Thames Tideway Tunnel
Thames Water Utilities Limited

Application for Development Consent

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Tackling London's Sewer Overflows

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Thames Tideway Tunnel
Creating a cleaner, healthier River Thames

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Tackling London's Sewer Overflows

Thames Tideway Tunnel and Treatment - Option Development

Objectives and Compliance Working Group Report,

Volume 2 - Modelling and Compliance

December 2006

Thames Tideway

Thames Water

CONTENTS

1 EXECUTIVE SUMMARY

In 2005, The Thames Tideway Strategic Study (TTSS) group reported on the potential solutions which could be developed to tackle the problems of Combined Sewer Overflow (CSO) discharges to the Thames Tideway. Since the TTS Studies reported in 2005, an instruction from Defra has been received to further investigate and compare two main options for tackling the CSO discharges to the Thames Tideway. As a result, a 2006 Thames Tideway Tunnel (TTT) options assessment study was set-up, during which it was decided that further water quality modelling was required in order to assess the additional solution options against the objectives for DO in the Tideway. The TTSS modelling group was reconvened to undertake the TTT options assessment.

Two main tunnel options, namely the complete 7.2 diameter tunnel from Hammersmith to Beckton (option 1a), and the two-part East-West tunnel option (option 2a) have been put through the water quality estuary model along with their variant options (options 1b, 1c, 2b & 2c) and have been assessed against an historical set of 154 of the most significant storm events occurring over a 34 year period. Each solution has also been analysed for the frequency with which they will be beaten and hence residual spills will occur on average per year.

Changes have been made to the modelling process since the TTS Studies reported in 2005, largely as a result of the better understanding of the various input assumptions in the model. The modelling process has also been improved to include:

- The impact of population change up to 2021,
- The impact of climate change up to the 2020's,
- The impact of smaller rainfall events occurring in between the historical set of 154 events used to assess compliance; and
- Revised Sewerage Treatment Works (STW) consent standards for the proposed Thames Tideway Quality Improvements (TTQI) STW projects currently under planning.

All the above factors have been included in the determination of compliance of the various solutions ensuring that the predicted performance of each solution is as robust as possible.

An assessment has also been made against potential compliance with the draft Water Framework Directive (WFD) Dissolved Oxygen (DO) standards for estuaries and the impacts of climate change as far ahead as the 2080s. Whilst these two factors have been modelled, they have not been used to determine the compliance of the various TTT solutions. The following table summarises the model results for each of the assessed solutions:

Modelling Results Summary: Options Assessment

Option	Compliant with DO Objectives?			WFD Dissolved Oxygen compliance		34 years - Residual Spill frequency	% volume of existing overflows addressed	% of unsatisfactory CSOs addressed
	Without climate change	With Climate change 2020 *	With Climate change 2080	Intermittent	5-percentile	Spill days p.a. on average **		
1a	YES	YES	NO	YES	Moderate status	3-4	94%	100%
1b	YES	YES	NO	YES	Moderate status	9	89%	100%
1c	YES	YES	NO	YES	Moderate status	3-4	94%	100%
2a	YES	NO	NO	YES	Moderate status	As baseline	72%	53%
2b	YES	NO	NO	YES	Moderate status	As baseline	72%	53%
2c	YES	NO	NO	YES	Moderate status	As baseline	72%	56%

* Results for Climate change up to 2020 only have been used to determine overall compliance with DO objectives

** Options 2a-2c spill as frequently as the baseline due to the CSO's not intercepted, CSOs which are intercepted spill 9 times per year on average.

The following conclusions can be drawn from the TTT modelling assessment:

- The future 2021 AMP4 baseline with the various TTQI upgrades in place will not meet compliance with the DO objectives, unless a CSO solution is implemented in tandem.

- Only the main tunnel Option 1a and its variant options 1b and 1c can meet all three DO standards and hence reach compliance with the DO objectives. As a result, only option 1a and it variants can be judged to achieve fish population sustainability. Options 1a and 1c are ‘more’ compliant than option 1b, which has more residual spills.

- Options 2a, 2b and 2c all fail the DO objective and hence are less likely to achieve sustainable fish populations.

- Options 1a and 1c would result in the lowest residual spills, with a predicted 3-4 spills per year on average. Option 1b results in 9 spills on average per year based on the most frequently spilling CSO. Options 2a, 2b and 2c would result in 9 residual spills (based on the most frequently spilling CSO) on average per year from the CSOs intercepted, but would spill as frequently as the baseline for those CSOs not intercepted.

- Options 1a and 1c would intercept and treat 94% of all CSO discharges on average per year; option 1b would treat 89%. In comparison, options 2a, 2b and 2c would treat only 72% of all CSO discharges.

- The modelling results for the TTT assessment have demonstrated a greater level of robustness as they have included changes to the modelling process which show that compliance with the DO objectives can still be met from a considerably worse baseline than was the case during the TTSS studies, including the impact of climate change up to the 2020s, population increases and the impact of smaller storm events occurring before the larger, more significant storm events are assessed.

- A method has been derived for the testing compliance against draft WFD DO standards. Modelling to date has shown little difference between solution performances for the WFD directive standards with all solutions deemed complaint for the intermittent discharge standard, and all solutions improving the reliance in the Tideway achieving ‘moderate status’. If 2020’s climate change and preceding events are included, the future baseline would result in a ‘poor’ categorisation for the Tideway without a CSO solution in place; modelling for a single option (1a) showed that the Tideway would return to moderate status if a solution of this magnitude were applied.

