GeoSmart Information

FloodSmart Plus

Flood Risk Assessment

Site Address

21 The Avenue
Twickenham
TW1 1QP

Grid Reference

516835, 174574

Report Prepared for

Gavin Hardcastle-Jones

Date

2024-11-25

Report Status

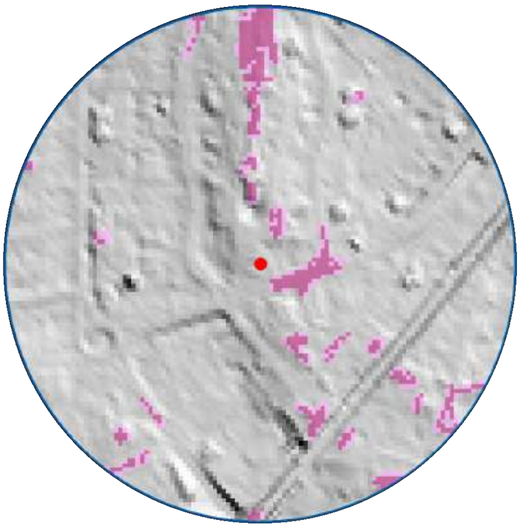
FINAL

Site Area

0.08 ha

Report Reference

84145R1



RISK – Very Low to Medium

The Site is mapped within the EA's Flood Zone 3 (High probability) associated with the River Thames Estuary.

Detailed flood model data obtained from the EA confirm that the Site will remain flood free in all scenarios up to and including the 1 in 1000 year event due to the presence of nearby defences. Flood depths of up to 0.79 m could however occur during the 2100 breach scenario. The risk of flooding from rivers and sea is Very Low, taking flood defences into account.

Following analysis of the baseline data the development is considered to be at a Very Low to Low risk of surface water (pluvial) flooding, a Low risk of groundwater flooding and a Low risk of flooding from artificial sources (sewers, canals and reservoirs).

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1. Executive summary

A review has been undertaken of national environmental data sets to assess the flood risk to the Site from all sources of flooding in accordance with the National Planning Policy Framework (NPPF) (2023) and National Planning Practice Guidance (NPPG) (published in 2014 and updated in August 2022). A site-specific flood risk assessment, to assess the flood risk to and from the development Site, is provided within this concise interpretative report written by an experienced GeoSmart consultant. Baseline flood risk and residual risks that remain after the flood risk management and mitigation measures are implemented are summarised in the table below.

Site analysis

Source of Flood Risk	Baseline*	Final **
River (fluvial) flooding	Very Low	Very Low
Sea (coastal/tidal) flooding	Very Low	Very Low
Surface water (pluvial) flooding	Very Low to Low	Very Low
Groundwater flooding	Negligible to Low	Negligible
Other flood risk factors present	Yes (reservoirs)	N/A
Is any other further work recommended?	Yes (see below)	

*BASELINE risks have been calculated for the whole Site, using national risk maps, including the benefit of EA flood defences.**FINAL RISK RATING Includes a detailed analyses of flooding risks over the lifetime of the proposed development, including allowances for climate change AND assumes recommended mitigation measures are implemented. N/A indicates where mitigation is not required.

Summary of existing and proposed development

The Site is currently used within a residential capacity as a three storey (plus loft and basement) detached, seven-bedroom dwelling including a garage, associated access, car parking and landscaping.

Development proposals comprise the demolition of the existing detached garage and the existing rear porch structure and the construction of an extension to the ground floor of the dwelling, with associated access and landscaping. It is understood that the development proposals also consist of some internal layout amendments although, no changes to the basement are proposed. Site plans are included within Appendix A.

Summary of flood risks

The flood risks from all sources have been assessed as part of this report and are as follows:

River (fluvial) and Sea (Estuarine/Coastal) flooding

According to the Environment Agency's (EA) Flood Map for Planning Purposes, the Site is located Choose an item. a fluvial and tidal Flood Zone 3 (High probability)

The Site benefits from the presence of flood defences, 390 m away, designed to provide a 1 in 1000 year event standard of protection.

According to the EA's Risk of Flooding from Rivers and Sea (RoFRS) map, which considers the type, condition and crest height of flood defences, the Site has a Very Low risk of flooding.

Modelled flood data obtained from the EA have been analysed in line with the most up to date guidance on climate change (EA, 2022), to confirm a maximum "design" flood level at the Site.

- During a 1 in 200 year 2100 scenario tidal flood event, the flood level within the channel would be 6.31 mAOD. The flood defence crest heights for the local area have been confirmed as a minimum of 5.94 mAOD for the existing barrier; it is proposed that the defences will be raised to 6.80 mAOD in the future (2120). Therefore, the Site is not anticipated to flood.
- Modelled breach data have been obtained from the ATKINS 2017 Breach Assessment; these data confirm that during a 2100 scenario tidal event a modelled flood level of 6.29 mAOD would be experienced at the Site, with corresponding flood depths of up to 0.79 m.

Emergency evacuation routes are available to the south west. In the event of a flood, safe refuge can be taken on the 1st floor levels and above.

Surface water (pluvial) flooding

According to the EA's Risk of Flooding from Surface Water (pluvial) flood mapping, the Site has a Very Low to Low risk of pluvial flooding.

- Flooding depths of up to 0.15-0.6 m are modelled to impact the area proposed for development in the 1 - 0.1% AEP (Low) risk event.

Groundwater flooding

Groundwater Flood Risk screening data indicate that there is a Negligible to Low potential risk of groundwater flooding at the surface in the vicinity of the Site during a 1 in 100 year event.

- On the basis of the likely continuity between the Site and the River Thames as well as nearby BGS borehole data (2024) the risk rating has been raised to Low.

Artificial sources of flooding

The risk of flooding from artificial (man-made) sources such as reservoirs, sewers and canals has been assessed:

- The EA's Risk of Flooding from Reservoir map confirms the Site is at risk of reservoir flooding. The potential for a breach of a reservoir to occur and flooding affecting the Site is low.
- Ordnance Survey (OS) data confirms there are no canals near to the Site.
- The Strategic Flood Risk Assessment (SFRA) (Metis Consultants, 2021) has identified 4 incidences or modelled incidences of flooding as a result of surcharging sewers within the Twickenham Riverside ward. A sewer flooding history report has been obtained from Thames Water which indicates that there have been no incidents of flooding at the property.

The risk of flooding from artificial sources is considered to be Low.

The risk to the development has been assessed over its expected 100 year lifetime, including appropriate allowances for the impacts of climate change which could increase the flood risk to the Site. Risks identified include sea level rise and appropriate mitigation measures are proposed.

Recommendations

Recommendations for flood mitigation are provided below, based upon the proposed development and the flood risk identified at the Site.

- As the development proposals are comprised of an extension to an existing dwelling, the raising of Finished Floor Levels (FFL) is unlikely to be a feasible method of flood mitigation. Finished floor levels should be raised as high as feasibly possible and set no lower than the existing building. Standard flood resilient design measures should be incorporated.
- Occupants of the Site should also be signed up to receive EA Flood Alerts.
- The ongoing management and maintenance of existing and any proposed drainage networks, under the riparian ownership of the developer, should be undertaken in perpetuity with the development.

GeoSmart recommend the mitigation measures discussed within this report are considered as part of the proposed development where possible and evidence of this is provided to the Local Planning Authority as part of the planning application.

2. Introduction

Background and purpose

A site-specific flood risk assessment has been undertaken, to assess the flood risk to and from the development Site. This assessment has been undertaken by firstly compiling information concerning the Site and the surrounding area. The information gathered was then used to construct a 'conceptual site model', including an understanding of the appropriateness of the development as defined in the NPPF (2023) and the source(s) of any flood risk present, guided by the NPPG (Published in 2014 and updated in August 2022). Finally, a preliminary assessment of the steps that can be taken to manage flood risk to the development was undertaken.

This report has been prepared with reference to the NPPF (2023) and NPPG (2022).

"*The National Planning Policy Framework set out the Government's planning policies for England and how these are expected to be applied*" (NPPF, 2023).

The NPPF (2023) and NPPG (2022) promote a sequential, risk based approach to the location of development. This also applies to locating a development within a Site which has a variable risk of flooding.

"*The approach is designed to ensure that areas at little or no risk of flooding from any source are developed in preference to areas at higher risk. This means avoiding, so far as possible, development in current and future medium and high flood risk areas considering all sources of flooding including areas at risk of surface water flooding*" (Paragraph: 023. NPPG, 2022).

The purpose of this report is to provide clear and pragmatic advice regarding the nature and potential significance of flood hazards which may be present at the Site.

Report scope

In accordance with the requirements set out within NPPG 2022 (Paragraph: 021 Reference ID: 7-021-20220825), a thorough review of publicly and commercially available flood risk data and EA supplied data indicating potential sources of flood risk to the Site from rivers and coastal sources, surface run-off (pluvial), groundwater and reservoirs, including historical flood information and modelled flood extent. Appropriate measures are recommended to manage and mitigate the flood risk to the property.

Information obtained from the EA and a review of the London Borough of Richmond Upon Thames Strategic Flood Risk Assessment (SFRA) (Metis Consultants, 2021), Surface Water Management Plan (SWMP) (Metis Consultants, 2021) and Local Flood Risk Management Strategy (Metis Consultants, 2023) are used to ascertain local flooding issues and, where appropriate, identify information to support a Sequential and/or Exception test required as part of the NPPF (2023).

The existing and future flood risk to and from the Site from all flood sources is assessed in line with current best practice using the best available data. The risk to the development has been assessed over its expected lifetime, including appropriate allowances for the impacts of climate change. Residual risks that remain after the flood risk management and mitigation measures are implemented, are considered with an explanation of how these risks can be managed to keep the users of the development safe over its lifetime.

An indication of whether the Site will potentially increase flood risk elsewhere is provided, including where the proposed development increases the building footprint at the Site.

Report limitations

It is noted that the findings presented in this report are based on a desk study of information supplied by third parties. Whilst we assume that all information is representative of past and present conditions, we can offer no guarantee as to its validity and a proportionate programme of site investigations would be required to fully verify these findings.

The basemap used is the OS Street View 1:10,000 scale, however the Site boundary has been drawn using BlueSky aerial imagery to ensure the correct extent and proportion of the Site is analysed.

This report excludes consideration of potential hazards arising from any activities at the Site other than normal use and occupancy for the intended land uses. Hazards associated with any other activities have not been assessed and must be subject to a specific risk assessment by the parties responsible for those activities.

Datasets

The following table shows the sources of information that have been consulted as part of this report:

Table 1. Datasets consulted to obtain confirmation of sources of flooding and risk

Source of flooding	Datasets consulted				
	Commercial Flood Maps	Local Policy & Guidance Documents*	Environment Agency (Appendix B)	Thames Water (Appendix C)	OS Data
Historical	X	X	X		
River (fluvial) / Sea (tidal/coastal)	X	X	X		
Surface water (pluvial)	X	X	X		

Source of flooding	Datasets consulted				
	Commercial Flood Maps	Local Policy & Guidance Documents*	Environment Agency (Appendix B)	Thames Water (Appendix C)	OS Data
Groundwater	X	X			
Sewer		X		X	
Culvert/bridges		X			X
Reservoir		X	X		

*Local guidance and policy, referenced below, has been consulted to determine local flood conditions and requirements for flood mitigation measures.

Local policy and guidance

For this report, several documents have been consulted for local policy and guidance and relevant information is outlined below:

Strategic Flood Risk Assessment (March, 2021):

Development Types and Definitions (as defined by gov.uk) The following are planning application definitions for development types:

• Major Developments: For residential developments, 10+ dwellings or site area over 0.5 hectares. For non-residential developments, total building floorspace exceeds 1,000m2 or site area over 1 hectare.

• Minor Developments: For residential developments, 1-9 dwellings, site area under 0.5 hectares. For non-residential developments, total building floorspace is less than 1,000m2, site area under 1 hectare.

• Change of Use: Developments classified as a 'Change of use' if - (i) the application does not concern a major development; and (ii(a)) no building or engineering work is involved; or (ii(b)) the building or engineering work would be permitted development were it not for the fact that the development involved a change of use (such as the removal of internal dividing walls in a dwelling house to provide more spacious accommodation for office use).

Land Uses and Development Restrictions (Information is from the Flood Risk and Coastal Change PPG)

Flood Zone 3b:

The Flood Risk Vulnerability and Flood Zone Compatibility table in the PPG highlights that only 'Essential Infrastructure' and 'Water Compatible' developments may be granted planning permission. As the functional floodplain, land in Flood Zone 3b will be protected by not permitting any form of development on undeveloped sites unless it is for 'Water Compatible' development or 'Essential Infrastructure'.

Redevelopment of existing developed sites will only be supported if there is no intensification of the land use and a net flood risk reduction is proposed; any restoration of the functional floodplain will be supported (see 'Flood Compensation Storage' section of this table).

Proposals for the change of use or conversion to a use with a higher vulnerability classification will not be permitted.

Flood Zone 3a:

The Flood Risk Vulnerability and Flood Zone Compatibility table in the PPG highlights that land use is restricted to 'Water Compatible', 'Less Vulnerable' and 'More Vulnerable' development. 'Highly Vulnerable' developments will not be permitted as it is not a permitted development type in Flood Zone 3a. Self-contained residential basements and bedrooms at basement level will not be permitted (see 'Basements' section of this table).

Flood Zone 2:

No land use restrictions. Self-contained residential basements and bedrooms at basement level will not be permitted (see 'Basements' section of this table).

Flood Zone 1:

No land use restrictions.

Sequential and Exception Tests (Information is from Policy LP 21 of the Local Plan – Refer to Section 6.2.1 and Section 6.3.1 for specific guidance on the application of these at the site specific scale)

The Sequential and Exception Tests do not need to be applied if your site:

- Is a 'minor development in relation to flood risk':
  - industrial/commercial/leisure etc extensions with a footprint less than 250 m^2.
  - development that does not increase the size of buildings, e.g. alterations to external appearance.
  - householder development within the curtilage of the existing dwelling (e.g. sheds, garages, games rooms), in addition to physical extensions to the existing dwelling itself.
- Is a change of use development – excluding caravans, camping chalets, mobile homes and park home sites.

The Sequential and Exception Tests need to be applied for all major developments and minor developments as set out below.

Flood Zone 3a:

Developments categorised as 'Essential Infrastructure' can only be considered following applications of the Sequential and Exception Tests.

Paragraph 15 of the PPG states: "If an area is intended to flood, then this should be safeguarded from development and identified as functional floodplain, even though it might not flood very often. Development can only be permitted following application of the Sequential Test, and a successful application of the Exception Test."

Flood Zone 3b:

The Sequential Test is required for all developments except for development proposals categorised as 'Highly Vulnerable' – 'Highly Vulnerable' development is not permitted (see 'Land Uses and Development Restrictions' section of this table).

Developments categorised as 'Essential Infrastructure' and 'More Vulnerable' can only be considered following application of the Exception Test.

Flood Zone 2:

The Sequential Test is required for all development types.

Developments categorised as 'Highly Vulnerable' can only be considered following application of the Exception Test.

Flood Zone 1:

The Sequential Test only needs to be applied for development proposals in Flood Zone 1 if the SFRA and accompanying Web Map indicates there may be existing flood issues from other sources (refer to Table 6-2) or flood issues in the future. This information may also come from other sources.

Site-specific FRA (Information is from Policy LP 21 of the Local Plan – Refer to Section 6.2.2 for further guidance)

Flood Zone 3b:

A site-specific FRA is required for all development proposals. Site-specific FRAs in Flood Zone 3b must also demonstrate that:

- Infrastructure will remain safe and operational for users during flood periods.
- The development will not impede flowing water.
- There will be no net loss of floodplain storage (see the 'Flood Compensation Storage' section of this table).
- Flood mitigation measures will reduce the overall flood risk of the site.

Flood risk from all sources should be assessed, including the potential impacts of climate change over the development's lifetime. The EA's 2016 climate change allowances (including subsequent updates) must be used when assessing peak river flows, sea level rises and peak rainfall intensities.

Flood Zone 3a:

A site-specific FRA is required for all development proposals.

Site-specific FRAs in Flood Zone 3a must also demonstrate that there will be no net loss of floodplain storage (see the 'Flood Compensation Storage' section of this table). Flood risk from all sources should be assessed, including the potential impacts of climate change over the development's lifetime. The EA's 2016 climate change allowances (including subsequent updates) must be used when assessing peak river flows, sea level rises and peak rainfall intensities.

Flood Compensation Storage (Information is from Policy LP 21 of the Local Plan)

Flood Zone 3a & 3b:

Flood compensation requirements are for major developments and minor developments only. If permissible development decreases the volume of a fluvial floodplain, flood storage compensation needs to be provided. The compensatory storage provided must be equal to or exceed the storage lost to ensure there will be no net loss of flood storage. Compensation should be provided on a level-for-level and volume-for-volume basis. The EA's 2016 climate change allowances (including subsequent updates) must also be incorporated to assess and calculate floodplain storage compensation. In most cases, the 'higher central' allowance should be used to calculate floodplain storage compensation. However, the 'upper end' allowance should be used if:

- The catchment is particularly sensitive to small changes in volume.
- affected area contains essential infrastructure or vulnerable uses.

Emergency Planning (Information is from Policy LP 21 of the Local Plan and the Flood Risk and Coastal Change PPG)

Flood Emergency Plans are required for all major developments and for minor developments where safe access/egress cannot be achieved and demonstrated as part of the FRA. Flood Warning and Emergency Plans need to feature measures to manage flood risk before, during, and after a flood, reducing the potential human impact of any flood event and making developments as resilient to flooding as possible. These plans need to be detailed and up to date, addressing the risks local to the site. The PPG highlights several important considerations, helping to define some key requirements including:

- Details of all the flood risk sources present at the proposed development site.
- Adequate flood warning procedures for people accessing the development.
- Potential mitigation measures following an assessment of the risks, including appropriate flood resistance or resilience measures to address predicted flood depths.
- Information regarding safe access and egress points across the site, ensuring that they remain so during flooding. These points need to be maintained over the development's lifetime.
- Suitable evacuation plans that consider the impact of climate change. These evacuation plans need to feature adequate routes and refuge areas for people to be taken to, accounting for the potential length of time of the evacuation. Developments categorised as 'Less vulnerable' are required to use the 'higher

central' allowance as per the EA's 2016 climate change allowances as the basis for designing safe access, escape routes and places of refuge.

Where the site is on a 'dry island' (area within a flood risk area that is surrounded by areas at higher risk of flooding) but not necessarily at high risk itself, an emergency plan must still address this risk and provide appropriate management measures. If the planning application is permitted, the onus to train, test and implement the stated measures become the responsibility of the applicant and ultimately the building owner, management company, or the adopter of a site for temporary use.

Surface Water Management Plan (December, 2021):

12.2 Catchment extents

This large Catchment consists of mostly urbanised areas including Hampton, Fulwell, Twickenham and St Margarets with parks throughout including Kempton Park, Fulwell Park and Marble Hill Park. The Longford River runs through the middle of this Catchment from northwest to southeast, being partly culverted where Feltham joins Hanworth. An unnamed drain which is also partly culverted and runs northeast of the Catchment to join the River Thames in Richmond. To the southwest, the Lower Feltham Brook joins the Portlane Brook. This Catchment also includes the Staines Reservoir Aqueduct, and the River Thames having influences around Sunbury-on-Thames. This Catchment is bounded by the River Crane on its eastern side and the River Thames on its south and north-east borders. Key infrastructure includes the Railway Stations running through Hampton, Fulwell, Strawberry Hill, Twickenham, and St Margarets Stations. The A305 (Staines Road) and the A311 (Wellington Road) cut north-east to Twickenham. The topography of this Catchment is generally highest in the centre with flow paths conveying south or northeast to the River Thames. Surface water flood risk in the Catchment can be seen in Figure 12-1.

12.3 Properties at risk and Hotspots

Table 12-1 summarises the number of properties predicted to be at risk within this Catchment (Richmond only). Richmond has had 5 historic reports of flooding in the Hanworth and South Twickenham Catchment H10. The incidents align with the predicted risk areas, along the surface water flow paths on The Avenue, the A313

(Park Road), River Way (next to the River Crane) and Church Lane where Hotspots are located.

In this Catchment, there are six Hotspots shown in Figure 12-2. This has been summarised in Table 12-2.

12.4 Historic Flood Incidents and Flood Incident Areas

Historic surface water flood incidents for Hounslow are located close to both banks of the Longford River, with most concentrated along the surface water flow paths within TW1 3 (see Figure 2-7 for postal codes) to the eastern bank of the Portlane Brook. Within Richmond, postcode area TW12 has had 11 reported sewer flood incidents reported on both banks of the Longford River. More recent reports include properties flooding in in the TW1 area of York Street in February 2021. In June 2021, at Park Road in the TW12 area property flooding was also reported. All flood reports have been in the urbanised areas of this Catchment. Recorded flood incidents are shown in Figure 12-3. There are no Flood Incident Areas in this Catchment. Most incidents align with the predicted risk areas and Hotspots, along the flow paths to the River Crane in the north of this Catchment, to the River Thames in the east of this Catchment and to the railway line and Fulwell Golf Course in the south of this Catchment. Further regular flood incidents have been reported at Twickenham Riverside on Park Road at the junction with Willoughby Road. In St Margarets and North Twickenham, Ailsa Road was reported as regularly flooding up to the outer walls of properties. In Hampton North, infrastructure and notable features have been reported as regularly flooding including Hampton Square, The Avenue, Courtlands Avenue, and the Green Link nature trail.

Guidance

Strategic Flood Risk Assessments are carried out by local authorities, in consultation with the Environment Agency, to assess the flood risk to the area from all sources both now and in the future due to climate change. They are used to inform planning decisions to ensure inappropriate development is avoided (NPPF, 2023).

3. Site analysis

Site information

The Site is located in 21 The Avenue, Twickenham TW1 1QP in a setting of residential land use at National Grid Reference TQ 16835 74575.

Figure 1. Aerial imagery of the Site (Bluesky, 2024)

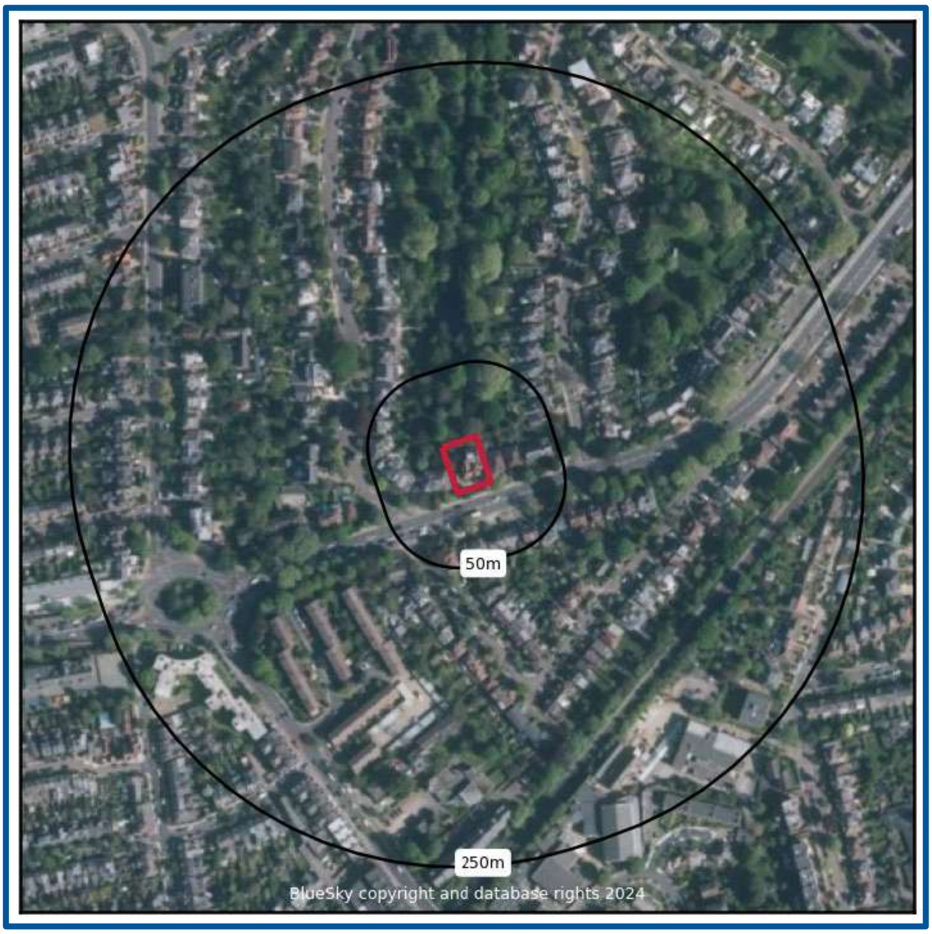
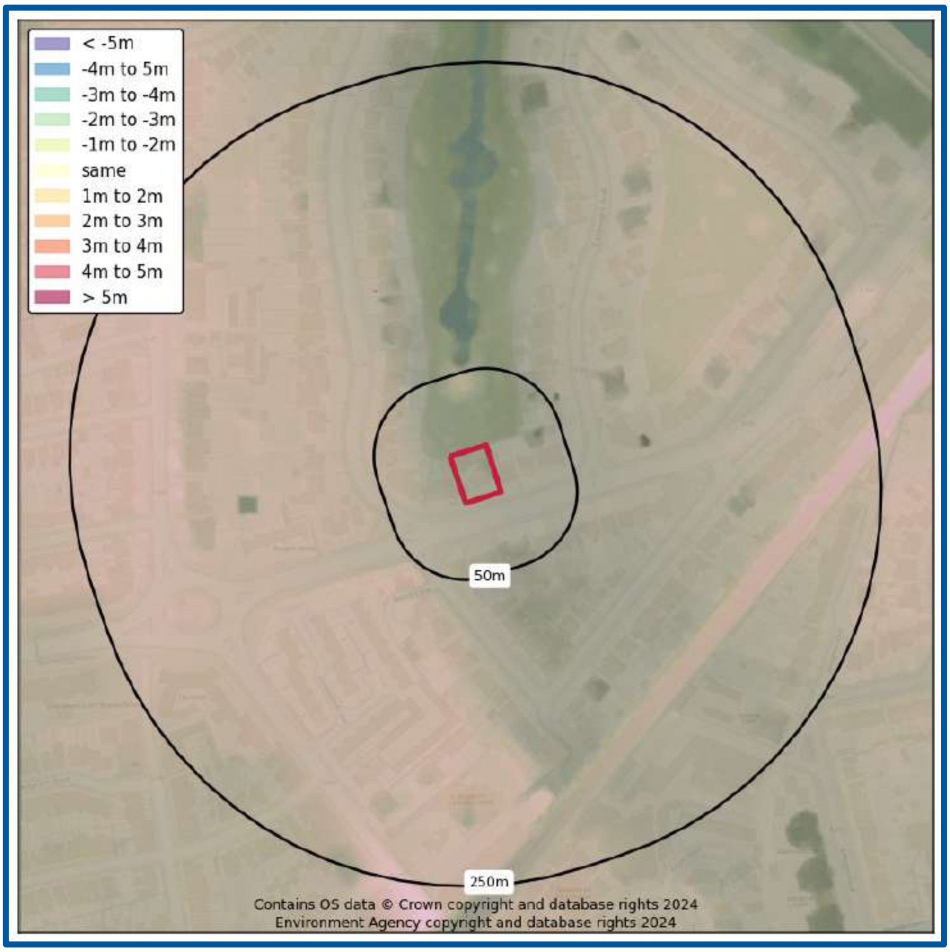


Figure 2 (overleaf) indicates ground levels within 500m of the Site fall in a northerly direction.

The general ground levels on the Site are between 4.55 and 5.88 mAOD with the Site falling in a northerly direction. In the area proposed for development approximate ground levels are approximately 5.50 mAOD. Generally lower ground levels are restricted to the rear landscaped areas of the Site. This is based on EA elevation data obtained for the Site to a 1 m resolution with a vertical accuracy of ±0.15 m (Appendix B).

Figure 2. Site Location and Relative Elevations (GeoSmart, 2024)



Development

The Site is currently used within a residential capacity as a three storey (plus loft and basement) detached, seven-bedroom dwelling including a garage, associated access, car parking and landscaping.

Development proposals comprise the demolition of the existing detached garage and the existing rear porch structure and the construction of an extension to the ground floor of the dwelling, with associated access and landscaping. It is understood that the development proposals also consist of some internal layout amendments although, no changes to the basement are proposed. Site plans are included within Appendix A.

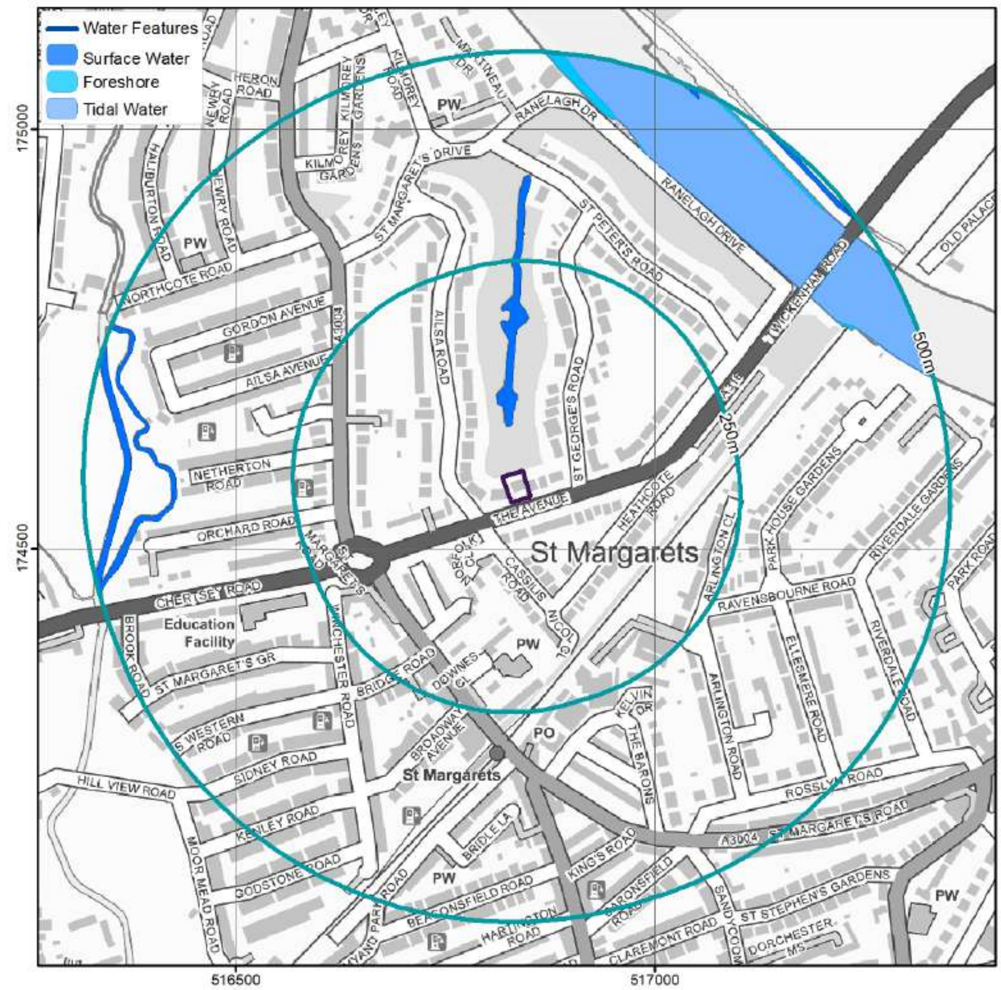
The effect of the overall development will not result in an increase in number of occupants and/or users of the building and will not result in the change of use, nature or times of occupation. According to Annex 3 of the NPPG (2022), the vulnerability classification of the existing development is More Vulnerable and proposed development is More Vulnerable. The estimated lifespan of the development is 100 years.

Hydrological features

According to Ordnance Survey (OS) mapping (Figure 3), there are numerous surface water features within 500 m of the Site.

- The River Thames is located approximately 380 m north east of the Site.
- There is an ornamental pond approximately 60 m to the north of the Site.
- The River Crane is approximately 520 m west of the Site at a lower elevation.

Figure 3. Surface water features (EA, 2024)



Lost Rivers

Lost Rivers are tributaries of the River Thames which have subsequently been culverted over or converted into sewers. According to London's Lost Rivers (2024) there are no subterranean rivers within 500 m of the Site.

GeoSmart Information

Proximity to relevant infrastructure

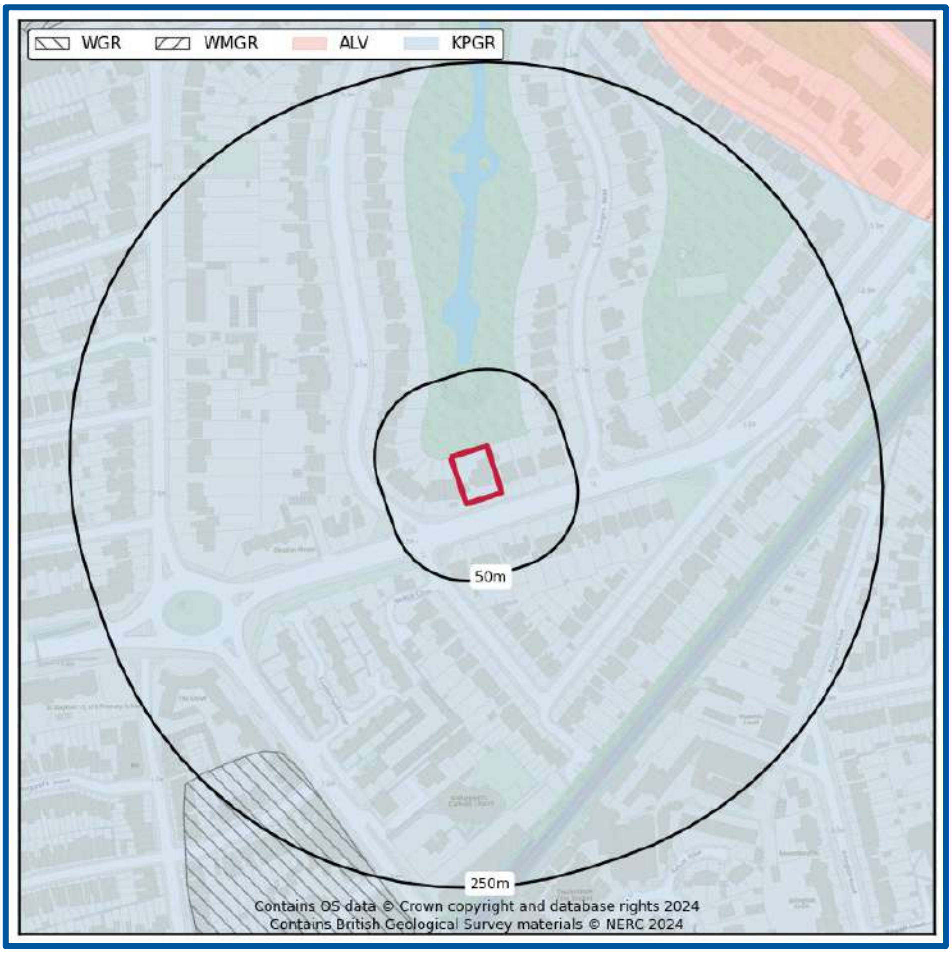
Infrastructure has been identified within 500 m of the Site which could influence the risks of flooding to existing or future occupants. These include:

- Twickenham Bridge is located upstream of the Site approximately 400 m to the north east.
- Richmond Lock Foot Bridge is located upstream of the Site Approximately 420 m to the north.
- There is a road bridge on the River Crane located approximately 830 m to the north, upstream from the Site. Multiple culverts and bridges are present on this river, some of which are upstream of the Site, all located to the north and east of the Site.
- Richmond Bridge is located downstream of the Site approximately 850 m to the east.

Hydrogeological features

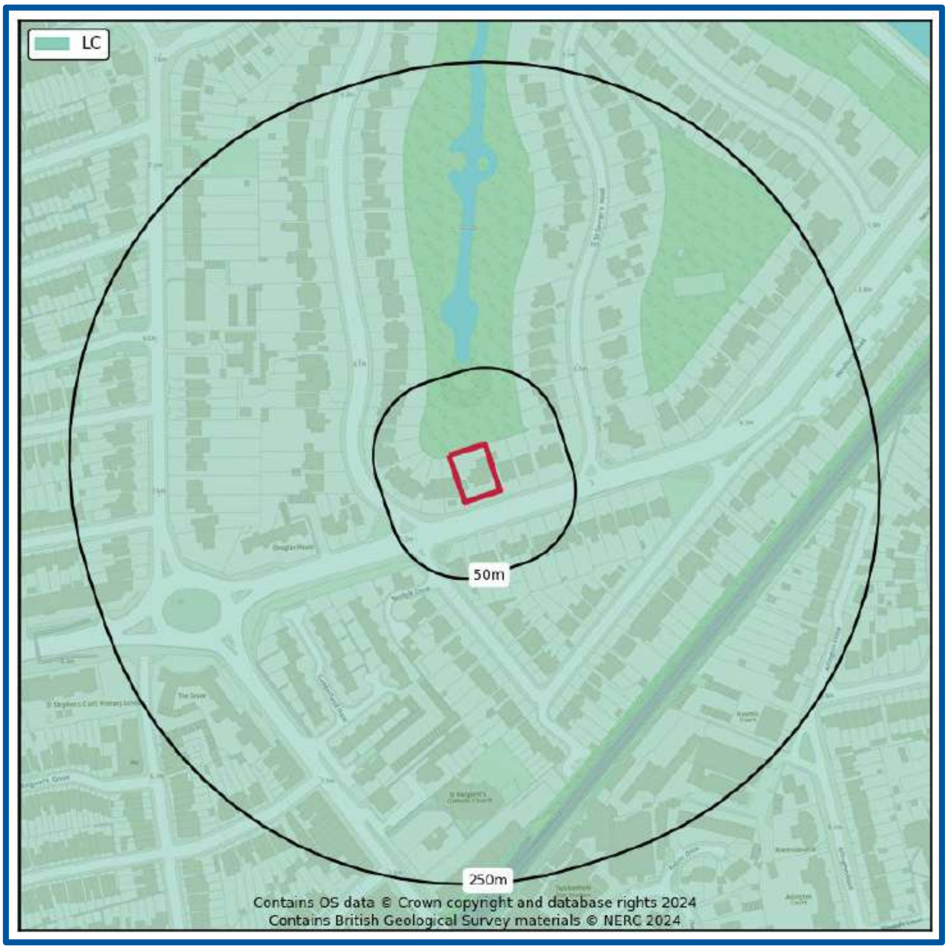
British Geological Survey (BGS) mapping indicates the underlying superficial geology (Figure 4) consists of Kempton Park Gravel Member – Sand and Gravel (KPGR) (BGS, 2024) and is classified as a Principal Aquifer (EA, 2024).

Figure 4. Superficial Geology (BGS, 2024)



BGS mapping indicates the underlying bedrock geology (Figure 5) consists of the London Clay Formation (LC) (BGS, 2024) and is classified as an Unproductive Strata (EA, 2024).

Figure 5. Bedrock Geology (BGS, 2024)



Geological conditions

A review of the BGS borehole database (BGS, 2024) indicates the nearest and most relevant borehole to the Site (ref: TQ17SE314) is located 30 m to the north west of the Site boundary at an elevation of 4.00 mAOD compared to the elevation at the Site of 5.38 mAOD. This borehole record indicates the underlying geology to consist brown sandy clay to a depth of 1.5 m below ground level (bgl) overlying brown sandy gravel to a depth of 7.50 m bgl, further overlying firm grey clay to a depth of 11 m, where the borehole was terminated.

Other relevant boreholes that surround the site include:

- Borehole (ref: TQ17SE313) - located 71 m to the east of the Site boundary at an elevation of 5.0 mAOD. This indicated the underlying geology consists of:
    - Chamber to a depth of 1m bgl, silty clay to a depth of 1.5 m bgl, sand and gravel to a depth of 7.5 m bgl and grey clay to a depth of 10.5 m bgl.
- Borehole (ref: TQ17SE252 and TQ17SE278) - located 122 m to the north east of the Site boundary at an elevation of 4 mAOD. This indicated the underlying geology consists of:

- Borehole (ref: TQ17SE252) – dark clay and sand to a depth of 2 m bgl overlying light coloured sand to a depth of 3 m bgl, sand and gravel to a depth of 4 m bgl, large gravel to a depth of 6 m bgl, gravel and grey clay to a depth of 6.5 m bgl and grey clay to a depth of 10.5 m bgl.
- Borehole (ref: TQ17SE278) – Made Ground to a depth of 0.3 m bgl overlying brown clayey sand to a depth of 1.7 m bgl, brown sand with some gravel to a depth of 4.5 m bgl, brown coarse sand and gravel to a depth of 7.7 m bgl and stiff blue clay to a depth of 12 m bgl.

These are relevant due to the shared superficial and bedrock geologies as well as being located at a comparable elevation (BGS, 2024).

Groundwater

Groundwater levels are recorded at

- 4.02 m below ground level (bgl) on 16/03/2015, subject to seasonal variations, at borehole TQ17SE314.
- 3 m bgl on 2/03/2015, subject to seasonal variations, at borehole TQ17SE313.
- 3.23 m bgl on 28/01/2008, subject to seasonal variations, at borehole TQ17SE278.
- 3.78 m bgl in July 2015, subject to seasonal variations, at borehole TQ17SE252.

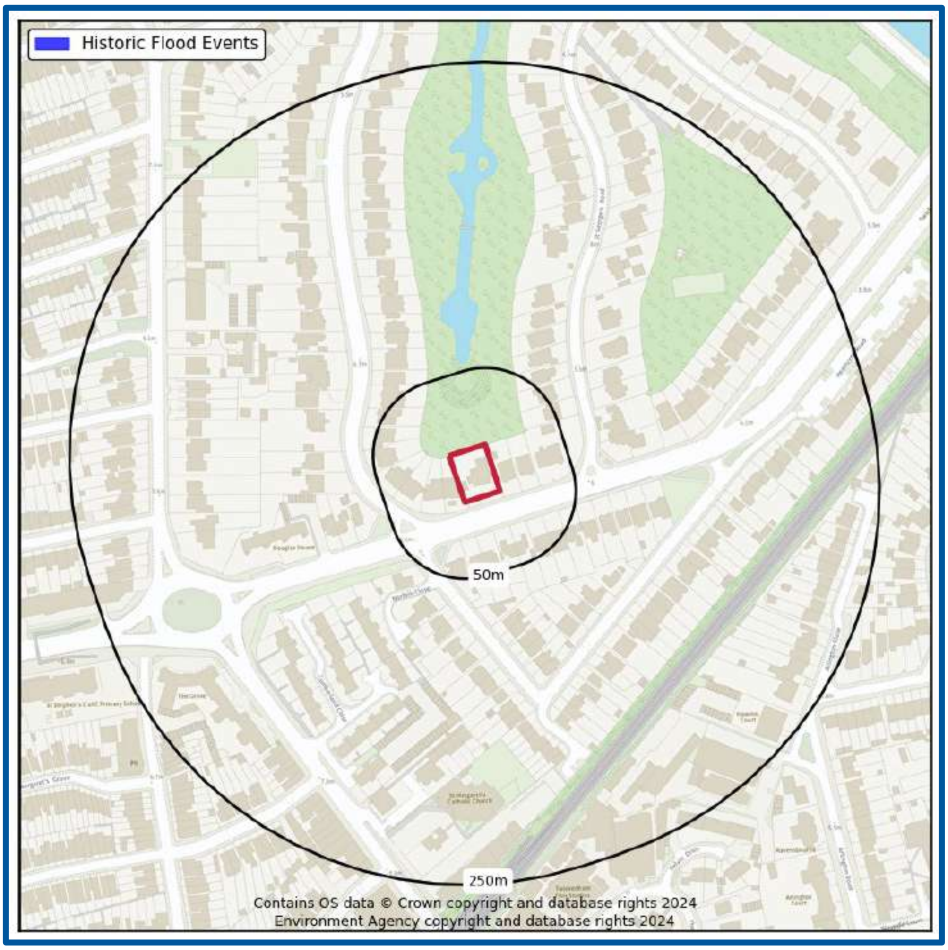
From the above measurements of groundwater levels in the borehole (ref: TQ17SE252) it is possible to approximate that groundwater levels at the Site are between 4.33 and 5.66 bgl.

4. Flood risk to the development

Historical flood events

According to the EA's Historical Flood Map (Figure 6) and the London Borough of Richmond Upon Thames SFRA (2021), there has been no flooding events affecting the Site

Figure 6. EA Historic Flood Map (EA, 2024)



Rivers (fluvial) / Sea (coastal) / Estuarine (tidal) flooding

The Site is located in an estuarine location and flooding could occur from a combination of the sea, termed as coastal flooding and from rivers, termed as fluvial flooding. There may be a predominant effect from either the sea or from the river.

River (fluvial) flooding occurs during times of heavy rainfall or snow melt when watercourses' capacity can be exceeded, over topping the banks and flood defences.

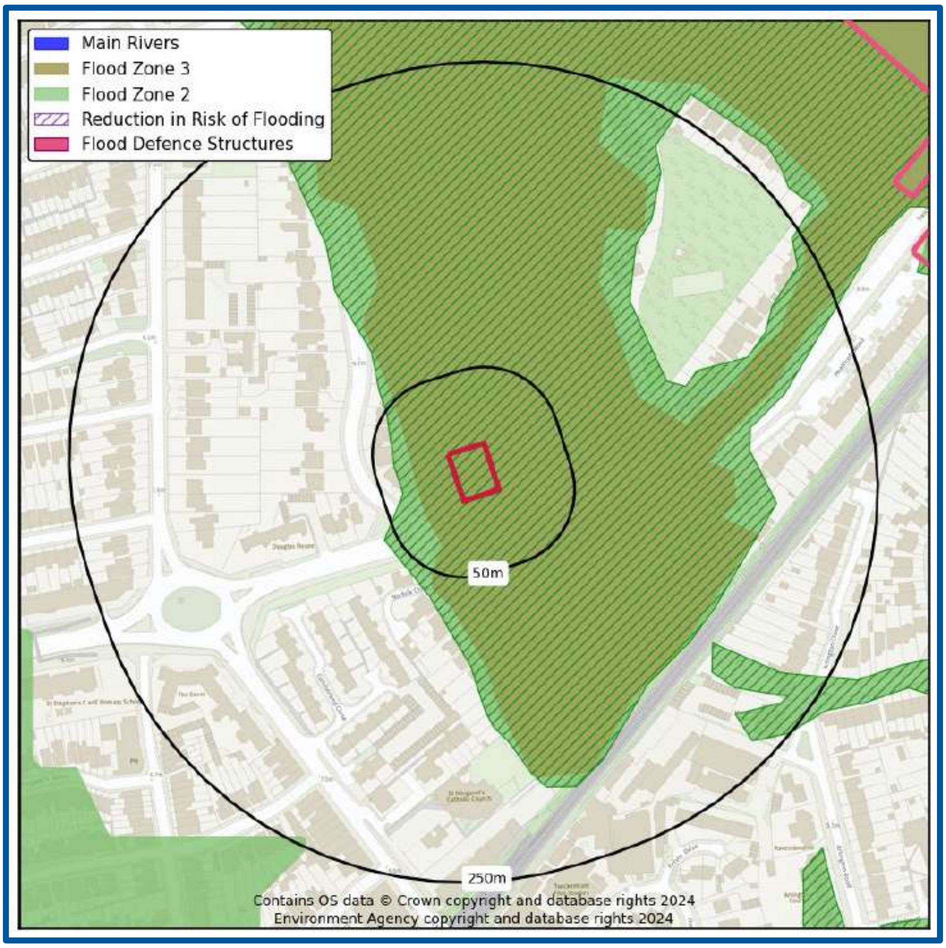
Estuarine flooding can occur from a combination of the sea, termed as coastal flooding and from rivers, termed as fluvial flooding. There may be a predominant effect from either the sea or from the river, through the following processes:

- High tide levels – variations in tidal levels due to gravitational effects of the sun and moon can result in higher sea levels – there is an approximate twice daily variation between high and low tide, onto which is superimposed a spring-neap tide cycle when extra high and low tides occur.
- Surge – an increase in sea level above tidal level caused by low atmospheric pressure which may be exacerbated by the wind acting on the sea. Tidal flooding is of greatest risk when tidal surges combine with high tides;

The Thames Estuary is one of the United Kingdom's major east-coast estuaries. It extends from the tidal limit of the River Thames at Teddington Lock in the west, through the heart of London, out to the North Sea. The character of the flooding changes from a fluvial dominance in the upstream reaches to the hazards posed by storm surges and waves in the downstream reaches.

According to the EA's Flood Map for Planning Purposes (Figure 7), the Site is located within fluvial and tidal Flood Zone 3 and is therefore classified as having a High Probability of flooding from the River Thames.

Figure 7. EA Flood Map for Planning Purposes (EA, 2024)



Guidance

As defined in the NPPF (2023):

Ignoring the presence of any defences, land located in a Flood Zone 3 is considered to have High probability of flooding with a 1 in 100 year or greater annual probability of fluvial flooding or a 1 in 200 or greater annual probability of coastal flooding in any one year.

Development of "Water-Compatible", "Essential Infrastructure", "Less Vulnerable" and "More Vulnerable" land uses are suitable for this zone with "Highly Vulnerable" land uses requiring an Exception Test to be passed prior to development taking place (see glossary for terminology).

Flood defences

Guidance

Sites that are located close to flood defences are likely to be zones where rapid inundation will occur in the event of the flood defences being overtopped or breached. A Site located close to flood defences (within 250 m) may require a more detailed FRA subject to local topography.

Existing flood defences

Information from the EA relating to the flood defences is outlined below.

- According to the EA (2024) the flood defences in place for this area are designed to defend up to a 1 in 1000 year flood event.
- The nearest and most applicable formal flood defences are comprised of a flood wall with a minimum crest level of 5.94 mAOD. The condition of this feature was not included in the dataset at time of writing.

Thames Estuary 2100 (TE2100)

The Thames Barrier requires regular maintenance and with additional closures the opportunity for maintenance will be reduced. When this happens, river levels - for which the Barrier would normally shut for the 2008 epoch - will have to be allowed through to ensure the barrier is not shut too often. For this reason, levels upriver of the barrier will increase and the tidal walls will need to be heightened to match.

Model data (Tidal)

As the Site is located within the EA's tidal floodplain, modelled flood elevation data was obtained from the EA. This data is more up to date than that which is included in the London Borough of Richmond Upon Thames SFRA (2021) and has been used to assess flood risk and to provide recommendations for mitigation for the proposed development. The data is provided in Table 2 below and included with Appendix B.

Thames Tidal Defences Study (Halcrow, 2006) and Thames Estuary 2100 Study (HR Wallingford, 2008)

In-channel flood level data have been taken from the nearest and most relevant node point (a2.6) (460 m to the north east of the Site, in the River Thames). When compared with the existing (2008) and proposed (2100) defence raising, the data confirm that even if the water level in the River Thames rises due to climate change, the defences are going to be raised too and therefore the Site will always be defended (EA, 2024).

Table 2. In-channel water levels and proposed flood defence heights

Flooding scenario	1 in 200 year scenario in-channel flood level (mAOD)		
	Present day	2065	2100
Flood Level (mAOD)	6.18	5.86	6.31
Flood defence height (mAOD)	5.94	6.35	6.80
Flood depths	No flooding anticipated		

Residual Tidal Flood Risk

The tidal flood assessment in this section represents the likelihood of flooding from overtopping at the Site, where flood defences are in good condition and are fully maintained. The Site is not at risk of overtopping, however there is a residual risk related to a breach in the Thames flood defences.

Thames Tidal Upriver Breach Inundation Modelling Study (May, 2017)

Modelled breach flood level data has been taken from the Thames Tidal Upriver Breach Assessment (Teddington Weir to Thames Barrier) (Atkins, 2017) to assess flood risk and provide recommendations for mitigation measures.

The breach flood level data has been extracted from the EA's 2D floodplain grid data using QGIS (v3.16.10).

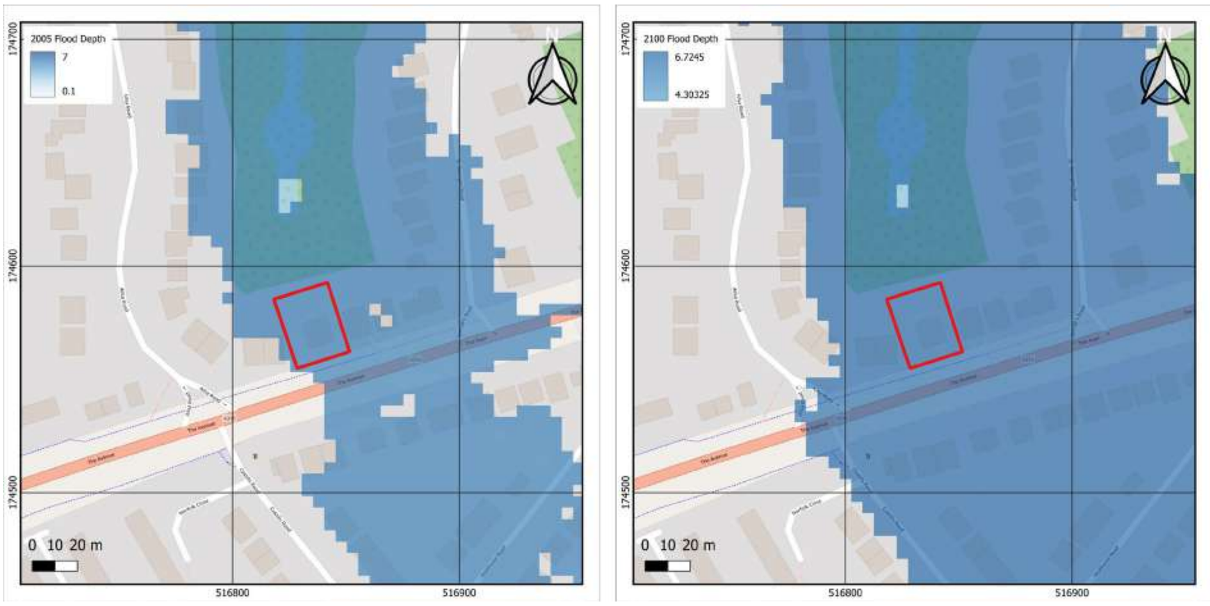
The mapped data indicates the Site would flood in the 2005 and 2100 breach flood scenarios.

Table 3. Modelled Breach Flood Levels

Ground levels at the area proposed for development (mAOD)	1 in 200 year scenario breach flood level (mAOD)	
	2005	2100
5.50	5.59	6.29
Flood depths (m)	Up to 0.09	Up to 0.79

As ground levels at the area proposed for development are approximately 5.50 mAOD, the flood depth at the Site would be up to approximately 0.79 m.

Figure 8. Modelled present data and future breach scenarios



Climate change factors

The EA's *Flood risk assessments: climate change allowances* guidance (Published 19 February 2016 and updated May, 2022) has been used to inform a suitable increase in peak river flows for the proposed development. The updated guidance confirms 'More Vulnerable' developments are required to undertake a Basic assessment approach.

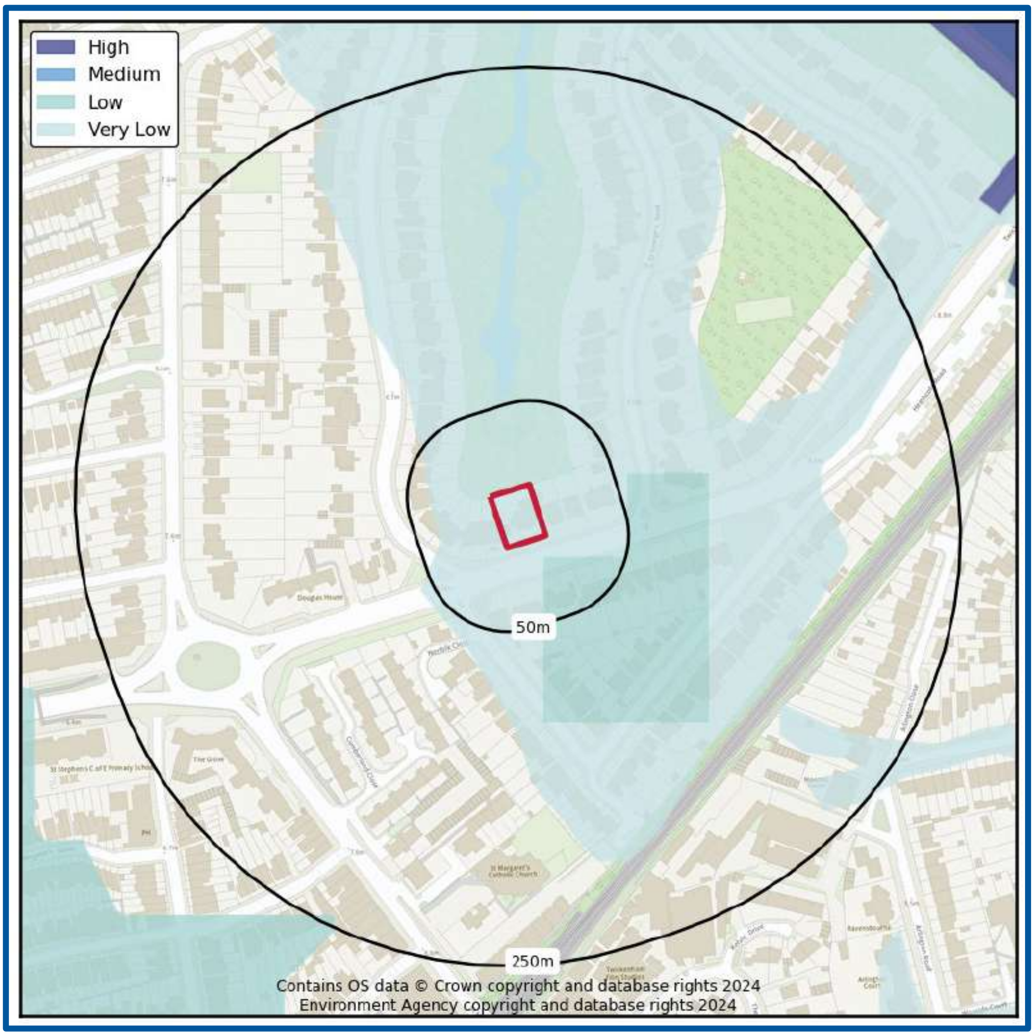
As the Site is located within the Thames River Basin and the proposed development is classed as More Vulnerable, where the proposed lifespan is approximately 100 years, the Central (25%) allowance has been incorporated into the TE2100 project modelled flood levels.

Flood risk including the benefit of defences

The type and condition of existing flood defences influence the 'actual' risk of fluvial flooding to the Site, albeit the long-term residual risk of flooding (ignoring the defences) should be considered when proposing new development.

According to the EA's Risk of Flooding from Rivers and Sea (RoFRS) map (Figure 8), which considers the type, condition and crest height of flood defences, the Site has a Very Low risk of flooding from the nearby watercourse, the Thames.

Figure 9. Risk of Flooding from Rivers and Sea map (EA, 2024)

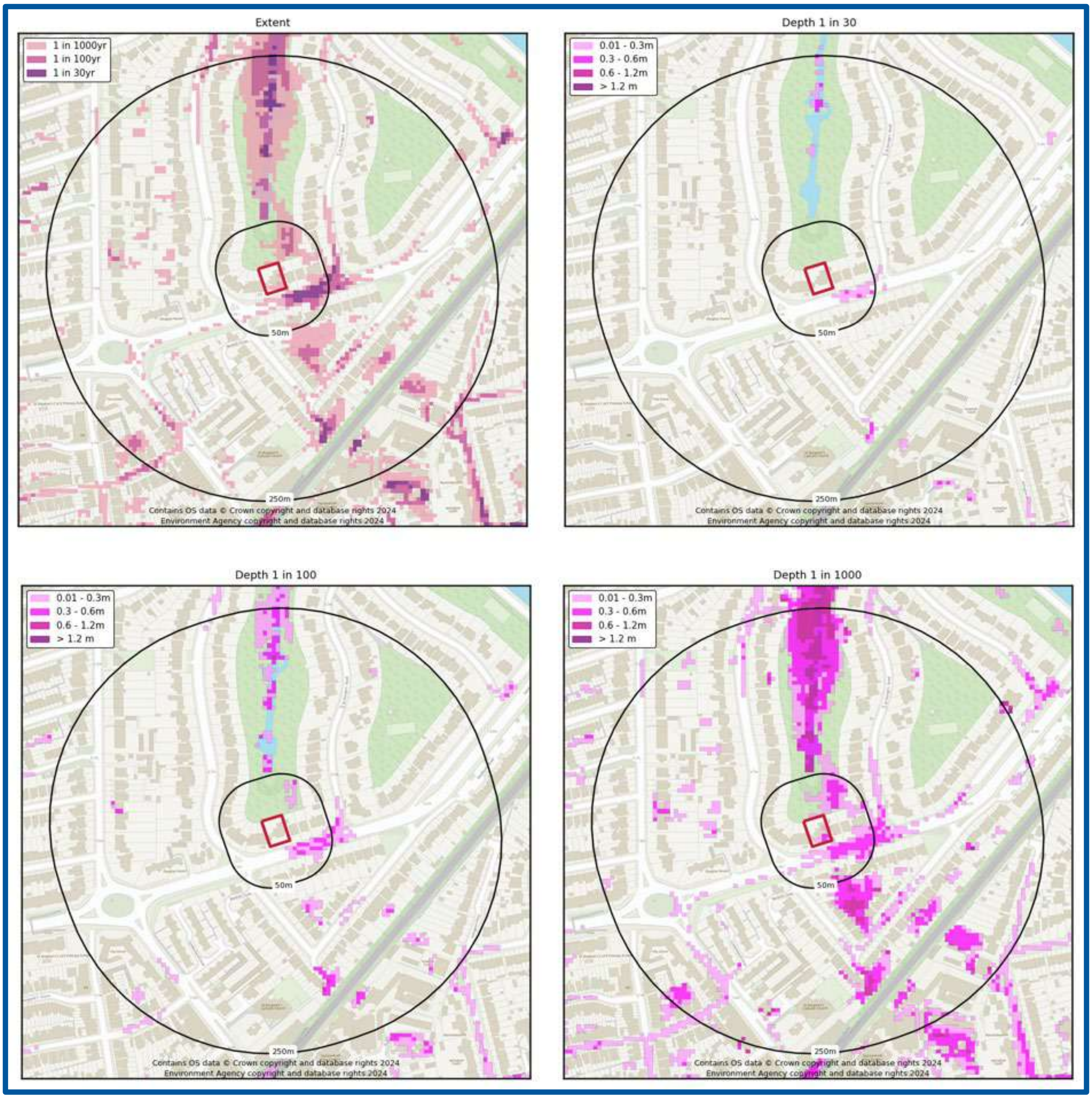


Surface water (pluvial) flooding

Surface water flooding occurs when intense rainfall exceeds the infiltration capacity of the ground and overwhelms the drainage systems. It can occur in most locations even at higher elevations and at significant distances from river and coastal floodplains.

According to the EA's Risk of Flooding from Surface Water (pluvial) flood mapping (Figure 9), the Site has a Very Low to Low risk of pluvial flooding.

Figure 10. EA surface water flood extent and depth map (EA, 2024)



Guidance
According to EA's surface water flood risk map the Site is at: • Very Low risk - chance of flooding of less than 1 in 1000 (0.1%). • Low risk - chance of flooding of between a 1 in 1000 & 1 in 100 (0.1% and 1%).

The SFRA does indicate reported incidents of historical surface water flooding within 100 m of the Site and confirms the Site is not located within a Critical Drainage Area (CDA)[1] (SFRA, 2015).

Figure 9 confirms the extent and depth of flooding in multiple modelled flood scenarios. Flooding depths of up to 0.15-0.6 m would impact the area proposed for development in the 1 - 0.1% AEP (Low) risk event.

Flooding depths of up to 0.6 m would impact the access routes to and from the Site in the 1 - 0.1% AEP (Low) risk event.

Guidance
According to EA's surface water flood risk map the following advisory guidance applies to the Site: Flood Depth • 0.15 to 0.3 m - Flooding would: typically exceed kerb height, likely exceed the level of a damp-proof course, cause property flooding in some areas • 0.3 to 0.9 m - Flooding is likely to exceed average property threshold levels and cause internal flooding. Resilience measures are typically effective up to a water depth of 0.6 m above floor level.

Climate change factors

Paragraph 002 of the National Planning Practice Guidance (August, 2022) requires consideration of the 1% AP (1 in 100 year) event, including an appropriate allowance for climate change.

As the Site is located within the London Management Catchment and the proposed development is classed as More Vulnerable, where the proposed lifespan is approximately

[1] A Critical Drainage Area (CDA) is an area that has critical drainage problems and which has been notified to the local planning authority as such by the Environment Agency in line with the National Planning Policy Framework (NPPF, 2023). CDA's are specific to Flood Zone 1, defined as areas where runoff can and may have historically contributed to flooding downstream, although they are not necessarily areas where flooding problems may occur. Where a Site is located in Flood Zone 1 and within a CDA, a Flood Risk Assessment (FRA) is required and the Council may also request Sustainable Drainage Scheme (SuDS) features to be included within the proposed development.

100 years. years, the Upper End (40%) allowance is required to determine a suitable climate change factor to apply to rainfall data.

The 0.1% AP (1 in 1000 year) surface water flooding event has been used as a proxy in this instance for the 1% AP (1 in 100 year) plus climate change event.

Surface water flooding flow routes

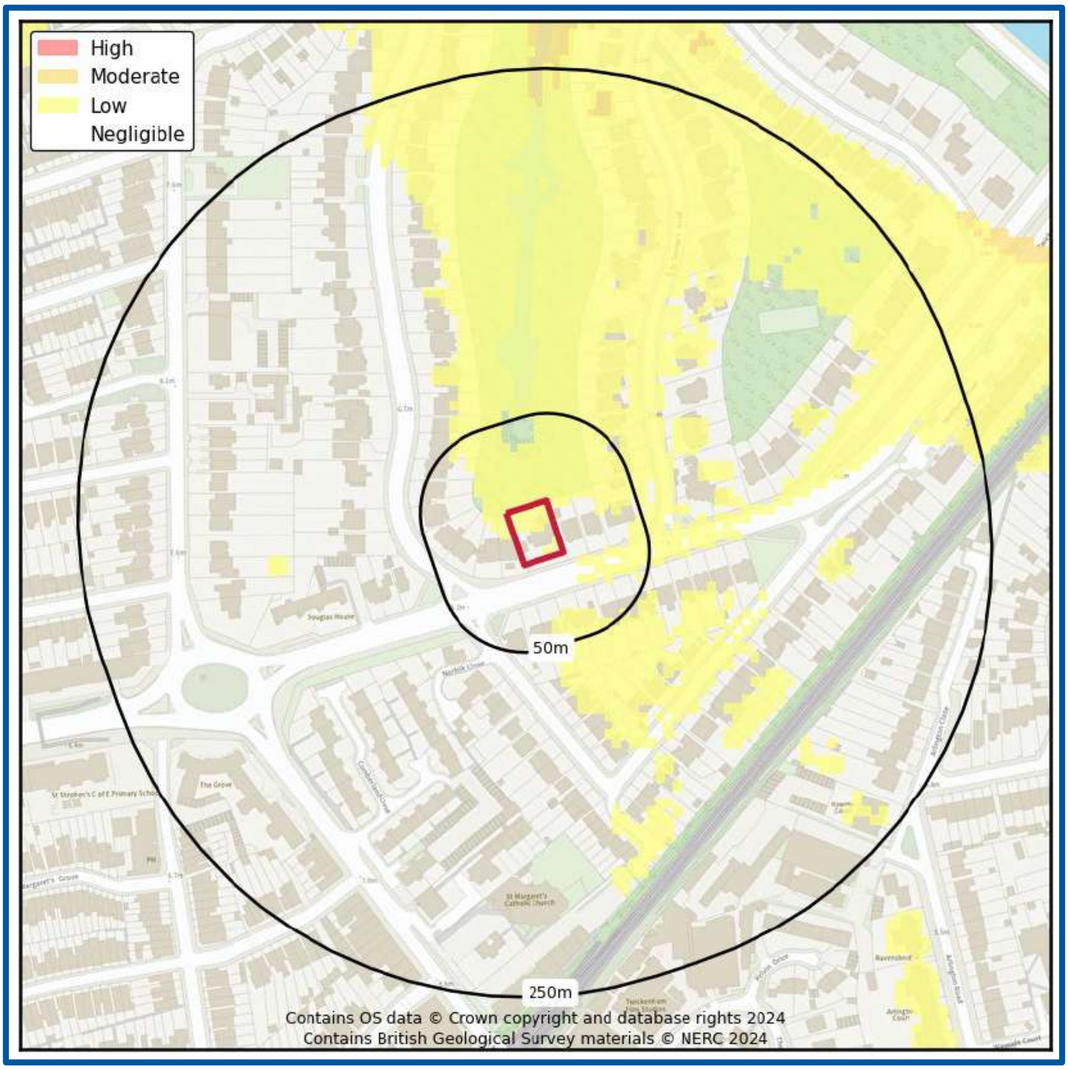
Analysis of OS mapping, ground elevation data and the EA's pluvial flow route mapping in the 1 in 1000 year (Low probability) event confirms the Site is not located on a potential overland flow route.

Groundwater flooding

Groundwater flooding occurs when sub-surface water emerges from the ground at the surface or into Made Ground and structures. This may be as a result of persistent rainfall that recharges aquifers until they are full; or may be as a result of high river levels, or tides, driving water through near-surface deposits. Flooding may last a long time compared to surface water flooding, from weeks to months. Hence the amount of damage that is caused to property may be substantially higher.

Groundwater Flood Risk screening data (Figure 12) indicates there is a Negligible to Low risk of groundwater flooding at surface in the vicinity from permeable superficial deposits during a 1 in 100 year event.

Figure 11. GeoSmart GW5 Groundwater Flood Risk Map (GeoSmart, 2024)



Mapped classes within the screening map combine likelihood, possible severity and the uncertainty associated with predicting the subsurface system. The map is a national scale screening tool to prompt site-specific assessment where the impact of groundwater flooding would have significant adverse consequences. Mapping limitations and a number of local factors may reduce groundwater flood risk to land and property even where it lies within mapped groundwater flood risk zones, which do not mean that groundwater floods will occur across the whole of the risk area.

A site-specific assessment has been undertaken to refine the groundwater risk screening information on the basis of site-specific datasets (see Section 3) including BGS borehole data, and the EA's fluvial and tidal floodplain data (where available) to develop a conceptual groundwater model. The risk rating is refined further using the vulnerability of receptors including occupants and the existing and proposed Site layout, including the presence of basements and buried infrastructure. The presence of any nearby or on-Site surface water features such as drainage ditches, which could intercept groundwater have also been considered.

- It is understood there are no existing basements and a basement is not proposed as part of the development.
- According to a review of the hydrogeology (Section 3), the Site is underlain by a significant thickness (>3m) of permeable superficial deposits above a low permeability bedrock. The groundwater system is therefore considered likely to be in continuity with the Site surface.
- Despite the presence of an aquifer the Site would only be at risk of groundwater flooding if the water table reaches the base of the Site development or the ground surface when groundwater seepage could lead to overland flow and ponding.
- According to a review of the hydrogeology (Section 3), the nearby boreholes (ref: TQ17SE314 and TQ17SE313) encountered groundwater at a depth of 3-4m bgl within the permeable superficial geology.
- The local topography and drainage is such that the development threshold is likely to be higher than the area where groundwater emerges in adjacent low points.

The hydrogeological characteristics suggest there is potential for a groundwater table beneath the Site. The baseline groundwater flood risk rating is Negligible to Low, but on the basis of the site-specific assessment the groundwater flood risk is considered to be Low.

Guidance
Low Risk - There will be a remote possibility that incidence of groundwater flooding could lead to damage to property or harm to other sensitive receptors at, or near, this location.

Climate change predictions suggest an increase in the frequency and intensity of extremes in groundwater levels. The impact of climate change on groundwater levels beneath the Site is linked to the predicted risk in both peak river levels and sea levels and also the variation in rainfall recharge which is uncertain.

- Rainfall recharge patterns will vary regionally resulting in changes to average groundwater levels.

- A rise in peak river levels will lead to a response of increased groundwater levels in adjacent aquifers subject to the predicted climate change increases in peak river level for the local catchment.
- Sea level rises of between 0.4m and 1m are predicted by 2100, leading to a rise in average groundwater levels in the adjacent coastal aquifer systems, and potential increases in water levels in the associated drainage systems. The 'backing up' of groundwater levels from both coast and tidal estuary locations may extend a significant distance inland and affect infrastructure previously constructed above average groundwater levels.

Flooding from artificial sources

Artificial sources of flood risk include waterbodies or watercourses that have been amended by means of human intervention rather than natural processes. Examples include reservoirs (and associated water supply infrastructure), docks, sewers and canals. The flooding mechanism associated with flood risk from artificial sources is primarily related to breach or failure of structures (reservoir, lake, sewer, canal, flood storage areas, etc.)

Sewer flooding

Interactive SFRA mapping confirms 4 incidences of flooding as a result of surcharging sewers within the Twickenham Riverside ward. However, it is recognised that this covers a large area and instances of flooding are not specific to the Site (Metis Consultants, 2021).

Records held by Thames Water indicate that there have been no incidences of flooding related to the surcharging of public sewers at the Site (Thames Water, 2024; Appendix C).

Guidance

Properties classified as "at risk" are those that have suffered, or are likely to suffer, internal flooding from public foul, combined or surface water sewers due to overloading of the sewerage system either once or twice in the ten year reference period. Records held by the sewage utility company provide information relating to reported incidents, the absence of any records does not mean that the Site is not at risk of flooding.

Canal failure

According to Ordnance Survey (OS) mapping, there are no canals within 500 m of the Site.

Water supply infrastructure

Water supply infrastructure is comprised of a piped network to distribute water to private houses or industrial, commercial or institution establishments and other usage points. In urban areas, this represents a particular risk of flooding due to the large amount of water supply infrastructure, its condition and the density of buildings. The risks of flooding to properties from burst water mains cannot be readily assessed.

If more information regarding the condition and history of the water supply infrastructure within the vicinity of the Site is required, then it is advisable to contact the local water supplier (Thames Water).

Culverts and bridges

The blockage of watercourses or structures by debris (that is, any material moved by a flowing stream including vegetation, sediment and man-made materials or refuse) reduces flow capacity and raises water levels, potentially increasing the risk of flooding. High water levels can cause saturation, seepage and percolation leading to failure of earth embankments or other structures. Debris accumulations can change flow patterns, leading to scour, sedimentation or structural failure.

Culverts and bridges have not been identified within 50 m of the Site.

Nearby structures are a significant distance upstream and downstream (minimum of 400m) from the Site and are unlikely to represent a flood risk to the Site in the event of a blockage.

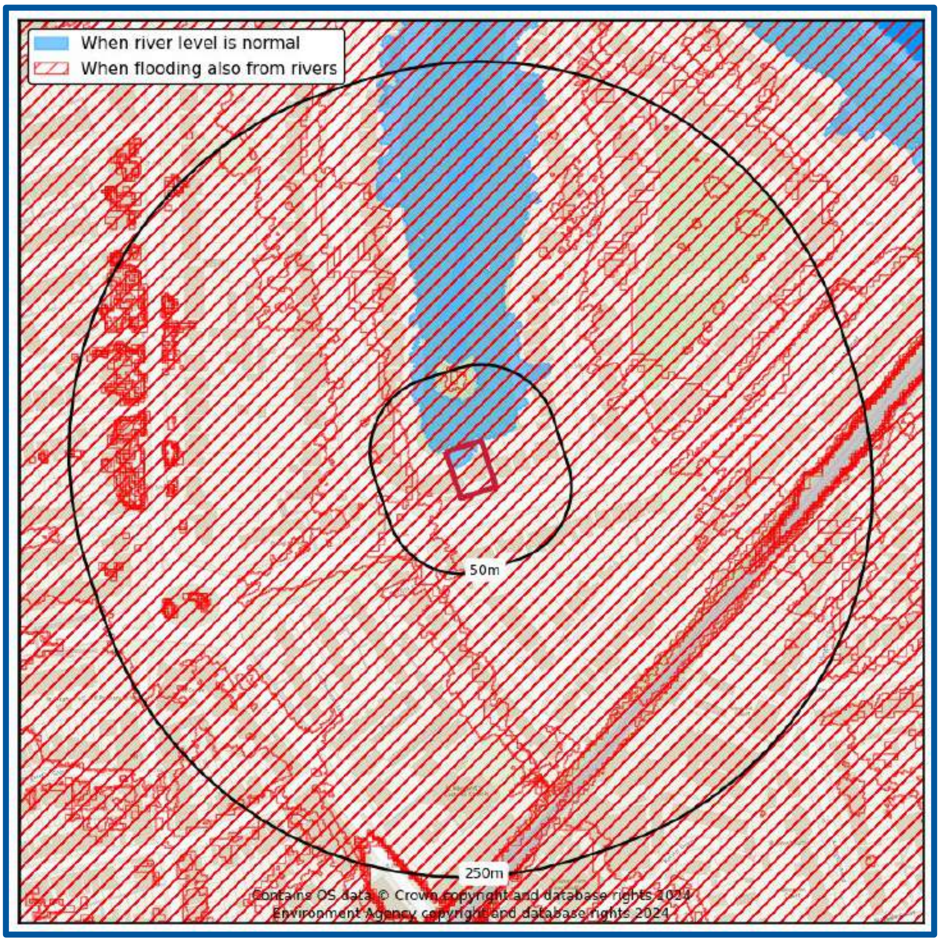
Reservoir flooding

According to the EA's Risk of Flooding from Reservoir mapping the Site is at risk of flooding from reservoirs (Figure 12, overleaf) (EA, 2024).

Reservoirs listed as possibly impacting flooding at the Site include:

- Island Barn Reservoir, located approximately 8 km away from the Site;
- King George VI Reservoir, located approximately 13 km away from the Site;
- Queen Elizabeth II Reservoir, located approximately 9 km away from the Site;
- Queen Mary Reservoir, located approximately 11 km away from the Site;
- Staines North and South Reservoir, located approximately 12 km away from the Site;
- Wraysbury Reservoir located approximately 14 km away from the Site.

Figure 12. EA Risk of Reservoir Flooding (EA, 2024)



Guidance

The risk of reservoir flooding is related to the failure of a large reservoir (holding over 25,000 m^3 of water) and is based on the worst-case scenario. Reservoir flooding is extremely unlikely to occur (EA, 2024).

5. Flood risk from the development

Floodplain storage

Where flood storage from any source of flooding is to be lost as a result of development, on-site level-for-level compensatory storage, accounting for the predicted impacts of climate change over the lifetime of the development, should be provided. Where it is not possible to provide compensatory storage on site, it may be acceptable to provide it off-site if it is hydraulically and hydrologically linked.

The loss of floodplain storage is less likely to be a concern in areas benefitting from appropriate flood risk management infrastructure or where the source of flood risk is solely tidal.

The development is located within an area which would be impacted by a 1 in 100 year plus 40% climate change pluvial events and involves an increase in building footprint. As the development would displace flood waters, compensatory flood storage may be required.

The proposed development is in an area which is largely permeable and is not positively drained to any existing surface water drainage networks. If a positive drainage network is installed the increase in built footprint would not displace any additional flood water.

Scoping estimates of the storage requirements can be made by multiplying the increase in building footprint by the average flood depth at the development, during the 1 in 100 year flood event with a 40% allowance for climate change.

Drainage and run-off

Based on the topography and surface water flood risk in the vicinity, interference or interaction with overland flow paths and inflows from off-Site is considered possible. It is recommended that steps are taken to manage these potential inflows within the Site drainage system.

The proposed development involves an increase of impermeable surfaces at the Site. An estimation of run-off is therefore required to permit effective Site water management and prevent any increase in flood risk to off-Site receptors from the Site.

A Sustainable Drainage Strategy has been prepared separately by GeoSmart (ref: 84145.01) to manage the increase in runoff from the Site.

6. Suitability of the proposed development

The information below outlines the suitability of proposed development in relation to national and local planning policy.

National policy and guidance

The aims of the national planning policies are achieved through application of the Sequential Test and in some cases the Exception Test.

Guidance

Sequential test: The aim of this test is to steer new development towards areas with the lowest risk of flooding (NPPF, 2023). Reasonably available sites located in Flood Zone 1 should be considered before those in Flood Zone 2 and only when there are no reasonably available sites in Flood Zones 1 and 2 should development in Flood Zone 3 be considered.

Exception test: In some cases, this may need to be applied once the Sequential Test has been considered. For the exception test to be passed it must be demonstrated that the development would provide wider sustainability benefits to the community that outweigh flood risk and a site-specific FRA must demonstrate that the development will be safe for its lifetime taking account of the vulnerability of its users, without increasing flood risk elsewhere, and, where possible, will reduce flood risk overall.

Suitability of the proposed development, and whether the Sequential and Exception Tests are required, is based on the Flood Zone the Site is located within and the flood risk vulnerability classification of the existing and proposed development. Some developments may contain different elements of vulnerability and the highest vulnerability category should be used, unless the development is considered in its component parts.

This report has been produced to assess all development types, prior to any development. The vulnerability classification and Flood Zones are compared within the table overleaf (Table 2 of the NPPG (2022)).

As the Site is located within Flood Zone 3a and the proposed development is defined as More Vulnerable; the proposals are acceptable, but may be subject to the Sequential and Exceptions Test.

The proposed development is a minor extension to the existing property which would extend out the existing snug and reception area of the ground floor (the extension would not result in any additional bedrooms) and is therefore defined as minor development.

Paragraph 174 of the NPPF states: *"Applications for some minor development and changes of use [60] should not be subject to the sequential or exception tests but should still meet the requirements for site-specific flood risk assessments set out in footnote 59"* (NPPF, 2023).

The NPPG (2022) defines a 'minor development' as *"householder development and small non-residential extensions (with a footprint of less than 250 m^2)."*

As a result, as the proposals are defined as "minor development – householder development" they are not subject to the Sequential Test or an Exception Test.

Table 4. Flood risk vulnerability and flood zone 'incompatibility (taken from NPPG, 2022)

Flood risk vulnerability classification		Essential infrastructure	Water compatible	Highly vulnerable	More vulnerable	Less vulnerable
Flood Zone	Zone 1 – low probability	✓	✓	✓	✓	✓
	Zone 2 – medium probability	✓	✓	Exception test required	✓	✓
	Zone 3a - high probability	Exception test required	✓	X	Exception test required*	✓
	Zone 3b – functional flood plain	Exception test required	✓	X	X	X

*As the development proposals are for a minor development the Sequential and Exception Tests are not required.

EA Flood Risk Standing Advice for vulnerable developments located in Flood Zones 2 or 3 (February, 2022)

The proposed development is considered to be a minor extension, this is defined as a household or non-domestic extension with a floor space of no more than 250 m^2.

In line with the 'Minor extensions standing advice'

- A plan is required showing the finished floor levels and the estimated flood levels.
- Floor levels are either no lower than existing floor levels or 0.3 m above the estimated flood level. If your floor levels aren't going to be 0.3 m above existing flood levels, you need to check with your local planning authority if you also need to take flood resistance and resilience measures.

Surface water management

Plans for the management of surface water need to meet the requirements set out in either the local authority's:

- Surface water management plan where available; OR
- Strategic flood risk assessment.

They also need to meet the requirements of the approved building regulations Part H: drainage and water disposal. Read section H3 rainwater drainage.

Planning permission is required to use a material that can't absorb water (e.g. impermeable concrete) in a front garden larger than $5m^2$.

Access and evacuation

Details of emergency escape plans should be provided for any parts of a building that are below the estimated flood level:

Plans should show:

- Single storey buildings or ground floors that don't have access to higher floors can access a space above the estimated flood level, e.g. higher ground nearby;
- Basement rooms have clear internal access to an upper level, e.g. a staircase;
- Occupants can leave the building if there's a flood and there's enough time for them to leave after flood warnings.

Floor levels

The following should be provided:

- Average ground level of your site
- Ground level of the access road(s) next to your building
- Finished floor level of the lowest room in your building

Finished floor levels should be a minimum of whichever is higher of 300mm above the:

- Average ground level of the site
- Adjacent road level to the building
- Estimated river or sea flood level

You should also use construction materials that have low permeability up to at least the same height as finished floor levels.

If you cannot raise floor levels to meet the minimum requirement, you will need to:

- Raise them as much as possible
- Consider moving vulnerable uses to upper floors
- Include extra flood resistance and resilience measures

When considering the height of floor levels, you should also consider any additional requirements set out in the SFRA. Flood water can put pressure on buildings causing structural issues. If your design aims to keep out a depth of more than 600mm of water, you should get advice from a structural engineer. They will need to check the design is safe.

Extra flood resistance and resilience measures

Follow the guidance in this section for developments in flood risk areas where you cannot raise the finished floor levels to the required height. You should design buildings to exclude flood water where possible and to speed recovery in case water gets in.

Make sure your flood resilience plans for the development follow the guidance in the CIRIA Property Flood Resilience Code of Practice. Please note that the code of practice uses the term 'recovery measures'. In this guide we use 'resilience measures'.

Flooding can affect the structural stability of buildings. If your building design would exclude more than 600mm of flood water, you should get advice from a structural engineer. They will need to check the design is safe. Only use resistance measures that will not cause structural stability issues during flooding. If it is not possible to safely exclude the estimated flood level, exclude it to the structural limit then allow additional water to flow through the property.

The design should be appropriately flood resistant and resilient by:

- Using flood resistant materials that have low permeability to at least 600mm above the estimated flood level
- Making sure any doors, windows or other openings are flood resistant to at least 600mm above the estimated flood level
- Using flood resilient materials (for example lime plaster) to at least 600mm above the estimated flood level
- By raising all sensitive electrical equipment, wiring and sockets to at least 600mm above the estimated flood level
- Making it easy for water to drain away after flooding such as installing a sump and a pump
- Making sure there is access to all spaces to enable drying and cleaning
- Ensuring that soil pipes are protected from back-flow such as by using non-return valves

Temporary or demountable flood barriers are not appropriate for new buildings. Only consider them for existing buildings when:

- There is clear evidence that it would be inappropriate to raise floor levels and include passive resistance measures
- An appropriate flood warning or other appropriate trigger is available

If proposals involve the development of buildings constructed before 1919, refer to Flooding and Historic Buildings guidance produced by Historic England.

For new developments, finished floor levels are set no lower than 300 millimetres above the 1 in 100 year return period event flood level for fluvial flooding. This includes an allowance for climate change. For tidal flood risk, the finished floor levels of all developments are set above the modelled Thames tidal breach flood level for the year 2100. As a minimum, any sleeping accommodation must be located above this breach level (Metis Consultants, 2021).

7. Resilience and mitigation

Based on the flood risk identified at the Site, the national and local policies and guidance and proposed development, the mitigation measures outlined within this section of the report are likely to help protect the development from flooding.

Tidal flood mitigation measures

The Site is located within an area which is potentially affected by flooding from tidal sources. Table 5 illustrates that the presence of flood defences (including the planned raising of crest heights) will offer suitable protection to the area proposed for development. However, should a breach to the flood defences occur, combined with climate change impacts, future flooding of the Site could occur (see Table 6).

Table 1. In-channel water levels and proposed flood defence raising

Flooding Scenario	1 in 200 year scenario in-channel flood level (mAOD)		
	Present day	2065	2100
Flood Level (mAOD)	6.18	5.86	6.31
Flood defence height (mAOD)	5.94	6.35	6.80
Flood depths (m)	No flooding anticipated		

Table 2. Modelled Breach flood levels at ground level

Ground levels on-Site (mAOD)	1 in 200 year scenario breach flood level (mAOD)	
	2005	2100
Flood Level (mAOD)	5.59	6.29
Flood depths (m)*	Up to 0.09	Up to 0.79

*Based on ground levels at the area proposed for development of 5.0 mAOD.

As the development proposals are comprised of an extension to an existing dwelling, the raising of Finished Floor Levels (FFL) is unlikely to be a feasible method of flood mitigation. Finished floor levels should be raised as high as feasibly possible and set no lower than existing. Flood resilience measures should be considered in lieu of raising the FFL.

Alternative Mitigation

In lieu of raising the FFL, it may be appropriate to adopt a water exclusion strategy for flood depths up to 0.3 m in line with the EA's Standing Advice. A water exclusion strategy, using avoidance and resistance measures, is appropriate where floods are expected to last for short durations. Potential water exclusion strategies include:

- Passive flood door systems;
- Temporary flood barriers;
- Air brick covers (manual or automatic closing); and,
- Non-return flap valves on sewer outfalls.

Avoidance and resistance measures are unlikely to completely prevent floodwater entering a property, particularly during longer duration flood events. Therefore, it is recommended that the following flood resilience measures are also considered.

- Flood resilient materials and designs:
    - Use of low permeability building materials up to 0.3 m such as engineering bricks (Classes A and B) or facing bricks;
    - Hard flooring and flood resilient metal staircases;
    - The use of internal lime plaster/render or where plasterboards are used these should be fitted horizontally instead of vertically and/or using moisture resistant plasterboard at lower levels;
    - Water, electricity and gas meters and electrical sockets should be located above the predicted flood level;
    - Communications wiring: wiring for telephone, TV, Internet and other services should be protected by suitable insulation in the distribution ducts to prevent damage.

Surface water (pluvial) flood mitigation measures

The mitigation measures detailed above for river and sea flood risk are likely to be suitable for the relatively shallow flood depths which could be experienced in a 1 in 100 year pluvial flood event.

In addition, the regular maintenance of any drains and culverts surrounding/on the Site should be undertaken to reduce the flood risk.

If these mitigation measures are implemented this would reduce the flood risk to the development from Low to Very Low.

Groundwater flood mitigation measures

It is likely the flood mitigation measures recommended for the tidal flood risk will reduce the groundwater flood risk at the development. However specific additional groundwater measures that may also be considered for the Low risk identified include:

- Interceptor drains;
- Automatic sump to extract flood water; and,
- Non-return flap valves on the proposed foul and surface water sewer lines.

Reservoir flood mitigation measures

According to EA data, the nearest reservoir is situated approximately 8 km to the southwest of the Site and flooding would affect the Site in this case.

There would be a relatively high rate and onset of flooding associated with a reservoir breach, it is therefore unlikely that safe access could be achieved unless a long warning period was provided. Therefore, occupants should get to the highest level of the building as possible and contact the emergency services.

Other flood risk mitigation measures

As the Site is not identified as at risk from other sources, mitigation measures are not required.

Residual flood risk mitigation measures

The risk to the Site has been assessed from all sources of flooding and appropriate mitigation and management measures proposed to keep the users of the development safe over its lifetime. There is however a residual risk of flooding associated with the potential for failure of mitigation measures if regular maintenance and upkeep isn't undertaken. If mitigation measures are not implemented or maintained, the risk to the development will remain as the baseline risk.

Further flood mitigation information

More information on flood resistance, resilience and water entry can be found here: http://www.planningportal.gov.uk/uploads/br/flood_performance.pdf

www.knowyourfloodrisk.co.uk

Emergency evacuation - safe access / egress and safe refuge

Emergency evacuation to land outside of the floodplain should be provided if feasible. Where this is not possible, 'more vulnerable' developments and, where possible, development in general (including basements), should have internal stair access to an area of safe refuge within the building to a level higher than the maximum likely water level. An area of safe refuge should be sufficient in size for all potential users and be reasonably accessible to the emergency services.

Emergency evacuation from the development and the Site should only be undertaken in strict accordance with any evacuation plans produced for the Site, with an understanding of the flood risks at the Site including available mitigation, the vulnerability of occupants and preferred evacuation routes.

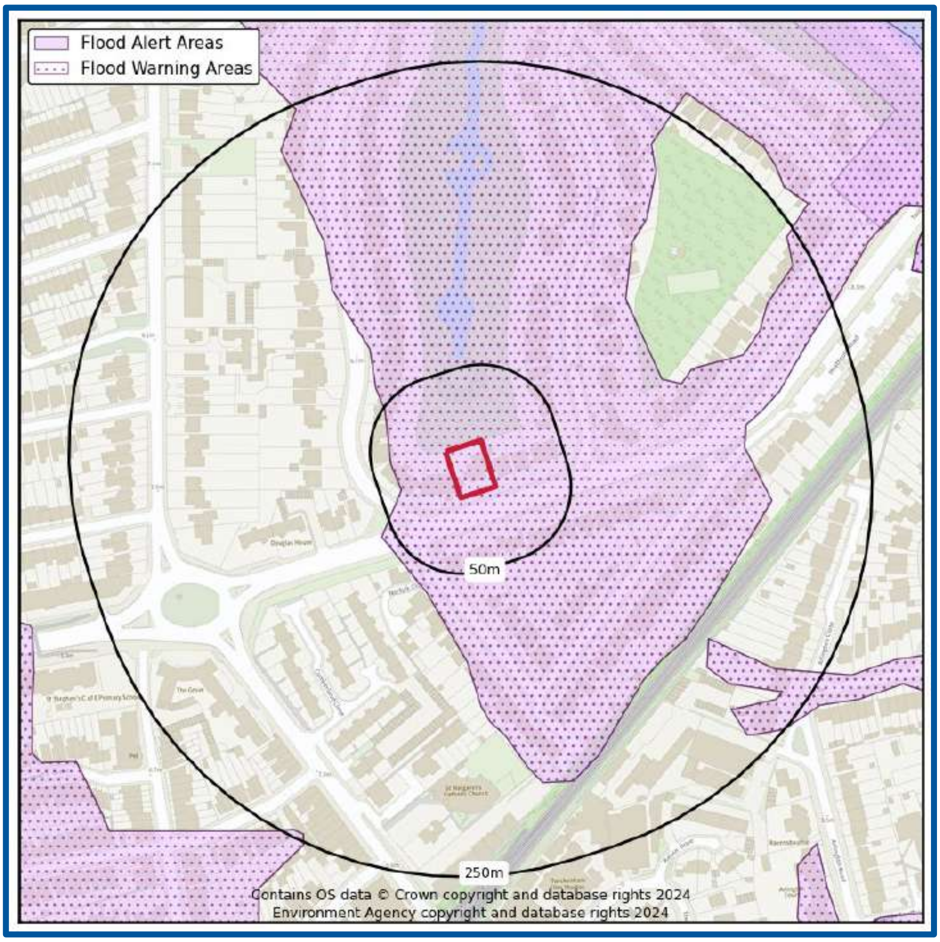
Flood warnings

The EA operates a flood warning service in all areas at risk of flooding; this is available on their website: https://www.gov.uk/check-flood-risk. The Site is located within an EA Flood Alerts/Warning coverage area (ref: 063FWT23Twicknhm and 063WAT231S, respectively) so is able to receive alerts and/or warnings (Figure 14). All warnings are also available through the EA's 24 hour Floodline Service 0345 988 1188.

