting and the Greenland and Antarctic ice sheets. We test sensitivity across the range of MSLR trajectories shown in Fig. 5. This spans the range of more recent projections of multi-century sea level rise (Nauels et al., 2017).

2.5. Adaptation options

Existing topography, land-use and infrastructure considerations restrict possible sites for a new Thames Barrier to three locations: near its existing location at Silvertown or at sites 17 km and 46 km towards the sea, at Long Reach and Canvey, respectively (see Fig. 1). At these sites the estuary is 520 m, 630 m and 2730 m wide respectively and the relative costs for a given amount of embankment and barrier raising at these three sites increase in a ratio of roughly 1:1.5:5.4 (Silvertown:Long Reach:Canvey) (Table 2). Operation costs for barriers and pumps are not included in the analysis.

Moving the barrier downriver has three potential objectives (i) to reduce the risk to property and people in case of dike failure, (ii) to reduce the length of dikes to be maintained, and (iii) to delay the need for pumping. A barrier closer to the estuary mouth will have greater capital cost; however, even if the barrier were to remain in the current position, it would have to be upgraded to withstand increased sea level.

Protection from storm surges also involves upgrades to the system of embankments, walls and smaller barriers on either bank of the estuary down-river of the Thames Barrier, which are estimated to cost approximately £5.2 million/km to raise by 1 m and upgrade. In this analysis we assume that raising the flood dikes is implemented in increments of 1 m elevation, in such a way to maintain flood protection of at least 1:1000. Moving the Thames Barrier downriver would reduce the length of wall and embankment construction (Table 3), with the associated cost saving compared to the upriver sites for the Thames Barrier.

3. Theory and calculation

3.1. Hydraulic behaviour of the Thames Barrier

The Thames Barrier is modelled as a set of independent gates, the closure of which is staggered over a period of 1.5 h in an attempt

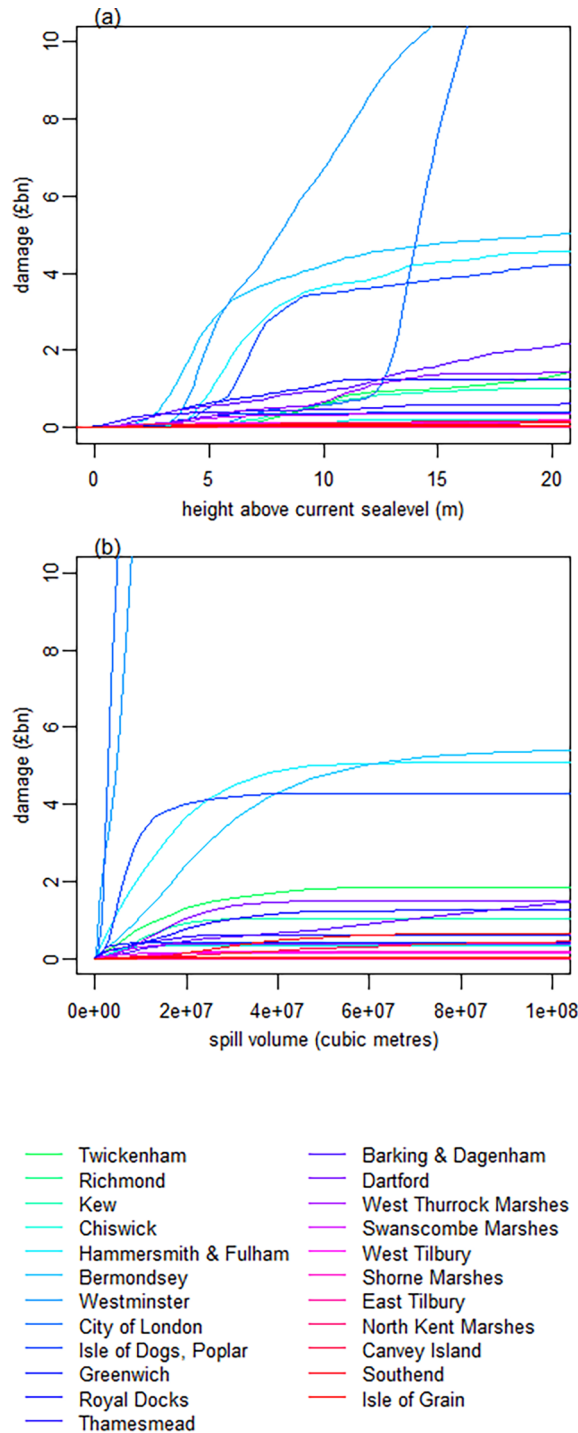


Fig. 3. Relationship between estimated damage and (a) flood water level and (b) spill volume in each embayment.

to reduce reflections. Analysis of barrier closures at the current time indicates that the majority of closures occur between 2 and 4 h before high tide at the barrier location at Silvertown (Halcrow, 2005); this translates to a closure time of between 1 and 3 h before high tide at Southend. The choice of closure time has a significant effect on upriver stage (Fig. 6), and for modelling purposes, time of completion of closure has been taken at 3.25 h before high tide at Southend. This optimises the water storage volume upriver of the barrier. For earlier closure times than this, there is not a clear improvement in the available storage volume under all conditions.

The barrier is reopened when water levels immediately upriver and downriver of it are the same. Upriver of the barrier, stage increases steadily while the barrier is closed, as river flow fills the reservoir made by the barrier (Fig. 7). The rate of water level

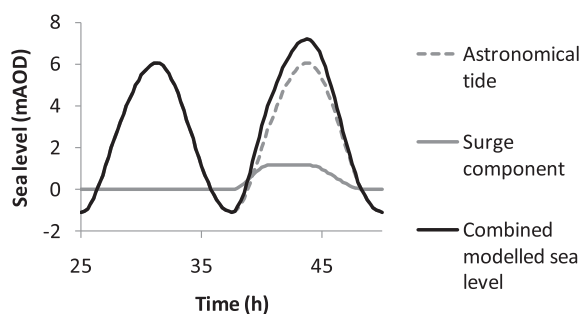


Fig. 4. Modelled sea level, accounting for both surge and mean sea level rise.

Table 1

Extreme high water level at Southend.