- Potential climate change impacts as far ahead as the 2080s was also assessed. All solutions would fail the DO objective with the impact of climate change up to 2080 included, although it is acknowledged that this would be the case even if all CSO discharges were removed and hence is not a discriminator between options for the TTT assessments.

2 INTRODUCTION

In 2005, The Thames Tideway Strategic Study (TTSS) group reported on the potential solutions, which could be developed to tackle the problems of Combined Sewer Overflow (CSO) discharges to the Thames Tideway. As part of the TTS Studies, a water quality modelling group was set-up whose remit was to assess the proposed solutions against the suggested interim objectives for dissolved oxygen (DO) in the Tideway

During the set up of the 2006 Thames Tideway Tunnel (TTT) options assessment study, it was decided that further water quality modelling was required in order to assess the additional solution options against the objectives for DO in the Tideway. The TTSS modelling group was reconvened for the TTT options assessment and included members of TWUL and its consultants[1] and the Environment Agency (EA). The scope of this report covers:

- The DO objectives and modelling assessment work undertaken
- The performance of each solution in meeting to the DO objectives
- The performance of each solution in terms of frequency of residual spills.

[1] WRc Group - Estuary modelling

3 DISSOLVED OXYGEN OBJECTIVES

The TTS Study produced a suggested list of interim DO standards, which should be met by any solution option for the Combined Sewer Overflow (CSO) discharges (table 1.1).

Table 1.1: Interim Dissolved Oxygen Standards for the Tideway, derived by the Objectives Working Group

Threshold	Dissolved Oxygen Concentration (mg/l)	Duration (tides)	Allowable Return Period (years)	Allowable Failures (over 34 years of event data)
1	4	29	1	34
2	3	3	3	11
3	2	1	5	6
4	1.5	1	10	3

Note: A tide is a single ebb or flood.

The interim DO standards were derived such that a future Tideway condition, which met the suggested standards, would be adequately protective of the ecology of the Thames Tideway. The standards state absolute levels for dissolved oxygen and stipulate for how long and how frequently the Tideway oxygen level can fall below this value and still be compliant, thus:

- **Threshold 1** - the DO level in the Tideway must not fall below 4mg/l for longer than 29 consecutive tides on more than one occasion per year.
- **Threshold 2** - the DO level in the Tideway must not fall below 3mg/l for longer than 3 consecutive tides on more than one occasion every 3 years.
- **Threshold 3** - the DO level in the Tideway must not fall below 2mg/l for longer than 1 tide on more than one occasion every 5 years.
- **Threshold 4** - the DO level in the Tideway must not fall below 1mg/l for longer than 1 tide on more than one occasion every 10 years.

In order for the Tideway to be compliant with the overall DO objective, any proposed solution must ensure that the future Tideway water quality meets all three standards all of the time i.e. it is not acceptable for a solution to comply with thresholds 1 and 2, but fail on threshold 3. The allowable durations were included to reflect that fish populations can withstand moderately low DO levels (e.g. 4mg/l) for a period of time before this level becomes potential lethal, whereas much lower concentrations (e.g. 2mg/l) are likely to cause lethality within a much shorter time frame (i.e. 1 tide). The return period for each threshold was included to reflect the concept of sustainability i.e. that fish populations are more likely to be able to withstand moderately low DO levels more frequently without affecting the ability of a given fish species to maintain sustainable population levels.

The return periods are reflected in the modelling results by the addition of an 'allowable failures' level. This allowable failures level is based on the return period for which the predicted DO can fall and still be compliant within the 34-year data set used in the modelling e.g. for Threshold 1 (4mg/l standard), the DO can fall below the 4mg/l for 29 tides on one occasion per year; because the 154 for events have been drawn from 34 years of data, the DO is able to fall below 4mg/l on 34 occasions and still be compliant. The allowable failures line is included in the modelling outputs to visually demonstrate whether a solution is compliant or not.

The interim DO standards were subsequently accepted as adequate to protect the sustainability of fish populations following a comprehensive three year fisheries study which ran in parallel with the TTSS water quality modelling study. The agreed TTS Study DO standards were therefore adopted as the measure against which the six TTT solution options would be tested for DO Objective compliance.

4 THAMES TIDEWAY TUNNEL MODELLING SET UP

4.1 WATER QUALITY MODELLING – PREVIOUS STUDIES

In order to assess the performance of the proposed six solutions against the DO objectives, an estuary simulation model was selected and developed. Previously, two models were utilised during the TTS Studies to ensure that the representation of the Tideway water quality dynamics was acceptable. For the TTT study however, it was agreed that the modelling would be sufficiently robust using a single water quality model developed by WRc, as both models were producing similar results. Of the two models used during the TTS Studies, WRc's one-dimensional Quests model proved to be the most efficient in terms of run time and presentation of results, hence Quests was selected as the modelling tool for the TTT study; the Quests model is referred to as 'the model' for the remainder of this report.

The model was used to simulate future scenarios for Tideway water quality, including the impact of the proposed solutions on Tideway DO.

4.2 MODEL REFINEMENTS FOR THE TTT STUDY

Several refinements have been made to the modelling process used for the TTT study since the TTS Studies reported in 2005. These changes are largely as a result of improvements in the coverage of input data used in the model, which have emerged from identification of data gaps from the TTS Study. The elements of the modelling process carried over from the TTS Study are outlined in the proceeding section.