The quick dial codes for the EA Flood Alerts/ Warnings are 174104 and 174105, respectively.

The EA aims to issue Flood Warnings 2 hours in advance of a flood event. Flood Warnings can provide adequate time to enable protection of property and evacuation from a Site, reducing risk to life and property.

Figure 13. EA Flood Warning Coverage for the local area (EA, 2024).



Emergency evacuation

Where possible, a safe access and egress route with a 'very low' hazard rating from areas within the floodplain to an area wholly outside the 1 in 100 year flood event including an allowance for climate change should be demonstrated.

Based on the EA's Flood Zone Map the closest dry evacuation area within Flood Zone 1 is along The Avenue (c.65 m south west – direct measurement). It is advised that evacuation from the premises would be the preferred option in a flood event if safe to do so. It is recommended that residents prepare to evacuate as soon as an EA Flood Warning is issued in order to completely avoid flood waters.

On-Site refuge

Evacuation should be the primary action in preference, however safe refuge could be sought at first floor level in a worst-case scenario as the residential areas of the development are situated on the first and second floor.

Other relevant information

A Flood Warning and Evacuation Plan (FWEP) is recommended, and occupants should be signed up to receive EA's Flood Alerts and/or Warnings.

Registration to the Environment Agency's flood warning scheme can be done by following this link: https://www.gov.uk/sign-up-for-flood-warnings.

It is recommended that main communication lines required for contacting the emergency services, electricity sockets/meters, water supply and first aid stations and supplies are not compromised by flood waters. Where possible these should all be raised above the extreme flood level.

8. Conclusions and recommendations

Table 3. Risk ratings following Site analysis

Source of Flood Risk	Baseline[1]	After analysis[2]	After Mitigation[3]
River (fluvial) flooding	Very Low		Very Low
Sea (coastal/tidal) flooding	Very Low		Very Low
Surface water (pluvial) flooding	Very Low to Low		Very Low
Groundwater flooding	Negligible to Low	Low	Negligible
Other flood risk factors present	Yes (reservoirs)		N/A
Is any other further work recommended?	Yes (see below)		

1 BASELINE risks assigned for the whole Site, using national risk maps, including the benefit of EA flood defences.

2 AFTER ANALYSIS modification of risk assessment based on detailed site specific analysis including some or all of the following: flood model data, high resolution mapping, building location, access routes, topographic and CCTV surveys. Reasons for the change in classification are provided in the text.

3 AFTER MITIGATION risks include risks to proposed development / asset and occupants if mitigation measures recommended in this report are implemented, including the impacts of climate change.

*N/A indicates where mitigation is not required.

The table below provides a summary of where the responses to key questions are discussed in this report. Providing the recommended mitigation measures are put in place it is likely that flood risk to this Site will be reduced to an acceptable level.

More vulnerable developments in a Flood Zone 3 are acceptable according to the NPPF and providing the recommended mitigation measures are put in place (see previous sections) it is likely that flood risk to this Site will be reduced to an acceptable level.

Table 4. Summary of responses to key questions in the report

Key sources of flood risks identified	Pluvial and tidal (see Section 4).

Are standard mitigation measures likely to provide protection from flooding to/from the Site?	Yes (see Section 7).
Is any further work recommended?	Yes (See exec summary and section 7)

9. Further information

The following table includes a list of additional products by GeoSmart:

Additional GeoSmart Products			
	Additional assessment: EnviroSmart Report		Provides a robust desk-based assessment of potential contaminated land issues, taking into account the regulatory perspective. Our EnviroSmart reports are designed to be the most cost effective solution for planning conditions. Each report is individually prepared by a highly experienced consultant conversant with Local Authority requirements. Ideal for pre-planning or for addressing planning conditions for small developments. Can also be used for land transactions. Please contact info@geosmartinfo.co.uk for further information.

10. References and glossary

References

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Glossary

General terms

BGS	British Geological Survey
EA	Environment Agency
GeoSmart groundwater flood risk model	GeoSmart's national groundwater flood risk model takes advantage of all the available data and provides a preliminary indication of groundwater flood risk on a 50m grid covering England and Wales. The model indicates the risk of the water table coming within 1 m of the ground surface for an indicative 1 in 100 year return period scenario.
Dry-Island	An area considered at low risk of flooding (e.g. In a Flood Zone 1) that is entirely surrounded by areas at higher risk of flooding (e.g. Flood Zone 2 and 3)
Flood resilience	Flood resilience or wet-proofing accepts that water will enter the building, but through careful design will minimise damage and allow the re-occupancy of the building quickly. Mitigation measures that reduce the damage to a property caused by flooding can include water entry strategies, raising electrical sockets off the floor, hard flooring.
Flood resistance	Flood resistance, or dry-proofing, stops water entering a building. Mitigation measures that prevent or reduce the likelihood of water entering a property can include raising flood levels or installation of sandbags.
Flood Zone 1	This zone has less than a 0.1% annual probability of river flooding
Flood Zone 2	This zone has between 0.1 and 1% annual probability of river flooding and between 0.1% and 0.5 % annual probability sea flooding
Flood Zone 3	This zone has more than a 1% annual probability of river flooding and 0.5% annual probability of sea flooding
Functional Flood Plain	An area of land where water has to flow or be stored in times of flood.
Hydrologic model	A computer model that simulates surface run-off or fluvial flow. The typical accuracy of hydrologic models such as this is ±0.25m for estimating flood levels at particular locations.

OS	Ordnance Survey
Residual Flood Risk	The flood risk remaining after taking mitigating actions.
SFRA	Strategic Flood Risk Assessment. This is a brief flood risk assessment provided by the local council
SuDS	A Sustainable drainage system (SuDS) is designed to replicate, as closely as possible, the natural drainage from the Site (before development) to ensure that the flood risk downstream of the Site does not increase as a result of the land being developed. SuDS also significantly improve the quality of water leaving the Site and can also improve the amenity and biodiversity that a Site has to offer. There are a range of SuDS options available to provide effective surface water management that intercept and store excess run-off. Sites over 1 Ha will usually require a sustainable drainage assessment if planning permission is required. The current proposal is that from April 2014 for more than a single dwelling the drainage system will require approval from the SuDS Approval Board (SABs).

Aquifer Types

Principal aquifer	These are layers of rock or drift deposits that have high intergranular and/or fracture permeability - meaning they usually provide a high level of water storage. They may support water supply and/or river base flow on a strategic scale.
Secondary A aquifer	Permeable layers capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers.
Secondary B aquifer	Predominantly lower permeability layers which may store and yield limited amounts of groundwater due to localised features such as fissures, thin permeable horizons and weathering.
Secondary undifferentiated	Has been assigned in cases where it has not been possible to attribute either category A or B to a rock type due to the variable characteristics of the rock type.
Unproductive Strata	These are rock layers or drift deposits with low permeability that has negligible significance for water supply or river base flow.

NPPF (2023) terms

Exception test	Applied once the sequential test has been passed. For the exception test to be passed it must be demonstrated that the development provides wider sustainability benefits to the community that outweigh flood risk and a site-specific FRA must demonstrate that the development will be safe for its lifetime taking account of the

	vulnerability of its users, without increasing flood risk elsewhere, and, where possible, will reduce flood risk overall.
Sequential test	Aims to steer new development to areas with the lowest probability of flooding.
Essential infrastructure	Essential infrastructure includes essential transport infrastructure, essential utility infrastructure and wind turbines.
Water compatible	Water compatible land uses include flood control infrastructure, water-based recreation and lifeguard/coastal stations.
Less vulnerable	Less vulnerable land uses include police/ambulance/fire stations which are not required to be operational during flooding and buildings used for shops/financial/professional/other services.
More vulnerable	More vulnerable land uses include hospitals, residential institutions, buildings used for dwelling houses/student halls/drinking establishments/hotels and sites used for holiday or short-let caravans and camping.
Highly vulnerable	Highly vulnerable land uses include police/ambulance/fire stations which are required to be operational during flooding, basement dwellings and caravans/mobile homes/park homes intended for permanent residential use.

Data Sources

Aerial Photography	Contains Ordnance Survey data © Crown copyright and database right 2024 BlueSky copyright and database rights 2024
Bedrock & Superficial Geology	Contains British Geological Survey materials © NERC 2024 Ordnance Survey data © Crown copyright and database right 2024
Flood Risk (Flood Zone/RoFRS/Historic Flooding/Pluvial/Surface Water Features/Reservoir/ Flood Alert & Warning)	Environment Agency copyright and database rights 2024 Ordnance Survey data © Crown copyright and database right 2024
Flood Risk (Groundwater)	GeoSmart, BGS & OS GW5 (v2.4) Map (GeoSmart, 2024) Contains British Geological Survey materials © NERC 2024

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Location Plan	Contains Ordnance Survey data © Crown copyright and database right 2024
Topographic Data	OS LiDAR/EA Contains Ordnance Survey data © Crown copyright and database right 2024 Environment Agency copyright and database rights 2024

11. Appendices

GeoSmart Information

Appendix A

Site plans

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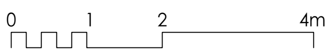

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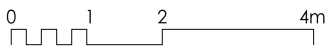

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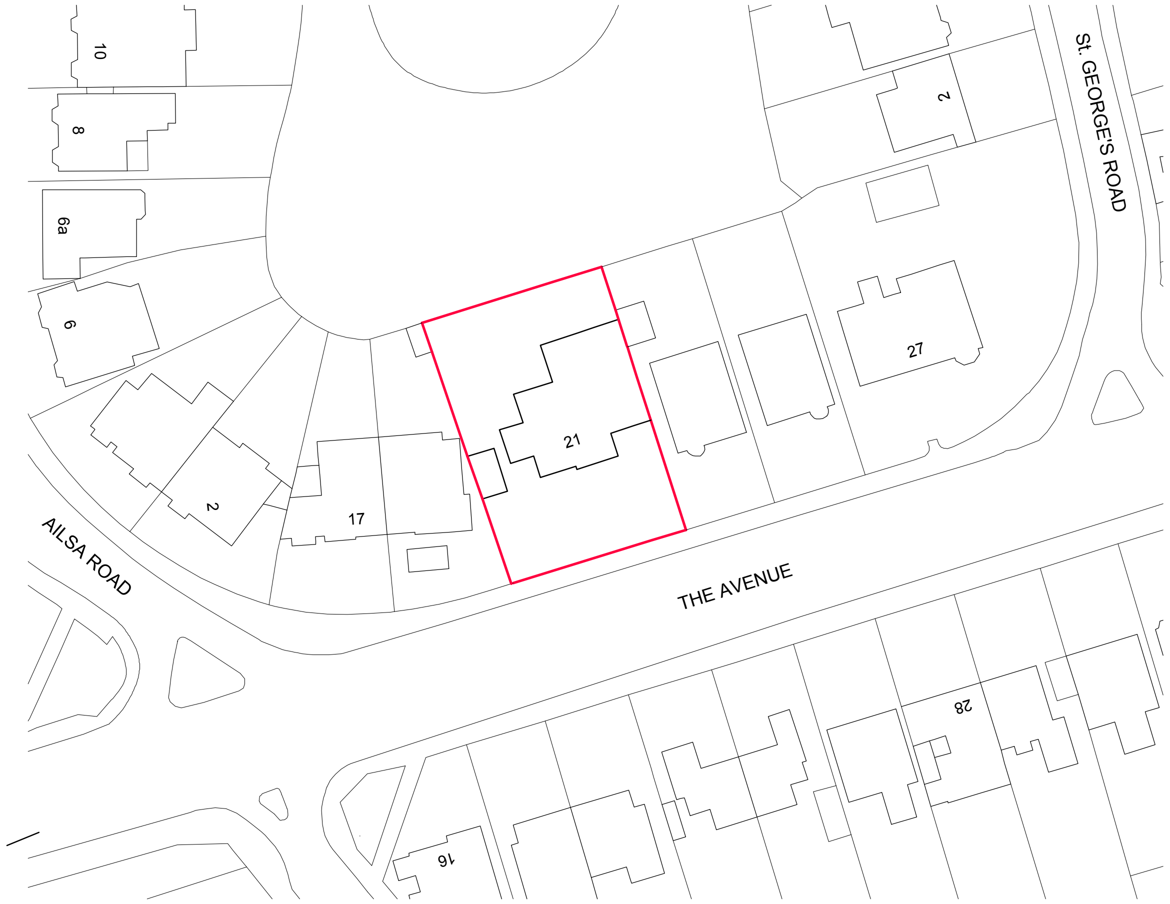

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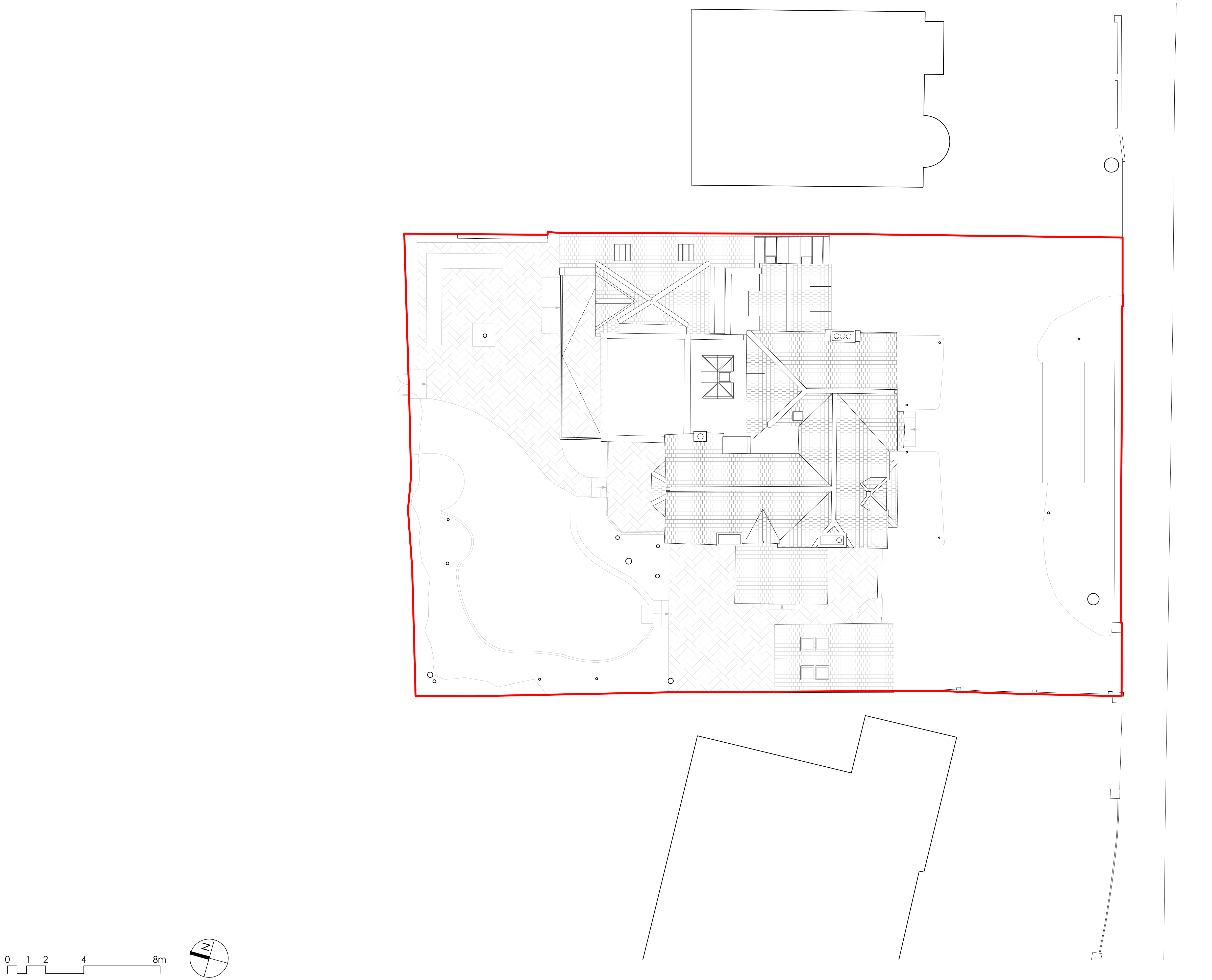

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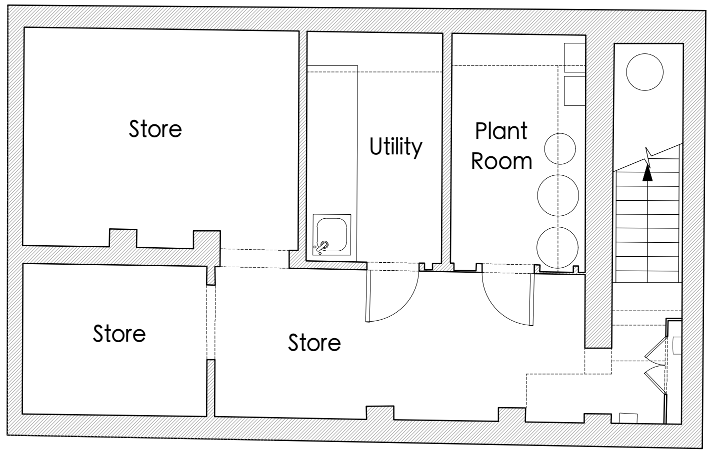

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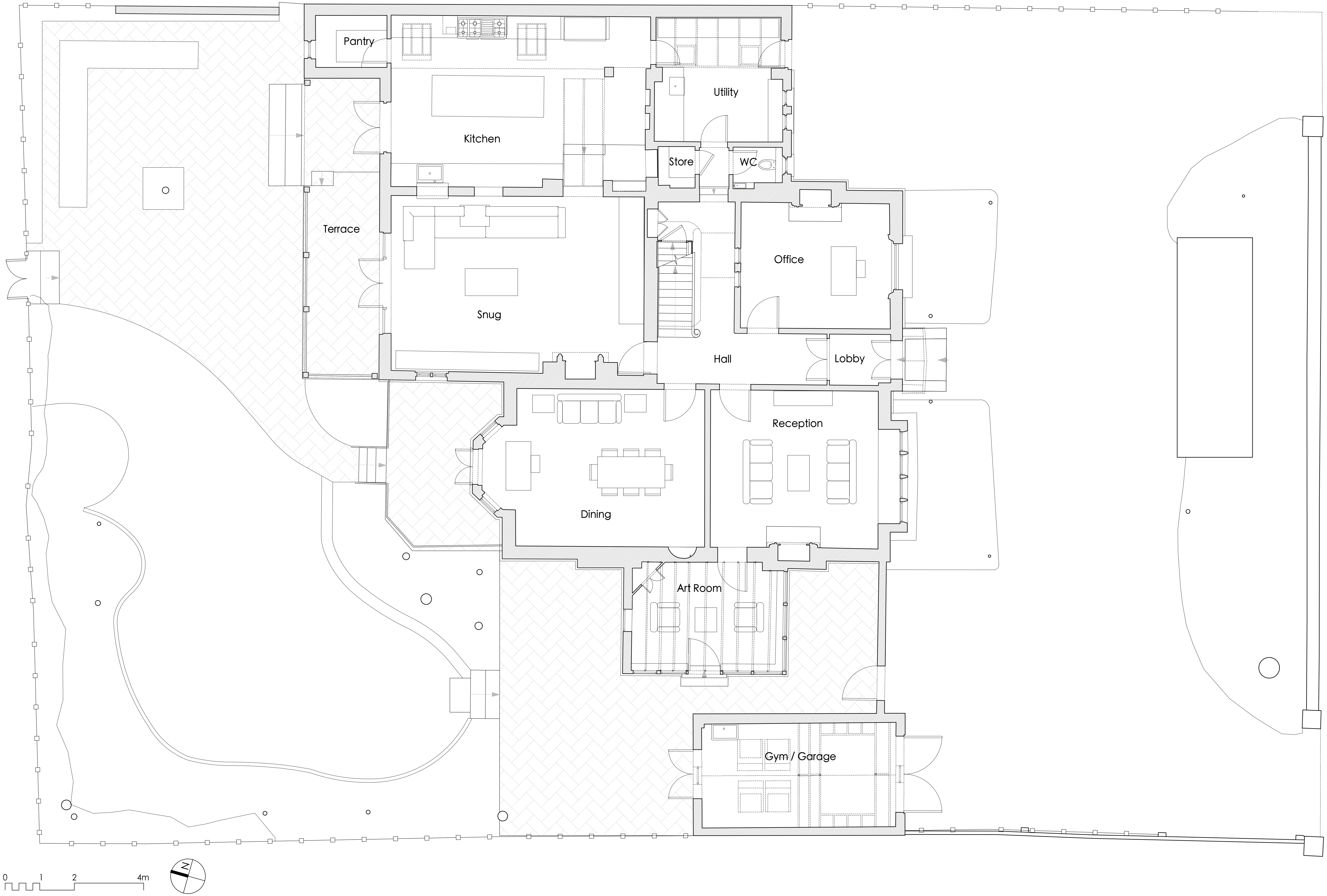

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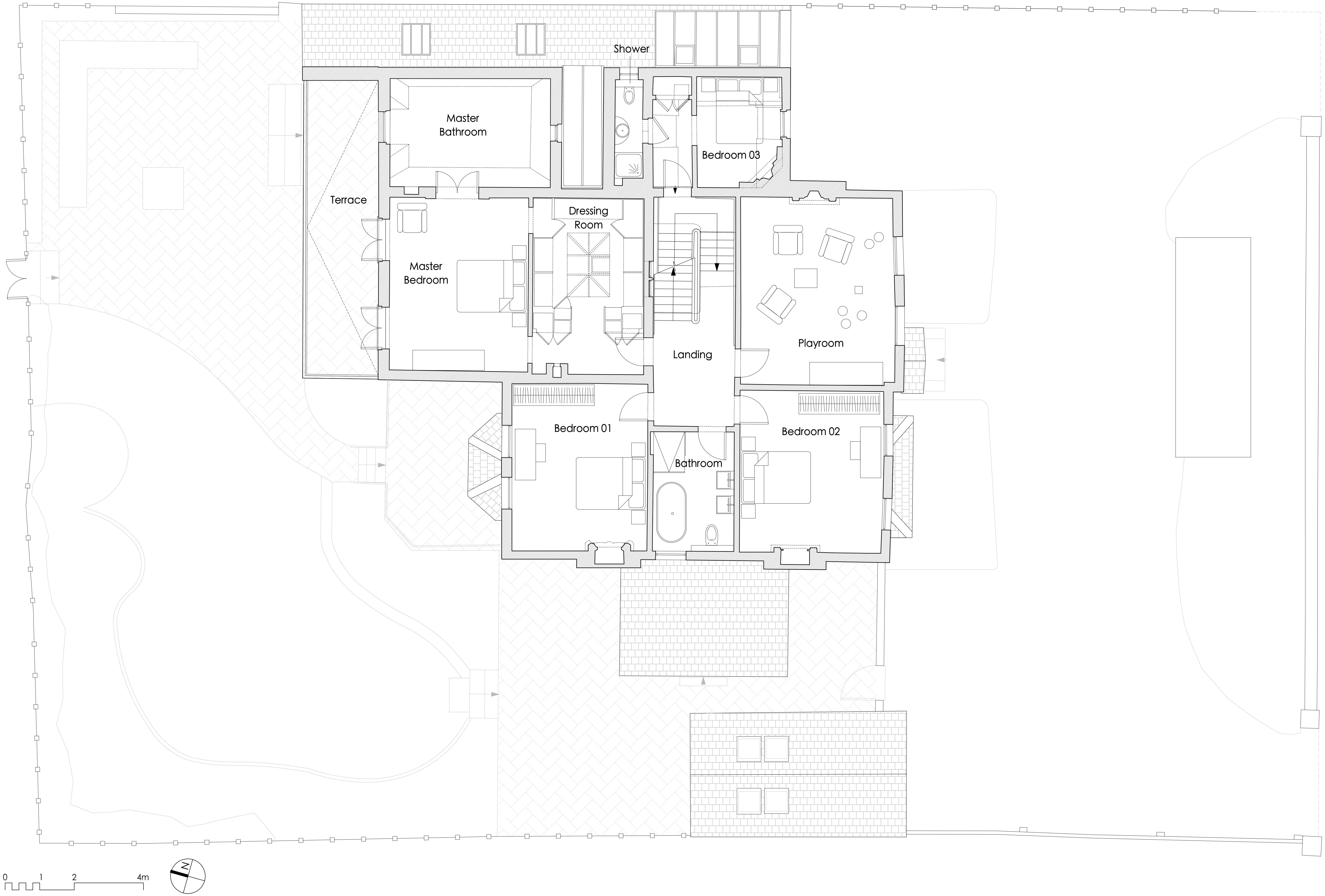

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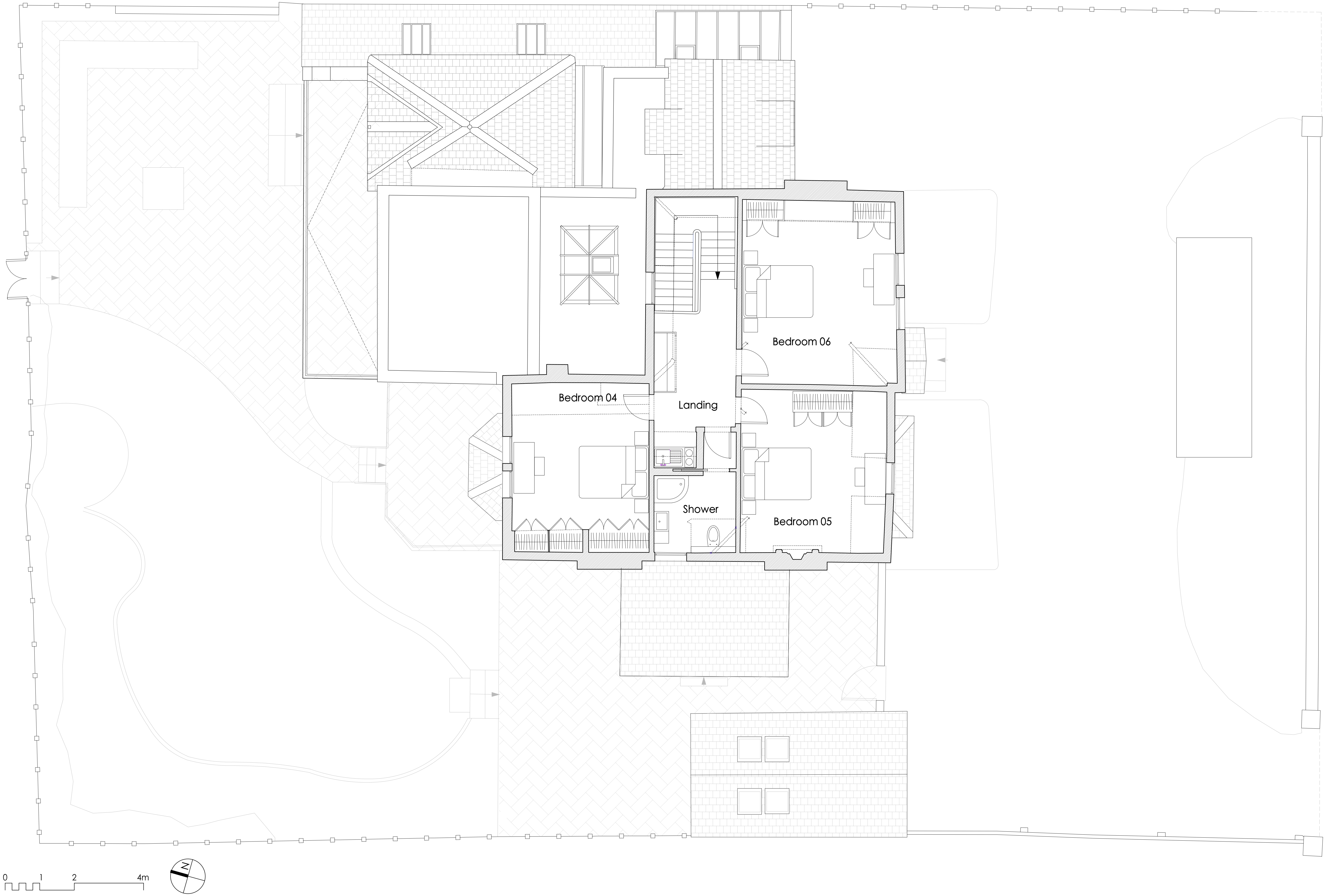

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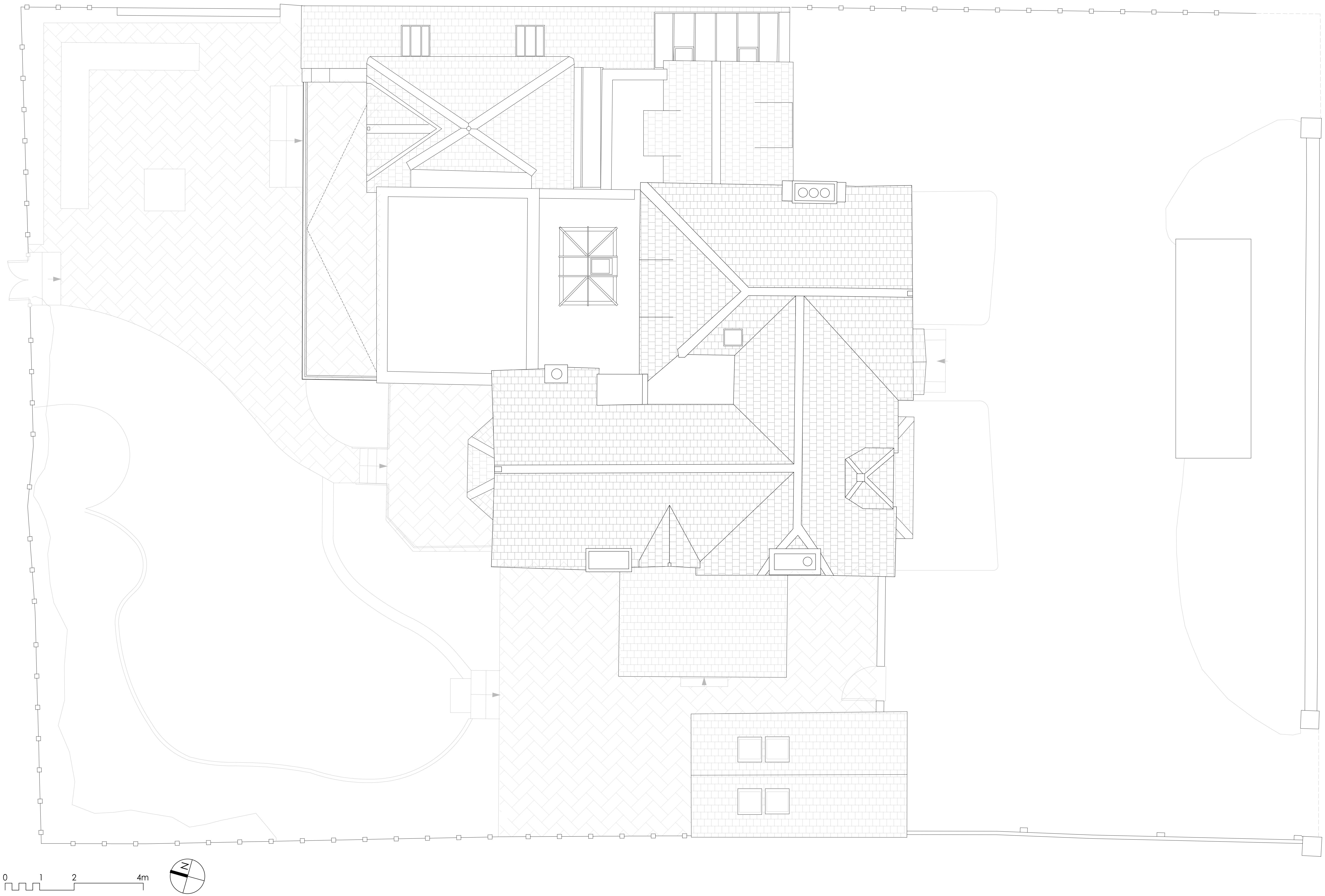

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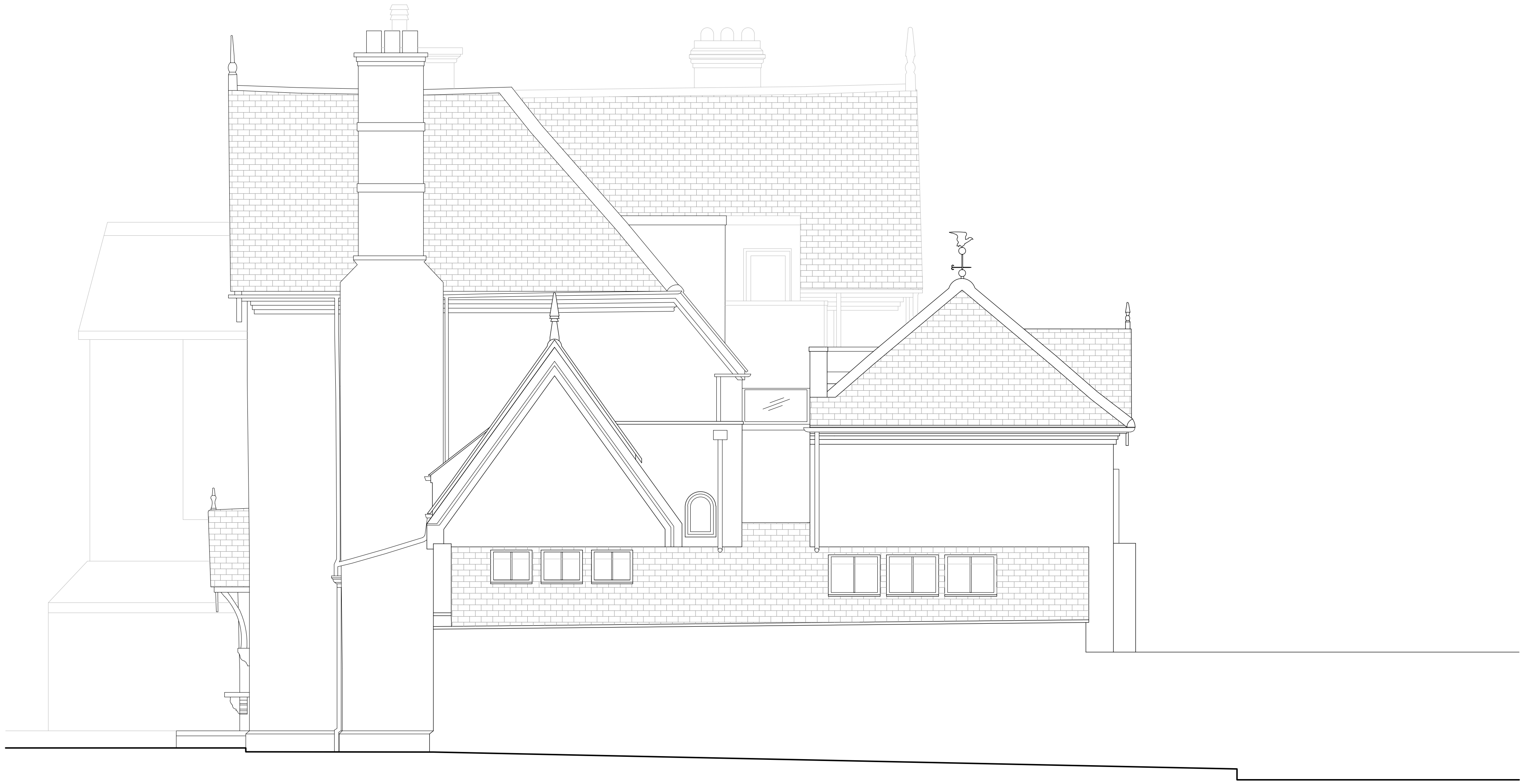

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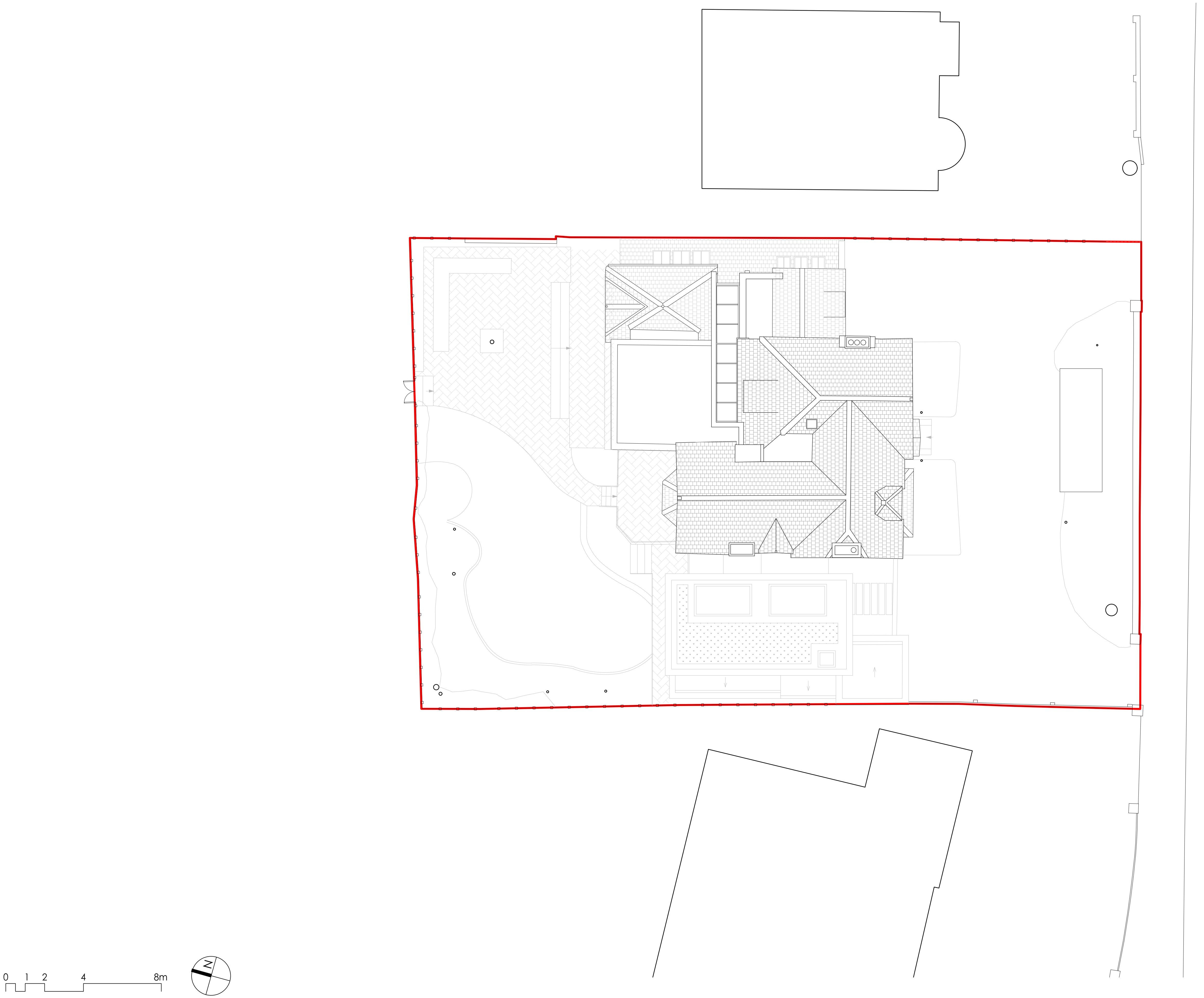

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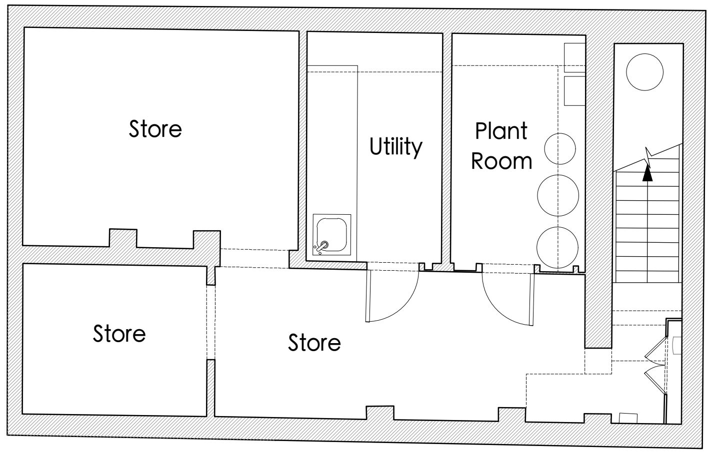

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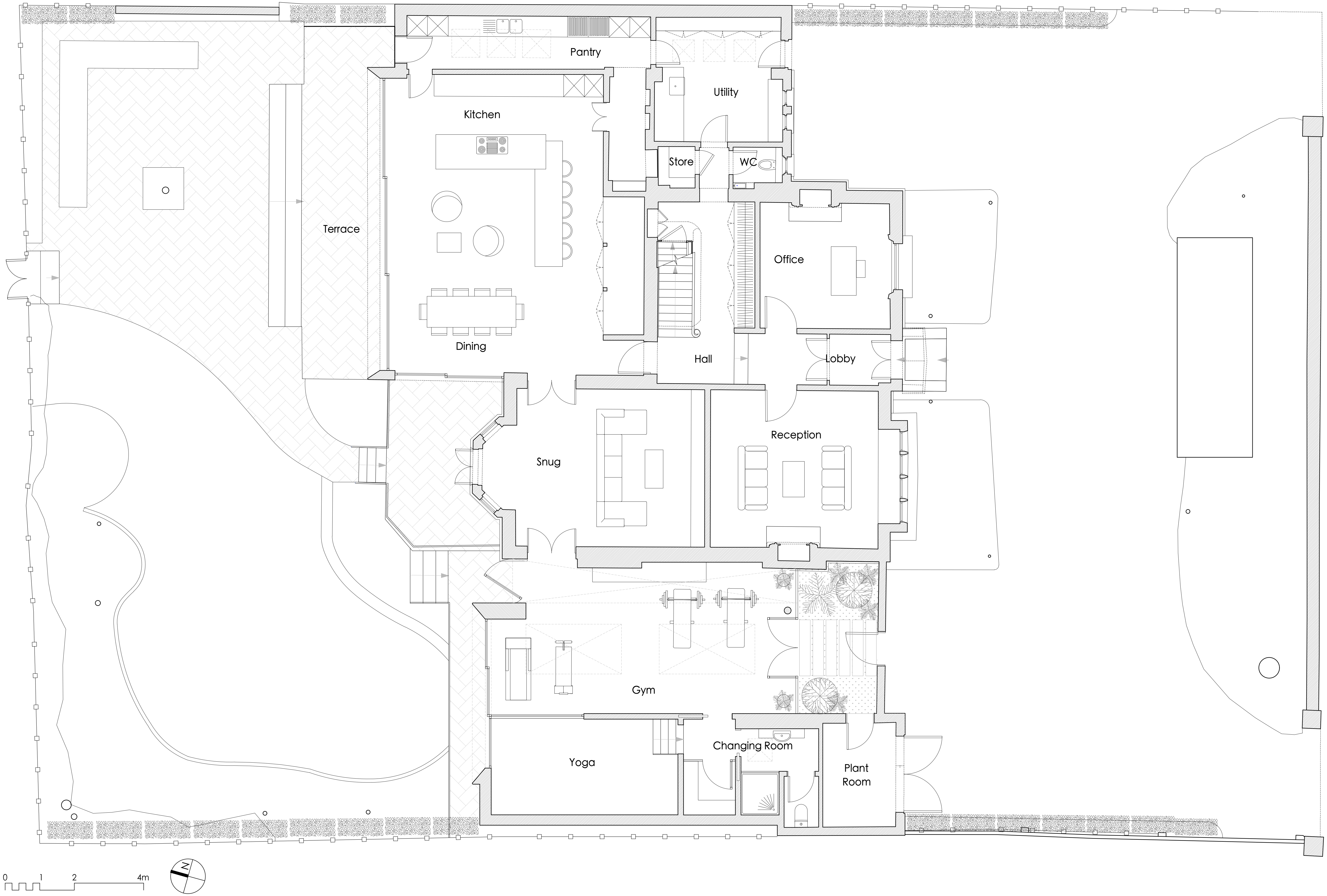

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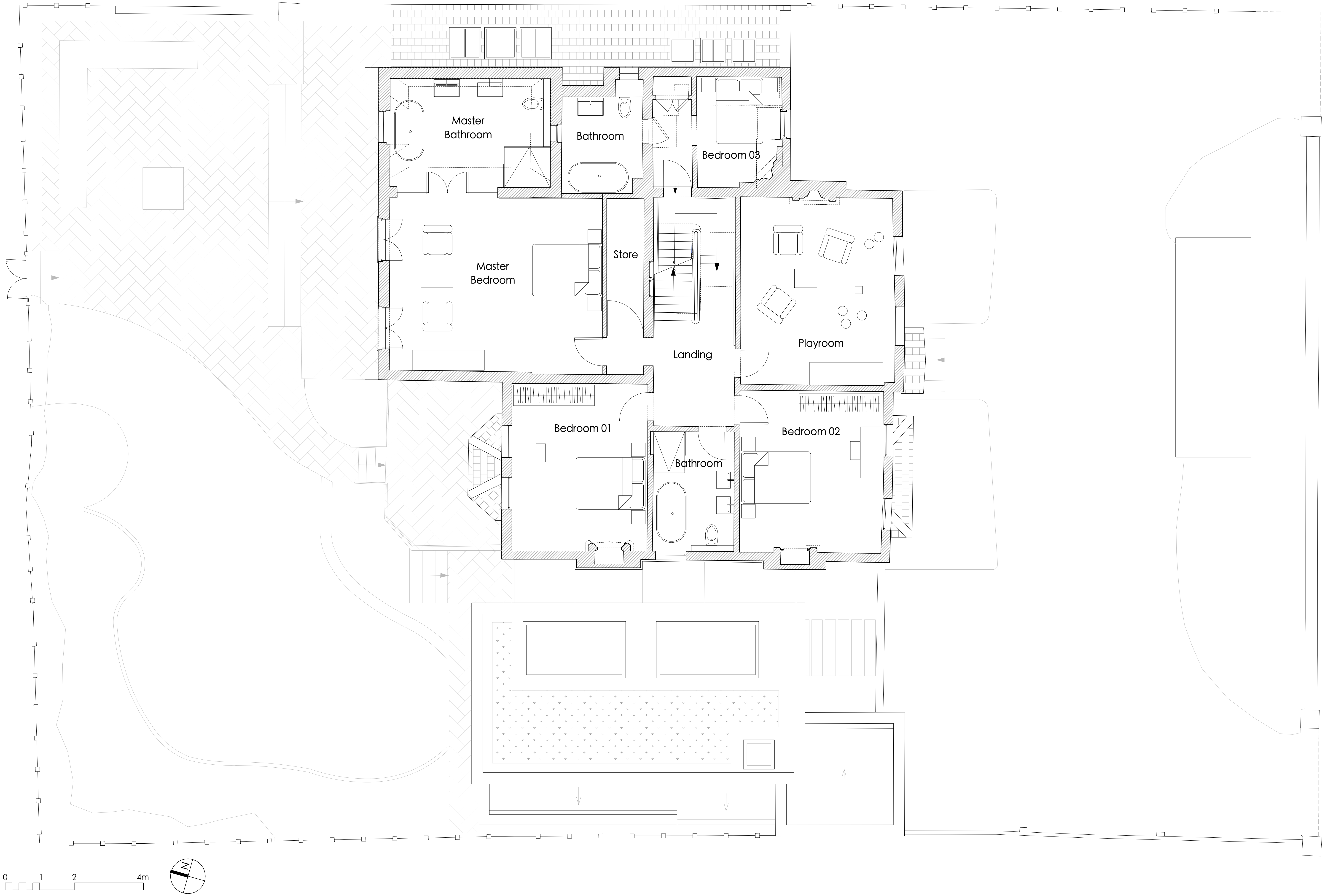

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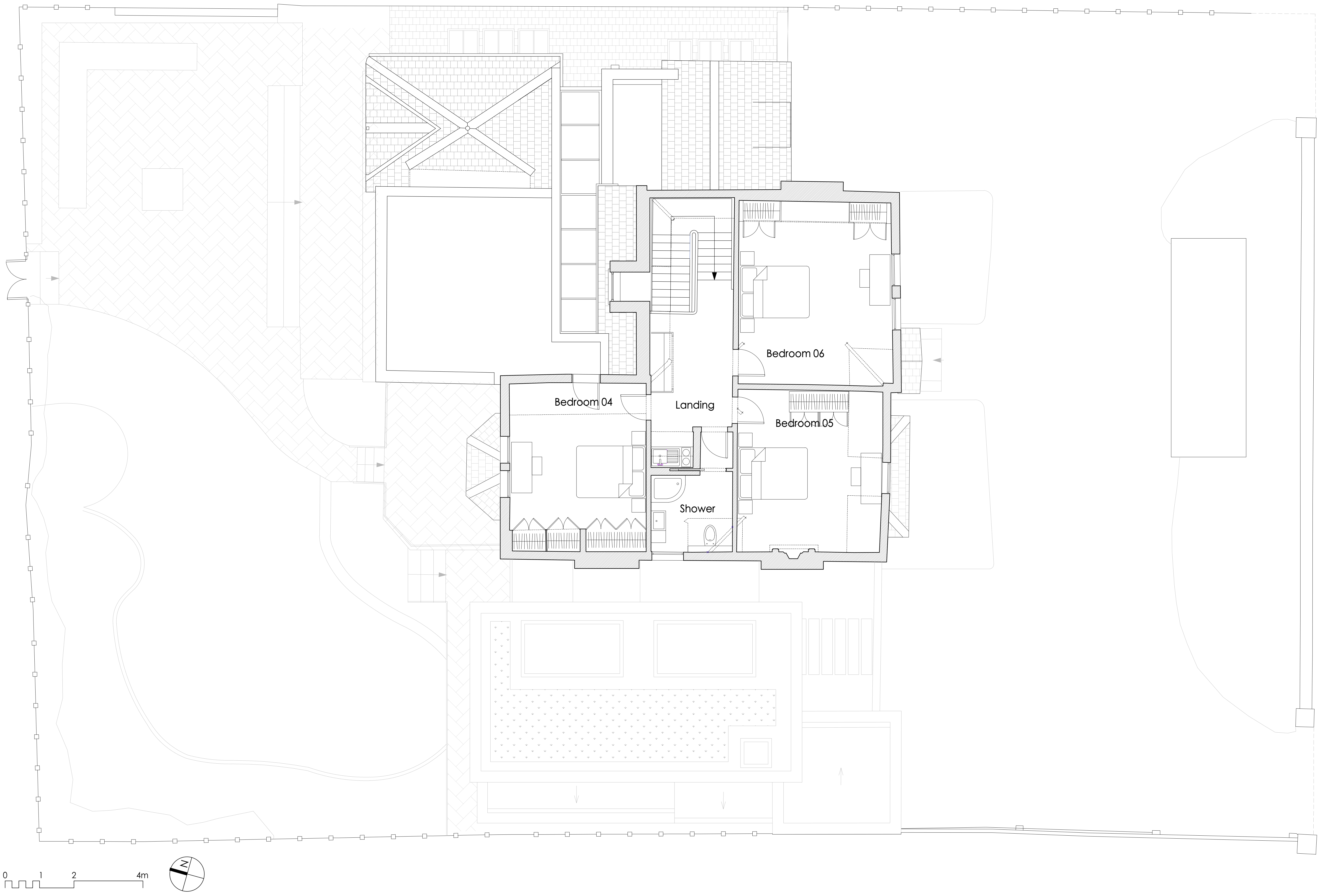
job title	21 The Avenue, Twickenham
client	Gavin & Linzi Hardcastle-Jones
drawing title	Proposed First Floor Plan
drawing number	1964.03.03.Pln01.023
rev	----
scale	1:100
date	Oct 2024
drawn by	VG
checked by	IP



revisions

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job title	21 The Avenue, Twickenham
client	Gavin & Linzi Hardcastle-Jones
drawing title	Proposed Second Floor Plan
drawing number	1964.03.03.Pln01.024
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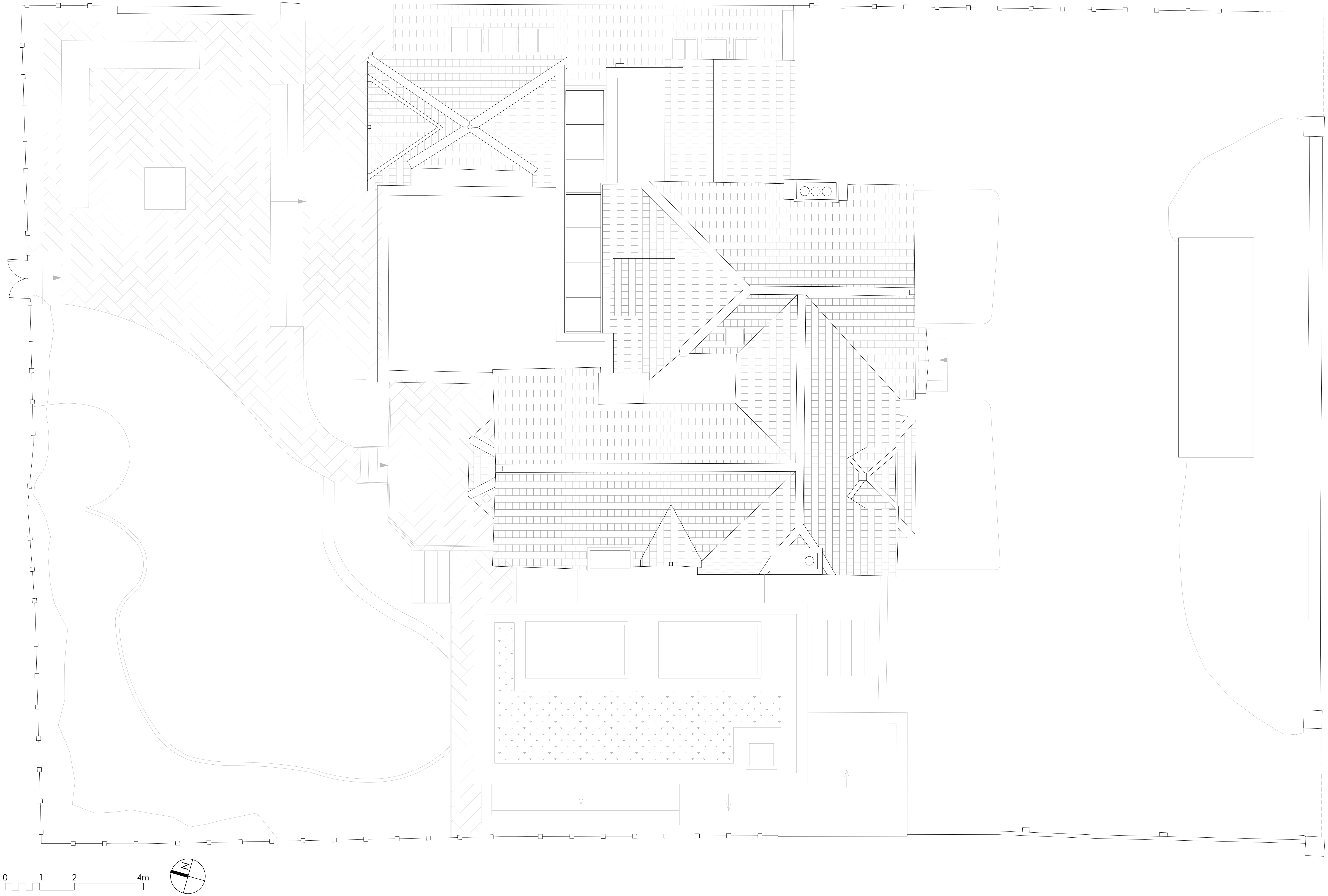

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job title
21 The Avenue, Twickenham

client
Gavin & Linzi Hardcastle-Jones

drawing title
Proposed Roof Plan

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rev
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GeoSmart Information

Appendix B

Environment Agency data

Thames Tidal Upriver Breach Inundation Assessment

Methodology Report

Environment Agency

May 2017

Contains *private* information

Notice

This document and its contents have been prepared and are intended solely for Environment Agency's information and use in relation to the Thames Tidal Upriver Breach Inundation Assessment

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This document has 23 pages including the cover.

Document history

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Revision	Purpose description	Originated	Checked	Reviewed	Authorised	Date
Rev 1.0	Issue	Rob Fulton	Rob Millington	Adam Schofield	Adam Schofield	05/05/17
Rev 2.0	Issue	Rob Fulton		Rob Millington	Adam Schofield	23/06/17

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Figures

1. Introduction

1.1. Background

London is a city that is constantly growing, and having a streamlined planning process to enable safe development is key to ensuring its sustainable growth. Any proposed development located within the Environment Agency's Flood Zone 2 and 3 needs to demonstrate that it has considered the flood risk to the development site. This evidence is expected to be provided within a Flood Risk Assessment, which considers all sources of flooding, to prove there will be no increase in flood risk to the site or elsewhere. A significant amount of London is sited on the floodplain of the River Thames, and therefore located within Flood Zones 2 and 3. The source of this flood risk is from both fluvial and tidal sources, with many areas in London being at a greater risk from the tidal source.

London benefits from a significant number of defences, which include the Thames Barrier and flood defence embankments upriver of the Barrier. With the combination of these defences, London receives a high standard of protection (SoP) from fluvial and tidal flooding, and a large proportion is in an 'Area Benefiting from Defence' (ABD). Within these areas, the risk of fluvial and tidal flooding is low, which enables certain development types to be constructed.

As noted however, all sources of flooding need to be considered and there is a residual risk of failure of a flood defence asset. If a failure were to occur during a flood event, the impacts could be devastating resulting in rapid inundation and extensive flooding. The residual risk of a breach of the defences therefore must be considered within a site-specific Flood Risk Assessment (FRA) for any proposed development.

The Environment Agency reviews hundreds if not thousands of Flood Risk Assessments on an annual basis within London. A significant proportion of these need to consider the residual risk of a breach, as they are within Flood Zones 2 or 3 and in an area benefitting from a defence. It would not be practical to either request every developer to undertake their own individual breach modelling, or review every model that would have to be provided alongside an FRA. As a result of this, breach modelling has previously been commissioned by the Environment Agency to quantify the results of a breach at key locations along the Thames defences. These locations were pre-defined as, at the time of the previous studies, model run times were around 6 hours per scenario and it was not practical to model every individual location. As a result, that only specific areas in London have had quantification of the results of a breach of the defences.

A separate study was commissioned by the Environment Agency to provide a maximum flood extent for London so that areas at risk were not missed. This study applied an Upstream Inundation Mapping (UIM) methodology based on removing all the flood defence embankments along the River Thames in London, which allowed a significant volume of water to spill out of the River Thames and onto the floodplain. Further details in relation to this study area available in the UIM modelling report (CH2M, 2015). Due to the methodology applied in the Upstream Inundation Modelling study, maximum flood extents and levels are generally significantly greater when compared to the existing breach modelling.

Using the existing breach modelling and UIM studies, the Environment Agency provide site specific flooding information to developers in the format of a Product 4 request. A developer will be expected to use this information to inform their site specific FRA and to allow the residual risk of a breach to be mitigated (by for example increasing finished floor levels above the maximum breach level). Queries and concerns however can arise during this process, specifically when the site is located outside of a modelled breach extent. Where developments are located outside on an existing modelled breach extent, the next best available data is the UIM. The EA will recommend using information from the UIM where a breach extent is not available, as only a limited number of breach locations have been modelled. The peak flood levels and extents are generally greater in the UIM compared to breach mapping, by up to 2 metres. This can lead to recommendations of finished floor levels for proposed developments to be unrealistically high. If a breach extent assessment was available the recommended level would be lower.

This discrepancy was noted by numerous members of the Environment Agency South East London and North Kent, and South West London and Mole Partnership and Strategic Overview (PSO) teams. A solution was proposed where all breach locations along the Thames are equitably modelled, to ensure a consistent approach across London. This study has completed breach modelling at every location between Teddington Weir and the Thames Barrier. Recent technological advancements in hydraulic modelling and computer GPU processing speed have been exploited to enable this. The objectives of this study are listed below, and the study area of where the breach modelling has been undertaken is in Figure 2-1 below.

1.2. Objectives

The objectives of the Thames Tidal Upriver Breach Inundation Assessment study are as follows:

- Model individual breaches of the Thames defence line, to cover the entire extent between Teddington Weir and the Thames Barrier (see Figure 2-1 below);
- Use the previous Thames Tidal Breach Modelling Study (CH2M, 2015) as a framework to inform the methodology of an individual breach taken in this study;
- Undertake breach modelling for 2 epochs to consider current and future hydrological conditions of the River Thames, namely the 2005 and 2100 epochs;
- Use computer scripting and GIS data processing to automate the generation of breach scenarios;
- Use computer scripting to automatically simulate the individual breach scenarios and export the outputs to include maximum flood extent, depth, hazard and velocity for each breach scenario; and
- Combine the individual breach scenario outputs to generate a single maximum flood extent, depth, hazard and velocity outputs that can be used for future planning in London.

The tidal influence along the River Thames dominates for a large proportion of London including the study area for this assessment. The defences in London are designed for extreme tidal events and have not been designed against extreme fluvial events. In areas such as Teddington therefore, there are areas where fluvial flooding is dominant and areas are not benefitting from a defence, as the fluvial flood will overtop the existing defences. Breach modelling has still been undertaken in these locations as agreed with the Environment Agency, considering the future plans for defence crest raising along the Thames. This study therefore refers to the tidal defences between Teddington Weir and the Thames Barrier.

1.3. This report

This report describes the work undertaken to develop a modelling framework to automatically generate and simulate individual breaches of the Thames tidal defences, between Teddington Weir and the Thames Barrier. This report outlines the methods that were used, the results and provides recommendations for future applications of the work including what opportunities the outputs bring.

2. Study Area

The study area of this project is shown in Figure 2-1, which highlights the extent of Thames tidal defence line considered in the breach modelling. The extent is from Teddington Weir (considering defences both sides of the Thames) down to the Thames Barrier. The study considers the impact of a breach occurring during a tidal event, between the Thames Barrier and the upriver tidal limit at Teddington Weir. The Thames Barrier is a flood defence structure that prevents tidal surges from flowing upriver along the Thames at times of high flow / forecast flood events. Downriver of Thames Barrier there is no protection from incoming tidal surges, and so the resulting probabilities of flooding are treated differently than upriver of the Barrier.

The tidal extents of the incoming tributaries of the River Thames (e.g. River Wandle, Ravensbourne etc.) have also been included in the breach modelling. These extents were identified using Ordnance Survey mapping and identifying the control structures along the respective tributaries that limit the tidal extents.

Figure 2-1 Study area for the breach modelling undertaken as part of this assessment: Teddington Weir to the Thames Barrier inclusive, including the tidal extents of the incoming tributaries between these structures.

3. Available Data

3.1. Introduction

This section of the report describes and outlines the data that was available to develop the InfoWorks ICM breach model. InfoWorks ICM is the modelling system developed by Innovyze for integrated catchment modelling, which includes fluvial, pipe and floodplain drainage. The following data were obtained for this assessment:

- LiDAR terrain data;
- TE2100 Maximum Likely Water Level (MLWL) hydrographs;
- Ordnance Survey MasterMap© Data (OSMM); and
- Thames Tidal Defence Line.

3.2. LiDAR terrain data

Light detection and ranging (LiDAR) data at 1m resolution was downloaded in November 2016 from the Environment Agency data share catalogue (Environment Agency, 2017). This LiDAR information has a vertical height accuracy of +/- 15cm and a horizontal accuracy of +/- 40cm. Further information on the LiDAR accuracy is available in the Environment Agency LiDAR data Technical Note (Environment Agency, 2016). A review of the LiDAR was undertaken, including a check against the prior DTM that was used as part of the Thames Tidal Breach Modelling Study (CH2M, 2015) to ensure gaps under bridges etc. were represented within the digital terrain model (DTM) within the ICM. The extent of the 1D LiDAR data covered the entire study catchment, ensuring a full representation of the modelled breach flood extents.

3.3. TE2100 Maximum Likely Water Level hydrographs

Thames Tidal water level profiles were obtained from the existing Thames 1D ISIS River Model (version 11), covering the extent from Teddington Weir down to the Thames Barrier. An extract from the Thames Tidal Breach Modelling Study (CH2M, 2015) is provided below that provides a summary of the methodology for these water level profiles:

> *Tide profiles are generated along the estuary using a separate 1D model (the Thames Barrier's operational model – version 11). The model has a fluvial flow-time (QT) boundary just upstream of Teddington and a tidal head-time (HT) boundary at Southend-on-Sea. The fluvial QT boundary is a constant (steady state) inflow, with the discharge depending upon the scenario being modelled (see below). A steady state fluvial flow is considered to be a reasonable assumption, as any change in flow over a 24 hour period at Teddington is generally gradual, reflecting the size of the catchment at this point (c. 10,000 km^2). The tidal HT boundary is unsteady, meaning that the flood and ebb of each tide are dynamically modelled.*
>
> *The HT boundary is prepared using a spreadsheet called the 'extreme tide generator'. The spreadsheet is the same as that applied to the TE2100 modelling, and combines a Mean High Water Spring (MHWS) tide with a scaled 1953 surge to achieve the target water level at Southend.*
>
> *Once the 1D model has been run for each scenario (see below), the resulting tidal hydrographs are scaled to match the TE2100 peak water levels along the Thames Estuary, to ensure an exact match. The exception is for the 1 in 200 year water levels downriver of the Thames Barrier, as TE2100 did not publish these water levels, so they have been generated using a 1 in 200 year boundary at Southend, but with no subsequent scaling (as there are no TE2100 levels to match exactly to). Where they existed, the Environment Agency provided the TE2100 water levels, referring in turn to the 'B0' results reported in table A1 of the TE2100 report "EX6158-Implementation Guidance_R2-0.pdf".*
>
> *Note also that the 2065 Southend Boundary was interpolated from the TE2100 2050 and 2080 boundaries, as reported in Table A1 within 'TN_Model_Boundaries.doc' (see Appendix F).*
>
> ***Model boundaries upstream of the Thames Barrier***
>
> *Upstream of the Thames Barrier, three combinations of flow and tide are modelled to create 'maximum likely water levels' for each model node between Teddington Weir (node 2.1) and the Thames Barrier (node 2.49). This approach considers the imposition of the barrier closure rule, which effectively limits*

the maximum water level that will be achieved upriver of the Thames Barrier. It is a simpler approach than the probabilistic modelling of upstream water levels that has been undertaken in the past, where the probability of the barrier closing (including uncertainty in the forecasts against which it operates) is calculated explicitly, but is consistent with the approach adopted by TE2100. The three combinations of flow and tide are:

- *Upstream of node 2.7 only; a 736 cumec flow with a 2.95mAOD tide at Southend.*
- *Downstream of 2.7 but upstream of the Thames Barrier; a 421 cumec flow with a 3.55m AOD tide.*
- *Downstream of 2.7 but upstream of the Thames Barrier a; 52 cumec flow with a 3.85m AOD tide.*

The three combinations are chosen because they are at the limit of the flow and tide conditions that would dictate closure of the Barrier, and have been shown by previous modelling to generate an aggregate maximum water level profile that is very close to the maximum water level profile produced by previous probabilistic methods.

For future scenarios (i.e. 2065 and 2100) the present day 2005 boundaries are used again, but scaled to fit with higher peaks, in accordance with the levels defined for each node by TE2100.

An example of a level hydrograph for node 2.23 is provided in Figure 3-1. The node IDs for the hydrographs have been renamed as part of this study, further details are provided in Section 4.2.1.

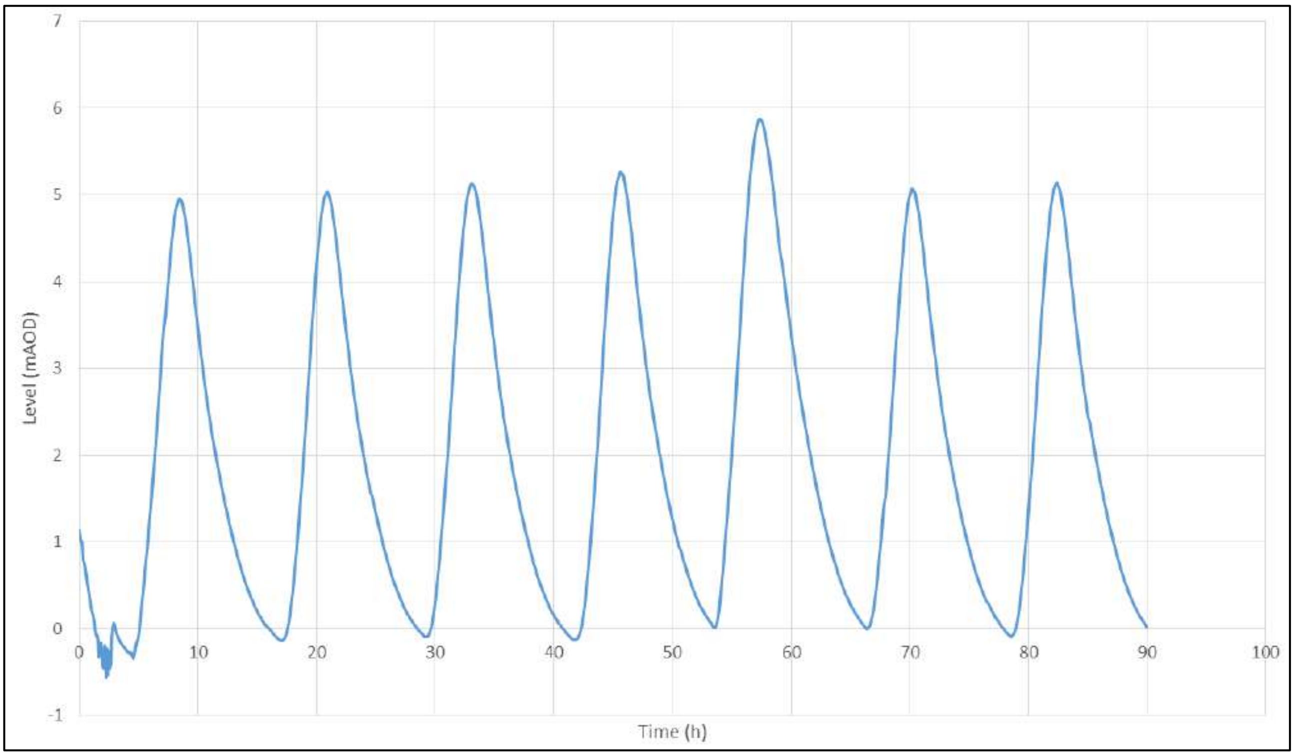

Figure 3-1 Level hydrograph for Node 2.23 (renamed as part of this study, see Section 4.2.1) for the 2100 epoch, showing the Maximum Likely Water Level (MLWL)

3.4. Ordnance Survey MasterMap©

Ordnance Survey MasterMap© (OSMM) data were obtained in ESRI shapefile format from the Environment Agency Partner Data Catalogue (Environment Agency, 2017). This data has been used to inform the building outlines for the hydraulic modelling, which is further described in Section 4.3.2.

3.5. Thames Tidal Defence Line

The NAFRA Thames Tidal defence line was obtained from the Environment Agency AIMS database in ESRI shapefile format. A detailed review of this defence line was undertaken against the LiDAR data and available aerial imagery, to ensure the line was located on the crest of the defences. Consultation was undertaken with the Environment Agency, including the issue of the final proposed defence line for review with the relevant

Environment Agency teams. Modifications were undertaken to the defence line, to ensure it fitted to the LiDAR data (so not to be located within the river at low ground levels) and gave a realistic representation of the defence crest. A shapefile of the final Thames Tidal defence line has been provided as part of this study.

4. Methodology

The following sections describe the methodology that was applied for the specific aspects of a breach scenario. The overall approach to the breach definition is presented first, followed by an explanation of how the relevant components were represented in the ICM. The Thames Tidal Breach Modelling Study (CH2M, 2015) methodology was used as a basis of defining an individual breach. Modifications however have been conducted when comparing to the original methodology, and the key changes are described in Section 4.5.

4.1. Breach definition

4.1.1. Breach width definition

The Thames Tidal defence line was used to define the breach locations. The defence line between Teddington Weir and the Thames Barrier was considered in the breach location definition (as shown in Figure 2-1). Firstly the defence line was split into 'hard' and 'soft' defence types, using the attribute definitions within the edited NAFRA Thames Tidal defence line. A hard defence was considered to be a concrete wall, embankment or similar, whilst a soft defence was considered to be an earth embankment. As per the previous methodology (CH2M, 2015), a hard defence was defined as a 20m wide breach, with a soft defence as a 50m wide breach.

Figure 4-1 below shows a section of the Thames tidal defences that were split into individual 20m lines; of which each 20m line will be breached individually.

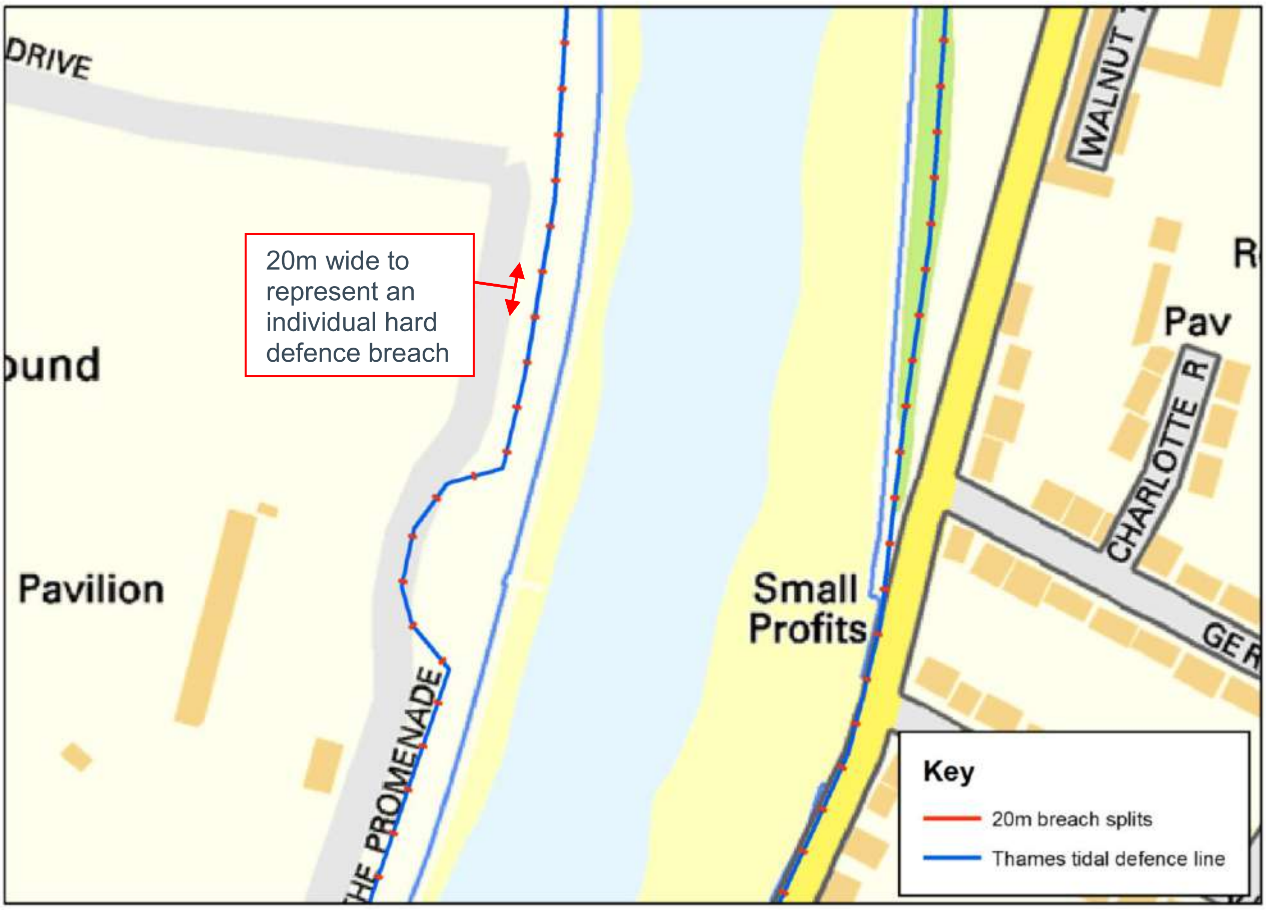

Figure 4-1 Individual 20m lines representing a breach width that will be individually modelled

Given that the hard and soft defence lines were not exact multiples of either 20m or 50m, there were residual lengths at the end of the defence lines, as shown in Figure 4-2. Where these short lines occurred, they were extended back to either 20m or 50m, so overlapping another breach line. This ensured consistency across the study area so that all breaches were either 20m or 50m wide (some edges were modified to fit the defence line so not precisely 20m or 50m).

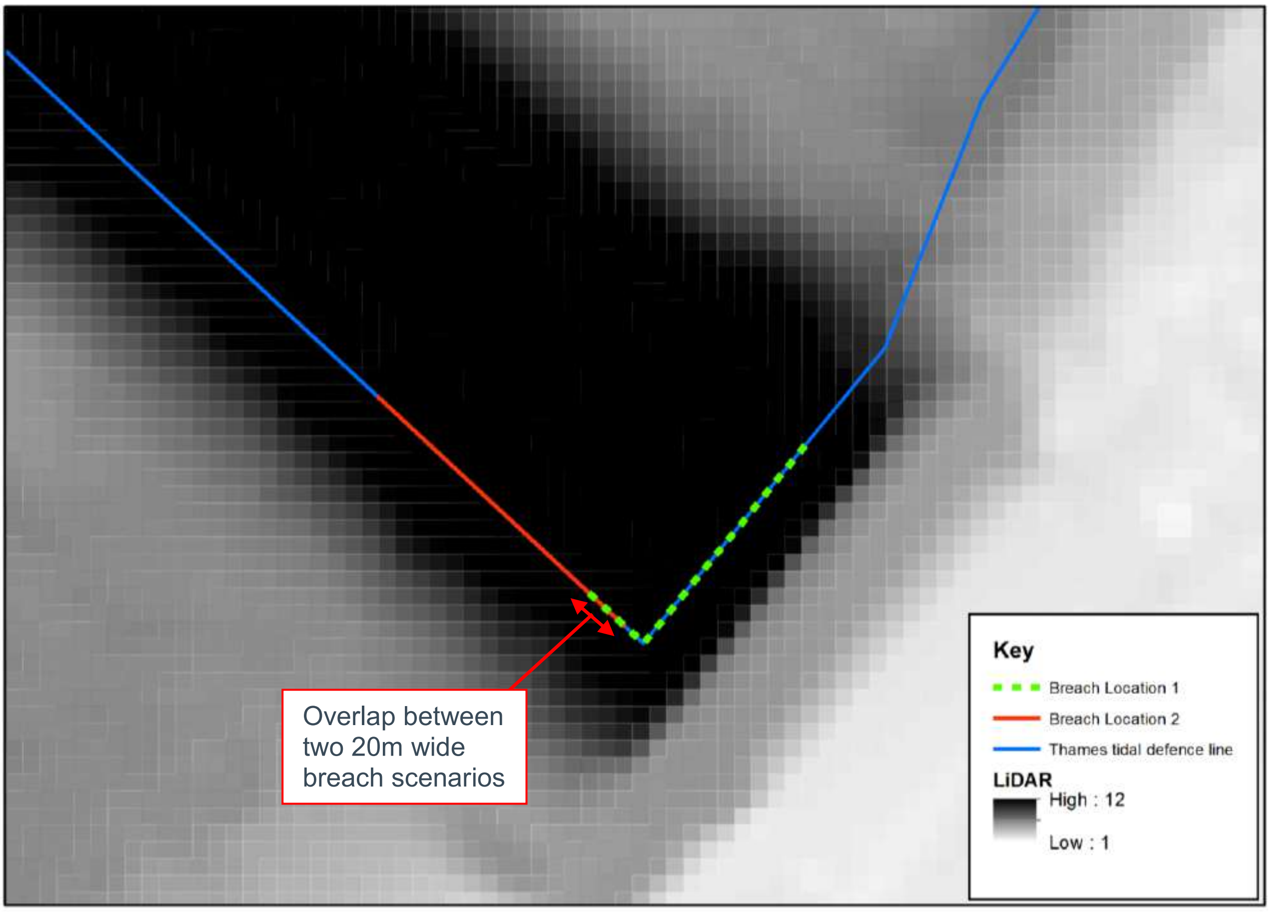

Figure 4-2 Overlap between two 20m wide separate breach scenarios

For soft defence breaches, where splits resulted in lengths of less than 10m at the end of the soft defence line, these were added to the next closest soft defence breach. This resulted in 32 breach widths being between 50 – 60m wide. For hard defence breaches, a similar approach was used, however as the breach widths were shorter the greatest difference of a breach width at 19.8m. These widths will cause minor changes to the hydraulics and resultant flood extents for those individual breach scenarios. However, given the entire defence line (within the study area) was tested for an individual breach, these impacts are likely to be negligible.

The result of the above GIS task generated a total of 5679 potential breach locations (the number per epoch were further refined as described in Section 4.2.2). This was a total of 5378 hard defence breaches and 301 soft defence breaches.

4.1.2. Breach sill level and scour zone definition

Given the Thames Tidal defence line is represented within the DTM, a sill level is required to lower the ground model to represent the breaching of the defence and resultant scouring that would occur. During discussions with the Environment Agency, it was agreed to repeat the prior methodology that was undertaken to define the breach sill level and scour zone.

Figure 4-3 shows the location of a single 20m (hard defence line) breach location that has been conducted as part of this assessment. GIS analysis was undertaken to generate a semicircle, the radius of which is the width of the breach itself from the centroid of the breach line (20m for hard defences and 50m for soft defences).

The lowest ground elevation within the semicircle was identified, and all levels within the semicircle were then lowered to that level for the respective breach scenario. This lowering represents the occurrence of the breach and the resultant scour. This lowering of the ground model was represented within the model at the start of the simulation, and so assumes that the failure of the defence occurs before the water fully abuts the defence line. Having the defence line failed/breached at the start of the event is the same approach taken from the prior methodology (CH2M, 2015). Figure 4-3 shows an example of a generated breach scour zone from a 20m hard defence breach line. This line and scour zone combination is what has been used to model an individual breach i.e. during a breach event water will flow through the breach width inland into the scour zone and then further inland.

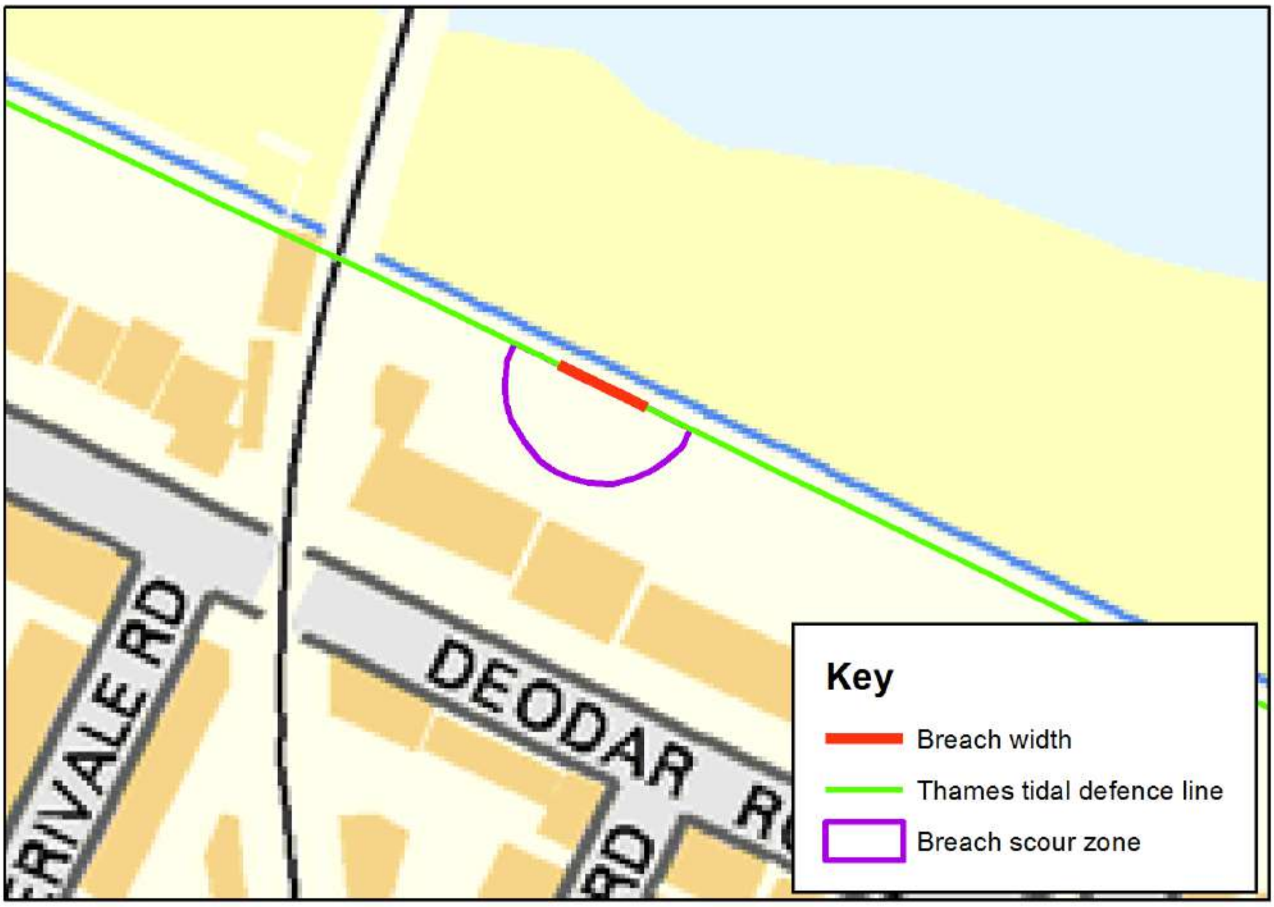

Figure 4-3 A 20m wide hard defence breach including the scour zone identified for this breach

As noted previously, a review of the Thames Tidal defence line was undertaken to ensure the line represented the crest of the defence and not the river. This was to ensure the correct sill level was identified and the river levels in the DTM were not used, which were likely to yield far lower ground levels for the scour zones.

4.2. Hydrology and Modelled Epochs

4.2.1. Hydrology

As noted in Section 3.3, the existing 1D ISIS Thames model has been used to extract the water level time series hydrographs. In total 47 hydrographs were available, covering the ISIS nodes from Teddington Weir down to the Thames Barrier. Given there were 47 hydrographs across the study area, breach locations were grouped and hydrographs were allocated to the groups. Starting from upstream, the breach locations were allocated to the closest hydrograph until another node location was crossed, to which the next set of breach locations were then allocated. The relevant breach location and allocated hydrograph is provided in the hydraulic model, breach location ESRI shapefile and model build spreadsheet (provided with the ICM model).

Given the presence of interpolates within the 1D ISIS model and requirements for the computer scripting, the hydrographs were renamed to a logical order, as shown in Appendix A. For each breach scenario, only one tidal cycle was included; which covered the Maximum Likely Water Level for the relevant epoch. The assumption with this approach, is that the breach occurs on the rising limb of the hydrograph, and once the event occurs and the tide recedes, the Thames Barrier will shut to prevent any further tides flowing upstream along the Thames. This would then allow the floodwater to drain out back into the Thames, and temporary repairs to take place to ensure that the next tide does not flood back through the breach. An example of this hydrograph is provided for node 19 for the 2100 epoch (previously node 2.23 – see 8.Appendix A).

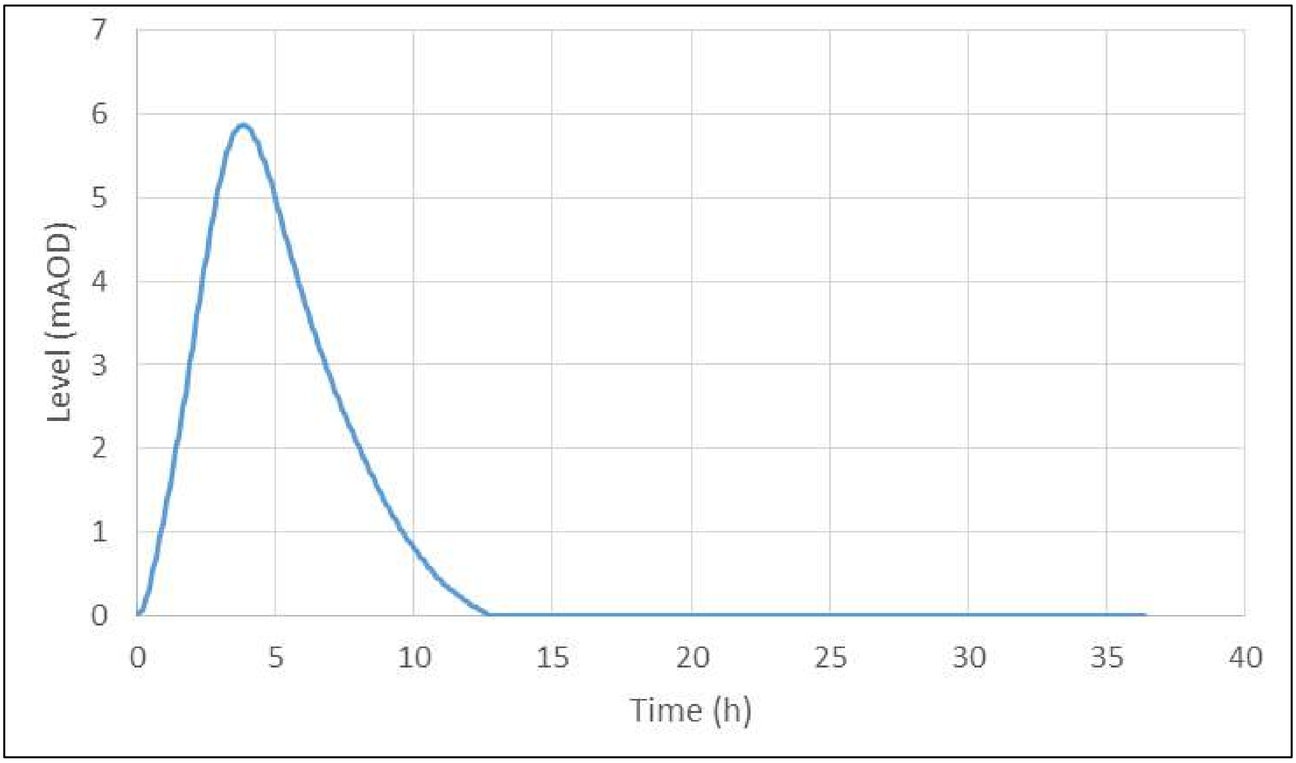

Figure 4-4 Level hydrograph for Node 19 (renamed as part of this study, see Section 4.2.1) for the 2100 epoch, showing the Maximum Likely Water Level (MLWL)

4.2.2. Modelled Epochs

Given this study is for the purpose of informing current and future planning in London, two epochs were modelled for each individual breach location, being 2005 and 2100. Both of these epochs were already modelled within the 1D ISIS Model of the Thames (see Section 3.3), and were the same used in the Thames Tidal Breach Modelling Study (CH2M, 2015). The hydrographs for the relevant node locations were extracted and modified as described in Section 4.2.1. No review of these hydrographs or the methodology in modelling the MLWLs for the relevant epochs was undertaken as part of this assessment.

A sense check was undertaken against the MLWL for both epochs against the identified breach sill levels. The purpose of this check was to identify areas of high land of which the MLWL did not exceed. These areas do not need to be modelled, as even with the identified sill level the ground is too high for water levels to spill over.

4.3. Hydraulic model representation

The following section details the technical representation of the components of a breach scenario within the hydraulic model. This study used Infoworks ICM v7.0.4 utilising the ICM Exchange module to automate the model build and simulation process.

4.3.1. Individual breach, sill and scour area

Section 4.1 describes how GIS data processing was undertaken to generate individual breach widths and related scour zones. Three further GIS shapefiles were generated from the breach width line, which were required for the hydraulic model build process. A line shapefile was generated that intersected the individual breach widths, with two point shapefiles generated at the vertices of these lines. These shapefiles were imported into Infoworks ICM as the relevant hydraulic model component types as described in Section 4.4.1. The sill identified as described in Section 4.1.2 defined the scour zone ground level.

This methodology relates to the previous approach that was undertaken as part of the Thames Tidal Breach Modelling Study (CH2M, 2015). There are however notable differences between the two approaches, which are described in Section 4.5.

4.3.2. Topographic features

Ordnance Survey MasterMap© data was used to represent building outlines within the model DTM. The previous study (CH2M, 2015) used the approach of adding 5m threshold on the building outlines. This approach was considered to be an overestimate, as storage of water within buildings would occur following a breach. The approach taken for this study was to represent building outlines within the model, setting a 300mm threshold to the building outlines. A porosity of 0.1 was set to give the buildings some permeability, allowing water to flow through.

Where a breach scour area was located either on or part on a building, the building area that was within the scour area was removed, as shown in Figure 4-5. This ensured consistency across the breach scenarios and allowed the representation of part collapse of a building following a breach event. The removed area was set to be 1m away from the edge of the scour area, to prevent the formation of very small mesh elements that can generate model instabilities.