Return Period (years)	Annual probability	High water (mAOD)
5	0.2	3.96
10	0.1	4.09
50	0.02	4.40
100	0.01	4.54
200	0.005	4.70
500	0.002	4.92
1000	0.001	5.10
10,000	0.0001	5.78

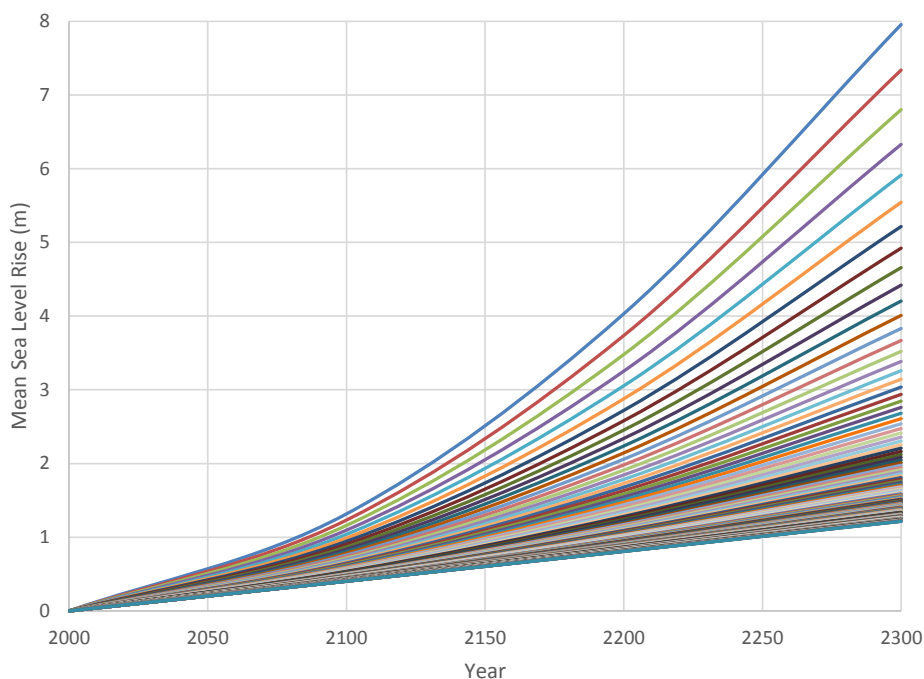


Fig. 5. Scenarios of mean sea level rise.

Table 2

Barrier costs for different crest elevations (£millions).

	7 m AOD	10 m AOD	13 m AOD
Silvertown	£680	£820	£970
Long Reach	£1060	£1270	£1440
Canvey	£3670	£4400	£5200

Table 3
Lengths of dike upriver and downriver of different Thames Barrier locations.

	Upriver	Downriver
Silvertown	112 km	206 km
Long Reach	163 km	155 km
Canvey	248 km	70 km

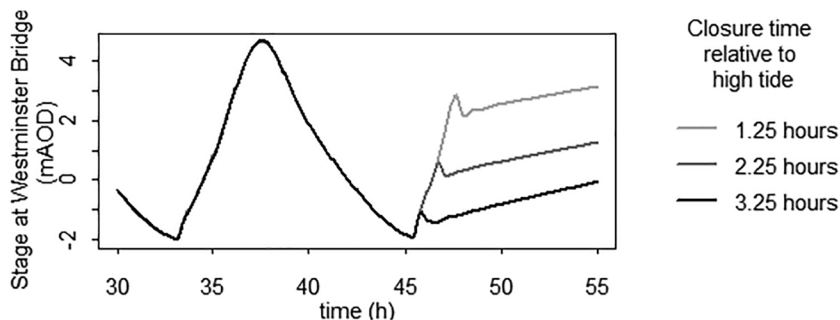


Fig. 6. Effect of barrier operation time on water level at Westminster Bridge.

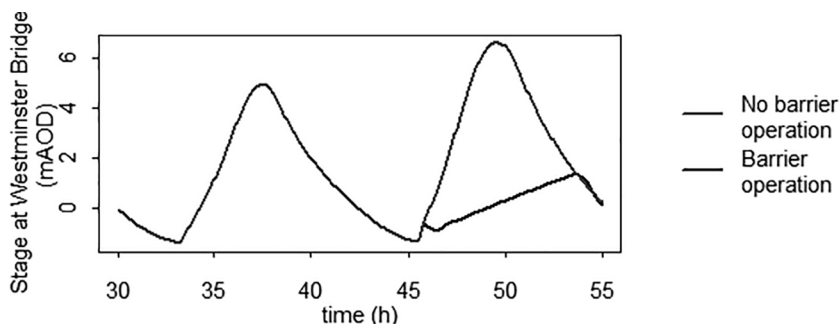


Fig. 7. Effect of barrier operation on upstream water level.

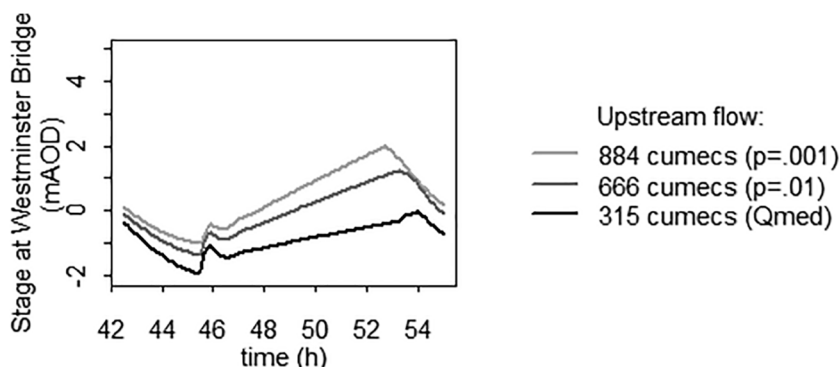


Fig. 8. Illustration of the effect of upriver flow rate on the rate of stage increase at Westminster Bridge; current barrier location.

increase depends on the inflow (Fig. 8) and the area of the reservoir, with the result that different barrier locations produce different rates of water level increase (Fig. 10b, c and d, and Table 4).

It should be noted that during barrier closure over a single tidal cycle, the upriver water level is always lower than the maximum level of a neap tide with the barrier open (Fig. 9). This would still be the case if a surge of up to 1.2 m were to coincide with low tide.

Fig. 10 shows the development of water level through time at selected locations along the estuary for a normal tidal cycle followed by a surge cycle, for a river flow of $666 \text{ m}^3 \text{ s}^{-1}$ (annual probability of exceedance 0.01) and a surge tide with peak water level 5.1 m AOD (1.7 m surge, annual probability of exceedance 0.001). Fig. 10a shows the situation where the barrier is not operated, while the other panels in Fig. 10 show the effect of barrier operation on the surge tide for each of the barrier locations. It can be seen that the stage at upriver locations is greatly reduced, with the greatest reduction in the vicinity of the barrier.