During the TTS Study, the model was calibrated using inputs from:

- Recorded Sewage Treatment Work (STW) data
- The EA's Automatic Quality Monitoring Stations (AQMS)
- Rainfall data
- The detailed Thames Water sewerage network model of the Mogden, Beckton and Crossness catchments.
- Various monitoring data

WRc were also commissioned to refine their model to produce a compliance testing procedure (CTP), which would create a systematic method of assessing the improvements made in compliance against the DO standards.

The CTP comprised of a set of the 154 historically most significant summer period rainfall events selected from a 34-year (1969-2002) period. The events were chosen via a sifting process, which looked at a combination of event intensity, duration, size and total CSO discharge load generated by the event. In selecting the 154 most significant events, a range of solution scenarios could be tested against the events to assess the number of DO standards breaches each scenario would generate. In order to determine the number of standard breaches each solution scenario would generate, the modelled DO profile in the river after each event was examined (see figure 1.1) as well as outputs from the models showing compliance plots for the full set of 154 events along the Tideway (see figure 1.2). The level of compliance achieved by each scenario allowed the Objectives Group to determine how compliant the proposed solutions would be against the interim standards.

Figure 2.1 – example 'half-tide' plot from the TTS Studies modelling report showing the impact of a single storm event on DO levels (mg/l) for 1 day along 1km sections of the Thames Tideway

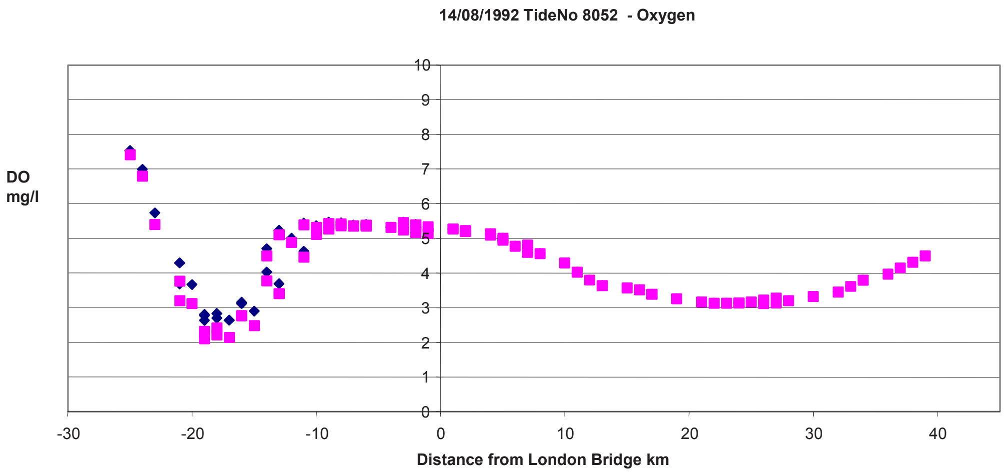
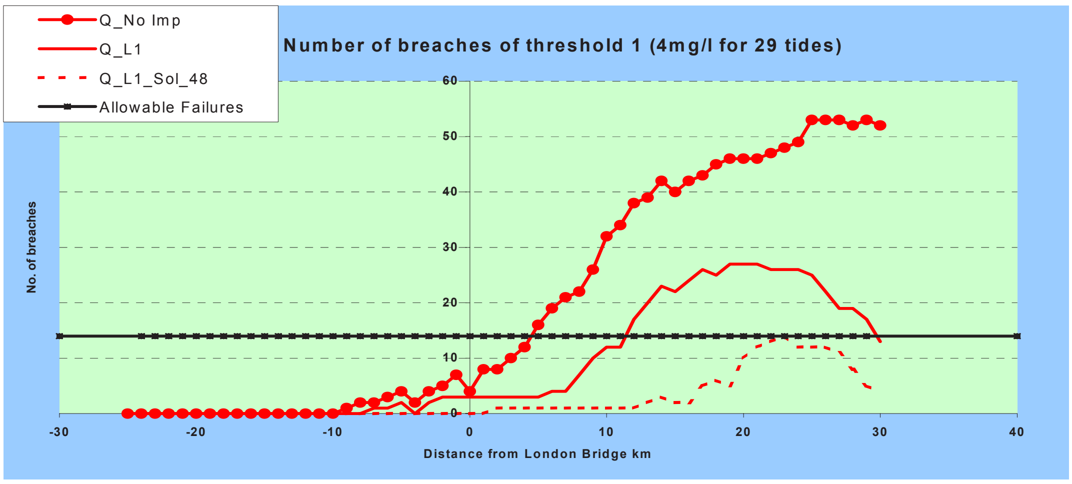


Figure 2.2 – compliance plot showing number of failures of the 4mg/l DO standard generated by solution option A (high) along 1km sections of the Tideway for all 154 events (TTS Studies modelling report output).



Details of how the models were chosen, calibrated and prepared for the CTP are detailed within a separate report: *The preparation and application of the modelling Framework for the Compliance Testing of Options: Audit Report, Sept 2003*.

At the end of the TTS Studies modelling work, is was concluded that only the optimised solution A (ref), upon which TTT option 1a is based would be complaint with the DO objective.

4.2.1 Model Limitation – TTS findings.

Before detailing the changes made to the modelling process for the TTT modelling study, it is important to consider the model limitations identified during the TTSS. As discussed, during the TTS Studies two estuary models were put through an extensive calibration programme prior to the commencement of the compliance testing process in 2003. However, it was not possible to obtain perfect agreement between modelled and observed conditions due, in part, to a lack of good quality input data. It was also concluded that there were some processes occurring in the estuary, which were not sufficiently well understood to be able to accurately reproduce them in the models. The following were considered to be the main sources of error: -

- The presence of algae is a major factor in the oxygen balance in the Tideway. Although attempts were made to include the algal component in the models, it was not possible to simulate growth and decay with any degree of confidence and all compliance testing was carried out with the algal component in the models switched off.