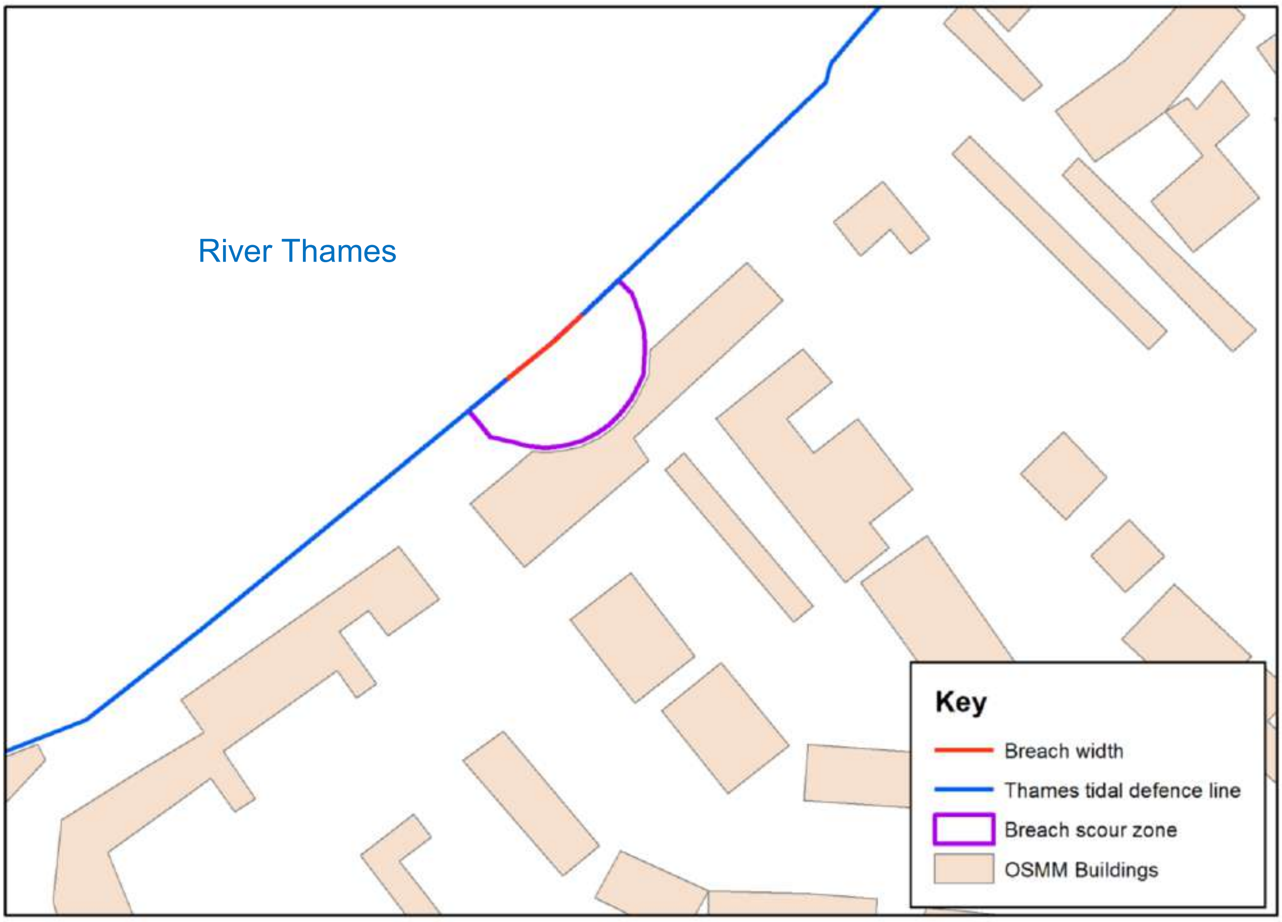

Figure 4-5 Example of removal of the building section overlapping the scour zone of a breach

Given the substantially high urbanisation of London, a global Manning's value of 0.02 was applied. No infiltration from soils was represented in the model. This is a conservative estimate ensuring the likely small influence of any infiltration is not overestimated, which would reduce the modelled impact of a breach.

4.4. Automation of ICM

Ruby scripting has been used alongside Infoworks ICM to automate the generation of all breach scenarios, simulating the individual scenarios, and extracting the results. This approach has never previously been undertaken for breach modelling within the UK, and has resulted in substantial benefits for the Environment Agency. This section describes the processes where Ruby scripting was used, and the manual adjustments made.

4.4.1. Model build

All individual breach scenarios were generated using a GIS data processing (as described in Section 4.1), generating a total of 28,395 individual model components. Each breach scenario contained 5 unique components, namely:

- A bank line to represent the breach width sill level;
- A mesh zone to represent the breach scour zone;
- An inline bank to connect to the bank line as defined above;
- An outflow node to connect the 1D breach component to the 2D mesh; and
- A break node to connect the 1D breach to the relevant hydrograph.

A common ID was retained across the five individual shapefiles that related to an individual breach scenario. This common ID was stored within an Excel spreadsheet that also defined the required attributes for the individual breach scenario including:

- Relevant shapefile names plus ID (Node_001, Inline Bank_001 etc.);
- Breach sill level (as defined in the GIS assessment);
- Model start time;
- Model duration (end time to be 24 hours from the peak of the hydrograph);
- Allocated hydrograph node ID; and
- Allocated model network (see Section 4.4.2).

All shapefiles were imported into a single model network in ICM representing the relevant breach model component. Further model components were generated common to all breach scenarios, these being a 2D zone to define the ground model (levels obtained from LiDAR - see Section 3.2), and porous polygons to represent buildings (see Section 4.3.2). A further outfall node and weir unit were also used for hydrograph allocation purposes, as defined in Section 4.4.3.

4.4.2. Model networks and mesh zone refinement

Within the current version of Infoworks ICM (v7.0.4), the 2D mesh required for floodplain modelling must be created manually. Because of this, the individual breach scenarios were split into the fewest possible number of models to minimise this part of the model creation process. The scenarios are split into 9 geographical areas, with each area containing 1 in 9 of the breaches in that area. This gives rise to a total of 81 models within which all 5679 breach scenarios are created. Figure 4-6 shows part of one of the sub-models, showing how every 9th breach is included in each sub-model.

This approach means that the scour zones for a number of inactive breaches are included in the model of any particular breach scenario. This potentially results in a small increase in floodplain storage if a modelled inundation floods into an adjacent scour zone. This storage however is considered negligible because of the approach which combines all outputs to produce maximum extents.

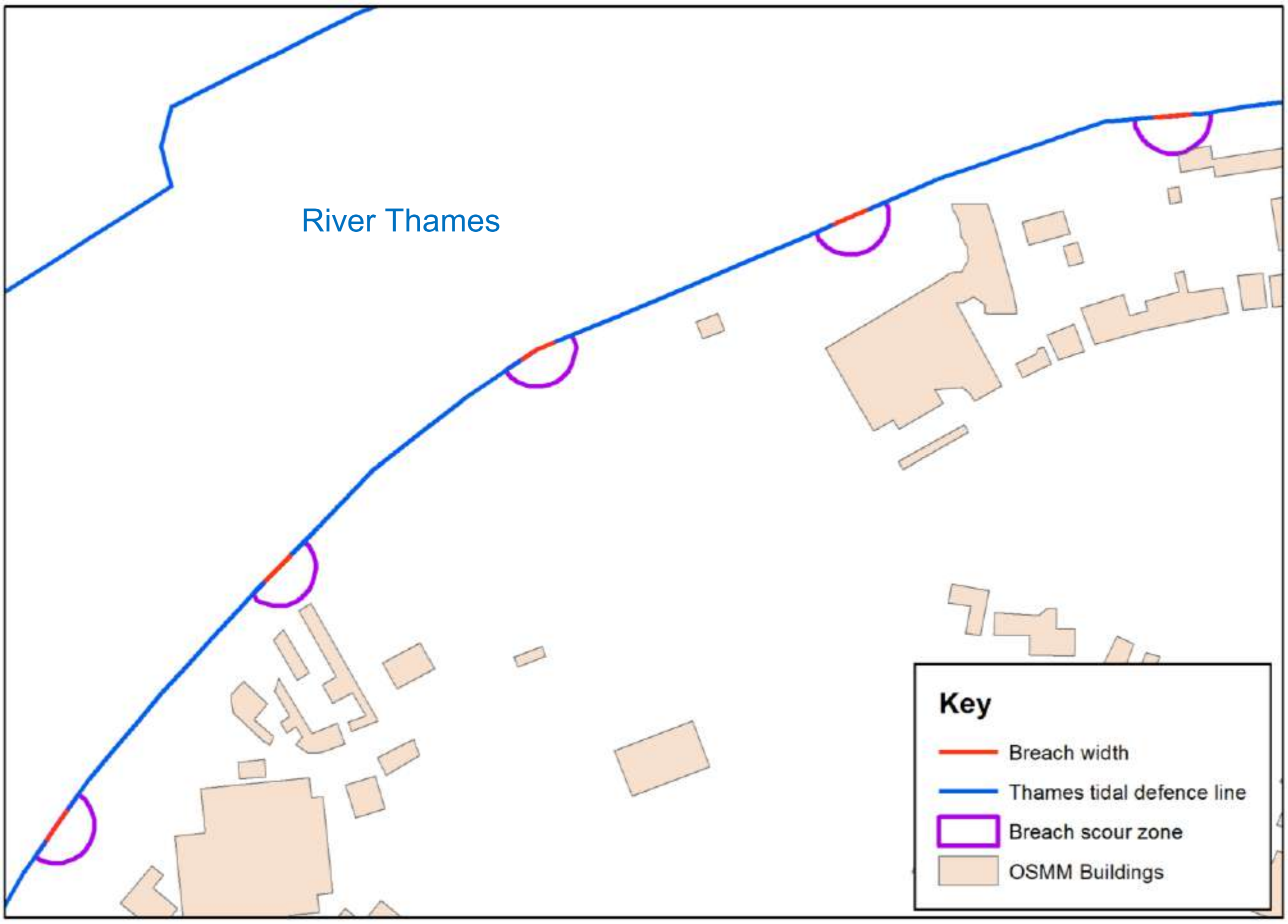

Figure 4-6 Breach scour zones present in the same model network (so mesh lowered in these areas for each individual breach scenario)

Mesh zones were predefined within the model networks. All breach scenarios were first simulated with a coarse mesh (maximum triangle area of 1000m^2), to identify the approximate maximum extent of flooding from the breach inundation. The results of this modelling were used to identify the approximate extent of floodplain to be modelled in detail. A detailed mesh at a higher resolution for the detailed breach modelling (with a maximum triangle area of 10m^2 which is approximately equivalent to a 5m grid size) ensuring that 2D domain was sufficiently large to cover the breach extents identified from the coarse modelling, with an additional 200m buffer applied. A key point in this process was to avoid glass walling (where the flood extent is artificially constrained by the edge of the 2D domain) and a review of the model outputs was also undertaken to identify any glass walling that occurred during any events. This point is discussed further in Section 6.

4.4.3. Hydrograph allocation

Each model network included up to 128 individual breach scenarios. Each breach scenario required the allocation of a specific level hydrograph, and ICM Exchange was used to automate this process, including the creation of the relevant modelling objects used to represent the breach. Each hydrograph boundary was connected to the appropriate breach through a combination of an outfall, weir link and break node.

4.4.4. Simulating and exporting results

ICM Exchange was used to automate the creation and simulation of run files in Infoworks ICM, using the information stored in the spreadsheet described in Section 4.4.1. This approach allowed each model run to be automatically created and populated with the following information for each breach scenario:

- Target model network;
- Target breach scenario;
- Allocated level hydrograph;
- Start time (with respect to the relevant hydrograph); and
- Model run time (end time to be 24 hours from the peak of the hydrograph).

The models were then batched on a workstation hosting multiple GPU cards that are supported by InfoWorks ICM for 2D simulations. Once the simulations had completed the maximum 2D mesh results were automatically exported and populated into a common folder. Post processing of this folder (containing all outputs for an individual epoch) was then undertaken to generate maximum flood depth, elevation, hazard and velocity outputs.

This above process allowed substantial reductions in user input, not only reducing the risk of error but allowing thousands of scenarios to be generated in a short period of time.

4.5. Key changes from prior breach modelling

The following summarises the key differences between the previous Thames Tidal Breach Modelling Study (CH2M, 2015) and this study. There are notable changes which are likely to result in significant differences in the outlines, namely:

- The breach location in the latest study is on the crest of the Thames tidal defence line, the previous study applied the breach width at the lowest point within the scour zone on the landward side of the flood defence;
- The hydrology with the previous study allowed three tidal cycles through the breach. The latest study only allows the MLWL tide, and allows the water to drain back into the Thames after this event (assuming the local topography permits this);
- Buildings were represented as 5m high in the previous study, essentially removing the building outline for storage. In the latest model, buildings are represented as porous polygons with a porosity of 10% and a threshold level of 300mm;
- A global Manning's of 0.02 was applied to the model due to the significantly high urbanisation of London. The previous study used varying Manning's values based on Ordnance Survey MasterMap© information, including very high values in areas for stability purposes;
- 113 breach locations were simulated as part of the previous study. This study considered the entire extent of the Thames tidal defences from Teddington Weir to the Thames Barrier, totalling 5679 breaches; and
- The latest LiDAR information available at the time of model build (November 2016) was used for this assessment. The previous study used the DTM generated for the Updated Flood Map for Surface Water (uFMfSW) available at the time of model build.

5. Assumptions and Limitations

There are key assumptions and limitations associated with the modelling that has been undertaken, namely:

- Breach widths for hard defences were set to 20m and soft defences at 50m, uniformly across the study area. The use of different breach widths would result in different flood extents;
- The breach sill levels were set to the lowest ground elevation within the scour zone, with all elevations within this zone set to that identified level. This assumes that everything within this area will be scoured out to the lowest ground level, irrespective of the material;
- Manning's values have been set to 0.02 across the entire model. Though London is highly urbanised, there are other materials within the catchment (such as grassland) that will increase roughness compared to a Manning's value of 0.02;
- Buildings have been represented as porous polygons with 10% porosity and a threshold of 300mm. This approach forces most flow around the buildings whilst still allowing storage of water within the building outline (irrespective of the building type). Whilst this has been considered the most appropriate method of building representation, this could overestimate or underestimate storage in some areas;
- A single breach has been modelled in each scenario. There is a risk that a breach may occur in multiple places across a defence line and this could significantly increase the depths and extents of flooding. However, this has not been assessed in this study;
- The hydrology uses the existing 1D ISIS model of the River Thames that calculated the MLWL for the 2005 and 2100 epochs and there has been no review of this hydrology as part of this assessment. The hydrology is consistent with the Thames Tidal Breach Modelling Study (CH2M, 2015);
- The breach has been assumed to be present during the rising limb of the tidal hydrograph. This could overestimate the volume of water entering through the breach, dependent at what stage of the tidal event the breach occurs;
- There has been no sensitivity testing as part of this assessment. The above limitations include components of the modelling that can be tested for their sensitivity, including breach width, number of breaches, breach timing, building representation and floodplain roughness;

- No consideration to flood defence stability or fragility has been considered in this assessment. The method of testing all locations however enables the quantification of the probabilistic and consequential risk of failure of a defence asset;
- The modelling undertaken has only considered breach modelling and no other sources of flooding are considered (such as groundwater or surface water);
- There is no representation of the below ground sewer network in the model. There is a risk that a breach may cause localised sewer flooding (including at locations remote from the breach) due to backing up of the network;
- There is no representation of any other below ground structures, such as entrances to the London Underground network or road tunnels. There is a risk that a breach would cause flooding of a below ground structure which would change the flood dynamics of a breach; and
- As with all hydraulic modelling, models are representations of reality and must be used proportionately and for the original purpose of the modelling study. If other uses of models are desired, the model must be reviewed (and updated as necessary) to ensure it is suitably fit for purpose.

6. Results

6.1. Individual breach output

Figure 6-1 shows the maximum flood extent of breach 418 for the 2100 epoch, an example of one of the modelled individual breaches for an epoch.

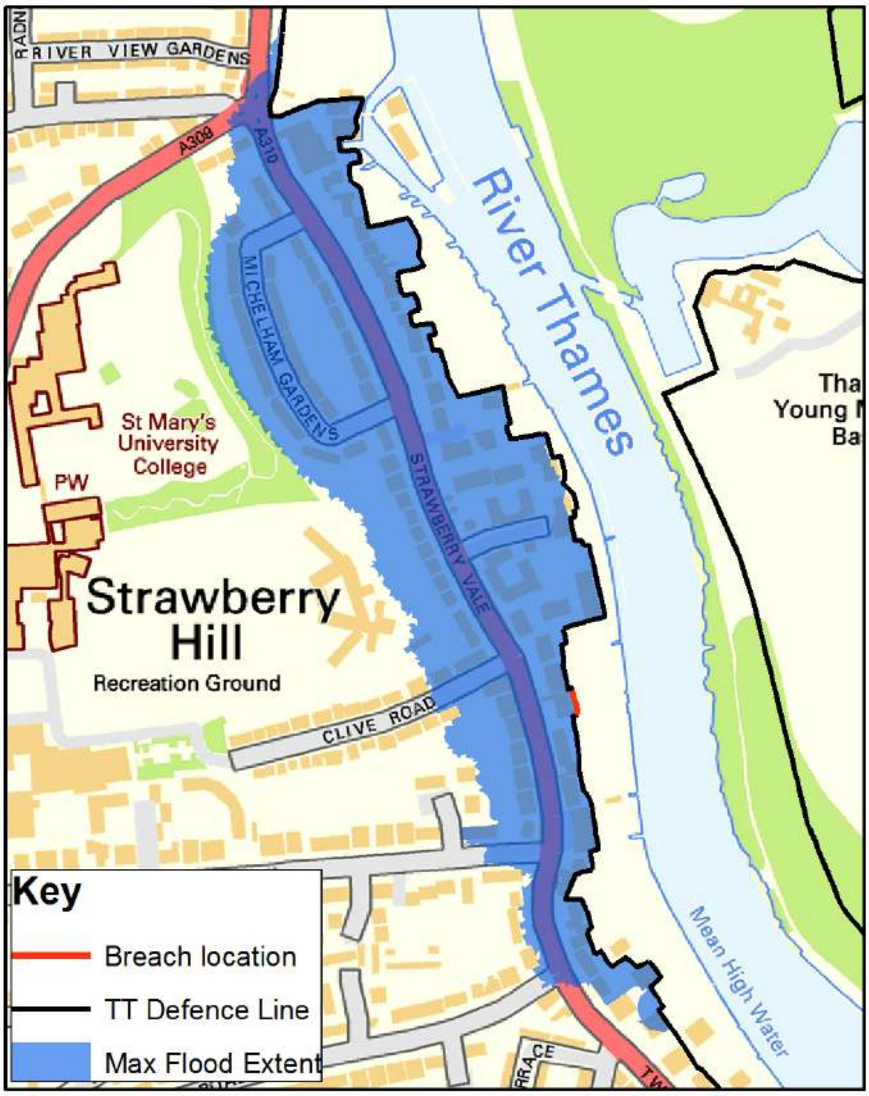

Figure 6-1 Maximum flood extent for Breach 418 for the 2100 epoch

The individual breach model flood extents have been combined for each epoch, as described below. All of the individual breach outputs have been stored and provided as part of this study. An associated shapefile has been provided which provides the information associated with the specific breach. This shapefile can also be cross referenced to the relevant maximum flood extent shapefile. This allows the breach scenarios to be individually assessed, which may have benefits for other applications, such as emergency response planning. Some opportunities to further use these outputs are described in Section 7.2.

A comparison of the previous modelling has not been undertaken as there are significant differences in the modelling methodology as described in Section 4.5.

Significant glass walling was identified in the results in the area to the north of the Thames Barrier and east of the River Lee. This occurred due to the breach extents reaching the extent of the supplied LiDAR and OS MasterMap© data, and an example is shown in Figure 6-2. As a result, the current outputs in this area (2D domain areas 6 and 7) have been marked as indicative. It is proposed that these breaches are rerun as part of extending the breach modelling downriver of the Thames Barrier, so that the flood risk outputs are fully integrated between breach locations upriver and downriver of the Barrier.

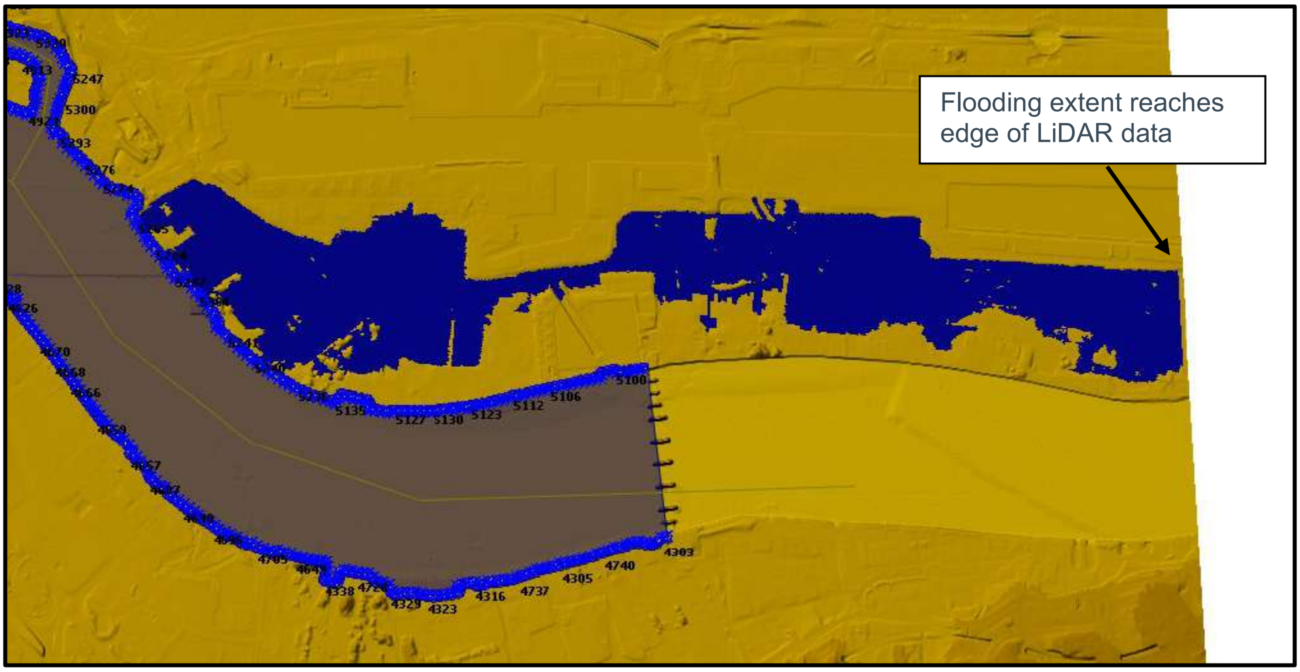

Figure 6-2 Example of glass walling downriver of Thames Barrier – Area 7, Breach 5306, 2100 epoch

6.2. Combining the outputs

The purpose of this study was to identify the maximum likely water level that would be achieved along the Thames tidal defence line if an individual breach were to occur at any point. All modelled breach scenarios for each epoch were extracted from the hydraulic model, and combined taking the maximum level achieved at each point within the study area. This was undertaken for elevation, depth, velocity and hazard, so generating four key outputs for each epoch which can be used for future planning. It is important to note there are assumptions and limitations associated with the work that has been undertaken, as described in Section 5.

For the 2100 epoch – two key outputs have been provided. Due to the higher volume of water that will breach out of the Thames, the extent of flooding is significantly greater than the 2005 epoch. As a result, some breaches in the area of the Lower Lee and Thames Barrier result in flooding that potentially extends a significant distance downriver of the Barrier. The outputs in this area have been marked as indicative, both because the flood extents extend to the limits of the modelled area, and conversely because the flood extents from downriver breaches require integration into the outputs of this study to create a representative, composite flood map.

The area within which the results are indicative covers the area bounded by the north bank of the River Thames, east bank of the River Lee, and areas north of the Channelsea River.

7. Conclusion, Recommendations and Opportunities

7.1. Conclusion

The following summarises the work that has been undertaken:

- Breach modelling has been undertaken on the Thames tidal defences between Teddington Weir and the Thames Barrier for both the left and right banks of the river;
- Breach scenarios have been modelled for current and future conditions of the Thames, namely the 2005 and 2100 epochs. The hydrology has been extracted from the 1D ISIS river model study (as described in Section 3.3); no hydrological assessment has been undertaken as part of this study;
- A total of 5679 breach locations were identified for this study by splitting hard defences to 20m wide individual breaches and soft defences to 50m wide individual breaches;
- A combination of GIS data processing, InfoWorks ICM modelling and ICM Exchange scripting has been used to automatically generate, simulate and export outputs for the individual breach scenarios. This method has provided substantial benefits and efficiencies, as described below;
- This study has built upon the methodologies applied as part of the Thame Tidal Breach Modelling Study (CH2M, 2015). The key differences between the two studies are described in Section 4.5;
- A single flood output per epoch has been generated that shows the maximum extent that would be achieved if a breach were to occur at any point along the Thames tidal defence line (within the study area, see Section 2). The associated maximum elevation, depth, velocity and hazard values have been provided alongside the maximum extents; and
- The purpose of the outputs is to assist the Environment Agency in future planning decisions for London; all development sites between the modelled extents receive the same information to help inform their FRA.

This work has used a completely new and innovative technique to model breaches of the Thames Tidal flood defences. The following summarises the key efficiencies that have been achieved:

- The hydraulic models have been simulated on high end workstations running dual GPU cards. Using GPU cards, InfoWorks ICM simulations are up to 100x faster than conventional methods. This has enabled the very high number of simulations to be modelled as part of this study;
- With a predefined approach, GIS data processing and computer scripting has automatically generated all of the individual breach scenarios. This has minimised the risk of user error during the model build process. Furthermore, this has also substantially reduced the user time input for a task that would have had to be undertaken manually, driving down the cost for undertaking the work; and
- Global changes to the modelling can be undertaken again with a substantially reduced user input time. If for example updates to hydrology are required, this will involve a small change to the hydrology files, which then the model can again automatically generate the required scenarios, simulate them and export the results.

7.2. Recommendations and Opportunities

This section provides recommendations for the work that has been undertaken and the opportunities of how else to make the most of the data that has been generated.

It is recommended that:

- The outputs from this assessment are used in preference to the previous breach modelling, which should also remove the requirement for the Upstream Inundation Modelling. This information can then be provided online and accessible to the public. This will remove the step of a data request from a developer to the EA for the information, reducing time inputs from both sides, further streamlining the planning process;
- The breach modelling work that has been undertaken here is also conducted downriver of the Thames Barrier and upstream of Teddington Weir. This will ensure consistency across London in how the residual risk of a breach of the defences is assessed;
- Sensitivity analysis is undertaken to consider the formation and size of a breach, the effect of multiple breach locations and the hydrology used to calculate the MLWL for the relevant epochs. This will

enable an uncertainty assessment / threshold to be considered, to gain more confidence in the maximum breach outputs provided as part of this study; and

- Any further modelling (including new study areas) that is undertaken should use the latest version of Infoworks ICM. InfoWorks v7.5 includes updates that address the issue of snap tolerances when data is imported from ArcMap , and improves the utilisation of GPU cards to reduce the overall processing time. Future updates are likely to include additional features that streamline the modelling process further.

The information / methodology generated as part of this assessment has also created opportunities to further this work and other work, namely:

- As noted in the recommendations, the approach for rapid breach model generation and simulation can be undertaken for the defences along the Thames outside of the study area. In fact this methodology can be applied to any location within the UK for large scale breach modelling;
- This methodology that has been used is not only applicable for river breach modelling. The framework that has now been created allows for other multiple scenario simulations to be automatically generated and simulated. An example of this is to test the consequence of a breach of the costal defences of the UK. The recent tidal surge along the East Coast that issued numerous Severe Flood Warnings could have led to a breach of the defences (Environment Agency, 2017). An assessment using the methodology applied here could quantify the impact of a breach at any given location, allowing the assessments of defences that have a high consequence of failure, optimising the cost of assessing and improving the tidal defences;
- As the individual outputs have been retained, there is an opportunity to undertake a breach priority assessment. This assessment could quantify the areas at greatest risk, considering the probability and consequence of a breach. Emergency planning and response could then be prioritised following the assessment;
- Infoworks ICM is an integrated catchment modelling platform. There are other sources of flooding that can be represented within the hydraulic model, including surface water, ground water and piped network flooding. This provides opportunities to further refine the breach modelling to consider the Thames Water storm water sewer network for example, which creates opportunities for collaboration of a London catchment scale; and
- Other areas for collaboration include identifying other underground infrastructure that are highly vulnerable to flooding following a breach. TfL and the London Underground network is an example of this; the Underground stations at greatest risk can be identified and mitigation measures put in place to reduce the impact following a breach of the defences.

8. References

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Appendix A. Hydrograph ID renaming

Old ID	New ID
2.02	1
2.1	2
2.2	3
2.3	4
2.5ad	5
2.6	6
a2.6	7
2.9u	8
2.10	9
2.14	10
2.15	11
2.16	12
2.17d	13
2.18	14
2.19	15
2.20	16
2.21	17
2.22u	18
2.23	19
2.24	20
2.24au	21
2.24ad	22
2.25	23
2.26	24

Old ID	New ID
2.27	25
2.28	26
2.29	27
2.30	28
2.31	29
2.32	30
2.33	31
2.34	32
2.36	33
2.37	34
2.38	35
2.39	36
2.40	37
2.41	38
2.42u	39
2.42d	40
2.43	41
2.44	42
2.45	43
2.46	44
2.46au	45
2.47	46
a2.49	47

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Environment Agency

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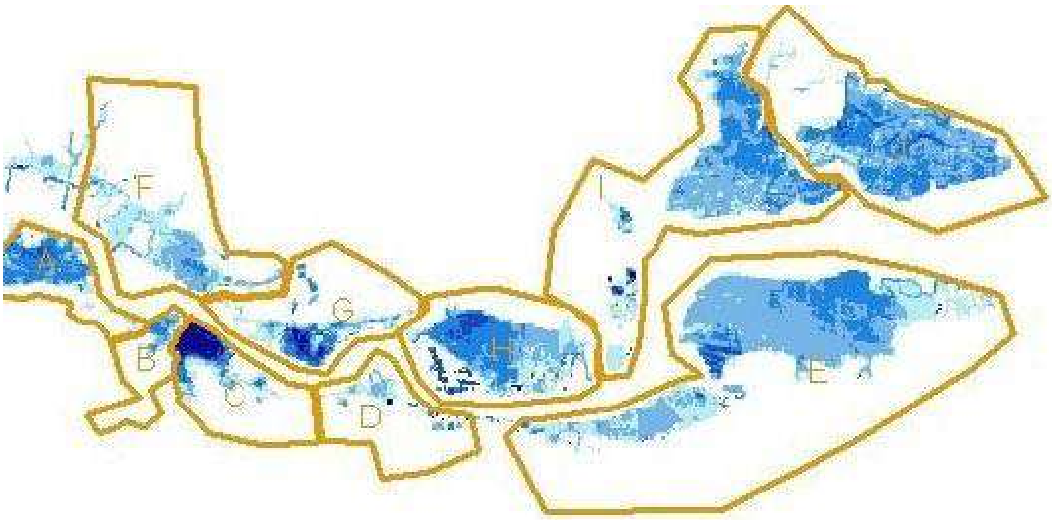
Thames Estuary 2100

Phase 3 Studies, Topic 1.5

Phase 3 Set 2 Estuary Wide Options Hydraulic modelling



Modelling the 1953 flood

EA Study Lead:	David Ramsbottom
Consultants:	HR Wallingford

Thames Estuary 2100

Status: Final

Date: December 2008

We are the Environment Agency. It's our job to look after your environment and make it **a better place** - for you, and for future generations.

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Produced by:

HR Wallingford on behalf of the Environment Agency
HR Wallingford Report Number EX 5944

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Executive Summary

The Thames Estuary 2100 project is developing a plan for managing flood risk on the Thames Estuary for the next 100 years. Options for flood risk management have been developed in the following stages:

1. Early Conceptual Options (ECO, 2005), in which approaches for managing flood risk were identified and assessed.
2. Pilot portfolios (2006), in which a wide range of possible 'portfolios of responses' were developed.
3. High Level Options (HLO, 2007), in which options were developed for a range of climate change scenarios
4. Phase 3 Set 1 Options (2008), in which the best options are refined to take account of other drivers of flood risk management including defence deterioration.
5. Phase 3 Set 2 Options (2008), in which the best options are refined to take account of other drivers of flood risk management including defence deterioration.

The Phase 3 Set 2 options comprise 11 different estuary-wide options including the 'Do-Minimum' case. The options include improvements to the defence system, flood storage, new barriers and new barriers with locks.

This report describes the hydraulic modelling carried out for the Phase 3 Set 2 options. The modelling covers the engineering options only. The modelling has been carried out using the same model as that used for the pilot portfolios, High Level Options, and Phase 3 Set 1 Options referred to above.

The results of the modelling have been used to develop outline designs for the Phase 3 Set 2 Estuary Wide Options. These results include:

- Design crest levels for the flood defences covering the period to 2170.
- Impacts of proposed changes to the closure rules for the Thames Barrier.
- Approximate gate sizes for new barrier and barrage structures (covered in the earlier Phase 3 Set 1 Options modelling report).
- Options for fluvial/tidal flood risk in West London and the tributaries.

In addition to earlier model validation work, the model has been used to simulate the 1953 flood, to demonstrate that the event can be reproduced with reasonable accuracy in spite of the lack of some detailed data, for example timing of breaches.

Results from other TE2100 Phase 3 studies have been used to inform the options, particularly studies on the hydraulic performance and design of flood storage areas, and the design of habitat creation areas by managed realignment of defences.

Contents

Tables

Figures

1 Background

The Thames Estuary 2100 project is developing a plan for managing flood risk on the Thames Estuary for the next 100 years. Options for flood risk management have been developed in the following stages:

1. Early Conceptual Options (ECO), in which approaches for managing flood risk were identified and assessed (TE2100 2006).
2. Pilot portfolios (2006), in which a wide range of possible ‘portfolios of responses’ were developed and hydraulically modelled, in order to determine the most effective options to control the probability of flooding (HR Wallingford 2006).
3. High Level Options (HLO), in which options were developed for a range of climate change scenarios, to demonstrate that future changes in extreme water levels caused by climate change can be accommodated by improvements to the flood risk management system (TE2100, 2007). In this context, an ‘option’ is a sequence of portfolios of responses to manage flood risk through the century.
4. Phase 3 Set 1 Options (2008), in which a wider range of drivers of flood risk management were taken into account including defence deterioration (TE2100, 2008).
5. Phase 3 Set 2 Options (2008), where the options were further refined taking account the Phase 3 Studies and results from the appraisal of the Phase 3 Set 1 Options (TE2100, 2008b).

After completion of the HLOs, a series of studies was commissioned to investigate the feasibility of the options and refine the details. Some of this work has been incorporated in the Phase 3 Set 1 options as results from the studies became available. Further results from these studies have been incorporated in the Phase 3 Set 2 options, including:

- Results from the appraisal of the Phase 3 Set 1 options;
- Consultation feedback;
- Further detail including flood risk management on tributaries, and local options for each of the Policy Management Units (PMUs).

The floodplains of the tidal Thames have been divided into 23 PMUs, which are (to a large degree) hydraulically independent and provide a convenient unit for the development of asset management plans for the Thames Estuary flood risk management system.

The Phase 3 Set 2 options are described in a separate parallel report (TE2100 2008b, referred to herein as the ‘Phase 3 Set 2 Options Report’). The options are listed in Table 1.1. HLO1, HLO2, HLO3 and HLO4 are the four generic High Level Options that were developed in the HLO study referred to above

Table 1.1 The Phase 3 Set 2 options

Option	Description	Comments
DM	DM = 'Do Minimum' FRM Policy P3 applies	This does not include managed realignments and therefore does not comply with legislation.
1	Improve the existing defences.	Options 1.1 to 1.4 achieve the same result in terms of flood defence locations and levels, but each have a different strategy for managing the defences.
1.1	Improve the existing defences by raising when needed and defence replacement when required.	No adaptation (i.e. only introduce responses when required). Defence replacement with minimum maintenance/repair.
1.2	Improve the existing defences by raising when needed, defence replacement when required, and adaptation of defences.	Adaptation built into the interventions (i.e. include allowances for future change, for example foundations for future defence raising). Defence replacement with minimum maintenance/repair.
1.3	Improve the existing defences by raising when the defences are replaced.	Intermediate approach involving raising defences when they are replaced (as carried out by TTD at present). Defence replacement with minimum maintenance/repair.
1.4	Improve the existing defences by raising when needed and repairing or replacing defences as required.	An alternative to 1.1 involving a more optimal maintenance/ repair regime.
2	Tidal flood storage	Incorporates the flood storage areas derived in the optimisation process (TE2100 2008c).
3.1	Barrier at Tilbury	Limit in the number of barrier closures (as for the Thames Barrier).
3.2	Barrier at Long Reach	Limit in the number of barrier closures (as for the Thames Barrier).
4.1	Barrier with locks at Tilbury	No limit in the number of barrier closures.
4.2	Barrier with locks at Long Reach	No limit in the number of barrier closures.
4.3	Convert Thames Barrier to a barrier with locks.	No limit in the number of barrier closures.

2 Structure of the report

The main text of the report describes the modelling of the above estuary-wide options. In addition, the report includes the following annexes:

A - Description of the model

B - Modelling of the 1953 surge tide event

C - Model instabilities

D - Base water levels

E - Analysis of the number of Thames Barrier closures

F - West London modelling

G - Hydraulic design of barriers and barrages

H - Impacts of failure of the Thames Barrier

I – Flood risk management on tributaries

3 Introduction to the modelling

3.1 The model

A one-dimensional (1D) numerical model of the Thames Estuary has been used to develop all the options, including the pilot portfolios, HLOs and the Phase 3 Set 1 Options. The model is described in Annex A.

The model has a long history of calibration and use on the tidal Thames, and is generally considered to be suitable for estuary-wide option development. In addition, the model has been used to simulate the 1953 flood event, to provide confidence that it is able to reproduce the flooding observed during the last major flood event on the estuary. The results are reported in Annex B.

In the hydraulic model, the Thames Barrier is represented by a set of 10 radial sluice gates. In the model the gates are closed for any surge tide greater than 3.85m AOD (the maximum Southend water level on the closure rule). For these surge tides the barrier gates in the model are closed when the water level at the Thames Barrier reaches 1m AOD. For very large surge tides it would be possible to close the Thames Barrier at the preceding low water to maximise the upriver storage volume and minimise potential reflected waves.

It should be noted that the nearer to low water the Barrier is closed, the lower the model instabilities related to closing the gates. Additional modelling has been completed to investigate the impact of timing of Barrier closure on peak water levels and model instability. This is described in Annex C.

3.2 Application of the model

The options have been included in the model, which has then been run for the ‘design events’, which are the surge tide and fluvial flow events that correspond to the design standard of protection provided by the defence system. The water levels predicted by the model are then used with an appropriate freeboard allowance to define the levels of the flood defences.

One of the main purposes of the modelling is to determine how the defence system changes with climate change, particularly sea level rise and increases in fluvial flows. The model is run for increases in the boundary conditions (sea level at Southend and fluvial flows at Teddington) to determine the dates when design water levels in different parts of the system are reached, and therefore when interventions are required to manage the flood risk. Interventions include raising defences, and the construction of new barriers and other works.

The design water levels are effectively set by Flood Risk Management (FRM) Policy requirements. These polices have been determined by Policy appraisal, where the most appropriate policies for each PMU are determined. The policies define whether flood risk should be allowed to increase, stay the same, or reduce (TE2100 2008d, Chapter 5).

In order to determine the dates for interventions a number of thresholds for extreme water levels have been identified. These are described in Section 3.3. A number of assumptions regarding climate change and FRM Policy have also been made. These are described in detail in Phase 3 Set 2 Options Report, and summarised in Section 3.4.

The numerical model of the estuary has been updated to include each intervention. For example, over-rotation of the Thames Barrier permits an increase in Barrier crest level of 0.4m and is implemented together with associated defence raising. The model is then run for a number of dates ('epochs') until the peak water levels are greater than the thresholds given in Section 3.3. This determines the end point of the intervention. The model is then adjusted for the next intervention and the process repeated.

3.3 Thresholds for interventions

The thresholds of water level at the Thames Barrier for which the Barrier must be modified to prevent overtopping of the gate crests in the design event are as follows:

- The existing design water level at the Thames Barrier is 6.5m AOD.
- Design water level at the Thames Barrier with over-rotation of the 31m RSG is 6.9m AOD.
- Design water level at the Thames Barrier with over-rotation of the 61m RSG and sill beams on the 31m RSG is 7.4m AOD.
- Design water level at the Thames Barrier with extended RSG and FRG is 8.4m AOD.

Note that RSG means 'Rising Sector Gates' and FRG means 'Falling Radial Gates'.

These levels do not include 'freeboard', which takes account of uncertainty in the estimated design water levels. Hence the crest levels of the gates are higher than these levels.

Water level thresholds are also imposed on flood defences in the PMUs which have an FRM Policy of P4 or P5. These determine the amount of crest level increase required to ensure that the design water level at a defence (defence crest level minus the freeboard allowance for uncertainty) is greater than or equal to the predicted water level for the design event at that defence.

Thresholds for PMU defences upriver of the Thames Barrier for extreme tidal events are set according to a reliability threshold for the Barrier, which is expressed in terms of the number of closures per year.

As the sea level rises, the number of Barrier closures increases. To avoid having a very high number of closures, which would lead to a reduction in the reliability of the Barrier, the upriver defences are raised thus permitting higher tides through the Barrier. Thus the number of Barrier closures is dependent on the sea level rise, the reliability of the Barrier, and the amount of upriver defence raising.

Thresholds for habitat creation by managed re-alignment are determined by areas of lost habitat due to sea level rise.

3.4 Assumptions

3.4.1 FRM Policy

The FRM Policy varies for each PMU, hence the design water levels also vary. For example, for a Policy of P4 downriver of the Thames Barrier, the design water level corresponds to an annual probability of 0.1% (1 in 1,000 years). For Policy P5 downriver of the Thames Barrier, the design water level corresponds to an annual probability of less than 0.1%. This has been assumed to correspond to an annual probability of 0.02% (1 in 5,000 years) or 0.01% (1 in 10,000 years) at different locations.

The FRM Policy for each PMU is shown in Phase 3 Set 2 Options Report. FRM Policy P5 is applied at the epoch of the first major intervention for PMUs downriver of the Thames Barrier. This was done to avoid immediate improvements to the flood defences which would then have to be further improved at a later date.

FRM Policies for PMUs downriver of the Thames Barrier where long lengths of defence are represented in the model are all P4 except:

Left Bank		
	Royal Docks (model nodes 3.1 to 3.5u)	P5 (1:10,000)
	Barking and Dagenham (model nodes 3.5d to 3.9)	P5 (1:5,000)
	East Tilbury (model nodes 3.28 to 3.30)	P3
Right Bank		
	Greenwich (model nodes 3.1 to 3.3)	P5 (1:10,000)
	North Kent (model nodes 3.27 to 3.35)	P3
Thames Barrier		
	Protection to upriver PMUs	P5 (1:10,000)

Model node locations are shown on the maps in Annex A. FRM Policy P3 involves maintaining the existing system, and therefore there are no changes in defence crest levels.

For PMUs upriver of the Thames Barrier (except West London) the Standard of Protection (SoP) for extreme tidal events is determined by the Thames Barrier. The SoP for tidal events is about 1 in 5,000 years for present day conditions. However, due to climate change, the SoP will reduce to below 1 in 1,000 years unless mitigation measures are introduced.

In this analysis it is assumed that the SoP for these PMUs is controlled by the way in which the Thames Barrier is operated. In West London, the SoP is lower (approximately 1% per annum or 1 in 100 years) and is determined by fluvial flood flow from the Thames at Teddington.

3.4.2 Climate change

The modelling has been undertaken using the Defra 2006 climate change scenario to determine extreme tidal boundary conditions for the model. The increments of sea level rise for Defra 2006 are shown in the Phase 3 Set 2 Options Report (Section 3.1.2). These are applied to the present day (2000) extreme tides for annual probabilities of occurrence of 0.5% (1 in 200 years), 0.1% (1 in 1,000 years), 0.05% (1 in 2,000 years), 0.02% (1 in 5,000 years) and 0.01% (1 in 10,000 years). The corresponding peak water levels for the year 2000 at Southend are:

- 1 in 200 years: 4.70m AOD
- 1 in1,000 years: 5.03m AOD
- 1 in 2,000 years: 5.16m AOD
- 1 in 5,000 years: 5.29m AOD
- 1 in 10,000 years: 5.51m AOD

For future epochs these extreme water levels are back dated to 1990 levels because the Defra 2006 guidance is 4mm/year from 1990 to 2025, whereas the above data are based on old guidance of 6mm/year to convert 1990 values to 2000. This effectively means that future levels are equal to the above levels, plus the Defra climate change allowance, minus 0.02m.

3.5 Complementary work elements

Modelling the Phase 3 Set 2 options has utilised findings and data from other TE2100 Phase 3 studies including the following:

- Phase 3 Set 1 Options (TE2100 2008)
- Topic 5.5 Barriers and Barrages (TE2100 2008e)
- Topic 4.6 West London Flood Risk Management Options (TE2100 2008f)
- Topic 5.2 Flood Storage (TE2100 2008g)
- Topic 5.3 Managed re-alignment (TE2100 2008h)
- Topic 8.7 Habitat creation strategy (TE2100 2008i)
- Topic 4.5 Flood Risk from the Tributaries (TE2100 2008j)

3.5.1 Topic 5.5 Barrier and Barrages

Topic 5.5 involved the outline design of barriers and barrages at four locations (Long Reach, Tilbury, Allhallows to Leigh and Sheerness to Shoeburyness). Hydraulic modelling was initially carried out to determine the approximate gate sizes needed to minimise impacts of structures on the tidal water level regime (TE2100 2008a).

These gate sizes were then used to produce initial designs for the barriers and barrages in Topic 5.5. Further work was then carried out to assess the impacts of the barriers on tidal water levels and flow velocities. The results are summarised in Annex G.

The final design of barriers and barrages in Topic 5.5 was then undertaken, including feedback from a review of the designs. As a result, the final designs are slightly different from those outlined in Annex G. One reason for this was the decision to have at least three navigation spans (one for upriver traffic, one for downriver traffic, and one spare to allow for maintenance, etc).

3.5.2 Topic 4.6 West London

Topic 4.6 considered options to manage fluvial and tidal/fluvial flood risk in West London. It built on previous modelling studies for West London, but also made decisions regarding option selection based on environmental and other criteria.

No hydraulic modelling was carried out in Topic 4.6. The proposed structural flood risk management interventions have been modelled in this study in order to determine their effectiveness. The results are presented in Annex F.

3.5.3 Topic 5.2 Flood storage

The flood storage areas at Erith, Rainham, Aveley, Crayford, Dartford, Tilbury, Shorne and North Kent identified in the HLOs have been studied in Topic 5.2.

This study looked at the filling and emptying performance of each storage area. This showed that the individual storage areas had varying benefit in terms of reductions in peak River Thames water levels of 0.1 to 0.3 m. The majority of storage areas were shown to empty during the following low tide, although North Kent required additional drainage structures due to its size.

The storage areas were then modelled in different combinations to assess the impact on River Thames peak water levels. The most practical combination of storage areas that gave reasonable reduction in peak water levels was Shorne, Dartford, Aveley and Erith.

It should be noted that these reductions were for a ‘glass wall’ model so they did not take into account the influence of defence overtopping in the outer estuary on hydrograph shape. It also assumed perfect forecasting of tides.

The final Phase 3 Set 2 estuary wide option involving flood storage includes the following areas being implemented as a single intervention: Erith Marshes, Aveley & Wennington Marshes, Dartford & Crayford Marshes, and Shorne Marshes. Topic 5.2 also investigated other factors including high tide forecasting requirements.

3.5.4 Topics 5.3 and 8.7 Habitat creation

The managed realignment areas identified for habitat creation in the HLOs were modified in Topic 8.7, based on an analysis of criteria for the establishment of managed realignment sites.

In Topic 5.3, two-dimensional (2D) models were set up for each managed re-alignment area and run for neap, mean and spring tides. These were used to assess the habitat creation potential for the selected areas.

The habitat creation areas identified in Topic 8.7 and modelling results in Topic 5.3 have been used to develop the habitat creation proposals in the Phase 3 Set 2 options. Preferred sites have been selected, although a wider range of sites will be presented for consultation as some sites may not be available because of planned development or other reasons.

3.5.5 Topic 4.5 Tributaries

Options were identified for flood risk management on the tributaries based on earlier TE2100 studies and other considerations including engineering and costs. However no modelling was carried out. Some further modelling work was carried out in this study to determine the magnitude of the works that might be required. The results are presented in Annex I.

4 Modelling for Option Design

The Phase 3 Set 2 Option models are similar to the Phase 3 Set 1 Options models, which are reported in TE2100 2008. The main differences are as follows:

- Changes in defence level for some PMUs as a result of changes in FRM Policy
- Changes in the managed re-alignment sites
- Changes in the storage areas in Option 2, which are based on those from Work Element 5.2.

The base models of the present day system without interventions are the same as in HLO option development. The base water levels for the following epochs; 2000, 2050, 2100 and 2170, are listed in Annex D. As with the Phase 3 Set 1 Options, each option consists of a series of Portfolios of responses through the century.

The options include responses for two main drivers:

- Increase in extreme water levels
  - Downriver of the Thames Barrier
  - Fluvial in West London
- Increase in mean sea levels

The modelling described in this Section is focused on the interventions downriver of the Thames Barrier for increases in extreme tide level. For responses to extreme water levels, the models have been run to determine the limits for each portfolio of responses, expressed in terms of the year when the limit (or threshold) is reached for the Defra ‘06 climate change scenario.

Thus, in the case of a portfolio consisting of improvement to the Thames Barrier and associated defences, the model is run for increasing water levels until the limit of the improvement is reached. The date corresponding to this water level corresponds to the date when a further portfolio must be implemented.

Responses to mean sea level rise are a pre-determined increase in defence levels upriver of the Thames Barrier in order to keep the annual number of closures below a threshold level. The limits of these responses are determined by analysis of the number of barrier closures. Modelling is used to show that water levels for the new closure rules are below the design water level of the raised defences. This analysis is described in Annex E.

For West London it is assumed that the extreme water level is produced by the fluvial flow and that the Thames Barrier is closed for fluvial flows greater than 1 in 30 years. The options for West London identified in Topic 4.6 have been modelled and the impacts on water levels for a number of design flows assessed. The results are reported in Annex F.

There are a number of tributaries that flow into the tidal Thames, and some of these cause significant amounts of flooding within the tidal Thames floodplains. Flood risk management interventions have been considered in the modelling work for the Phase 3 Set 2 Options, and the results are reported in Annex I.

4.1 Do Minimum

The ‘Do Minimum’ Option involves continuing with existing actions to manage flood risk. This means keeping the flood defence system as it is at present. Whilst this requires major investment in the maintenance of the flood defence system, the crest levels of flood defences and sizes of flood control structures will not change. The level of flood risk will increase as the sea level rises and fluvial flows increase.

In terms of modelling for option design, no new work is required as all the elements representing the flood defence systems in the model are unchanged.

4.2 Option 1 (Improve the existing system)

Option 1 consists of the following portfolios of interventions for extreme water level:

- Raise defences as required (suitable until the design water level at the Thames Barrier reaches 6.5m AOD).
- Over-rotate Thames Barrier and raise defences (limit is when the design water level at the Thames Barrier reaches 6.9m AOD).
- Improve Thames Barrier and raise defences (limit is when the design water level at the Thames Barrier reaches 7.4m AOD).
- Improve Thames Barrier and raise defences (limit is when the design water level at the Thames Barrier reaches 8.4m AOD).

Models were set up for each intervention and run for design tides for a number of epochs to determine the limit of each intervention. Generic option 1 has four sub-options (numbered 1.1 to 1.4). These represent different ways of achieving the required improvements (for example, by constructing adaptable defences), but do not change the physical dimensions or levels of the defences. Therefore these options are hydraulically the same.

Limit of the existing Thames Barrier

The model for Phase 3 Set 2 Option 1 to determine the limit of the Thames Barrier to increase in extreme water level includes managed realignments that take place in 2040, 2050 and 2065. These areas are on the Isle of Grain and North Kent marshes. These were modelled as reservoir units with large gaps or breaches in the spill units which correspond to the breaches used to create the manage realignments in Topic 5.3.

The first managed re-alignment in 2020 is expected to be in the Fobbing /Vange /Bowers /Canvey West area. It is not included in the hydraulic model because it is behind the Barriers on the Canvey Island creeks and has no influence on extreme water levels.

The first intervention predicted by the modelling is to raise defences in the lower estuary as the sea level rises. The approximate date when this would occur under the Defra06 climate change scenario is 2040.

The present limit of the Thames Barrier caused by rising sea levels and increasing extreme high tide levels would occur in about 2070. The model results for this limit are shown in Figure 4.1 and Table 4.1.

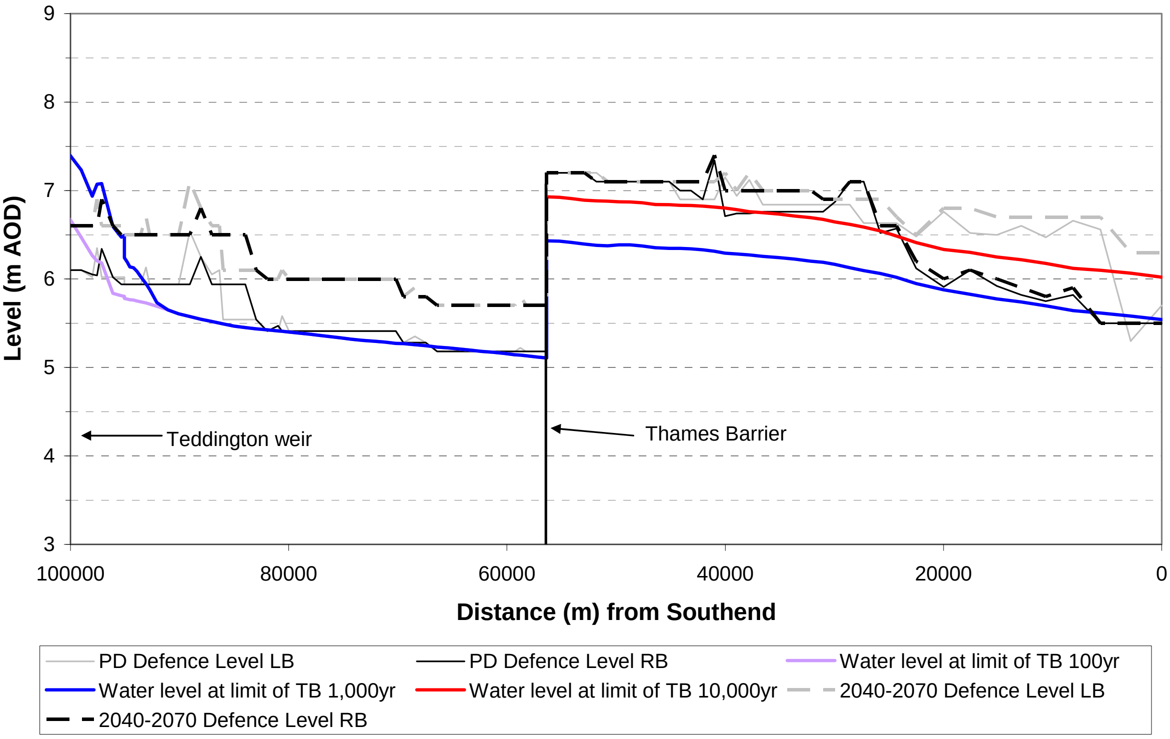

Figure 4.1 Design water levels at the limit of the existing Thames Barrier

Note that in Figure 4.1 the upriver defences have been increased by 0.5m and the upriver water levels are derived from the barrier closure rule adjusted by plus 0.5m.

Table 4.1 Water levels at the limit of the Thames Barrier (in 2070) (FRM Policy P4 except where indicated)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2070)		Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	6.43	6.93	-	-
	3.2	7.20	7.20	6.50	6.50	6.43	6.92	-	-
	3.3	7.20	7.20	6.50	6.50	6.41	6.91	-	-
	3.4	7.20	7.20	6.50	6.50	6.39	6.89	-	-
Roding	a3.5u	7.20	7.10	6.50	6.40	6.38	6.89	-	-
	a3.5d	7.20	7.10	6.50	6.40	6.38	6.89	-	-
	3.6	7.10	7.10	6.40	6.40	6.38	6.88	-	-
	3.7	7.10	7.10	6.40	6.40	6.38	6.87	-	-
Beam	3.8	7.10	7.10	6.40	6.40	6.38	6.87	-	-
	3.9	7.10	7.10	6.40	6.40	6.37	6.86	-	-
	3.10	7.10	7.10	6.40	6.40	6.35	6.84	-	-
	3.11	7.10	7.10	6.40	6.40	6.35	6.84	-	-
	3.12	6.90	7.00	6.20	6.30	6.35	6.83	0.15	0.04
	3.13	6.90	7.00	6.20	6.30	6.34	6.83	0.14	0.04
	3.14	6.90	6.90	6.20	6.20	6.33	6.82	0.13	0.13
Darent	3.15u	6.90	7.34	6.20	6.64	6.31	6.81	0.11	-
	3.15d	6.90	7.34	6.20	6.64	6.31	6.81	0.11	-
	3.16	7.15	6.71	6.45	6.01	6.29	6.80	-	0.28
	3.17	6.94	6.74	6.24	6.04	6.28	6.79	0.04	0.24
	3.18	7.12	6.74	6.42	6.04	6.27	6.76	-	0.23
	3.19	6.84	6.76	6.14	6.06	6.26	6.75	0.12	0.20
	3.20	6.84	6.76	6.14	6.06	6.24	6.73	0.10	0.18
	3.21	6.84	6.76	6.14	6.06	6.23	6.71	0.09	0.17
	3.22	6.84	6.76	6.14	6.06	6.20	6.69	0.06	0.14
	3.23	6.84	6.76	6.13	6.05	6.19	6.67	0.06	0.14
	3.24	6.84	6.87	6.11	6.14	6.17	6.65	0.06	0.02
	3.25	6.84	7.10	6.10	6.36	6.13	6.62	0.03	-
Tilbury	3.26	6.63	7.10	5.87	6.34	6.10	6.59	0.23	-
	3.27	6.63	6.52	5.85	5.74	6.06	6.54	0.21	0
	3.28	6.63	6.57	5.83	5.77	6.02	6.49	0	0
	3.29	6.48	6.12	5.66	5.30	5.95	6.41	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	5.88	6.33	0	0
	3.31	6.52	6.10	5.64	5.22	5.83	6.30	0.19	0
	3.32	6.50	5.92	5.59	5.01	5.78	6.25	0.19	0
	3.33	6.60	5.82	5.66	4.88	5.74	6.22	0.08	0
	3.34	6.47	5.75	5.50	4.78	5.70	6.18	0.20	0
Canvey	3.35	6.66	5.82	5.66	4.82	5.64	6.12	0	0
	3.36	6.56	5.50	5.56	4.50	5.61	6.10	0.05	0
	3.37	5.30	5.50	4.60	4.50	5.58	6.07	0.65	0
Southend	3.38	5.70	5.50	5.00	4.50	5.54	6.02	0.21	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

Table 4.1 shows that 1,000 year water levels are below the threshold of 6.5m AOD at the Thames Barrier, and that low levels of defence raising are required before 2070. This defence raising would be needed in about 2040.

Limit of over-rotation of the Thames Barrier

The first major intervention is not only required to improve the overall defence system because of sea level rise, but also to allow for an increase in the Standard of Protection (SoP) for Policy P5. The increase in SoP for an annual probability of flooding of 0.01%

(1 in 10,000 years) corresponds to an increase in defence level of about 0.5m at the Barrier.

If FRM Policy P5 (1 in 10,000 years SoP at the Thames Barrier) were to be applied before 2070, over-rotation of the Thames Barrier would be required. Table 4.1 shows that the 10,000 year water level (FRM Policy P5) in 2070 is greater than the threshold level for the over-rotated Thames Barrier (of 6.9m AOD). The limit for the over-rotated barrier would be reached with Policy P5 shortly before 2070.

Limit of improvement of the Thames Barrier

This improvement to Policy P5 could be achieved by over-rotation of the Thames Barrier and defence raising. However, as mentioned above, there is also a need for improvement to manage sea level rise, as the Thames Barrier will have reached its design limit. Therefore, for Option 1, additional improvement is needed to accommodate both rising sea levels and a change in FRM Policy. This can be achieved by improving the Thames Barrier together with raising the downriver defences.

Improvement of the Thames Barrier includes:

- over-rotation of the 31m RSG
- over-rotation of the 61m RSG
- sill beams for the 31m RSG

These improvements to the Thames Barrier mean that the gate units have been modified to reach a crest level of 7.8m AOD (design water level of 7.4m AOD).

In addition to improving the Barrier, the defences for PMUs with Policy P5 and P4 have been raised by up to about 1.5m.

Table 4.2 shows the intervention in 2070 involving improvement of the Thames Barrier because of rising sea levels and implementation of the P5 FRM Policy. Table 4.2 also shows the downriver PMUs where the FRM Policy has been increased to P5.

The water levels in Table 4.2 are shown for 2130. The 10,000-year level exceeds the design level of 7.4m AOD. The limit for this intervention is therefore earlier that 2130, and is set at 2120. The water levels at the limit of the Thames Barrier improvement are shown in Figure 4.2.

Table 4.2 Option 1: Improvement of the Thames Barrier (implemented in 2070)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2130)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	6.99	7.42	0.92	0.92
	3.2	7.20	7.20	6.50	6.50	6.98	7.42	0.92	0.92
	3.3	7.20	7.20	6.50	6.50	6.97	7.41	0.91	0.91
	3.4	7.20	7.20	6.50	6.50	6.96	7.41	0.91	0.46
Roding	a3.5u	7.20	7.10	6.50	6.40	6.96	7.41	0.91	0.56
	a3.5d	7.20	7.10	6.50	6.40	6.96	7.41	0.70	0.56
	3.6	7.10	7.10	6.40	6.40	6.97	7.41	0.80	0.57
	3.7	7.10	7.10	6.40	6.40	6.97	7.40	0.80	0.57
Beam	3.8	7.10	7.10	6.40	6.40	6.97	7.39	0.79	0.57
	3.9	7.10	7.10	6.40	6.40	6.95	7.38	0.78	0.55
	3.10	7.10	7.10	6.40	6.40	6.94	7.36	0.54	0.54
	3.11	7.10	7.10	6.40	6.40	6.94	7.34	0.54	0.54
	3.12	6.90	7.00	6.20	6.30	6.94	7.34	0.74	0.64
	3.13	6.90	7.00	6.20	6.30	6.93	7.33	0.73	0.63
	3.14	6.90	6.90	6.20	6.20	6.92	7.32	0.72	0.72
Darent	3.15u	6.90	7.34	6.20	6.64	6.90	7.30	0.70	0.26
	3.15d	6.90	7.34	6.20	6.64	6.90	7.30	0.70	0.26
	3.16	7.15	6.71	6.45	6.01	6.88	7.28	0.43	0.87
	3.17	6.94	6.74	6.24	6.04	6.86	7.28	0.62	0.82
	3.18	7.12	6.74	6.42	6.04	6.84	7.27	0.42	0.80
	3.19	6.84	6.76	6.14	6.06	6.83	7.25	0.69	0.77
	3.20	6.84	6.76	6.14	6.06	6.81	7.23	0.67	0.75
	3.21	6.84	6.76	6.14	6.06	6.79	7.21	0.65	0.73
	3.22	6.84	6.76	6.14	6.06	6.76	7.18	0.62	0.70
	3.23	6.84	6.76	6.13	6.05	6.74	7.15	0.61	0.69
	3.24	6.84	6.87	6.11	6.14	6.72	7.12	0.61	0.58
	3.25	6.84	7.10	6.10	6.36	6.68	7.07	0.58	0.32
Tilbury	3.26	6.63	7.10	5.87	6.34	6.64	7.03	0.77	0.30
	3.27	6.63	6.52	5.85	5.74	6.61	7.02	0.76	0
	3.28	6.63	6.57	5.83	5.77	6.60	7.02	0	0
	3.29	6.48	6.12	5.66	5.30	6.58	7.02	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	6.56	7.02	0	0
	3.31	6.52	6.10	5.64	5.22	6.55	7.01	0.91	0
	3.32	6.50	5.92	5.59	5.01	6.53	7.00	0.94	0
	3.33	6.60	5.82	5.66	4.88	6.52	6.99	0.86	0
	3.34	6.47	5.75	5.50	4.78	6.50	6.97	1.00	0
Canvey	3.35	6.66	5.82	5.66	4.82	6.48	6.95	0.82	0
	3.36	6.56	5.50	5.56	4.50	6.46	6.93	0.90	0
	3.37	5.30	5.50	4.60	4.50	6.44	6.91	1.51	0
Southend	3.38	5.70	5.50	5.00	4.50	6.40	6.88	1.07	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

The defence raising would be applied in 2070 to cover the period until 2120. The defence levels become more variable due to the mixed standards of protection associated with FRM Policy P3, P4 and P5. In practice defence raising can occur in stages as the sea level rises, but it should be designed to accommodate the full change.

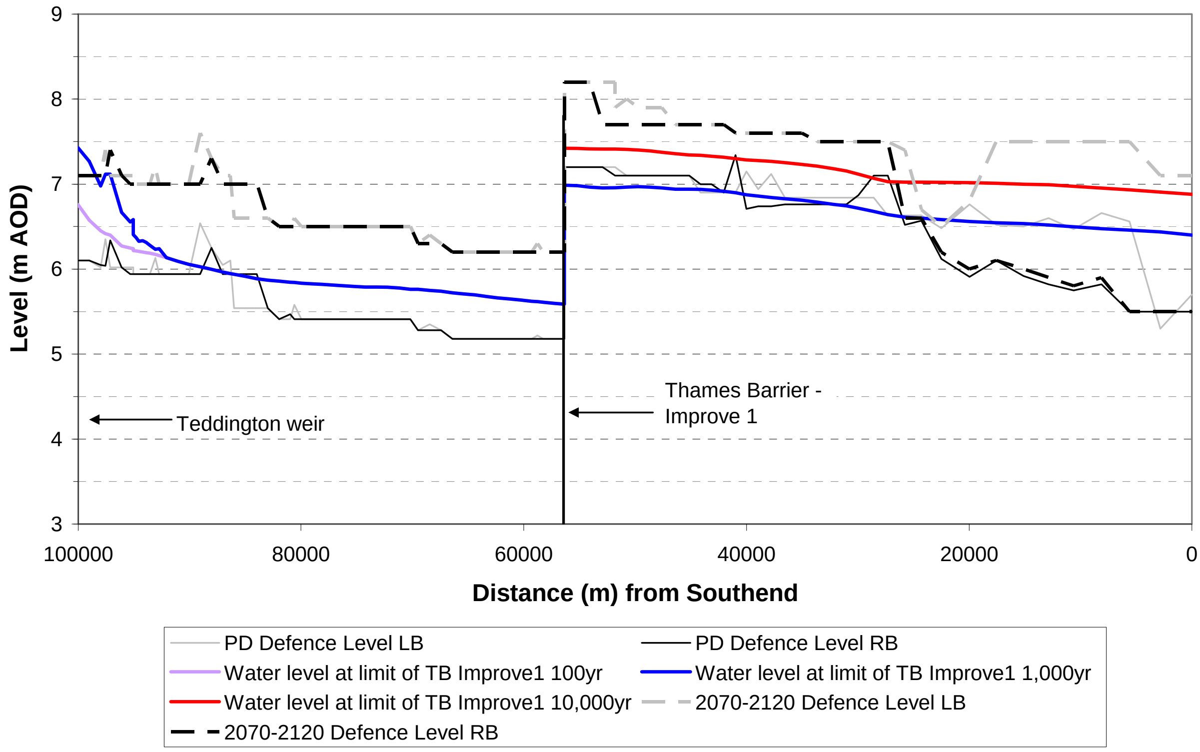

Figure 4.2 Design water levels at the limit of the Thames Barrier improvement (in 2120)

Note that in Figure 4.2 the upriver defences have been increased by 1.0m and the upriver water levels are derived from the barrier closure rule adjusted by plus 1.0m.

Limit of further improvement of the Thames Barrier

The next intervention is to improve the Thames Barrier by extending the gates and raising downriver defences. The Thames Barrier gate units have been modified to reach the improved crest level of 8.8m AOD (design water level of 8.4m AOD).

Table 4.3 shows the intervention in 2170, the limit of the TE2100 interventions. The defence raising covers the period to 2170 (but not beyond). The improvements to the Thames Barrier would last beyond 2170.

Table 4.3 Option 1: Improvement of the Thames Barrier (implemented in 2120)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2170)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	7.32	7.96	1.46	1.46
	3.2	7.20	7.20	6.50	6.50	7.32	7.96	1.46	1.46
	3.3	7.20	7.20	6.50	6.50	7.30	7.95	1.45	1.45
	3.4	7.20	7.20	6.50	6.50	7.30	7.94	1.44	0.80
Roding	a3.5u	7.20	7.10	6.50	6.40	7.30	7.92	1.42	0.90
	a3.5d	7.20	7.10	6.50	6.40	7.30	7.92	1.13	0.90
	3.6	7.10	7.10	6.40	6.40	7.29	7.91	1.21	0.89
	3.7	7.10	7.10	6.40	6.40	7.27	7.89	1.20	0.87
Beam	3.8	7.10	7.10	6.40	6.40	7.27	7.86	1.18	0.87
	3.9	7.10	7.10	6.40	6.40	7.26	7.83	1.16	0.86
	3.10	7.10	7.10	6.40	6.40	7.25	7.80	0.85	0.85
	3.11	7.10	7.10	6.40	6.40	7.25	7.76	0.85	0.85
	3.12	6.90	7.00	6.20	6.30	7.25	7.73	1.05	0.95
	3.13	6.90	7.00	6.20	6.30	7.24	7.73	1.04	0.94
	3.14	6.90	6.90	6.20	6.20	7.22	7.72	1.02	1.02
Darent	3.15u	6.90	7.34	6.20	6.64	7.21	7.70	1.01	0.57
	3.15d	6.90	7.34	6.20	6.64	7.21	7.70	1.01	0.57
	3.16	7.15	6.71	6.45	6.01	7.19	7.69	0.74	1.18
	3.17	6.94	6.74	6.24	6.04	7.17	7.68	0.93	1.13
	3.18	7.12	6.74	6.42	6.04	7.14	7.67	0.72	1.10
	3.19	6.84	6.76	6.14	6.06	7.12	7.66	0.98	1.06
	3.20	6.84	6.76	6.14	6.06	7.09	7.64	0.95	1.03
	3.21	6.84	6.76	6.14	6.06	7.07	7.63	0.93	1.01
	3.22	6.84	6.76	6.14	6.06	7.03	7.61	0.89	0.97
	3.23	6.84	6.76	6.13	6.05	7.01	7.59	0.88	0.96
	3.24	6.84	6.87	6.11	6.14	7.02	7.57	0.91	0.88
	3.25	6.84	7.10	6.10	6.36	7.03	7.54	0.93	0.67
Tilbury	3.26	6.63	7.10	5.87	6.34	7.05	7.53	1.18	0.71
	3.27	6.63	6.52	5.85	5.74	7.06	7.51	1.21	0
	3.28	6.63	6.57	5.83	5.77	7.06	7.51	0	0
	3.29	6.48	6.12	5.66	5.30	7.05	7.51	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	7.05	7.51	0	0
	3.31	6.52	6.10	5.64	5.22	7.05	7.53	1.41	0
	3.32	6.50	5.92	5.59	5.01	7.05	7.51	1.46	0
	3.33	6.60	5.82	5.66	4.88	7.04	7.49	1.38	0
	3.34	6.47	5.75	5.50	4.78	7.04	7.50	1.54	0
Canvey	3.35	6.66	5.82	5.66	4.82	7.04	7.50	1.38	0
	3.36	6.56	5.50	5.56	4.50	7.03	7.50	1.47	0
	3.37	5.30	5.50	4.60	4.50	7.01	7.49	2.08	0
Southend	3.38	5.70	5.50	5.00	4.50	7.00	7.48	1.67	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

The defence raising would be applied in 2120 to cover the period until 2170.

For upriver of the Thames Barrier, defence levels are required to be raised by 0.5m in 2065, a further 0.5m in 2100 and a further 0.5m in 2135. This is based on an assumed operational limit of the Thames Barrier of 50 closures per year with forecast/operation uncertainty of 0.2m. If the maximum amount of upriver defence raising is 1m, the limit of Option 1 is reached 2135. At this decision point a new barrage or barrier with locks is required to avoid further raising of the upriver defences.

4.3 Option 2 (flood storage)

Option 2 consists of the following interventions for extreme water level:

- Raise defences as required (suitable until the design water level at the Thames Barrier reaches 6.5m AOD).
- Flood storage, over-rotate 31m RSG and raise defences (limit is when the design water level at the Thames Barrier reaches 6.9m AOD).
- Improve Thames Barrier and raise defences (limit is when the design water level at the Thames Barrier reaches 7.4m AOD).
- Improve Thames Barrier and raise defences (limit is when the design water level at the Thames Barrier reaches 8.4m AOD).

Models were set up for each intervention and run for design tides for a number of epochs to determine the limit of each intervention.

Limit of the existing Thames Barrier

The model for Phase 3 Set 2 Option 2 to determine the limit of the current Thames Barrier (design water level 6.5m AOD) to extreme water level is the same as that in Phase 3 Set 2 Option 1. This is because it covers the period before any major interventions take place.

The limit of the Thames Barrier is the same as Option 1 in 2070, and the defence raising required in 2040 (to 2070) is also the same as in Option 1.

Limit of flood storage and over-rotation of the Thames Barrier

The first major intervention(s) allows for the implementation of Policy P5 together with further improvement for sea level rise. For Phase 3 Set 2 Option 2 this consists of a combination of flood storage and over-rotation of the Thames Barrier. For Phase 3 Set 2 the recommended combination of storage areas from Work Element 5.2 has been modified to provide greater area for storage. These modifications are described in the Phase 3 Set 2 Options Report.

In the model the Thames Barrier gate units have been modified to reach the over-rotated crest level of 7.3m AOD (design water level of 6.9m AOD). Downriver defences have also been raised by an additional 0.4m for PMUs where Policy P5 is implemented. This is consistent with the over rotation of the Thames Barrier, which provides Policy P5 for the upriver PMUs. The model includes the combination of storage areas (Shorne, Aveley, Dartford-Crayford, and Erith) as defined in the Phase 3 Set 2 Options Report.

Model results for the intervention in 2070 are shown in Table 4.4 and Figure 4.3. The limit of this intervention is 2115, when a further intervention would be needed. Table 4.4 also shows the downriver PMUs where the FRM Policy has been increased to P5.

Table 4.4 Storage and over-rotation of the Thames Barrier (implemented in 2070, limit in 2115)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2115)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	6.39	6.88	0.38	0.38
	3.2	7.20	7.20	6.50	6.50	6.39	6.86	0.36	0.36
	3.3	7.20	7.20	6.50	6.50	6.37	6.84	0.34	0.34
	3.4	7.20	7.20	6.50	6.50	6.38	6.84	0.34	-
Roding	a3.5u	7.20	7.10	6.50	6.40	6.38	6.85	0.35	-
	a3.5d	7.20	7.10	6.50	6.40	6.38	6.85	0.13	-
	3.6	7.10	7.10	6.40	6.40	6.37	6.86	0.23	-
	3.7	7.10	7.10	6.40	6.40	6.36	6.86	0.22	-
Beam	3.8	7.10	7.10	6.40	6.40	6.35	6.85	0.21	-
	3.9	7.10	7.10	6.40	6.40	6.35	6.81	0.20	-
	3.10	7.10	7.10	6.40	6.40	6.35	6.80	-	-
	3.11	7.10	7.10	6.40	6.40	6.34	6.79	-	-
	3.12	6.90	7.00	6.20	6.30	6.35	6.79	0.15	0.05
	3.13	6.90	7.00	6.20	6.30	6.35	6.79	0.15	0.05
	3.14	6.90	6.90	6.20	6.20	6.34	6.79	0.14	0.14
Darent	3.15u	6.90	7.34	6.20	6.64	6.33	6.80	0.13	-
	3.15d	6.90	7.34	6.20	6.64	6.33	6.80	0.13	-
	3.16	7.15	6.71	6.45	6.01	6.32	6.79	-	0.31
	3.17	6.94	6.74	6.24	6.04	6.32	6.78	0.08	0.28
	3.18	7.12	6.74	6.42	6.04	6.32	6.79	-	0.28
	3.19	6.84	6.76	6.14	6.06	6.32	6.80	0.18	0.26
	3.20	6.84	6.76	6.14	6.06	6.31	6.80	0.17	0.25
	3.21	6.84	6.76	6.14	6.06	6.31	6.78	0.17	0.25
	3.22	6.84	6.76	6.14	6.06	6.30	6.78	0.16	0.24
	3.23	6.84	6.76	6.13	6.05	6.30	6.77	0.17	0.25
	3.24	6.84	6.87	6.11	6.14	6.28	6.76	0.17	0.14
	3.25	6.84	7.10	6.10	6.36	6.27	6.74	0.17	-
Tilbury	3.26	6.63	7.10	5.87	6.34	6.26	6.74	0.39	-
	3.27	6.63	6.52	5.85	5.74	6.27	6.73	0.42	0
	3.28	6.63	6.57	5.83	5.77	6.27	6.72	0	0
	3.29	6.48	6.12	5.66	5.30	6.26	6.72	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	6.25	6.71	0	0
	3.31	6.52	6.10	5.64	5.22	6.26	6.72	0.62	0
	3.32	6.50	5.92	5.59	5.01	6.24	6.71	0.65	0
	3.33	6.60	5.82	5.66	4.88	6.24	6.71	0.58	0
	3.34	6.47	5.75	5.50	4.78	6.23	6.70	0.73	0
Canvey	3.35	6.66	5.82	5.66	4.82	6.22	6.70	0.56	0
	3.36	6.56	5.50	5.56	4.50	6.22	6.70	0.66	0
	3.37	5.30	5.50	4.60	4.50	6.21	6.69	1.28	0
Southend	3.38	5.70	5.50	5.00	4.50	6.18	6.66	0.85	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

The limit of the over-rotated Thames Barrier with flood storage is reached in approximately 2115. Defence raising for PMUs with Policy P4 and P5 is required in 2070 to cover the period until 2115.

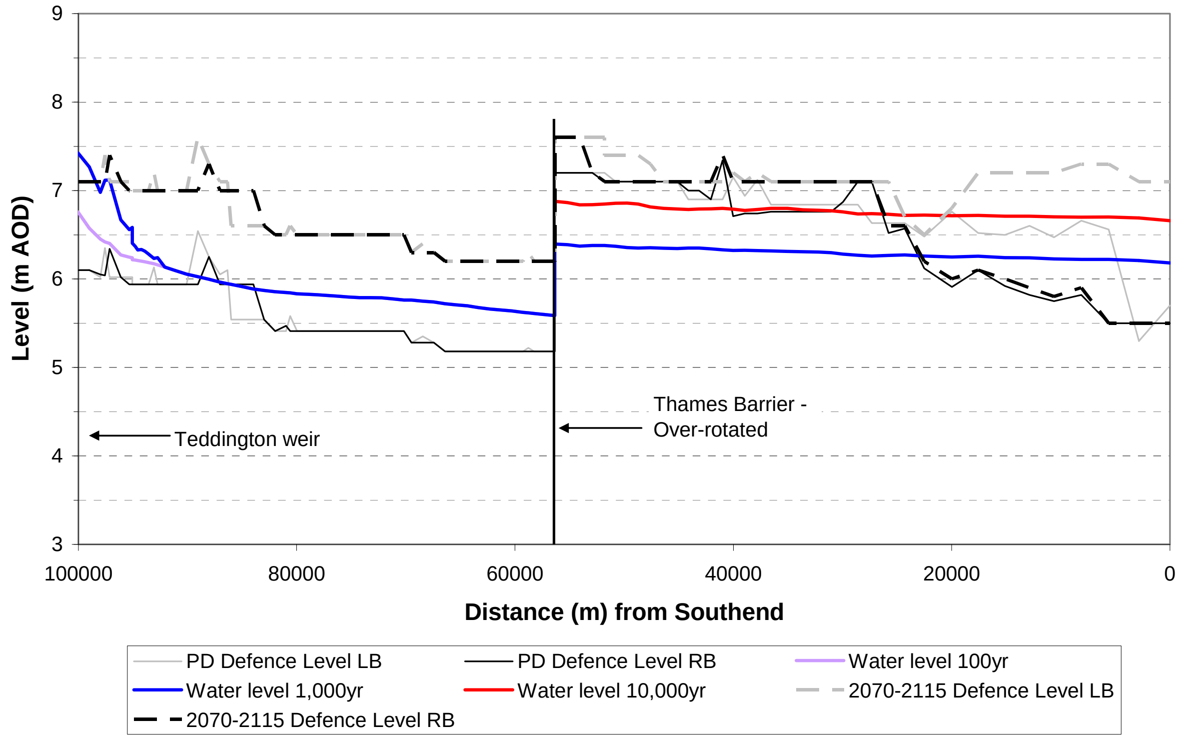

Figure 4.3 Design water levels at the limit of flood storage and the over-rotated Thames Barrier (in 2115)

Limit of flood storage and improvement of the Thames Barrier

The next intervention involves improving the Thames Barrier together with raising the downriver defences. Improvement of the Thames Barrier includes:

- over-rotation of the 61m RSG
- sill beams for the 31m RSG

These improvements to the Thames Barrier mean that the gate units have been modified to reach a crest level of 7.8m AOD (design water level of 7.4m AOD). The flood storage areas are still included in the model.

Model results for the intervention in 2115 are shown in Table 4.5.

Table 4.5 Storage and improvements to the Thames Barrier (implemented in 2115, limit in 2140)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2140)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	6.80	7.26	0.76	0.76
	3.2	7.20	7.20	6.50	6.50	6.79	7.26	0.76	0.76
	3.3	7.20	7.20	6.50	6.50	6.79	7.25	0.75	0.75
	3.4	7.20	7.20	6.50	6.50	6.78	7.24	0.74	0.28
Roding	a3.5u	7.20	7.10	6.50	6.40	6.77	7.23	0.73	0.37
	a3.5d	7.20	7.10	6.50	6.40	6.77	7.23	0.52	0.37
	3.6	7.10	7.10	6.40	6.40	6.76	7.22	0.60	0.36
	3.7	7.10	7.10	6.40	6.40	6.75	7.22	0.60	0.35
Beam	3.8	7.10	7.10	6.40	6.40	6.75	7.22	0.60	0.35
	3.9	7.10	7.10	6.40	6.40	6.75	7.21	0.59	0.35
	3.10	7.10	7.10	6.40	6.40	6.74	7.20	0.34	0.34
	3.11	7.10	7.10	6.40	6.40	6.74	7.19	0.34	0.34
	3.12	6.90	7.00	6.20	6.30	6.73	7.18	0.53	0.43
	3.13	6.90	7.00	6.20	6.30	6.73	7.18	0.53	0.43
	3.14	6.90	6.90	6.20	6.20	6.73	7.17	0.53	0.53
Darent	3.15u	6.90	7.34	6.20	6.64	6.73	7.16	0.53	0.09
	3.15d	6.90	7.34	6.20	6.64	6.73	7.16	0.53	0.09
	3.16	7.15	6.71	6.45	6.01	6.72	7.15	0.27	0.71
	3.17	6.94	6.74	6.24	6.04	6.70	7.13	0.46	0.66
	3.18	7.12	6.74	6.42	6.04	6.68	7.11	0.26	0.64
	3.19	6.84	6.76	6.14	6.06	6.67	7.09	0.53	0.61
	3.20	6.84	6.76	6.14	6.06	6.65	7.07	0.51	0.59
	3.21	6.84	6.76	6.14	6.06	6.64	7.05	0.50	0.58
	3.22	6.84	6.76	6.14	6.06	6.63	7.05	0.49	0.57
	3.23	6.84	6.76	6.13	6.05	6.63	7.05	0.50	0.58
	3.24	6.84	6.87	6.11	6.14	6.62	7.03	0.51	0.48
	3.25	6.84	7.10	6.10	6.36	6.61	7.03	0.51	0.25
Tilbury	3.26	6.63	7.10	5.87	6.34	6.61	7.04	0.74	0.27
	3.27	6.63	6.52	5.85	5.74	6.60	7.05	0.75	0
	3.28	6.63	6.57	5.83	5.77	6.59	7.06	0	0
	3.29	6.48	6.12	5.66	5.30	6.59	7.05	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	6.58	7.03	0	0
	3.31	6.52	6.10	5.64	5.22	6.59	7.04	0.95	0
	3.32	6.50	5.92	5.59	5.01	6.59	7.05	1.00	0
	3.33	6.60	5.82	5.66	4.88	6.58	7.05	0.92	0
	3.34	6.47	5.75	5.50	4.78	6.58	7.05	1.08	0
Canvey	3.35	6.66	5.82	5.66	4.82	6.57	7.05	0.91	0
	3.36	6.56	5.50	5.56	4.50	6.57	7.05	1.01	0
	3.37	5.30	5.50	4.60	4.50	6.56	7.04	1.83	0
Southend	3.38	5.70	5.50	5.00	4.50	6.55	7.03	1.22	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

The limit of the improved Thames Barrier with flood storage is reached in approximately 2140. Defence raising for PMUs with Policy P4 and P5 is required in 2115 to cover the period until 2140. Water levels at the limit of this intervention are shown on Figure 4.4.

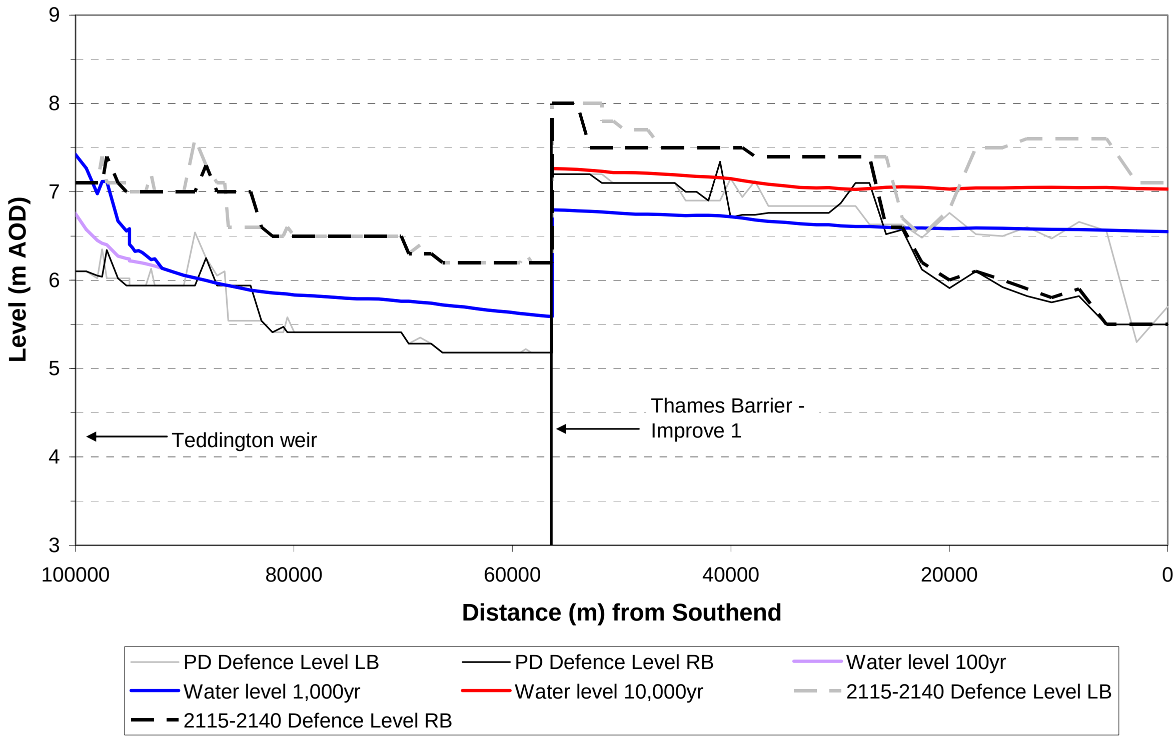

Figure 4.4 Design water levels at the limit of flood storage and improvement of the Thames Barrier (in 2140)

Limit of further improvements to the Thames Barrier

The next improvement to the Thames Barrier is to modify the gate units to reach the improved crest level of 8.8m AOD (design water level of 8.4m AOD). However, Option 2 is limited in 2135 due to the number of barrier closures. If this limit did not exist, the second improvement to the Thames Barrier would be introduced in 2140 and the downriver defences raised.

The flood storage areas would not be in use after 2140, because they are no longer effective compared to Option 1. The purpose of flood storage is to delay the date at which improvements are required for the Thames Barrier and associated downriver defences by reducing peak water levels.

This limit is reached in approximately 2140, after which the benefit of flood storage reduces as the sea level increases, as shown in Table 4.6 below. The benefit of designed flood storage decreases for tides greater than around 6.5m due to large areas of overtopping in the outer estuary producing un-planned storage which modifies the tide shape to a broad peak. Small areas of designed storage do not produce further reductions in water level.

Table 4.6 Reduction in peak water level at the Thames Barrier due to flood storage compared to Option 1

Epoch	Reduction in water level (m)	
	1000yr	10000yr
2100	0.38	0.46
2115	0.46	0.42
2130	0.36	0.33
2140	0.26	0.25
2155	0.18	0.14
2170	-0.01	-0.14

Flood storage areas are therefore no longer included in the modelling after 2140, and the Option 2 model becomes the same as the Option 1 model. The water levels and required defence levels for Option 2 in 2170 (assuming no limit due to closures) are the same as in Option 1 (and are shown in Table 4.3).

4.4 Option 3 (new barriers)

Option 3 consists of the following interventions for extreme water level:

- Raise defences as required (suitable until the design water level at the Thames Barrier reaches 6.5m AOD).
- New barrier and raised downriver defences.

Models were set up for each intervention and run for design tides for a number of epochs to determine the limit of each intervention.

The model for Phase 3 Set 2 Option 3 to determine the limit of the current Thames Barrier (design water level 6.5m AOD) to extreme water level is the same as that in Phase 3 Set 2 Option 1. This is because it covers the period before any major interventions take place. The limit of the Thames Barrier is the same as Option 1 in 2070, and the defence raising required to 2070 is also the same as in Option 1.

4.4.1 Option 3-1 (New Barrier at Tilbury)

In the model for Phase 3 Set 2 Option 3-1 the new barrier at Tilbury has been included. The sizes of the gates have been determined by hydraulic analysis using the option development model (TE2100 2008a Appendix D). These are based on the Thames Barrier gate units, with the size of the gates increased.

The crest level of the gates is set at 8.9m AOD based on recommendations in the TE2100 Barriers and Barrages Study. Raised defences are included across the floodplains to prevent bypassing of the barrier. The Policy P5 and P4 defences downriver of the new barrier have been raised by about 2 m.

The crest level must be high enough to prevent overtopping of the barrier. The actual design defence level is determined from the modelling of this option. The results are shown in Table 4.7 and Figure 4.5.

Table 4.7 New Barrier at Tilbury (implemented in 2070, limit in 2135)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2140)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	5.61	5.61	-	-
	3.2	7.20	7.20	6.50	6.50	5.59	5.59	-	-
	3.3	7.20	7.20	6.50	6.50	5.58	5.58	-	-
	3.4	7.20	7.20	6.50	6.50	5.57	5.57	-	-
Roding	a3.5u	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	a3.5d	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	3.6	7.10	7.10	6.40	6.40	5.54	5.54	-	-
	3.7	7.10	7.10	6.40	6.40	5.53	5.53	-	-
Beam	3.8	7.10	7.10	6.40	6.40	5.51	5.51	-	-
	3.9	7.10	7.10	6.40	6.40	5.49	5.49	-	-
	3.10	7.10	7.10	6.40	6.40	5.48	5.48	-	-
	3.11	7.10	7.10	6.40	6.40	5.46	5.46	-	-
	3.12	6.90	7.00	6.20	6.30	5.45	5.45	-	-
	3.13	6.90	7.00	6.20	6.30	5.43	5.43	-	-
	3.14	6.90	6.90	6.20	6.20	5.42	5.42	-	-
Darent	3.15u	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.15d	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.16	7.15	6.71	6.45	6.01	5.39	5.39	-	-
	3.17	6.94	6.74	6.24	6.04	5.37	5.37	-	-
	3.18	7.12	6.74	6.42	6.04	5.35	5.35	-	-
	3.19	6.84	6.76	6.14	6.06	5.33	5.33	-	-
	3.20	6.84	6.76	6.14	6.06	5.31	5.31	-	-
	3.21	6.84	6.76	6.14	6.06	5.30	5.30	-	-
	3.22	6.84	6.76	6.14	6.06	5.27	5.27	-	-
	3.23	6.84	6.76	6.13	6.05	5.25	5.25	-	-
	3.24	6.84	6.87	6.11	6.14	5.23	5.23	-	-
	3.25	6.84	7.10	6.10	6.36	5.20	5.20	-	-
Tilbury	3.26	6.63	7.10	5.87	6.34	5.18	5.18	-	-
	3.27	6.63	6.52	5.85	5.74	6.61	7.11	1.26	1.37
	3.28	6.63	6.57	5.83	5.77	6.61	7.11	0	0
	3.29	6.48	6.12	5.66	5.30	6.60	7.10	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	6.60	7.08	0	0
	3.31	6.52	6.10	5.64	5.22	6.59	7.07	0.95	0
	3.32	6.50	5.92	5.59	5.01	6.59	7.07	1.00	0
	3.33	6.60	5.82	5.66	4.88	6.58	7.06	0.92	0
	3.34	6.47	5.75	5.50	4.78	6.57	7.06	1.07	0
Canvey	3.35	6.66	5.82	5.66	4.82	6.57	7.05	0.91	0
	3.36	6.56	5.50	5.56	4.50	6.56	7.05	1.00	0
	3.37	5.30	5.50	4.60	4.50	6.56	7.04	1.63	0
Southend	3.38	5.70	5.50	5.00	4.50	6.55	7.03	1.22	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

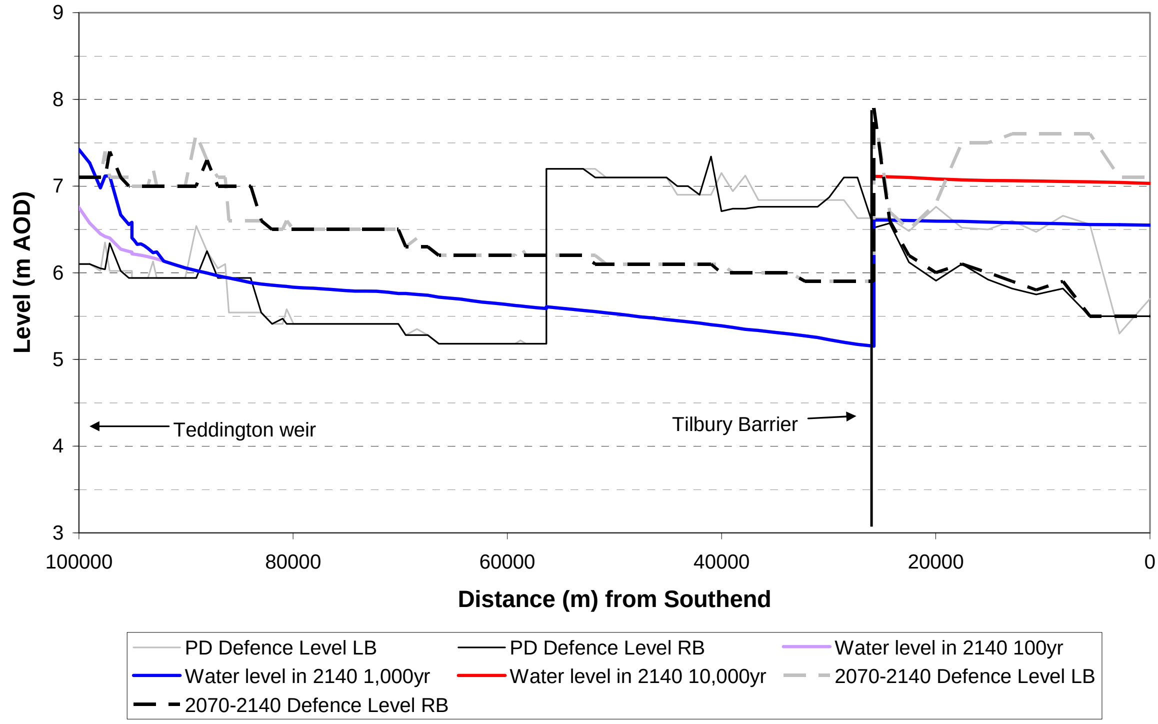

Figure 4.5 Design water levels at the limit in 2135

Note that water levels downriver of the barrier are for 2140.