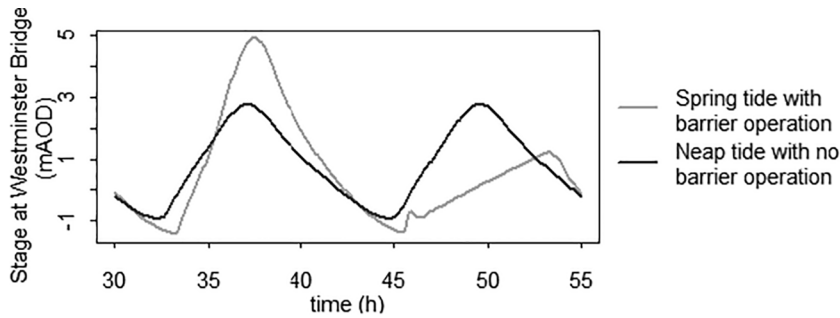


Fig. 9. Comparison of peak water level at spring and neap tide, with and without barrier operation.

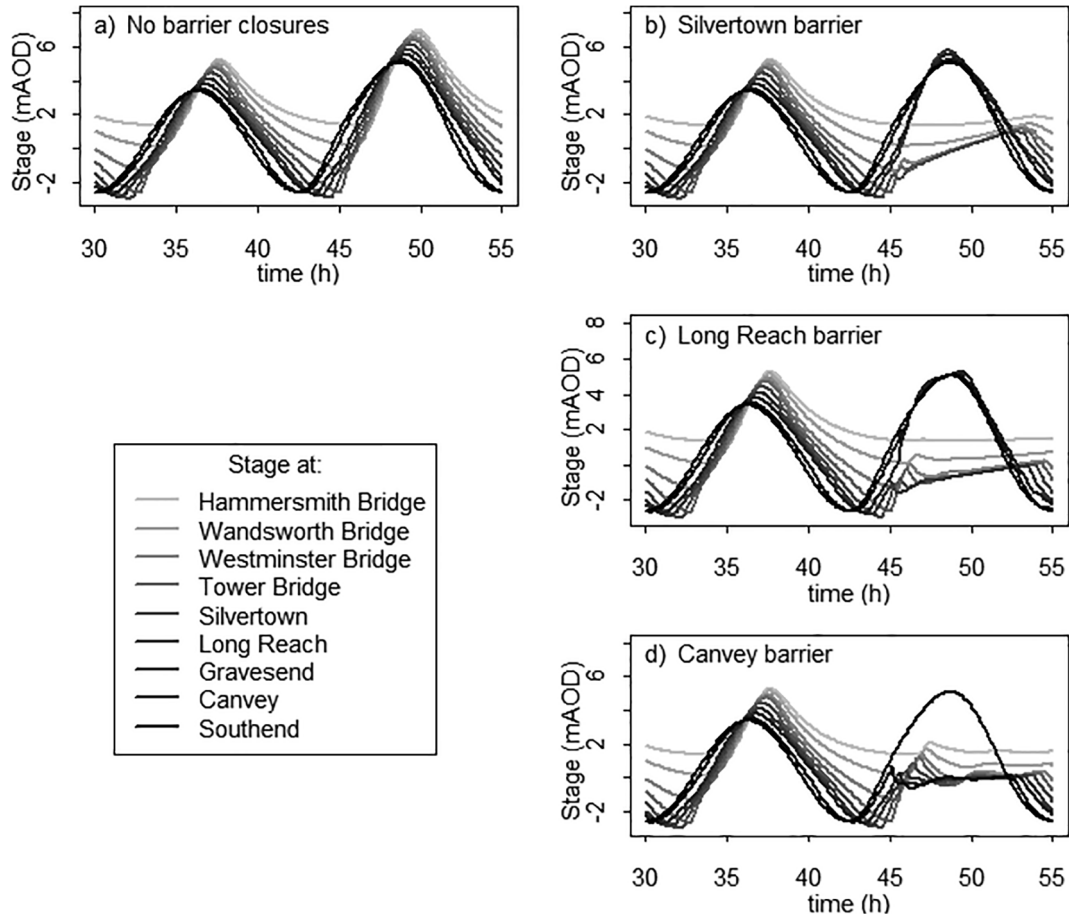


Fig. 10. Modelled stage at different locations along the river for a normal tidal cycle and a surge cycle, showing the difference in upriver stage with barrier operation. Upriver flow, annual probability 0.01; surge level, annual probability 0.001.

Consideration of the hydraulic behaviour depends on whether or not the location is protected by barrier operation. In the absence of barrier protection, the water level at a given location is dependent on a number of factors, namely the stage in the lunar cycle, the level of sea surge, and the extent of mean sea level rise. Fig. 11 shows how these influences can affect the water level at Westminster Bridge over a tidal cycle.

In the case of barrier operation, the maximum upriver water levels are also affected by the stage in the lunar cycle, the level of sea surge, and the extent of mean sea level rise, since these affect the water level at closure time. The water level at closure time is also affected by barrier closure time influencing maximum water level (Fig. 6). Fig. 10b–d show that maximum upriver water levels are also affected by barrier location. In addition, these levels are affected by upriver flow rate, and the possibility of pumping, to reduce the rate at which upriver stage rises after closure.

In order to increase protection against rising mean sea level, pumps may be installed to evacuate the water upriver of the barrier

Table 4

Rate of rise of water level (m/hr) a) immediately above the barrier and b) at Westminster Bridge, dependent on barrier location and upriver flow. Calculations under current conditions.

a	Upriver flow m^3s^{-1}		
	315 (Qmed)	666 ($p = 0.01$)	884 ($p = 0.001$)
Silvertown	0.17	0.33	0.42
Long Reach	0.07	0.15	0.20
Canvey	0.01	0.03	0.04

b	Upriver flow m^3s^{-1}		
	315 (Qmed)	666 ($p = 0.01$)	884 ($p = 0.001$)
Silvertown	0.16	0.31	0.39
Long Reach	0.07	0.12	0.15
Canvey	0	0	0.01