- Observed DO levels in the Tideway show a correlation with the spring/neap cycle, particularly in the middle reaches. It has been hypothesised that this may be due to the re-suspension of deposited material, creating an increased oxygen demand. Lack of available data and limitations in the modelling processes prevented this effect being modelled.

- The quality of the tributaries, including the freshwater Thames, varies diurnally and also changes rapidly under high flow conditions, particularly when rainfall occurs after hot, dry spells. This is due to the effects of urban run-off and variations in quality of the sewage effluent that is discharged to most of these rivers. Lack of comprehensive data for these tributaries resulted in the need to use mean quality conditions for these significant inputs.

- The performance of the Sewage Treatment Works (STW) which discharge directly to the Tideway is one of the major factors affecting DO levels. Fairly comprehensive data sets exist for continuous loads discharged from the works but there are gaps in this data and very little information is available on the quality of intermittent discharges from the Sewage Treatment Works STW and Mogden & Crossness storm tanks, which have a significant impact on DO levels during wet weather. The compliance testing process used fixed concentrations and flows from the STWs to establish pre-event conditions; these would have differed from the actual works performance.

- Investigations carried out as part of the TTSS project revealed that quantities of activated sludge are sometimes discharged from the Mogden STW at times of high flow. Further laboratory tests confirmed that this discharge could have a major effect on DO levels in the upper reaches. Despite efforts to recreate the effect of activated sludge in Mogden storm discharges, the lack of data on the load imposed by this discharge and lack of knowledge of which storm events trigger the release of activated sludge, precluded its inclusion in the models.

- Of the 57 CSO which discharge to the Tideway, indicative flow data only exists for around 9 of the pumped discharges and there is also some historical quality data. There is no flow data and virtually no quality data for the remainder. Obviously, comprehensive flow and quality data is essential for all these discharges if individual rainfall events are to be modelled precisely. It is likely that, depending on rainfall patterns, the quality of discharges from these outfalls will vary considerably throughout the event and each CSO will display a different pattern of discharge. It is also likely that antecedent conditions will influence the amount of solid matter flushed from the system. Under these conditions it is unlikely that it will ever be possible to acquire sufficiently comprehensive data. The sewer model was therefore used to generate flow and quality data for all the discharges from the CSOs and this data was fed into the estuary models. The sewer model has been refined over many years and represents the latest state of the art in hydraulic modelling. It is unlikely, however, that it can mirror the actual loads discharged to the river under all types of rainfall events, and it has no facility for generating data on re-suspension of silt and consequent discharge to the river, which is thought to occur under some conditions of high velocity in the sewers.

It is important that these possible sources of error are considered when data from the models is analysed. It is noted that several of these sources of error are a consequence of the lack of availability of comprehensive and good quality input data. As a result, a range of data collection and model calibration studies were proposed following the submission of the TTS Study reports and this data has informed subsequent modelling that has taken place. Despite the limitations, at the end of the calibration phase, the models were considered to provide a reasonable indication of the dynamic changes in DO that occur in the river following rainfall events; the models represent a very robust and sophisticated tool for testing solutions.

4.3 TTT – Model refinement - 2006

As discussed, several changes were made to the modelling process in the interim period between the TTS Studies reporting in 2005 and the commencement of the TTT study in September 2006.

4.3.1 Thames Tideway Quality Improvements (TTQI) – Sewage Treatment Works Assumptions

The initial TTS Studies indicated that improvements would be required to the STWs in order to achieve compliance with the DO objective and that dealing with the CSO problems in isolation would not be sufficient to ensure compliance. There were two areas of improvement required for the STWs.

- A reduction in continuous dry weather loads from the STWs discharging to the middle reaches (achieved by improved quality in continuous effluent discharge)
- A reduction in intermittent storm tank discharges during wet weather from the Mogden, Crossness and Beckton works (achieved by increasing flow to full treatment [FFT] capacity of the Tideway works to prevent diversion to storm tanks or CSOs)

In order to achieve both of these requirements, the EA proposed a revised set of standards to be applied to the STWs in the model and which would be considered improvements to the STWs necessary as part of the AMP4 process (table 3.1).

Table 3.1 Existing and Proposed STW Standards in 2003.

	Existing Standards 2003			*Upgraded Standards Proposed in 2003*		
	FFT*	**BOD**	**NH3**	**FFT***	**BOD**	**NH3**
	Ml/d	*mg/l*	*mg/l*	*Ml/d*	*mg/l*	*mg/l*
Mogden	690	11	1	1075	11	1
Beckton	1420	6	1	1800	5	1
Crossness	982	10	7	1485	5	1
Longreach	298	20	25	298	15	15
Riverside	177	15	20	177	7	7

* FFT = Flow to Full Treatment ($M^3 X 10^6$)

As a result of the required STW upgrades identified during the TTS Studies, Thames Water are required to undertake the improvement works needed to meet these new STW consent standards. The planning and design for the upgrades are underway as part of the current Asset Management Plan 4 (AMP4) programme of works. These upgrade work projects are referred to as The Thames Tideway Quality Improvements (TTQI).