For upriver of the Thames Barrier, defence levels are required to be raised by 0.5m in 2065, a further 0.5m in 2100 and a further 0.5m in 2135. This is based on an assumed operational limit of the new barrier of 50 closures per year with forecast/operation uncertainty of 0.2m. If the maximum amount of upriver defence raising is 1m, and the new barrier has the same operational limit as the Thames Barrier, the limit of Option 3-1 is reached 2135. At this decision point a new barrage or a barrier with locks is required.

4.4.2 Option 3-2 (New Barrier at Long Reach)

In the model for Phase 3 Set 2 Option 3-2 the new barrier at Long Reach has been included. The sizes of the gates have been determined by hydraulic analysis (TE2100 2008a Appendix D). The gates are based on the Thames Barrier gate units, with the size of the gates increased.

The crest level of the gates is 8.9m AOD based on recommendations in the TE2100 Barriers and Barrages Study (TE2100 2008e). Raised defence are included across the floodplain to prevent bypassing of the barrier. The Policy P5 and P4 defences downriver of the new barrier have been raised by about 1 m. The results are shown in Table 4.8 and Figure 4.6.

Table 4.8 New Barrier at Long Reach (implemented in 2070, limit in 2135)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2140)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	5.61	5.61	-	-
	3.2	7.20	7.20	6.50	6.50	5.59	5.59	-	-
	3.3	7.20	7.20	6.50	6.50	5.58	5.58	-	-
	3.4	7.20	7.20	6.50	6.50	5.57	5.57	-	-
Roding	a3.5u	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	a3.5d	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	3.6	7.10	7.10	6.40	6.40	5.54	5.54	-	-
	3.7	7.10	7.10	6.40	6.40	5.53	5.53	-	-
Beam	3.8	7.10	7.10	6.40	6.40	5.51	5.51	-	-
	3.9	7.10	7.10	6.40	6.40	5.49	5.49	-	-
	3.10	7.10	7.10	6.40	6.40	5.48	5.48	-	-
	3.11	7.10	7.10	6.40	6.40	5.46	5.46	-	-
	3.12	6.90	7.00	6.20	6.30	5.45	5.45	-	-
	3.13	6.90	7.00	6.20	6.30	5.43	5.43	-	-
	3.14	6.90	6.90	6.20	6.20	5.42	5.42	-	-
Darent	3.15u	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.15d	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.16	7.15	6.71	6.45	6.01	5.39	5.39	-	-
	3.17	6.94	6.74	6.24	6.04	7.01	7.41	1.17	1.37
	3.18	7.12	6.74	6.42	6.04	7.01	7.41	0.59	0.97
	3.19	6.84	6.76	6.14	6.06	7.00	7.40	0.86	0.94
	3.20	6.84	6.76	6.14	6.06	6.99	7.40	0.85	0.93
	3.21	6.84	6.76	6.14	6.06	6.98	7.39	0.84	0.92
	3.22	6.84	6.76	6.14	6.06	6.96	7.38	0.82	0.90
	3.23	6.84	6.76	6.13	6.05	6.95	7.37	0.82	0.90
	3.24	6.84	6.87	6.11	6.14	6.93	7.35	0.82	0.79
	3.25	6.84	7.10	6.10	6.36	6.90	7.33	0.80	0.54
Tilbury	3.26	6.63	7.10	5.87	6.34	6.88	7.30	1.01	0.54
	3.27	6.63	6.52	5.85	5.74	6.85	7.28	1.00	0
	3.28	6.63	6.57	5.83	5.77	6.83	7.26	0	0
	3.29	6.48	6.12	5.66	5.30	6.79	7.23	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	6.75	7.18	0	0
	3.31	6.52	6.10	5.64	5.22	6.72	7.15	1.08	0
	3.32	6.50	5.92	5.59	5.01	6.70	7.13	1.11	0
	3.33	6.60	5.82	5.66	4.88	6.68	7.11	1.02	0
	3.34	6.47	5.75	5.50	4.78	6.65	7.09	1.15	0
Canvey	3.35	6.66	5.82	5.66	4.82	6.63	7.08	0.97	0
	3.36	6.56	5.50	5.56	4.50	6.60	7.06	1.04	0
	3.37	5.30	5.50	4.60	4.50	6.57	7.05	1.64	0
Southend	3.38	5.70	5.50	5.00	4.50	6.55	7.03	1.22	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

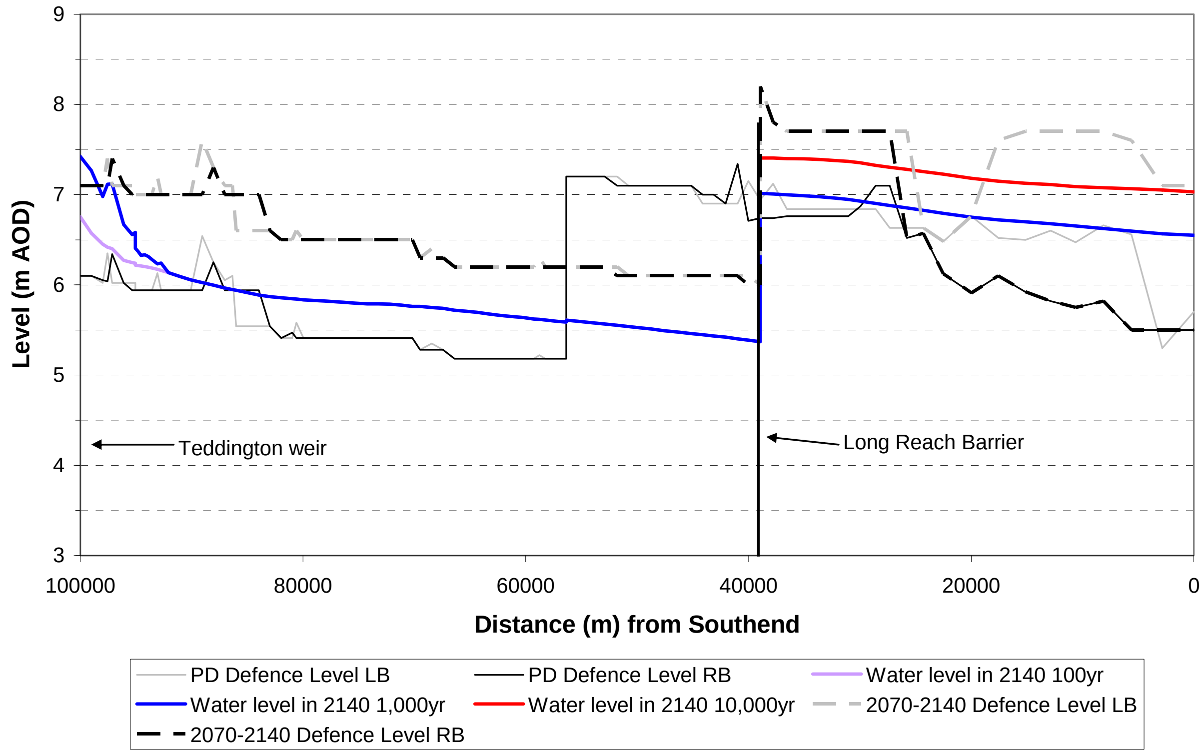

Figure 4.6 Design water levels at the limit in 2135

Note that water levels downstream of the barrier are for 2140.

4.5 Option 4 (barriers with locks)

Option 4 includes the introduction of new barriers with locks once the design water level at the Thames Barrier reaches 6.5m AOD. This is an alternative to raising the crest level of the existing barrier and raising significant lengths of embankment.

The model for Phase 3 Set 2 Option 4 to determine the limit of the current Thames Barrier (design water level 6.5m AOD) to extreme water level is the same as that in Phase 3 Set 2 Option 1. This is because it covers the period before any major interventions take place. The defence raising intervention required to get to the limit of the Thames Barrier (2070) is the same as in Option 1.

4.5.1 Option 4-1 (New Barrier with Locks at Tilbury)

When the barrier with locks is closed during extreme tides, the Phase 3 Set 2 Option 4-1 model is the same as the Phase 3 Set 2 Option 3-1 model.

This is because the basic function of the barriers is to prevent high surge tides propagating upriver, and they all present the same blockage to the estuary at each location. Variations caused by gate openings are eliminated by closing the gates at low tide.

The new barrier with locks is located in Tilbury and is introduced in 2070. Water levels downriver of the new barrier with locks together with increases to downriver defence crest levels required for the period until 2170 are shown in Table 4.9 and Figure 4.7.

Table 4.9 New Barrier with locks at Tilbury (implemented in 2070, limit in 2170)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2170)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	5.61	5.61	-	-
	3.2	7.20	7.20	6.50	6.50	5.59	5.59	-	-
	3.3	7.20	7.20	6.50	6.50	5.58	5.58	-	-
	3.4	7.20	7.20	6.50	6.50	5.57	5.57	-	-
Roding	a3.5u	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	a3.5d	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	3.6	7.10	7.10	6.40	6.40	5.54	5.54	-	-
	3.7	7.10	7.10	6.40	6.40	5.53	5.53	-	-
Beam	3.8	7.10	7.10	6.40	6.40	5.51	5.51	-	-
	3.9	7.10	7.10	6.40	6.40	5.49	5.49	-	-
	3.10	7.10	7.10	6.40	6.40	5.48	5.48	-	-
	3.11	7.10	7.10	6.40	6.40	5.46	5.46	-	-
	3.12	6.90	7.00	6.20	6.30	5.45	5.45	-	-
	3.13	6.90	7.00	6.20	6.30	5.43	5.43	-	-
	3.14	6.90	6.90	6.20	6.20	5.42	5.42	-	-
Darent	3.15u	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.15d	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.16	7.15	6.71	6.45	6.01	5.39	5.39	-	-
	3.17	6.94	6.74	6.24	6.04	5.37	5.37	-	-
	3.18	7.12	6.74	6.42	6.04	5.35	5.35	-	-
	3.19	6.84	6.76	6.14	6.06	5.33	5.33	-	-
	3.20	6.84	6.76	6.14	6.06	5.31	5.31	-	-
	3.21	6.84	6.76	6.14	6.06	5.30	5.30	-	-
	3.22	6.84	6.76	6.14	6.06	5.27	5.27	-	-
	3.23	6.84	6.76	6.13	6.05	5.25	5.25	-	-
	3.24	6.84	6.87	6.11	6.14	5.23	5.23	-	-
	3.25	6.84	7.10	6.10	6.36	5.20	5.20	-	-
Tilbury	3.26	6.63	7.10	5.87	6.34	5.18	5.18	-	-
	3.27	6.63	6.52	5.85	5.74	7.06	7.62	1.77	1.88
	3.28	6.63	6.57	5.83	5.77	7.06	7.62	0	0
	3.29	6.48	6.12	5.66	5.30	7.05	7.61	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	7.05	7.59	0	0
	3.31	6.52	6.10	5.64	5.22	7.04	7.58	1.40	0
	3.32	6.50	5.92	5.59	5.01	7.04	7.55	1.45	0
	3.33	6.60	5.82	5.66	4.88	7.03	7.51	1.37	0
	3.34	6.47	5.75	5.50	4.78	7.02	7.49	1.52	0
Canvey	3.35	6.66	5.82	5.66	4.82	7.02	7.49	1.36	0
	3.36	6.56	5.50	5.56	4.50	7.02	7.49	1.46	0
	3.37	5.30	5.50	4.60	4.50	7.01	7.49	2.08	0
Southend	3.38	5.70	5.50	5.00	4.50	7.00	7.48	1.67	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

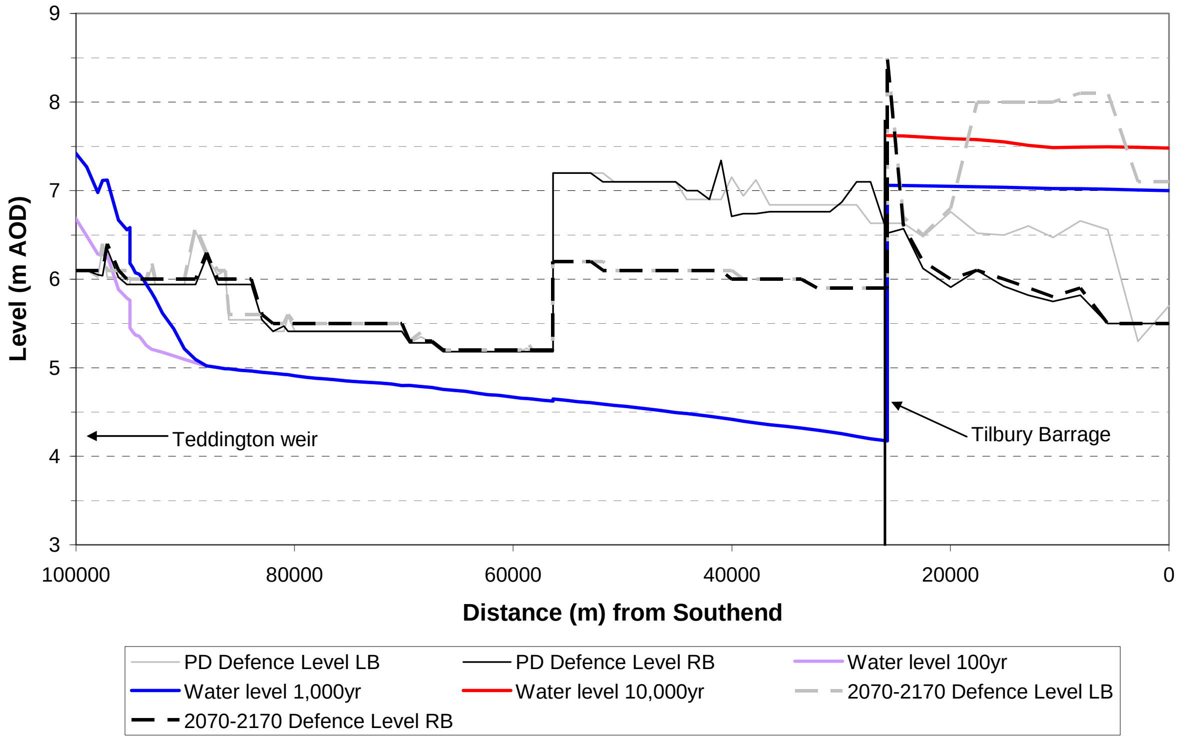

Figure 4.7 Design water levels at the limit in 2170

4.5.2 Option 4-2 (New Barrier with Locks at Long Reach)

The new barrier with locks is located in Long Reach and is introduced in 2070. When the barrier with locks is closed during extreme tides, the Phase 3 Set 2 Option 4-2 model is the same as the Phase 3 Set 2 Option 3-2 model.

Water levels downriver of the Long Reach barrier with locks together with increases to downriver defence crest levels required for the period until 2170 are shown in Table 4.10 and Figure 4.8.

Table 4.10 New Barrier with locks at Long Reach (implemented in 2070, limit in 2170)

Location	Node	Defence Level		Defence Level - Freeboard		Peak Water Level (2170)		Total Defence Raising Required	
		LB	RB	LB	RB	1,000yr	10,000yr	LB	RB
Barrier	a3.1	7.20	7.20	6.50	6.50	5.61	5.61	-	-
	3.2	7.20	7.20	6.50	6.50	5.59	5.59	-	-
	3.3	7.20	7.20	6.50	6.50	5.58	5.58	-	-
	3.4	7.20	7.20	6.50	6.50	5.57	5.57	-	-
Roding	a3.5u	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	a3.5d	7.20	7.10	6.50	6.40	5.55	5.55	-	-
	3.6	7.10	7.10	6.40	6.40	5.54	5.54	-	-
	3.7	7.10	7.10	6.40	6.40	5.53	5.53	-	-
Beam	3.8	7.10	7.10	6.40	6.40	5.51	5.51	-	-
	3.9	7.10	7.10	6.40	6.40	5.49	5.49	-	-
	3.10	7.10	7.10	6.40	6.40	5.48	5.48	-	-
	3.11	7.10	7.10	6.40	6.40	5.46	5.46	-	-
	3.12	6.90	7.00	6.20	6.30	5.45	5.45	-	-
	3.13	6.90	7.00	6.20	6.30	5.43	5.43	-	-
	3.14	6.90	6.90	6.20	6.20	5.42	5.42	-	-
Darent	3.15u	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.15d	6.90	7.34	6.20	6.64	5.40	5.40	-	-
	3.16	7.15	6.71	6.45	6.01	5.39	5.39	-	-
	3.17	6.94	6.74	6.24	6.04	7.32	7.79	1.55	1.75
	3.18	7.12	6.74	6.42	6.04	7.32	7.79	0.90	1.28
	3.19	6.84	6.76	6.14	6.06	7.31	7.78	1.17	1.25
	3.20	6.84	6.76	6.14	6.06	7.31	7.77	1.17	1.25
	3.21	6.84	6.76	6.14	6.06	7.31	7.76	1.17	1.25
	3.22	6.84	6.76	6.14	6.06	7.30	7.77	1.16	1.24
	3.23	6.84	6.76	6.13	6.05	7.29	7.76	1.16	1.24
	3.24	6.84	6.87	6.11	6.14	7.28	7.76	1.17	1.14
	3.25	6.84	7.10	6.10	6.36	7.26	7.74	1.16	0.90
Tilbury	3.26	6.63	7.10	5.87	6.34	7.24	7.73	1.37	0.90
	3.27	6.63	6.52	5.85	5.74	7.23	7.72	1.38	0
	3.28	6.63	6.57	5.83	5.77	7.21	7.69	0	0
	3.29	6.48	6.12	5.66	5.30	7.19	7.68	0	0
Mucking	3.30	6.76	5.91	5.91	5.06	7.16	7.66	0	0
	3.31	6.52	6.10	5.64	5.22	7.13	7.65	1.49	0
	3.32	6.50	5.92	5.59	5.01	7.10	7.62	1.51	0
	3.33	6.60	5.82	5.66	4.88	7.08	7.57	1.42	0
	3.34	6.47	5.75	5.50	4.78	7.06	7.50	1.56	0
Canvey	3.35	6.66	5.82	5.66	4.82	7.05	7.50	1.39	0
	3.36	6.56	5.50	5.56	4.50	7.04	7.50	1.48	0
	3.37	5.30	5.50	4.60	4.50	7.02	7.50	2.09	0
Southend	3.38	5.70	5.50	5.00	4.50	7.00	7.48	1.67	0

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

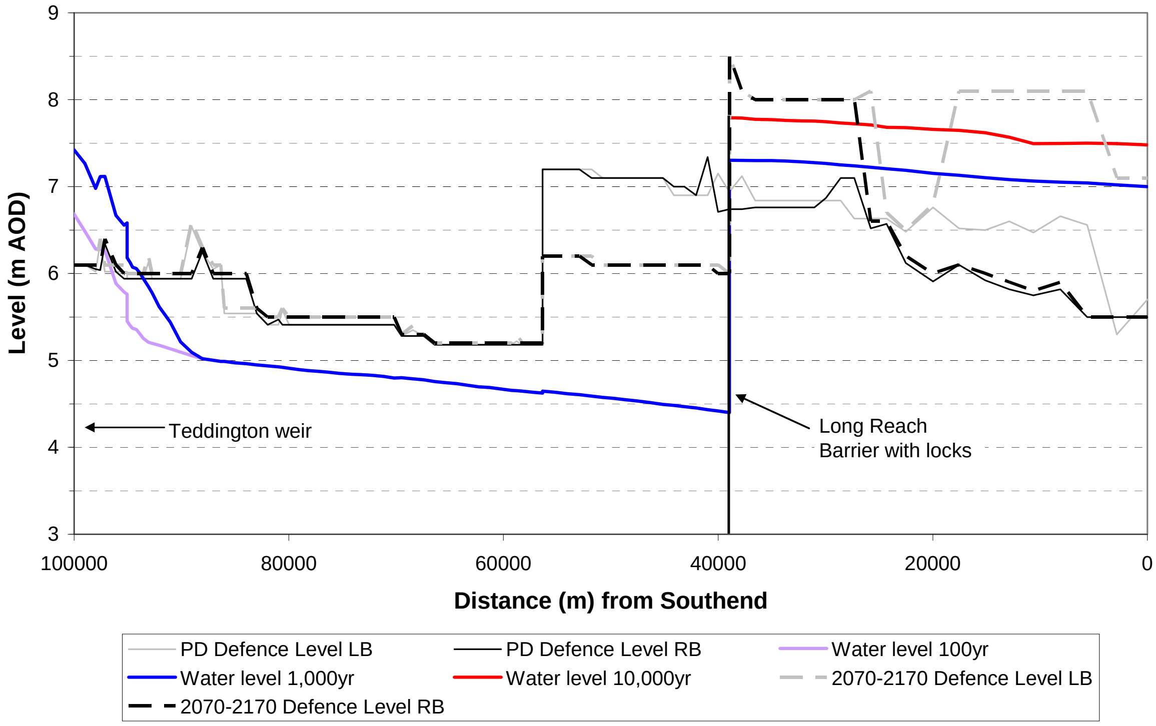

Figure 4.8 Design water levels at the limit in 2170

4.5.3 Option 4-3 (Conversion of the Thames Barrier to a Barrier with Locks)

The Thames Barrier is converted to a barrier with locks in 2070. Water levels downriver of the structure together with increases to downriver defence crest levels required for the period until 2170 are the same as in Option 1, and are shown in Table 4.3.

5 Summary results

5.1 Option 1 (Improve the existing system)

Table 5.1 shows sequence of interventions required for Option 1. The intervention dates are determined from the modelling described in Section 4.2.

Table 5.1 Works required for Option 1

Approximate date	Work required
2020	Habitat creation (Site 1). West Canvey has been assumed in the design of the options.
2040	Habitat creation (Site 2). St. Mary's Marshes has been assumed in the design of the options. Defences downriver of Erith raised by up to 0.3m. Defences at Southend raised by up to 0.7m. New defences at Gravesend (east of urban area).
2050	Habitat creation (Site 3). Grain Marshes has been assumed in the design of the options.
2065	Habitat creation (Site 4). Allhallows Marshes has been assumed in the design of the options. Raise defences by 0.5m upriver of the Thames Barrier.
2070	Over-rotate and Improve Thames Barrier (design water level 7.4m, crest level 7.8m) and introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised by about 1.0 to 1.5m (to cover the period to 2170).
2100	Raise defences by further 0.5m upriver of the Thames Barrier
2120	Improve Thames Barrier (design water level 8.4m, crest level to 8.8m).
2135	Limit reached for this option because of the number of closures of the Thames Barrier and maximum acceptable amount of upriver defence raising.

Note: Because the limit for number of closures is reached in 2135 the improvement of the Thames Barrier in 2120 is likely to be replaced with conversion to a barrier with locks (required crest level 8.4m for 10,000-year SoP).

Table 5.2 (a and b) shows the new defence levels required for Option 1. These results have been combined with deterioration data for the defences to produce tables of replacement and defence raising requirements for each PMU by decade, to take account of the range of dates when defences will require replacement.

Table 5.2a New defence levels upriver of the Thames Barrier for Option 1

OPTION 1.1 DEFENCE LEVELS		Existing defence levels (m AOD)		New defence levels (m AOD)			
				2065 (to 2100)		2100 (to 2135)	
Location	Node	LB	RB	LB	RB	LB	RB
Teddington	2.1	6.10	6.10	6.60	6.60	7.10	7.10
Eel Pie Island	2.3	6.02	6.05	6.60	6.60	7.10	7.10
Marble Hill	2.4	6.02	6.34	6.60	6.90	7.10	7.40
Richmond	a2.6	6.02	5.94	6.60	6.50	7.10	7.00
Richmond	a2.7	5.94	5.94	6.50	6.50	7.00	7.00
R Crane	2.9d	5.94	5.94	6.50	6.50	7.00	7.00
R Brent	2.13d	5.94	5.94	6.50	6.50	7.00	7.00
	2.17d	6.25	6.25	6.30	6.30	7.30	7.30
Hammersmith	2.21	5.54	5.94	6.10	6.00	6.60	7.00
R Wandle	2.24ad	5.58	5.41	6.10	6.00	6.60	6.50
Chelsea	2.29	5.41	5.41	6.00	6.00	6.50	6.50
Tower Pier	2.36	5.28	5.28	5.80	5.80	6.30	6.30
R Ravensbourne	2.42d	5.18	5.18	5.70	5.70	6.20	6.20
R Lee	2.47	5.18	5.18	5.70	5.70	6.20	6.20
Thames Barrier	a2.49	5.18	5.18	5.70	5.70	6.20	6.20

Note: Areas shaded in blue do not show any additional raising for fluvial flood risk.

Table 5.2b New defence levels downriver of the Thames Barrier for Option 1

OPTION 1. DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2120)		2120 (to 2170)	
Location	Node	LB	RB	LB	RB	LB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	8.20	8.20	8.70	8.70
	3.2	7.20	7.20	7.20	7.20	8.20	8.20	8.70	8.70
	3.3	7.20	7.20	7.20	7.20	8.20	8.20	8.70	8.70
	3.4	7.20	7.20	7.20	7.20	8.20	7.70	8.70	8.00
Roding	a3.5u	7.20	7.10	7.20	7.10	8.20	7.70	8.70	8.00
	a3.5d	7.20	7.10	7.20	7.10	7.90	7.70	8.40	8.00
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	8.00	7.70	8.40	8.00
	3.7	7.10	7.10	7.10	7.10	7.90	7.70	8.30	8.00
Beam	3.8	7.10	7.10	7.10	7.10	7.90	7.70	8.30	8.00
	3.9	7.10	7.10	7.10	7.10	7.90	7.70	8.30	8.00
	3.10	7.10	7.10	7.10	7.10	7.70	7.70	8.00	8.00
	3.11	7.10	7.10	7.10	7.10	7.70	7.70	8.00	8.00
	3.12	6.90	7.00	7.10	7.10	7.70	7.70	8.00	8.00
	3.13	6.90	7.00	7.10	7.10	7.70	7.70	8.00	8.00
	3.14	6.90	6.90	7.10	7.10	7.70	7.70	8.00	8.00
Darent	3.15u	6.90	7.34	7.10	7.34	7.60	7.60	8.00	8.00
	3.15d	6.90	7.34	7.10	7.34	7.60	7.60	8.00	8.00
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	7.60	7.60	7.90	7.90
	3.17	6.94	6.74	7.00	7.00	7.60	7.60	7.90	7.90
	3.18	7.12	6.74	7.12	7.00	7.60	7.60	7.90	7.90
	3.19	6.84	6.76	7.00	7.00	7.60	7.60	7.90	7.90
	3.20	6.84	6.76	7.00	7.00	7.60	7.60	7.80	7.80
	3.21	6.84	6.76	7.00	7.00	7.50	7.50	7.80	7.80

OPTION 1. DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2120)		2120 (to 2170)	
	3.22	6.84	6.76	6.90	6.90	7.50	7.50	7.80	7.80
	3.23	6.84	6.76	6.90	6.90	7.50	7.50	7.80	7.80
	3.24	6.84	6.87	6.90	6.90	7.50	7.50	7.80	7.80
	3.25	6.84	7.10	6.90	7.10	7.50	7.50	7.80	7.80
Tilbury	3.26	6.63	7.10	6.90	7.10	7.50	7.50	7.90	7.90
	3.27	6.63	6.52	6.90	6.52	7.40	6.52	7.90	6.52
	3.28	6.63	6.57	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	7.50	6.10	8.00	6.10
	3.32	6.50	5.92	6.70	5.92	7.50	5.92	8.00	5.92
	3.33	6.60	5.82	6.70	5.82	7.50	5.82	8.00	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	7.50	5.75	8.10	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	7.50	5.82	8.10	5.82
	3.36	6.56	Cliff	6.70		7.50		8.10	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	6.80	5.50	7.40	5.50
Southend	3.38	5.70	5.50	6.00	5.50	6.80	5.50	7.40	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	6.80	N/A	7.40

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

5.2 Option 2 (Flood storage)

Table 5.3 shows sequence of interventions required for Option 2. The intervention dates are determined from the modelling described in Section 4.3.

Table 5.3 Works required for Option 2

Approximate date	Work required
2020	Habitat creation (Site 1). West Canvey has been assumed in the design of the options.
2040	Habitat creation (Site 2). St. Mary's Marshes has been assumed in the design of the options. Defences downriver of Erith raised by up to 0.3m. Defences at Southend raised by up to 0.7m. New defences at Gravesend (east of urban area).
2050	Habitat creation (Site 3). Grain Marshes has been assumed in the design of the options.
2065	Habitat creation (Site 4). Allhallows Marshes has been assumed in the design of the options. Raise defences by 0.5m upriver of the Thames Barrier.
2070	Over-rotate Thames Barrier (design water level 6.9m, crest level to 7.3m). Flood storage at Erith, Aveley, Dartford/Crayford and Shorne Marshes. Introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised to cover the period to 2115.
2100	Raise defences by further 0.5m upriver of the Thames Barrier
2115	Improve Thames Barrier (design water level 7.4m, crest level 7.8m). Flood storage at Erith, Aveley, Dartford/Crayford and Shorne Marshes still in use. Introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised to cover the period to 2140.
2135	Limit reached for this option because of the number of closures of the Thames Barrier and maximum acceptable amount of upriver defence raising.
2140	Improve Thames Barrier (design water level 8.4m, crest level 8.8m). Flood storage no longer effective compared to Option 1. Downriver defences raised to cover the period to 2170.

Note: Because the limit for number of closures is reached in 2135 the improvement of the Thames Barrier in 2140 is likely to be replaced with conversion to a barrier with locks (required crest level 8.4m for 10,000-year SoP).

Table 5.4 shows the new defence levels required for Option 2.

Table 5.4a New defence levels upriver of the Thames Barrier for Option 2

OPTION 2 DEFENCE LEVELS		Existing defence levels (m AOD)		New defence levels (m AOD)			
				2065 (to 2100)		2100 (to 2135)	
Location	Node	LB	RB	LB	RB	LB	RB
Teddington	2.1	6.10	6.10	6.60	6.60	7.10	7.10
Eel Pie Island	2.3	6.02	6.05	6.60	6.60	7.10	7.10
Marble Hill	2.4	6.02	6.34	6.60	6.90	7.10	7.40
Richmond	a2.6	6.02	5.94	6.60	6.50	7.10	7.00
Richmond	a2.7	5.94	5.94	6.50	6.50	7.00	7.00
R Crane	2.9d	5.94	5.94	6.50	6.50	7.00	7.00
R Brent	2.13d	5.94	5.94	6.50	6.50	7.00	7.00
	2.17d	6.25	6.25	6.30	6.30	7.30	7.30
Hammersmith	2.21	5.54	5.94	6.10	6.00	6.60	7.00
R Wandle	2.24ad	5.58	5.41	6.10	6.00	6.60	6.50
Chelsea	2.29	5.41	5.41	6.00	6.00	6.50	6.50
Tower Pier	2.36	5.28	5.28	5.80	5.80	6.30	6.30
R Ravensbourne	2.42d	5.18	5.18	5.70	5.70	6.20	6.20
R Lee	2.47	5.18	5.18	5.70	5.70	6.20	6.20
Thames Barrier	a2.49	5.18	5.18	5.70	5.70	6.20	6.20

Note: Areas shaded in blue do not have additional raising for fluvial flow

Table 5.4b New defence levels downriver of the Thames Barrier for Option 2

OPTION 2 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2115)		2115 (to 2140)	
Location	Node	LB	RB	LB	RB	LB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	7.60	7.60	8.00	8.00
	3.2	7.20	7.20	7.20	7.20	7.60	7.60	8.00	8.00
	3.3	7.20	7.20	7.20	7.20	7.60	7.60	8.00	8.00
	3.4	7.20	7.20	7.20	7.20	7.60	7.20	8.00	7.50
Roding	a3.5u	7.20	7.10	7.20	7.10	7.60	7.10	8.00	7.50
	a3.5d	7.20	7.10	7.20	7.10	7.40	7.10	7.80	7.50
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	7.40	7.10	7.80	7.50
	3.7	7.10	7.10	7.10	7.10	7.40	7.10	7.70	7.50
Beam	3.8	7.10	7.10	7.10	7.10	7.40	7.10	7.70	7.50
	3.9	7.10	7.10	7.10	7.10	7.30	7.10	7.70	7.50
	3.10	7.10	7.10	7.10	7.10	7.10	7.10	7.50	7.50
	3.11	7.10	7.10	7.10	7.10	7.10	7.10	7.50	7.50
	3.12	6.90	7.00	7.10	7.10	7.10	7.10	7.50	7.50
	3.13	6.90	7.00	7.10	7.10	7.10	7.10	7.50	7.50
	3.14	6.90	6.90	7.10	7.10	7.10	7.10	7.50	7.50
Darent	3.15u	6.90	7.34	7.10	7.34	7.10	7.40	7.50	7.50
	3.15d	6.90	7.34	7.10	7.34	7.10	7.40	7.50	7.50
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	7.20	7.10	7.50	7.50
	3.17	6.94	6.74	7.00	7.00	7.10	7.10	7.50	7.50

OPTION 2 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2115)		2115 (to 2140)	
	3.18	7.12	6.74	7.12	7.00	7.20	7.10	7.40	7.40
	3.19	6.84	6.76	7.00	7.00	7.10	7.10	7.40	7.40
	3.20	6.84	6.76	7.00	7.00	7.10	7.10	7.40	7.40
	3.21	6.84	6.76	7.00	7.00	7.10	7.10	7.40	7.40
	3.22	6.84	6.76	6.90	6.90	7.10	7.10	7.40	7.40
	3.23	6.84	6.76	6.90	6.90	7.10	7.10	7.40	7.40
	3.24	6.84	6.87	6.90	6.90	7.10	7.10	7.40	7.40
	3.25	6.84	7.10	6.90	7.10	7.10	7.10	7.40	7.40
Tilbury	3.26	6.63	7.10	6.90	7.10	7.10	7.10	7.40	7.40
	3.27	6.63	6.52	6.90	6.52	7.10	6.52	7.40	6.52
	3.28	6.63	6.57	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	7.20	6.10	7.50	6.10
	3.32	6.50	5.92	6.70	5.92	7.20	5.92	7.50	5.92
	3.33	6.60	5.82	6.70	5.82	7.20	5.82	7.60	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	7.20	5.75	7.60	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	7.30	5.82	7.60	5.82
	3.36	6.56	Cliff	6.70		7.30		7.60	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	6.60	5.50	7.00	5.50
Southend	3.38	5.70	5.50	6.00	5.50	6.60	5.50	7.00	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	6.60	N/A	7.00

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

5.3 Option 3 (new barriers)

5.3.1 Option 3-1 (New barrier at Tilbury)

Table 5.5 shows sequence of interventions required for Option 3.1. The intervention dates are determined from the modelling described in Section 4.4.1.

Table 5.5 Works required for Option 3.1

Approximate date	Work required
2020	Habitat creation (Site 1). West Canvey has been assumed in the design of the options.
2040	Habitat creation (Site 2). St. Mary's Marshes has been assumed in the design of the options. Defences downriver of Erith raised by up to 0.3m. Defences at Southend raised by up to 0.7m. New defences at Gravesend (east of urban area).
2050	Habitat creation (Site 3). Grain Marshes has been assumed in the design of the options.
2065	Habitat creation (Site 4). Allhallows Marshes has been assumed in the design of the options. Raise defences by 0.5m upriver of the Thames Barrier.
2070	New Barrier at Tilbury (gate crest level 8.3m). Cut-off defences on north and south banks. Introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised by about 1.0 to 1.5m to cover the period to 2170. Potential to allow lowering the defences over time as replacement is required, between new barrier and the Thames Barrier site (by 1.0m).
2100	Raise defences by further 0.5m upriver of the Thames Barrier
2135	Limit reached for this option because of the number of closures of the Thames Barrier and maximum acceptable amount of upriver defence raising.

Note: Because the limit for number of closures is reached in 2135 the Tilbury Barrier is likely to be replaced by conversion to a barrage or a barrier with locks.

New defence levels in Option 3.1

The new defence levels at each intervention epoch are shown in Table 5.6.

Table 5.6a New defence levels upriver of the Thames Barrier in Option 3.1

OPTION 3.1 DEFENCE LEVELS		Existing defence levels (m AOD)		New defence levels (m AOD)			
				2065 (to 2100)		2100 (to 2135)	
Location	Node	LB	RB	LB	RB	LB	RB
Teddington	2.1	6.10	6.10	6.60	6.60	7.10	7.10
Eel Pie Island	2.3	6.02	6.05	6.60	6.60	7.10	7.10
Marble Hill	2.4	6.02	6.34	6.60	6.90	7.10	7.40
Richmond	a2.6	6.02	5.94	6.60	6.50	7.10	7.00
Richmond	a2.7	5.94	5.94	6.50	6.50	7.00	7.00
R Crane	2.9d	5.94	5.94	6.50	6.50	7.00	7.00
R Brent	2.13d	5.94	5.94	6.50	6.50	7.00	7.00
	2.17d	6.25	6.25	6.30	6.30	7.30	7.30
Hammersmith	2.21	5.54	5.94	6.10	6.00	6.60	7.00
R Wandle	2.24ad	5.58	5.41	6.10	6.00	6.60	6.50
Chelsea	2.29	5.41	5.41	6.00	6.00	6.50	6.50
Tower Pier	2.36	5.28	5.28	5.80	5.80	6.30	6.30
R Ravensbourne	2.42d	5.18	5.18	5.70	5.70	6.20	6.20
R Lee	2.47	5.18	5.18	5.70	5.70	6.20	6.20
Thames Barrier	a2.49	5.18	5.18	5.70	5.70	6.20	6.20

Note: Areas shaded in blue do not have additional raising for fluvial flow

Table 5.6b New defence levels downriver of the Thames Barrier in Option 3.1

OPTION 3.1 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2140)		2140 (to 2170)	
Location	Node	LB	RB	LB	RB	LB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
	3.2	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
	3.3	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
	3.4	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
Roding	a3.5u	7.20	7.10	7.20	7.10	6.20	6.10	6.20	6.10
	a3.5d	7.20	7.10	7.20	7.10	6.20	6.10	6.20	6.10
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.7	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
Beam	3.8	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.9	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.10	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.11	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.12	6.90	7.00	7.10	7.10	6.10	6.10	6.10	6.10
	3.13	6.90	7.00	7.10	7.10	6.10	6.10	6.10	6.10
	3.14	6.90	6.90	7.10	7.10	6.10	6.10	6.10	6.10
Darent	3.15u	6.90	7.34	7.10	7.34	6.10	6.10	6.10	6.10
	3.15d	6.90	7.34	7.10	7.34	6.10	6.10	6.10	6.10
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	6.10	6.00	6.10	6.00
	3.17	6.94	6.74	7.00	7.00	6.00	6.00	6.00	6.00
	3.18	7.12	6.74	7.12	7.00	6.00	6.00	6.00	6.00
	3.19	6.84	6.76	7.00	7.00	6.00	6.00	6.00	6.00

OPTION 3.1 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2140)		2140 (to 2170)	
	3.20	6.84	6.76	7.00	7.00	6.00	6.00	6.00	6.00
	3.21	6.84	6.76	7.00	7.00	6.00	6.00	6.00	6.00
	3.22	6.84	6.76	6.90	6.90	5.90	5.90	5.90	5.90
	3.23	6.84	6.76	6.90	6.90	5.90	5.90	5.90	5.90
	3.24	6.84	6.87	6.90	6.90	5.90	5.90	5.90	5.90
	3.25	6.84	7.10	6.90	7.10	5.90	5.90	5.90	5.90
Tilbury	3.26	6.63	7.10	6.90	7.10	5.90	5.90	5.90	5.90
	3.27	6.63	6.52	6.90	6.52	8.50	8.50	8.50	8.50
	3.28	6.63	6.57	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	7.50	6.10	8.00	6.10
	3.32	6.50	5.92	6.70	5.92	7.50	5.92	8.00	5.92
	3.33	6.60	5.82	6.70	5.82	7.60	5.82	8.00	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	7.60	5.75	8.00	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	7.60	5.82	8.10	5.82
	3.36	6.56	Cliff	6.70		7.60		8.10	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	7.00	5.50	7.40	5.50
Southend	3.38	5.70	5.50	6.00	5.50	7.00	5.50	7.40	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	7.00	N/A	7.40

5.3.2 Option 3-2 (New barrier at Long Reach)

Table 5.7 shows sequence of interventions required for Option 3.2. The intervention dates are determined from the modelling described in Section 4.4.2.

Table 5.7 Works required for Option 3.2

Approximate date	Work required
2020	Habitat creation (Site 1). West Canvey has been assumed in the design of the options.
2040	Habitat creation (Site 2). St. Mary's Marshes has been assumed in the design of the options. Defences downriver of Erith raised by up to 0.3m. Defences at Southend raised by up to 0.7m. New defences at Gravesend (east of urban area).
2050	Habitat creation (Site 3). Grain Marshes has been assumed in the design of the options.
2065	Habitat creation (Site 4). Allhallows Marshes has been assumed in the design of the options. Raise defences by 0.5m upriver of the Thames Barrier.
2070	New Barrier at Long Reach (gate crest level 8.3m). Cut-off defences on north and south banks. Introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised by about 1.0 to 1.5m to cover the period to 2170. Potential to allow lowering the defences over time as replacement is required, between new barrier and the Thames Barrier site (by 1.0m).
2100	Raise defences by further 0.5m upriver of the Thames Barrier
2135	Limit reached for this option because of the number of closures of the Thames Barrier and maximum acceptable amount of upriver defence raising.

Note: Because the limit for number of closures is reached in 2135 the Long Reach Barrier is likely to be replaced by conversion to a barrage or a barrier with locks.

New defence levels in Option 3.2

The new defence levels at each intervention epoch are shown in Table 5.8.

Table 5.8a New defence levels upriver of the Thames Barrier for Option 3.2

OPTION 3.2 DEFENCE LEVELS		Existing defence levels (m AOD)		New defence levels (m AOD)			
				2065 (to 2100)		2100 (to 2135)	
Location	Node	LB	RB	LB	RB	LB	RB
Teddington	2.1	6.10	6.10	6.60	6.60	7.10	7.10
Eel Pie Island	2.3	6.02	6.05	6.60	6.60	7.10	7.10
Marble Hill	2.4	6.02	6.34	6.60	6.90	7.10	7.40
Richmond	a2.6	6.02	5.94	6.60	6.50	7.10	7.00
Richmond	a2.7	5.94	5.94	6.50	6.50	7.00	7.00
R Crane	2.9d	5.94	5.94	6.50	6.50	7.00	7.00
R Brent	2.13d	5.94	5.94	6.50	6.50	7.00	7.00
	2.17d	6.25	6.25	6.30	6.30	7.30	7.30
Hammersmith	2.21	5.54	5.94	6.10	6.00	6.60	7.00
R Wandle	2.24ad	5.58	5.41	6.10	6.00	6.60	6.50
Chelsea	2.29	5.41	5.41	6.00	6.00	6.50	6.50
Tower Pier	2.36	5.28	5.28	5.80	5.80	6.30	6.30
R Ravensbourne	2.42d	5.18	5.18	5.70	5.70	6.20	6.20
R Lee	2.47	5.18	5.18	5.70	5.70	6.20	6.20
Thames Barrier	a2.49	5.18	5.18	5.70	5.70	6.20	6.20

Note: Areas shaded in blue do not have additional raising for fluvial flow.

Table 5.8b New defence levels downriver of the Thames Barrier for Option 3.2

OPTION 3.2 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2140)		2140 (to 2170)	
Location	Node	LB	RB	LB	RB	LB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
	3.2	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
	3.3	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
	3.4	7.20	7.20	7.20	7.20	6.20	6.20	6.20	6.20
Roding	a3.5u	7.20	7.10	7.20	7.10	6.20	6.10	6.20	6.10
	a3.5d	7.20	7.10	7.20	7.10	6.20	6.10	6.20	6.10
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.7	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
Beam	3.8	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.9	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.10	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.11	7.10	7.10	7.10	7.10	6.10	6.10	6.10	6.10
	3.12	6.90	7.00	7.10	7.10	6.10	6.10	6.10	6.10
	3.13	6.90	7.00	7.10	7.10	6.10	6.10	6.10	6.10
	3.14	6.90	6.90	7.10	7.10	6.10	6.10	6.10	6.10
Darent	3.15u	6.90	7.34	7.10	7.34	6.10	6.10	6.10	6.10
	3.15d	6.90	7.34	7.10	7.34	6.10	6.10	6.10	6.10
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	6.10	6.00	6.10	6.00
	3.17	6.94	6.74	7.00	7.00	8.20	8.20	8.50	8.50
	3.18	7.12	6.74	7.12	7.00	8.20	8.20	8.50	8.50
	3.19	6.84	6.76	7.00	7.00	8.20	8.20	8.50	8.50
	3.20	6.84	6.76	7.00	7.00	8.20	7.70	8.50	8.00
	3.21	6.84	6.76	7.00	7.00	8.20	7.70	8.50	8.00
	3.22	6.84	6.76	6.90	6.90	7.70	7.70	8.00	8.00
	3.23	6.84	6.76	6.90	6.90	7.70	7.70	8.00	8.00

OPTION 3.2 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)					
				2040 (to 2070)		2070 (to 2140)		2140 (to 2170)	
	3.24	6.84	6.87	6.90	6.90	7.70	7.70	8.00	8.00
	3.25	6.84	7.10	6.90	7.10	7.70	7.70	8.00	8.00
Tilbury	3.26	6.63	7.10	6.90	7.10	7.70	7.70	8.00	8.00
	3.27	6.63	6.52	6.90	6.52	7.70	6.52	8.10	6.52
	3.28	6.63	6.57	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	7.60	6.10	8.10	6.10
	3.32	6.50	5.92	6.70	5.92	7.70	5.92	8.10	5.92
	3.33	6.60	5.82	6.70	5.82	7.70	5.82	8.10	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	7.70	5.75	8.10	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	7.70	5.82	8.10	5.82
	3.36	6.56	Cliff	6.70		7.60		8.10	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	7.00	5.50	7.40	5.50
Southend	3.38	5.70	5.50	6.00	5.50	7.00	5.50	7.40	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	7.00	N/A	7.40

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

For upstream of the Thames Barrier defence levels are required to be raised by 0.5m in 2065, a further 0.5m in 2100 and a further 0.5m in 2135. This is based on an assumed operational limit of the Thames Barrier of 50 closures per year with forecast/operation uncertainty of 0.2m. If the maximum amount of upriver defence raising is 1m, and the new barrier has the same operational limit as the Thames Barrier, the limit of Option 3-2 is reached 2135. At this decision point a new barrage or a barrier with locks is required.

5.4 Option 4 (barriers with locks)

5.4.1 Option 4-1 (Barriers with locks at Tilbury)

Table 5.9 shows sequence of interventions required for Option 4.1. The intervention dates are determined from the modelling described in Section 4.5.1.

Table 5.9 Works required for Option 4.1

Approximate date	Work required
2020	Habitat creation (Site 1). West Canvey has been assumed in the design of the options.
2040	Habitat creation (Site 2). St. Mary's Marshes has been assumed in the design of the options. Defences downriver of Erith raised by up to 0.3m. Defences at Southend raised by up to 0.7m. New defences at Gravesend (east of urban area).
2050	Habitat creation (Site 3). Grain Marshes has been assumed in the design of the options.
2065	Habitat creation (Site 4). Allhallows Marshes has been assumed in the design of the options. Raise defences by 0.5m upriver of the Thames Barrier. Not required due to barrier with locks in 2070.
2070	New barrier with locks at Tilbury (gate crest level 8.3m). Cut-off defences on north and south banks. Introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised by about 1.0 to 1.5m to cover the period to 2170. Potential to allow lowering the defences over time as replacement is required, between new barrier and the Thames Barrier site (by 1.0m).

New defence levels in Option 4.1

The new defence levels at each intervention epoch are shown in Table 5.10.

Table 5.10 New defence levels downriver of the Thames Barrier in Option 4.1

OPTION 4.1 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)			
				2040 (to 2070)		2070 (to 2170)	
Location	Node	LB	RB	LB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	6.20	6.20
	3.2	7.20	7.20	7.20	7.20	6.20	6.20
	3.3	7.20	7.20	7.20	7.20	6.20	6.20
	3.4	7.20	7.20	7.20	7.20	6.20	6.20
Roding	a3.5u	7.20	7.10	7.20	7.10	6.20	6.10
	a3.5d	7.20	7.10	7.20	7.10	6.20	6.10
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	6.10	6.10
	3.7	7.10	7.10	7.10	7.10	6.10	6.10
Beam	3.8	7.10	7.10	7.10	7.10	6.10	6.10
	3.9	7.10	7.10	7.10	7.10	6.10	6.10
	3.10	7.10	7.10	7.10	7.10	6.10	6.10
	3.11	7.10	7.10	7.10	7.10	6.10	6.10
	3.12	6.90	7.00	7.10	7.10	6.10	6.10
	3.13	6.90	7.00	7.10	7.10	6.10	6.10
	3.14	6.90	6.90	7.10	7.10	6.10	6.10
Darent	3.15u	6.90	7.34	7.10	7.34	6.10	6.10
	3.15d	6.90	7.34	7.10	7.34	6.10	6.10
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	6.10	6.00
	3.17	6.94	6.74	7.00	7.00	6.00	6.00
	3.18	7.12	6.74	7.12	7.00	6.00	6.00
	3.19	6.84	6.76	7.00	7.00	6.00	6.00
	3.20	6.84	6.76	7.00	7.00	6.00	6.00
	3.21	6.84	6.76	7.00	7.00	6.00	6.00
	3.22	6.84	6.76	6.90	6.90	5.90	5.90
	3.23	6.84	6.76	6.90	6.90	5.90	5.90
	3.24	6.84	6.87	6.90	6.90	5.90	5.90
	3.25	6.84	7.10	6.90	7.10	5.90	5.90
Tilbury	3.26	6.63	7.10	6.90	7.10	5.90	5.90
	3.27	6.63	6.52	6.90	6.52	8.50	8.50
	3.28	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	8.00	6.10
	3.32	6.50	5.92	6.70	5.92	8.00	5.92
	3.33	6.60	5.82	6.70	5.82	8.00	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	8.00	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	8.10	5.82
	3.36	6.56	Cliff	6.70		8.10	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	7.40	5.50
Southend	3.38	5.70	5.50	6.00	5.50	7.40	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	7.40

Note: Areas shaded in blue are Policy P3, where no defence raising is needed

5.4.2 Option 4-2 (Barriers with locks at Long Reach)

Table 5.11 shows sequence of interventions required for Option 4.2. The intervention dates are determined from the modelling described in Section 4.5.2.

Table 5.11 Works required for Option 4.2

Approximate date	Work required
2020	Habitat creation (Site 1). West Canvey has been assumed in the design of the options.
2040	Habitat creation (Site 2). St. Mary's Marshes has been assumed in the design of the options. Defences downriver of Erith raised by up to 0.3m. Defences at Southend raised by up to 0.7m. New defences at Gravesend (east of urban area).
2050	Habitat creation (Site 3). Grain Marshes has been assumed in the design of the options.
2065	Habitat creation (Site 4). Allhallows Marshes has been assumed in the design of the options. Raise defences by 0.5m upriver of the Thames Barrier. Not required due to barrier with locks in 2070.
2070	New Barrier with locks at Long Reach (gate crest level 8.3m). Cut-off defences on north and south banks. Introduce an improved SoP in areas where FRM Policy P5 is required. Downriver defences raised by about 1.0 to 1.5m to cover the period to 2170. Potential to allow lowering the defences over time as replacement is required, between new barrier and the Thames Barrier site (by 1.0m).

New defence levels in Option 4.2

The new defence levels at each intervention epoch are shown in Table 5.12

Table 5.12 New defence levels downriver of the Thames Barrier in Option 4.2

OPTION 4.2 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)			
				2040 (to 2070)		2070 (to 2170)	
Location	Node	LB	RB	LB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	6.20	6.20
	3.2	7.20	7.20	7.20	7.20	6.20	6.20
	3.3	7.20	7.20	7.20	7.20	6.20	6.20
	3.4	7.20	7.20	7.20	7.20	6.20	6.20
Roding	a3.5u	7.20	7.10	7.20	7.10	6.20	6.10
	a3.5d	7.20	7.10	7.20	7.10	6.20	6.10
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	6.10	6.10
	3.7	7.10	7.10	7.10	7.10	6.10	6.10
Beam	3.8	7.10	7.10	7.10	7.10	6.10	6.10
	3.9	7.10	7.10	7.10	7.10	6.10	6.10
	3.10	7.10	7.10	7.10	7.10	6.10	6.10
	3.11	7.10	7.10	7.10	7.10	6.10	6.10
	3.12	6.90	7.00	7.10	7.10	6.10	6.10
	3.13	6.90	7.00	7.10	7.10	6.10	6.10
	3.14	6.90	6.90	7.10	7.10	6.10	6.10
Darent	3.15u	6.90	7.34	7.10	7.34	6.10	6.10
	3.15d	6.90	7.34	7.10	7.34	6.10	6.10
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	6.10	6.00
	3.17	6.94	6.74	7.00	7.00	8.50	8.50
	3.18	7.12	6.74	7.12	7.00	8.50	8.50
	3.19	6.84	6.76	7.00	7.00	8.50	8.50
	3.20	6.84	6.76	7.00	7.00	8.50	8.00
	3.21	6.84	6.76	7.00	7.00	8.50	8.00
	3.22	6.84	6.76	6.90	6.90	8.00	8.00
	3.23	6.84	6.76	6.90	6.90	8.00	8.00
	3.24	6.84	6.87	6.90	6.90	8.00	8.00
	3.25	6.84	7.10	6.90	7.10	8.00	8.00
Tilbury	3.26	6.63	7.10	6.90	7.10	8.00	8.00
	3.27	6.63	6.52	6.90	6.52	8.10	6.52
	3.28	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	8.10	6.10
	3.32	6.50	5.92	6.70	5.92	8.10	5.92
	3.33	6.60	5.82	6.70	5.82	8.10	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	8.10	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	8.10	5.82
	3.36	6.56	Cliff	6.70		8.10	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	7.40	5.50
Southend	3.38	5.70	5.50	6.00	5.50	7.40	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	7.40

Note: Areas shaded in blue are Policy P3, where no defence raising is needed

5.4.3 Option 4-3 (Conversion of the Thames Barrier to a Barrier with Locks)

The Thames Barrier is converted to a barrier with locks in 2070. Water levels downstream of the barrier with locks, and increases to defence crest levels required until 2170 downriver of the structure are the same as in Option 1. Upriver of the structure, defence levels are not required to be raised (except for West London) because there is no limitation to the number of closures.

Table 5.13 New defence levels downriver of the Thames Barrier for Option 4.3

OPTION 4.3 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)			
				2040 (to 2070)		2070 (to 2170)	
Location	Node	LB	LB	RB	RB	LB	RB
Barrier	a3.1	7.20	7.20	7.20	7.20	8.70	8.70
	3.2	7.20	7.20	7.20	7.20	8.70	8.70
	3.3	7.20	7.20	7.20	7.20	8.70	8.70
	3.4	7.20	7.20	7.20	7.20	8.70	8.00
Roding	a3.5u	7.20	7.10	7.20	7.10	8.70	8.00
	a3.5d	7.20	7.10	7.20	7.10	8.40	8.00
	River Roding	R5.80	N/A	N/A	N/A	N/A	N/A
	3.6	7.10	7.10	7.10	7.10	8.40	8.00
	3.7	7.10	7.10	7.10	7.10	8.30	8.00
Beam	3.8	7.10	7.10	7.10	7.10	8.30	8.00
	3.9	7.10	7.10	7.10	7.10	8.30	8.00
	3.10	7.10	7.10	7.10	7.10	8.00	8.00
	3.11	7.10	7.10	7.10	7.10	8.00	8.00
	3.12	6.90	7.00	7.10	7.10	8.00	8.00
	3.13	6.90	7.00	7.10	7.10	8.00	8.00
	3.14	6.90	6.90	7.10	7.10	8.00	8.00
Darent	3.15u	6.90	7.34	7.10	7.34	8.00	8.00
	3.15d	6.90	7.34	7.10	7.34	8.00	8.00
	River Darent	N/A	R5.30	N/A	N/A	N/A	N/A
	3.16	7.15	6.71	7.15	7.00	7.90	7.90
	3.17	6.94	6.74	7.00	7.00	7.90	7.90
	3.18	7.12	6.74	7.12	7.00	7.90	7.90
	3.19	6.84	6.76	7.00	7.00	7.90	7.90
	3.20	6.84	6.76	7.00	7.00	7.80	7.80
	3.21	6.84	6.76	7.00	7.00	7.80	7.80
	3.22	6.84	6.76	6.90	6.90	7.80	7.80
	3.23	6.84	6.76	6.90	6.90	7.80	7.80
	3.24	6.84	6.87	6.90	6.90	7.80	7.80
	3.25	6.84	7.10	6.90	7.10	7.80	7.80
Tilbury	3.26	6.63	7.10	6.90	7.10	7.90	7.90
	3.27	6.63	6.52	6.90	6.52	7.90	6.52
	3.28	6.63	6.57	6.63	6.57	6.63	6.57
	3.29	6.48	6.12	6.48	6.12	6.48	6.12
Mucking	3.30	6.76	5.91	6.76	5.91	6.76	5.91
	3.31	6.52	6.10	6.80	6.10	8.00	6.10
	3.32	6.50	5.92	6.70	5.92	8.00	5.92
	3.33	6.60	5.82	6.70	5.82	8.00	5.82
	Vange Creek	R4.00	N/A	N/A	N/A	N/A	N/A
	3.34	6.47	5.75	6.70	5.75	8.10	5.75
Canvey	3.35	6.66	5.82	6.70	5.82	8.10	5.82
	3.36	6.56	Cliff	6.70		8.10	

OPTION 4.3 DEFENCE LEVELS		Existing defence levels (m AOD)		New Defence Levels (m AOD)			
				2040 (to 2070)		2070 (to 2170)	
	EH Creek	R4.20	N/A	N/A	N/A	N/A	N/A
	Hadleigh Marsh	R6.00	N/A	N/A	N/A	N/A	N/A
	3.37	5.30	5.50	6.00	5.50	7.40	5.50
Southend	3.38	5.70	5.50	6.00	5.50	7.40	5.50
	Grain east	N/A	5.70	N/A	6.00	N/A	7.40

Note: Areas shaded in blue are Policy P3, where no defence raising is needed.

5.5 Summary of results

The intervention dates of the options are summarised in Table 5.14 with a brief description of the intervention.

Table 5.14 Initial assessment of the options

Date	Mean Sea Level rise	Peak surge tide level at Southend (m AOD)				Level at Thames Barrier (m AOD)		Interventions
		1:1000	1:2000	1:5000	1:10000	1:1000	1:10000	
2000	0	5.03	5.16	5.29	5.51	6.03	6.60	
2030	0.14	5.15	5.28	5.41	5.64	6.15	6.69	
Option 1 Improve the defence system								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	Improve Thames Barrier (including over-rotation) Raise downriver defences
2120	1.24	6.26			6.73	6.85	7.30	Improve Thames Barrier
2135	1.47	6.48			6.96	6.99	7.42	Limit of option due to number of closures
Option 2 Flood storage								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	Storage plus over-rotate Thames Barrier Raise downriver defences
2115	1.17	6.18			6.66	6.39	6.88	Storage plus Improve Thames Barrier Raise downriver defences
2135	1.47	6.48			6.96	6.80	7.26	Limit of option due to number of closures
Option 3.1 New barrier at Tilbury								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	New barrier Raise downriver defences
2135	1.47	6.48			6.96	6.61	7.11	Limit of option due to number of closures
Option 3.2 New barrier at Long Reach								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	New barrier with locks Raise downriver defences
2135	1.47	6.48			6.96	7.01	7.41	Limit of option due to number of closures
Option 4.1 New barrier with locks at Tilbury								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	New barrier with locks Raise downriver defences
2170	1.99	7.00			7.48	7.06	7.62	Limit of option not reached
Option 4.2 New barrier with locks at Long Reach								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	New barrier with locks Raise downriver defences
2170	1.99	7.00			7.48	7.30	7.79	Limit of option not reached

Date	Mean Sea Level rise	Peak surge tide level at Southend (m AOD)				Level at Thames Barrier (m AOD)		Interventions
		1:1000	**1:2000**	**1:5000**	**1:10000**	**1:1000**	**1:10000**	
Option 4.3 Convert Thames Barrier to a barrier with locks.								
2070	0.53	5.54	5.67	5.80	6.02	6.43	6.93	Convert Thames Barrier to a barrier with locks
2170	1.99	7.00			7.48	7.32	7.96	Limit of option not reached

Notes to Table 5.14:

1. Only the key interventions are shown. Detailed defence raising requirements determined by modelling are given in Sections 5.1 to 5.4 for generic options 1 to 4 respectively.
2. For Option 2, there is a decision point in 2115 where a new barrier with locks could be implemented rather than undertaking work on the Thames Barrier.
3. For sea level rise of 2m (in 2170), flood storage has no impact on extreme water levels due to large amounts of non designated storage elsewhere in the estuary.

The implementation of Policy P5 at the same time as the first major intervention means that both flood storage and Barrier over-rotation as single interventions do not provide sufficient flood mitigation. For the estimated 10,000 year tide (Policy P5), the limits for each of these interventions are in 2060 to 2070. These are similar dates to the limit of the existing Thames Barrier under Policy P4, which occurs in about 2070. They must therefore be combined.

5.6 Summary of conclusions from annexes

The main conclusions from the supporting information provided in the annexes are as follows:

- The model used for option development has been extensively validated. Whilst it is generally suitable for flood modelling, there are some limitations in the modelling approach (Annex A).
- The model reproduces the 1953 surge tide event with reasonable accuracy between Westminster and the sea, bearing in mind the uncertainties in the data (Annex B).
- There are some instabilities in the model but these are small if an adaptive timestep is used, and the Barrier is closed at low water (Annex C).
- Base water levels are reported for the 100, 1,000 and 10,000 year tidal water levels downriver of the Thames Barrier, and water levels for fluvial flows upriver of the Thames Barrier (Annex D).
- Managed realignments can cause small water level reductions during extreme events at the Thames Barrier (Annex E).
- Water surface profiles upriver of the Thames Barrier have been developed for the case where larger tides are permitted through the Barrier to reduce Barrier closures (Annex E).
- Options for West London have been assessed and interventions with little benefit to the standard of defence have been rejected. Defence raising and receptor responses are the interventions taken forward (Annex F).

The defence raising presented in Annex F was intended to achieve Flood Risk Management Policy P4. However the Policy adopted for West London is P3+, which means that any reduction in flood risk will be implemented by floodplain management. This will not however prevent the need for defence raising for tidal flood risk.

- Opening sizes for barrier and barrier with locks designs have been developed. For barriers and barriers with locks, an assessment has been made of the impacts on the upriver tidal regime (Annex G).

  The barrier designs generally reduce upriver high tide levels by about 0.1m and increase low tide levels by a similar amount. However the barrier with locks options have three navigation openings, one of which could be closed for gate maintenance. With one of the main openings closed, the reduction in high tide levels would be about 0.2m.

- The effects of gates failures at the Thames Barrier on upriver water levels have been identified by modelling (Annex H).

- Defence raising and flood storage requirements have been estimated for the main tributaries of the tidal Thames. A summary of these requirements is given in Annex I.

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Annexes

Annex A The Thames Model

A.1 Introduction

A number of the TE2100 studies have used a 1D model of the Thames Estuary to define tidal-fluvial interaction (EP3 and EP4), develop interventions for flood risk management (Pilot Portfolios) and to develop estuary wide options for flood risk management and provide water levels for appraisal (HLOs, Phase 3 Set 1 Options, Phase 3 Set 2 Options).

The accuracy of this model is therefore important for the level of confidence that can be given to the results and conclusions of these studies. The model has been developed through the course of the TE2100 project and various calibration and sensitivity analysis have been performed.

The locations of model nodes on the estuary are shown on Figures A.3 to A.6 at the end of this Annex. These maps do not show the model layout on the floodplains.

A.1.1 Model History

The 1D model of the Thames used in the TE2100 studies is an ISIS model developed for use at the Thames Barrier. It is known as the Operational Model (OM) and has a number of versions, as it is continually developed and improved.

- OM (2002) – Developed by Halcrow for the EA and used to produce the design water levels in the May 2002 Report.
- OM5 (December 2004) – This model was used in the TE2100 EP3 study.
- OM6 (January 2005) – Interpolated sections for flood cell and 2D modelling.
- OM7 (March 2005) – Fully georeferenced node points.
- OM8 (April 2005) – The Jacobs model of reach 4 of the Lower Thames was added to the model upstream of Teddington to replace the old data for this reach.

As part of the TE2100 EP3 Study the OM5 model was modified to include Richmond Bridge because this was found have significant afflux.

The model used for option development was the estuary model with the addition of floodplains (the 'OM Flood cell model'). The OM Flood cell model was developed as part of the Thames Embayments Project and includes the floodplain represented by ISIS flood cells. The in-bank part of the model is OM7. This model has been used in the HLO Pilot Portfolios and Option Development studies. The model has also been used on the development of the Phase 3 Set 1 and Phase 3 Set 2 Options.

A.2 Previous calibration of the OM model

A.2.1 Halcrow 2002 calibration

For the study to determine defence standards on the Thames Estuary in 2002, Halcrow calibrated the model of the tidal Thames on the December 1978 and December 1985 events. The peak flows in these events were 225 m^3/s and 315 m^3/s respectively and the peak tide levels at Southend were 4.02 m AOD and 3.54 m AOD respectively.
The model adequately represented the calibration events and also a high flow event in 1990 (Halcrow, 2002). Halcrow also tested the ability of the model to replicate four events for which the Thames Barrier was closed. It was found that the overall mean error was between -100 mm and + 200 mm for these events, although larger errors

were found at Teddington, and at the Thames Barrier in the barrier closure events. For more details of this calibration see the Halcrow 2002 Report.

The calibration and verification analysis performed by Halcrow in 2002 shows that the 1D model of the tidal Thames is able to replicate low to moderate tide and flow events accurately.

A.2.2 TE2100 Sensitivity analysis

The Thames Estuary studies are generally concerned with events of greater return periods than those calibrated by Halcrow. Because observed data are not available for extreme events (the largest flow event in 1947, is approximately a 1 in 50 year flow and the largest tide on record in 1953 is approximately 1 in 200 year event), the ISIS 1D model has been compared with a Telemac 2D model.

The following events have been simulated with the barrier open and with the barrier operational:

- 3.0 m AOD tide and fluvial flow of 750 m^3/s (approx. 1 in 100 year flow)
- 4.0 m AOD tide and fluvial flow of 1050 m^3/s (approx. 1 in 1,000 year flow)
- 5.0 m AOD tide (approx. 1 in 1,000 year tide) and fluvial flow of 10 m^3/s

The EP3 modelling showed that in the outer estuary water levels were similar in ISIS to those in Telemac for both barrier open and barrier closed events. The ISIS model produced higher water levels upstream of Westminster for both barrier open and barrier closed events.

The models both show similar reflected waves due to barrier closure. In Telemac the timing of the tidal hydrographs is slightly earlier than in the ISIS model. For more details on the comparison of ISIS and Telemac see Appendix H of the EP3 2006 Report (TE2100 EP3 2006).

This comparison shows that the 1D model can replicate the propagation of the tide up the estuary and the dynamic effects of barrier closure on water levels.

The ISIS 'Glass Wall' model (excluding floodplains) has also been compared to Telemac for extreme tides of 6 m AOD and 7 m AOD as part of the Pilot Portfolios study. This was to provide a check on the representation of the Thames Barrier when it is overtopped and whether in the ISIS model there was some influence on the boundary condition at Southend. The Telemac model was extended to include part of the southern North Sea, in order to remove the limitation of a model boundary condition at Southend. The results of this comparison are shown in Table A.1.

Table A.1 Difference in water level between the Telemac and OM HLO model for the 'Glass wall' case

Barrier:	Scenario	Difference in water level (m)			
		Barrier d/s	Dartford	Tilbury	Southend
CLOSED	6 m AOD	0.191	0.353	0.393	0.091
CLOSED	7 m AOD	0.598	0.564	0.381	0.008
OPEN	6 m AOD	0.049	0.091	0.208	0.053
OPEN	7 m AOD	0.033	0.070	0.195	-0.007

Table A.1 shows that, for the Thames Barrier closed, water levels in the Telemac model are 0.5 m higher than water levels in the OM HLO model at the Thames Barrier in the 7 m AOD event, and are around 0.2 m higher at all locations in the 6 m AOD event. With the Thames Barrier open, water levels in the two models are similar.

Comparisons with other model results indicates that the ISIS model under predicts water levels for cases where the Southend peak water level is similar to the Barrier crest level (i.e. about 7m AOD). Whilst this is unlikely to affect much of the design work in the options (where design high tide levels are lower), it is advisable to model the main options using both Telemac and ISIS to ensure that this problem does not affect the final designs.

The reason for the under prediction is not known, but there could possibly be some interaction between flow overtopping the Barrier and the amount of rise in tide amplitude (hence peak water level) due to the shape of the estuary. Whatever the cause, the 'Glass Wall' ISIS model appears to significantly underestimate water levels between Tilbury and the Thames Barrier for the extreme 7 m AOD tide.

A.2.3 Independent comparison of the ISIS model with Telemac

The ISIS and Telemac models have been compared in detail for observed events by an independent specialist on behalf of the Environment Agency (EdenVale, 2005). This produced similar results to the comparison in EP3, showing that water levels in the ISIS model were greater than those in Telemac upriver of Westminster.

A.3 Validation of the 1D flood-cell model for the HLOs

The model used on the HLO studies includes the floodplain modelled with ISIS reservoir (flood cell) units. The floodplain is linked to the river by spill units representing the flood embankments and defences. The reservoir units were created on the Thames Embayments project following detailed analysis of the topography in each embayment and 2D modelling.

For flow and tide conditions that do not overtop the flood defences the model performance is the same as that used in TE2100 EP3 and by Halcrow in 2002. The HLO flood cell model has been run for three historical tides (1938, 1953 and 1965) for validation. Observed water levels at points on the estuary were available for these events, and have been compared with the modelled water levels.

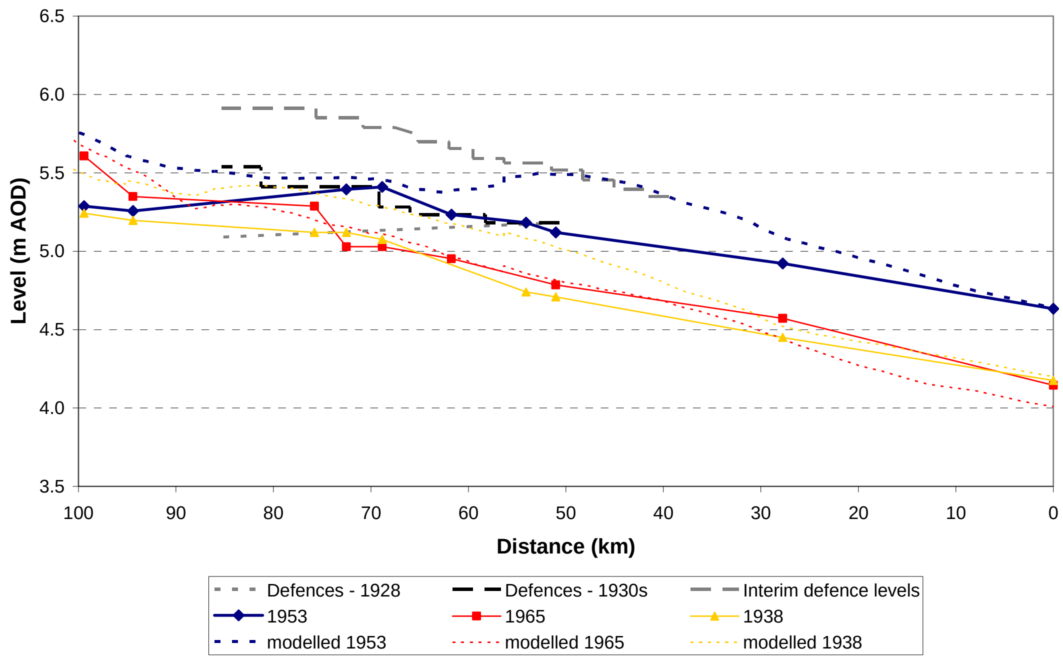

Figure A.1 Comparison of the ISIS flood cell model with three historical events

Figure A.1 shows that the ISIS model over predicts water levels in the 1953 event by up to 0.4 m. This is partly because in the actual event there was extensive breaching and inundation in the lower estuary which is not replicated in the model. There were 275 breaches in the 1953 event, although physical modelling showed the impact of this on reducing peak water levels to be only 0.10 m (Allen et al., 1955). This has been further investigated (see Annex B).

The model water levels for the 1965 event give reasonable agreement with the observed levels, although again the model over predicts levels in West London. For the 1938 event the model over estimates water levels by approximately 0.25 m upstream of Dartford.

Some of the difference between the models and the observed events is because of changes in the channel morphology between the observed events and the survey the model cross sections are derived from (a period greater then 30 years). This is especially relevant between Teddington and Hammersmith as noted in the Halcrow 2002 report.

A.4 1-D flood-cell model compared to linked 1D-2D model

It is necessary to provide an indication of the accuracy of the 1D flood cell model for events that inundate the floodplain. Due to the rareness of these events there is no accurate observed data with which to calibrate the model. The ISIS flood cell model has therefore been compared to the ISIS-Tuflow model for the following extreme tidal events:

- Present day 1,000 year tide
- Medium High 1,000 year tide in 2100
- High + 200 year tide in 2100
- High + 10,000 year tide in 2100

The river water levels up to the Thames Barrier are shown in Figure A.2. The longitudinal profiles for the present day 1,000 year tide and the high plus 10,000 year tide in 2100 are similar in both models. This reflects that in the present day 1,000 year tide there is little overtopping except for Cliffe marshes, and in the High plus 10,000 year tide there is overtopping in vast areas of the estuary.

In the medium high 1,000 year tide and the High plus 200 year tide there are some differences between the models. This is partly due to the inclusion of the Grain and Allhallows marshes in the ISIS-Tuflow model which adds considerable storage volume relative to the ISIS flood cell model.

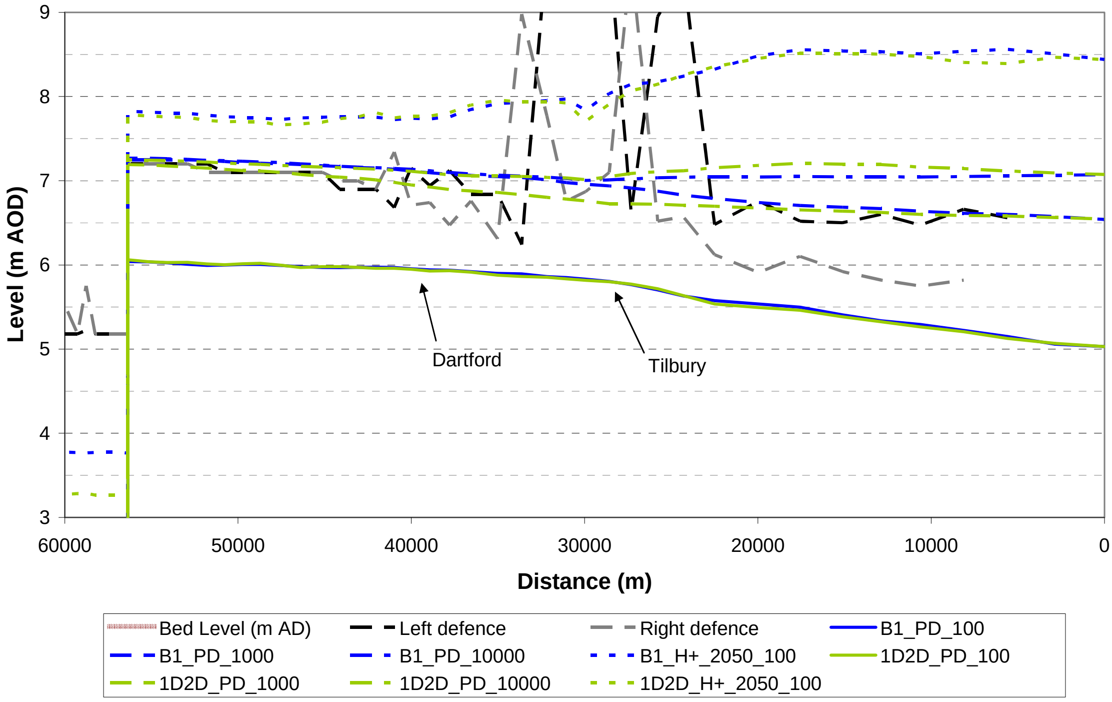

Figure A.2 Longitudinal profile of river water level

In the ISIS flood cell model water is able to move between flood cells easily if the water level is greater than the spill level. This means that there is often a shallow depth of flooding in cells adjacent to overtopping locations. Because of this the ISIS flood cell model has greater extents of flooding in the Medium High 1,000 year and High Plus 200 year events. This is also likely to be the result of water not being able to overtop into the Grain and Southend areas. In the Medium High 1,000 year event this also explains the small extent and depth of flooding in Canvey Island in the ISIS-Tuflow model compared to the ISIS flood cell model.

In terms of providing loadings for the IA model and designing FRM options the good agreement of river water levels between the two models in extreme events is more important than differences in extent and depth of flooding in the embayments.

A.5 Areas for improvement

A.5.1 Floodplain representation at Teddington

The spill level on the right bank at Teddington weir should be increased to the same level as the high ground. At present this allows some bypass of flow around the structure because there are artificial low levels in the reservoir unit representing the floodplain to prevent instability.

A.5.2 Floodplain representation under extreme flow

For extreme flows run for the climate change scenarios there are instabilities in the fluvial reach due to interaction of flow in flood cells with flow in the channel. Under these conditions, representation of the floodplain with storage reservoirs may not be accurate and introduces model instability. A possible solution would be to use extended cross sections for extreme flows which produce the same water levels in the channel and on the floodplain above the defence levels.

A.5.3 Teddington weir under extreme flow

For extreme flows run for the climate change scenarios there are instabilities at Teddington weir where some re-circulation of flow occurs due to the looped channels in the model. For extreme flows it may be more appropriate to model the complex structure in a simplified way with a single channel and weirs to prevent instability.

A.5.4 Extension of the model downstream

The comparison of the ISIS flood cell model with the ISIS-Tuflow model has shown the impact of not including the floodplains of Grain and Southend in the flood cell model. It may be necessary to extend the floodplain in this model. However this would mean that spilling occurs very close to the downstream boundary of the model which may lead to instabilities and inaccuracies. The model would therefore have to be extended further into the North Sea, similar to the Telemac model.

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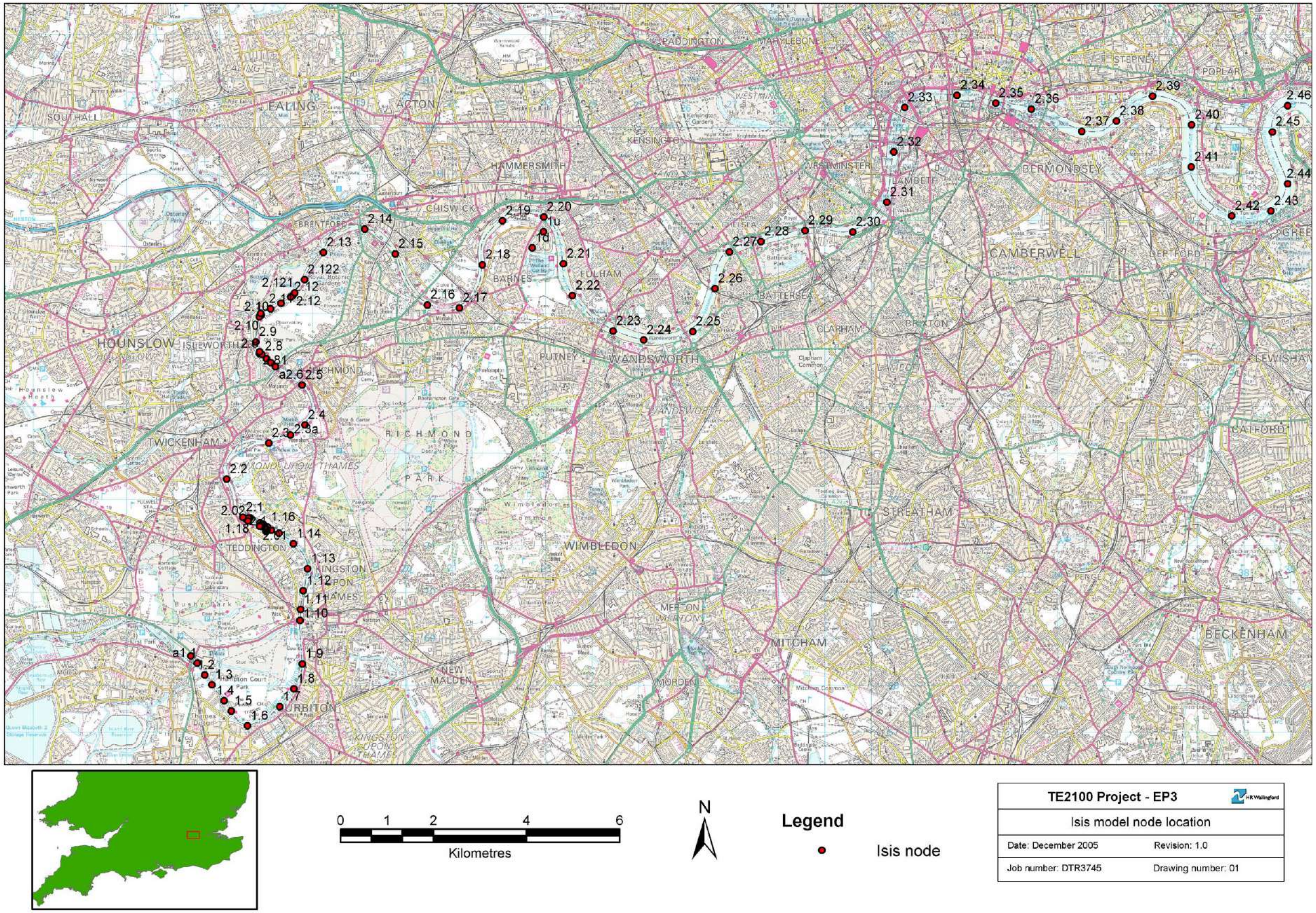

Figure A.3 Model estuary node locations: Molesey to Greenwich

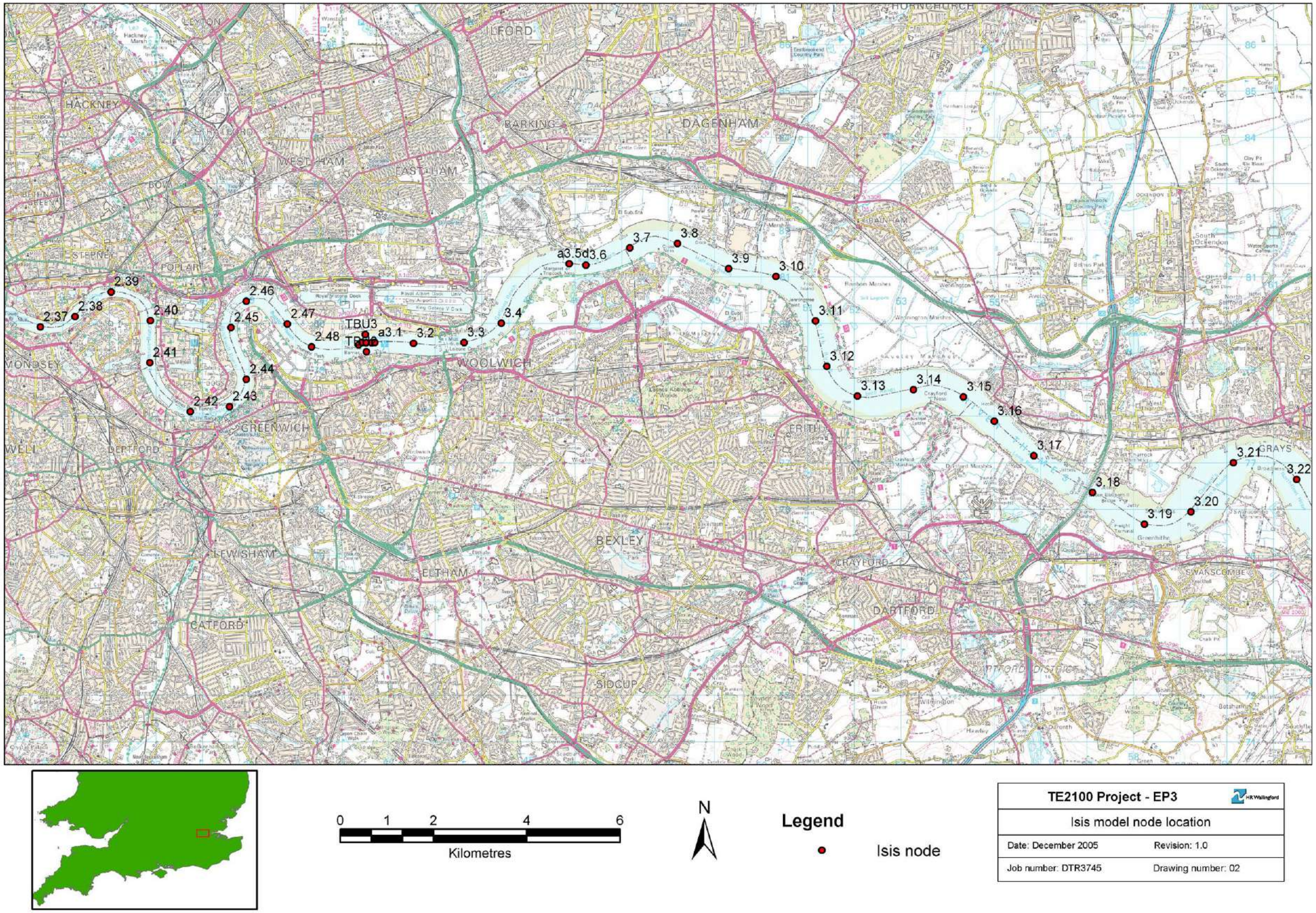

Figure A.4 Model estuary node locations: Greenwich to Greenhithe

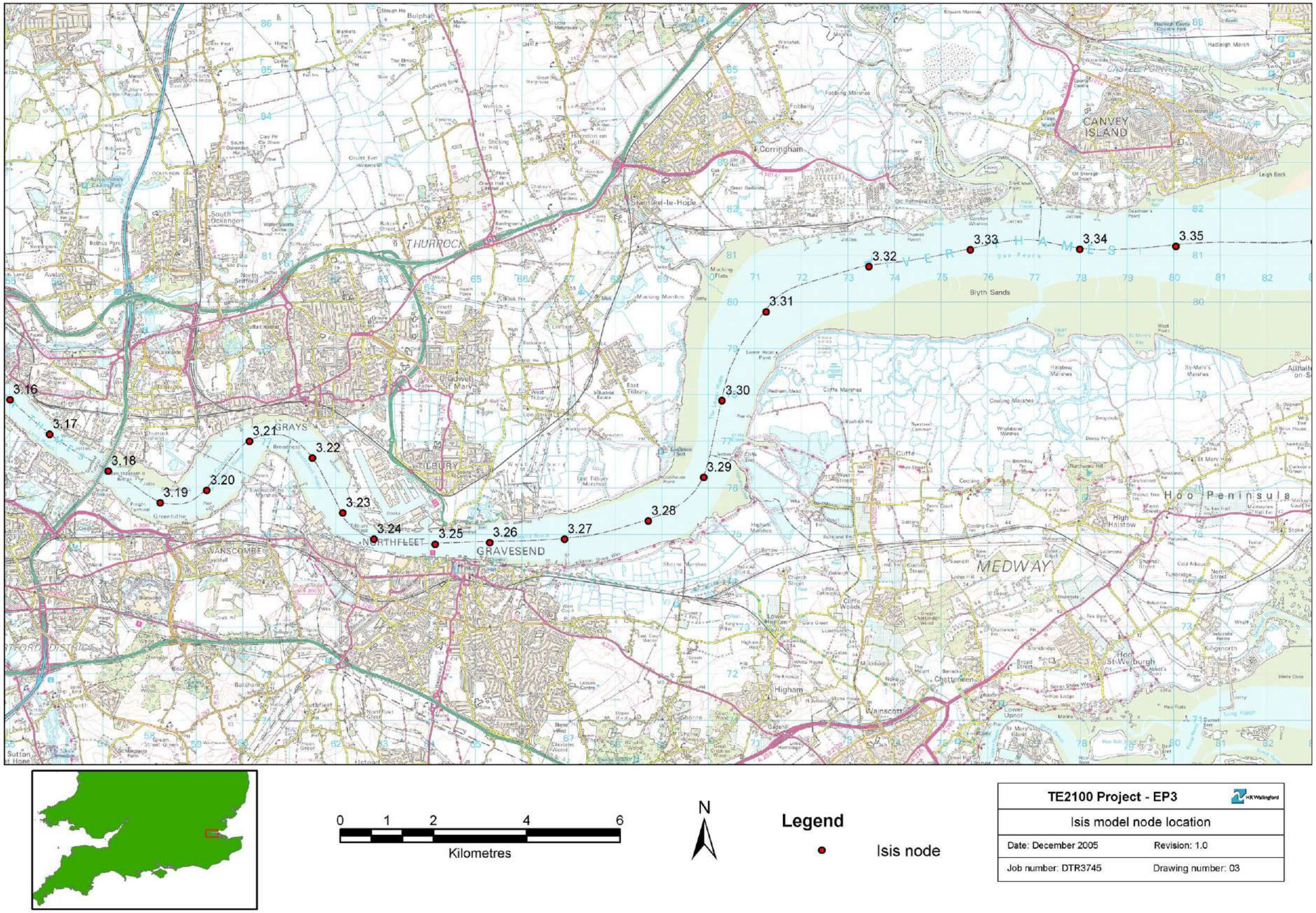

Figure A.5 Model estuary node locations: Greenhithe to Canvey Island

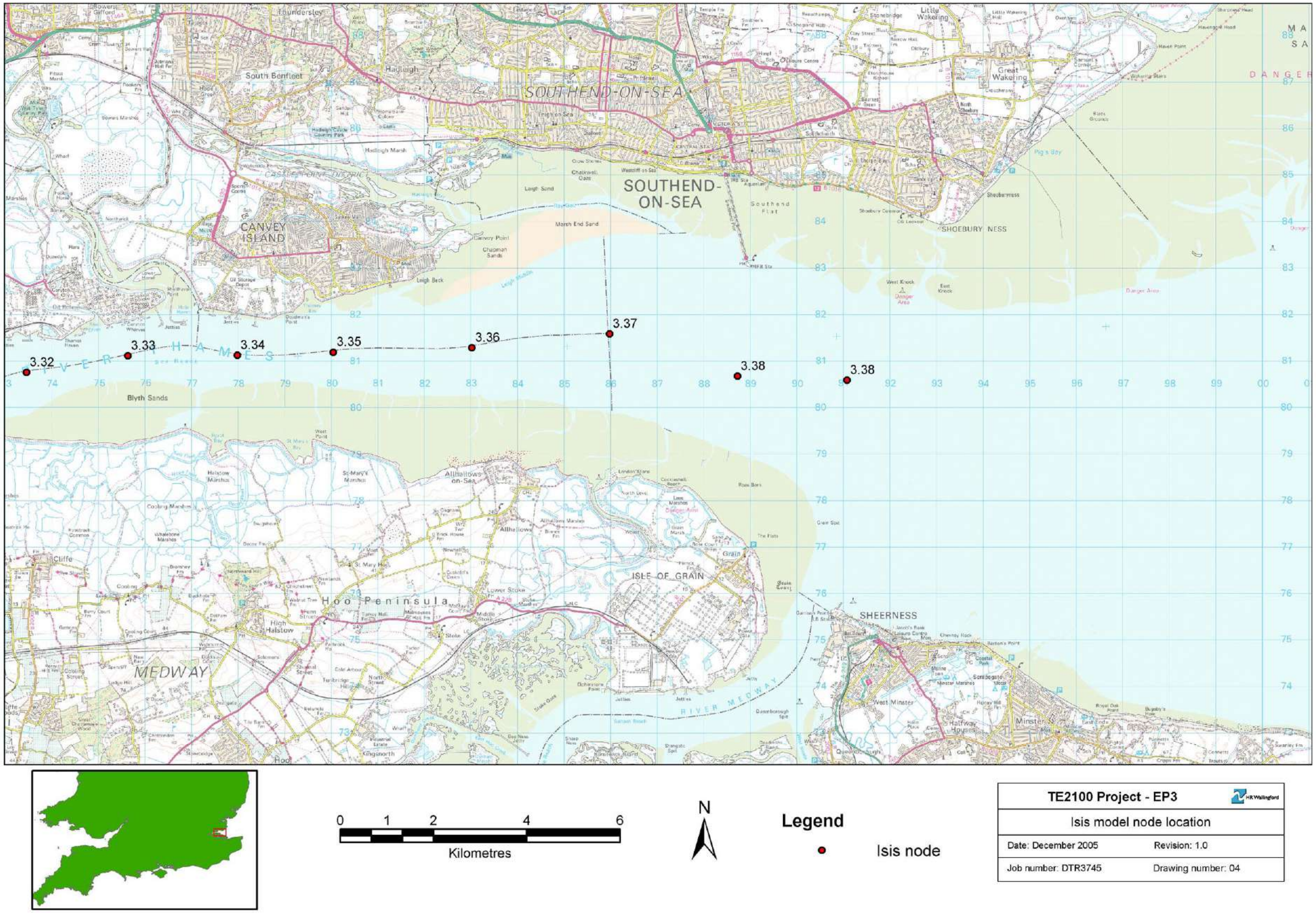

Figure A.6 Model estuary node locations: Canvey Island to Southend

Annex B Validation of the model for the 1953 event

B.1 Introduction

The storm surge on the 31st January to 1st February 1953 produced the highest water levels recorded on the Thames Estuary. The peak water level at Southend was 4.64 m AOD. The tidal event coincided with a relatively low fluvial flow of approximately 74 m^3/s.