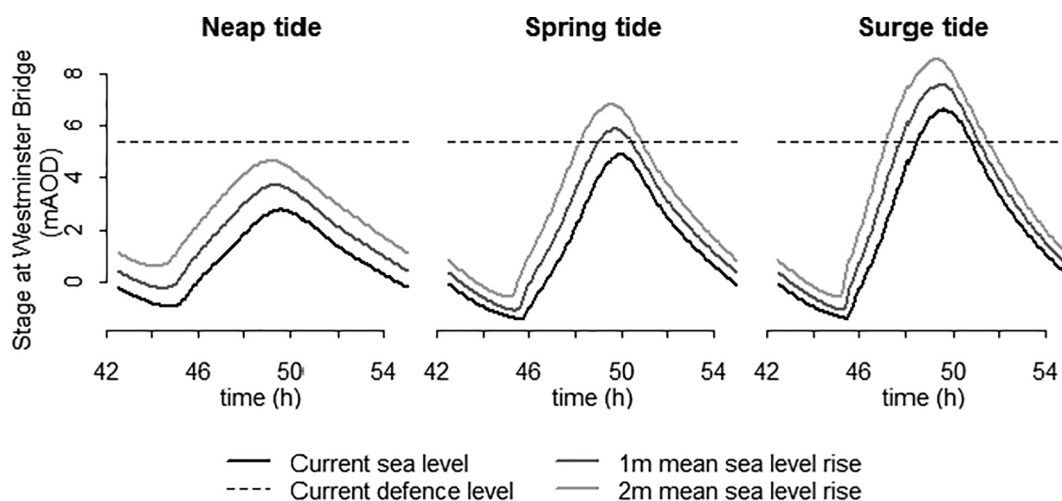


Fig. 11. Influences on maximum water levels at Westminster Bridge; no barrier operation.

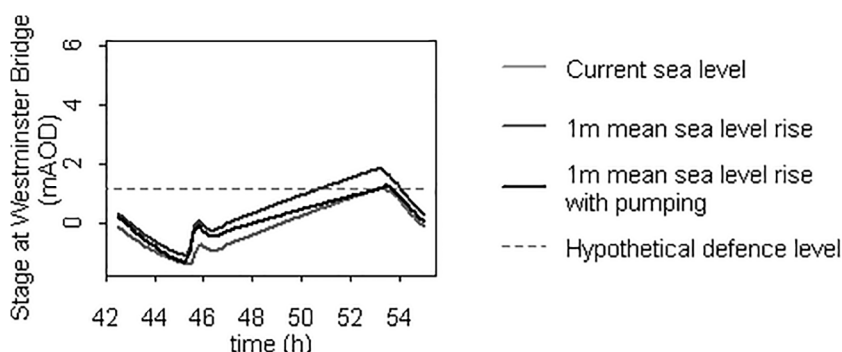


Fig. 12. Illustration of flow reduction required to maintain the same defence crest with sea level rise.

as an alternative to, or in addition to upriver defence crest level increase. The effect of pumping on upriver water levels is shown in Fig. 12. This illustrates the case where the current defence level is just sufficient to contain the design event. Additional sea level rise without pumping would result in overtopping.

3.2. Probability of failure of flood protection

The analysis also incorporated the probability that embankments and walls might collapse, in which case more water is able to enter the floodplain than in the situation where the flood defences are simply overtopped. The probability of failure is characterised

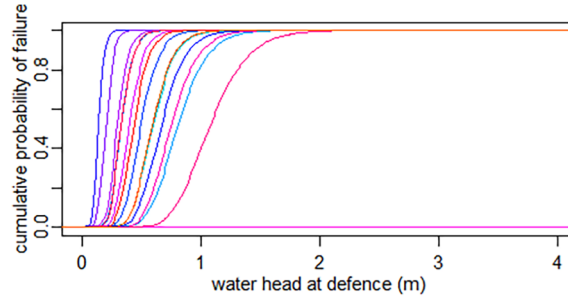


Fig. 13. Fragility curves for the different defence classes found on the Thames estuary.

by a conditional probability of failure (fragility curve), conditional upon the water level at the defence. The conditional probability of defence failure for each defence is based on reliability analysis conducted for the TE2100 project (Gouldby et al., 2008). The defence fragility curves, which give the relationship between water height and probability of failure, are defined empirically, based on data collected by the Environment Agency, and shown in Fig. 13.

3.3. Volume of flood water flowing into the floodplain

If the flood defence does not fail then water might still overtop its crest. The volume v of water arriving at the floodplain at flood defence section i is predicted using the standard equation for flow over a broad-crested weir

$$v_i = 1.71l \int (\max\{0, h(t)\})^{\frac{3}{2}} dt \quad (1)$$

where l is the crest length and $h(t)$ is the water head over the crest at time t , i.e. $h(t) = wl(t) - d_i$, where $wl(t)$ is the water level at time t and d_i is the crest level of defence section i .

If the defence does fail, an assumption is made that the failure takes place at time $t = \frac{T}{2}$, during the surge tide cycle, where T is the length of the cycle, with breach depth $d = d(h_{max})$ and width $b = b(h_{max})$, where h_{max} is the maximum water level during the surge event. For each section i of defence we define a binary defence state s_i , which is set to 1 to depict defence failure and 0 for non-failure. The breach volume is estimated as

$$\begin{aligned} v_i(s_i, wl_i) &= \int_{t=0}^{T/2} q(t) dt + \int_{t=T/2}^T q'(t) dt \\ &= 1.71l \int_{t=0}^{T/2} (\max\{0, h(t)\})^{\frac{3}{2}} dt \\ &\quad + 1.71(l - bs_i) \int_{t=T/2}^T (\max\{0, h(t)\})^{\frac{3}{2}} dt \\ &\quad + 1.71bs_i \int_{t=T/2}^T (\max\{0, h'(t)\})^{\frac{3}{2}} dt \end{aligned} \quad (2)$$