A TTQI modelling exercise was undertaken through the course of 2006, which reviewed the TTSS modelling process and investigated the impact of varying the proposed STW flow and quality consent improvements. The driver for these model investigations was to ensure that there was adequate justification for the individual planning applications required for the upgrades works at each of the three main STWs (Mogden, Beckton and Crossness). Many of the modelling changes outlined in the remainder of section 3 of this report were introduced as a result of a modelling review that took place for the TTQI modelling. This was because the changes in the input values and assumptions had altered the predicted performance of the proposed TTSS solution A (ref) such that it was no longer compliant with the DO objectives even with the STW upgrades in place.

4.3.2 Population Increases – 2021

The modelled solution performance undertaken for the TTS Study was based on 2001 population and hence 2001 levels of wastewater generation in London. For the TTT study it was considered that the population increases up to 2021 should be factored into the sewerage network modelling to take account of the additional wastewater that would be generated once any potential solution was in place.

4.3.3 Dry weather flow changes

Flow and load surveys for each sewerage catchment were undertaken following submission of the TTS Studies reports. Data from the surveys was used to verify the STW input assumptions used in the modelling and as a result changes were made to the STW dry weather flow assumptions in the sewerage network models as well as the estuary model.

4.4 STW QUALITY ASSUMPTIONS

To better reflect the performance of the upgraded STW, changes were made to the quality assumptions of the STW discharges during dry and wet weather to reflect that the treated quality of STW effluent during dry weather is higher than it is during wet weather when the flow arriving at in this report are included in a separate report: *Thames Tideway Project - Quests modelling results Report, Dec 2006.*

4.4.1 Revised STW upgrade assumptions: AMP4 baseline

The main change to result from the TTQI model review and sensitivity check was the requirement to alter the consent improvements required to meet the objectives. As discussed, the previous STW improvement baseline was no longer allowing the TTSS solution A (ref) to reach compliance largely as a result of the changes in dry weather flow assumptions and the inclusion of population increases to 2021. Sensitivity analysis was therefore carried out on a range of different STW upgrade scenarios, which also factored in changes to the smaller Riverside and Long Reach STW downstream of Beckton. It was found that further improvements at these two smaller downstream works were having a greater improvement on the DO levels in the middle reaches of the estuary. By improving the quality of Riverside and Long Reach STW discharges to a similar level as proposed at Beckton and

Crossness, the estuary could once again meet compliance with the TTSS solution option A(ref) in place and therefore achieve the same benefits as the previous STW upgrade consents derived during the TTS Studies. The improvement in DO predicted as a result of the Riverside and Long Reach improvements allowed the proposed consents at Beckton and Crossness to be relaxed but still achieve compliance with the DO objectives. The revised TTQI STW improvements have therefore been taken forward as the modelled 'baseline' for the TTT modelling assessment (table 3.2). This modelled baseline is henceforth referred to as the AMP4 baseline.

Table 3.2 Previous TTSS STW Standards and revised TTQI STW standards used for the TTT AMP4 baseline

	Upgraded STW Standards Proposed in 2003			*Revised TTQI STW standards used for TTT AMP4 baseline*		
	FFT*	**BOD**	**NH3**	**FFT***	**BOD**	**NH3**
Units	*Ml/d*	*mg/l*	*mg/l*	*Ml/d*	*mg/l*	*mg/l*
Mogden	1075	11	1	1064	11	1
Beckton	1420	5	1	1800	8	1
Crossness	1485	5	1	1118	8	1
Longreach	298	15	15	337.5	10	3
Riverside	177	7	7	206	8	1

4.4.2 Long Reach and Riverside catchment models

The Riverside and Long Reach STWs were not explicitly modelled in the CTP testing undertaken for the TTS Study modelling work as it was considered that the much larger Beckton and Crossness STWs dominated the water quality of the middle reaches of the estuary. It was considered that representing the smaller Riverside and Long Reach STWs as constant inputs would be sufficient to model their effects; however, because the changes in quality consents for these works were so important to allowing a CSO solution to meet compliance, the TTT modelling group agreed that for robustness, the two STW's catchments should be fully represented by separate sewerage network models as was the case for the Mogden, Beckton and Crossness catchments. These models were developed and the inputs included in the TTT modelling assessment.

4.4.3 Inclusion of preceding events

AS part of the CTP developed for the TTSS modelling, each of the historical rainfall events was modelled as a discrete event that occurred following a 6-week period of dry weather assumed in the model. This assessment process was adopted because it was considered too time consuming to run the estuary model for a continuous time series of actual rainfall data over a long enough period to ensure that statistically, the historically largest rainfall events would be modelled. At the time, it was considered that by modelling the events individually from 34-year period of rainfall data, the CTP would be an adequate tool to allow comparison of solution performance relative to each other but would ensure that the number and spread of historical events was sufficient to be considered statistically robust.