The 1D ISIS floodcell model used for the development of HLOs and the Phase 3 Set 1 Options has been run with 1953 event to validate the performance of the model for large tidal events. The return period of the 1953 surge tide is estimated to be approximately 1 in 200 years, whereas the model is being used for events up to the estimated 1 in 10,000 year tide under conditions of future climate change.

The first step was to compare modelled peak water levels in the river to those observed. The second step was to compare volumes of water and depths on the floodplain from the model with those estimated following the event.

B.2 Peak river water levels

B.2.1 1D model with present day defence levels

The initial run of the 1D floodcell model for the 1st February 1953 event produced water levels 0.15 to 0.35 m higher than the observed peak water levels between Tilbury and the current Thames Barrier site at Greenwich.

In West London the model produced water levels approximately 0.5 m higher than observed. Some of this increase can be explained by the model being effectively 'glass walled', as the crest levels of the defences were generally above the water level. As a result, large volumes of water were not lost to the floodplain whereas extensive flooding took place in the actual event.

The defence crest levels were lower in 1953 than at present, and the defences were raised by around 1m immediately after the 1953 event. The bathymetry of the model cross sections are also different to how the river would have been in 1953.

B.2.2 1D model with defence levels as in 1953

To account for the impact of lower defence levels in 1953, the crest levels of the spill units in the model were lowered to the approximate levels of the actual defences in 1953. The model results are shown on Figure B.1.

Comparison of the peak water level profile from the adjusted model with the observed water level shows peak error of 0.15 m in the reach from Southend to Greenwich. The modelled water levels are greater than the observed by 0.05 m Westminster to 0.3 m at Richmond. At Teddington this error is 0.4 m.

These model results show a reduction in peak water level (hence error compared to the observed level) of about 0.2 m in the reach between Tilbury and Greenwich and a reduction of approximately 0.1 m in peak water level upstream of Westminster, due to overtopping. This is in contrast to physical modelling undertaken in 1954 which suggested that reductions in peak water level due to overtopping were below 0.05 m.

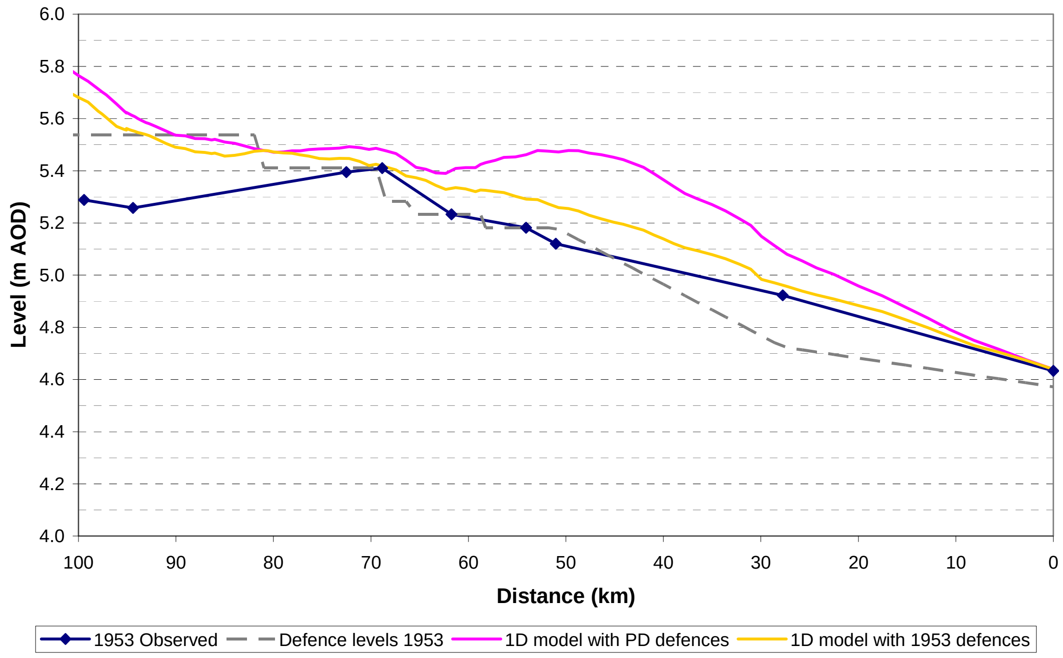

Figure B.1 Comparison of modelled and observed peak water level profiles

The 1953 water surface profile rises from Southend to Westminster, but then falls in the reach up to Richmond. This differs from the model results, where the peak water levels continue to rise upriver of Westminster. Comparison with a wider range of events indicates that the reduction in water levels upriver of Westminster is unusual, as indicated on Figure B.2 (from Work Element DC10 in Phase 2 of the TE2100 studies).

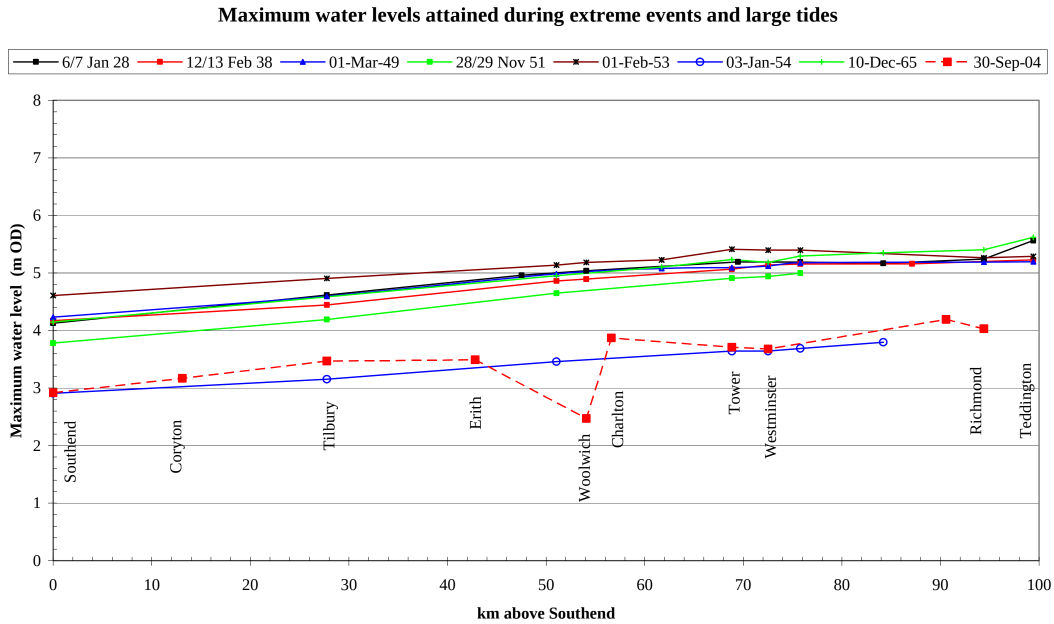

Figure B.2 Observed peak water level profiles (HRW 2006)

To investigate the cause of the difference between the modelled and observed water levels in West London, the model has been re-run with the sluice gates of Richmond Sluice open. Figure B.3 shows that this has little impact on the modelled peak water levels in West London. This difference is at present unexplained. Inspection of hydrographs at Tower Pier and Westminster suggests that the cause might be loss of tidal volume due to breaching of defences before the peak of the tide (Figures B.7 and B.8).

However it can be concluded that the model comparison is reasonable for the reaches downriver of central London where the main flooding occurred.

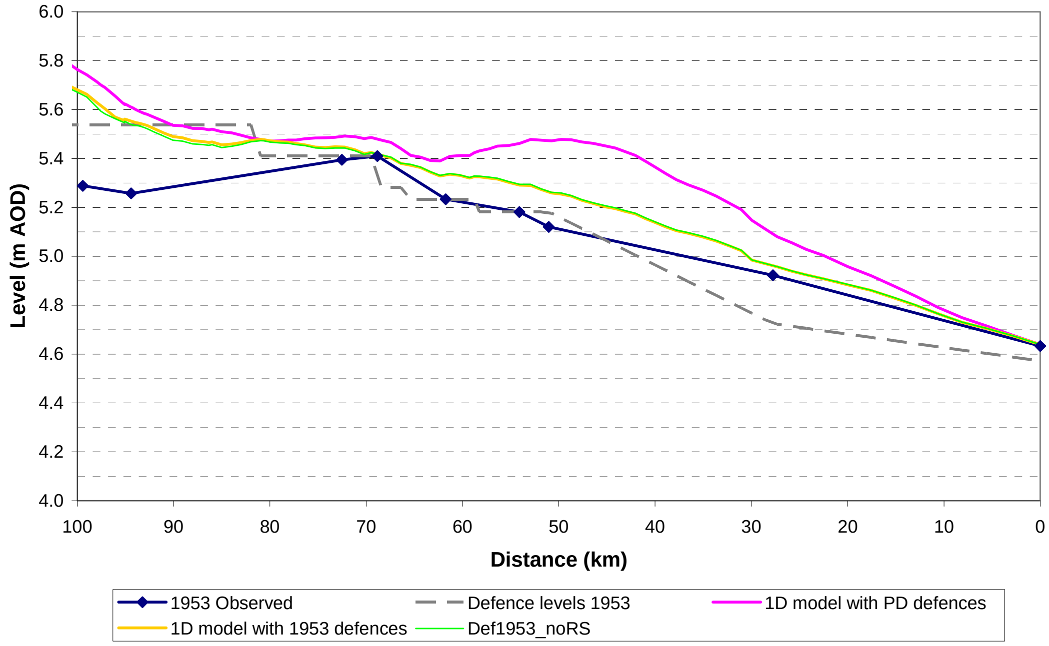

Figure B.3 Model with Richmond Sluice open

B.2.3 Inclusion of breach volumes

The numerical model was then adjusted to account for the volumes of water entering the floodplain due to breaching. Breach volumes were taken from the 1954 physical model. These were firstly applied after high water (breachvols1), which had no impact on peak water levels in the river.

The timing of breaches was then moved to 30 minutes before the exact point of high water (note water levels are close to high water for about 1 hour). This assumption reduced peak water levels in the river by around 0.05 m (breachvols2). This is around the reduction (approximately 3 inches) found in the physical model when breaching was taken into account.

In breachvols3 the Dartford breach is assumed to occur 30 minutes earlier than in breachvols2. This has a local reduction in water level, but has no effect on water levels upstream of Westminster.

The results for the removal of estimated breaching volumes from the model are shown on Figure B.4.

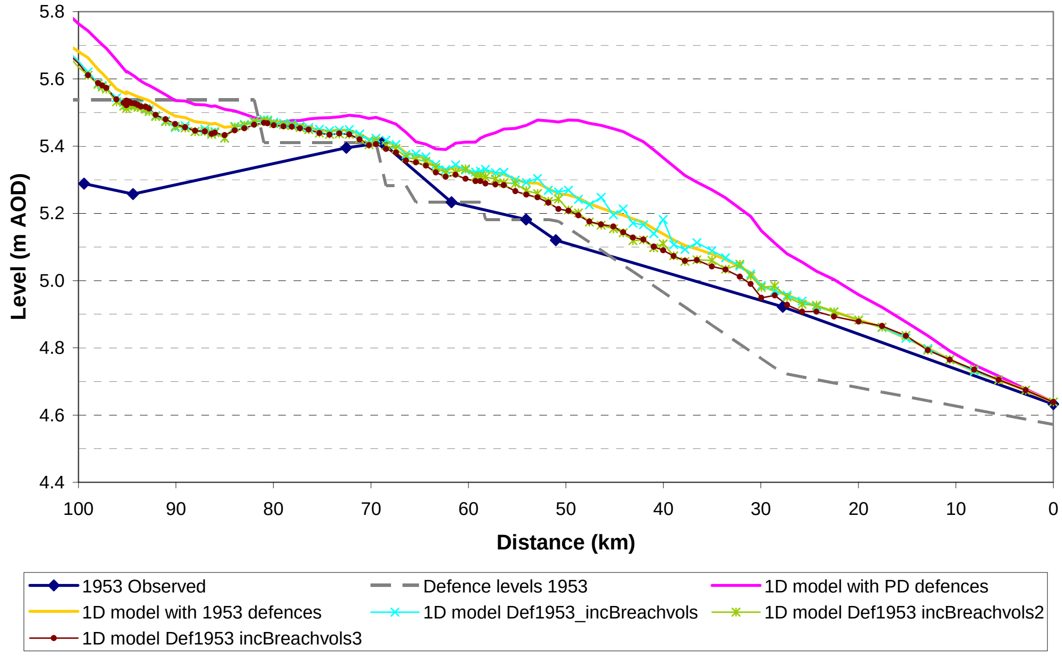

Figure B.4 Impact of including breach volumes in the 1D model

B.2.4 Modelled breaches

The 1D model spill units can be modified to simulate the impact of a breach. Locations for breaches and the frontage length for the breach have been taken from the assumptions made in the physical model study in 1955.

The depth of the breach in the 1D model has been assumed to extend to 2m AOD which is approximately the ground level for most of the floodplains in the outer estuary. The breaches were firstly timed so that they occurred at high water, then re-modelled so that breaches were 30 minutes before high water.

In the breach v3 model, the breaches downstream of Tilbury occur at high water and upstream of Tilbury the breaches occur 30 minutes before high water. Figure B.2.5 shows that the breaching has a small impact on peak water levels. Between Tilbury and Greenwich the peak levels are reduced by approximately 0.05 m, which reduces the error between the observed and modelled water levels.

Upstream of Hammersmith there is also a small reduction in peak water level, but this does not have a significant impact on the difference between the observed and modelled water levels. The results of modelling breaches give similar peak water levels as when the estimated breach volumes from the 1953 event are removed the channel cross-sections (comparison of Figure B.4 and Figure B.5).

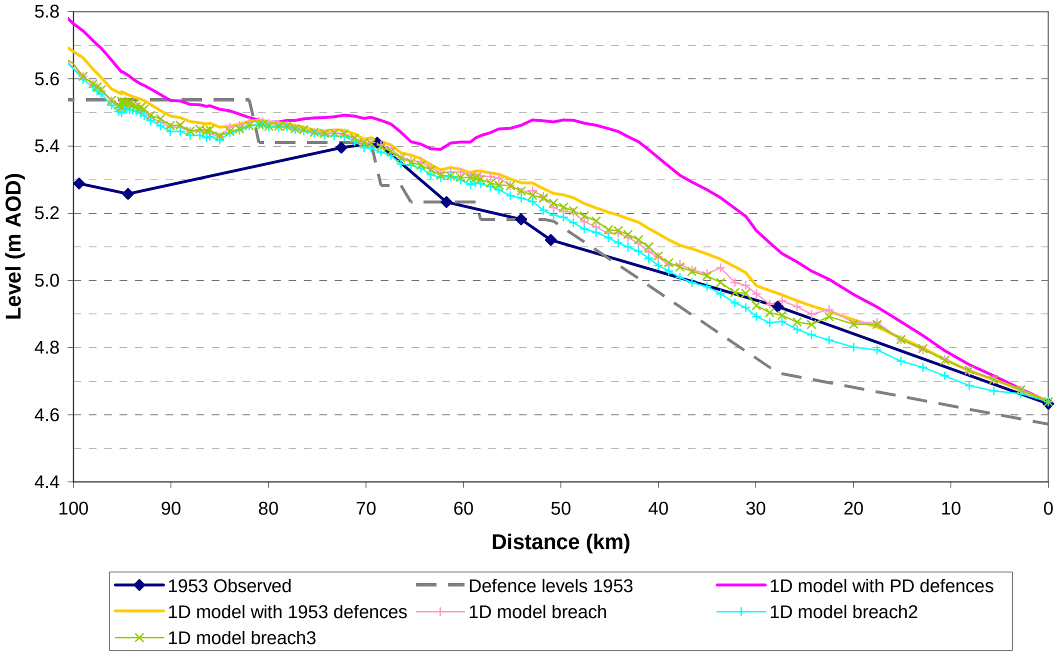

Figure B.5 Impact of modelled breaches on peak water level

The modelled water level hydrographs are compared with the observed water level hydrographs at Tilbury, Tower Pier and Westminster in Figures B.6, B.7 and B.8 respectively.

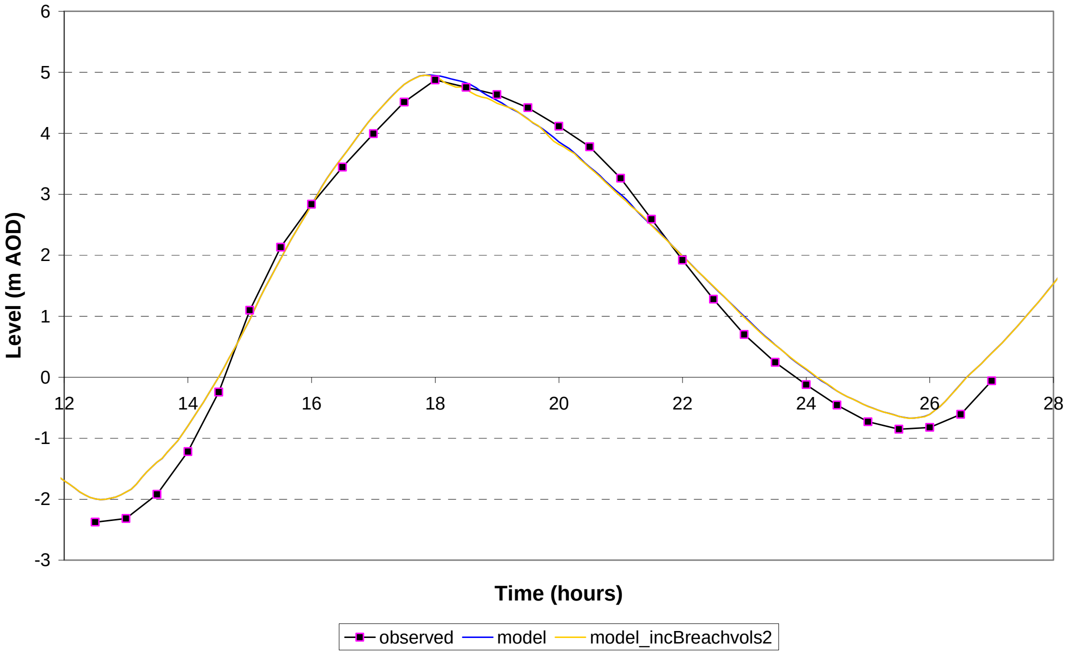

Figure B.6 Modelled and recorded water level hydrographs at Tilbury Pier

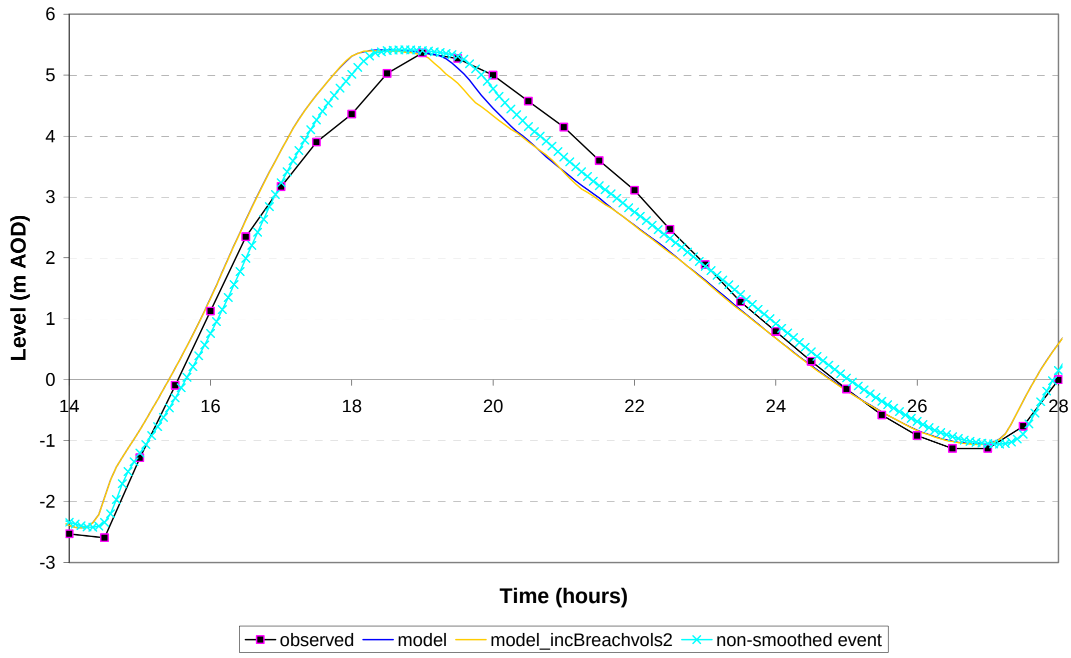

Figure B.7 Modelled and recorded water level hydrographs at Tower Pier

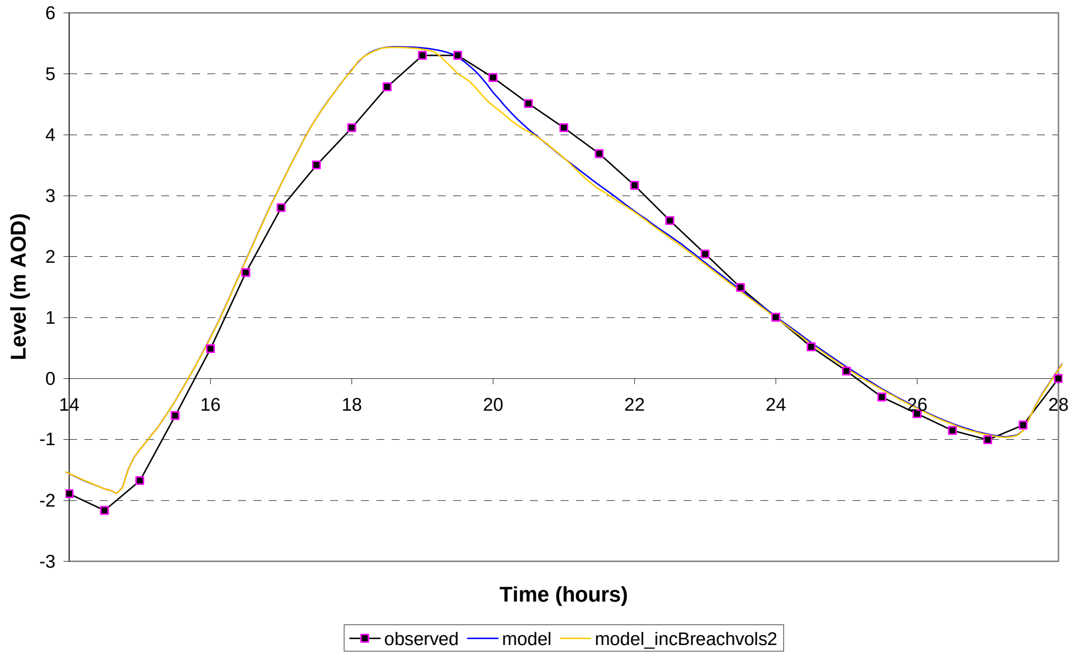

Figure B.8 Modelled and recorded water level hydrographs at Westminster

At Tilbury there is reasonable agreement between the model and the observed water level hydrographs. The peak of the hydrograph in the model is slightly steeper and higher than the observed.

When the modelled water level hydrographs are compared with the observed at Tower Pier and Westminster it can be seen that the rise in water level of the upper part of the hydrograph in the model is greater than was observed. This indicates that breaching occurred before the high tide peak, and that water was lost into storage during this period.

In addition, there are areas on the estuary where flooding could have occurred that are not included in the 1D model. The 1D model does not include the following areas that would have provided additional storage:

- Canvey Island Creeks
- River Darent
- Purfleet tidal creeks (Mar Dyke, Beam, Ingrebourne etc)
- River Roding
- River Lee
- Medway estuary

In addition the bathymetry of the 1D model cross-sections is likely to be different from the channel topography in 1953 which may account for some of the error between the model and observed water levels.

B.3 Floodplain volumes and depths

Flood extents from the modelling are shown in Figures B.9 and B.10 for the cases where breach volumes have been used (from the physical model) and breaches have been included in the model. The figures also show the floodplain areas represented in the physical model. The results for the two cases in terms of depth and extent of flooding are similar.

The figures indicate flooding in areas upriver of Thamesmead. Whilst this is understood to have small in 1953, it reflects the fact that the modelled water levels exceed the modelled defence levels (as shown on Figure B.5).

The flood volumes and average depths on the floodplains from the 1D model have been compared to estimates made by the Kent and Essex River Boards in 1953 and the results are shown in Table B.1.

Table B.1 Volume of water on the floodplains (Million m^3)

Embayment	Location	Estimated volume	1D model with 1953 defences	1D model inc breach volumes 3	1D model inc breach v3
A	Erith	3.72	0.87	5.96	6.01
B	Crayford	0.88	0.38	0.18	0.81
C	Dartford	5.77	0.86	8.03	6.63
D	Swans	1.40	1.20	0.70	0.47
E	Cliffe	9.50	2.23	16.64	20.53
F	A,W,R	1.00	1.06	0.55	2.81
G	Thurrock	5.18	1.80	3.11	4.10
H	Tilbury	5.99	3.22	4.23	9.55
I	East Tilbury to Fobbing	8.75	3.15	12.35	12.42
J	Canvey	11.73	1.29	15.80	14.52

These results show that there are greater volumes of water on the floodplain in the 1D model with breaching than were estimated (observed) following the 1953 flood. The total volume on the floodplain in the 1D model is 67.5 million m^3 (breach volumes) or 77.8 million m^3 (breach model) and the estimated volume for the event was 53.9 million m^3.

Modelling the breaches produces greater volumes of water on the floodplain than when a volume of water corresponding to that from breaches in the 1954 physical model study was extracted from the 1D model. The volume spilled of 16 million m^3 is similar to that of 13.3 million m^3 from the 1954 physical model study, during which weir equations (similar to the 1D model) estimated an over topping volume of 16 million m^3.

Similar comparisons of average water depths are shown in Table B.2.

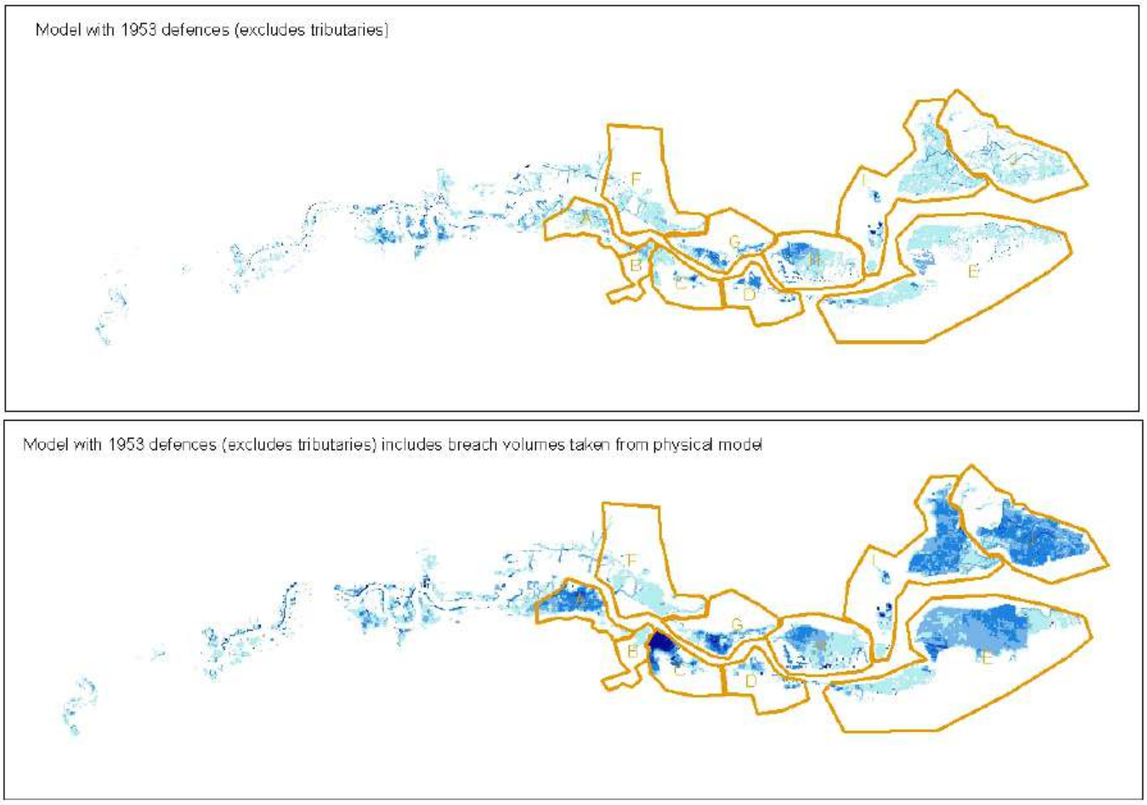

Figure B.9 Flood extents based on breach volumes

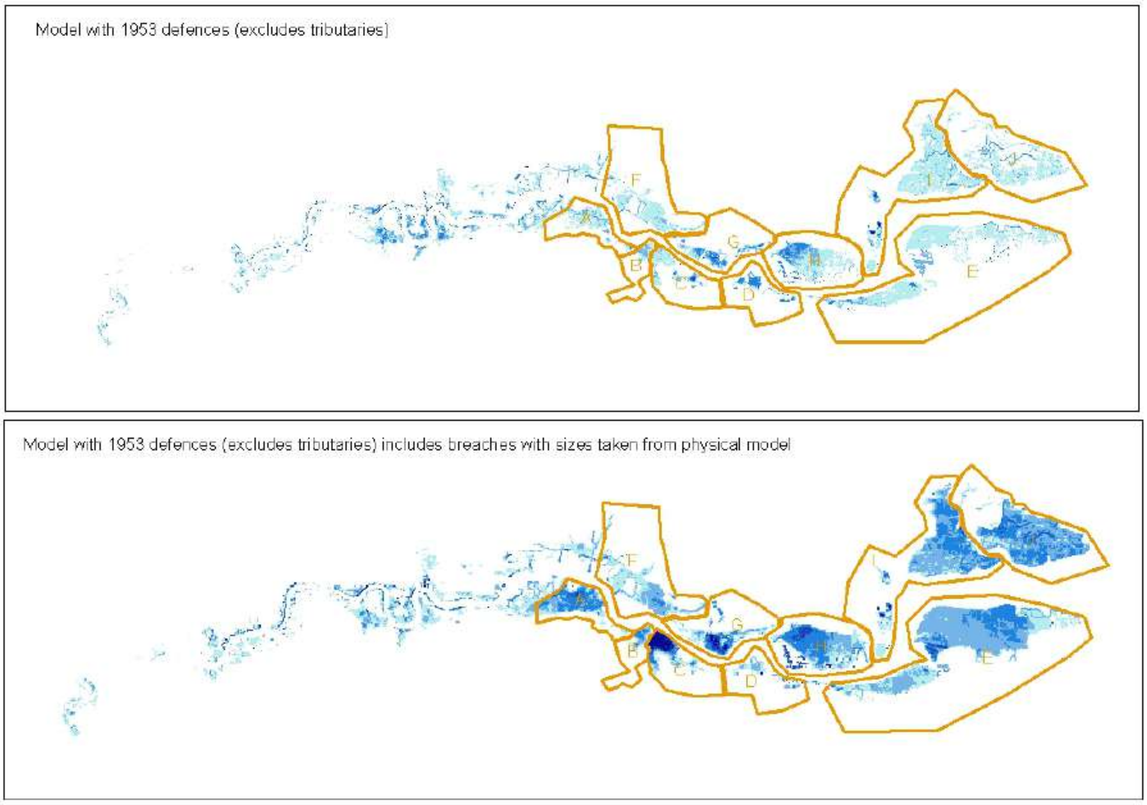

Figure B.10 Flood extent with discrete modelling of breaches

Table B.2 Average water depth (m)

Embayment	Location	Estimated average depth	1D model with 1953 defences	1D model with 1953 defences and breach volumes	1D model with 1953 defences and breaching
A	Erith	0.91	0.45	1.10	1.11
B	Crayford	0.61	0.51	0.31	0.90
C	Dartford	1.22	0.47	2.21	2.12
D	Swans	0.91	1.09	0.78	0.59
E	Cliffe	0.30	0.28	0.75	0.82
F	A,W,R	0.37	0.34	0.26	0.61
G	Thurrock	1.83	0.82	1.19	1.44
H	Tilbury	0.61	0.64	0.65	1.15
I	East Tilbury to Fobbing	1.07	0.43	0.95	0.93
J	Canvey	1.22	0.36	1.10	1.01

In the 1D model with breach volumes included, the average depth of water on the floodplain is similar to the estimates made following the event for each location except Dartford, where the 1D model produces greater depths, and Thurrock, where the 1D model produces significantly lower average depths.

Areas where the 1D model produces lower average depths may be explained by the presence of landfill in some of these areas raising the ground level in the model compared to the actual ground level in 1953.

B.4 Conclusion

The 1D model with 1953 defence crest levels performs reasonably well between Southend and Westminster. The modelled water levels are generally 0.05m higher than the observed, with the peak error of 0.15m higher than the observed in this reach.

The model over predicts water levels by 0.05m to 0.3m from Westminster to Richmond and 0.3 to 0.4m in the reach downstream of Teddington. Water levels produced by the ISIS 1D model are generally higher when compared to the observed water levels from the 1953 event.

These results are based on the assumption that the first breaches occur 30 minutes before high water. However inspection of the 1953 water levels hydrographs at Tower Pier and Westminster suggests that breaching occurred earlier. In this case, water would have been lost to storage before the peak of the high tide. This will affect the subsequent peak water levels along the estuary.

B.5 References

Allen, F.H., Price, W.A., and Inglis, C.C., (1954*). Model experiments on the storm surge of 1953 in the Thames Estuary and the reduction of future surges*. Proceedings of the ICE, Vol 4 Part III.

HR Wallingford 2006. *Rationalisation of actual, predicted and forecast sea levels*, Report from TE2100 Phase 2 Work Element DC10.

Annex C Model instability

Hydrographs of water levels show fluctuations in water levels around the peak tide level following gate closure in the model. In Work Element 5.2 it was found that closure of the gates at low tide reduced these fluctuations and reduced peak water level compared to when the gates were closed at 1m AOD.

These issues have been investigated further to determine whether reductions in peak water level with different closure levels are the result of reduced instability or a real effect.

C.1 Impact of timing of gate closure on peak water levels and instability

The following runs have been carried out with different closure levels for the Thames Barrier to investigate instability:

- Close when water level is +2 m AOD
- Close when water level is +1 m AOD
- Close when water level is +0 m AOD
- Close when water level is -1 m AOD
- Close when water level is -2 m AOD

The water level hydrograph downstream of the Thames Barrier for each run is shown on Figure C.1. This shows that lower peak water levels occur when the barrier is closed at low water (-1 m and -2 m AOD). The hydrograph is smooth for these runs, and for barrier closure when the water level is 0 m AOD.

This compares to barrier closures at +1 m AOD and +2 m AOD, which show instabilities. These instabilities increase water level compared to closures at lower water levels. The difference in peak water level is approximately 0.2 m between early and late closures.

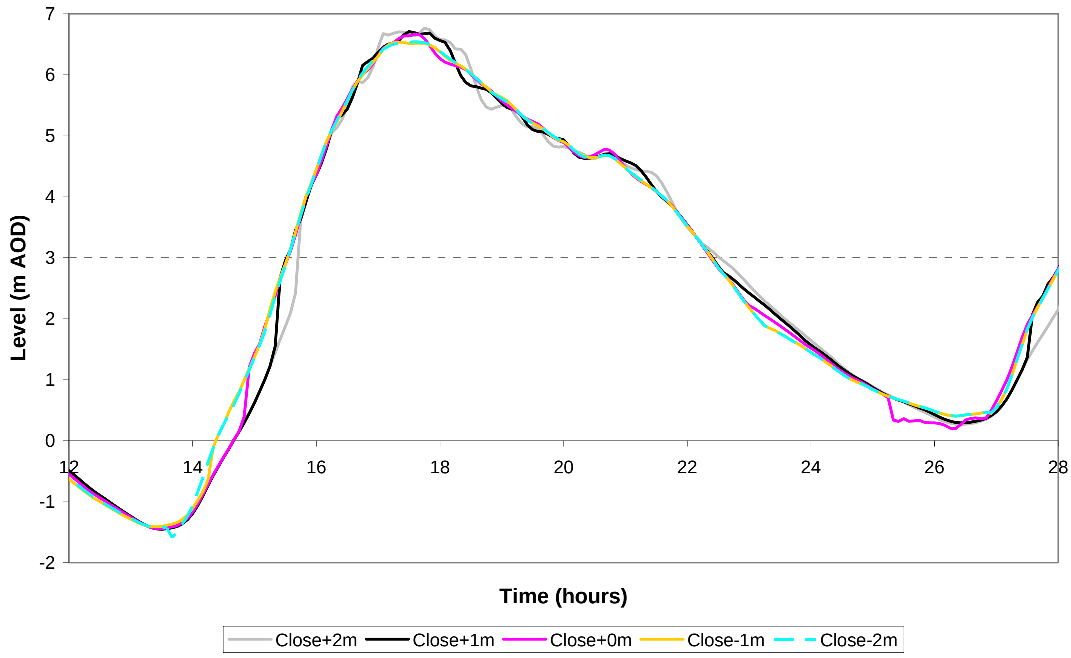

Figure C.1 Water level hydrographs for different barrier closure levels

A study into the operation of the barrier by Pinless in 1975 also found that downstream water levels are higher for later barrier closures (Table C.1). Although it appears that higher closure levels were used (unless they refer to Southend, rather than local to the barrier). This study used a tide of 18.4 ft and a flow of 2,500 cusecs, which converts to approximately 5.61 m AOD and 230 m^3/s.

Table C.1 Results of Pinless (1975)

Closure level (ft)	Water level (ft)	Difference to closure at 0 ft (m)
Open	21.8	-
0	22.4	-
4	22.2	-0.06
8	23	0.18
12	23.5	0.34

C.2 Instability due to model timestep

There is also instability introduced by the timestep used in the model. For the model runs this has been adaptive with a maximum of 300 seconds, minimum of 1 second and a start of 20 seconds. The model with barrier closure at 1 m AOD (Rule 1) has been run with the following timesteps:

- 5 seconds
- 20 seconds
- 50 seconds
- 100 seconds
- 180 seconds

The water level hydrograph downstream of the Thames Barrier for each run is on Figure C.2. This shows that model instabilities are greatest for small timesteps. This is because of the relatively large cross-section spacing (500 to 1000 m) and large depth of flow in the tidal reach. The water level hydrograph downstream of the Thames Barrier is smoothest (least unstable) when the timestep is 180 seconds.

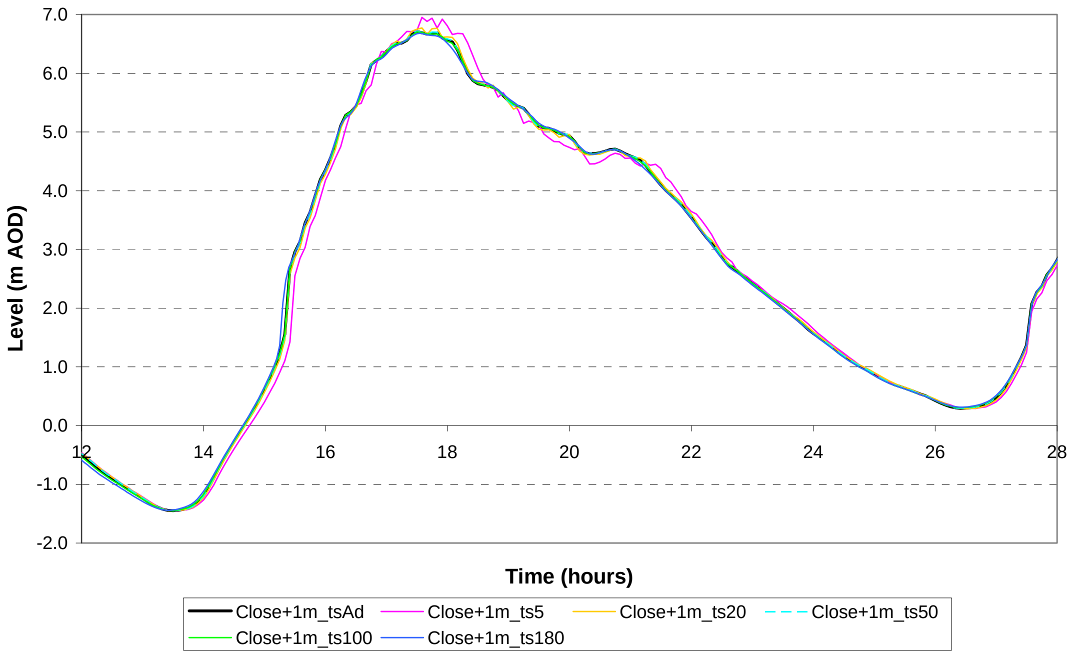

Figure C.2 Water level hydrographs for different simulation timesteps

In terms of maximum water level downstream of the barrier the smooth hydrograph with timestep of 180 seconds is 0.03 m lower than the base timestep (Table C.2). If the timestep is reduced to 5 seconds, the instabilities increase the peak water level by 0.24 m.

Table C.2 Water level and difference from base water level

Timestep	Peak water level (m AOD)	Difference from base (m)
Adaptive (base)	6.71	-
5 seconds	6.95	+0.24
20 seconds	6.77	+0.06
50 seconds	6.72	+0.01
100 seconds	6.70	-0.01
180 seconds	6.68	-0.03

C.3 Conclusion

The results show that instability in the model with an adaptive timestep is relatively small, and that early barrier closures reduce instability in the model and the peak water levels.

Annex D Base water levels

D.1 Assumptions

Design water levels have been produced for 3 conditions:

- Basecase 0 – The model of the estuary is 'glass walled' so that there is no overtopping and water levels in the channel are higher than with the floodplains (conservative).
- Base case 1 – The model of the estuary includes the floodplains and uses the present day defence levels.
- Basecase 2 – The model of the estuary includes the floodplains and uses the present day defence levels with the freeboard removed.

The design water levels for the case where the Thames Barrier is operational are based on the following assumptions:

- Downriver of the barrier water levels are produced for tides of given return periods. The design tides are the 1,000 year and 10,000 year tides.
- Upriver of Hammersmith the water levels are determined by interactions between tide and flow, but at high flows are dominated by the fluvial flow.
- In present day conditions the water levels between the Thames Barrier and Hammersmith are controlled by the operational rules of the barrier. The maximum water levels are determined by the range of tides that can pass through the Thames Barrier (Figure D.1).

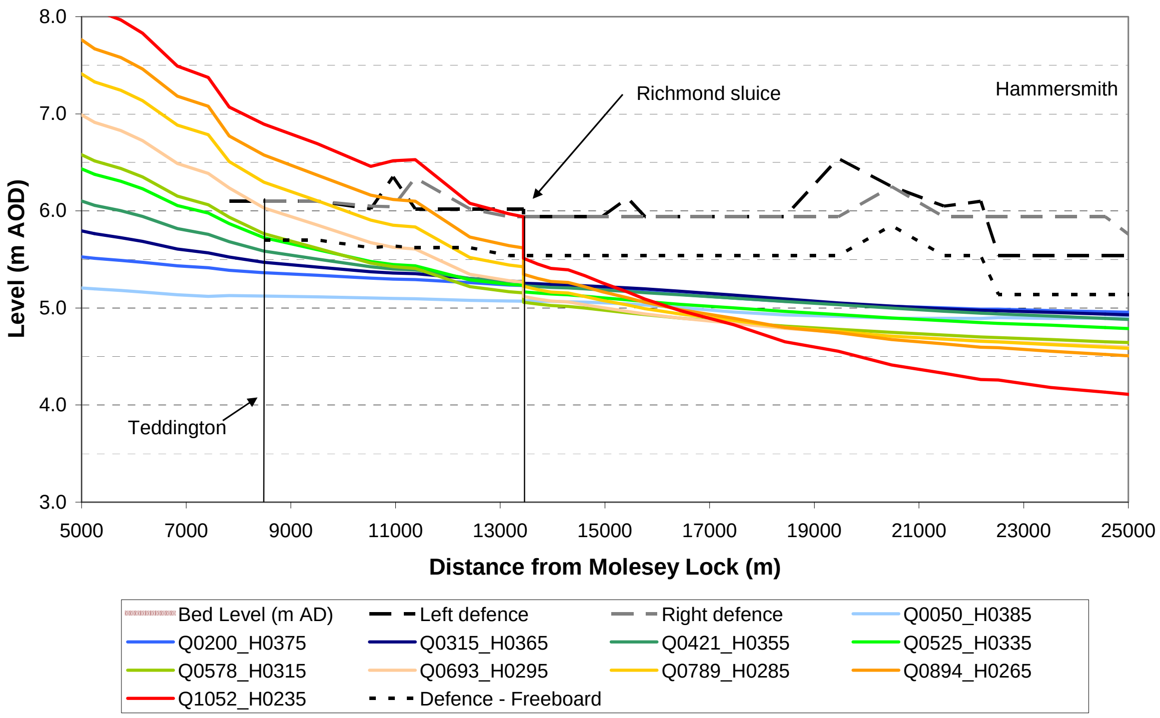

Figure D.1 Water level profiles for combinations of flow and tide for which the Thames Barrier is not closed

D.2 Barrier Closed According to Rule 1

D.2.1 Present Day

Long profiles of water level have been plotted for tides of 1,000 year and 10,000 year return periods under present day conditions with the barrier closed. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

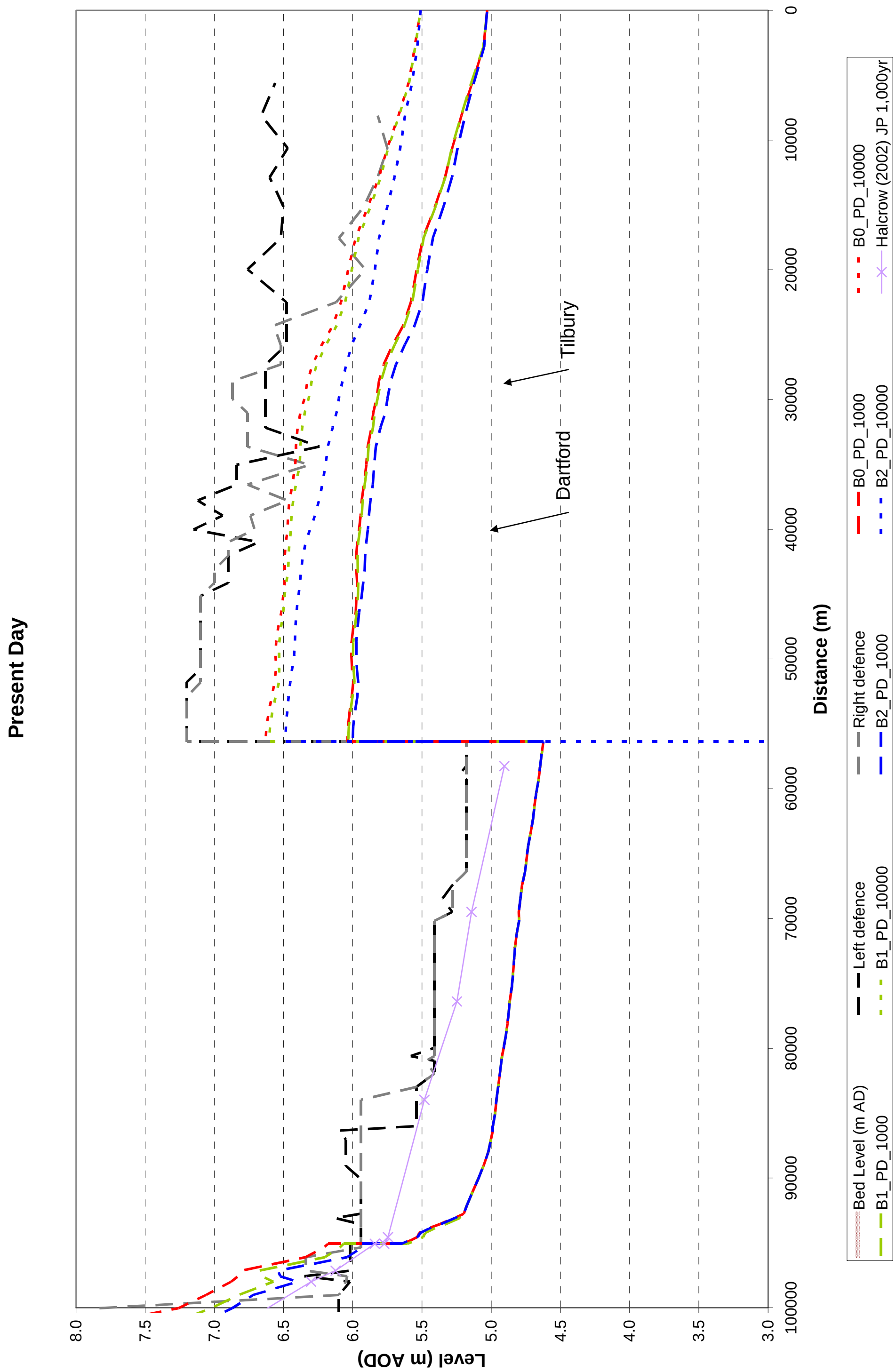

Figure D.2 Peak water levels: barrier closed; present day

River water levels are approximately 0.1 m lower for the model without freeboard in the 1,000 year tide and approximately 0.2 m lower with the 10,000 year tide. Water levels with the actual defences are similar to the glass wall model in all present day events because there is very little overtopping of the actual defences.

Upstream of the Thames Barrier the water levels between the barrier and Richmond are from the barrier closure rule. Upstream of Richmond the water levels are from the 1,000 year fluvial flow. These water levels are lower than the Halcrow (2002) joint probability 1,000 year water levels, which included uncertainty in closure of the barrier. In West London the water levels are greater than the Halcrow (2002) joint probability water levels because Halcrow used lower flows.

Table D.1 Peak water levels: barrier closed; present day

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	6.05	6.04	6.05	7.26	7.02	6.87	-	-	-
	2.3	5.56	5.54	5.55	6.88	6.57	6.40	-	-	-
	2.4	5.46	5.44	5.45	6.80	6.68	6.54	-	-	-
Richmond	a2.6	5.27	5.27	5.27	6.18	6.07	5.94	-	-	-
	a2.7	5.26	5.26	5.26	5.64	5.61	5.65	-	-	-
	2.9d	5.24	5.24	5.24	5.54	5.49	5.53	-	-	-
	2.21	4.96	4.96	4.96	4.96	4.96	4.96	-	-	-
	2.29	4.87	4.87	4.87	4.87	4.87	4.87	-	-	-
	2.36	4.80	4.80	4.80	4.80	4.80	4.80	-	-	-
	2.47	4.65	4.65	4.65	4.65	4.65	4.65	-	-	-
Barrier	a3.1	5.53	5.52	5.52	6.04	6.03	6.00	6.63	6.60	6.49
	3.2	5.52	5.52	5.52	6.03	6.03	6.00	6.62	6.60	6.48
	3.3	5.50	5.50	5.50	6.02	6.02	5.99	6.61	6.58	6.47
	3.4	5.49	5.49	5.48	6.01	6.00	5.97	6.59	6.56	6.46
Roding	a3.5u	5.48	5.47	5.47	6.00	5.99	5.96	6.57	6.53	6.45
	a3.5d	5.48	5.47	5.47	6.00	5.99	5.96	6.57	6.53	6.45
	3.6	5.48	5.47	5.46	6.01	5.99	5.97	6.56	6.53	6.44
	3.7	5.48	5.47	5.46	6.01	6.00	5.98	6.56	6.53	6.42
Beam	3.8	5.48	5.47	5.47	6.01	6.00	5.98	6.56	6.53	6.42
	3.9	5.47	5.47	5.46	6.00	5.99	5.97	6.54	6.52	6.42
	3.10	5.45	5.45	5.45	5.98	5.97	5.95	6.52	6.50	6.41
	3.11	5.44	5.44	5.44	5.97	5.96	5.94	6.50	6.49	6.39
	3.12	5.43	5.43	5.43	5.97	5.96	5.93	6.49	6.48	6.38
	3.13	5.43	5.43	5.42	5.97	5.97	5.91	6.49	6.47	6.37
	3.14	5.43	5.43	5.42	5.98	5.97	5.91	6.49	6.47	6.36
Darent	3.15u	5.43	5.43	5.42	5.97	5.96	5.90	6.48	6.46	6.34
	3.15d	5.43	5.43	5.42	5.97	5.96	5.90	6.48	6.46	6.34
	3.16	5.43	5.43	5.42	5.95	5.95	5.89	6.47	6.45	6.31
	3.17	5.41	5.42	5.41	5.94	5.94	5.88	6.47	6.44	6.27
	3.18	5.41	5.41	5.40	5.94	5.93	5.87	6.46	6.43	6.24
	3.19	5.40	5.40	5.39	5.92	5.91	5.86	6.44	6.41	6.22
	3.20	5.38	5.39	5.38	5.90	5.90	5.85	6.42	6.38	6.20
	3.21	5.37	5.37	5.36	5.89	5.89	5.83	6.41	6.38	6.18
	3.22	5.35	5.34	5.33	5.86	5.85	5.80	6.40	6.37	6.15
	3.23	5.34	5.34	5.32	5.85	5.84	5.77	6.38	6.35	6.12
	3.24	5.32	5.32	5.31	5.83	5.82	5.75	6.35	6.32	6.10
	3.25	5.28	5.29	5.28	5.81	5.80	5.73	6.33	6.30	6.08
Tilbury	3.26	5.25	5.25	5.24	5.78	5.76	5.69	6.29	6.26	6.05
	3.27	5.19	5.19	5.18	5.71	5.70	5.62	6.22	6.19	6.01
	3.28	5.13	5.13	5.12	5.64	5.63	5.55	6.14	6.12	5.95
	3.29	5.09	5.09	5.08	5.58	5.57	5.50	6.09	6.06	5.88
Mucking	3.30	5.05	5.05	5.04	5.54	5.53	5.46	6.03	6.01	5.84
	3.31	5.01	5.01	5.00	5.49	5.49	5.42	5.98	5.96	5.81
	3.32	4.93	4.93	4.93	5.41	5.40	5.34	5.89	5.87	5.75
	3.33	4.86	4.87	4.86	5.33	5.33	5.28	5.81	5.80	5.70
	3.34	4.82	4.82	4.82	5.28	5.29	5.24	5.75	5.74	5.66
Canvey	3.35	4.75	4.76	4.76	5.22	5.22	5.19	5.67	5.67	5.62
	3.36	4.68	4.69	4.69	5.14	5.14	5.13	5.60	5.59	5.57
	3.37	4.61	4.61	4.61	5.06	5.06	5.05	5.55	5.55	5.54
Southend	3.38	4.57	4.57	4.57	5.03	5.03	5.03	5.51	5.51	5.51

D.2.2 Defra '06 climate change scenario: 2050

Long profiles of water level have been plotted for tides of 1,000 year and 10,000 year return periods under Defra '06 2050 scenario with the barrier closed. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

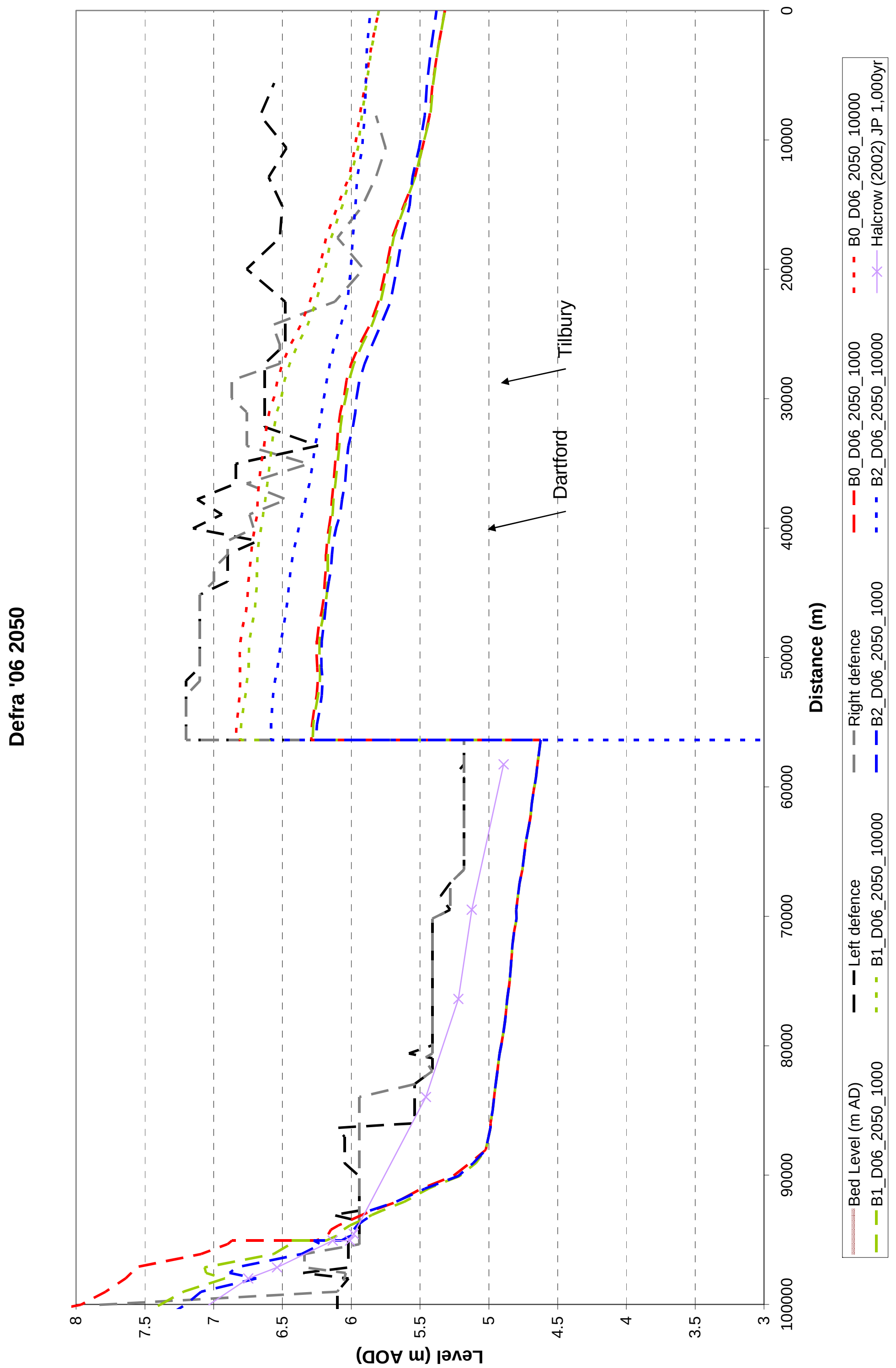

Figure D.3 Peak water levels: barrier closed; 2050 (Defra climate change)

The water levels for the B2 case are from older model runs using a tide that is 0.06m too high at Southend. This is because 10 years of climate change between 1990 and 2000 have been double counted. This was corrected for the Phase 3 Set 1 Options, and the base conditions for the B0 and B1 cases were re-run. For Defra'06 in 2050 this has an influence on water levels in the 100 and 1,000 year tides. In the 10,000 year tide in 2050 (and for 1,000 and 10,000 year tides after 2050) the impact of this error is constrained to Southend and North Kent because of overtopping. In the 1,000 year tide the model with the actual defence levels gives water levels approximately the same as the glass wall model, and the model without freeboard are approximately 0.1 m lower than the glass wall model. In the 10,000 year tide these differences are approximately 0.05 m and 0.3 m, upstream of Tilbury.

Upstream of the Thames Barrier the water levels between the barrier and Richmond are from the barrier closure rule. Upstream of Richmond the water levels are from the 1,000 year fluvial flow plus 20% due to climate change. These water levels are lower than the Halcrow (2002) joint probability 1,000 year water levels for 2050, which included uncertainty in closure of the barrier. In West London the water levels are greater than the Halcrow (2002) joint probability water levels for 2050 because Halcrow used lower flows.

Table D.2 Peak water levels: barrier closed; 2050 (Defra climate change)

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	6.63	6.60	6.50	7.97	7.39	7.21	-	-	-
	2.3	6.19	6.15	6.03	7.64	6.92	6.69	-	-	-
	2.4	6.11	6.07	6.11	7.57	7.07	6.84	-	-	-
Richmond	a2.6	5.54	5.50	5.52	6.87	6.46	6.27	-	-	-
	a2.7	5.26	5.26	5.26	6.26	6.18	6.07	-	-	-
	2.9d	5.24	5.24	5.24	6.17	6.07	5.97	-	-	-
	2.21	4.96	4.96	4.96	4.96	4.96	4.96	-	-	-
	2.29	4.87	4.87	4.87	4.87	4.87	4.87	-	-	-
	2.36	4.80	4.80	4.80	4.80	4.80	4.80	-	-	-
	2.47	4.65	4.65	4.65	4.65	4.65	4.65	-	-	-
Barrier	a3.1	5.74	5.74	5.76	6.29	6.28	6.26	6.84	6.81	6.58
	3.2	5.73	5.74	5.76	6.29	6.28	6.25	6.83	6.80	6.58
	3.3	5.73	5.73	5.74	6.27	6.26	6.23	6.82	6.79	6.58
	3.4	5.72	5.72	5.74	6.25	6.24	6.21	6.81	6.77	6.57
Roding	a3.5u	5.73	5.72	5.73	6.24	6.23	6.21	6.81	6.76	6.55
	a3.5d	5.73	5.72	5.73	6.24	6.23	6.21	6.81	6.76	6.55
	3.6	5.73	5.73	5.74	6.25	6.23	6.22	6.81	6.75	6.54
	3.7	5.73	5.73	5.74	6.25	6.23	6.22	6.81	6.75	6.52
Beam	3.8	5.73	5.73	5.74	6.25	6.23	6.21	6.81	6.74	6.51
	3.9	5.72	5.72	5.73	6.24	6.22	6.20	6.79	6.72	6.49
	3.10	5.70	5.70	5.72	6.21	6.20	6.19	6.76	6.70	6.47
	3.11	5.68	5.68	5.69	6.20	6.18	6.18	6.75	6.69	6.46
	3.12	5.68	5.68	5.69	6.19	6.17	6.16	6.75	6.68	6.45
	3.13	5.67	5.67	5.68	6.18	6.17	6.15	6.74	6.69	6.44
	3.14	5.67	5.67	5.68	6.18	6.17	6.14	6.73	6.68	6.42
Darent	3.15u	5.67	5.67	5.68	6.18	6.16	6.13	6.72	6.67	6.40
	3.15d	5.67	5.67	5.68	6.18	6.16	6.13	6.72	6.67	6.40
	3.16	5.66	5.66	5.67	6.16	6.15	6.11	6.70	6.66	6.38
	3.17	5.65	5.65	5.66	6.15	6.14	6.08	6.68	6.64	6.36
	3.18	5.64	5.64	5.64	6.14	6.13	6.07	6.68	6.63	6.33
	3.19	5.63	5.63	5.63	6.13	6.12	6.05	6.67	6.61	6.30
	3.20	5.61	5.61	5.62	6.12	6.10	6.04	6.65	6.59	6.28
	3.21	5.60	5.60	5.61	6.10	6.09	6.02	6.63	6.58	6.26
	3.22	5.59	5.59	5.59	6.10	6.08	5.99	6.62	6.56	6.23
	3.23	5.58	5.58	5.58	6.08	6.06	5.97	6.60	6.54	6.22
	3.24	5.56	5.56	5.56	6.05	6.04	5.96	6.56	6.51	6.20
	3.25	5.53	5.53	5.53	6.04	6.02	5.94	6.54	6.48	6.18
Tilbury	3.26	5.50	5.50	5.50	6.00	5.98	5.90	6.50	6.45	6.16
	3.27	5.45	5.45	5.45	5.94	5.92	5.85	6.44	6.39	6.12
	3.28	5.39	5.38	5.38	5.87	5.85	5.78	6.37	6.32	6.08
	3.29	5.33	5.33	5.32	5.80	5.79	5.72	6.30	6.26	6.03

Location	Node	100 year			1,000 year			10,000 year		
		B0	**B1**	**B2**	**B0**	**B1**	**B2**	**B0**	**B1**	**B2**
Mucking	3.30	5.29	5.28	5.27	5.75	5.73	5.67	6.23	6.19	6.00
	3.31	5.25	5.25	5.24	5.70	5.69	5.63	6.18	6.15	5.99
	3.32	5.16	5.16	5.16	5.62	5.61	5.58	6.10	6.07	5.97
	3.33	5.09	5.09	5.10	5.54	5.53	5.56	6.02	6.00	5.96
	3.34	5.04	5.05	5.05	5.48	5.49	5.51	5.97	5.95	5.92
Canvey	3.35	4.98	4.98	5.02	5.43	5.42	5.47	5.94	5.92	5.90
	3.36	4.95	4.94	5.00	5.41	5.40	5.45	5.90	5.89	5.90
	3.37	4.91	4.91	4.96	5.37	5.37	5.42	5.86	5.85	5.89
Southend	3.38	4.86	4.86	4.92	5.32	5.32	5.38	5.80	5.80	5.86

D.2.3 Defra '06 climate change scenario: 2100

Long profiles of water level have been plotted for tides of 1,000 year and 10,000 year return periods under Defra '06 2100 scenario with the barrier closed. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

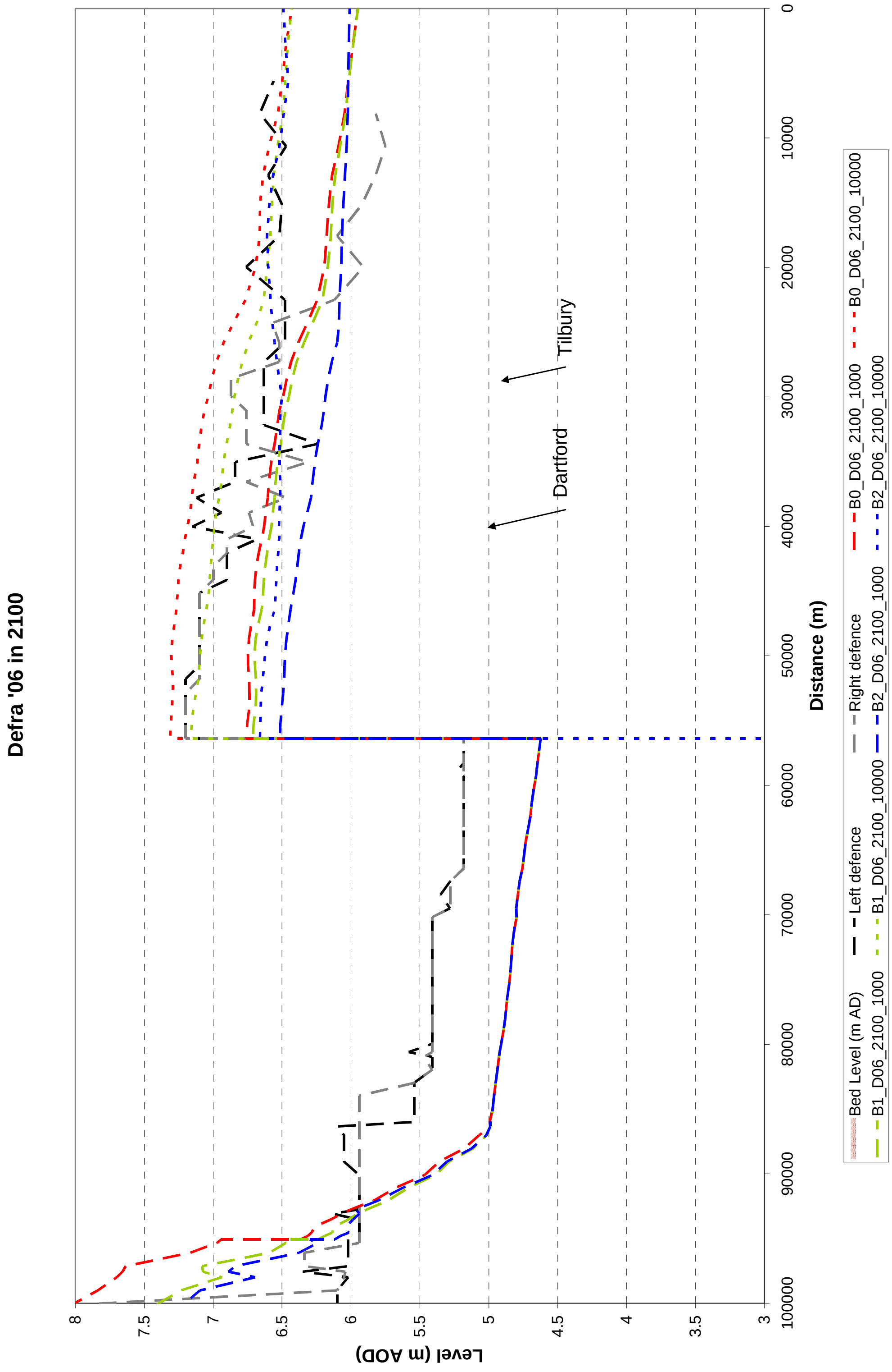

Figure D.4 Peak water levels: barrier closed; 2100 (Defra climate change)

Table D.3 Peak water levels: barrier closed; 2100 (Defra climate change)

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	6.68	6.63	6.52	8.01	7.40	7.21	-	-	-
	2.3	6.27	6.20	6.07	7.70	6.94	6.70	-	-	-
	2.4	6.18	6.15	6.16	7.64	7.08	6.84	-	-	-
Richmond	a2.6	5.64	5.60	5.60	6.94	6.49	6.30	-	-	-
	a2.7	5.28	5.26	5.27	6.37	6.24	6.12	-	-	-
	2.9d	5.24	5.24	5.24	6.29	6.14	6.02	-	-	-
	2.21	4.96	4.96	4.96	4.96	4.96	4.96	-	-	-
	2.29	4.87	4.87	4.87	4.87	4.87	4.87	-	-	-
	2.36	4.80	4.80	4.80	4.80	4.80	4.80	-	-	-
	2.47	4.65	4.65	4.65	4.65	4.65	4.65	-	-	-
Barrier	a3.1	6.22	6.20	6.21	6.76	6.71	6.52	7.31	7.16	6.66
	3.2	6.22	6.20	6.20	6.75	6.71	6.51	7.31	7.16	6.66
	3.3	6.20	6.19	6.18	6.74	6.69	6.50	7.30	7.14	6.65
	3.4	6.20	6.18	6.17	6.74	6.69	6.49	7.29	7.13	6.65
Roding	a3.5u	6.20	6.19	6.15	6.74	6.69	6.48	7.29	7.11	6.64
	a3.5d	6.20	6.19	6.15	6.74	6.69	6.48	7.29	7.11	6.64
	3.6	6.20	6.19	6.14	6.75	6.70	6.48	7.30	7.10	6.63
	3.7	6.21	6.19	6.14	6.75	6.70	6.48	7.30	7.09	6.62
Beam	3.8	6.20	6.19	6.13	6.74	6.69	6.47	7.30	7.08	6.61
	3.9	6.18	6.17	6.11	6.72	6.67	6.46	7.28	7.07	6.59
	3.10	6.19	6.17	6.08	6.70	6.65	6.44	7.27	7.05	6.55
	3.11	6.19	6.17	6.06	6.70	6.64	6.42	7.26	7.03	6.55
	3.12	6.18	6.17	6.06	6.70	6.63	6.40	7.25	7.03	6.54
	3.13	6.17	6.15	6.06	6.69	6.62	6.39	7.24	7.02	6.54
	3.14	6.15	6.13	6.05	6.67	6.61	6.38	7.22	7.01	6.53
Darent	3.15u	6.13	6.11	6.04	6.65	6.60	6.36	7.21	7.00	6.52
	3.15d	6.13	6.11	6.04	6.65	6.60	6.36	7.21	7.00	6.52
	3.16	6.11	6.09	6.03	6.63	6.58	6.35	7.19	6.99	6.52
	3.17	6.10	6.08	6.01	6.62	6.57	6.32	7.17	6.98	6.52
	3.18	6.09	6.08	5.99	6.60	6.56	6.29	7.16	6.96	6.51
	3.19	6.08	6.06	5.98	6.60	6.55	6.28	7.14	6.94	6.51
	3.20	6.06	6.04	5.97	6.58	6.53	6.26	7.11	6.93	6.52
	3.21	6.04	6.03	5.95	6.55	6.51	6.24	7.10	6.90	6.52
	3.22	6.02	6.01	5.93	6.54	6.49	6.21	7.08	6.88	6.51
	3.23	5.99	5.99	5.91	6.52	6.48	6.20	7.06	6.86	6.51
	3.24	5.97	5.96	5.89	6.49	6.45	6.19	7.04	6.85	6.50
	3.25	5.94	5.94	5.86	6.47	6.43	6.17	7.01	6.82	6.52
Tilbury	3.26	5.91	5.91	5.83	6.44	6.40	6.14	6.98	6.79	6.54
	3.27	5.87	5.86	5.79	6.38	6.34	6.10	6.92	6.74	6.55
	3.28	5.82	5.80	5.74	6.32	6.28	6.09	6.85	6.68	6.57
	3.29	5.76	5.75	5.73	6.25	6.21	6.08	6.77	6.63	6.58
Mucking	3.30	5.73	5.72	5.72	6.19	6.17	6.07	6.69	6.61	6.60
	3.31	5.70	5.69	5.69	6.18	6.15	6.07	6.66	6.58	6.61
	3.32	5.69	5.68	5.67	6.16	6.14	6.06	6.66	6.57	6.59
	3.33	5.67	5.66	5.66	6.14	6.11	6.04	6.64	6.56	6.57
	3.34	5.63	5.63	5.64	6.09	6.08	6.03	6.59	6.53	6.52
Canvey	3.35	5.60	5.60	5.62	6.05	6.04	6.02	6.53	6.49	6.49
	3.36	5.56	5.56	5.60	6.02	6.02	6.02	6.50	6.48	6.45
	3.37	5.53	5.53	5.58	5.99	5.99	6.02	6.47	6.46	6.48
Southend	3.38	5.49	5.49	5.55	5.95	5.95	6.01	6.43	6.43	6.49

Water level profiles for the 100 year tide in 2100 under Defra ‘06 are similar to the 1,000 year tide in 2050 under Defra ‘06. In the 1,000 year tide the model with the actual defence levels gives water levels approximately 0.05 m lower than the glass wall model, and the model without freeboard are approximately 0.3 m lower than the glass wall model, upstream of Tilbury. In the 10,000 year tide these differences upstream of Tilbury are approximately 0.35 m and 0.7 m. Downstream of Tilbury the water levels are 0.1 m lower than the glass wall model in the other models. In the B2 model the water levels are above the defence (with freeboard removed) levels in the 10,000 year event. With the actual defence levels (B1 model) the 10,000 year tide levels around the crest level of the defences between the Thames Barrier and Tilbury.

D.2.4 Defra '06 climate change scenario: 2170

Long profiles of water level have been plotted for tides of 100 year, 1,000 year and 10,000 year return periods under Defra '06 2170 scenario with the barrier closed. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

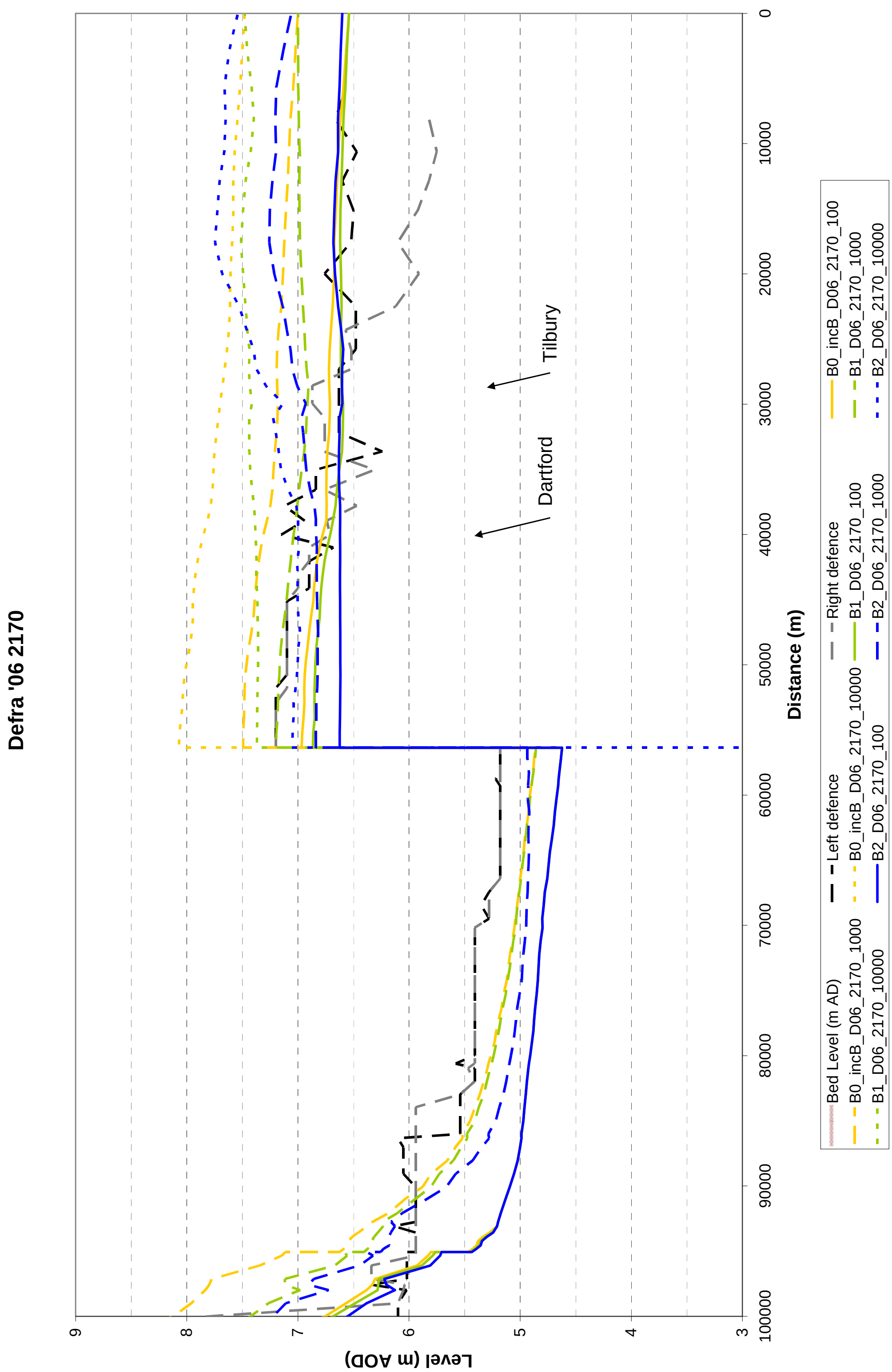

Figure D.5 Peak water levels: barrier closed; 2170 (Defra climate change)

Table D.4 Peak water levels: barrier closed; 2170 (Defra climate change)

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	6.76	6.69	6.56	8.12	7.43	7.23	-	-	-
	2.3	6.38	6.28	6.13	7.83	6.98	6.72	-	-	-
	2.4	6.31	6.27	6.22	7.78	7.12	6.86	-	-	-
Richmond	a2.6	5.80	5.76	5.71	7.12	6.58	6.38	-	-	-
	a2.7	5.47	5.45	5.44	6.63	6.40	6.26	-	-	-
	2.9d	5.39	5.37	5.36	6.57	6.33	6.18	-	-	-
	2.21	4.96	4.96	4.96	5.41	5.37	5.19	-	-	-
	2.29	4.87	4.87	4.87	5.17	5.16	5.03	-	-	-
	2.36	4.80	4.80	4.80	5.04	5.04	4.94	-	-	-
	2.47	4.65	4.65	4.65	4.88	4.88	4.92	-	-	-
Barrier	a3.1	6.97	6.87	6.62	7.49	7.20	6.84	8.07	7.37	7.05
	3.2	6.96	6.86	6.62	7.49	7.19	6.84	8.07	7.37	7.05
	3.3	6.95	6.85	6.62	7.49	7.18	6.84	8.05	7.37	7.04
	3.4	6.94	6.85	6.62	7.48	7.18	6.83	8.04	7.37	7.04
Roding	a3.5u	6.94	6.85	6.62	7.48	7.18	6.83	8.03	7.36	7.02
	a3.5d	6.94	6.85	6.62	7.48	7.18	6.83	8.03	7.36	7.02
	3.6	6.94	6.85	6.62	7.47	7.17	6.82	8.02	7.36	7.01
	3.7	6.93	6.84	6.62	7.46	7.16	6.82	8.00	7.36	7.00
Beam	3.8	6.91	6.83	6.62	7.44	7.15	6.82	7.98	7.36	7.00
	3.9	6.90	6.82	6.62	7.42	7.14	6.82	7.96	7.36	6.98
	3.10	6.88	6.81	6.62	7.40	7.12	6.82	7.95	7.36	7.00
	3.11	6.86	6.80	6.62	7.39	7.10	6.83	7.94	7.37	7.00
	3.12	6.86	6.79	6.62	7.38	7.09	6.83	7.94	7.37	7.01
	3.13	6.84	6.78	6.62	7.37	7.08	6.83	7.92	7.37	7.00
	3.14	6.83	6.76	6.62	7.35	7.07	6.83	7.90	7.37	7.01
Darent	3.15u	6.80	6.74	6.62	7.33	7.05	6.83	7.88	7.38	6.99
	3.15d	6.80	6.74	6.62	7.33	7.05	6.83	7.88	7.38	6.99
	3.16	6.78	6.71	6.62	7.31	7.04	6.84	7.85	7.38	7.00
	3.17	6.74	6.69	6.62	7.28	7.02	6.84	7.81	7.39	7.00
	3.18	6.74	6.66	6.62	7.25	7.01	6.85	7.78	7.40	7.01
	3.19	6.75	6.65	6.63	7.23	6.99	6.89	7.77	7.41	7.09
	3.20	6.74	6.63	6.63	7.22	6.97	6.93	7.76	7.43	7.15
	3.21	6.73	6.60	6.63	7.21	6.94	6.94	7.75	7.44	7.17
	3.22	6.72	6.60	6.63	7.19	6.93	6.95	7.73	7.44	7.20
	3.23	6.72	6.60	6.63	7.18	6.92	6.97	7.71	7.44	7.22
	3.24	6.71	6.59	6.60	7.18	6.91	6.93	7.70	7.41	7.13
	3.25	6.72	6.61	6.60	7.19	6.91	7.01	7.68	7.43	7.29
Tilbury	3.26	6.72	6.61	6.60	7.19	6.92	7.05	7.66	7.44	7.37
	3.27	6.71	6.61	6.59	7.19	6.93	7.07	7.64	7.44	7.40
	3.28	6.70	6.61	6.61	7.17	6.94	7.10	7.62	7.46	7.46
	3.29	6.69	6.61	6.64	7.15	6.96	7.14	7.61	7.47	7.53
Mucking	3.30	6.67	6.61	6.67	7.13	6.97	7.21	7.61	7.49	7.68
	3.31	6.67	6.62	6.68	7.12	6.98	7.26	7.59	7.51	7.75
	3.32	6.66	6.62	6.67	7.11	6.99	7.25	7.58	7.49	7.73
	3.33	6.65	6.61	6.66	7.09	6.99	7.23	7.58	7.47	7.71
	3.34	6.64	6.60	6.64	7.08	6.99	7.20	7.57	7.43	7.66
Canvey	3.35	6.62	6.59	6.64	7.07	6.99	7.20	7.54	7.40	7.65
	3.36	6.59	6.57	6.63	7.04	7.00	7.19	7.52	7.42	7.66
	3.37	6.57	6.56	6.62	7.02	7.00	7.13	7.50	7.46	7.62
Southend	3.38	6.54	6.54	6.60	7.00	7.00	7.06	7.48	7.48	7.54

The 1,000 and 10,000 year water levels are above the defence levels in the B1 and B2 models.

D.3 Barrier Open

The events for the basecase water level profiles when the Thames Barrier is open are as follows:

- 100 year tide and 100 year fluvial flow
- 1,000 year tide and 1,000 year fluvial flow
- 10,000 year tide and 10,000 year fluvial flow

While these events are not the joint probability 100, 1,000 or 10,000 year return periods they give a high level appreciation of the water level profiles under extreme tides and flows if the Thames Barrier is not closed.

The water levels for the Thames Barrier open case are from older model runs using a tide that is 0.06m too high at Southend. This is because 10 years of climate change between 1990 and 2000 have been double counted. For the B0 case this has an influence on water levels in the 100, 1,000 and 10,000 year tides. In the B1 and B2 case the impact of this error is constrained to downstream of Dartford until 2050 because of overtopping upstream of the Thames Barrier. In 2100 the influence of the error in the B1 and B2 cases is downstream of Tilbury due to the impact of overtopping in the outer estuary as well as upstream of the Thames Barrier. For the B1 and B2 runs in 2170 the error is only in the water levels at Southend because of overtopping along the majority of the estuary.

D.3.1 Present Day

Long profiles of water level have been plotted for tides of 100 year, 1,000 year and 10,000 year return periods under present day conditions with the barrier open. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

In all return periods overtopping upstream of the barrier has a significant impact on water levels in the model with actual defences and the model without freeboard relative to the glass wall model. The reduction is approximately 0.7 m in the 10,000 year tide, 0.5 m in the 1,000 year tide and 0.2 m in the 100 year tide for the model with actual defence levels. For the model without freeboard the water levels are further reduced by approximately 0.2 m. Downstream of Dartford river water levels are approximately 0.1 m lower for the model without freeboard in the 1,000 year tide and approximately 0.2 m lower with the 10,000 year tide compared to the glass wall model.