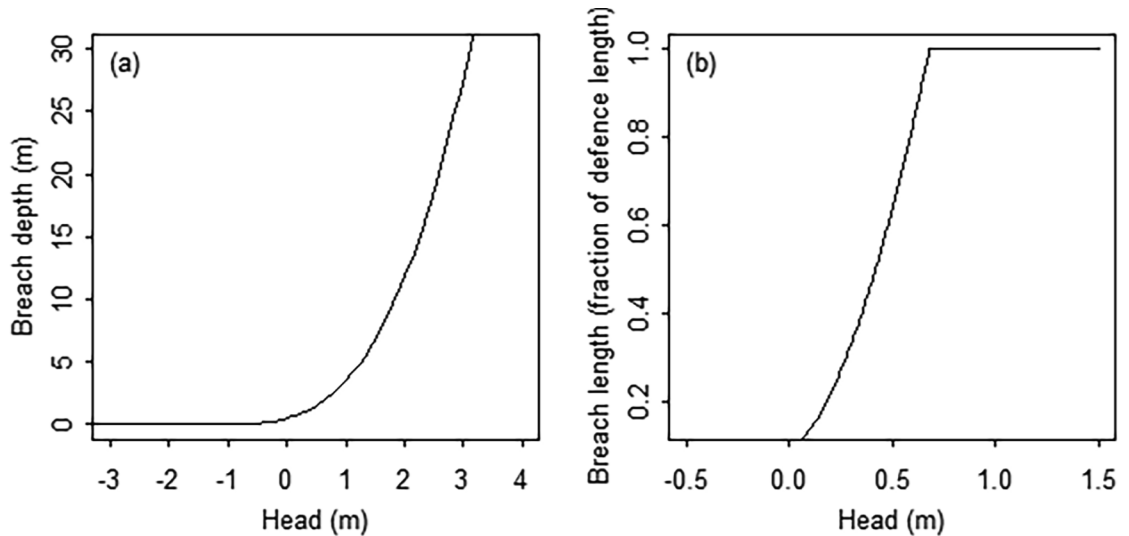


Fig. 14. Functions used to determine breach dimensions; (a) depth and (b) breadth.

$$\text{where } h'(t) = wl_i(t) - (cl_i - d) = h(t) + d$$

The breach dimensions d and b are found using formulae adapted from the defence breach model used in the TE2100 risk analyses (HR Wallingford, 2007). In TE2100, breach dimensions were estimated as a function of the ratio between event return period and defence standard of protection. In the current study, they are assumed to depend only on the maximum head h_{max} and are found by normalising the TE2100 model to present day 1:1000 year standard of protection (Fig. 14).

The cumulative probability distribution of water flowing into the floodplain was calculated for each embayment (Harvey et al., 2012).

3.4. Expected flood damage calculation

Appraisal of the management options introduced above involves analysis of flood risk. Flooding can occur due to overtopping and breaching of flood defences, as well as barrier operation failure and pump failure.

The different embayments are treated separately, under the assumption that they have been defined so that there is no flow connection between them. The expected damage for a given embayment, whether in terms of economic cost, mortality or other measures, can be written as

$$E(D) = \int_h D(h)f(h)dh \quad (3)$$

where D is the damage, h the depth of water in the embayment and $f(h)$ the probability distribution of h . Under the assumption of a uniform height of water in the embayment, a direct relationship can be found between the height h and volume V of water in the embayment, and Equation (3) could equally be written as

$$E(D) = \int_V D(V)f(V)dV \quad (4)$$

For each embayment, consider a finite number N of discrete defence sections (Hall et al., 2003). Water may reach the floodplain either by overtopping of a defence section, or by structural failure. It is assumed that failure of each defence is independent of the others, given local estuary water level. The structural state of defence i is denoted s_i , where $s_i = 1$ indicates failure, while $s_i = 0$ represents no failure. The total volume in the embayment, V can be considered as the sum of the volumes v_i arising from each defence section i , each volume depending on the defence state s_i and the maximum water height in the estuary adjacent to the defence h_{maxi} during an event e , defined by the maximum high water level at Southend. Taking all the defences together, the system state comprises the states of all individual defences $\{s_1, s_2, \dots, s_N\}$; since each s_i has two states, there are 2^N system states. If the system states are referenced using index k , the expected damage is

$$E(D) = \int_e \sum_{k=1}^{2^N} \{D(V)V(k|e)p(k|e)\}f(e)de \quad (5)$$

Evaluation of integral (5) requires some additional modelling assumptions. Since the system state k is defined as $\{s_1, s_2, \dots, s_N\}$, and the failure of each defence is assumed conditionally independent of the others, then

$$p(k|e) = \sum_{i=1}^N p(s_i|e) = \sum_{i=1}^N p(s_i|h_{maxi})$$

where the dependence of the maximum water level h_{maxi} on the event e is given by the hydraulic model.

Further, since $V = \sum_{i=1}^N v_i$, then

$$V(k|e) = \sum_{i=1}^N v_i(s_i, h_{maxi})$$

where the functions $p(s_i|h_{maxi})$ and $v_i(s_i, h_{max})$ are defined in Fig. 13 and Equation 2 respectively.

4. Results

4.1. Adaptation thresholds

Sea level rise increases the frequency with which the Thames Barrier has to be closed each year. The Thames Barrier could in principle be closed on all 703 tides per year, though the existing Thames Barrier is not designed mechanically to operate that frequently. However, closing the Thames Barrier restricts the outflow of water from the River Thames, and sea level rise also raises the low tide level, which determines the rate at which river water is discharged out past the Thames Barrier. The problem of discharging water from the River Thames is acute during river floods, when there is a risk that river flood water levels will exceed the level of the walls in central London. This risk increases with sea level rise, and a point is reached when in order to manage the risk of river flooding in central London, gravity drainage of the River Thames past the Thames Barrier has to be supplemented with mechanical pumping. The size of pumps required also depends on the height of the walls in central London. For the current height of walls in central London pumps with a total capacity of $500 \text{ m}^3 \text{ s}^{-1}$ would be able to cope with a river flood with an AEP of 0.001 ($884 \text{ m}^3 \text{ s}^{-1}$) for mean sea level rise of up to 5.4 m (Table 5).

Table 5

Mean sea level rise (m) which can be accommodated, in addition to a flow of annual exceedance probability 0.001, dependent on pumping capacity at the barrier, assuming closure on every tide.

		Pumping capacity (m^3s^{-1})					
		0	100	200	300	400	500
Increase in up-river flood wall level (m)	0	4.3	4.5	4.7	5.0	5.2	5.4
	1	4.6	4.8	5.0	5.3	5.5	5.7
	2	5.4	5.7	5.9	6.1	6.3	6.6
	3	6.2	6.5	6.7	6.9	7.2	7.4
	4	7.0	7.3	7.5	7.7	8.0	8.2

A further adaptation threshold is reached when the low tide level has risen so much that, for a given level of walls in central London, there is no net outward flux of water with the Thames Barrier open, so at that mean sea level the engineering solution switches to a closed barrage (with locks to permit navigation) and mechanical pumping to discharge all of the flood water in the River Thames. When that adaptation threshold occurs depends on the location of the Thames Barrier, as moving the barrier towards the sea (to Long Reach or Canvey) affords more storage volume for flood water up-river of the barrier, so delays the threshold when pumping is required (Fig. 15).