Despite this conclusion, sensitivity testing at the start of the TTT modelling demonstrated that the model was particularly sensitive to the 'background quality' of the estuary water before any storm event was assessed. The sensitivity modelling showed that if smaller wet weather discharges had occurred in the 6 week period before a major storm event occurs, the estuary water would already be of a slightly poorer quality due to the continuous wet weather discharges from the STW but also smaller CSO spills that may have occurred in this period; as such, an assessed storm event was more likely to lead to failure of the DO standards than if the modelled background quality of the estuary water was 'good' as was assumed in the dry weather assumption of the CTP. The TTT modelling group agreed that the TTS Study CTP was fine as a comparator tool to assess relative performance of solutions, but by not modelling the other wet weather discharges that occur before a major storm event is assessed, the TTSS CTP was over optimistic in it's assessment of how a solution would perform in reality. There was therefore a need to include the impact of rainfall events that preceded the main 154 events in a revised CTP; this was a recommendation for further work as highlighted in the TTS modelling studies (report: *TTSS – Objectives Working Group Report: Vol 2, modelling Study, Feb 2005*). The TTT modelling group therefore developed a simplified representation of the sewerage catchments for each of the modelled solutions and AMP4 baseline such that the 'preceding events' for each of the main 154 storm events could be modelled in the 6-week modelled period leading up to the DO standard compliance assessment. The details of how this simplified modelling was developed are included in a separate report: *TTT: Thames Tideway Project - Quests modelling results Report, Dec 2006*

4.4.4 Sewerage Network models – changes

As discussed in section 2, Thames Water's sewerage network model (based on the Infoworks modelling software) was used to provide the predicted CSO discharges for the AMP4 baseline and each of the TTT solutions. For each of the solutions, a separate solution model was developed and used to predict the changes in CSO discharge frequency and tunnel pump-out. Before the solution models were developed however, several changes had to be made to the base catchment models for Mogden, Beckton and Crossness to accommodate the population increases and also to develop the models for Long reach and Riverside STWs for use as inputs to the estuary model. As well as these changes, several more subtle changes had been made to the base models in between their use for the TTSS reporting and the commencement of the TTT modelling assessment; All of these changes as well as how the models were used are documented in appendix 1.

4.4.5 Climate Change – 2020's

With the inclusion of population increases up to 2021, it was decided that the future conditions being modelling for the solutions and baseline should also take account of the potential climate change impacts up to the 2020's. Previous climate change modelling undertaken for the 2080's for the TTS Studies demonstrated that the largest influence on compliance was the increase in estuary water temperature as a result of increases in air temperature and summer solar radiation. As a result, climate change impacts for the 2020's were focused on temperature changes only and used the UKCIP02 'medium low' and 'medium high' emissions scenarios to input water temperature changes into the solution modelling.

4.5 CLIMATE CHANGE ASSESSMENT – 2080'S

A further Climate change sensitivity was undertaken up to the 2080's and all scenario runs were undertaken for these predicted climate change impacts. The methodology used was identical to the climate change assessment runs used in the TTS Studies with the exception of the hydrology changes (freshwater flow inputs to the Tideway) as these were not considered to significantly impact on compliance in the middle reaches of the estuary.

The TTSS modelling group devised a method by which UKCIP predictions for climate change could be used to assess the performance of the solution under future climate change conditions. It was originally suggested that the stochastic rainfall model used in the phase 2 CTP could be applied in generating a future rainfall data set which would drive the sewerage network model and produce revised storm spill data to run the estuary models. However, future UKCIP rainfall series are based on a single gauge at Greenwich only, and it was concluded that interpolating the entire catchment from a single gauge would not give the spatial confidence required from the results.

An analysis was therefore carried out between two UKCIP rainfall series at Greenwich for now (2000) and predicted in 2080 (both based on the medium high scenario). 2080 was considered the most distant forecast that could be assessed with reasonable confidence in the results whilst representing a robust assessment of the future solution performance at some point in its projected long life operation.

The storm events as predicted by the UKCIP scenarios in both the 2000 and 2080 sets were grouped into 'event size' categories according to their depth. A comparison was then made between the depths categories of the two rainfall sets such that a ratio was determined of all the depth categories between the 2 years. The ratios were then used to calculate how the generated storm events from the TTSS CTP would change in 2080. For the summer, the ratios showed that there would be an increase in bigger depth (greater intensity) rainfall events but a decrease in the frequency of lower depth events. Using the figures for the ratios, the current rainfall events used in the TTSS CTP were adjusted accordingly to create a set of 2080 storm events to run through the CTP and these where then put through the model to create a 2080 scenario. (tables 3.3a-c)

In addition to this, the environmental conditions were altered to reflect the climatic and environmental input conditions expected in 2080. This included temperature predictions, changes in solar radiation and dew point temperature all used to calculate changes in river temperature and air temperature within the model. All changes were based on historical data using UKCIP predictions for climatic changes. Sea level changes, which affect tidal levels in the estuary, were included in the modelling.

Tables 3.3a-c showing the difference in intensity of rainfall events between the 2000 and 2080 rainfall series for Greenwich.

Present Data (Greenwich 2000) after manual grouping. 10

No events/month idepthcategory

Month	6-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
Apr	0	0	0	0	0	1	0	0
May	0	0	0	0	1	0	0	0
Jun	0	0	0	3	0	0	0	0
Jul	3	3	1	2	0	0	0	0
Aug	6	11	6	0	2	1	0	1
Sep	3	3	4	4	0	0	1	0
Oct	0	0	0	2	1	0	1	2
Grand Total	12	17	11	11	4	2	2	3

Future Data (Greenwich 2080) after manual grouping. 10

No events/month idepthcategory

Month	6-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
Apr	0	0	0	0	0	0	2	2
May	0	0	0	1	1	0	0	0
Jun	0	0	0	2	0	0	1	0
Jul	1	3	3	1	0	1	0	0
Aug	5	2	4	2	1	1	2	3
Sep	0	2	5	3	1	0	0	0
Oct	0	0	1	0	0	0	0	3
Grand Total	6	7	13	9	3	2	5	8