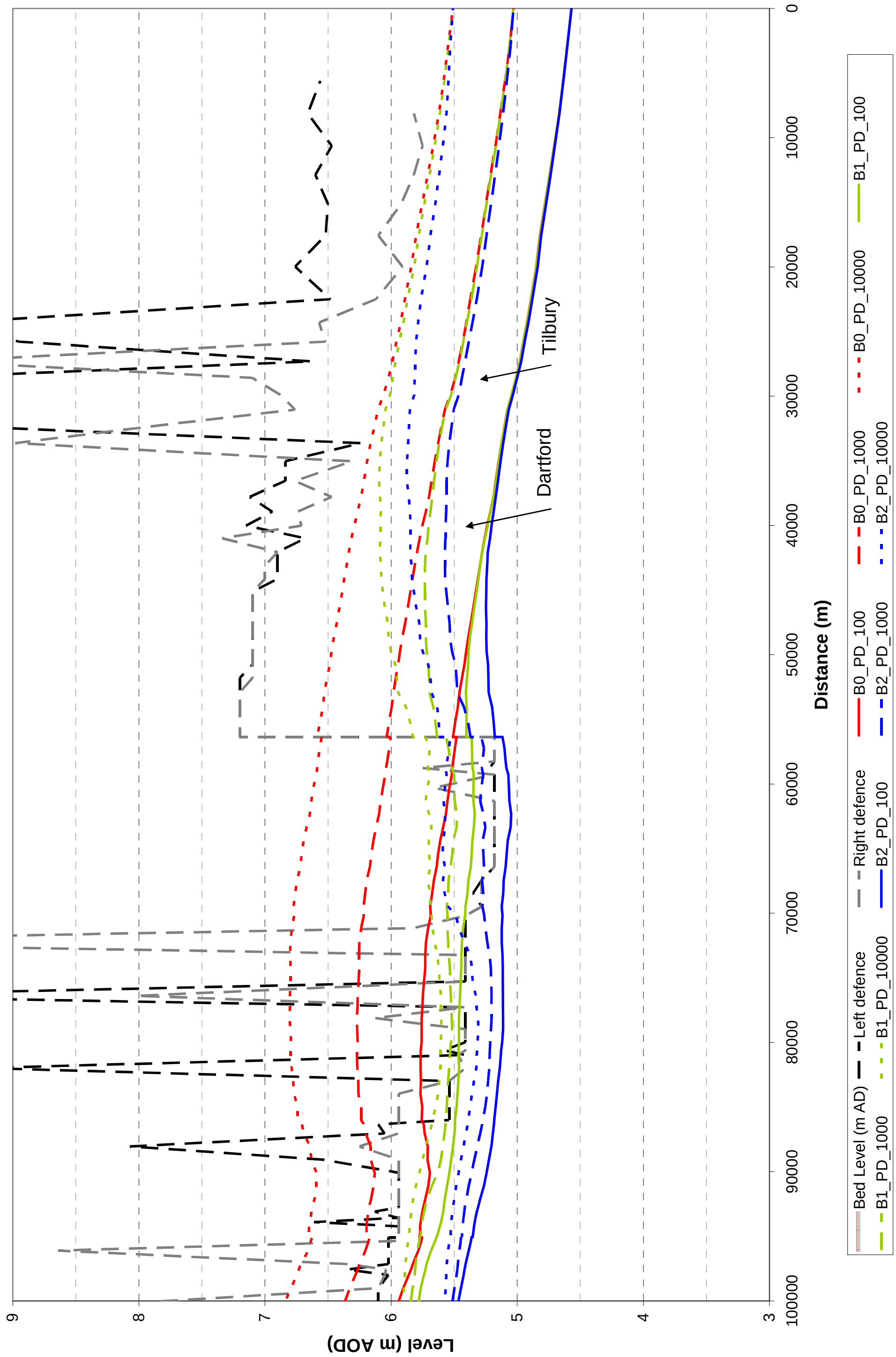

Figure D.6 Peak water levels: barrier open; present day

Table D.5 Peak water levels: barrier open; present day

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	5.94	5.78	5.47	6.37	5.85	5.51	6.84	5.91	5.57
	2.3	5.86	5.74	5.43	6.28	5.81	5.48	6.75	5.89	5.56
	2.4	5.83	5.72	5.41	6.25	5.81	5.47	6.72	5.89	5.56
Richmond	a2.6	5.75	5.64	5.36	6.17	5.77	5.45	6.63	5.86	5.54
	a2.7	5.78	5.64	5.35	6.20	5.77	5.44	6.66	5.86	5.53
	2.9d	5.77	5.62	5.35	6.19	5.76	5.43	6.65	5.85	5.53
	2.21	5.77	5.47	5.16	6.26	5.56	5.24	6.77	5.63	5.36
	2.29	5.75	5.45	5.11	6.27	5.53	5.20	6.80	5.61	5.33
	2.36	5.69	5.41	5.12	6.22	5.56	5.28	6.77	5.69	5.55
	2.47	5.51	5.36	5.09	6.03	5.53	5.28	6.58	5.70	5.56
Barrier	a3.1	5.51	5.40	5.18	6.04	5.64	5.37	6.59	5.83	5.62
	3.2	5.49	5.40	5.19	6.02	5.65	5.39	6.56	5.85	5.62
	3.3	5.47	5.40	5.20	6.00	5.67	5.42	6.54	5.88	5.63
	3.4	5.46	5.41	5.23	5.98	5.70	5.48	6.53	5.95	5.68
Roding	a3.5u	5.44	5.40	5.23	5.96	5.70	5.48	6.51	5.95	5.69
	a3.5d	5.44	5.40	5.23	5.96	5.70	5.48	6.51	5.95	5.69
	3.6	5.42	5.39	5.23	5.94	5.70	5.49	6.49	5.97	5.70
	3.7	5.41	5.39	5.24	5.93	5.72	5.52	6.47	6.00	5.75
Beam	3.8	5.39	5.38	5.25	5.91	5.72	5.53	6.46	6.02	5.77
	3.9	5.37	5.36	5.24	5.89	5.73	5.54	6.43	6.03	5.78
	3.10	5.35	5.34	5.25	5.87	5.73	5.55	6.41	6.05	5.80
	3.11	5.33	5.32	5.25	5.85	5.73	5.56	6.39	6.07	5.82
	3.12	5.31	5.31	5.24	5.83	5.74	5.57	6.37	6.08	5.84
	3.13	5.30	5.29	5.24	5.81	5.73	5.57	6.35	6.08	5.84
	3.14	5.28	5.28	5.23	5.80	5.73	5.58	6.34	6.09	5.85
Darent	3.15u	5.26	5.26	5.22	5.77	5.71	5.57	6.31	6.09	5.85
	3.15d	5.26	5.26	5.22	5.77	5.71	5.57	6.31	6.09	5.85
	3.16	5.24	5.23	5.20	5.75	5.70	5.57	6.29	6.09	5.85
	3.17	5.21	5.21	5.19	5.73	5.69	5.56	6.27	6.08	5.85
	3.18	5.19	5.19	5.17	5.70	5.67	5.56	6.24	6.09	5.86
	3.19	5.17	5.17	5.15	5.68	5.66	5.56	6.22	6.10	5.87
	3.20	5.15	5.15	5.13	5.65	5.64	5.55	6.19	6.09	5.88
	3.21	5.12	5.12	5.11	5.63	5.62	5.54	6.16	6.08	5.87
	3.22	5.10	5.10	5.09	5.60	5.59	5.52	6.13	6.06	5.86
	3.23	5.08	5.08	5.07	5.57	5.57	5.50	6.10	6.04	5.85
	3.24	5.05	5.05	5.04	5.53	5.53	5.47	6.06	6.01	5.82
	3.25	5.01	5.01	5.00	5.49	5.49	5.44	6.02	5.99	5.81
Tilbury	3.26	4.98	4.98	4.97	5.46	5.46	5.41	5.99	5.97	5.81
	3.27	4.95	4.95	4.94	5.43	5.43	5.38	5.96	5.94	5.80
	3.28	4.92	4.92	4.91	5.40	5.40	5.36	5.93	5.90	5.79
	3.29	4.89	4.89	4.88	5.37	5.36	5.32	5.89	5.87	5.76
Mucking	3.30	4.85	4.85	4.84	5.33	5.32	5.28	5.84	5.82	5.72
	3.31	4.82	4.82	4.81	5.29	5.28	5.24	5.80	5.78	5.69
	3.32	4.78	4.78	4.77	5.25	5.24	5.21	5.75	5.74	5.65
	3.33	4.74	4.74	4.74	5.21	5.21	5.18	5.71	5.70	5.62
	3.34	4.71	4.71	4.70	5.17	5.17	5.14	5.67	5.65	5.59
Canvey	3.35	4.67	4.67	4.67	5.13	5.13	5.11	5.62	5.61	5.56
	3.36	4.64	4.64	4.63	5.10	5.10	5.08	5.58	5.58	5.55
	3.37	4.60	4.60	4.60	5.06	5.06	5.05	5.55	5.55	5.53
Southend	3.38	4.57	4.57	4.57	5.03	5.03	5.03	5.51	5.51	5.51

D.3.2 Defra '06 2050

Long profiles of water level have been plotted for tides of 100 year, 1,000 year and 10,000 year return periods under Defra 2050 scenario with the barrier open. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

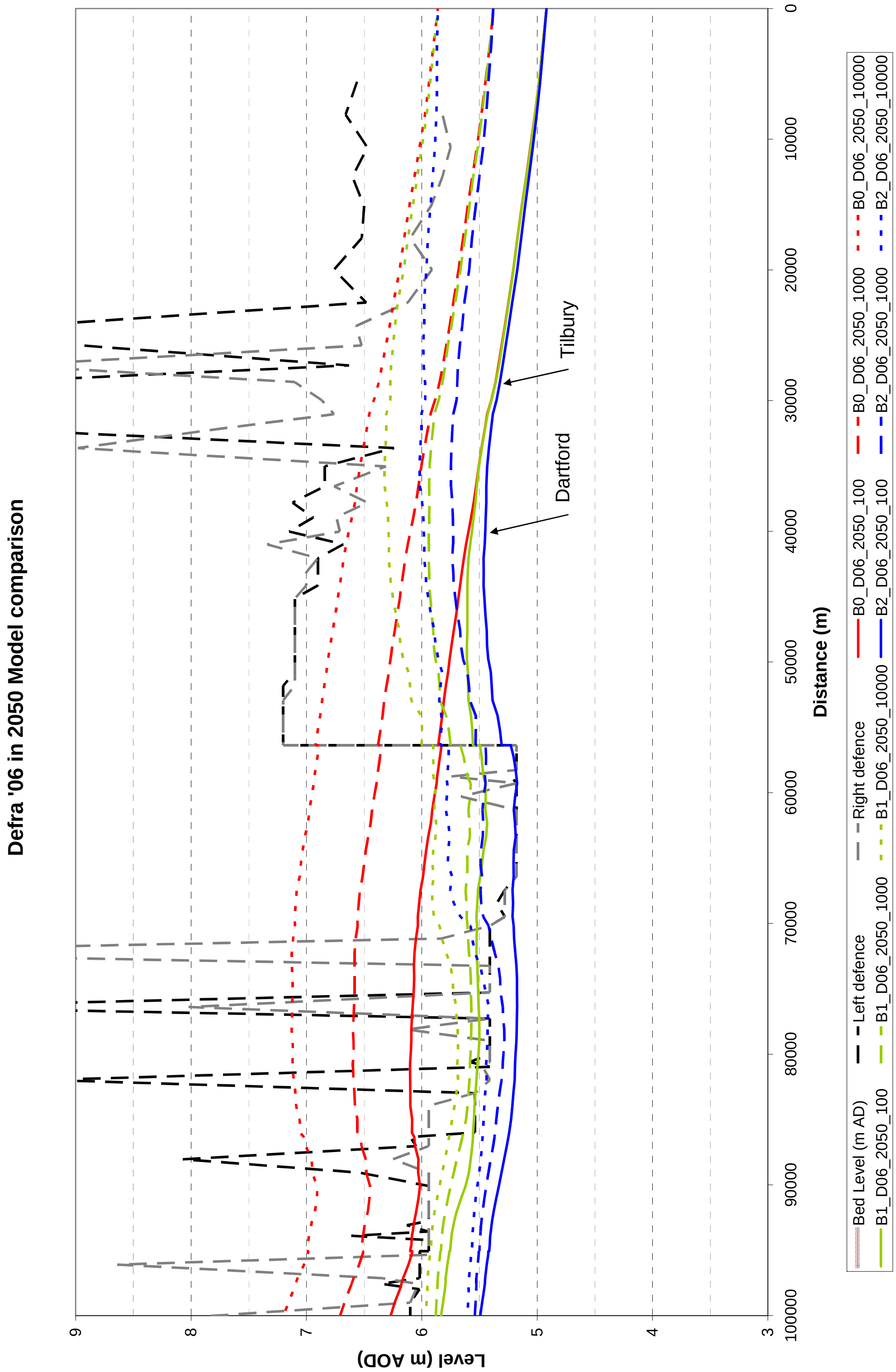

Figure D.7 Peak water levels: barrier open; 2050 (Defra climate change)

Table D.6 Peak water levels: barrier open; 2050 (Defra climate change)

Location	Node	100 year			1,000 year			10,000 year		
		B0	**B1**	**B2**	**B0**	**B1**	**B2**	**B0**	**B1**	**B2**
Teddington	2.1	6.27	5.83	5.49	6.71	5.88	5.54	7.20	5.96	5.61
	2.3	6.19	5.80	5.46	6.63	5.87	5.53	7.11	5.95	5.59
	2.4	6.16	5.79	5.45	6.59	5.86	5.53	7.08	5.95	5.59
	a2.6	6.08	5.76	5.42	6.51	5.84	5.51	6.98	5.93	5.57
	a2.7	6.10	5.75	5.42	6.53	5.83	5.50	7.00	5.92	5.57
	2.9d	6.09	5.75	5.41	6.52	5.83	5.50	6.99	5.92	5.56
	2.21	6.10	5.54	5.22	6.58	5.60	5.34	7.09	5.72	5.46
	2.29	6.08	5.51	5.17	6.59	5.57	5.30	7.12	5.70	5.42
	2.36	6.04	5.53	5.21	6.56	5.61	5.47	7.10	5.90	5.66
	2.47	5.86	5.47	5.19	6.38	5.62	5.44	6.92	5.90	5.78
Barrier	a3.1	5.86	5.56	5.31	6.38	5.75	5.53	6.92	6.00	5.84
	3.2	5.84	5.56	5.32	6.36	5.77	5.53	6.90	6.00	5.83
	3.3	5.82	5.57	5.35	6.34	5.79	5.53	6.88	6.01	5.83
	3.4	5.81	5.60	5.39	6.33	5.84	5.58	6.86	6.09	5.85
Roding	a3.5u	5.79	5.60	5.39	6.31	5.85	5.59	6.85	6.10	5.84
	a3.5d	5.79	5.60	5.39	6.31	5.85	5.59	6.85	6.10	5.84
	3.6	5.77	5.60	5.40	6.29	5.86	5.61	6.83	6.12	5.82
	3.7	5.76	5.61	5.42	6.27	5.88	5.64	6.81	6.16	5.86
Beam	3.8	5.74	5.61	5.43	6.26	5.90	5.66	6.79	6.19	5.88
	3.9	5.72	5.61	5.44	6.24	5.90	5.67	6.77	6.19	5.89
	3.10	5.70	5.61	5.45	6.21	5.91	5.69	6.75	6.22	5.92
	3.11	5.68	5.61	5.46	6.19	5.93	5.71	6.73	6.25	5.94
	3.12	5.67	5.61	5.46	6.18	5.94	5.72	6.71	6.27	5.96
	3.13	5.65	5.60	5.46	6.16	5.94	5.73	6.69	6.27	5.97
	3.14	5.64	5.60	5.46	6.14	5.94	5.74	6.68	6.29	5.98
Darent	3.15u	5.62	5.58	5.46	6.12	5.94	5.73	6.66	6.28	5.98
	3.15d	5.62	5.58	5.46	6.12	5.94	5.73	6.66	6.28	5.98
	3.16	5.60	5.57	5.45	6.10	5.94	5.73	6.63	6.29	5.98
	3.17	5.57	5.55	5.45	6.07	5.94	5.73	6.61	6.29	5.99
	3.18	5.55	5.54	5.44	6.05	5.93	5.74	6.58	6.30	6.00
	3.19	5.53	5.52	5.44	6.03	5.94	5.75	6.56	6.32	6.02
	3.20	5.51	5.50	5.43	6.00	5.93	5.75	6.54	6.32	6.02
	3.21	5.48	5.48	5.42	5.98	5.92	5.74	6.51	6.31	6.01
	3.22	5.45	5.45	5.40	5.95	5.90	5.74	6.48	6.31	6.00
	3.23	5.43	5.43	5.38	5.92	5.89	5.73	6.46	6.31	6.00
	3.24	5.40	5.40	5.35	5.88	5.85	5.70	6.41	6.27	5.97
	3.25	5.36	5.36	5.32	5.85	5.82	5.69	6.37	6.27	5.97
Tilbury	3.26	5.34	5.33	5.30	5.82	5.80	5.69	6.34	6.27	5.98
	3.27	5.31	5.31	5.27	5.79	5.77	5.67	6.31	6.25	5.99
	3.28	5.28	5.28	5.25	5.76	5.74	5.65	6.28	6.23	5.98
	3.29	5.25	5.25	5.22	5.73	5.71	5.63	6.25	6.21	5.98
Mucking	3.30	5.21	5.21	5.17	5.68	5.67	5.59	6.19	6.16	5.96
	3.31	5.17	5.17	5.14	5.64	5.63	5.57	6.15	6.12	5.95
	3.32	5.13	5.13	5.10	5.60	5.59	5.53	6.11	6.08	5.92
	3.33	5.10	5.09	5.07	5.56	5.55	5.50	6.06	6.04	5.91
	3.34	5.06	5.06	5.04	5.52	5.52	5.47	6.02	6.00	5.89
Canvey	3.35	5.02	5.02	5.00	5.48	5.48	5.44	5.97	5.96	5.87
	3.36	4.98	4.98	4.98	5.45	5.45	5.42	5.94	5.93	5.87
	3.37	4.95	4.95	4.95	5.41	5.41	5.40	5.90	5.89	5.87
Southend	3.38	4.92	4.92	4.92	5.38	5.38	5.38	5.86	5.86	5.86

In the B1 and B2 models the peak water level is in the reach between Erith and Dartford. The river water level falls in the reach between Erith and the Thames Barrier because of overtopping upstream of the Thames Barrier, where defence levels are lower. In the 100 year event water levels downstream of Dartford are similar in the three models, because of no local overtopping and little influence from upstream. In the 1,000 year tide the overtopping upstream of the barrier has an influence on water levels to downstream of Tilbury.

D.3.3 Defra '06 2100

Long profiles of water level have been plotted for tides of 100 year, 1,000 year and 10,000 year return periods under Defra 2100 scenario with the barrier open. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

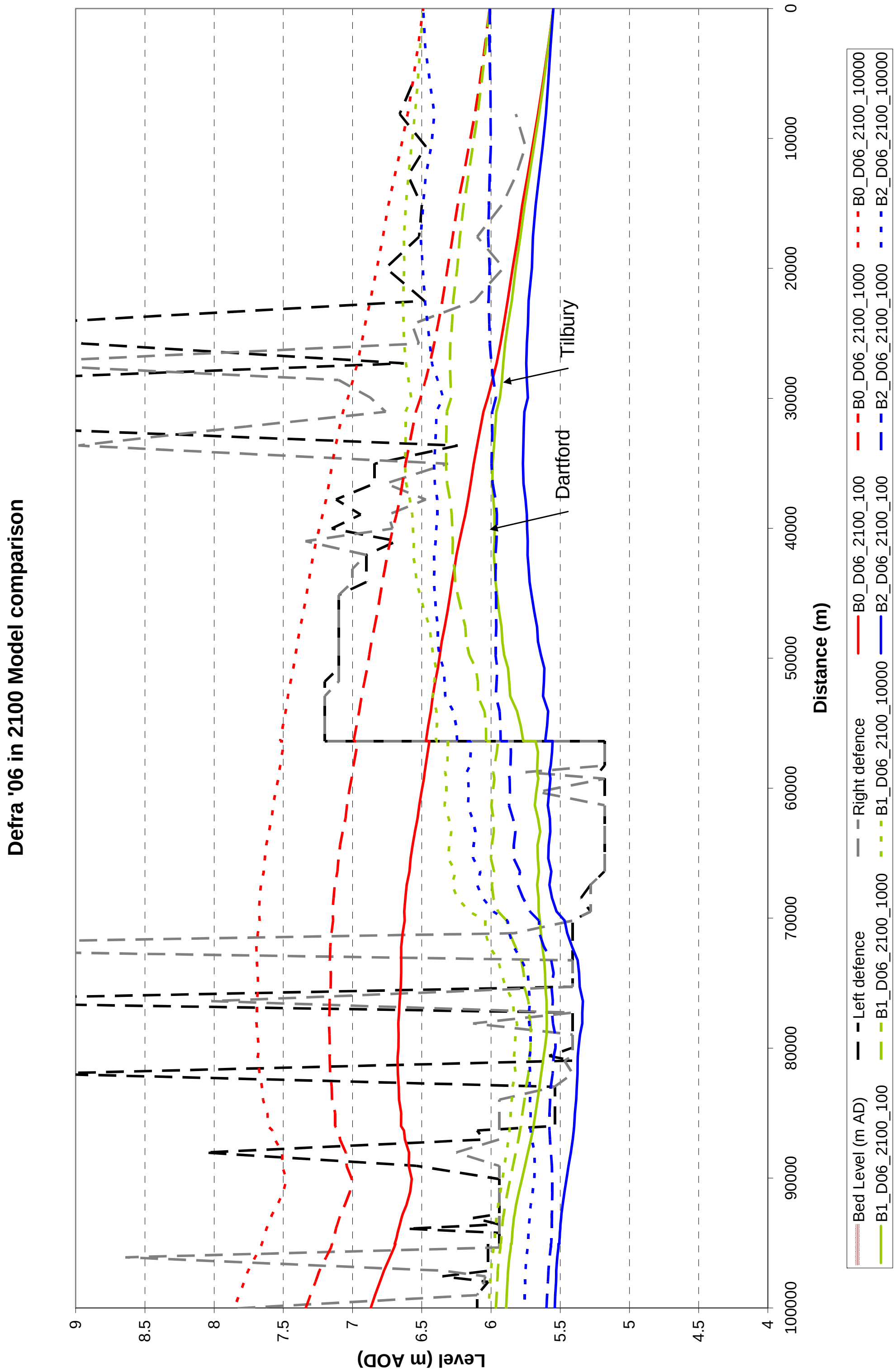

Figure D.8 Peak water levels: barrier open; 2100 (Defra climate change)

Table D.7 Peak water levels: barrier open; 2100 (Defra climate change)

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	6.87	5.89	5.54	7.34	5.97	5.60	7.86	6.02	5.76
	2.3	6.80	5.88	5.53	7.27	5.96	5.59	7.78	6.01	5.75
	2.4	6.77	5.88	5.53	7.24	5.95	5.59	7.76	6.00	5.75
	a2.6	6.69	5.86	5.51	7.15	5.93	5.57	7.66	5.98	5.73
	a2.7	6.70	5.85	5.51	7.15	5.93	5.57	7.66	5.98	5.73
	2.9d	6.68	5.85	5.50	7.13	5.93	5.56	7.64	5.97	5.73
	2.21	6.67	5.66	5.39	7.15	5.76	5.57	7.65	5.85	5.72
	2.29	6.66	5.60	5.34	7.17	5.73	5.55	7.69	5.84	5.72
	2.36	6.63	5.66	5.53	7.15	5.95	5.72	7.68	6.16	5.98
	2.47	6.47	5.67	5.57	6.99	5.97	5.86	7.52	6.32	6.15
Barrier	a3.1	6.47	5.77	5.61	6.99	6.04	5.93	7.52	6.40	6.25
	3.2	6.45	5.79	5.60	6.97	6.04	5.93	7.50	6.39	6.25
	3.3	6.44	5.81	5.59	6.95	6.05	5.94	7.48	6.39	6.27
	3.4	6.42	5.86	5.62	6.94	6.09	5.97	7.47	6.42	6.33
Roding	a3.5u	6.40	5.87	5.62	6.91	6.10	5.96	7.45	6.41	6.34
	a3.5d	6.40	5.87	5.62	6.91	6.10	5.96	7.45	6.41	6.34
	3.6	6.38	5.88	5.62	6.90	6.11	5.96	7.43	6.40	6.34
	3.7	6.37	5.91	5.64	6.88	6.16	5.97	7.41	6.42	6.37
Beam	3.8	6.36	5.92	5.66	6.86	6.18	5.97	7.40	6.43	6.39
	3.9	6.34	5.92	5.67	6.84	6.19	5.96	7.38	6.44	6.38
	3.10	6.31	5.94	5.69	6.82	6.21	5.96	7.35	6.48	6.40
	3.11	6.30	5.96	5.71	6.80	6.24	5.96	7.33	6.51	6.41
	3.12	6.28	5.97	5.72	6.78	6.26	5.97	7.32	6.54	6.41
	3.13	6.27	5.97	5.73	6.77	6.26	5.97	7.30	6.55	6.41
	3.14	6.25	5.98	5.74	6.75	6.28	5.97	7.28	6.56	6.41
Darent	3.15u	6.23	5.98	5.74	6.73	6.28	5.96	7.26	6.56	6.40
	3.15d	6.23	5.98	5.74	6.73	6.28	5.96	7.26	6.56	6.40
	3.16	6.21	5.98	5.74	6.71	6.28	5.96	7.24	6.56	6.40
	3.17	6.19	5.98	5.74	6.68	6.28	5.96	7.22	6.57	6.39
	3.18	6.17	5.98	5.75	6.66	6.30	5.97	7.19	6.59	6.39
	3.19	6.15	5.99	5.77	6.64	6.32	5.99	7.17	6.61	6.41
	3.20	6.13	5.99	5.77	6.62	6.33	6.00	7.15	6.62	6.41
	3.21	6.10	5.98	5.77	6.59	6.32	5.99	7.12	6.62	6.40
	3.22	6.08	5.97	5.76	6.56	6.32	5.99	7.09	6.62	6.40
	3.23	6.06	5.96	5.76	6.54	6.32	5.99	7.07	6.62	6.40
	3.24	6.02	5.94	5.73	6.51	6.29	5.96	7.03	6.58	6.35
	3.25	5.99	5.92	5.74	6.47	6.29	5.98	7.00	6.60	6.39
Tilbury	3.26	5.96	5.91	5.75	6.44	6.30	6.00	6.97	6.62	6.43
	3.27	5.93	5.90	5.74	6.41	6.29	6.01	6.94	6.63	6.44
	3.28	5.91	5.88	5.73	6.38	6.28	6.01	6.91	6.63	6.46
	3.29	5.88	5.85	5.73	6.35	6.27	6.02	6.87	6.64	6.48
Mucking	3.30	5.84	5.82	5.70	6.31	6.24	6.01	6.82	6.63	6.49
	3.31	5.81	5.79	5.70	6.28	6.23	6.02	6.78	6.63	6.51
	3.32	5.77	5.76	5.68	6.24	6.20	6.02	6.74	6.62	6.49
	3.33	5.74	5.72	5.65	6.20	6.16	6.01	6.70	6.60	6.47
	3.34	5.70	5.69	5.63	6.16	6.13	6.00	6.65	6.58	6.43
Canvey	3.35	5.66	5.65	5.60	6.12	6.10	6.00	6.60	6.55	6.41
	3.36	5.62	5.62	5.59	6.08	6.07	6.01	6.56	6.53	6.44
	3.37	5.59	5.59	5.57	6.04	6.04	6.01	6.53	6.51	6.48
Southend	3.38	5.55	5.55	5.55	6.01	6.01	6.01	6.49	6.49	6.49

With the Thames Barrier open overtopping upstream of the barrier has a large influence on river water levels downstream of the barrier in the B1 and B2 models. In the 1,000 and 10,000 year tides there is some overtopping of the downstream defences in the B1 and B2 models.

D.3.4 Defra '06 2170

Long profiles of water level have been plotted for tides of 100 year, 1,000 year and 10,000 year return periods under Defra 2170 scenario with the barrier open. This is for the 'glass wall' model, actual defences model, and defences without freeboard model.

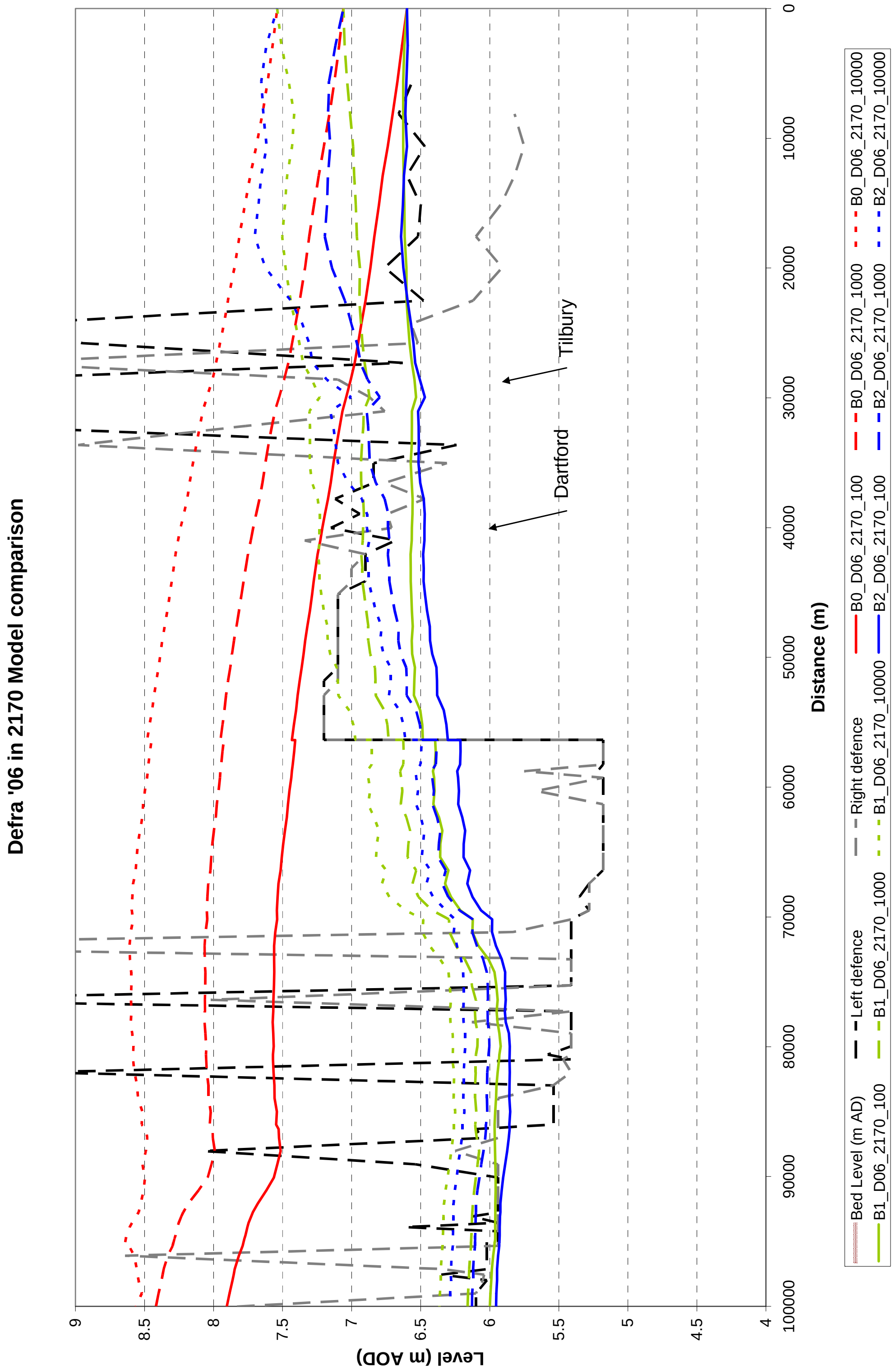

Figure D.9 Peak water levels: barrier open; 2170 (Defra climate change)

Table D.8 Peak water levels: barrier open; 2170 (Defra climate change)

Location	Node	100 year			1,000 year			10,000 year		
		B0	B1	B2	B0	B1	B2	B0	B1	B2
Teddington	2.1	7.90	6.00	5.96	8.42	6.16	6.13	8.56	6.36	6.29
	2.3	7.86	5.99	5.95	8.38	6.15	6.12	8.54	6.36	6.28
	2.4	7.85	5.99	5.95	8.36	6.15	6.12	8.56	6.36	6.28
	a2.6	7.78	5.97	5.93	8.29	6.14	6.11	8.61	6.34	6.27
	a2.7	7.78	5.96	5.93	8.29	6.14	6.11	8.64	6.34	6.27
	2.9d	7.77	5.96	5.93	8.28	6.13	6.11	8.63	6.34	6.27
	2.21	7.56	5.96	5.86	8.04	6.11	6.02	8.55	6.26	6.19
	2.29	7.57	5.94	5.89	8.06	6.10	6.01	8.60	6.28	6.19
	2.36	7.54	6.21	6.06	8.05	6.42	6.22	8.59	6.61	6.32
	2.47	7.43	6.40	6.22	7.95	6.63	6.39	8.47	6.85	6.50
Barrier	a3.1	7.43	6.49	6.30	7.95	6.73	6.49	8.48	6.97	6.61
	3.2	7.42	6.49	6.31	7.94	6.74	6.51	8.46	6.99	6.63
	3.3	7.40	6.50	6.33	7.92	6.77	6.53	8.45	7.02	6.65
	3.4	7.39	6.55	6.38	7.91	6.83	6.60	8.43	7.10	6.73
Roding	a3.5u	7.38	6.55	6.38	7.90	6.83	6.60	8.42	7.10	6.72
	a3.5d	7.38	6.55	6.38	7.90	6.83	6.60	8.42	7.10	6.72
	3.6	7.36	6.54	6.39	7.88	6.83	6.61	8.40	7.11	6.72
	3.7	7.35	6.56	6.42	7.87	6.87	6.65	8.39	7.16	6.77
Beam	3.8	7.34	6.57	6.43	7.85	6.88	6.66	8.37	7.17	6.79
	3.9	7.32	6.56	6.44	7.83	6.88	6.66	8.35	7.18	6.78
	3.10	7.30	6.56	6.45	7.82	6.90	6.69	8.34	7.20	6.83
	3.11	7.29	6.57	6.47	7.80	6.91	6.71	8.32	7.22	6.86
	3.12	7.28	6.57	6.48	7.78	6.92	6.73	8.30	7.23	6.88
	3.13	7.26	6.57	6.48	7.77	6.92	6.73	8.29	7.23	6.88
	3.14	7.25	6.57	6.48	7.75	6.93	6.74	8.28	7.24	6.89
Darent	3.15u	7.23	6.57	6.47	7.73	6.92	6.73	8.26	7.23	6.87
	3.15d	7.23	6.57	6.47	7.73	6.92	6.73	8.26	7.23	6.87
	3.16	7.21	6.56	6.47	7.71	6.92	6.74	8.24	7.23	6.89
	3.17	7.19	6.56	6.47	7.69	6.91	6.74	8.22	7.23	6.89
	3.18	7.17	6.56	6.48	7.67	6.92	6.76	8.19	7.25	6.93
	3.19	7.15	6.57	6.50	7.65	6.93	6.82	8.17	7.29	7.02
	3.20	7.13	6.57	6.52	7.63	6.93	6.87	8.15	7.31	7.10
	3.21	7.11	6.57	6.51	7.60	6.93	6.88	8.13	7.30	7.12
	3.22	7.09	6.56	6.52	7.58	6.92	6.88	8.10	7.30	7.13
	3.23	7.07	6.56	6.52	7.56	6.91	6.89	8.08	7.31	7.15
	3.24	7.04	6.53	6.47	7.53	6.87	6.80	8.05	7.23	7.00
	3.25	7.01	6.55	6.51	7.49	6.89	6.88	8.01	7.29	7.18
Tilbury	3.26	6.98	6.56	6.54	7.46	6.91	6.94	7.98	7.35	7.28
	3.27	6.95	6.58	6.55	7.43	6.92	6.96	7.95	7.38	7.31
	3.28	6.93	6.59	6.57	7.41	6.93	7.00	7.93	7.41	7.36
	3.29	6.90	6.60	6.60	7.38	6.95	7.05	7.90	7.44	7.44
Mucking	3.30	6.86	6.60	6.63	7.34	6.94	7.14	7.85	7.48	7.62
	3.31	6.84	6.62	6.64	7.31	6.96	7.19	7.81	7.50	7.70
	3.32	6.80	6.62	6.63	7.27	6.97	7.18	7.77	7.48	7.68
	3.33	6.78	6.62	6.62	7.24	6.98	7.17	7.73	7.47	7.66
	3.34	6.74	6.63	6.60	7.20	6.99	7.15	7.69	7.43	7.62
Canvey	3.35	6.70	6.63	6.61	7.16	7.01	7.17	7.65	7.42	7.64
	3.36	6.67	6.63	6.60	7.13	7.03	7.16	7.61	7.46	7.66
	3.37	6.64	6.62	6.59	7.09	7.05	7.12	7.57	7.51	7.62
Southend	3.38	6.60	6.60	6.60	7.06	7.06	7.06	7.54	7.54	7.54

For the Defra ’06 climate change scenario in 2170 there is overtopping of the majority of defences in the B1 and B2 models in the 1,000 year tide and above. There is overtopping of the lower defences (North Kent and upstream of the Thames Barrier) in the 100 year tide.

Annex E Analysis of the number of barrier closures

E.1 Introduction

This annex assesses the impact of sea level rise under different climate change scenarios on the frequency of barrier closures, and the implications of this for the Phase 3 Set 2 Options.

The barriers on the Thames Estuary were all constructed over 20 years ago with a similar design Standard of Protection (SoP) of 0.1% annual probability of flooding at 2030 to mirror the SoP of the downriver walls and embankments. No standard was set for the reliability of the barriers other than using proven technologies and a high degree of redundancy, including manual back-up systems, to provide a very high expected reliability.

This approach has so far resulted in no failures to close the barriers in response to a tidal surge event. However, with potential increasing sea level and more frequent fluvial events it is likely that the reliability of the barriers will decrease as they operate with an increasing frequency. Therefore it is necessary for TE2100 to consider potential flood risk management options that will ensure an acceptable level of reliability is maintained for the barriers on the Thames Estuary, particularly the Thames Barrier.

These options could include:

- A change in the maintenance regimes of the barriers
- A change in the operational regime brought about through:
    - Improvements to the closure forecasting systems
    - Changes to the management of fluvial flood risk
    - Improvements to the other defences, for example the introduction of flood storage to reduce the level of high tides
- Mitigation of other constraints to barrier closures.

This annex concentrates on the Thames Barrier as it is by far the most important barrier on the estuary. Similar issues exist for the other barriers, particularly Barking and Dartford where there are extensive developed areas upriver of the barriers.

This annex covers:

- The number of barrier closures (Sections E.2 and E.3)
- Data and methods (Sections E.3.1 and E.3.2)
- Historical Thames Barrier closures (Section E.3.3)
- Impacts of uncertainty and climate change (Sections E.3.4 and E.3.5)
- Implications for Phase 3 Set 2 Options (Section E.3.6)

E.2 Closures of the Thames Barrier

Whilst the Thames Barrier could theoretically be closed on every tide, in practice there is a limit to the number of closures per year before the reliability of the Barrier is affected. Reasons why the number of closures is limited include:

- Limitations on the reliability of the Barrier.
- Impacts on navigation, including passenger ferries and waste disposal barges.
- Environmental impacts including water quality and the effects of changes in the water regime on the natural environment.

The performance of the Barrier is expressed in terms of the following variables:

- Standard of Protection (SoP). This is related to the maximum extreme water level that the Barrier can protect against. Some of the High Level Options include changes to the Barrier so that it can protect against higher water levels in the future.
- Standard of reliability (SoR). This is the ability of the Barrier to be closed on demand and is expressed in terms of the ratio between barrier failures and barrier closures.
- Annual Probability of Failure (APF). This is the product of the SoR and the number of closures per year.

As the number of closures per year increases, the APF will increase. This is not only because of the increase in number of closures but also because the SoR will reduce. This is because (a) there is less time to undertake maintenance work and (b) elements of the system will be used more often and deteriorate more quickly.

The seasonality of Barrier closures must also be taken into account. More closures will occur during the ‘surge season’ than at other times of the year. In addition, closures caused by high fluvial flows are much more likely to occur in the winter, although it is expected that alternatives ways of managing fluvial flooding will be developed as the number of closures for high tides increases.

Work within TE2100 on the Thames Barrier suggests that the maximum practical number of closures could be between 50 and 60 per year whilst maintaining a satisfactory APF (TE2100 IA5 2005).

The upper limit of this number is based on the ability to maintain all of the critical systems to their current standard given the greater level wear and tear, and the reduced time window available for maintenance due to the increased frequency of operation.

The HLOs and the Phase 3 Set 1 Options assumed the threshold number of barrier closures per year was 70. The threshold number of barrier closures per year has been set to 50 in the Phase 3 Set 2 Options.

E.3 Analysis of number of barrier closures

E.3.1 Data

The following data sets were available for this study:

- Daily average flows at Teddington and tidal high waters (2 records per day) at Southend covering the period 01/01/1939 to 31/12/2001 (Halcrow 2002).

- Tidal high waters at Sheerness for the period 01/01/1993 to 31/12/2000. This dataset was used in an earlier appendix on the frequency of barrier closure, included in the Pilot Portfolio report (HR Wallingford 2006).

- JOIN-SEA dataset on the combined occurrence of sea levels and fluvial flows (TE2100 2006). This was used to develop probabilities of extreme combined events occurring in order to determine extreme conditions in the estuary for option development and other purposes. However the JOIN-SEA data does not provide adequate definition of the more frequent events required for this analysis, as outlined in Section 3.

- Thames Barrier closure rule for flow at Teddington and water level at Southend. The Environment Agency's Thames Barrier Official critical closure rule based on water levels at London Bridge is shown on Figure E.1. The barrier is closed for combinations of flow and tide forecast to fall above this closure curve.

- Increases to boundary conditions caused by climate change including flow at Teddington and increases to maximum surge tide level and Mean Sea Level for the Defra 2006, UKCIP02 Medium High, and High+ climate change scenarios.

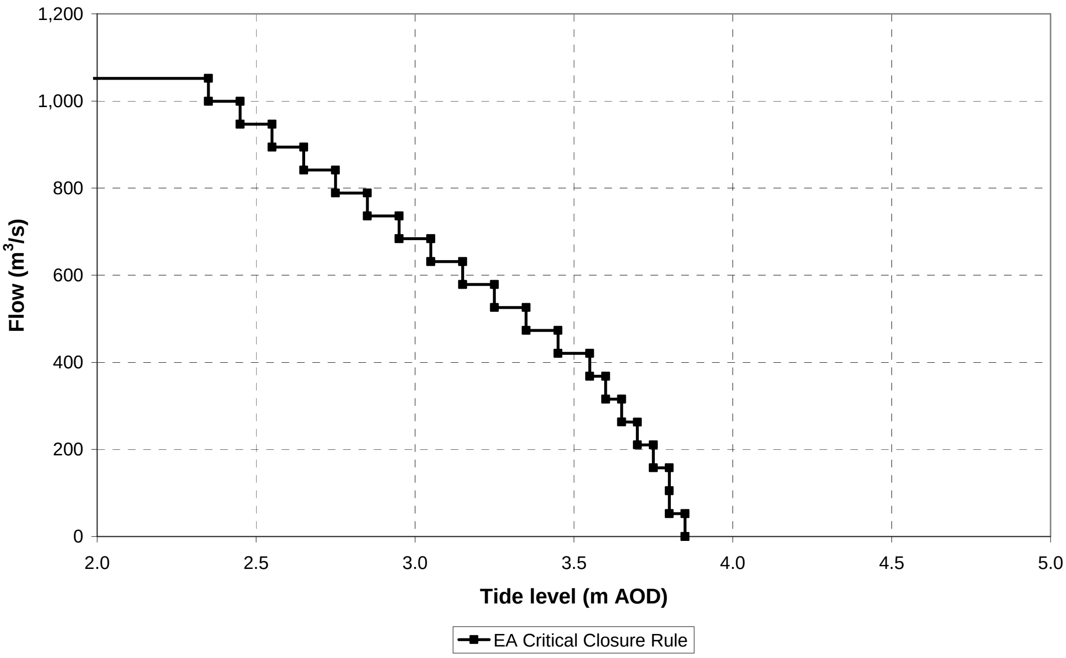

Figure E.1 Environment Agency Thames Barrier Official Closure Rule

E.3.2 Methodology for analysis

The barrier closure rule used to define whether a particular combination of flow and tide causes a closure is the Environment Agency official critical closure rule shown in Figure E.1.

Fluvial flood events have been separated into the number of high tides which occur during the flood event. For example a flood hydrograph lasting 5 days, occurs during 10 high tides (2 per day), and so could cause up to 10 closures of the barrier. This ensures that the maximum number of possible closures is taken into account.

For this reason the existing JOIN-SEA data has not been used because it uses a record/event definition suitable for identifying floods (one record per 14-day neap-to-neap tidal cycle) whereas to find the number of barrier closures it is necessary to have one record per tide. Although JOIN-SEA would represent random record-by-record variability, the source data set probably gives a better indication of true year-by-year variability.

The 1939 to 2001 dataset has been used in this analysis because the long length of record should give a good annual average compared to the short Sheerness record. It also contains years that had high fluvial flow, for example 1947, and the highest tide on record in 1953. The dataset has not been de-trended to account for sea level rise that has occurred between the start of the record and present day. The impact of not de-trending the data on the annual average calculated by the analysis is expected to be small.

The sequence of the analysis is as follows:

- Assessment of the likely number of historical Thames Barrier closures based on the HLO closure rule.
- Assessment of the likely impacts of climate change on the number of future Thames Barrier closures.
- Assessment of the number of actual closures compared with the HLO closure rule.

E.3.3 Historical barrier closures

This section considers the number of historical closures that would have occurred according to the Environment Agency closure rule (*not the actual number of closures that have occurred)* through an analysis of the historical data set.

Combinations of observed flows and tides that would have caused barrier closures according to the official rule defined in Figure E.1 have been counted for each year in the 1939 to 2002 record. The numbers of barrier closures that would have occurred in each year according to the Environment Agency closure rule are shown in Figure E.2.

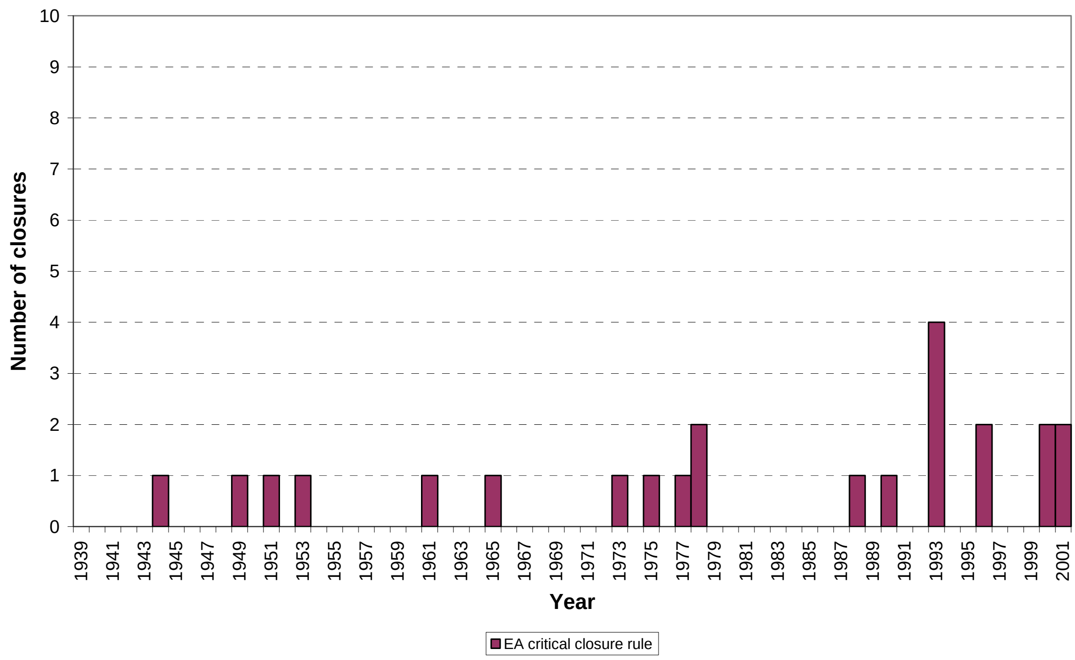

Figure E.2 Number of barrier closures in each year according to the official closure rule

Figure E.2 shows that in general the number of barrier closures required each year is low. Under present day sea levels the presence of a large (infrequent) fluvial event can significantly affect the number of barrier closures required in single year. Figure E.2 shows that the annual variability in the number of barrier closures is generally small, but can be significantly influenced by an infrequent fluvial flood event.

This numerical simulation suggests that there would have been 39 barrier closures in 63 years. Inspection of the data record identified that there were no tide records for

1986 and 1987. These years have therefore been removed from the calculation of the average number of barrier closures in a given year.

Significant amounts (1 month or more) of tide records were missing from the years 1948, 1949, 1950 and 2001. These years have therefore also been removed from the calculation of the annual average number of barrier closures. This analysis shows that at present the average number of barrier closures per year might be expected to be on average once every three years according to the official rule.

However because the number of barrier closures is given as the average annual value (number of times the threshold is exceeded per year) based on 57 years of data covering the period 1939 to 2001, the actual number in a given year may be higher.

E.3.4 Uncertainty in defining a threshold for barrier closure

The barrier was closed 31 times between 1982 and 1998, and closed 32 times between 1998 and 2001 (Halcrow 2002). This is significantly greater than the 23 times the barrier would be closed according to the critical rule over the period 1939 to 2002. This is because of uncertainty in the forecast water level on which the decision to close the barrier is made, and the fact that the Barrier is also closed below the critical rule to improve the SoP for undefended areas in West London.

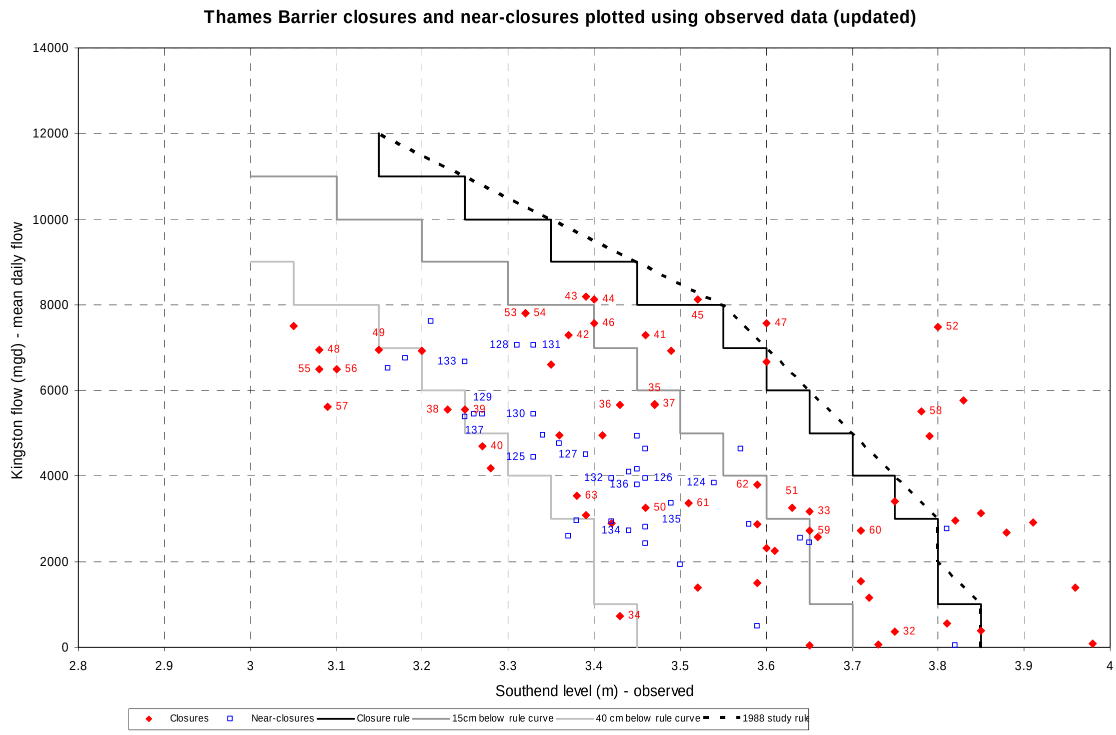

Figure E.3 Actual Thames Barrier closures in relation to the critical rule
Source: Halcrow 2002

The majority of the closures below the critical rule are within 0.4m of the rule. The number of barrier closures has been re-calculated for the 0.4 m below rule curve. Figure E.4 shows the number of barrier closures in each year for the critical closure rule, the conservative closure rule (0.4 m below the critical rule), and for an intermediate closure rule (0.2m below the critical rule).

The annual average number of barrier closures using the conservative rule is 5. Between 1998 and the end of 2001 the total number of closures identified by this analysis is 45. The intermediate closure rule identifies 16 events for which the barrier would be closed during this period.

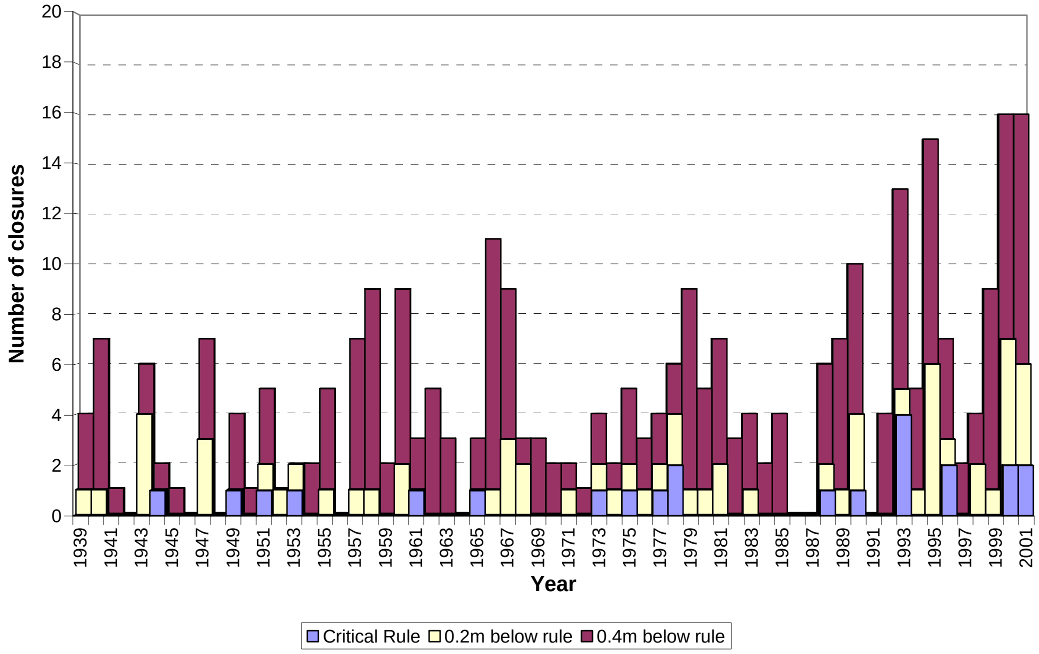

Figure E.4 Annual number of barrier closures with the critical rule, conservative rule (0.4m below critical rule), and intermediate rule (0.2m below critical rule)

To achieve the critical rule it would be necessary to eliminate many of the medium flow closures. There are however a significant number of closures that are lower than the rule where the flows are low. This is a forecasting issue, and there is therefore a need to improve forecasting.

HLO studies for West London show that there is spare capacity to account for uncertainty in tidal water levels if the closure rule is followed (TE2100 2007). It should therefore be possible to improve forecasting and operate closer to the critical rule. However this does not apply to the fluvial flood risk problem in West London.

In summary, more accurate (or at least perceived by Thames Barrier operators to be more accurate) forecasts might lead to far fewer closures and a longer projected period of time before the Barrier reaches its operational limit.

E.3.5 Climate change

E.3.5.1 Scenarios

To assess how the average annual number of barrier closures may change in the future, the increase in fluvial flow and rise in Mean Sea Level (MSL) under various climate scenarios needs to be taken into account. The increase in fluvial flow at Teddington and rise in MSL at Southend were available for a range of climate change scenarios for 2050 and 2100 from the EP7.3 study (TE2100 2005). These are shown in Table E.1.

Table E.1 Change in flow and mean sea level due to climate change

Scenario	Year	Mean Sea Level rise (m)	Increase in flow (%)
Defra (2006)	2050	0.35	20
Defra (2006)	2100	0.98	40
UKCIP02 Medium High	2050	0.18	8
UKCIP02 Medium High	2100	0.45	19
High Plus	2050	0.64	16
High Plus	2100	1.60	40

E.3.5.2 Mean Sea Level (MSL)

The MSL rise and increase to fluvial flows have been applied to the observed data record to produce a representative data series for each climate change scenario in Table E.1. The analysis therefore assumes that the patterns of the past will be repeated apart from changes in MSL and fluvial flow magnitude.

Figure E.5 shows the number of high tides that exceed different water level thresholds. This analysis was undertaken on the Sheerness record for the period 01/01/1993 to 31/12/2000 (TE2100 2006).

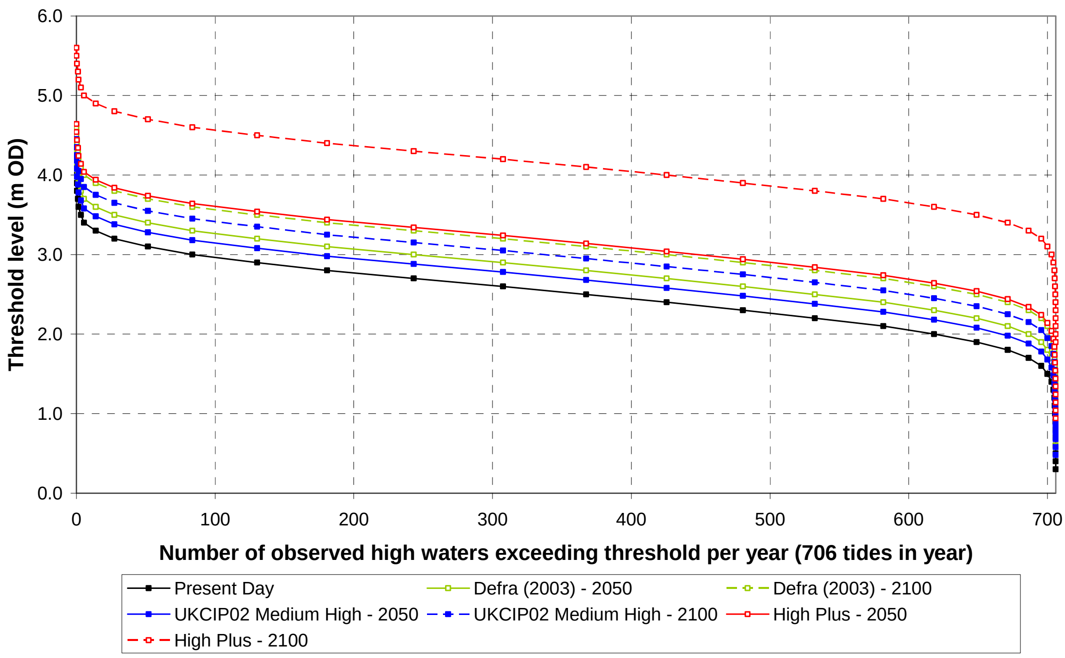

Figure E.5 Annual average number of high tides that exceed water level thresholds

As the sea level rises, the curves shown on Figure E.5 rise and the number of high tides that exceed a specified threshold increases. The Thames Barrier closes for tides that exceed 3.85m AOD at Southend. From Figure E.5, the peak tide level that is exceeded 50 times per year is about 3.1m AOD. It therefore follows that:

- The Thames Barrier will reach its operational limit (assuming 50 closures per year) when the MSL has risen by about 0.75m.

These are first estimates. In practice the Barrier sometimes closes at lower tide levels (according to the closure rule). Hence the need for the more detailed analysis outlined below.

E.3.5.3 Analysis methodology for climate change

The analysis contained in this section is based on MSL and does not take into account the increase in surge magnitude due to climate change. This was not possible without knowing the surge components of each high water in the observed record and their corresponding return periods. The Defra 2006 climate change scenario does not include an increase in the surge component and the approach is therefore acceptable in this case. In the High+ scenario and in the UKCIP02 Medium High scenario the magnitude of the surge component increases as well as the rise in MSL.

In the scenarios developed for the TE2100 studies (TE2100 2005) assumed that there was no increase in surge magnitude in the 1 in 1 year tide, but includes an increase in surge component for tides with higher return periods (corresponding to tides greater than approximately 3.6m AOD).

Tides with a return period greater than approximately the 1 in 3 year tide have a water level that is greater than 3.8m AOD. This means that the majority of tides for which the additional surge component would be applied are already greater than the closure threshold for the barrier, and that excluding this from the analysis does not have a significant impact on the calculation of the number of barrier closures under climate change.

For the 1 in 2 year tide the increase in surge magnitude according to EP7.3 is 0.04 m in 2050 and approximately 0.1 m in 2100. This is a relatively small increase compared to the increase in MSL, and applies to a small range of tide levels between 3.6 and 3.85m AOD. It is therefore unlikely that excluding the increase in surge magnitude has an impact on the annual average number of barrier closures calculated for the climate change scenarios. In addition the MSL increase is enough to make the 1 in 1 year tide greater than the barrier closure level in all climate change scenarios except UKCIP02 Medium High in 2050.

E.3.5.4 Frequency of future barrier closures

The average annual number of barrier closures has been plotted on Figure E.6 under each climate change scenario. This suggests that under the UKCIP02 Medium High scenario the critical number of barrier closures (assumed to be 50) would on average not be exceeded by 2100. This is because the Medium High scenario has a very low component of mean sea level rise.

The critical number of closures is exceeded in the Defra 2006 and the High Plus climate change scenarios before 2100. In addition, for the High Plus scenario the barrier would on average need to be closed more frequently than every other tide by 2100.

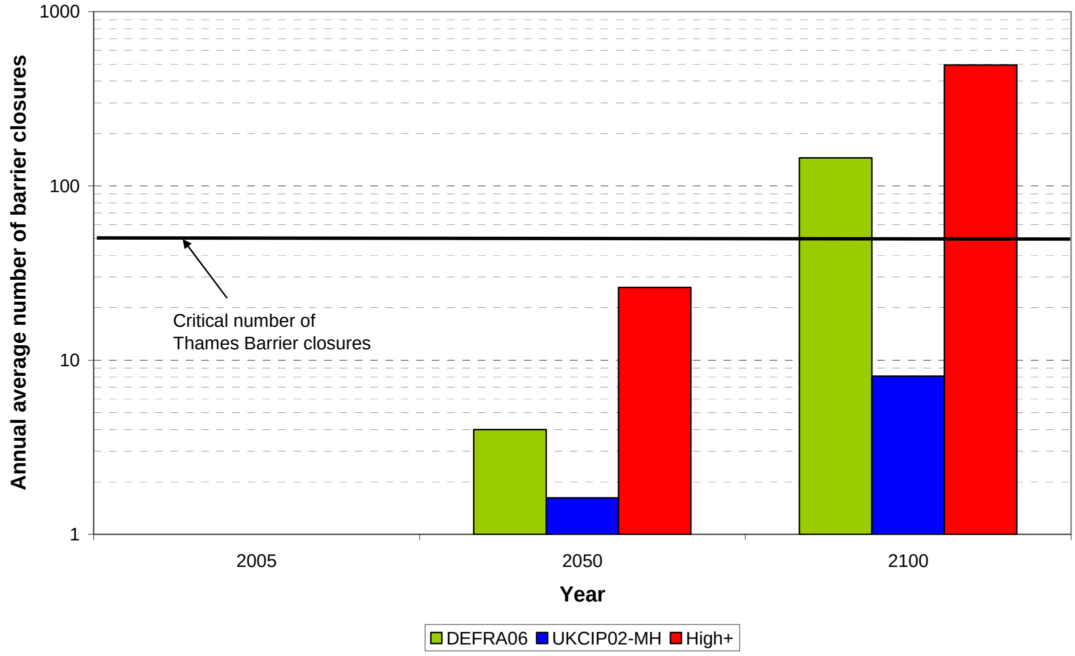

Figure E.6 Average annual number of barrier closures under different climate change scenarios
(It is assumed that the barrier is closed according to the critical rule)

For the Defra 2006 climate change scenario the average number of barrier closures has been calculated for simulations with the three closure rules for different levels of forecast uncertainty. These are shown on Figure E.7. The numerical simulations show that in 2050 the annual average number of barrier closures exceed the threshold of 50 if the barrier is operated conservatively. By 2100 even with perfect forecasting and operation to the critical rule the threshold is well exceeded.

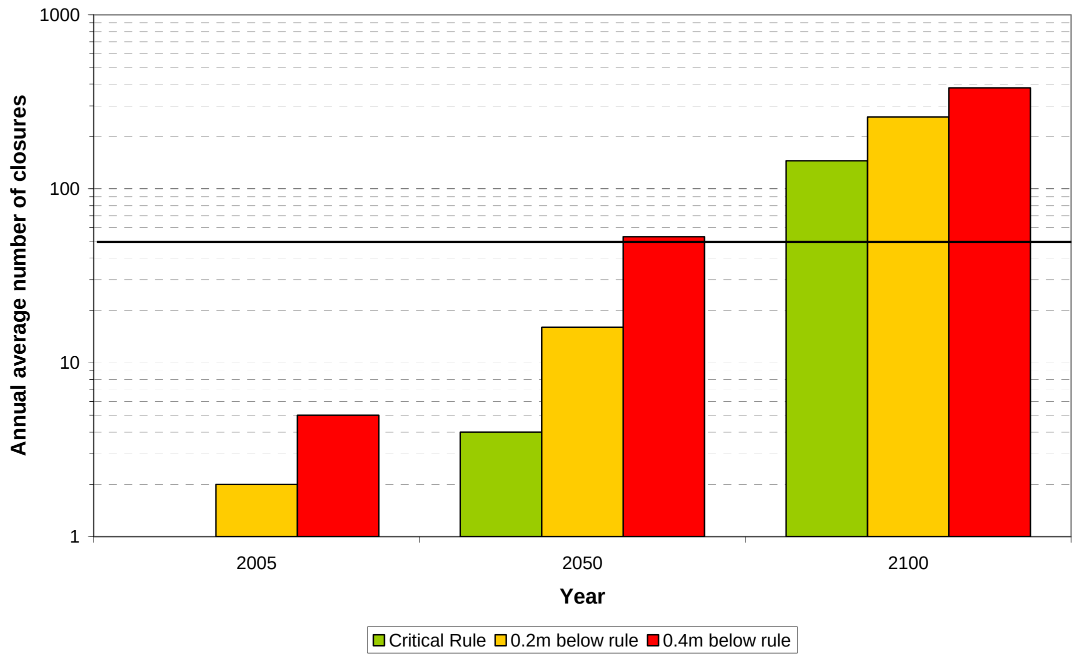

Figure E.7 Average annual number of barrier closures under the Defra 2006 climate change scenario for the critical, conservative and intermediate closure rules

E.3.6 Implication for Phase 3 Set 2 Options

E.3.6.1 Introduction

As the Mean Sea Level and fluvial flow rise due to climate change the number of tide flow combinations that fall above the critical barrier closure rule will increase (Figure E.7). Hence the Barrier will be required to close more frequently as the Mean Sea Level rises.

The threshold number of barrier closures is the maximum acceptable annual number of closures. This limitation is needed to permit adequate maintenance of the Barrier, and prevent a reduction in the reliability of the Thames Barrier. Any reduction in reliability will affect the SoP provided to the PMUs upriver of the Barrier.

Responses to mean sea level rise are pre-determined increase (Two increments of 0.5m) in defence levels upstream of the Thames Barrier. The tide level on the barrier closure rule can then be increased by the same increment to reduce the number of closures below the threshold level. The limits of these responses are determined by analysis of the number of barrier closures.

The HLOs and the Phase 3 Set 1 Options assumed the threshold number of barrier closures per year was 70. However other thresholds were also considered in Option 1.2 of the Phase 3 Set 1 Options.

The threshold number of barrier closures per year has been set to 50 in the Phase 3 Set 2 Options. In addition the critical closure rule has been lowered by 0.2m. This is to account for imperfect forecasting of peak tide level, and operation uncertainty resulting in barrier closure for tide flow combinations that fall below the critical rule.

E.3.6.2 Phase 3 Set 2 Analysis of the number of barrier closures

The annual average number of barrier closures was determined in section E.3.5 for the Defra 2006 climate change scenario and the critical closure rule lowered by 0.2m. This shows that the critical number of barrier closures (50 per year) is reached in 2065.

It is assumed that by raising defences upriver of the Thames Barrier the closure rule can be modified so that the barrier is not closed for tides and flows greater than at present. The justification for this is discussed in section E.3.6.3. The analysis of the number of barrier closures has been repeated with the following modifications to the closure rule:

Tide increased by 0.5m and flows increased by 40%
Tide increased by 1.0m and flows increased by 40%

The revised closure rules are shown on Figure E.8.

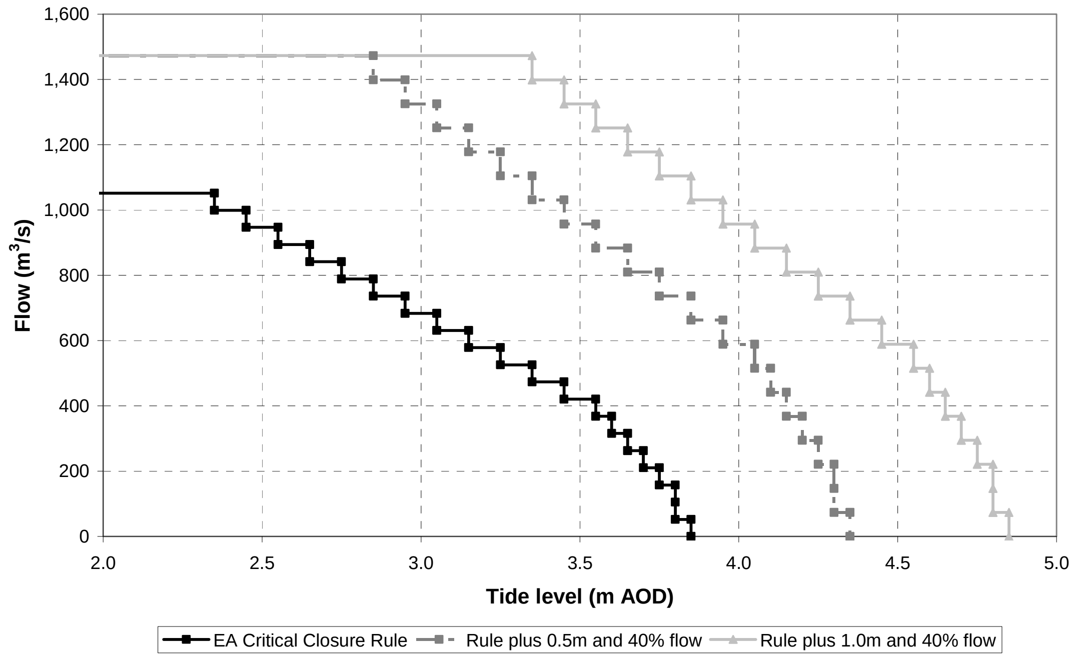

Figure E.8 Barrier closure rules in present day, 2065 and 2100

The results are shown in Figure E.9 and summarised in Table E.2. The results are shown for the critical closure rule, closure at 0.2m below the rule (referred to as 'MID'), and 0.4m below the rule (referred to as 'LOW'). 'MID' and 'LOW' include allowances for forecasting error.

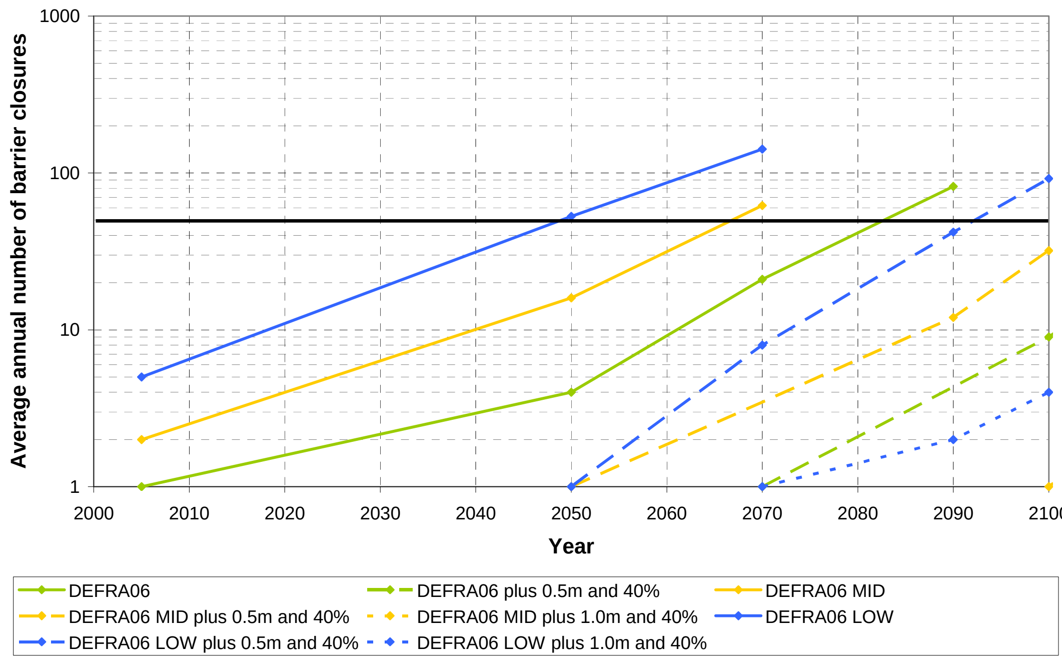

Figure E.9a Annual average number of barrier closures for different closure rules to reflect increases to upriver defences (2000 to 2100)

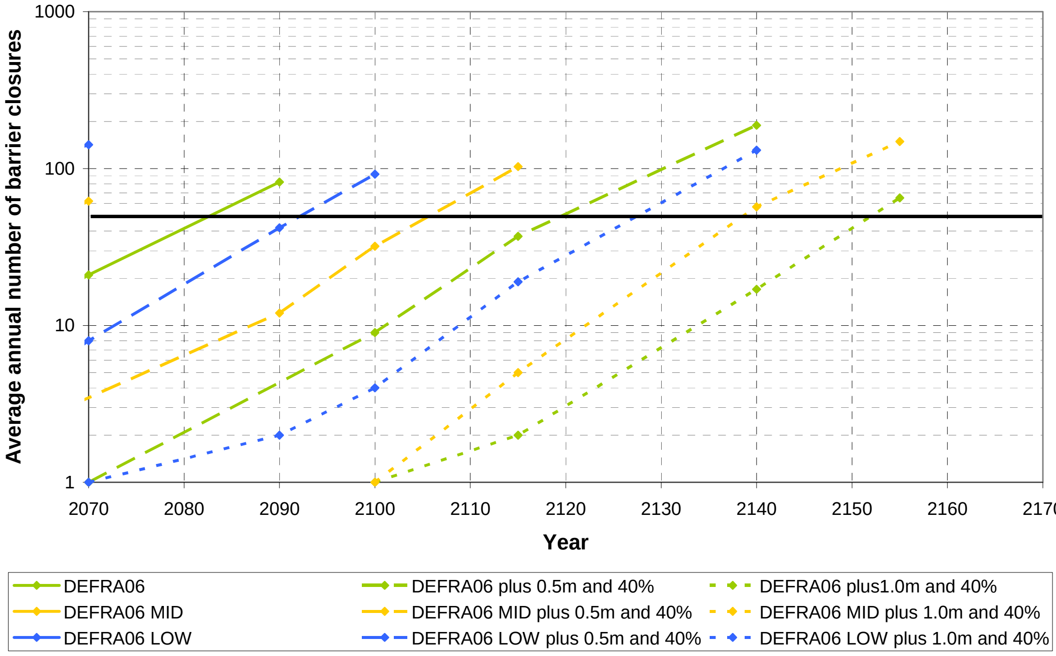

Figure E.9b Annual average number of barrier closures for different closure rules to reflect increases to upriver defences (2070 to 2170)

Table E.2 Date of interventions
Assumptions:

- The climate change scenario is Defra '06
- The forecasting allowance is 0.2m
- The maximum annual number of closures of the Thames Barrier is reduced from 70 to 50.

Intervention	**70 closures per year**	**50 closures per year**
Raise u/s defence 0.5m	2075	2065
Raise u/s defence 0.5m	2110	2100/5
New barrier with locks/barrage	2145	2135

For Options 1, 2 and 3 this means that the upriver defence raise of 0.5m is required 10 years earlier, the second raise to upriver defences is required 5 to 10 years earlier, and a barrier with locks or barrage is required 10 years earlier.

If the maximum amount of upriver defence raising is 1m, the limits of Option 1, 2 and 3 are reached in 2135 due to the threshold number of barrier closures per year being exceeded. At this decision point a new barrage or barrier with locks is required.

E.3.6.3 Justification for upriver defence raising to increase the water levels for which the Thames Barrier is closed
The numerical model used for the development of the Phase 3 Set 2 Options has been run for a range of combinations of flow and tide for which the barrier is not closed, defined by the closure rule. The tide levels have been increased by 0.5m and the flows by 40%.

Table E.3a shows the water levels upstream of the Thames Barrier in 2065, as a result of changing the barrier closure rule to respond to increases in mean sea level. The increase in defence level required to ensure the freeboard level of the defence is greater than the water level has been calculated. This shows that with the exception of West London the required increase in defence level is less than the 0.5m the defence are raised. The additional defence raising in West London to account for the increase in fluvial flow is determined in Annex F.

Table E.3a Raised defences upstream of the Thames Barrier (implemented in 2065, limit in 2100)

Location	Node	PD Defence Level		Defence Level - Freeboard		Water level at limit	Defence Raising Required	
		LB	RB	LB	RB	100yr	LB	RB
Teddington	2.1	6.10	6.10	5.70	5.70	7.37	1.67	1.67
Eel Pie Island	2.3	6.02	6.05	5.62	5.65	7.05	1.43	1.40
Marble Hill	2.4	6.02	6.34	5.62	5.94	6.98	1.36	1.04
Richmond	a2.6	6.02	5.94	5.62	5.54	6.44	0.82	0.90
Richmond	a2.7	5.94	5.94	5.54	5.54	6.05	0.51	0.51
R Crane	2.9d	5.94	5.94	5.54	5.54	5.99	0.45	0.45
R Brent	2.13d	5.94	5.94	5.54	5.54	5.95	0.41	0.41
	2.17d	6.25	6.25	5.85	5.85	5.55	-	-
Hammersmith	2.21	5.54	5.94	5.14	5.54	5.45	0.31	-
R Wandle	2.24ad	5.58	5.41	5.18	5.01	5.42	0.24	0.41
Chelsea	2.29	5.41	5.41	5.01	5.01	5.36	0.35	0.35
Tower Pier	2.36	5.28	5.28	4.88	4.88	5.30	0.42	0.42
R Ravensbourne	2.42d	5.18	5.18	4.78	4.78	5.22	0.44	0.44
R Lee	2.47	5.18	5.18	4.78	4.78	5.14	0.36	0.36
Thames Barrier	a2.49	5.18	5.18	4.78	4.78	5.12	0.34	0.34

Note: Areas shaded in green are raised by 0.5m.

For upriver of the Thames Barrier, Table E.3b shows the second 0.5m raise to defence levels upstream of the Thames Barrier in 2100, and the water levels as a result of changing the barrier closure rule to respond to increases in mean sea level. The increase in defence level required to ensure the freeboard level of the defence is greater than the water level has been calculated. This shows that with the exception of West London the required increase in defence level is less than the total 1.0m the defence are raised by in 2100.

Table E.3b Raised defences upstream of the Thames Barrier (implemented in 2100, limit in 2135)

Location	Node	PD Defence Level		Defence Level - Freeboard		Water level at limit	Defence Raising Required	
		LB	RB	LB	RB	100yr	LB	RB
Teddington	2.1	6.10	6.10	5.70	5.70	7.49	1.79	1.79
Eel Pie Island	2.3	6.02	6.05	5.62	5.65	7.20	1.58	1.55
Marble Hill	2.4	6.02	6.34	5.62	5.94	7.14	1.52	1.20
Richmond	a2.6	6.02	5.94	5.62	5.54	6.64	1.02	1.10
Richmond	a2.7	5.94	5.94	5.54	5.54	6.67	1.13	1.13
R Crane	2.9d	5.94	5.94	5.54	5.54	6.61	1.07	1.07
R Brent	2.13d	5.94	5.94	5.54	5.54	6.15	0.61	0.61
	2.17d	6.25	6.25	5.85	5.85	6.00	0.15	0.15
Hammersmith	2.21	5.54	5.94	5.14	5.54	5.89	0.75	0.35
R Wandle	2.24ad	5.58	5.41	5.18	5.01	5.85	0.67	0.84
Chelsea	2.29	5.41	5.41	5.01	5.01	5.82	0.81	0.81
Tower Pier	2.36	5.28	5.28	4.88	4.88	5.77	0.89	0.89
R Ravensbourne	2.42d	5.18	5.18	4.78	4.78	5.69	0.91	0.91
R Lee	2.47	5.18	5.18	4.78	4.78	5.62	0.84	0.84
Thames Barrier	a2.49	5.18	5.18	4.78	4.78	5.60	0.82	0.82

Note: Areas shaded in green are raised by 1.0m.

The maximum water level profiles shown in Figure E.10 for the modified closure rules are approximately 0.5 and 1.0 m above the present day profile (Figure E.11) downstream of Brentford. Figure E.10 shows that water levels with the new closure rules are below the freeboard level on the defences downstream of the River Brent. Water levels in West London are above the freeboard level, as for the Present Day critical closure rule, with high fluvial flows. As a result of the 40% increase in fluvial flow this is extended downstream to the River Brent. The additional defence raising in West London to account for the increase in fluvial flow is determined in Annex F.

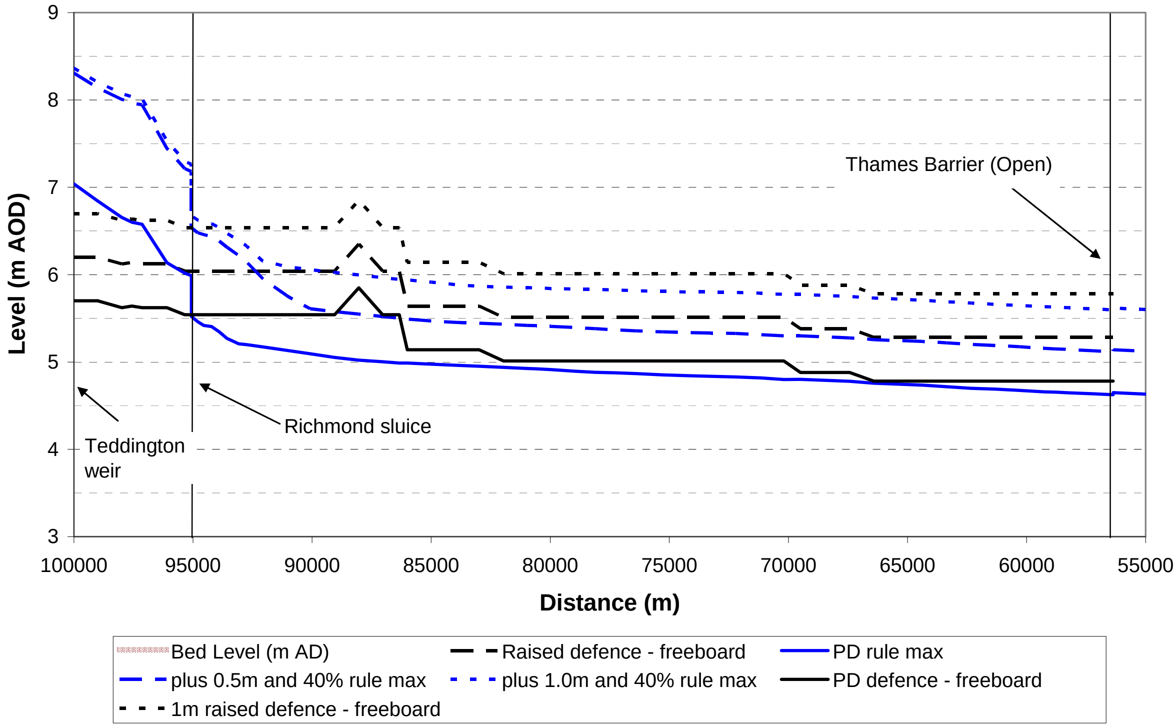

Figure E.10 Maximum water level profiles from events under the closure rules

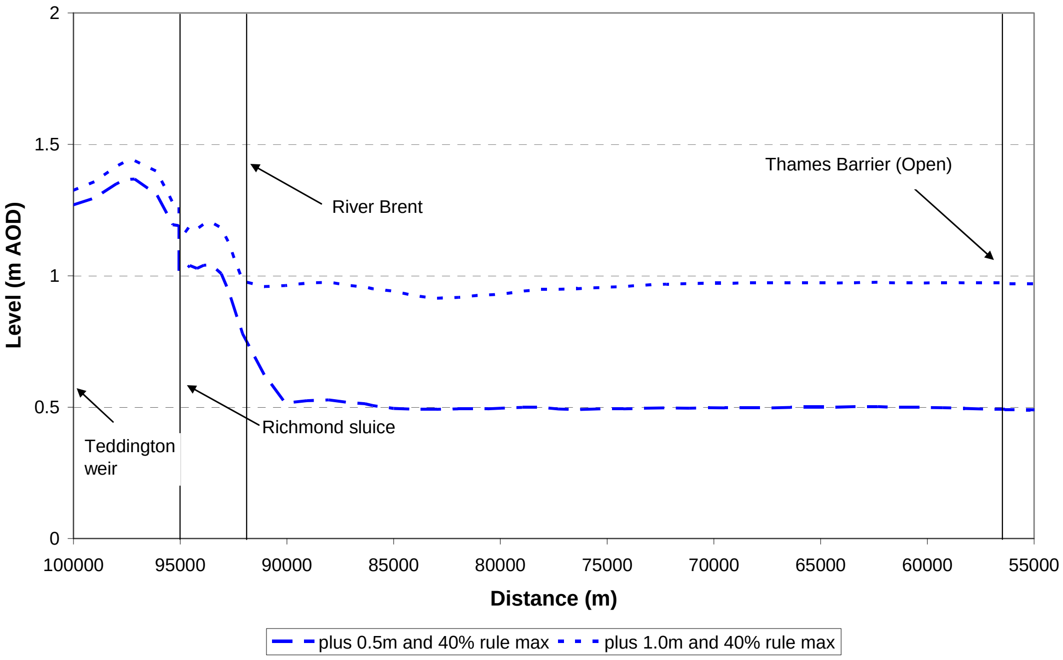

Figure E.11 Difference between water levels from events under the new closure rules and events under the present day closure rule

E.3.6.4 Other mitigation measures

The options use raising of upriver defences as a means of mitigating the operational limits of the Thames Barrier. This is however an expensive and inconvenient response as it would cause considerable disruption to the estuary through central London.

There is a need to consider alternatives, but before doing this it is first necessary to establish the operational constraints in more detail. For example:

- If the constraint is external to the Barrier (for example water quality or navigation), an alternative response would be to mitigate these constraints (for example, a lock for navigation).
- If the constraint is internal to the Thames Barrier (i.e. the Annual Probability of Failure based on the reliability of the structure), an alternative response might be to extend the Barrier and provide a second emergency gate in each bay.

Particular responses that should therefore be considered include the following:

- Improve forecasting, to optimise the number of closures.
- Improve flood management measures in West London, to reduce the need to close for fluvial flows.
- Use tidal flood storage to reduce peak water levels at the Barrier for the frequent events when the Barrier would otherwise close.
- In the case where the constraint is internal to the Thames Barrier,
    - Improve the Standard of Reliability of the existing structure and systems.
    - Improve the Standard of Reliability by modifying the structure (for example, the introduction of new gates referred to above).
- In the case where the constraint is external to the Thames Barrier, develop specific responses depending on the particular constraint, for example:
    - Navigation lock for navigation.
    - Working with Thames Water to improve water quality.
    - Replacement or compensation habitats where the ecological function of the estuary would otherwise be damaged by Barrier operation.

Whilst this analysis has concentrated on the Thames Barrier, similar issues exist for the other barriers, particularly Barking and Dartford where there are extensive developed areas upriver of the barriers.

E.4 Conclusions

- Under present day conditions the annual average number of barrier closures is less than one, assuming that the barrier is operated to the critical rule. A high flow event can cause the number of barrier closures in a year to be high. For example the 1947 event would result in 14 closures.

- In practice the Thames Barrier is closed for events below the critical rule because of a combination of forecast uncertainties and a desire to reduce flood risk in West London, particularly for undefended areas. The number of closures has also been assessed for a conservative rule (closure at 0.4m below the critical rule level). In this case the annual average number of barrier closures in present day conditions is 5.

- It has been assumed in the development of the Options that the operational limit of the Thames Barrier (and any new barriers) is 50 closures per barrier per year.

- The impact of the annual number of closures of the Thames Barrier on the options is not very sensitive once the number of closures for tidal events exceeds about 30 per year. This is because the Barrier would then be closed for normal spring tides and not just extreme surge tide events.

- Under the Defra 2006 climate change scenario the annual average number of Barrier closures of 50 would occur in about 2065, assuming an 0.2m allowance for uncertainty in forecasts.

- Raising of defences upriver of the Thames Barrier would delay the point at which the operational limit of the Barrier is reached. This mitigation response has been used in the options, and delays the operational limit to about 2135 assuming the Defra climate change scenario for sea level rise and a maximum upriver defence raising of 1m.

- In order to prolong the life of the Thames Barrier, the following measures have been considered:

    - More accurate forecasts, which would lead to fewer tidal closures.

    - Reduction of the number of closures for fluvial flood risk in West London.

    - Raising of upriver defences, referred to above. Increases of about 0.5m and 1.0m have been considered in the options.

    - Tidal flood storage to reduce peak water levels at the Barrier.

    - Improve the Standard of Reliability of the Thames Barrier.

    - Specific responses to mitigate constraints that are external to the Thames Barrier including navigation, water quality and ecology.

- Similar issues must be considered for other barriers, particularly Barking and Dartford.

E.5 References

TE2100 2007. *Thames Estuary 2100 – Phase 2 Report, Annex 13 Potential Flood Risk Management Options for West London*, (Draft), Environment Agency, January 2007

TE2100 2006. *High Level Options: Pilot Portfolios*, Report for TE2100, HR Wallingford, September 2006 (2 volumes)

TE2100 2005. *Climate change allowances to use in the TE2100 Programme*, Technical Note for TE2100 Work Element EP7.3 Part C, HR Wallingford, September 2005

Annex F Options for West London

F.1 Introduction

Topic 4.6 of the TE2100 Phase 3 studies has identified the following Options for West London that can be taken forward following reviews of previous work (Pilot Portfolios, Local Options, High Level Options):

- Improvements to conveyance by managed realignment on Ham Lands
- Improvements to conveyance by managed realignment at Barnes
- Flood storage at Grove Park
- Increase to defence levels

Figure F.1 shows the locations of managed realignments in West London at Ham Lands and Barnes, and Figure F.2 shows the location of flood storage in the Kew to Grove Park reach.

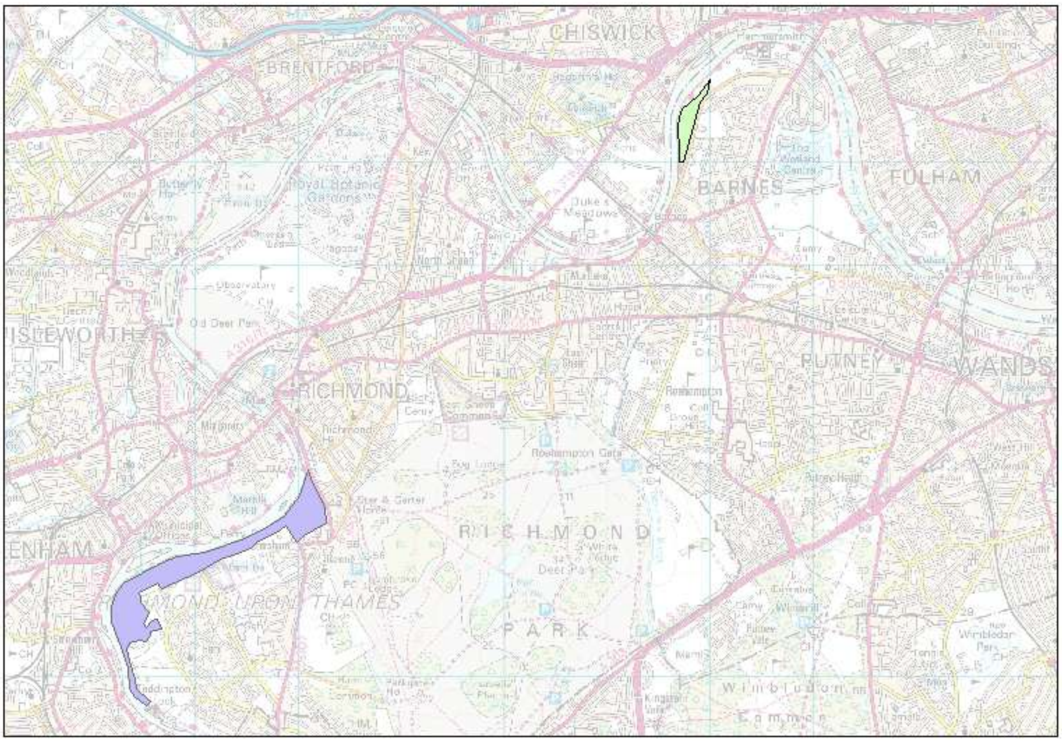

Figure F.1 Location of managed re-alignment

Figure F.2 Location of flood storage areas

Of these options raised defences were modelled in Pilot Portfolios, and a managed realignment at Ham Lands was modelled in the HLOs but this was shown to have little impact on peak water levels. These Options need to be modelled to identify whether they have an impact on reducing peak water levels in the West London reach (Teddington to Hammersmith).

In the HLOs the Responses that were shown to have greatest impact on reducing water levels in West London were improvements to conveyance by widening and deepening the channel. These responses have been rejected in Topic 4.6 due to the environmental consequences of the changes.

F.1.1 Present day defence standards in West London

Assessing the defence standard in terms of return period is difficult in West London because water levels are influenced by fluvial flows, tides, and by the operation of the Thames Barrier. Because of the Thames Barrier, extreme tides do not influence the water levels in West London. The fluvial flow has the strongest influence on peak flood water level, although the water levels are affected by the small range of tides that can pass through the Thames Barrier.

Figure F.3 shows the water level profiles for a range of events that are on the Environment Agency closure rule for the Thames Barrier. These events represent maximum conditions for which the Thames Barrier is not closed.

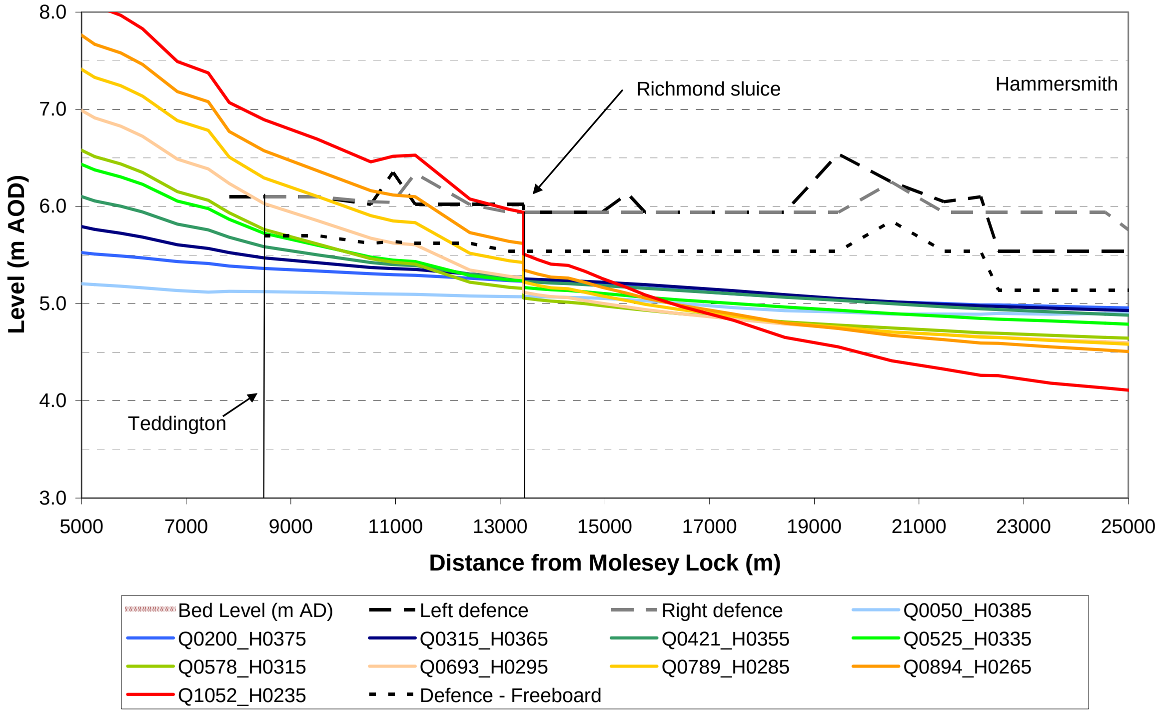

Figure F.3 Water level profiles for combinations of flow and tide for which the Thames Barrier is not closed

Comparison of the water levels with the defence level with the freeboard removed in Figure F.4 shows that at Teddington the defence limit (design) is just exceeded by the 1 in 30 year fluvial flow of 578 m^3/s, the defence standard is therefore approximately 1 in 30 years. Upstream of Richmond Sluice the design level is exceeded by the 1 in 200 year fluvial flow but not the 1 in 100 year flow, and downstream of Richmond Sluice the design level of the defences is not exceeded by the 1 in 500 year fluvial flow.

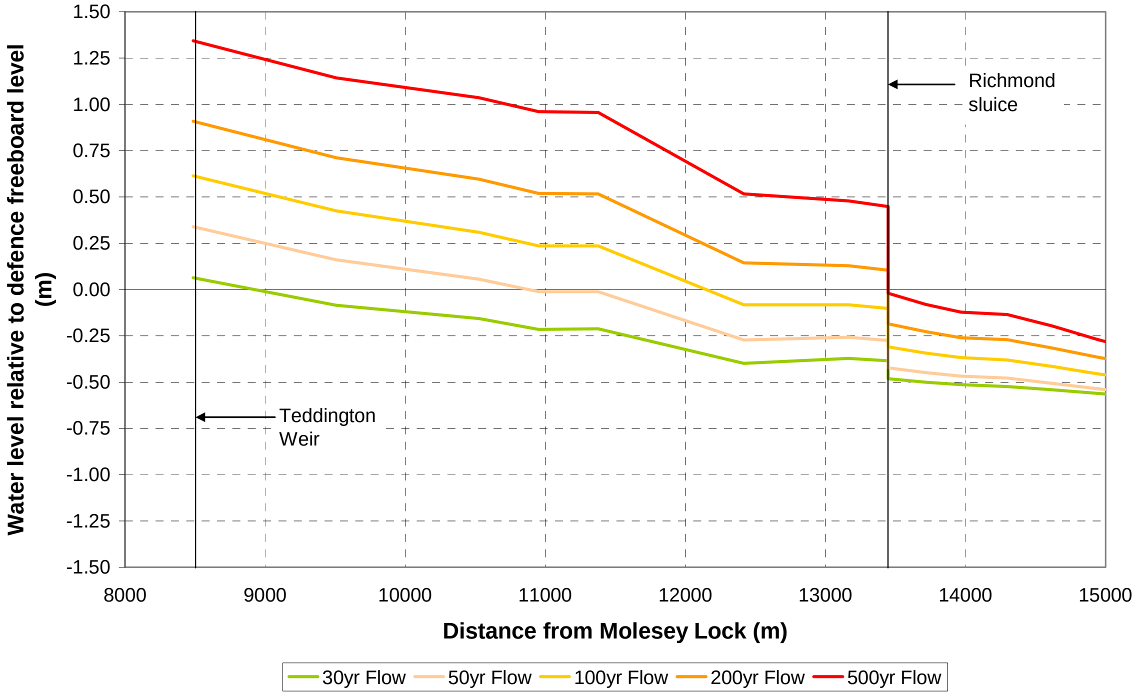

Figure F.4 Water levels relative to defence freeboard level for combinations of flow and tide for which the Thames Barrier is not closed

Note: The 'defence freeboard level' is the defence crest level minus a freeboard allowance of 0.4m. This also applies in Figures F.7, F.9 and F.11.

The Thames Barrier can be operated to raise the standard of defence to fluvial flow in West London. Figure F.5 shows the impact of barrier closure on water levels for the above events. The design standard of the defences at Teddington is increased to the 1 in 50 year fluvial flow, the design level upstream of Richmond Sluice is greater than the 1 in 200 year flow and the design level downstream of the sluice is greater than the 1 in 500 year flow when the barrier is closed.