4.2. Adaptation pathways

There is a range of feasible and mutually exclusive adaptation pathways, assuming that only one Thames Barrier is maintained. All of these pathways start with the current situation of an opening Thames Barrier at Silvertown, and finish with a closed barrage at one of the three sites. Narrowing the adaptation options to trigger points at 1 m increments of mean sea level rise yields the seven adaptation pathways illustrated in Fig. 16.

For all adaptation pathways the residual flood risk (expressed in terms of the expected annual damage (EAD) of tidal flooding is low, considering the £200 billion value of assets in London's tidal floodplain (Environment Agency, 2009) (Fig. 17). This reflects the high standard of flood protection in all of the adaptation pathways. Moving the Thames Barrier towards the sea to Long Reach or Canvey reduces residual risk, because if a flood does occur in either of these system configurations, the inundation of London is less severe so the damage is less significant. In that sense these adaptation pathways are more resilient to extreme surges that exceed the design standard.

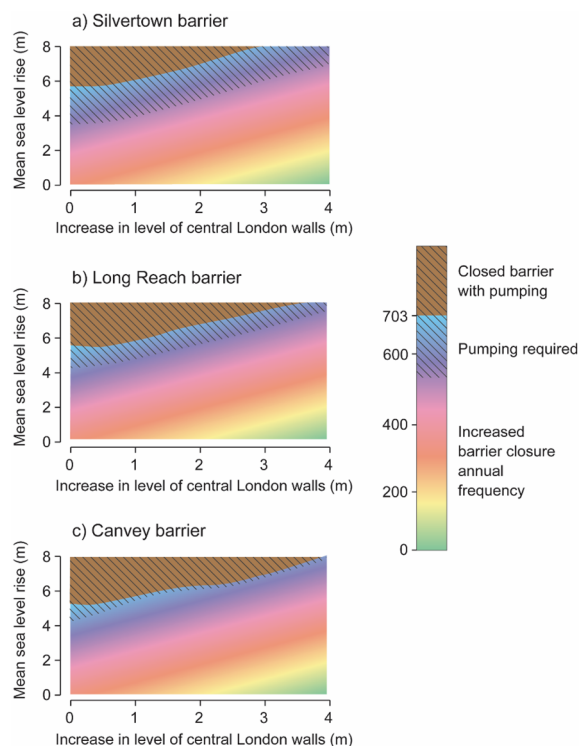


Fig. 15. Adaptation thresholds in the Thames Estuary.

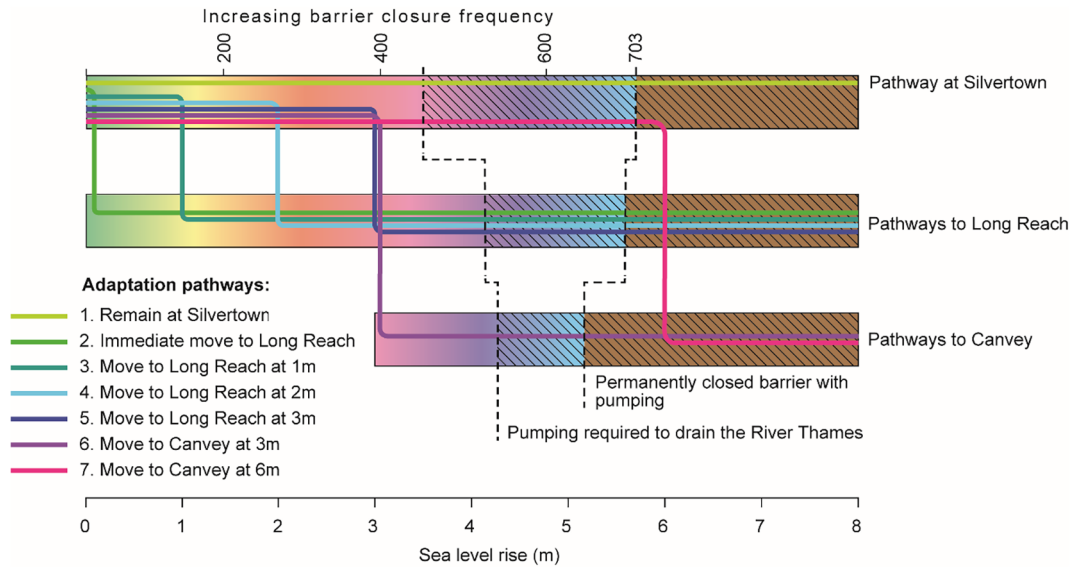


Fig. 16. Adaptation pathways for the Thames Estuary flood dikes, assuming no raising of the flood walls in central London.

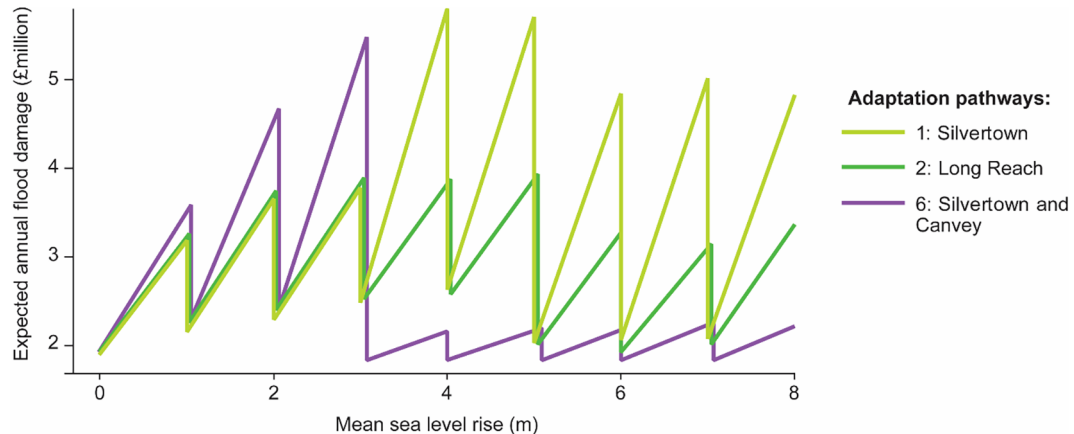


Fig. 17. Residual risk associated with three adaptation pathways, expressed as expected annual damage (EAD).