Difference in event numbers (2080-2000) 10

Month	6-10	10-15	15-20	20-25	25-30	30-35	35-40	>40
Apr	0	0	0	0	0	-1	2	2
May	0	0	0	1	0	0	0	0
Jun	0	0	0	-1	0	0	1	0
Jul	-2	0	2	-1	0	1	0	0
Aug	-1	-9	-2	2	-1	0	2	2
Sep	-3	-1	1	-1	1	0	-1	0
Oct	0	0	1	-2	-1	0	-1	1
Grand Total	-6	-10	2	-2	-1	0	3	5
Pro rata to 34 years	-20.4	-34	6.8	-6.8	-3.4	0	10.2	17
	Less events		No change			More events		

4.5.1 CSO quality and sewer retention periods

An additional component which was considered for inclusion in the runs, was the impact of increased sewer sediment and subsequent ‘flush out’ following extended dry periods expected during the summer with climate change. This effect is referred to as ‘first flush’ and represents a higher pollutant loading from CSOs during a large rainfall event, which re-erodes the sediment accumulated during drier spells. As mentioned in the model limitation section of this report, the CTP design and the lack of comprehensive observed CSO quality data for calibration makes it extremely difficult to apply varying CSO quality loads with different events and antecedent conditions. Although it is acknowledged that possible longer drier spells in the summer months would increase polluting loads for climate change scenarios, it is not possible to include this in the current compliance testing framework without substantial improvements to the sewerage network model’s functionality and a very comprehensive monitoring programme to analyse CSO discharge quality under different rainfall patterns.

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5 CTP RESULTS DISCUSSION

The requirement of the TTT modelling group was to provide an assessment of the likely future performance of the 2 main TTT solutions and their variant options against the DO Standards, in turn providing fish risk data to be assessed as part of the Cost Benefit studies.

In the summer of 2003, the TTSS Modelling Group agreed on the model as 'fit for purpose'; defined as being suitable for use in the testing of CSO solutions for compliance. A similar view was taken by the TTT modelling group in 2006 once the changes to the modelling process had been agreed and initial simulations checked. The final list of TTT solution options and intervention levels to run through the revised CTP were agreed by the TTT Objectives Group and used in the final assessment. The solution scenarios were assessed against an 'AMP4 baseline' to represent the improvement made in DO levels against the theoretical future baseline conditions i.e. the conditions with the proposed TTQI STW upgrades in place at 2021. The following scenario runs and their detail are included below:

- ***Main Option 1a; complete tunnel – 7.2m diameter:*** 154 storm events run through the estuary model for a future 2021 baseline with the proposed TTQI STW upgrades in place, but with TTT option 1a as CSO tunnel solution in operation. Option 1a is the complete main tunnel of 7.2m diameter running from Hammersmith to Beckton with a link tunnel capturing Abbey Mills discharges and joining the main tunnel at Charlton. This option requires additional treatment capacity at Beckton of 536Ml/d giving a total FFT at Beckton of 2336Ml/d when the TTQI upgrade (1800Ml/d) is included; this additional treatment is required to allow the tunnel to be emptied and treated in 48 hours after the storm has receded. This TTT option is essentially the same as option A(ref) identified as the preferred solution from the TTS modelling Studies.

- ***Variant Option 1b; complete tunnel – 6m diameter:*** 154 storm events run through the estuary model for a future 2021 baseline with the proposed TTQI STW upgrades in place, but with TTT option 1b as the CSO tunnel solution in operation. Option 1b is a variant of 1a in that the tunnel route and set-up is similar to option 1a, but has a smaller tunnel diameter of 6m and hence a smaller storage capacity than option 1a. As the storage is smaller than 1a, 1b requires a smaller additional treatment capacity at Beckton of 305Ml/d giving a total FFT at Beckton of 2105Ml/d when the TTQI upgrade (1800Ml/d) is included.

- ***Variant Option 1c; complete tunnel – Direct Abbey Mills link:*** 154 storm events run through the estuary model for a future 2021 baseline with the proposed TTQI STW upgrades in place, but with TTT option 1c as the CSO tunnel solution in operation. Option 1c has the same volume and dimensions as option 1a but has a direct tunnel linking Abbey Mills to Beckton as opposed to joining the main tunnel at Charlton.

- ***Main Option 2a; East-West tunnel – Direct Abbey Mills link – 13m diameter:*** 154 storm events run through the estuary model for a future 2021 baseline with the proposed TTQI STW upgrades in place, but with TTT option 2a as the CSO tunnel solution in operation. Option 2a is a two-part tunnel solution that has a western tunnel linking Hammersmith to Heathwall and an eastern tunnel linking Abbey Mills to Beckton STW. The CSOs in between Heathwall and Beckton are not intercepted. The western tunnel returns stored discharges to the sewerage system once the storm has subsided where it eventually flows back to Beckton and Crossness STWs for full treatment. The eastern section is a 13m-diameter tunnel transferring flows from Abbey Mills to Beckton where it is fully treated. This option requires additional treatment capacity at Beckton of 198Ml/d giving a total FFT at Beckton of 1998Ml/d when the TTQI upgrade (1800Ml/d) is included; this additional treatment is required to allow the Eastern and Western tunnels to be emptied and treated in 48 hours after the storm has receded. This TTT option is essentially the same as the two-part solution identified in the independent review of the TTSS by Jacobs-Babtie as commissioned by Ofwat.