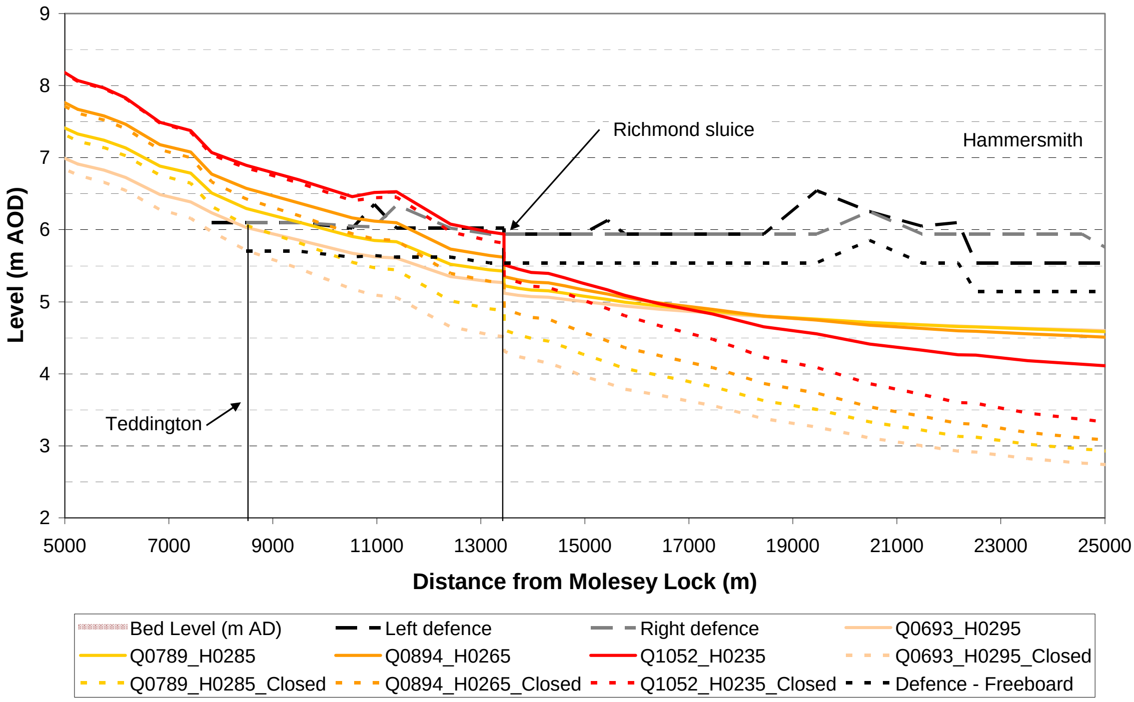

Figure F.5 Impact of barrier closure on water levels in West London

The Options for West London selected in Topic 4.6 can be tested against the events which produce water levels around the design defence levels through West London to identify if they provide an improvement in defence standard.

F.2 Raise defences in West London

The increase to defence height in West London depends on the design criteria for the defences. The following design criteria can be proposed for assessing increases to defence level:

- Increase present day defence standard
- Maintain present day defence standard in the future
- Maintain present day defence standards in the future with modifications to the barrier closure rule
- Change the barrier closure rule so that there are no closures for tides less than 3.85m AOD

F.2.1 Increase present day defence standard

To increase present day standards for high flow events when the Thames Barrier is not closed the increases to crest level shown in Table F.1 are required for different fluvial return periods. Long profiles of these increases in defence crest level are shown in Figure F.4.

Table F.1 Increases to defence crest level for fluvial design standards

Location	Node	Increase to defence level (m) for			
		Approx 1 in 50 year fluvial flow	**Approx 1 in 100 year fluvial flow**	**Approx 1 in 200 year fluvial flow**	**Approx 1 in 500 year fluvial flow**
Teddington	2.1	0.34	0.61	0.91	1.34
	2.2	0.16	0.43	0.71	1.14
	2.3	0.06	0.31	0.60	1.04
	2.3a	-	0.24	0.52	0.96
Marble Hill	2.4	-	0.24	0.52	0.96
	2.5	-	-	0.14	0.52
	2.6	-	-	0.13	0.48
Richmond u/s sluice	a2.6	-	-	0.10	0.45
Richmond d/s sluice	a2.7	-	-	-	-
	2.8	-	-	-	-
	2.81	-	-	-	-
r. Crane	2.9d	-	-	-	-

Note that the design water levels calculated from a full joint probability analysis may produce higher water levels for parts of the reach than the design fluvial flow for a particular return period combined with a tide for which the Thames Barrier is not closed. For example the Halcrow 2002 study produces higher 100 year water levels downriver of Marble Hill than the 100 year fluvial flow (although this used a different barrier closure rule, and included uncertainty of barrier closure).

F.2.2 Maintain present day defence standard in the future

If the design criteria to maintain the current standard of protection in the future, then the defences must be raised equivalent to the increase in peak water level resulting from climate change.

Under the Defra 2006 climate change scenario the fluvial increases by 20% after 2050. If it is assumed that the closure rule of the Thames Barrier is not modified, then the return periods of the fluvial events for which the barrier is not closed are changed as follows:

- the present day 1 in 50 year flow becomes the future 1 in 30 year flow,
- the present day 1 in 100 year flow becomes the future 1 in 50 year flow,
- the present day 1 in 200 year flow becomes approximately the future 1 in 100 year flow,
- the present day 1 in 500 year flow becomes the future 1 in 200 year flow.

For the 1 in 30 year flow this corresponds to a 0.3m increase in water level at Teddington, and for the 1 in 200 year flow this corresponds to a 0.35m increase in water level at Richmond (Figure F.6). To maintain present day defence standards (Policy P4) for fluvial flows in West London with climate change increase of 20% the defences must be raised by 0.35m.

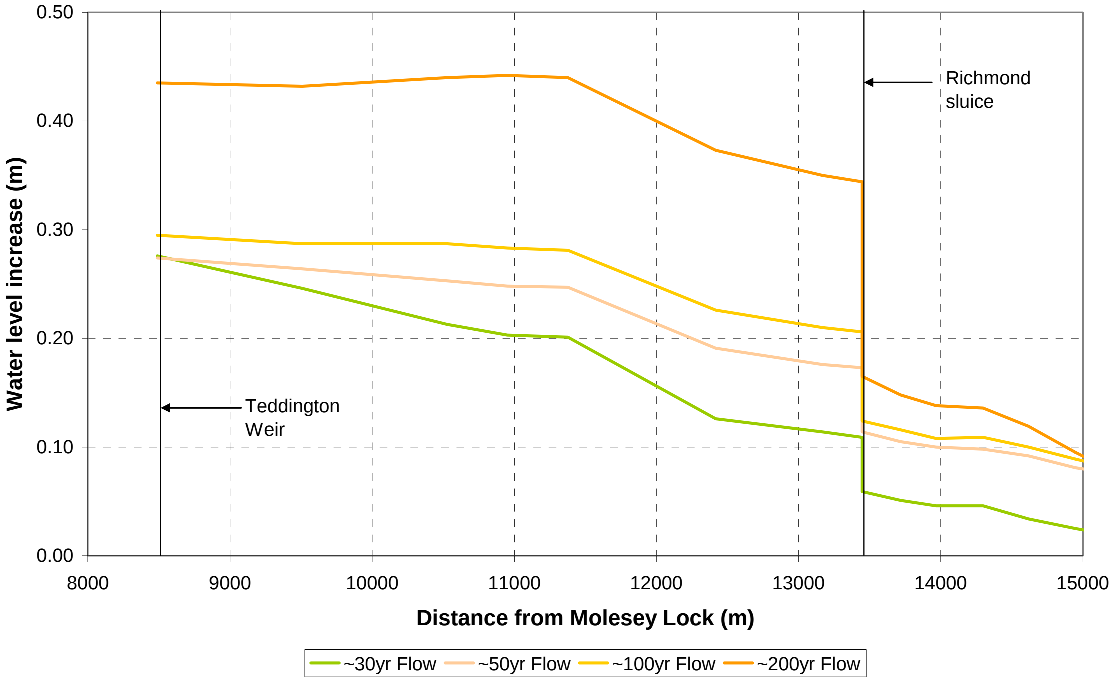

Figure F.6 Increase in water level due to climate change increase to flows of 20%

The required increases to defence levels for improving the future standard of protection for fluvial flows in West London are shown in Figure F.7.

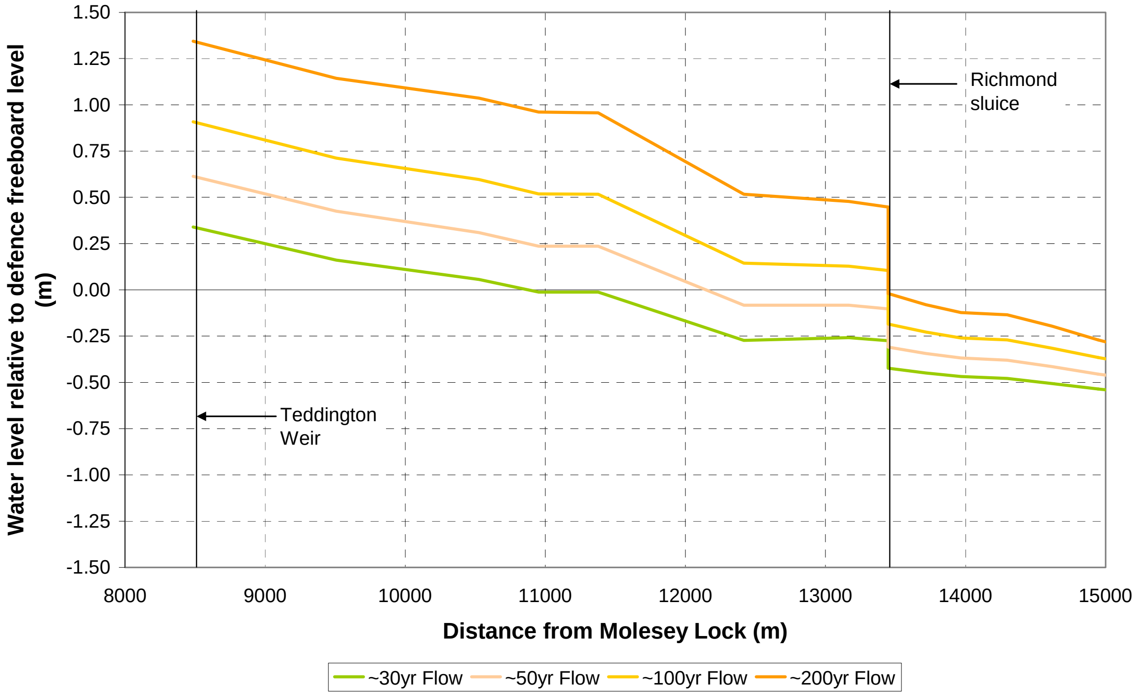

Figure F.7 Water levels relative to defence freeboard level for combinations of flow and tide for which the Thames Barrier is not closed. Fluvial return periods adjusted for climate change

Under the Defra 2006 climate change scenario the fluvial increases by 40% after 2065. If it is assumed that the closure rule of the Thames Barrier is not modified, then the return periods of the fluvial events for which the barrier is not closed are changed as follows:

- the present day 1 in 100 year flow becomes the future 1 in 30 year flow,
- the present day 1 in 300 year flow becomes the future 1 in 50 year flow,
- the present day 1 in 500 year flow becomes approximately the future 1 in 100 year flow.

To maintain present day defence standards (Policy P4) for fluvial flows in West London with climate change increase of 40% the defences must be raised by between 0.60m at Teddington and 0.75m at Richmond.

F.2.3 Maintain present day defence standard in the future with modifications to the barrier closure rule

If the design criteria to maintain the current standard of protection in the future with modifications to the barrier closure rule, then the defences must be raised equivalent to the increase in peak water level resulting from climate change and from the modification to the closure rule.

The Phase 3 Set 2 Options Reports showed that to maintain reliable operation of the Thames Barrier it would be necessary to modify the closure rule in 2065 so that the barrier is not closed for peak tides 0.5m greater than at present. Under the Defra 2006 climate change scenario the fluvial increases by 40% after 2065. Because of the change in barrier closure rule all the defences upstream of the barrier are raised by 0.5m to account for the increase in tide levels. Figure F.8 shows the increase in water levels as a result of modification to the closure rule and increased flow of 40% due to climate change.

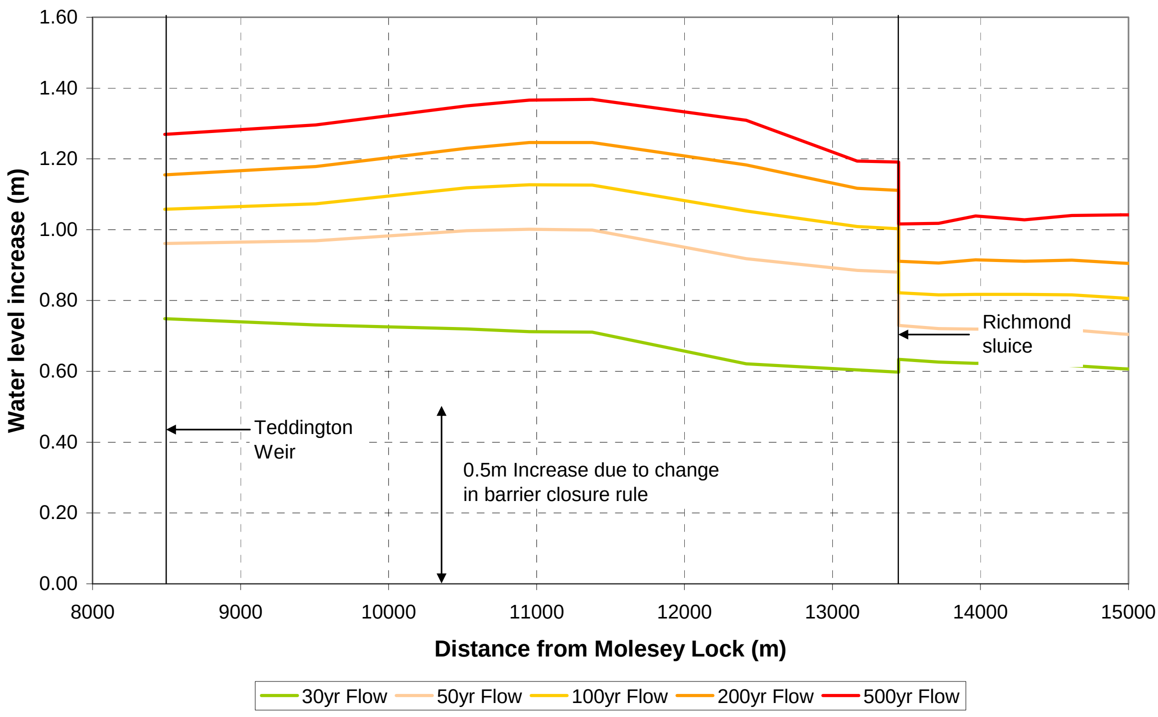

Figure F.8 Increase in water level due to modification to the barrier closure rule and climate change increase to flows of 40%

Figure F.8 shows that the increase in water level due to modification to the barrier closure rule and increase in flow of 40% is greater than the 0.5m the defences have been raised. Because the water levels for some of these events are greater than the design water levels at the defences under present day conditions (Figure F.3 and F.4) defence raising would be needed. The amount of raising is calculated by comparing the required design water level for a given standard of protection with the current design water level (defence crest level minus freeboard).

Figure F.9 shows the water levels for climate change with modification to the closure rule relative to the freeboard level of the defences in West London. The solid lines show the total increase and the dotted lines the additional increase above the generic 0.5m increase to defence crest levels.

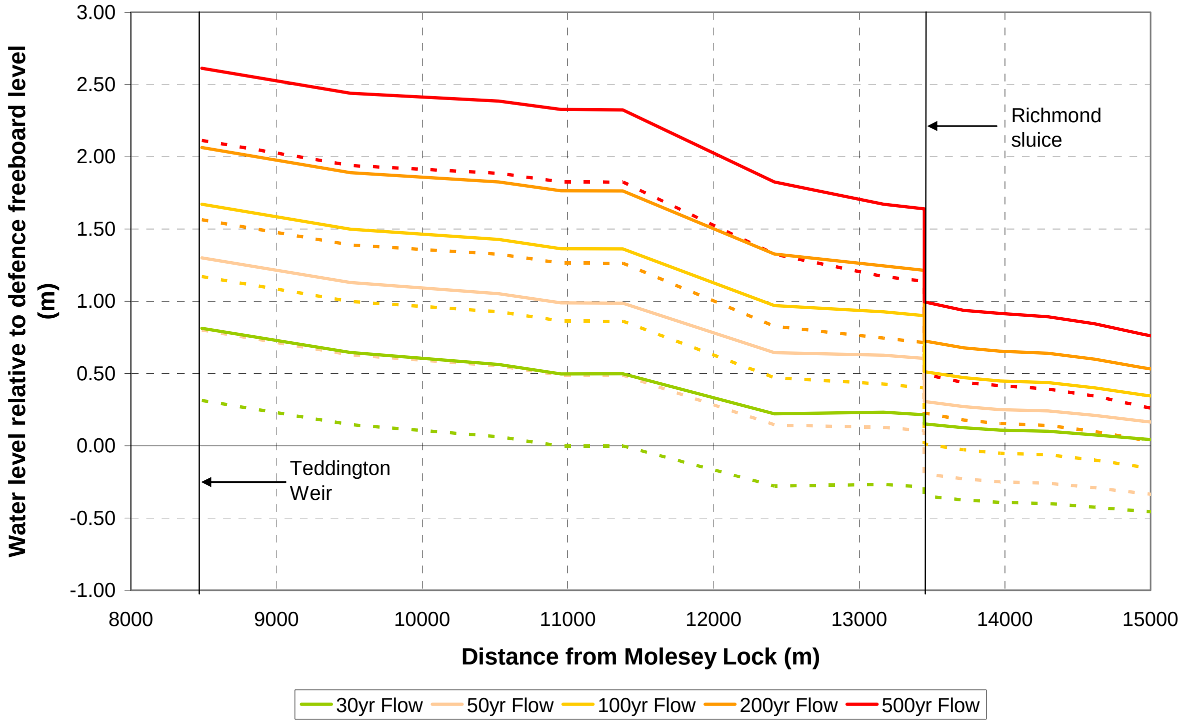

Figure F.9 Water levels relative to the freeboard level of the defences in West London for present day and for climate change with modification to the closure rule in 2065

This shows that to maintain the present day standard of protection in 2065 when the barrier closure rule has been modified the defence levels are raised by 0.5m. In West London the defences need additional increase in crest level of 0.3m at Teddington, 0.5m at Eel Pie Island, and 0.5m at Richmond to maintain present day standards.

Note that an additional 0.5m increase to defence crest level is required downstream of Richmond Sluice to the River Brent. A total increase in defence level of 1m is therefore required upstream of Brentford in 2065.

The Phase 3 Set 2 Options Reports showed that to maintain reliable operation of the Thames Barrier it would be necessary to modify the closure rule in 2100 so that the barrier is not closed for peak tides 1.0m greater than at present. Because of the change in barrier closure rule all the defences upstream of the barrier are raised by 1.0m to account for the increase in tide levels. Figure F.10 shows the water levels relative to the freeboard level of the defences in West London for climate change with modification to the closure rule.

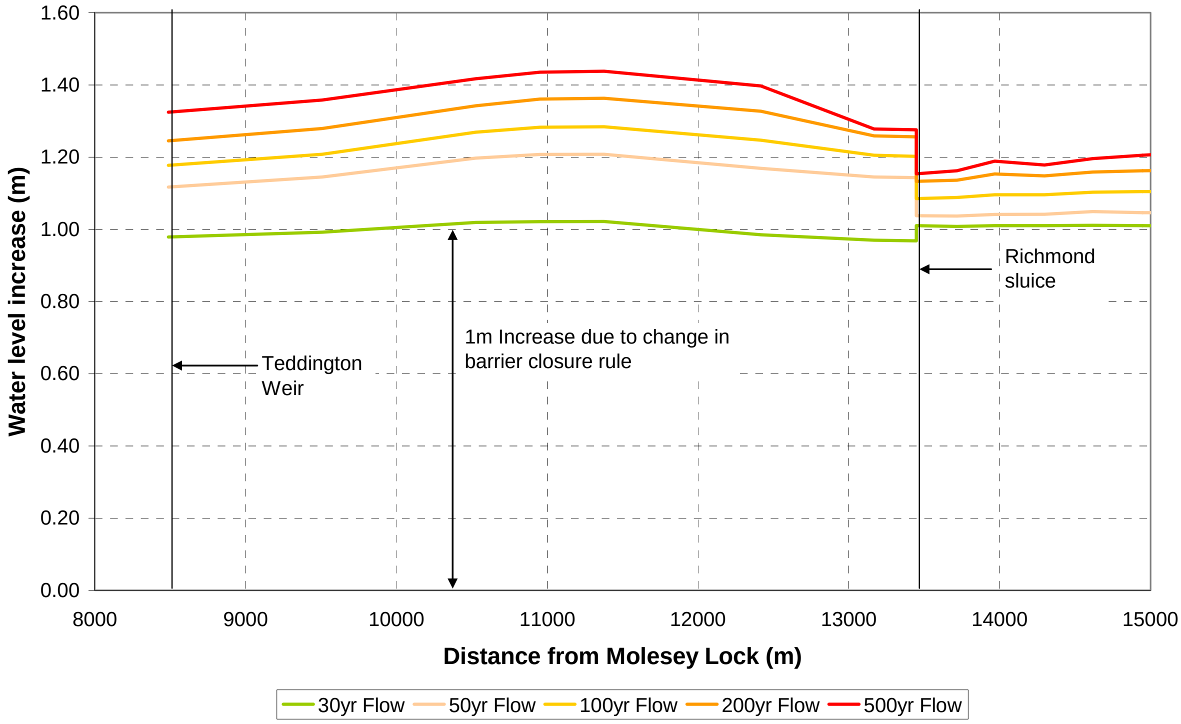

Figure F.10 Increase in water level due to modification to the barrier closure rule and climate change increase to flows of 40%

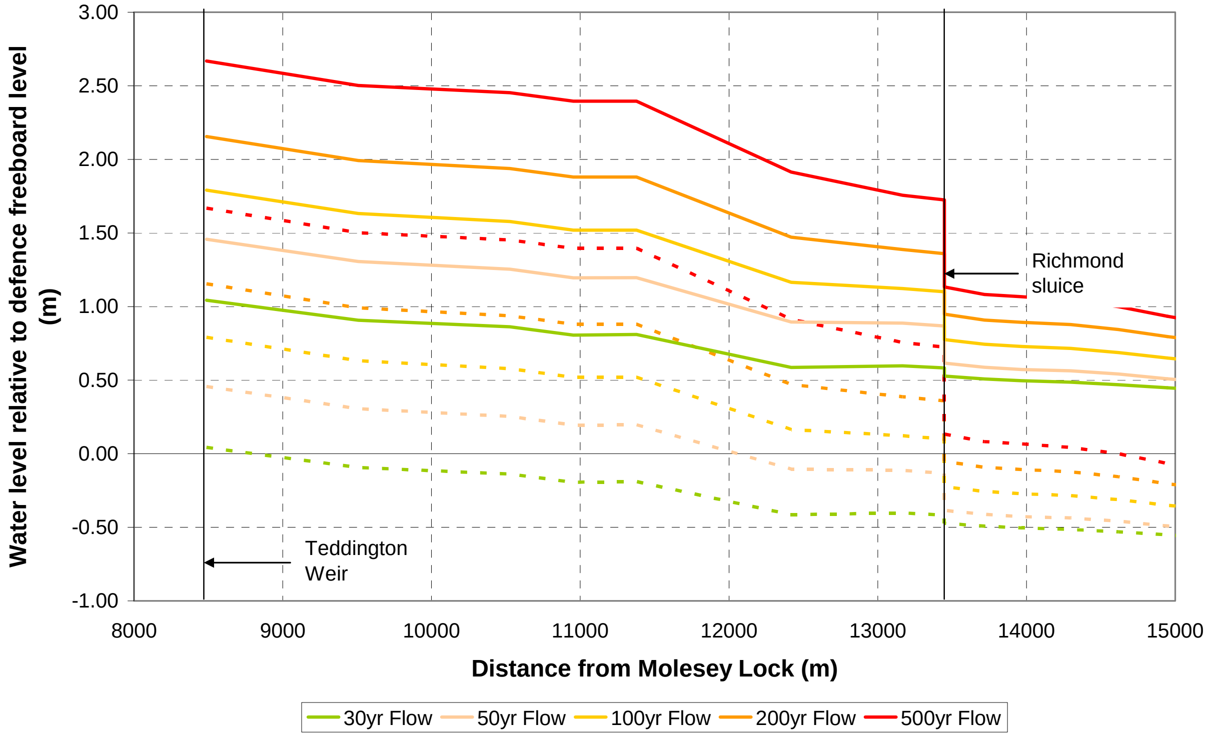

Figure F.11 Water levels relative to the freeboard level of the defences in West London for present day and for climate change with modification to the closure rule in 2100

Figure F.10 shows that the increase in water level due to modification to the barrier closure rule and increase in flow of 40% is greater than the 1.0m the defences have been raised. Because the water levels for some of these events are greater than the freeboard level of the defences under present day conditions (Figure F.3 and F.4) the water levels are compared to the freeboard level of the defences to calculate the defence raising required for a given standard in West London.

Figures F.10 and F.11 shows that the increase in defence levels of 1m required for modification of the barrier closure rule accounts for the increase of 40% in fluvial flow at Teddington. Additional defence raising of 0.2 to 0.3m above this 1m increase is required to maintain the present day standard in West London between Eel Pie Island and the River Crane. Figure F.11 shows the water levels relative to the freeboard level of the defences in West London for present day and for climate change with modification to the closure rule. The solid lines show the total increase and the dotted lines the additional increase above the generic 1m increase to defence crest levels.

Note that this additional 0.3m increase to defence crest level is required downstream of Richmond Sluice to the River Brent. A total increase in defence level of 1.3m is therefore required upstream of Brentford in 2100.

F.3 Managed realignment at Ham Lands

Cross sections in the 1D model at Ham Lands have been extended and regions of high ground removed, as detailed in the Topic 4.6 report. The model has been run for the range of events for which the Thames Barrier is not closed, and the resulting water levels compared to those from the base runs in Figure F.12.

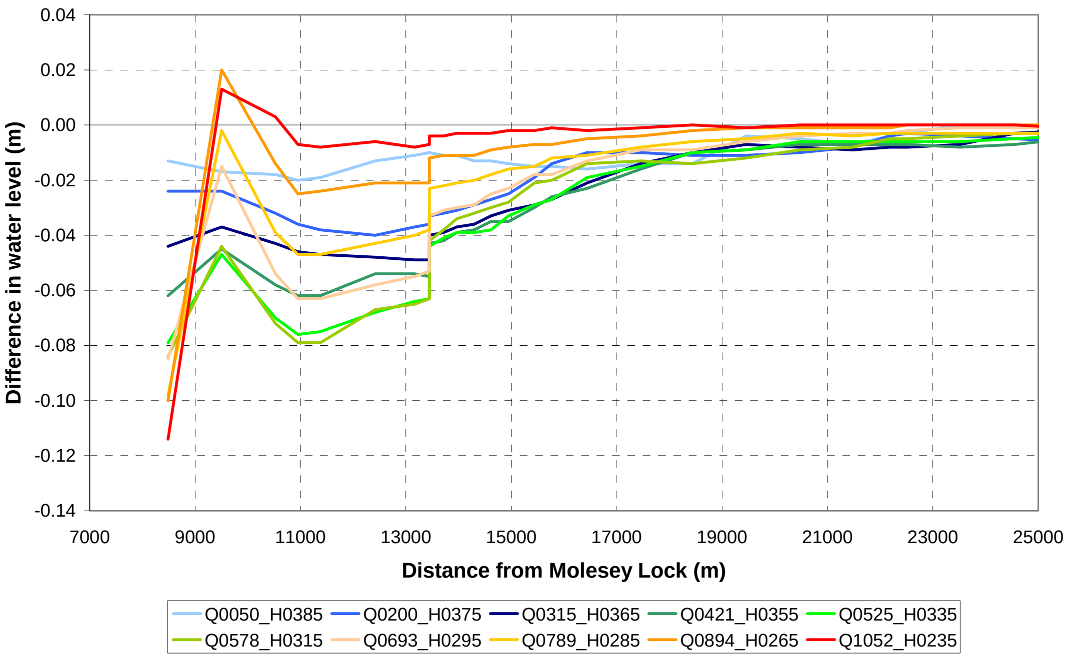

Figure F.12 Impacts of managed realignment at Ham Lands on flood water levels

This shows that maximum reductions in peak water level are small in the Teddington to Richmond reach, and there is little or no reduction at node 2.2. The managed re-alignment at Ham Lands only produces a small increase in standard of protection over present day conditions. It should also be noted that when the Thames Barrier is closed there is no discernable reduction in peak water levels.

In terms of mitigation against climate change this response is likely to have little impact. This is because the impact of a 20% increase in flow is to make the present day 1 in 50 year flow become the future 1 in 30 year flow, and the present day 1 in 100 year flow become the future 1 in 50 year flow. For the 1 in 30 year flow this corresponds to a 0.3m increase in water level at Teddington, and for the 1 in 200 year flow this corresponds to a 0.15m increase in water level at Richmond. These increases in water level due to climate change are at least 3 times greater than the reductions in water level that can be achieved by the managed realignment.

F.4 Managed realignment at Barnes

Cross sections in the 1D model at Barnes have been extended and regions of high ground removed, as detailed in the Topic 4.6 report. The model has been run for the range of events for which the Thames Barrier is not closed, and the resulting water levels compared to those from the base runs in Figure F.13.

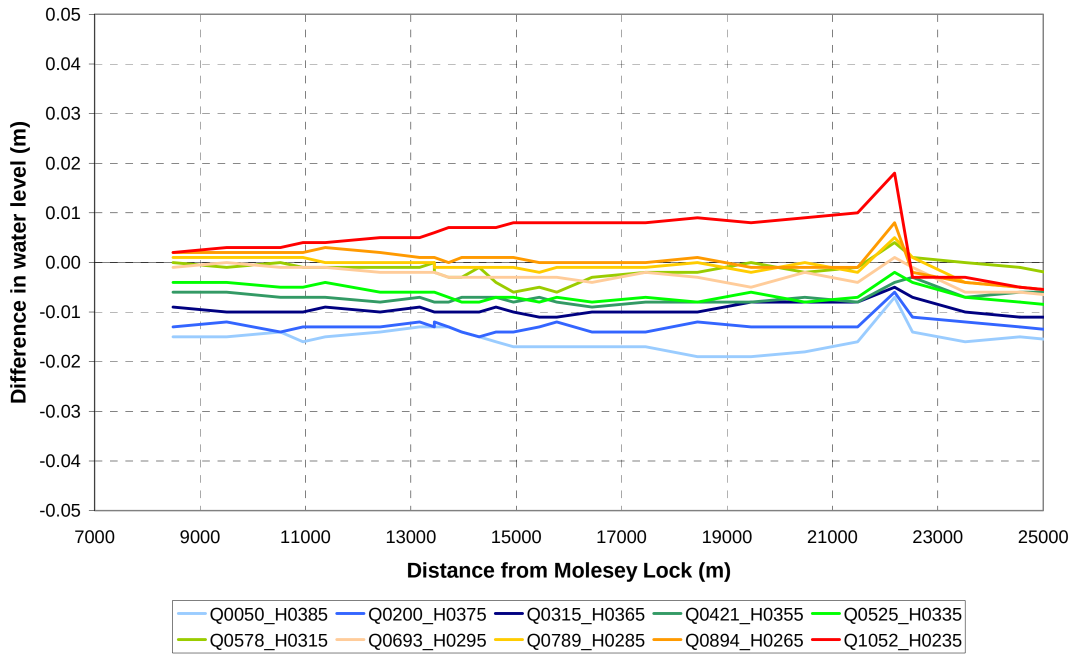

Figure F.13   Impacts of managed realignment at Barnes on flood water levels

This shows that changes in peak water level as a result of the managed re-alignment at Barnes are small. For the majority of events for which the Thames Barrier is not closed there is a reduction in peak water level of approximately 1cm. For the largest flow event there is an increase in water level between Richmond and Hammersmith of approximately 1cm. This managed re-alignment has no impact on the defence standards in the West London reach.

F.5 Flood storage at Grove Park and Kew

Topic 4.6 identified two areas for flood storage in West London, one at Grove Park and the other at Kew. These areas are relatively small and are in the reach where the flow and tide combine to produce peak water levels. The Pilot Portfolios showed that flood storage at Barnes and Battersea Park in the more tidally influenced reach were reasonably effective at reducing peak water levels.

The flood storage areas identified by Topic 4.6 have been included in the 1D model, which has been run for a range of events for which the Thames Barrier is not closed. Because of the multiple events that influence peak water levels in West London calibration of spill lengths and crest levels proved difficult. Differences in peak water level between the storage model with crest level at 4m AOD and crest length of 50m and the base model are shown in Figure F.14. This shows that upstream of Hammersmith the storage has a small reduction in peak water level of less than 0.1m, downstream of Hammersmith there is an increase in water level for some events.

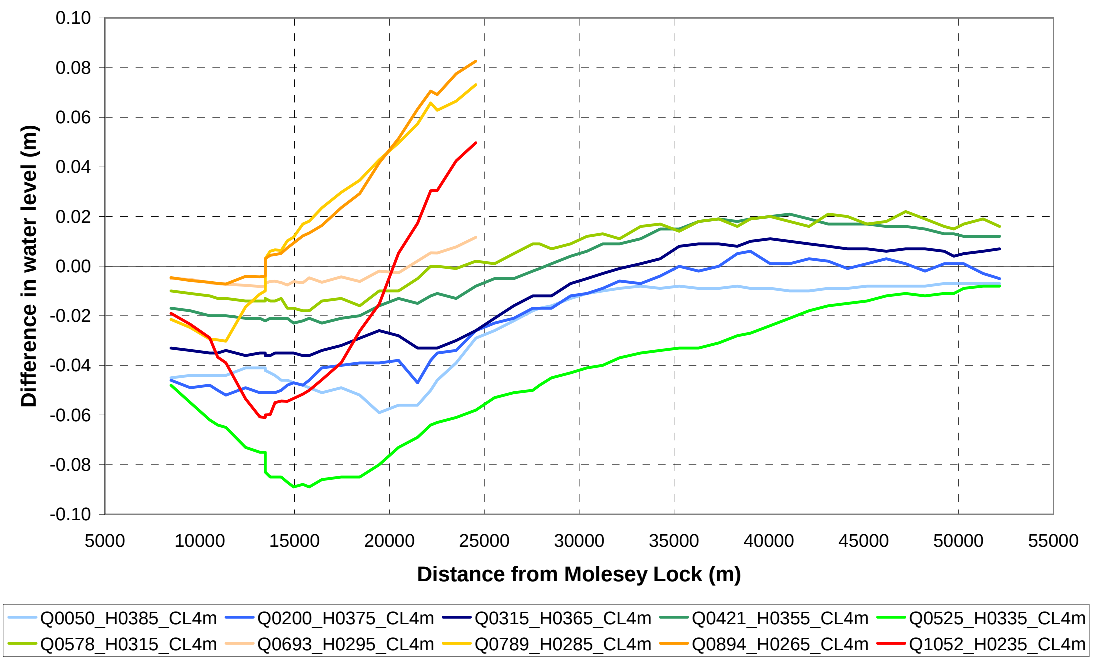

Figure F.14 Impacts of flood storage at Grove Park and Kew on flood water levels

The modelling shows that the volume of available storage is too small to cause significant reductions in peak water level. The maximum water level in the river (hence in storage) is between 4.5 and 5m AOD. At these water levels approximately 50% of the total area of the flood storage areas is available because the ground levels are too high in some parts of the storage areas. To increase the volume that can be stored, the flood storage areas need to be excavated down to around 3m AOD.

In the HLO Pilot Portfolios flood storage was modelled at Barnes and Battersea Park. This showed that reductions in water level of 0.35m could be obtained. Flood storage at Battersea Park is not feasible due to environmental / historical / cultural constraints. The impact of the Barnes storage on river water levels is likely to be in the order of 0.1 to 0.2m reduction. The Barnes flood storage area has been modelled on its own for the same range of events as the Topic 4.6 storage areas and the results are shown on Figure F.15.

This modelling shows maximum reductions of around 0.1m for present day events for which the barrier is not closed. This storage are has little impact on peak water levels associated with large fluvial flows, and therefore would not be used to increase present standards of defence for West London. The usefulness of this storage area is to reduce future water levels if the barrier closure rule is modified.

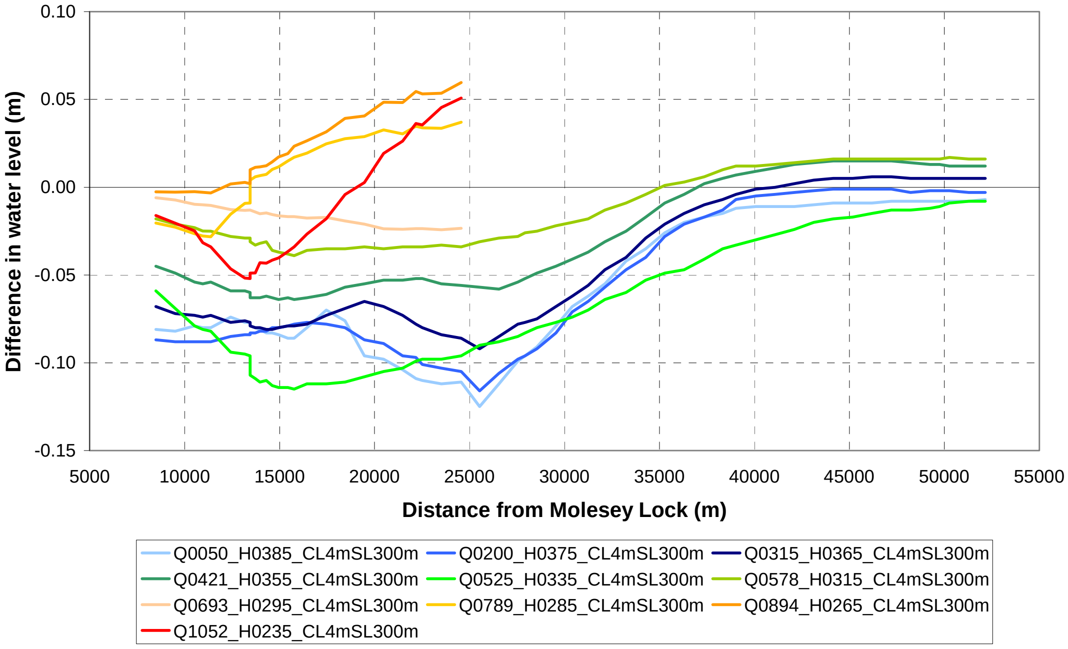

Figure F.15 Reduction in water level due to flood storage at Barnes
(Note: Hammersmith is about 24000m from Molesey)

F.6 Other conveyance options

In the HLOs improvements to conveyance were made by modifying the Richmond Sluice and Teddington Weir structures. The results were as follows:

- Modifying the operation of Richmond Sluice was shown to have reduction in water level of less than 0.1m.
- Removal of the sluice was shown to reduce water levels by between 0.15 and 0.1m.
- Removal of the sluice and Teddington Weir was shown to reduce water levels by between 0.25 and 0.15m in West London.

Removal of Richmond Sluice and Teddington Weir has been rejected in Topic 4.6 due to the environmental / historical / cultural value of the structures. The modelling of the modified Richmond Sluice assumed that the sluice gates could be lifted clear of the water.

F.7 Summary

The design criteria for the increase in fluvial flow is an increase by 20% from 2025 and 40% from 2065. The current Standard of Protection for fluvial flows provided by the defences is 3% per annum (1:30) at Teddington and 0.7% per annum (1:150) at Richmond.

The managed realignment and flood storage options identified in Topic 4.6 are shown to have little impact on peak water levels in West London, especially when compared to the increase in water level due to increased flow from climate change. These interventions are not able to achieve a P4 policy to maintain the current Standard of Protection.

Defence raising interventions in West London to achieve a P4 policy are as follows:

- For generic estuary wide options 1, 2, and 3, raise the defences by 0.5m in 2065 and 1.0m in 2100 to manage tidal flooding with fluvial influence. This is included in the total amount of raising given below.

- No defence raising is required for tidal flood management in generic estuary wide option 4 (barrier with locks).

- For generic estuary wide options 1, 2, and 3, raise the defences by the following amounts to manage fluvial and tidal flood risk:
    - 2025: 0.3m between Teddington and Richmond.
    - 2065: total of 1.0m between Teddington and Brentford. This includes the 2025 raising for fluvial flood risk, and the 0.5m raise required in 2065 for tidal flood management.
    - 2100: further raising of 0.3m between Teddington and Brentford. This gives a total raise of 1.3m of which 1.0m is needed for tidal flood management.

- For generic option 4 (barrier with locks), raise defence by the following amounts to manage fluvial flood risk:
    - 2025: 0.3m between Teddington and Richmond.
    - 2065: total of 0.8m between Teddington and Brentford. This includes the 2025 raising given above.
    - 2100: no further raising needed.

Annex G Hydraulic impacts of Barriers

Outline hydraulic design of barrier options was carried out in the Phase 3 Set 1 Options, to determine gate numbers, widths and sill levels. Outline designs for barriers and barrages were then developed based on these hydraulic designs (Phase 3 studies, Topic 5.5).

The new barrier structures in Long Reach or Tilbury cause a constriction in the estuary compared to present day conditions. The structures have been modelled using a tide with a peak level of 3m AOD at Southend and the barrier gates open to identify impacts of the structures on upriver water levels under normal conditions.

The gate configurations were modified in the final options after this modelling was carried out. However there is little change to the overall opening areas.

G.1 Tilbury Barrier

The gate dimensions of the Tilbury Barrier used in this analysis were as follows:

2 gates 100m wide with sill level at -12m,
2 gates 100m wide with sill level at -8m,
4 gates 50m wide with sill level at -6m.

With the gates open the flow area for a 3m tide at Southend is about 7,160m^2 compared to the no structure flow area of 8,700m^2. The impact on peak water level upstream of the barrier is shown in Figure G.1.

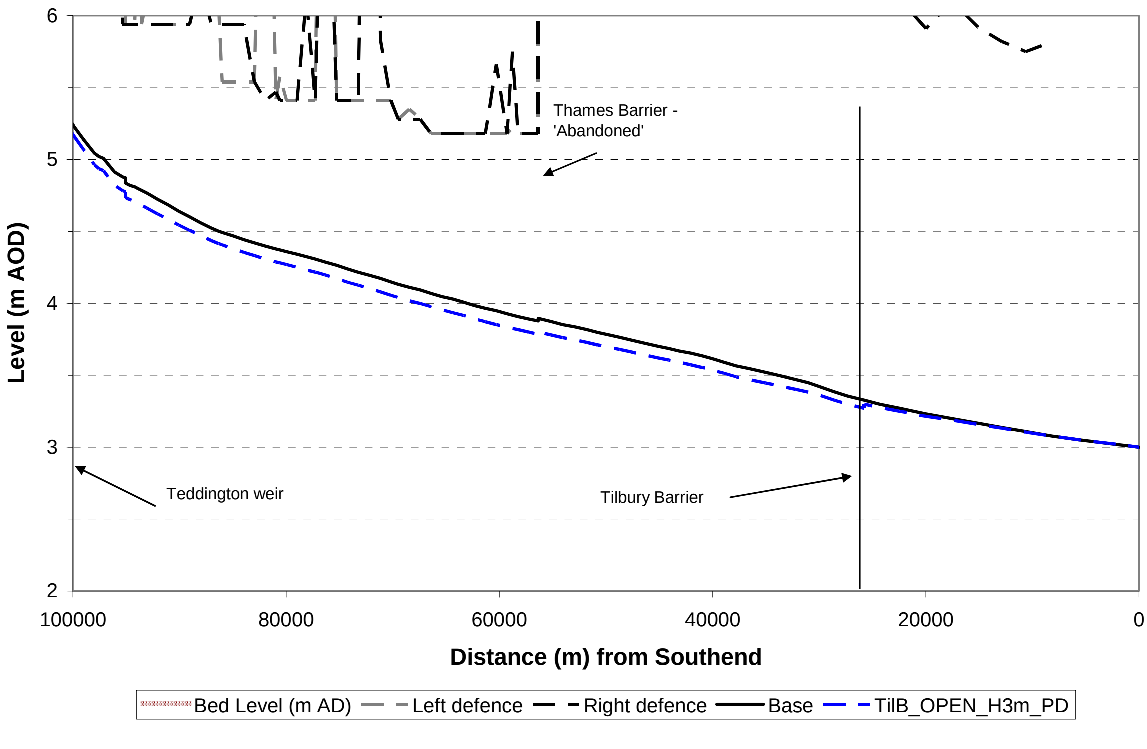

Figure G.1 Peak water level for a 3m tide at Southend with and without the Tilbury Barrier

The impact on the tide shape upriver of the structure is shown on Figure G.2a and the impact on the tide shape at Hammersmith is shown on Figure G.2b. These figures show that the peak tide level upriver of the barrier is reduced by approximately 0.1m. The level at low tide is increased by less than 0.1m immediately upriver of the barrier.

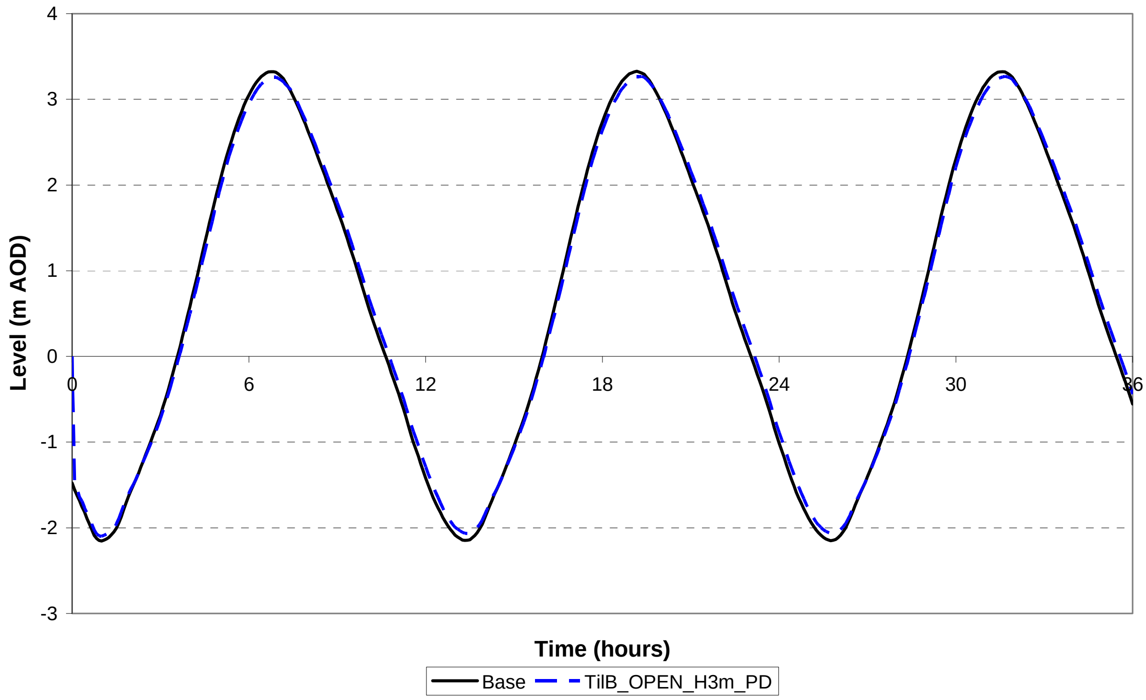

Figure G.2a Water levels upriver of the Tilbury Barrier

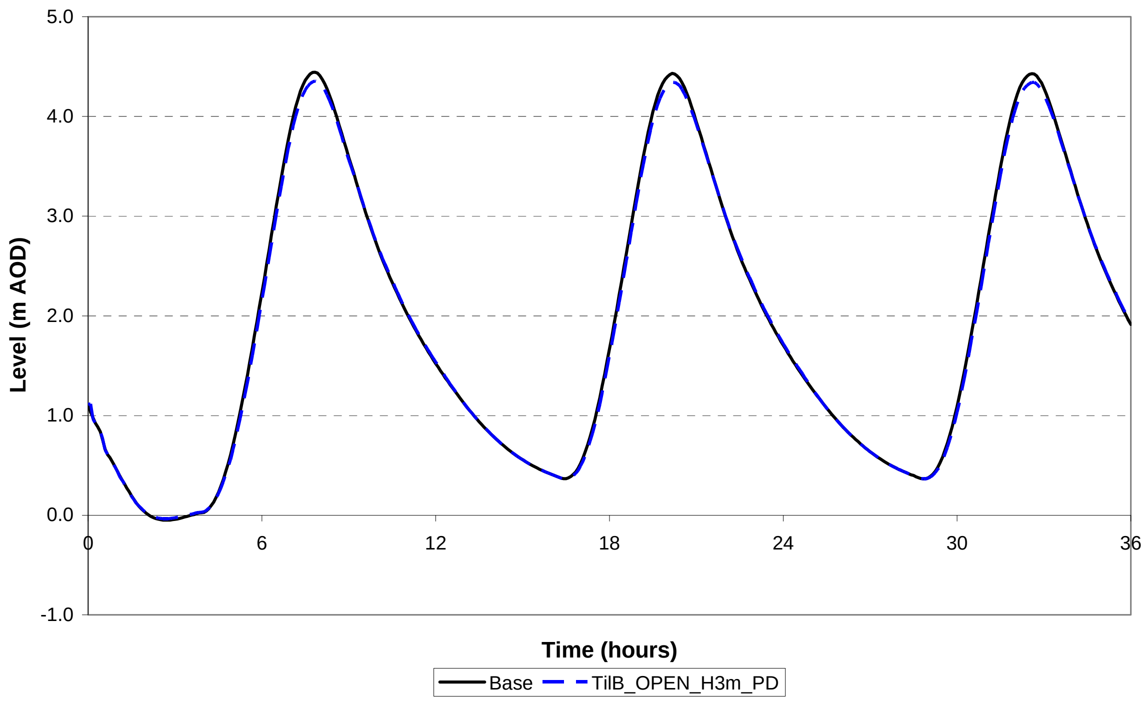

Figure G.2b Water levels at Hammersmith upriver of the Tilbury Barrier

The velocity at the structure is increased by approximately 0.2m/s.

G.2 Long Reach Barrier

The gate dimensions of the Long Reach Barrier were as follows:

2 gates 80m wide with sill level at -10m,
2 gates 50m wide with sill level at -9m,
4 gates 25m wide with sill level at -5m.

With the gates open the flow area for a 3m tide at Southend is about 4,260m^2 compared to the no structure flow area of about 8,000m^2. The impact on peak water level upriver of the barrier is shown in Figure G.3.

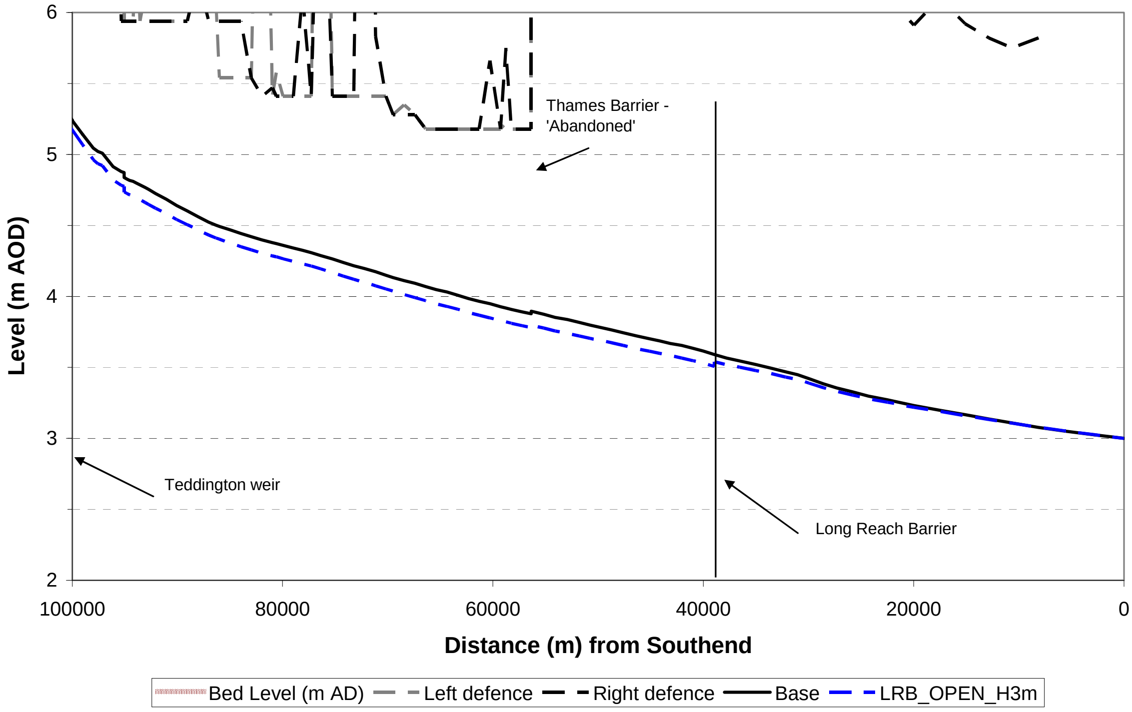

Figure G.3 Peak water level for a 3m tide at Southend with and without the Long Reach Barrier

The impact on the tide shape upriver of the structure is shown on Figure G.4a and the impact on the tide shape at Hammersmith is shown on Figure G.4b. These figures show that the peak tide level upriver of the barrier is reduced by approximately 0.1m. The level at low tide is increased by approximately 0.1m immediately upriver of the barrier.

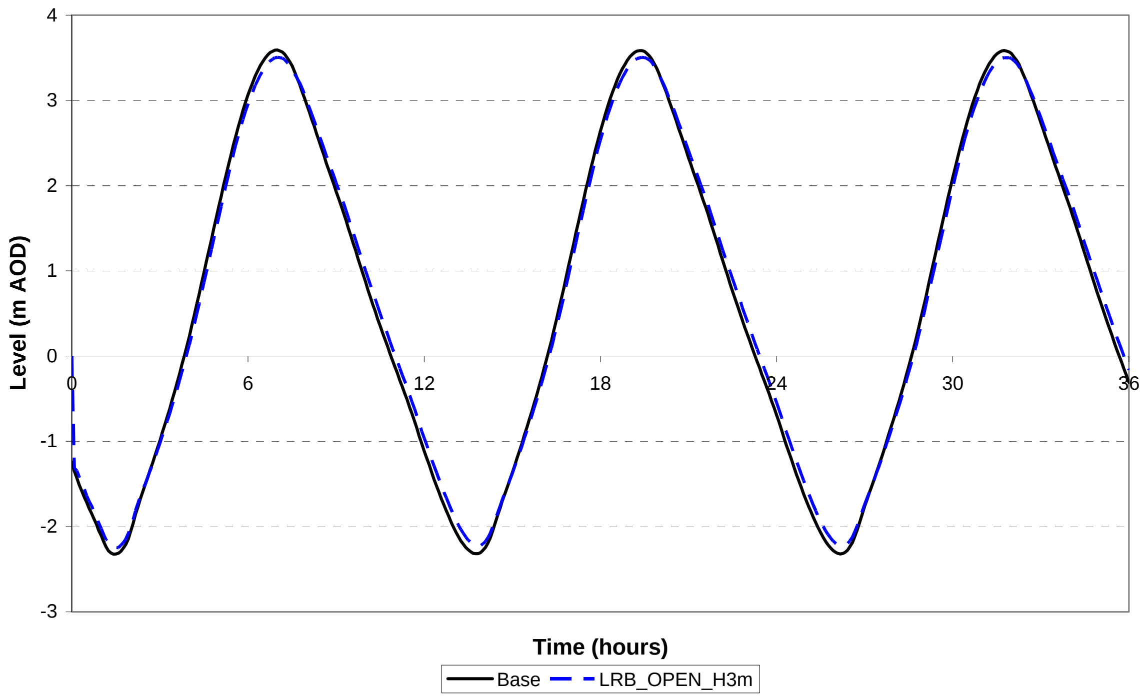

Figure G.4a Water levels upriver of the Long Reach Barrier

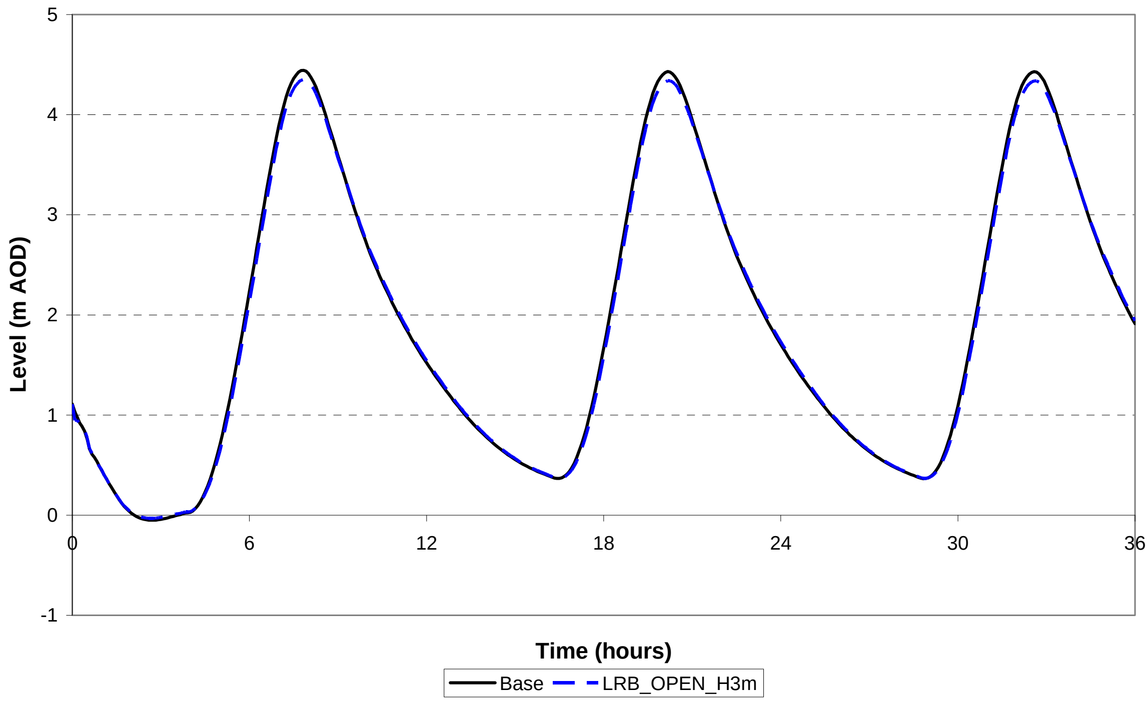

Figure G.4b Water levels at Hammersmith upriver of the Long Reach Barrier

The velocity at the structure is increased by approximately 1m/s.

G.3 Tilbury Barrier with locks

The gate dimensions of the Tilbury Barrier with locks are as follows:

2 gates 100m wide with sill level at -12m,
1 gate 100m wide with sill level at -8m,
4 gates 30m wide with sill level at -8m,
6 gates 30m wide with sill level at -6m.

With the gates open the flow area for a 3m tide at Southend is about 7,160m^2 compared to the no structure flow area of about 8,700m^2. The impact on peak water level upriver of the barrier with locks is shown in Figure G.5.

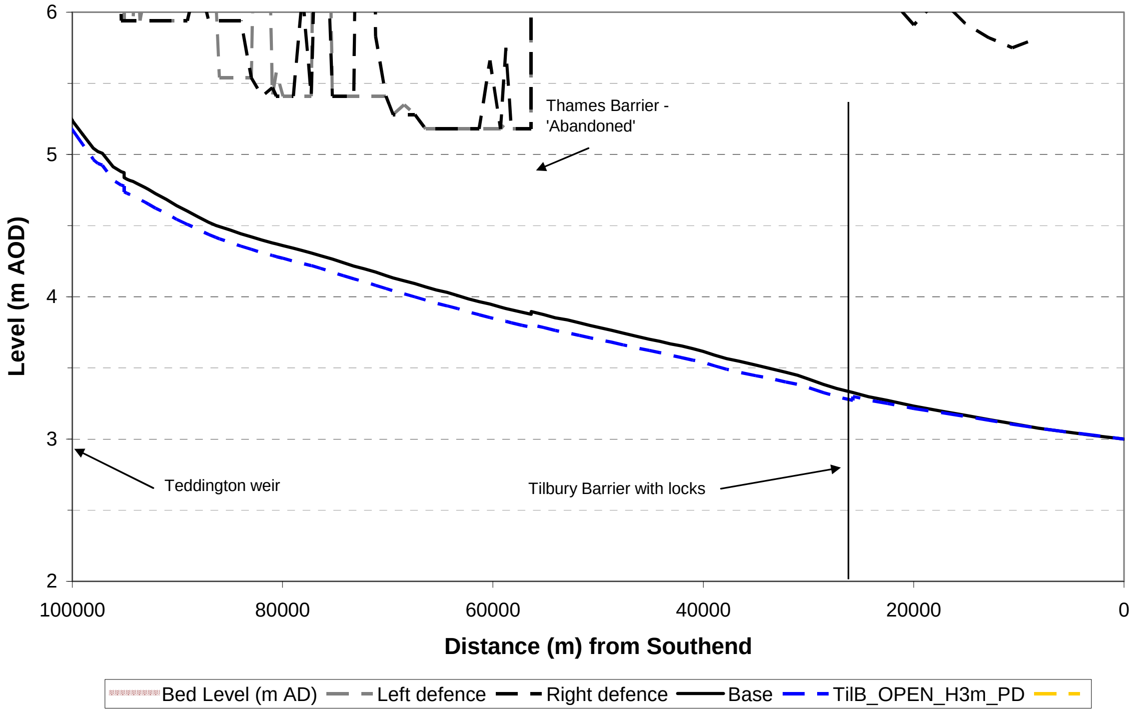

Figure G.5 Peak water level for a 3m tide at Southend with and without the Tilbury Barrier with locks

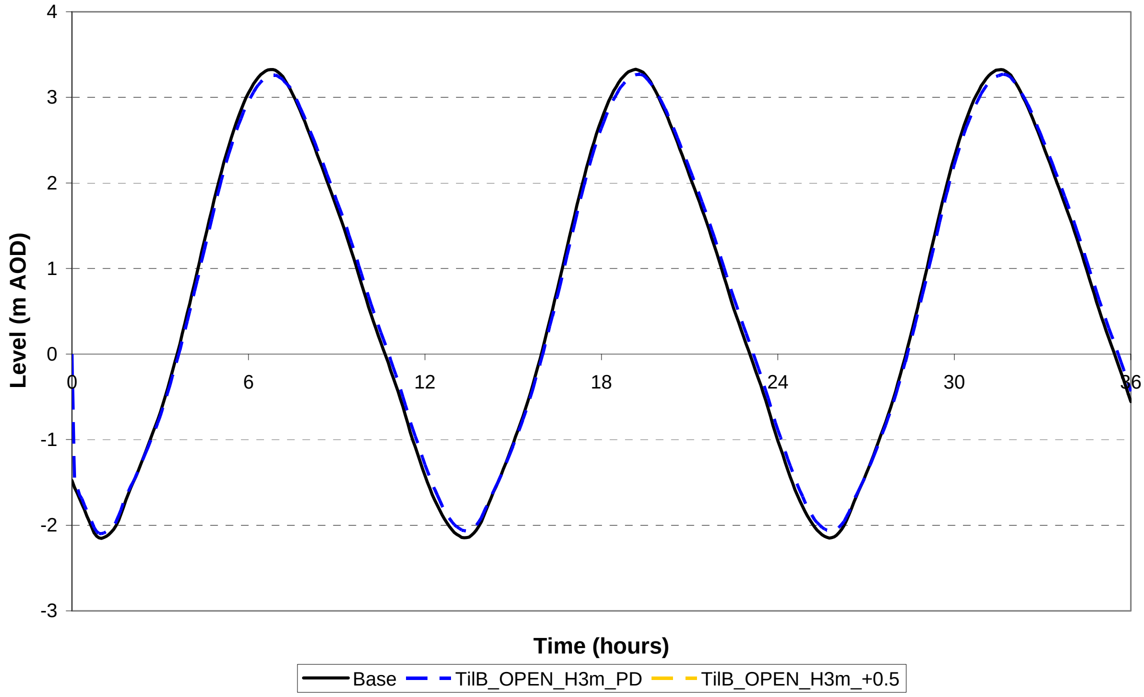

Figure G.6a Water levels upriver of the Tilbury Barrier with locks

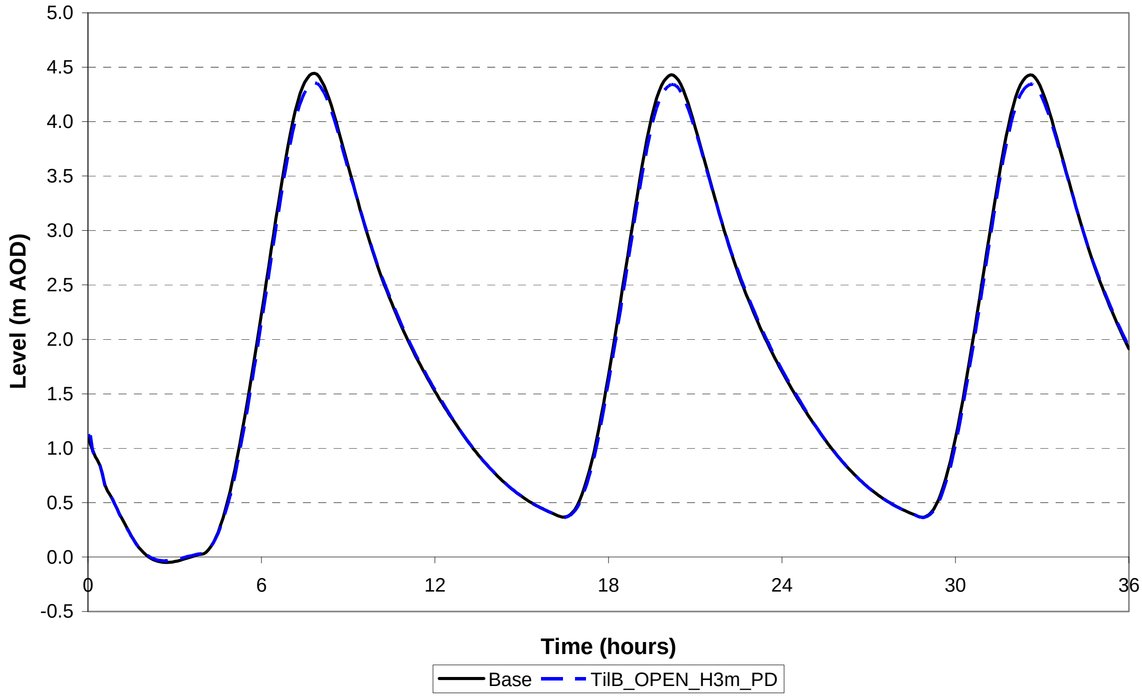

Figure G.6b Water levels at Hammersmith upriver of the Tilbury Barrier with locks

The results are very similar to those for the Tilbury Barrier, as the flow area is very similar.

G.4 Long Reach Barrier with locks

The gate dimensions of the Long Reach Barrier with locks are as follows:

3 gates 80m wide with sill level at -10m,
2 gates 20m wide with sill level at -6m.

With the gates open the flow area for a 3m tide at Southend is about 3,600m^2 compared to the no structure flow area of 8,000m^2. The impact on peak water level upriver of the barrier is shown in Figure G.7. When one of the 80m wide navigation gates is closed, the flow area reduces to about 2,500m^2.

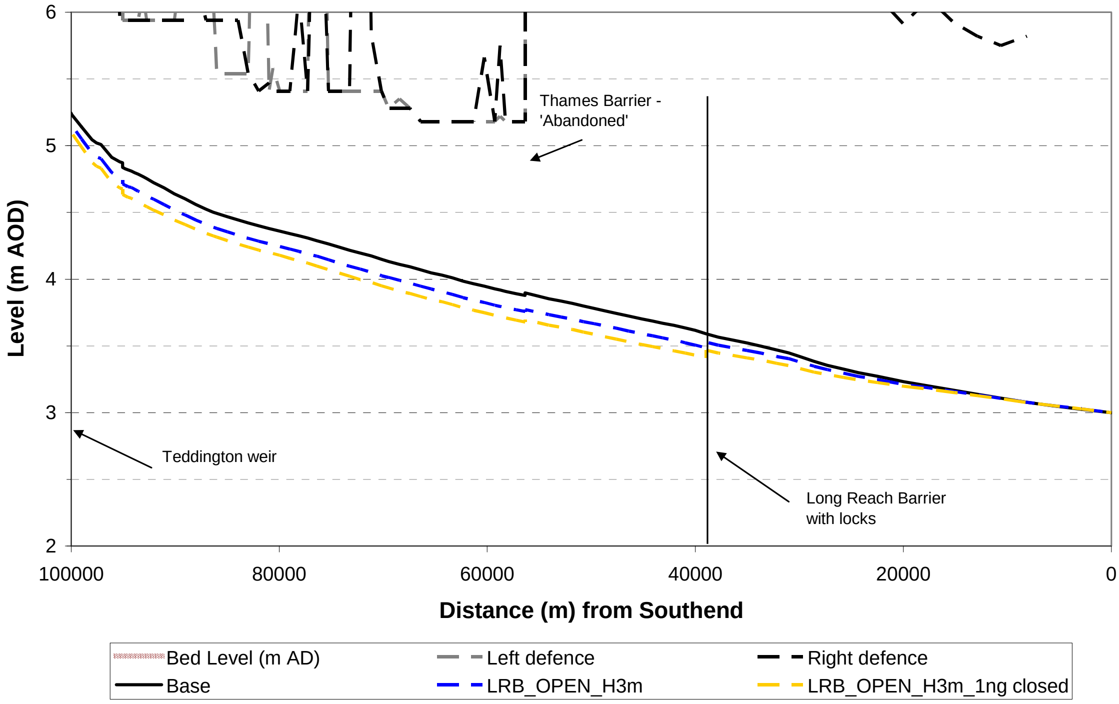

Figure G.7 Peak water level for a 3m tide at Southend with and without the Long Reach Barrier with locks

Figure G.7 shows that peak water levels upriver of the barrier with locks are reduced by approximately 0.1m. If one of the 80m wide navigation gates is closed for maintenance, the peak water levels are reduced by approximately 0.2m.

The impact on the tide shape upriver of the structure is shown on Figure G.8a and the impact on the tide shape at Hammersmith is shown on Figure G.8b. The level at low tide is increased by approximately 0.1m immediately upriver of the barrier. With one of the 80m wide navigation gates closed the low tide level is increased by approximately 0.2m immediately upriver of the structure.

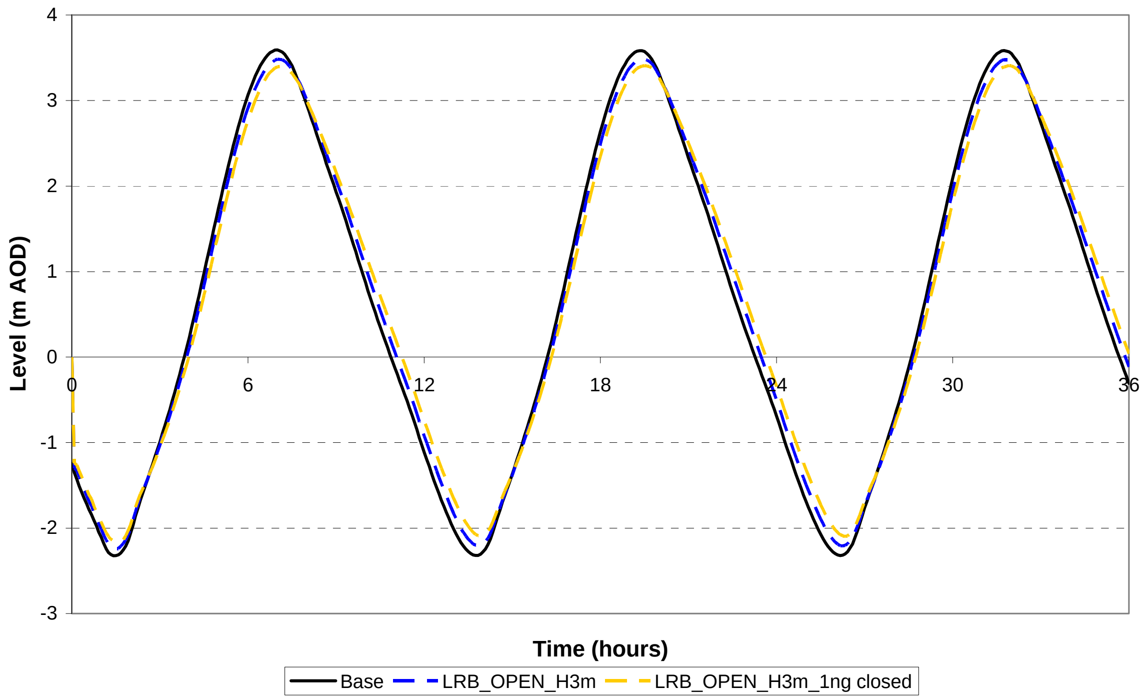

Figure G.8a Water levels upriver of the Long Reach Barrier with locks

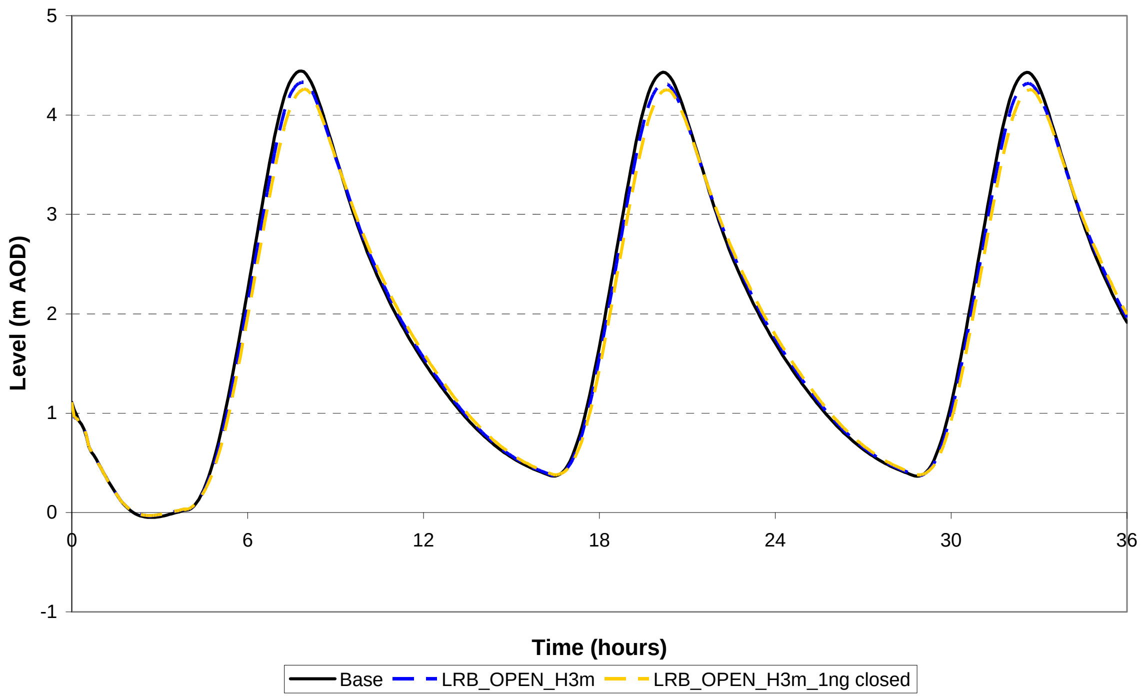

Figure G.8b Water levels at Hammersmith upriver of the Long Reach Barrier with locks

The velocity at the structure is increased by approximately 1.4m/s to a peak of 2.35m/s. This may be too great for ships to pass through the barrier openings safely. With one of the 80m wide navigation gates closed the velocity is increased by 2.4m/s, to a peak of 3.37m/s, which may be too great for ships to safely pass through the barrier openings.

Annex H Thames Barrier gate failure

The reliability of the Thames Barrier is important for the standard of protection it provides for upstream embayments. The barrier crest level provides protection for the 10,000 year tide under present day conditions. The SoP of the Thames Barrier when taking into account the probability of failure is determined by the number of barrier closures.

Operational limits are therefore imposed on the Barrier to meet the required SoP. For example if the probability of failure is 1 in 10,000 closures, to maintain a SoP of 1 in 10,000 years there would only be one closure a year. As the number of closures increases, the reliability must also be increased.

There is likely to be different probabilities of failure for different combinations of the gates that make up the barrier. The barrier has 4 large gates that are 61m wide with a sill level at -9m AOD, 2 smaller gates that are 31.5m wide with a sill level at -6m AOD, and 4 gates that are 31.5m wide with a sill level at 0m AOD. The area of opening in the 1,000 year tide in 2100 under the Defra '06 climate change scenario for all gates is 5165 m^2.

The model has been run for the following combinations of gates open:

- 1 large 61m wide gate (open area of 885 m^2)
- 4 large 61m wide gates (open area of 3,650 m^2)
- 1 medium 31.5m wide gate (open area of 340 m^2)
- 2 medium 31.5m wide gates (open area of 720 m^2)
- 1 small 31.5m wide gate (open area of 120 m^2)
- 2 small 31.5m wide gates (open area of 290 m^2)
- 4 small 31.5m wide gates (open area of 680 m^2)
- All gates open (open area of 5,165 m^2)

Figure H.1 shows the change in maximum water level at the River Lee (upstream of the Thames Barrier) for these combinations of gates. Figure H.2 shows the impact on flood levels along the estuary.

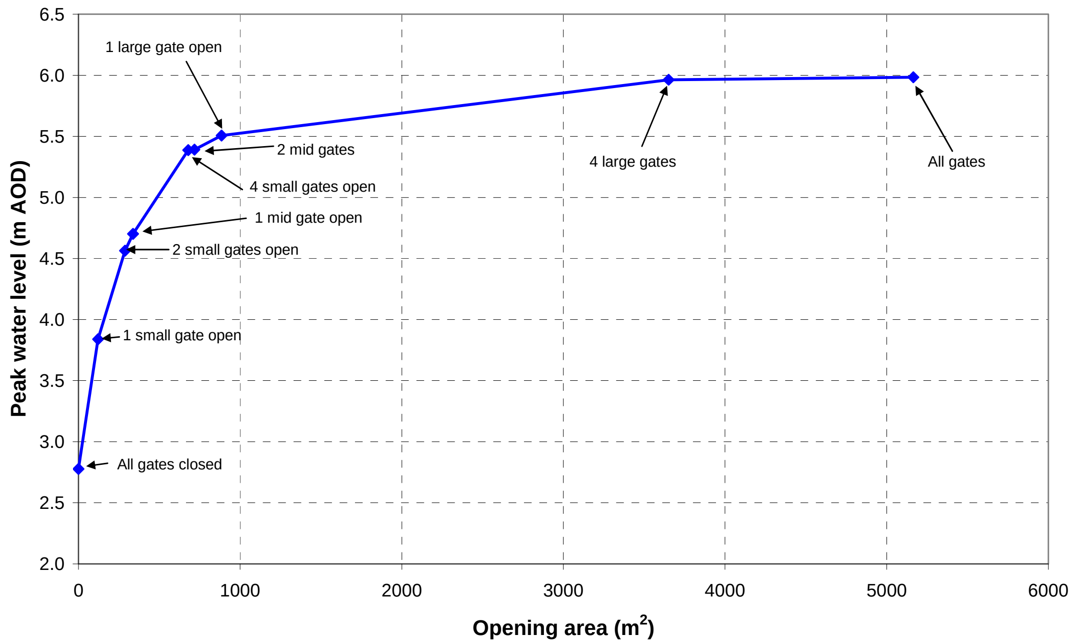

Figure H.1 Maximum water level upriver of the Thames Barrier
Defra '06 1,000 year tide in 2100 with a flow of 400 m^3/s with different combinations of open gates

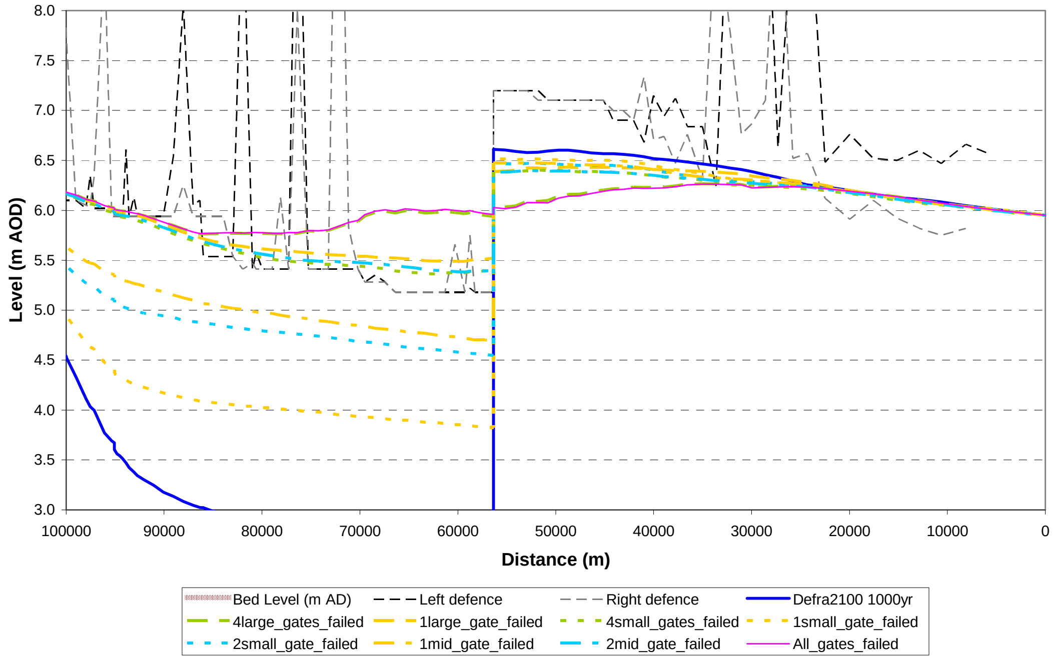

Figure H.2 Long profile of maximum water levels

Defra '06 1,000 year tide in 2100 with a flow of 400 m^3/s with different combinations of open gates.

The main conclusions are as follows:

- Failure of the four large gates to close produces similar upriver water levels to the Barrier open case. In this case the water levels upstream of the Thames Barrier are greater than the defence levels and would cause flooding.

- Similar upstream water levels occur if any of the following gate combinations fail:

    - The 4 small gates
    - One of the large gates
    - Two of the medium sized gates.

  The headloss across the Barrier for these three cases is about 0.5m. Whilst there would be a large increase in upriver flood risk if these gates failed, it would be less than the Barrier open case.

Failure of up to 2 of the small gates or 1 of the medium sized gates is unlikely to cause upriver flooding.

Figure H.2 shows the large headlosses that would occur at the Barrier if one or more gates failed. The figure also shows the water levels that would occur if the Thames Barrier was left open, taking account of the flooding that would occur and the consequent reduction in water levels.

Annex I Flood risk management on tributaries

I.1 Introduction

Flood risk management on tributaries is a local issue and does not form part of the estuary wide options. However there is a high level of flood risk associated with some of the tributaries. Potential flood risk management responses have been identified in earlier studies (particularly the High Level Options and Phase 3 studies Topic 4.5).

In addition to present day flood risk, the climate change studies indicate that fluvial flows could increase by 40% in the next 100 years. This annex considers the potential flood mitigation works that might be required for this increase in flow for tributaries of the tidal Thames.

I.2 River Crane

Potential flood mitigation measures include a combination of flood storage and defence raising. Figure I.1 shows the 1 in 100 year flow with and without the 40% increase due to climate change. The area shaded with green lines indicates the volume of water that would need to be stored to mitigate against the impact of climate change.

The area shaded in blue shows the volume of water that would need to be stored to prevent climate change increasing the peak flow and hence the peak flood water level in the reaches downstream. As there is already a risk of flooding, storage of flow above the existing flood peak only would increase the duration of flooding.

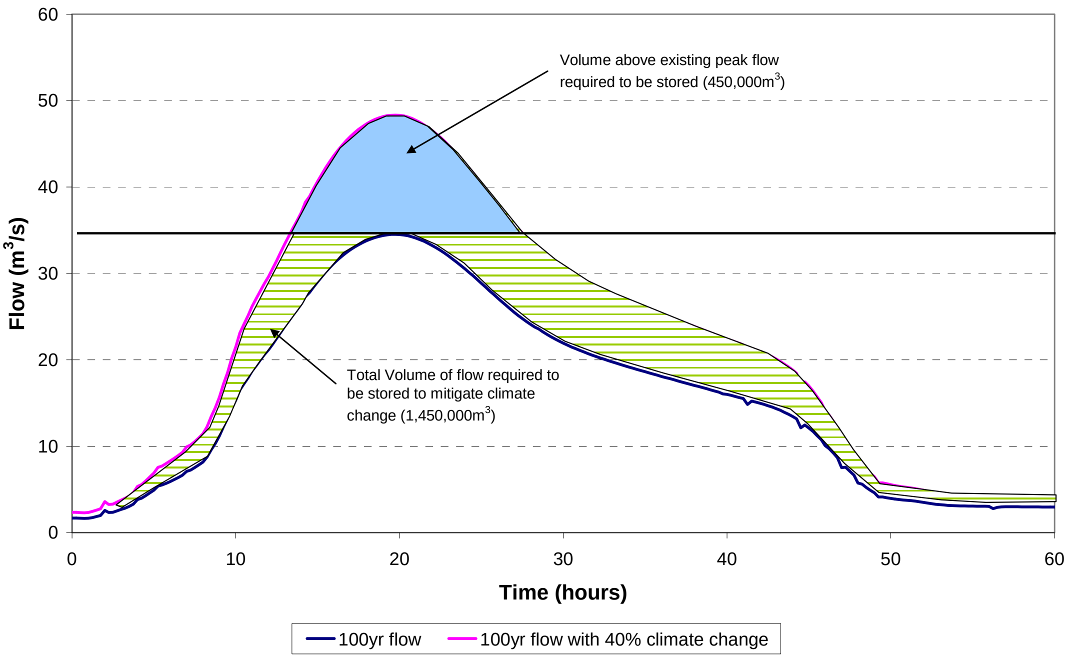

Figure I.1 River Crane: Storage volumes required to mitigate against increased flow due to climate change

The storage volume required for a 100-year event plus a 40% climate change allowance is 1.45 million m^3 for the full event and 0.45 million m^3 to maintain the peak flow at 35 m^3/s. Alternatively a flood diversion channel would be required to have capacity for a flow of at least 15 m^3/s.

For the estimated 1,000-year event, the storage requirements to mitigate the effects of a 40% increase in flow is 1.9 million m^3 for the full event and 0.59 million m^3 to maintain the peak flow at 46 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the change in River Thames level at the downstream end of the River Crane due to change in barrier operation are shown in Figure I.2. The increase in downstream water level of 0.5m occurs in 2065 and the increase of 1.0m occurs in 2100.

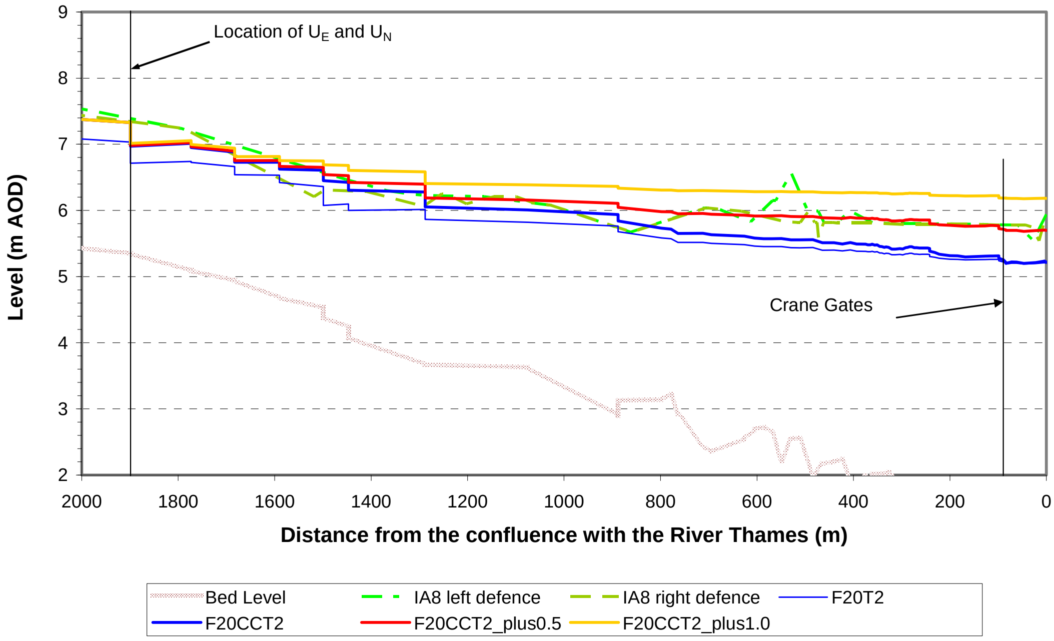

Figure I.2a River Crane: 1 in 20 year water levels

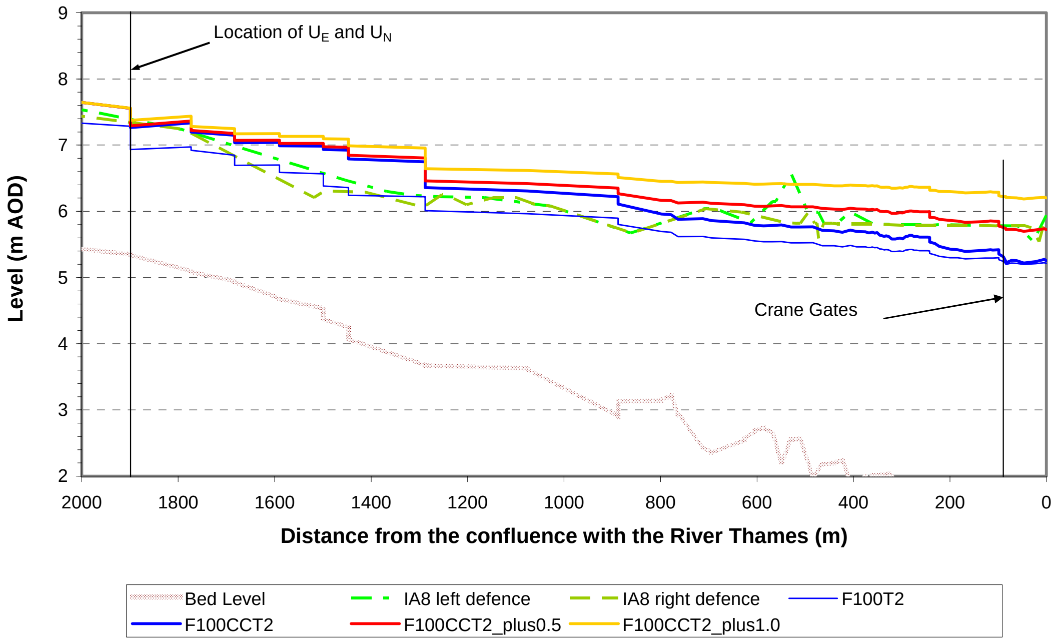

Figure I.2b River Crane: 1 in 100 year water levels

Figure I.2a shows that the lower reaches of the River Crane can generally accommodate a 20-year flow. In addition, the 1 in 20 year flow with an additional 40%

due to climate change has little impact on water levels in the lower 1 km of the River Crane as levels are controlled by water levels in the Thames. However, further upstream the peak water levels would increase by about 0.4m.

If levels in the Thames are allowed in increase by 0.5m, design water levels in the tidally influenced reach would increase by about 0.5m including the 40% increase in fluvial flow. Defence raising of about 0.5m would therefore be needed to maintain the present standard of protection.

Figure I.2b indicates that design water levels would increase by up to 0.8m to accommodate a 40% increase in flow during a 100-year event. Defence raising of up to about 1.2m would be needed to accommodate this flow with an allowance for freeboard. If this is combined with a 1m increase in water levels in the Thames, the results indicate that defence raising of about 1.0 to 1.2m would be needed along the tidally influenced reach of the River Crane.

I.3 Beverley Brook

Figure I.3 shows the estimated 1 in 100 year flow with and without the 40% increase due to climate change. The area shaded with green lines indicates the volume of water that would need to be stored to mitigate against the impact of climate change.

The area shaded in blue shows the volume of water that would need to be stored to prevent climate change increasing the peak flow and hence the peak flood water level in the reaches downstream. As there is already a risk of flooding, storage of flow above the existing flood peak only would increase the duration of flooding.

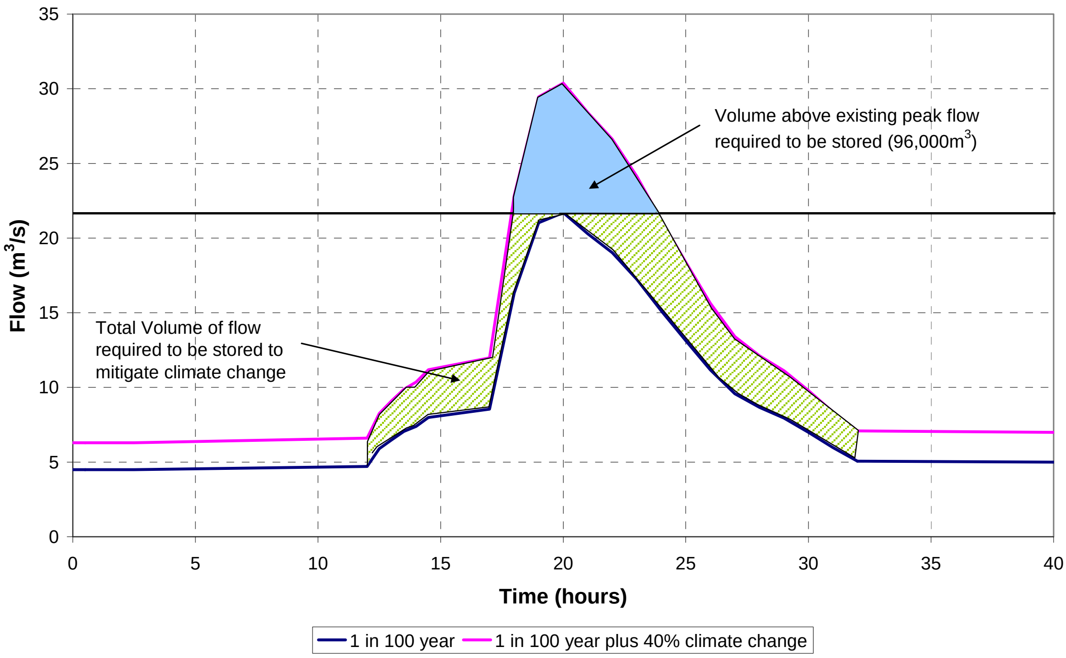

Figure I.3 Beverley Brook: Storage volumes required to mitigate against increased flow due to climate change

The storage volume required for a 100-year event plus a 40% climate change allowance is 0.37 million m^3 for the full event and 0.1 million m^3 to maintain the peak flow at 22 m^3/s.