Pathways involving construction of a Thames Barrier at Canvey are the most costly. In all cases the total cost depends on how many projects to raise the elevation of the flood dikes are triggered, hence the stepped curves (Fig. 18a). The total cumulative cost plus the total cumulative residual risk (TCC + TCRR) provides a metric for comparing the costs and benefits of alternative adaptation pathways (Fig. 18b). For SLR at 2300 of 2.0 m or less, all pathways other than Pathway 2 are indistinguishable because the decision to relocate the Thames Barrier is never triggered. However, for higher rates of sea level rise Pathway 2 becomes one of the three better performers (Pathways 2,3,4), all of which involve moving the Thames Barrier to Long Reach. Pathway 1, which maintains the current Thames Barrier site at Silvertown shows mediocre performance because of higher residual risk even though the costs are similar to the better performing Pathways. Pathway 7 is the same as Pathway 1 for all but the highest rates of sea level rise, when it incurs the additional cost of the Canvey barrier. Pathways 6 and 7 which transfer to Canvey at high sea level rise perform less well because of the high cost, in particular Pathway 6 which involves the need to repeatedly upgrade a very expensive barrier at the estuary mouth.

Moving the Thames Barrier to Long Reach after 1 m of SLR is the adaptation pathway that minimises regret over the range of SLR scenarios. It is the preferred pathway according to the TCC + TCRR metric for all rates of SLR, other than mean sea level rise of between 2.0 m and 2.4 m in 2300, when its slightly higher cost (because of a larger number of dike raising projects) means that the pathway that moves to Canvey after 2 m of SLR has slightly lower TCC + TCRR. Thus, for low rates of sea level rise the best performing pathways involve keeping the Thames Barrier at Silvertown. Once sea level increases by over 2 m during the 300 year appraisal period, pathways are preferred that involve moving the Thames Barrier to Long Reach as soon as a new barrier is needed but not before.

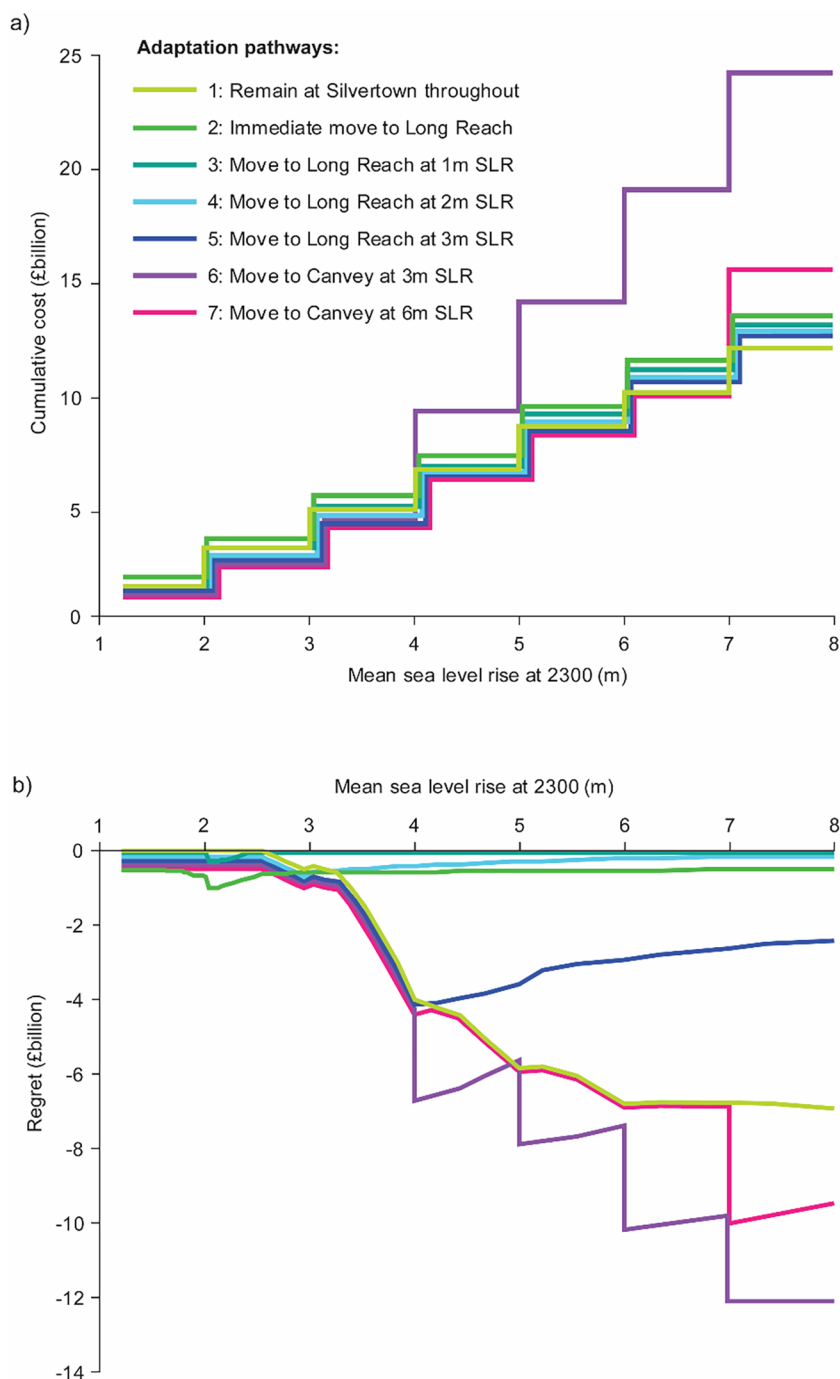


Fig. 18. (a) Total cumulative cost over the adaptation pathway (b) Regret, expressed in terms of the difference in TCC + TCRR relative to the best performing adaptation pathway i.e. the best performing adaptation pathway has a regret of zero.

4.3. Sensitivity to different increments of adaptation

In the results presented above, barriers were assumed to be upgraded in 1 m steps, and upgrades were assumed to cost the same as a new build. Upgrades are timed to provide 1:1000 year standard of protection with 1 m freeboard at construction time, dropping to 1:1000 year with no freeboard immediately prior to the next upgrade. In order to reduce the costs associated with repeatedly upgrading barriers, variant options were constructed in which barriers were constructed with 2 m and 3 m freeboard, with correspondingly reduced frequency of upgrade. Where options specify barrier relocation this is implemented as specified regardless of any

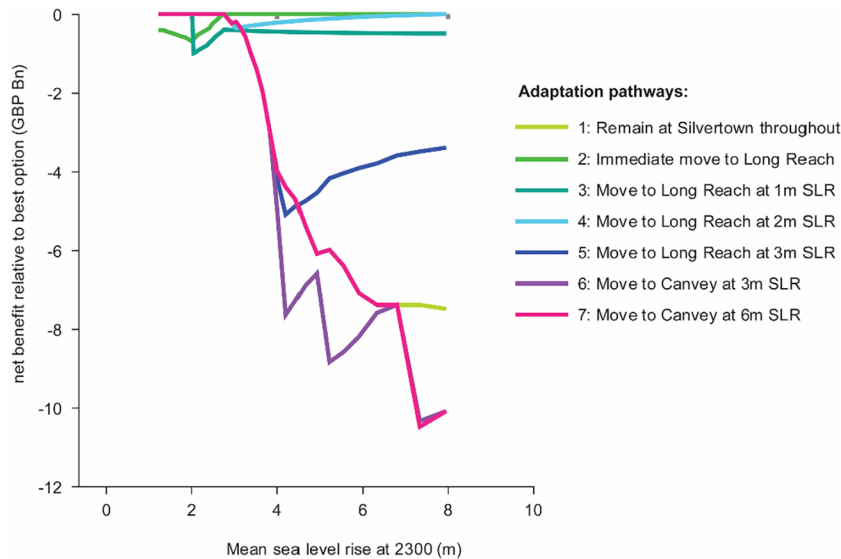


Fig. 19. Performance of options (shown relative to best performing option) vs. rate of sea level rise, barriers constructed with 2 m initial freeboard.

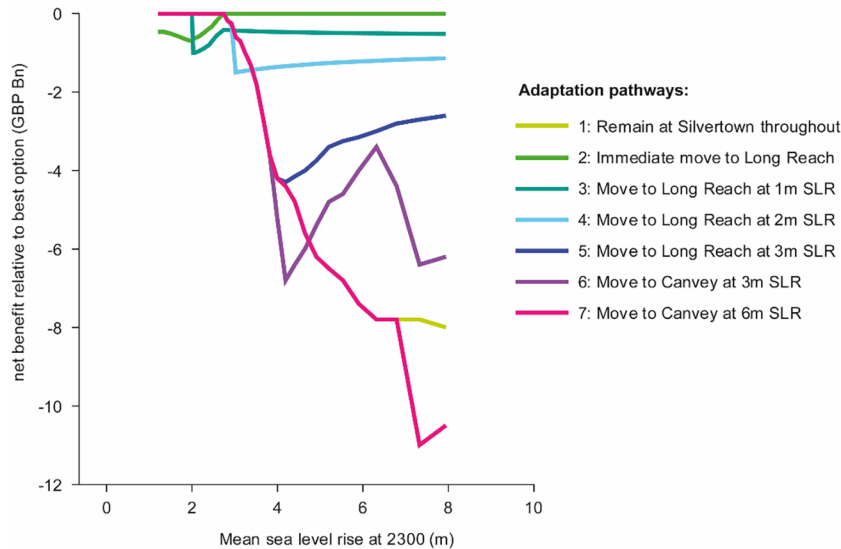


Fig. 20. Performance of options (shown relative to best performing option) vs. rate of sea level rise, barriers constructed with 3 m initial freeboard.

residual freeboard on the existing barrier. The results of these variants are shown in Fig. 19 (2 m freeboard at construction) and Fig. 20 (3 m).

These variant options show generally somewhat improved performance at higher rates of sea level rise, and the rank ordering of options changes. Option 4, which previously performed as well as any other option through most of the range of possible rates of sea level rise, is now outperformed at high rates of SLR by option 5. This happens because with larger steps in barrier height, option 4 implements a barrier upgrade at Silvertown which is then rendered obsolete by a new barrier at Long Reach, while option 5 moves the barrier to Long Reach immediately.

5. Discussion and conclusions

Our analysis has demonstrated that, provided that pumping is included as an adaptation option, the ultimate adaptation threshold in the Thames Estuary (an overall engineering limit to adaptation) identified by Ranger et al.'s (2013) is never reached within the wide range of sea level rise scenarios we have considered. It is possible to engineer the tidal flood protection system to a level that maintains flood risk at a tolerable level. On the other hand, our detailed hydraulic modelling has demonstrated that adaptation thresholds *can* be defined, notably the sea level at which gravity drainage in the Thames Estuary needs to be supplemented with

pumping and the sea level at which gravity drainage no longer functions, so an opening barrier has to be replaced by a permanently closed barrier. We have demonstrated that in London the mean sea level adaptation thresholds depend upon the location of the Thames Barrier. The adaptation thresholds are also contingent upon the amount by which the flood walls are raised up-river from the barrier and the tolerable level of risk (in our case taken as being associated with an annual exceedance probability of tidal flooding of 0.001). Thus our analysis demonstrates that precise adaptation thresholds do exist, but are contingent upon a complex set of other circumstances and decisions.

Our analysis is clearly in the tradition of the adaptation pathways literature (Haasnoot et al., 2013; Haasnoot et al., 2012; Kingsborough et al., 2016, 2017; Zandvoort et al., 2017). That literature has been influential in promoting the concept of flexibility in adaptation decision-making, so as to permit coping with a wide range of possible climatic and socio-economic conditions. The work described in this paper has sought to expand on the growing literature of adaptation pathways by providing estimates of cost and residual risk associated with each adaptation pathway. We have tested the sensitivity of cost plus residual risk to sea level rise, in order to identify adaptation pathways that are robust to uncertainty. This sensitivity analysis has also enabled us to identify the rates of sea level rise at which there is switching between preferred adaptation pathways.

The cumulative risks and costs that we have considered have not been discounted. Over the extended timescale considered here, discounting would render irrelevant any costs or risks later in the appraisal period. Discounting is most useful when large up-front capital costs are to be compared with an annual stream of benefits over some appraisal period. Over the timescale of this study we are also considering a series of incremental capital costs. The plots in Fig. 18 are designed to illustrate how the balance between costs and benefits vary over the long term for different options. Use of discounting would have suppressed this important message.

We recognise that there are multiple benefits associated with management of flood risk, for people, the economy and the environment. By focussing upon a tolerable probability of flooding, we have avoided having to value these benefits. Depending on how these different dimensions of cost and benefit are weighed up, the preference ordering of adaptation options may change.

We recognise that over the timescales considered there will be major and unpredictable socio-economic changes, which will co-evolve with the sea level rise scenarios that we have considered. The unpredictable nature of these changes in part motivates our use of today's economic exposure and risk tolerability in London as the basis for our flood risk analysis and decision analysis methodology. Assuming constant exposure enables more transparent scrutiny of the relative residual risks of different adaptation pathways. Nonetheless, the analysis could be extended to include possible socio-economic changes as another sources of deep uncertainty in the decision analysis (Hallegatte et al., 2012).

Conflict of interests

None.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.crm.2019.04.001>.

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