For the estimated 1,000-year event, the storage requirements to mitigate the effects of a 40% increase in flow is 0.45 million m^3 for the full event and 0.12 million m^3 to maintain the peak flow at 26 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the change in River Thames level at the downstream end of the River Crane due to change in barrier operation is shown in Figure I.4. The increase in downstream water level of 0.5m occurs in 2065 and the increase of 1.0m occurs in 2100.

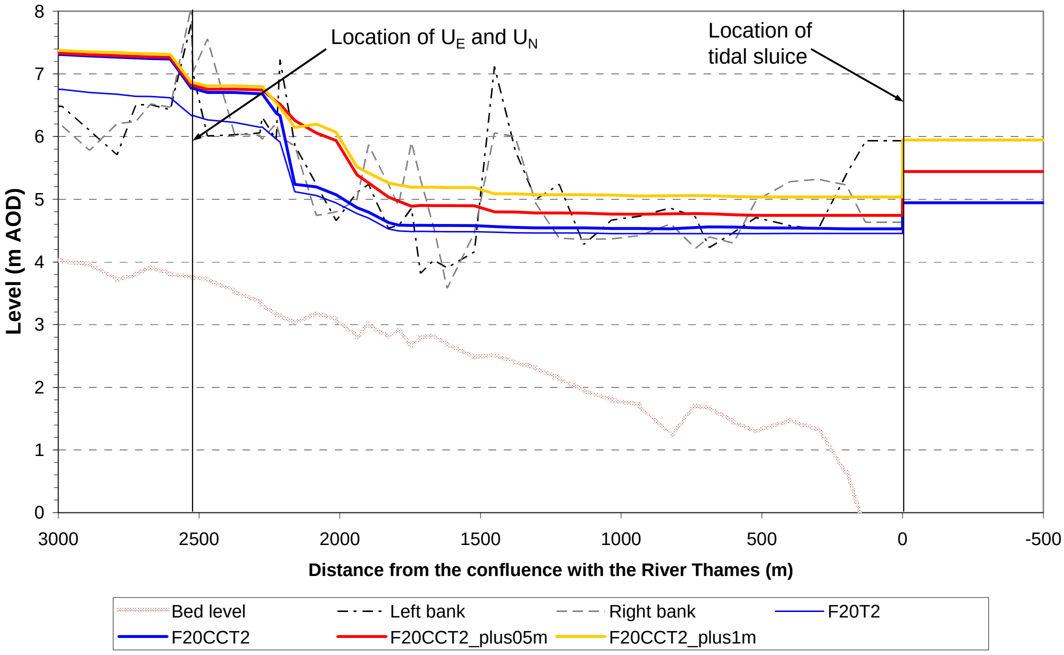

Figure I.4a Beverley Brook: 1 in 20 year water levels

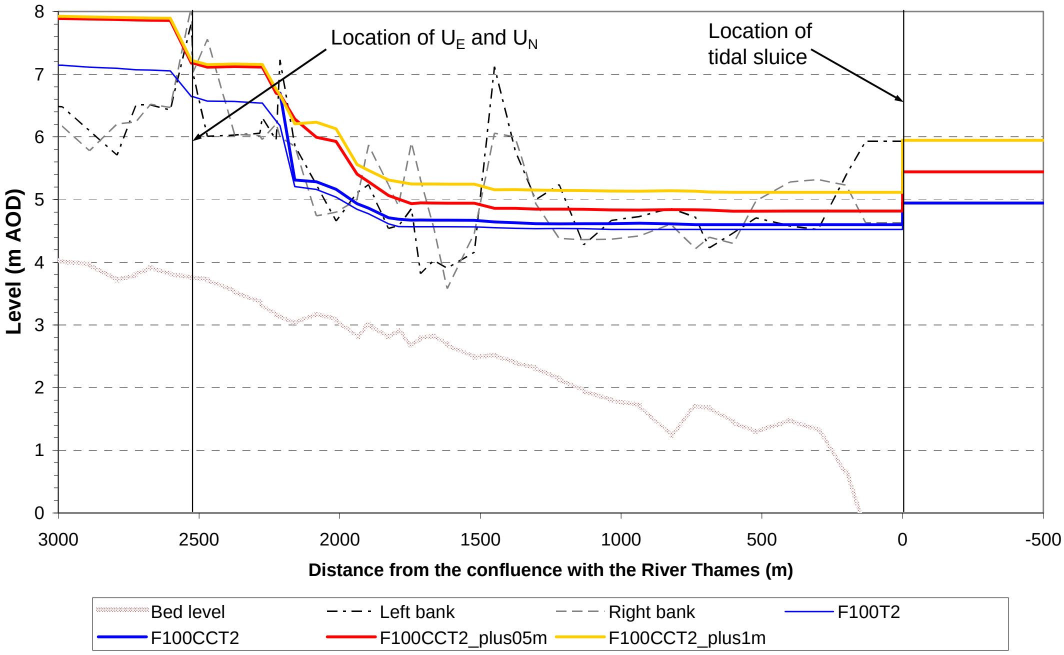

Figure I.4b Beverley Brook: 1 in 100 year water levels

Figures I.4a and b show that the bank levels are below the 20-year level in some areas. The Figures also show the effect of the outfall structure in reducing the effects of high water levels in the Thames.

The 40% increase in flow would cause an increase in design water levels of up to 0.5m for a 20-year flow and up to 0.8m for a 100-year flow. However in the lower 2.2km length of the Brook the effect is small because water can spread onto the floodplains. This indicates that formal flood storage could be effective in this reach.

The effect of increases in water level in the Thames would be to increase levels in the lower reach of the Brook, as the tide lock period would be longer and the amount of fluvial flood water stored in this reach would be greater. The increase for a 1m increase in Thames levels is about 0.6m.

The results indicate that a combination of flood storage and defence raising could mitigate the effects of fluvial flood risk in the tidally influenced part of Beverley Brook. Other options for reducing water levels at the downstream end of the Beverley Brook would be to provide additional outfalls at higher levels, or to provide pumps at the existing outfall to increase discharge to the River Thames.

I.4 River Lee

Figure I.5 shows the 1 in 100 year flow in the main channel of the River Lee with and without the 40% increase due to climate change.

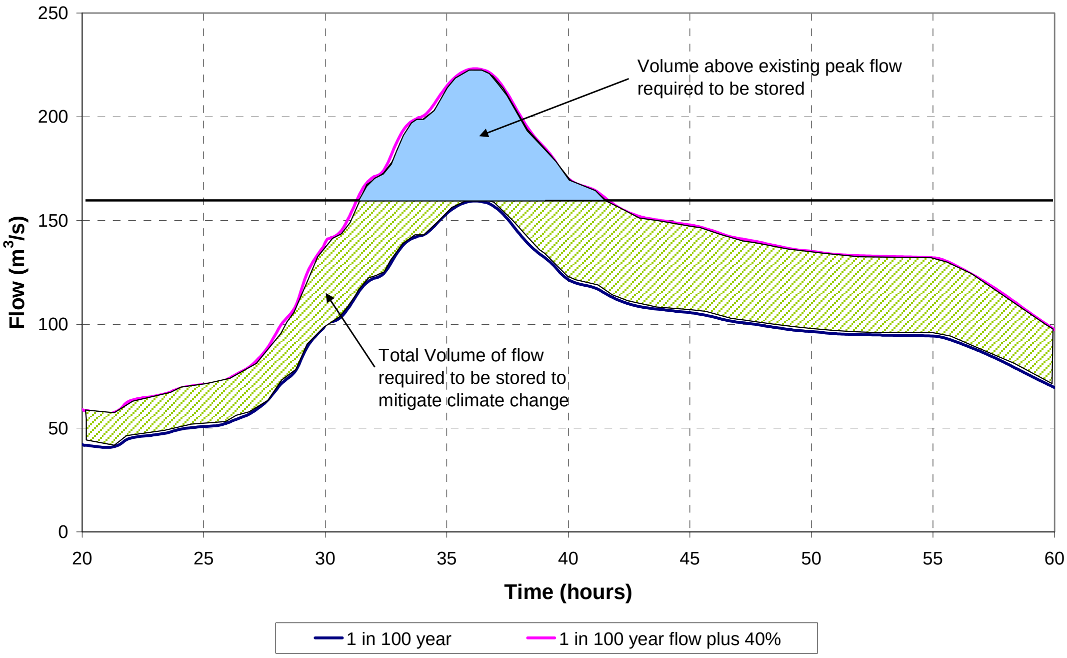

Figure I.5 River Lee: Storage volumes required to mitigate against increased flow due to climate change

Because of the long duration of the event and high flow, the volume of storage required for the River Lee is considerable.

The storage volume required for a 100-year event plus a 40% climate change allowance is 6.13 million m^3 for the full event and 1.54 million m^3 to maintain the peak flow at about 160 m^3/s.

For the estimated 1,000-year event, the storage requirements to mitigate the effects of a 40% increase in flow is 8.1 million m^3 for the full event and 2 million m^3 to maintain the peak flow at about 235 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase River Thames level at the downstream end of the River Lee due to change in barrier operation is shown in Figure I.6. The increase in downstream water level of 0.5m occurs in 2065 and the increase of 1.0m occurs in 2100.

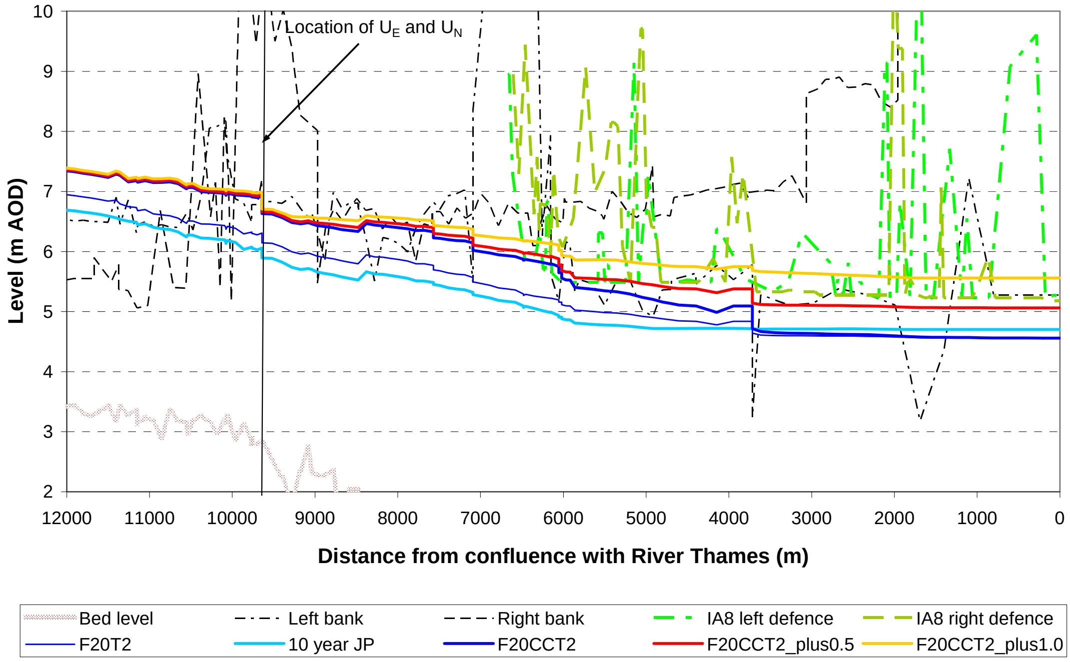

Figure I.6a River Lee: 1 in 20 year water levels

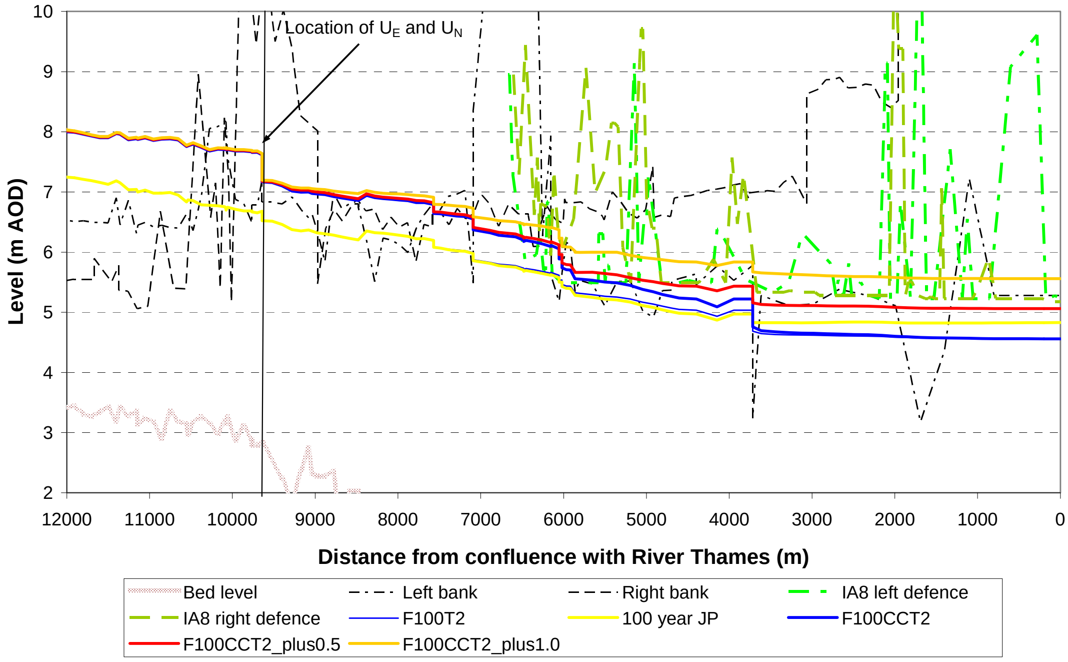

Figure I.6b River Lee: 1 in 100 year water levels

The 40% increase in flow would cause an increase in design water levels of up to 0.6m for a 20-year flow and up to 0.9m for a 100-year flow. However in the lower reaches the effect is smaller because water levels are controlled by water levels in the Thames.

The effect of increases in water level in the Thames would be to increase levels in the lower reach of the River Lee. A combination of a 1m increase in Thames levels and a 40 % increase in the 100-year fluvial flow would cause an increase in design water levels of up to 1m for the whole tidally influenced reach. Fluvial flood storage or a new (or enlarged) flood relief channel could mitigate fluvial increases, but this would not prevent an increase in tidal levels. A combination of an 0.5m increase in Thames levels and a 40 % increase in the 100-year fluvial flow would cause an increase in design water levels of about 0.5 to 0.7m for the tidally influenced reach.

I.5 River Roding

Figure I.7 shows the 1 in 100 year flow in the main channel of the River Roding with and without the 40% increase due to climate change.

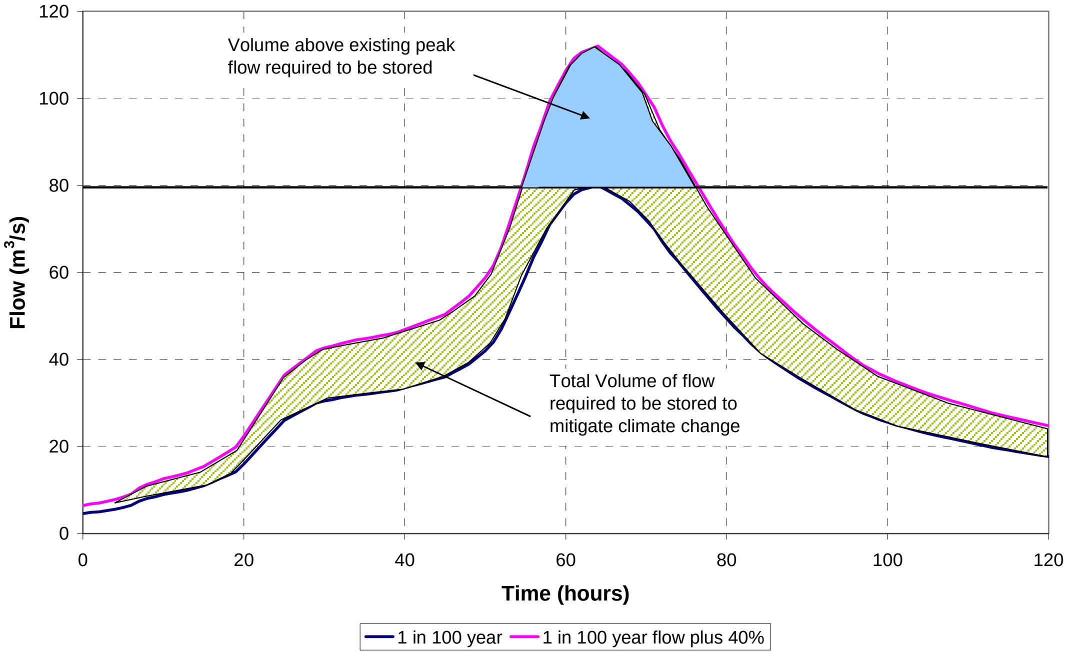

Figure I.7 River Roding: Impact of climate change on the 1 in 100 year flow

Because of the long duration of the event and high flow, the volume of storage required for the River Roding is considerable. Storage in the tidally influenced reach is only available in the channel unless water is diverted to marsh areas east of the Roding.

The storage volume required for a 100-year event plus a 40% climate change allowance is 6 million m^3 for the full event and 1.5 million m^3 to maintain the peak flow at about 80 m^3/s.

For the estimated 1,000-year event, the storage requirements to mitigate the effects of a 40% increase in flow is about 10 million m^3 for the full event and 2.5 million m^3 to maintain the peak flow at about 135 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase River Thames level at the downstream end of the River Roding due to rise in extreme tide level (MSL and surge) in 2100 is shown in Figure I.8.

Figure I.8a shows that under present day conditions the standard of defence between 6 km and 8 km from the Barking Barrier is around 1 in 20 years. Upstream of this reach the standard of protection is less than 1 in 20 years based on the river bank data extracted from the Roding hydraulic model. Figure I.8b shows that in the tidal reach the standard of protection is greater than 1 in 100 years.

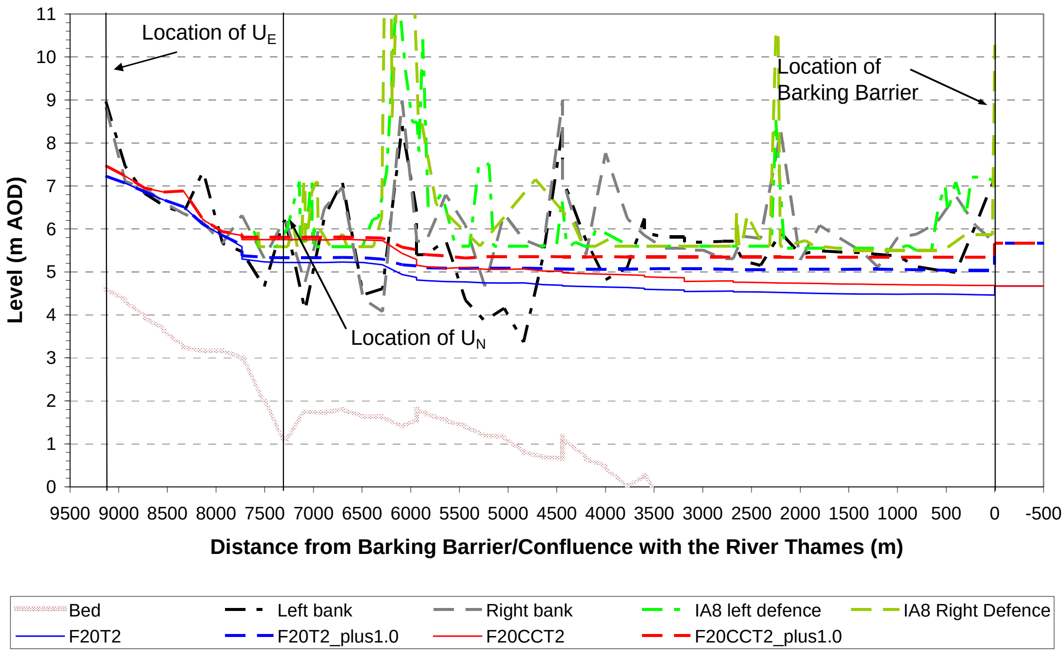

Figure I.8a River Roding: 1 in 20 year water levels

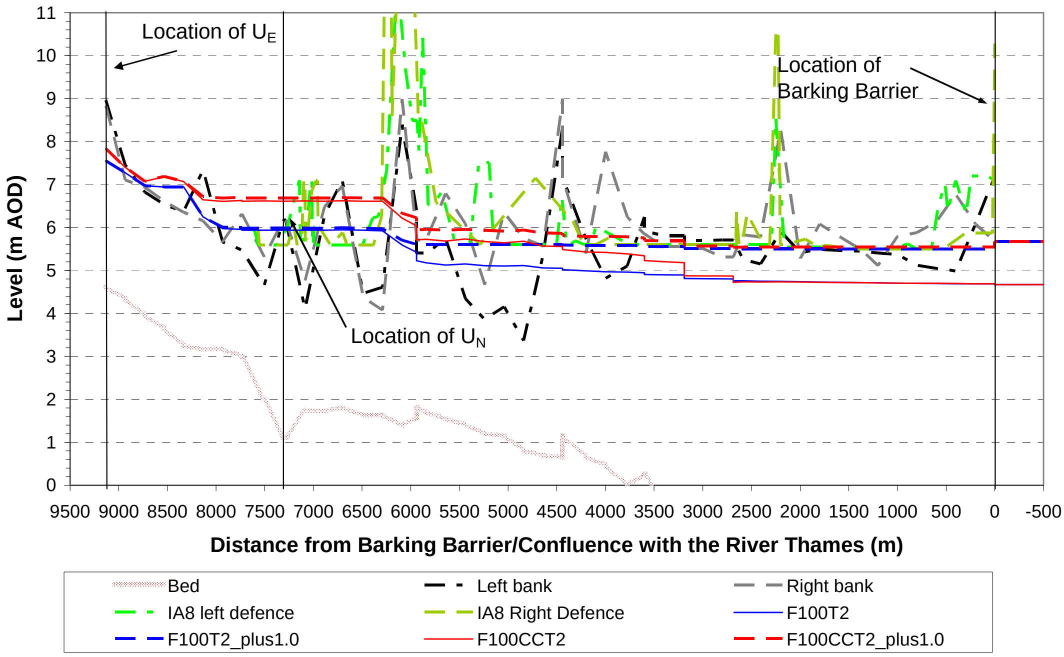

Figure I.8b River Roding: 1 in 100 year water levels

Figure I.8b shows that with increased flow of 40% and increase in tide level of 1m in approximately 2100 the tidal defences would need to be raised by approximately 1m to maintain the present standard of defence. For protection in the 1 in 100 year flow the defences would be raised by about 0.4m for 3km upstream of the Barking Barrier, and then by approximately 0.8m between 3 and 6km upstream of the Barking Barrier.

Figure I.8a indicates that to maintain the 1 in 20 year fluvial standard between 6 and 8 km upstream of the Barking Barrier the defences would need to be raised by around 0.6m.

I.6 River Darent

Figure I.9 shows the 1 in 100 year flow in the River Darent with and without the 40% increase due to climate change.

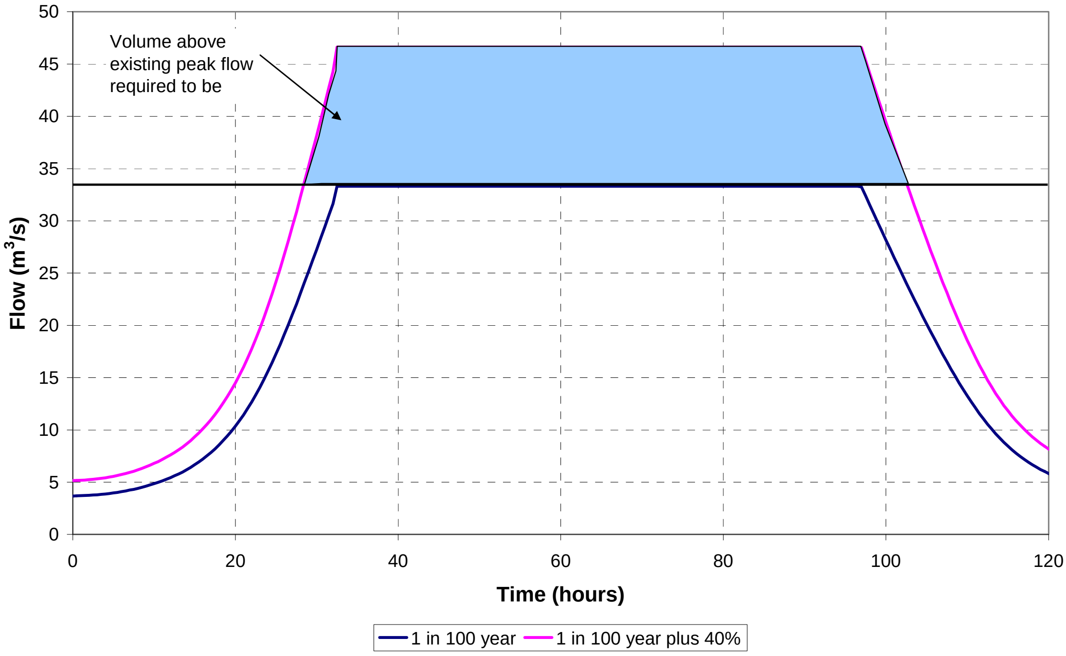

Figure I.9 River Darent: Impact of climate change on the 1 in 100 year flow

The origin of the unusual hydrograph shape for the Rivers Darent and Cray is discussed in the TE2100 Phase 2 Study on tributaries (Study EP4).

The storage volume required for a 100-year event plus a 40% climate change allowance is about 4 million m^3 for the full event and about 3.3 million m^3 to maintain the peak flow at about 33 m^3/s.

For the estimated 1,000-year event, the storage requirements to mitigate the effects of a 40% increase in flow is about 5 million m^3 for the full event and 4.1 million m^3 to maintain the peak flow at about 42 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase River Thames level at the downstream end of the River Darent due to rise in extreme tide level (MSL and surge) in 2100 is shown in Figure I.10.

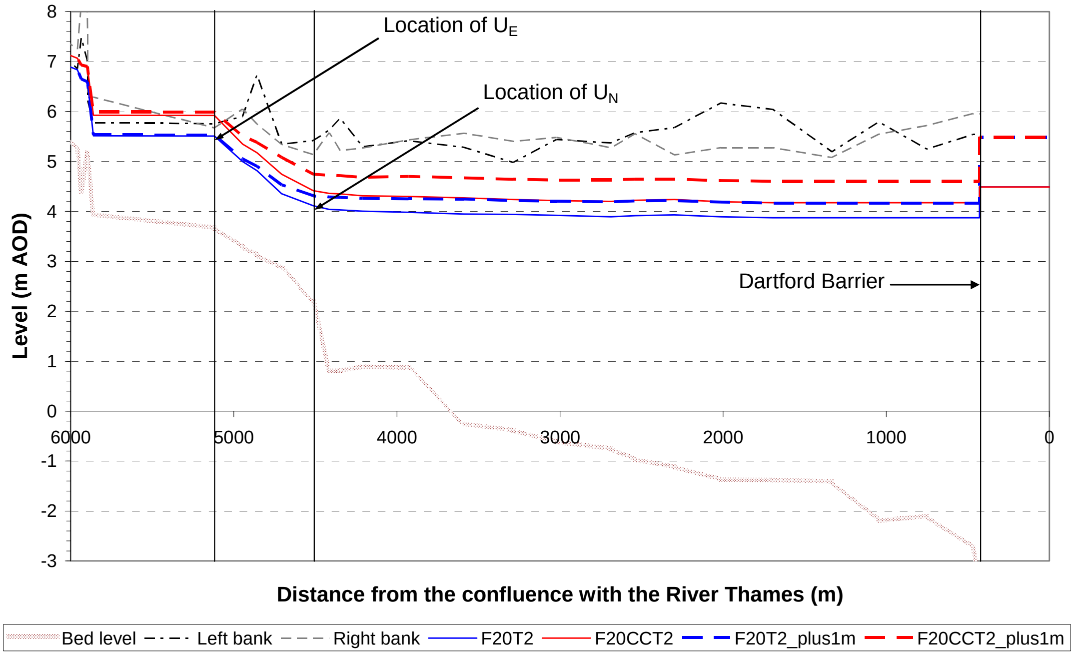

Figure I.10a River Darent: 1 in 20 year water levels

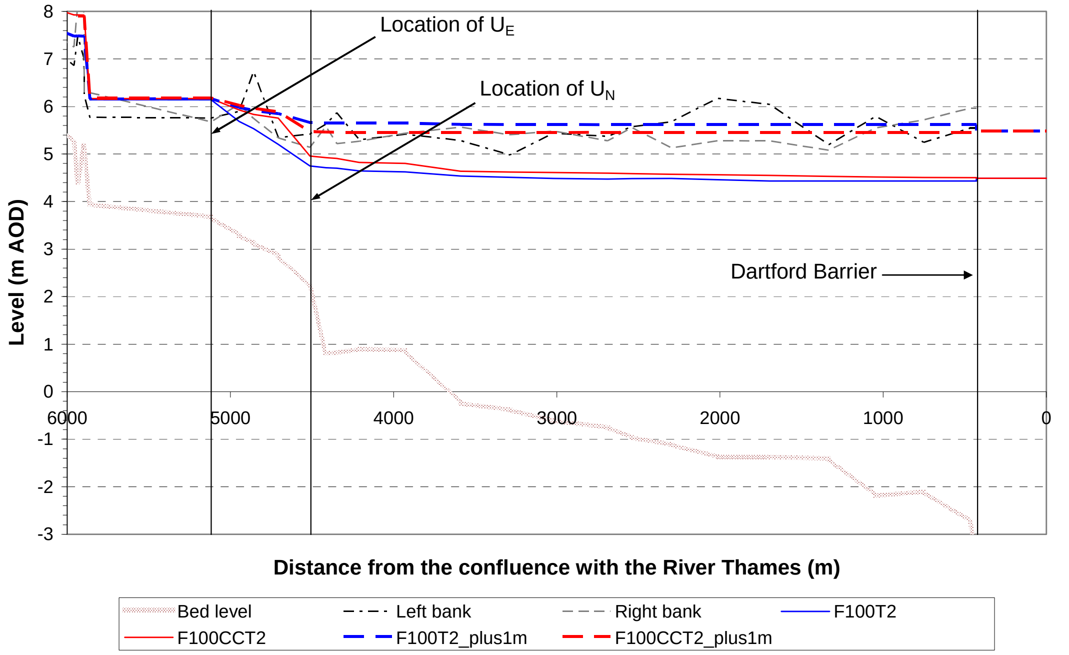

Figure I.10b River Darent: 1 in 100 year water levels

Figure I.10a shows that upstream of the zone of fluvial-tidal interaction the defences must be raised by at least 0.6m to maintain the present day standard of protection with a 40% increase in fluvial flow.

Figure I.10b shows that in the tidally influenced reach the defence levels must be raised by 1m to allow for the increase in tide level of 1m. Further raising may be required to allow for the increase in fluvial flow of 40%. There is overtopping into the marshes for the 100 year plus 40% event when the model is run with present day defence levels, and therefore the full increase in defence level required to maintain a freeboard of 0.4m above the 100 year water level is not known. The results indicate that if a 100-year fluvial event occurred with a 2-year tide, the peak levels upriver of Dartford Barrier would be similar to those in the Thames and the Dartford Barrier would provide no benefit.

I.7 River Cray

Figure I.11 shows the 1 in 100 year flow in the River Cray with and without the 40% increase due to climate change.

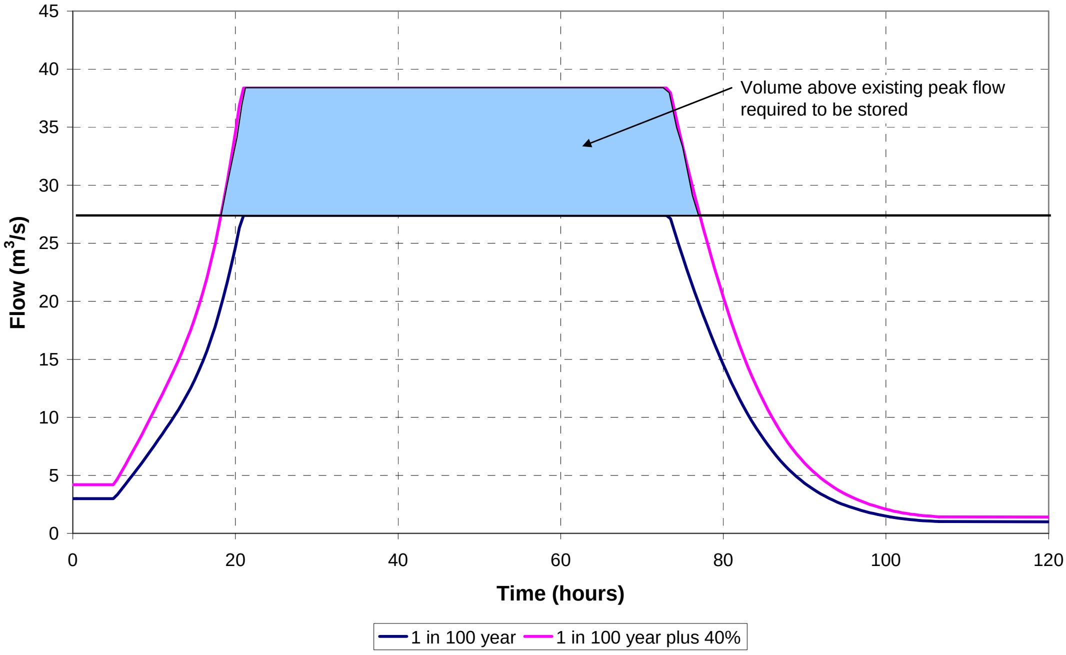

Figure I.11 River Cray: Impact of climate change on the 1 in 100 year flow

The storage volume required for a 100-year event plus a 40% climate change allowance is about 2.7 million m^3 for the full event and about 2.2 million m^3 to maintain the peak flow at about 27 m^3/s.

For the estimated 1,000-year event, the storage requirements to mitigate the effects of a 40% increase in flow is about 3.5 million m^3 for the full event and 2.8 million m^3 to maintain the peak flow at about 35 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase River Thames level at the downstream end of the River Darent due to rise in extreme tide level (MSL and surge) in 2100 is shown in Figure I.12.

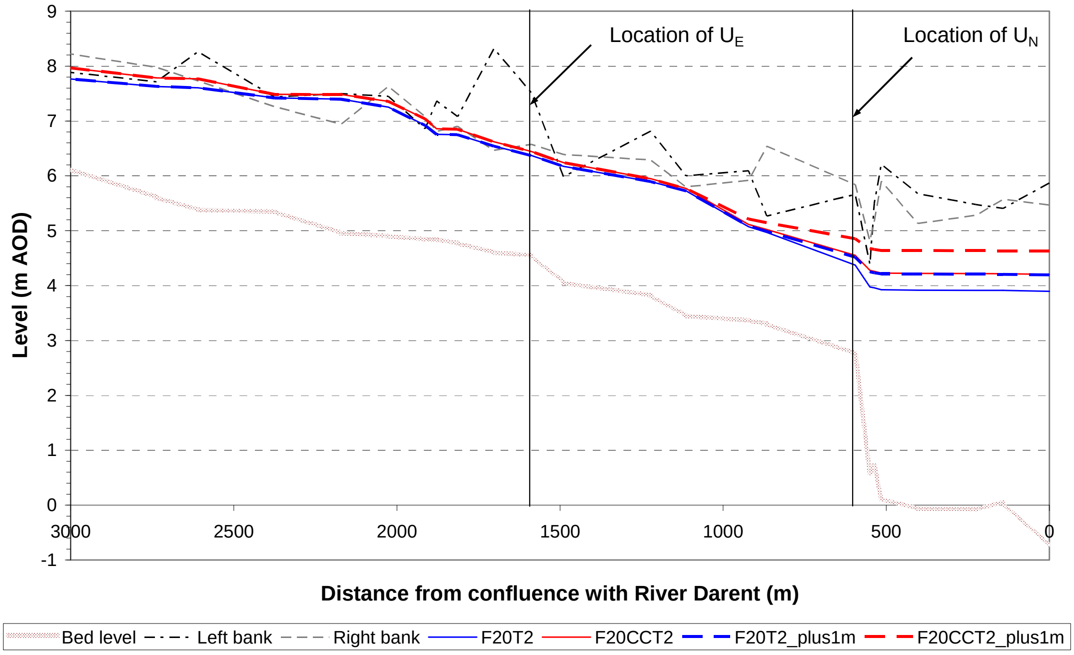

Figure I.12a River Cray: 1 in 20 year water levels

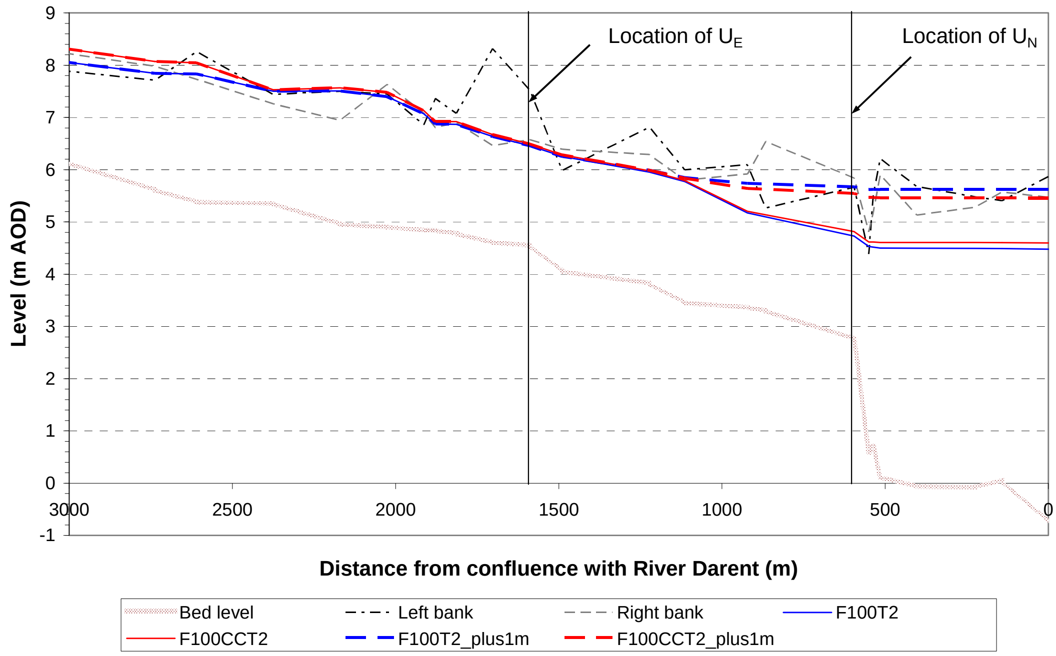

Figure I.12b River Cray: 1 in 100 year water levels

Figure I.12a shows that upstream of the zone of fluvial-tidal interaction the defences must be raised by at least 0.4m to maintain the present day standard of protection with a 40% increase in fluvial flow.

Figure I.12b shows that in the tidally influenced reach the defence levels must be raised by between 0.5 and 1m to allow for the increase in tide level of 1m, and to allow for the increase in fluvial flow of 40% further raising may be required. There is overtopping into the marshes for the 100 year plus 40% event when the model is run with present day defence levels, and therefore the full increase in defence level required to maintain a freeboard of 0.4m above the 100 year water level is not known.

I.8 River Brent

Figure I.13 shows the 1 in 100 year flow in the River Brent with and without the 40% increase due to climate change.

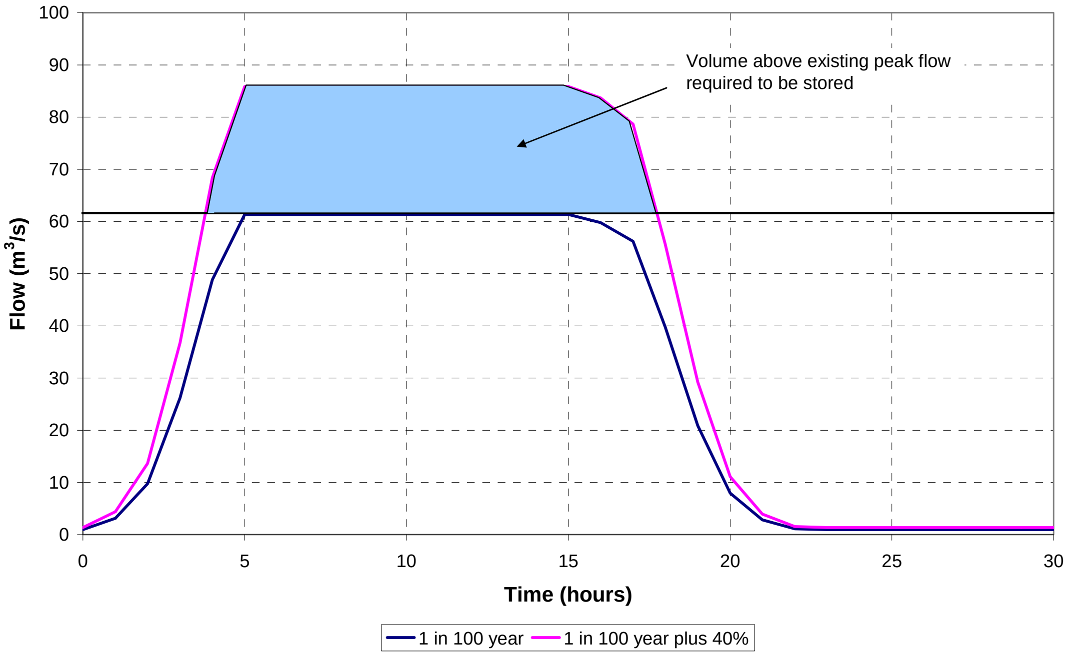

Figure I.13 River Brent: Impact of climate change on the 1 in 100 year flow

The origin of the unusual hydrograph shape for the River Brent is discussed in the TE2100 Phase 2 Study on tributaries (Study number EP4).

The storage volume required for a 100-year event plus a 40% climate change allowance is about 1.4 million m^3 for the full event and about 1.3 million m^3 to maintain the peak flow at about 60 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase in River Thames level at the downstream end of the River Brent due to change in barrier operation is shown in Figure I.14. The increase in downstream water level of 0.5m occurs in 2065 and the increase of 1.0m occurs in 2100.

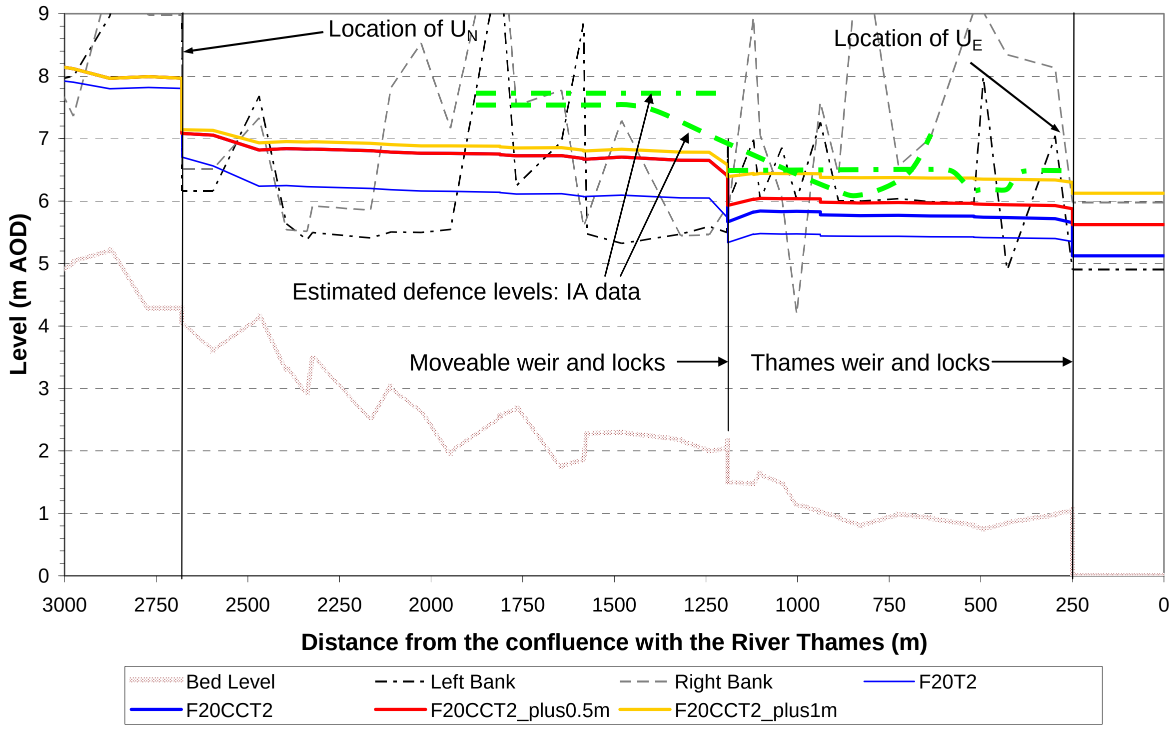

Figure I.14a River Brent: 1 in 20 year water levels

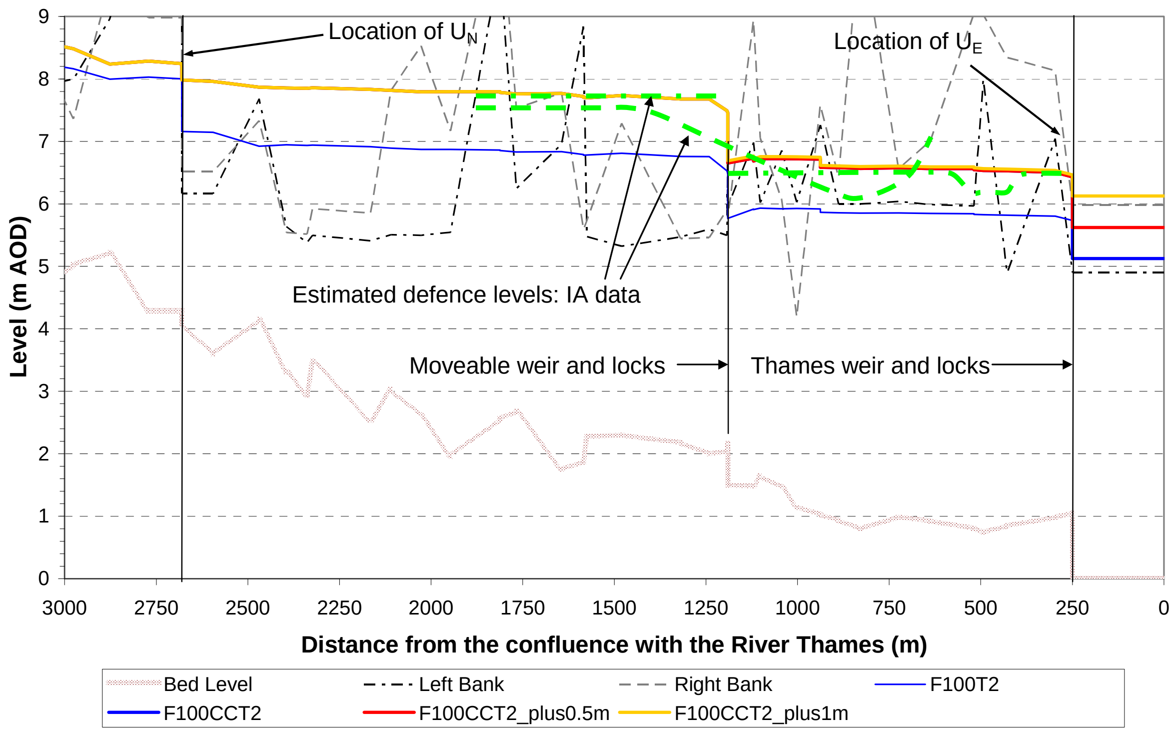

Figure I.14b River Brent: 1 in 100 year water levels

In the tidal zone the defences are raised by 0.5m in 2065 and 1.0m in 2100 to be consistent with the River Thames defences. The model of the River Brent is essentially glass walled at the edge of the channel and does not include the floodplain. Water levels produced from the model can therefore be used to assess the amount of defence required to maintain standards of protection with climate change.

Figure I.14a shows that in the 1 in 20 year flow event with climate change the increase in River Thames water level has a greater impact than the increase in flow between the moveable weir and locks and the Thames weir and locks.

Figure I.14b shows that the increase in fluvial flow of 40% due to climate change has a significant increase in water level of approximately 1m in the lower 2.7km of the River Brent. This is because the cross section width is constrained by the tidal defences and significant head losses occur at the weir and lock structures.

In the 1 in 100 year flow the increase in flow due to climate change is the main cause of the increase in river water levels rather than the increase in the River Thames water level. For the 1 in 100 year flow the downstream defences would need to be raised by 1.0m in 2065 to mitigate for the increased flow.

With the combination of flow increase and downstream level increase, the higher tide levels do not have an impact on the water level upstream of the moveable weir and locks in the 1 in 100 year flow event, and a small increase of 0.1m in the 1 in 20 year flow event.

Raised defences in 2065 and 2100 can contain the 100 year flow plus climate change on the Brent with a 2 year water level on the Thames.

I.9 Beam River

Figure I.15 shows the 1 in 100 year flow in the Beam River with and without the 40% increase due to climate change.

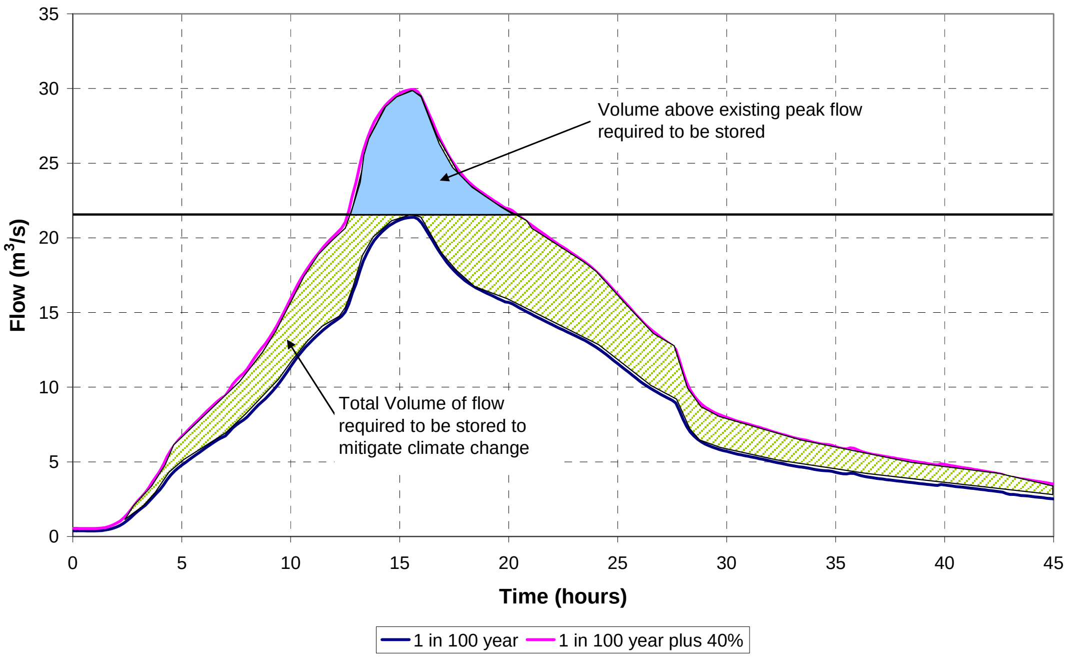

Figure I.15 Beam River: Impact of climate change on the 1 in 100 year flow

The storage volume required for a 100-year event plus a 40% climate change allowance is about 0.56 million m^3 for the full event and about 0.13 million m^3 to maintain the peak flow at about 21 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase River Thames level at the downstream end of the Beam River due to rise in extreme tide level (MSL and surge) in 2100 is shown in Figure I.16.

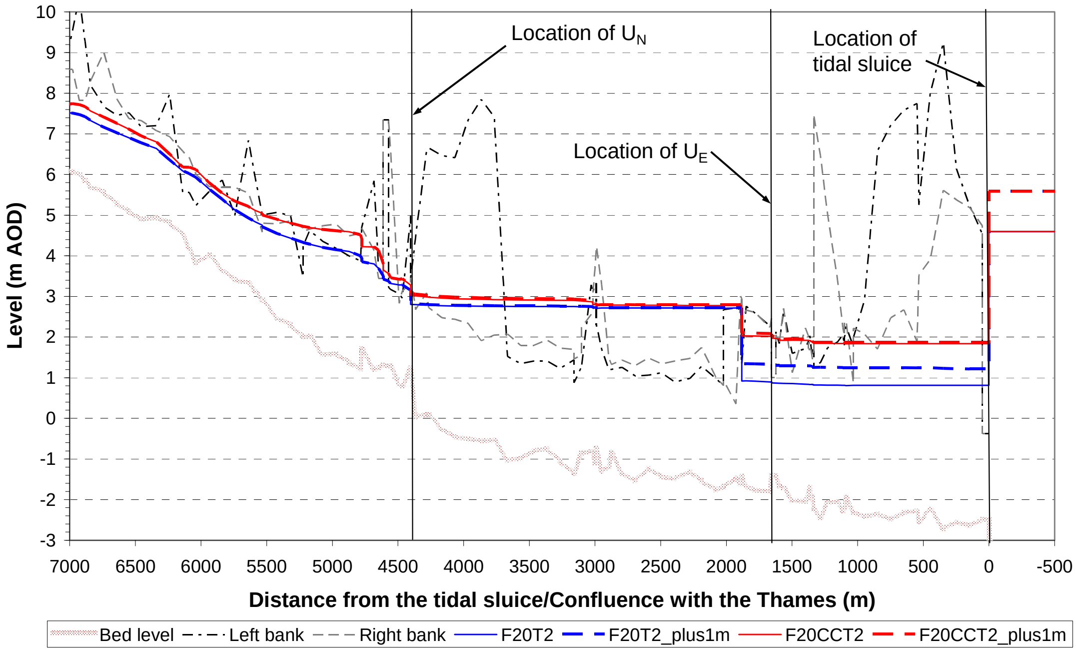

Figure I.16a Beam River: 1 in 20 year water levels

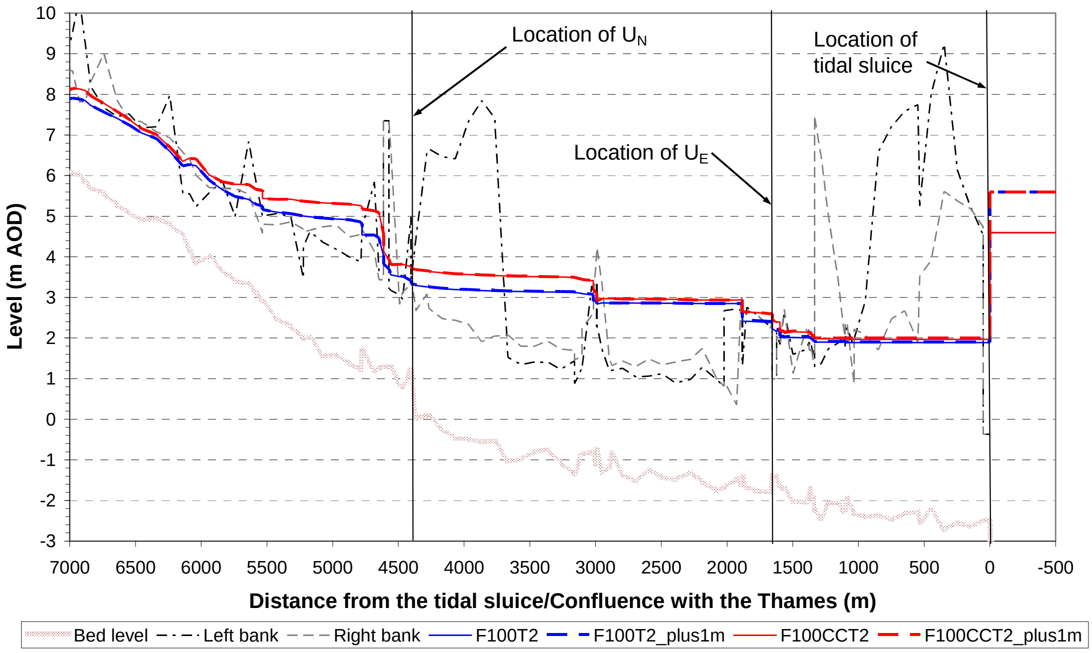

Figure I.16b Beam River: 1 in 100 year water levels

Figures I.16a and b demonstrate the importance of the outfall structure in preventing tidal flow from the Thames to the Beam River. These Figures also show that climate change has little impact on water levels in the river channel upstream of the tidal sluice because of large storage volumes on the washlands.

It is unclear from this analysis whether the capacity of the designed storage is exceeded and there is flooding of the general floodplain (e.g. the Ford motor works). Upstream of the tidal-fluvial zone the defences would need to be raised by up to 0.5m to provide the same standard of protection taking account of the increased flow due to climate change.

I.10 River Wandle

Figure I.17 shows the 1 in 100 year flow in the River Wandle with and without the 40% increase due to climate change.

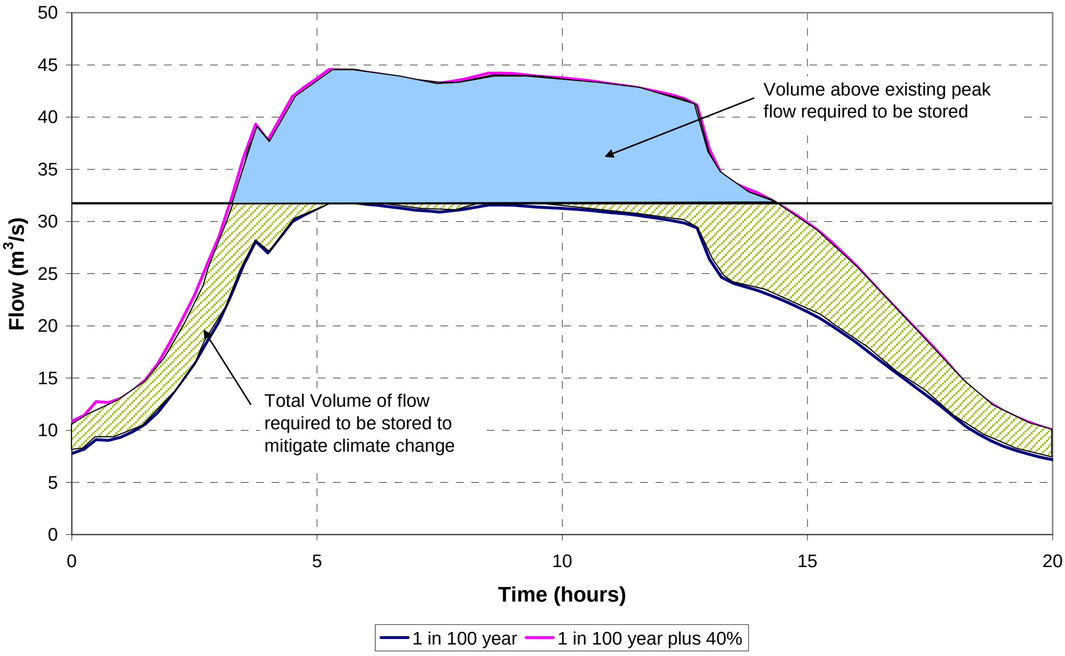

Figure I.17 River Wandle: Impact of climate change on the 1 in 100 year flow

The storage volume required for a 20-year event plus a 40% climate change allowance is about 0.5 million m^3 for the full event and about 0.25 million m^3 to maintain the peak flow at about 28 m^3/s.

For the estimated 100-year event, the storage requirements to mitigate the effects of a 40% increase in flow is about 0.65 million m^3 for the full event and 0.35 million m^3 to maintain the peak flow at about 32 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase in River Thames level at the downstream end of the River Wandle due to change in barrier operation is shown in Figure I.18. The increase in downstream water level of 0.5m occurs in 2065 and the increase of 1.0m occurs in 2100.

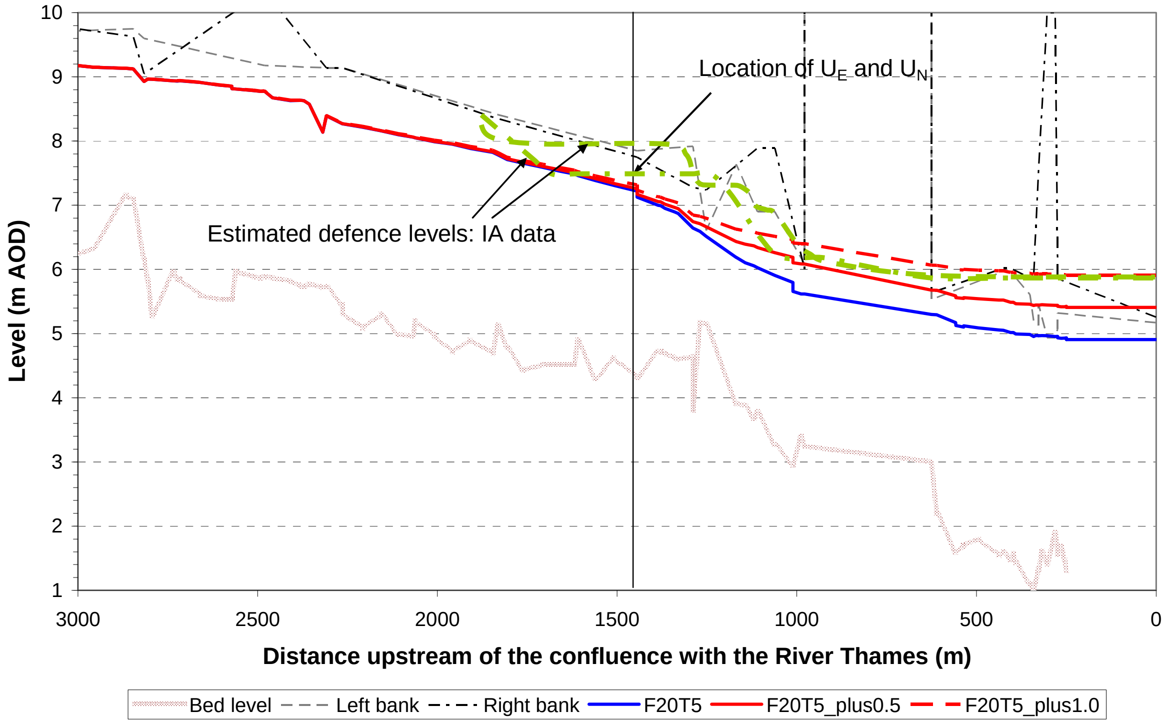

Figure I.18a River Wandle: 1 in 20 year water levels

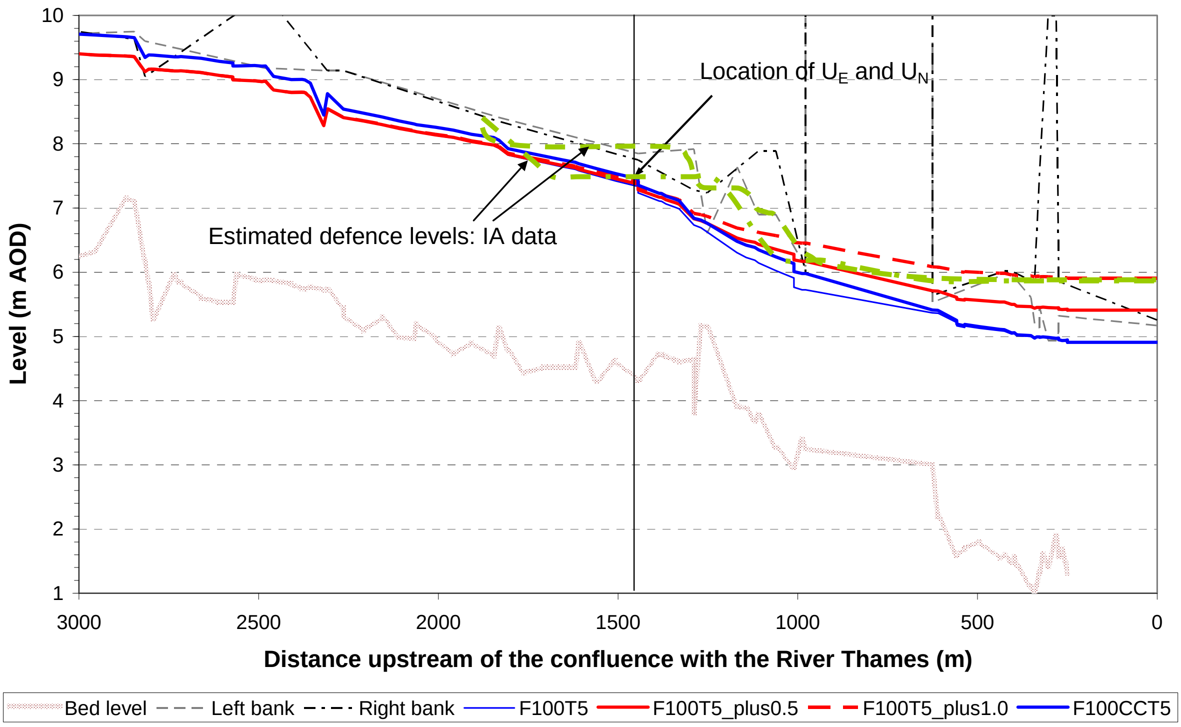

Figure I.18b River Wandle: 1 in 100 year water levels

Figure I.18b shows that in some locations of the fluvial zone the defence levels are required to be raised by around 0.5m to provide the same level of protection as in present day. The additional 40% flow due to climate change increases water levels by approximately 0.2 to 0.4m. In the tidal zone the defences would be raised by 0.5m in 2065 and 1.0m in 2100 to be consistent with the River Thames defences. The raised defences are able to contain the 100 year flow on the Wandle with a 5 year water level on the Thames. It is likely that the raised defences in the tidal reach will cope with the increased fluvial flow.

I.11 River Ravensbourne

Figure I.19 shows the 1 in 100 year flow in the River Ravensbourne with and without the 40% increase due to climate change.

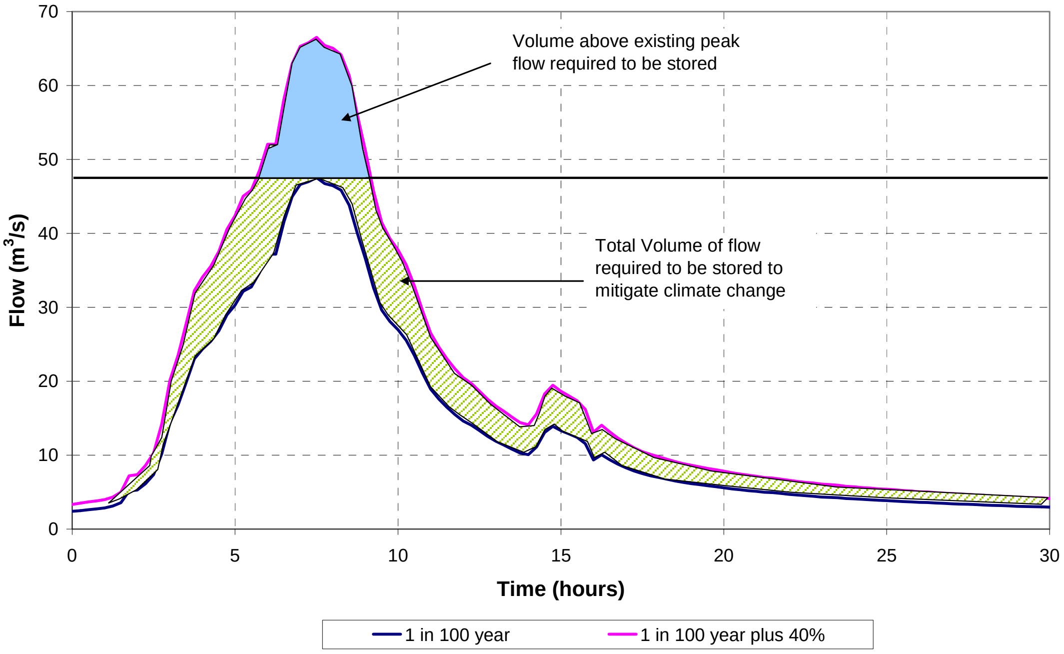

Figure I.19 River Ravensbourne: Impact of climate change on the 1 in 100 year flow

The storage volume required for a 20-year event plus a 40% climate change allowance is about 0.5 million m^3 for the full event and about 0.12 million m^3 to maintain the peak flow at about 37 m^3/s.

For the estimated 100-year event, the storage requirements to mitigate the effects of a 40% increase in flow is about 0.64 million m^3 for the full event and 0.15 million m^3 to maintain the peak flow at about 47 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase in River Thames level at the downstream end of the River Ravensbourne due to change in barrier operation is shown in Figure I.20. The increase in downstream water level of 0.5m occurs in 2065 and the increase of 1.0m occurs in 2100.

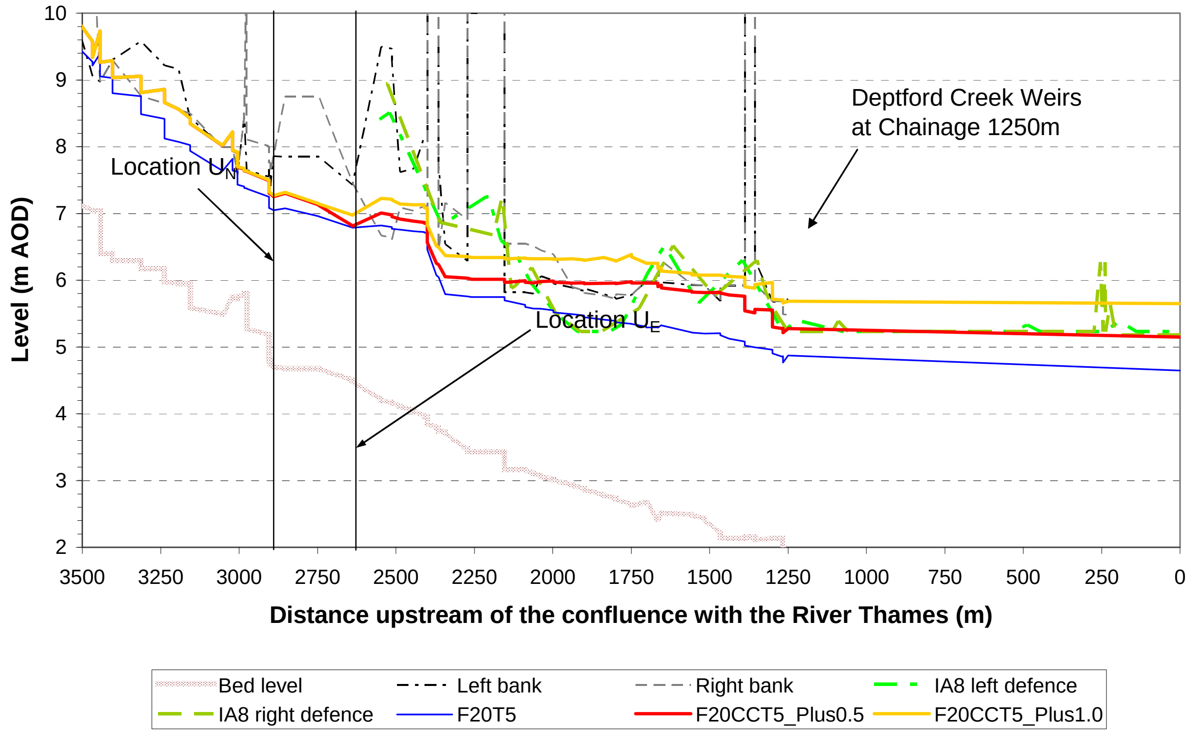

Figure I.20a River Ravensbourne: 1 in 20 year water levels

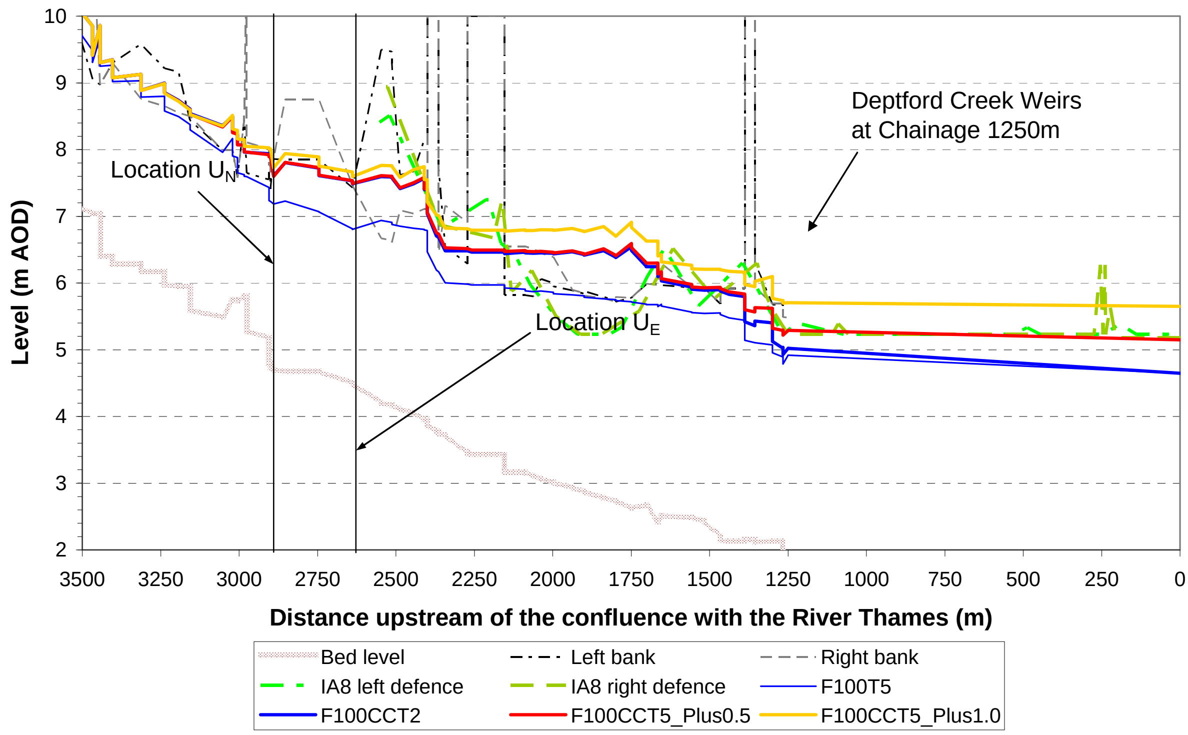

Figure I.20b River Ravensbourne: 1 in 100 year water levels

Figure I.20b indicates that defences in the tidally influenced reach would need to be raised by 1m to maintain the current standard of protection with an increase in flow of 40% and increase in downstream water level. In the tidal zone the defences are raised by 0.5m in 2065 and 1.0m in 2100 to be consistent with the River Thames defences.

Between 2.5 and 3km upstream from the River Thames the impact of climate change on the 1 in 20 year flow is less than for the 1 in 100 year flow. Defence raising of approximately 0.4m would be needed in the fluvial reaches for the 1 in 20 year flow.

Note that at the downstream end of the Ravensbourne there is flow on the floodplain with the increased tide levels, caused by backing up of the fluvial flow. This means that the increase in defence levels required to prevent flooding from the Thames may be greater than 0.5m in 2065 and 1.0m in 2100 in some locations.

I.12 River Ingrebourne

Figure I.21 shows the 1 in 100 year flow in the River Ingrebourne with and without the 40% increase due to climate change.

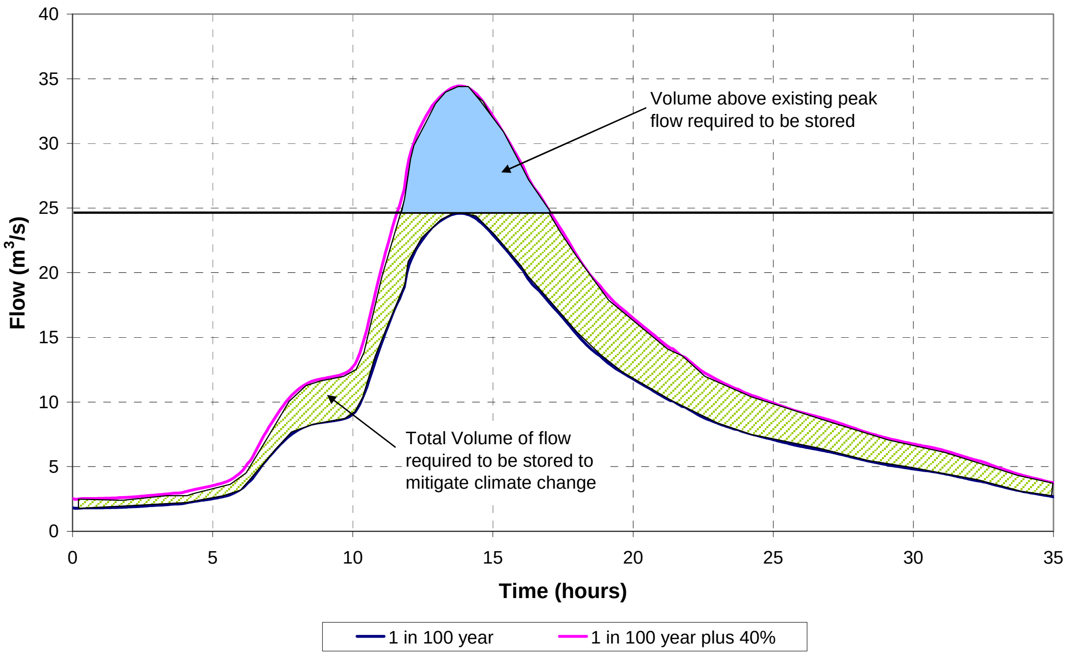

Figure I.21 River Ingrebourne: Impact of climate change on the 1 in 100 year flow

The storage volume required for a 20-year event plus a 40% climate change allowance is about 0.3 million m^3 for the full event and about 85,000 m^3 to maintain the peak flow at about 17 m^3/s.

For the estimated 100-year event, the storage requirements to mitigate the effects of a 40% increase in flow is about 0.5 million m^3 for the full event and 0.12 million m^3 to maintain the peak flow at about 25 m^3/s.

The impact of the increase in flow by 40% due to climate change, and the increase River Thames level at the downstream end of the River Ingrebourne due to rise in extreme tide level (MSL and surge) in 2100 is shown in Figure I.22.

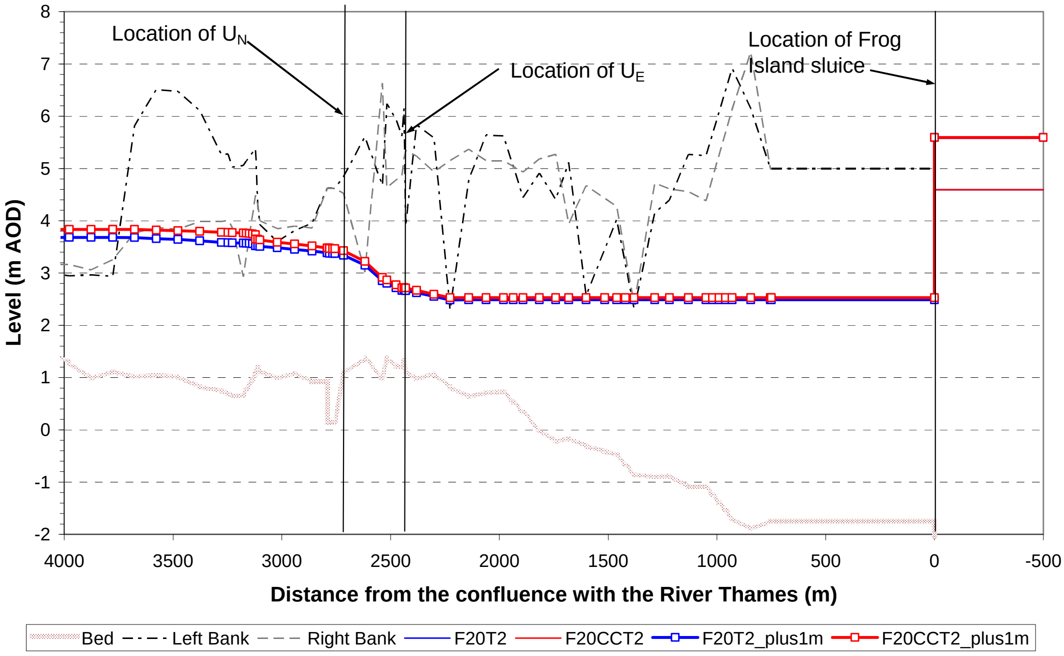

Figure I.22a River Ingrebourne: 1 in 20 year water levels

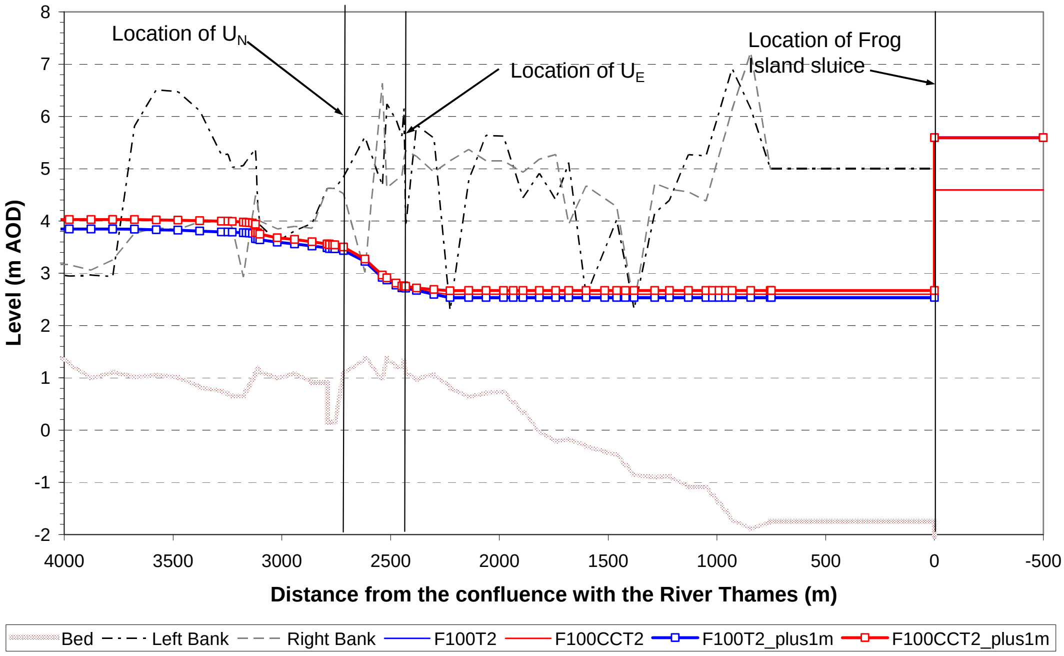

Figure I.22b River Ingrebourne: 1 in 100 year water levels

Figure I.22 shows that for 2.5km upstream of Frog Island Sluice the peak water levels are controlled by storage of water when the sluice is tide locked. For this reason there is little difference between water levels with and without climate change in the 1 in 20 year flow. Upstream of the tidal limits the increased flow of 40% causes an increase in water level of approximately 0.3m. Upstream of Bridge Road there is flow on the marsh to the right of the river channel and there is also some floodplain storage at about 2.5km from Frog Island Sluice.

I.13 Summary

The above flood storage volumes and increases in design water levels and potential defence raising requirements are summarised in Table I.1. These results are approximate, but give an indication of the works that could be required. The defence raising requirements are particularly tentative as the flood defence crest level data used for the study has not been checked. In some areas the levels are very variable.

No attempt has been made to assess the viability of schemes involving defence raising or storage on the tributaries.

Table I.1 Tributary storage volumes and defence raising requirements

Tributary	**Flood mitigation options**[1]	**Storage volume** (million m^3)[2]	**Increase in design water level with 40% increase in 100-year flow (m)**		**Approximate defence raising**[3]
			Fluvial only	Combined with 1m increase in Thames levels	
Crane	Raise defences Storage Diversion	0.4 – 1.4	Up to 0.8	1.0	1.2m for 1.8km
Beverley Brook	Raise defences Storage Improve outfall	0.1 – 0.4	Up to 0.8	0.6 – 0.8	1.2m for 3km including storage area
Lee	Raise defences Storage	1.5 – 6.1	Up to 0.9	1.0	1.0m for 9.5km
Roding	Raise defences Storage Diversion	1.5 – 6.0	Up to 0.7	1.0	1.0m for 9km
Darent	Raise defences Storage	3.3 – 4.0	Up to 0.6	1.2	>1.0m for 5km plus storage
Cray	Raise defences Storage	2.2 – 2.7	Up to 0.4	1.2	>1.0m for 1.5km plus storage
Brent	Raise defences	1.3 – 1.4	Up to 1.0	1.0	0.8m for 2.7km
Beam River	Raise defences Storage Improve outfall	0.1 – 0.6	Up to 0.5	0.5	Depends on storage
Wandle	Raise defences	0.2 – 0.5	Up to 0.5	1.0	0.8m for 1.5km
Ravensbourne	Raise defences	0.1 – 0.6	Up to 0.8	1.0	1.0m for 2.9km
Ingrebourne	Storage	0.1 – 0.5	Up to 0.3	0.3	Depends on storage

[1]From earlier TE2100 studies including TE2100 2008j
[2]For 40% increase in fluvial flow
[3]For 40% increase in 100-year flow and 1m increase in Thames level. Amount in m, length of channel in km

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GeoSmart Information

Appendix C

Thames Water sewer flooding history

Sewer Flooding

History Enquiry

Thames Water Property Searches

GeoSmart Information Ltd

Bellstone

Search address supplied	21 The Avenue Twickenham TW1 1QP

Your reference	84145
Our reference	SFH/SFH Standard/2024_5079035
Received date	**12 November 2024**
Search date	**12 November 2024**

Thames Water Utilities Ltd
Property Searches, PO Box 3189, Slough SL1 4WW

searches@thameswater.co.uk
www.thameswater-propertysearches.co.uk

0800 009 4540

Search address supplied: 21,The Avenue,Twickenham,TW1 1QP

This search is recommended to check for any sewer flooding in a specific address or area

TWUL, trading as Property Searches, are responsible in respect of the following:-

(i) any negligent or incorrect entry in the records searched;

(ii) any negligent or incorrect interpretation of the records searched;

(iii) and any negligent or incorrect recording of that interpretation in the search report

(iv) compensation payments

Thames Water Utilities Ltd
Property Searches, PO Box 3189, Slough SL1 4WW

searches@thameswater.co.uk
www.thameswater-propertysearches.co.uk

0800 009 4540

Sewer Flooding
History Enquiry

Thames Water Property Searches

History of Sewer Flooding

Is the requested address or area at risk of flooding due to overloaded public sewers?

The flooding records held by Thames Water indicate that there have been no incidents of flooding in the requested area as a result of surcharging public sewers.

For your guidance:

- A sewer is “overloaded” when the flow from a storm is unable to pass through it due to a permanent problem (e.g. flat gradient, small diameter). Flooding as a result of temporary problems such as blockages, siltation, collapses and equipment or operational failures are excluded.
- “Internal flooding” from public sewers is defined as flooding, which enters a building or passes below a suspended floor. For reporting purposes, buildings are restricted to those normally occupied and used for residential, public, commercial, business or industrial purposes.
- “At Risk” properties are those that the water company is required to include in the Regulatory Register that is presented annually to the Director General of Water Services. These are defined as properties that have suffered, or are likely to suffer, internal flooding from public foul, combined or surface water sewers due to overloading of the sewerage system more frequently than the relevant reference period (either once or twice in ten years) as determined by the Company’s reporting procedure.
- Flooding as a result of storm events proven to be exceptional and beyond the reference period of one in ten years are not included on the At Risk Register.
- Properties may be at risk of flooding but not included on the Register where flooding incidents have not been reported to the Company.
- Public Sewers are defined as those for which the Company holds statutory responsibility under the Water Industry Act 1991.
- It should be noted that flooding can occur from private sewers and drains which are not the responsibility of the Company. This report excludes flooding from private sewers and drains and the Company makes no comment upon this matter.
- For further information please contact Thames Water on Tel: 0800 316 9800 or website www.thameswater.co.uk

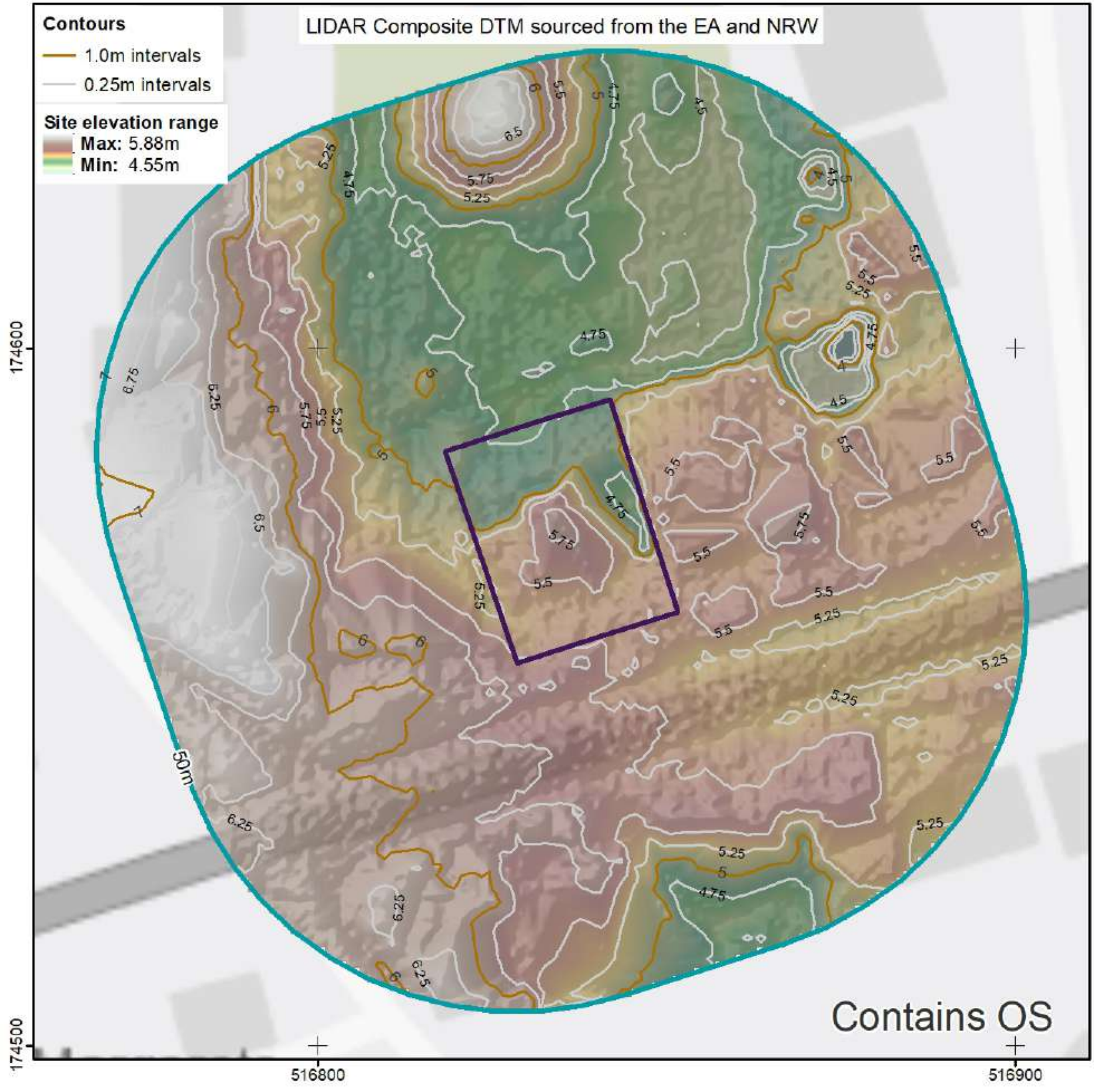
Thames Water Utilities Ltd
Property Searches, PO Box 3189, Slough SL1 4WW

searches@thameswater.co.uk
www.thameswater-propertysearches.co.uk

0800 009 4540

Appendix D

Environment Agency LiDAR ground elevation data



Contours
1.0m intervals
0.25m intervals
Site elevation range
Max: 5.88m
Min: 4.55m
LIDAR Composite DTM sourced from the EA and NRW
50m
Contains OS
174600
174500
516800
516900

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Tel: 01743 298 100

Email: info@geosmartinfo.co.uk

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The Property Ombudsman scheme

Milford House

43-55 Milford Street

Salisbury

Wiltshire SP1 2BP

Tel: 01722 333306

Fax: 01722 332296

Email: admin@tpos.co.uk

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- Normally deal with it fully and provide a final response, in writing, within 20 working days of receipt.
- Keep you informed by letter, telephone or e-mail, as you prefer, if we need more time.
- Provide a final response, in writing, at the latest within 40 working days of receipt.
- Liaise, at your request, with anyone acting formally on your behalf.

If you are not satisfied with our final response, or if we exceed the response timescales, you may refer the complaint to The Property Ombudsman scheme (TPOs): Tel: 01722 333306, E-mail: admin@tpos.co.uk.

We will co-operate fully with the Ombudsman during an investigation and comply with his final decision. Complaints should be sent to:

Martin Lucass

Commercial Director

GeoSmart Information Limited

Suite 9-11, 1st Floor,

Old Bank Buildings,

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Tel: 01743 298 100

martinlucass@geosmartinfo.co.uk

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