- ***Variant Option 2b; East-West tunnel – Direct Abbey Mills link – 10m diameter:*** 154 storm events run through the estuary model for a future 2021 baseline with the proposed TTQI STW upgrades in place, but with TTT option 2b as the CSO tunnel solution in operation. Option 2b is identical to option 2a except the eastern section of the tunnel has a smaller 10m diameter and hence smaller storage capacity. This variant solution was designed to have a similar residual spill frequency as option 2b, but because it has a smaller storage capacity it therefore requires a much larger increase in treatment capacity at Beckton to ensure that the tunnel can be pumped out to treatment whilst the tunnel is still filling. This option therefore requires additional treatment capacity at Beckton of 900Ml/d Ml/d giving a total FFT at Beckton of 2700Ml/d when the TTQI upgrade (1800Ml/d) is included.

- ***Variant Option 2c; East-West tunnel –Abbey Mills to Beckton link via Charlton:*** 154 storm events run through the estuary model for a future 2021 baseline with the proposed TTQI STW upgrades in place, but with TTT option 2c as the CSO tunnel solution in operation. Option 2c is similar to option 2a with the exception that the eastern section of the tunnel diverts to, and intercepts Charlton CSO before terminating at Beckton. The storage capacity is similar to that of the eastern section of 2a hence this option requires the same treatment set up as option 2a with an additional treatment capacity at Beckton of 198Ml/d giving a total FFT at Beckton of 1998Ml/d when the TTQI upgrade (1800Ml/d) is included.

All Scenarios described above were undertaken with all the modelling changes as described in section 3 and including the impact of preceding events, population increases and climate change up to 2021.

5.1 DO STANDARD ANALYSIS

Sensitivity testing undertaken for the TTT modelling demonstrated that there was very little variation in levels of compliance between the different TTT options for DO Thresholds 2 (3mg/l) and 3 (2mg/l) hence much of the analysis focused on DO threshold 1 (4mg/l standard). This standard has been adopted by the Cost Benefit Group as the key indicator for significant events, which affect fish populations in the estuary. The TTS Studies used threshold 2 as the indicator on the basis that 3mg/l was a critical DO likely to lead to mortality of most species if exposure to this level was prolonged. Threshold 1 however was considered as the differentiator for the TTT studies because it showed the most variation between solutions but also because it is the DO level at which sensitive migration movements of sensitive species such as salmon are adversely affected and on occasions may result in mortality of Salmon and other sensitive species. It is also acknowledged that some less sensitive species exhibit ‘avoidance behaviour at 4mg/l DO or less which prevents full use of estuary habitat for feeding and breeding which may influence population sustainability. As stated in section 2 it is important to understand that in order to be compliant with the DO objective, each solution must pass all three DO standards to adequately protect the sustainability of all fish species, but for the remainder of this report, the compliance of solutions with the DO objective largely focuses on the 4mg/l standard.

5.2 2006 CTP Results

Table 4.1 highlights the factors that were included in each of the model run scenarios
With the scenario labels which have been used in the graphical outputs

Table 4.1 – Plotting labels for model results

Label	Climate Change included[2]	Pre-ceding events included
AMP4 Baseline		
AMP4_baseline_A	No	No
AMP4_baseline_A_2020_PE	Climate Change -2020	Yes
AMP4_baseline_A_2080RF_PE	Climate Change -2080	Yes
Option 1a		
Main_7.2m_A	No	No
Main_7.2m_A _2020_PE	Climate Change -2020	Yes
Main_7.2m_A _2080RF_PE	Climate Change -2080	Yes
Option 1b		
Main_6m_A	No	No
Main_6m_A _2020_PE	Climate Change -2020	Yes
Main_6m_A _2080RF_PE	Climate Change -2080	Yes
Option 1c		
Main_AMtoBeckton	No	No
Main_AMtoBeckton_2020_PE	Climate Change -2020	Yes
Main_AMtoBeckton_2080RF_PE	Climate Change -2080	Yes
Option 2a		
EW_direct_13m_A	No	No
EW_direct_13m_A _2020_PE	Climate Change -2020	Yes
EW_direct_13m_A _2080RF_PE	Climate Change -2080	Yes
Option 2b		
EW_direct_10m_A	No	No
EW_direct_10m_A _2020_PE	Climate Change -2020	Yes
EW_direct_10m_A _2080RF_PE	Climate Change -2080	Yes
Option 2c		
EW_via_charlton_A	No	No
EW_via_charlton_A _2020_PE	Climate Change -2020	Yes
EW_via_charlton_A _2080RF_PE	Climate Change -2080	Yes

In terms of compliance with the DO objectives, the final results, which have been used to determine whether a solution is compliant, are the scenarios with both 2020 climate change and preceding events included (highlighted in blue text in table 4.1) as this is the predicted condition for when the tunnel becomes operational. As described in the TTS modelling Studies, the impacts observed as a result of climate change up to 2080 are as a result of the further increases in the water temperature of the river which alters the biological dynamics of the estuary in a way which would be difficult to mitigate against even if all CSO discharges into the estuary were intercepted and treated; therefore, a CSO solution is unlikely to achieve compliance using the 2080 compliance scenarios described. It would take further improvements in the treatment at the major STWs as well as the treatment quality of the tunnel discharge for the impact on DO objective compliance to be realised; this would be

[2] Climate change - 2020 scenarios include predicted temperature changes up to 2020 only
Climate change - 2080 scenarios include a 2080's perturbed rainfall series and sea level rise as well as the predicted 2080's temperature changes.

something that would need to be addressed in future AMPs and not as part of a CSO solution assessment.

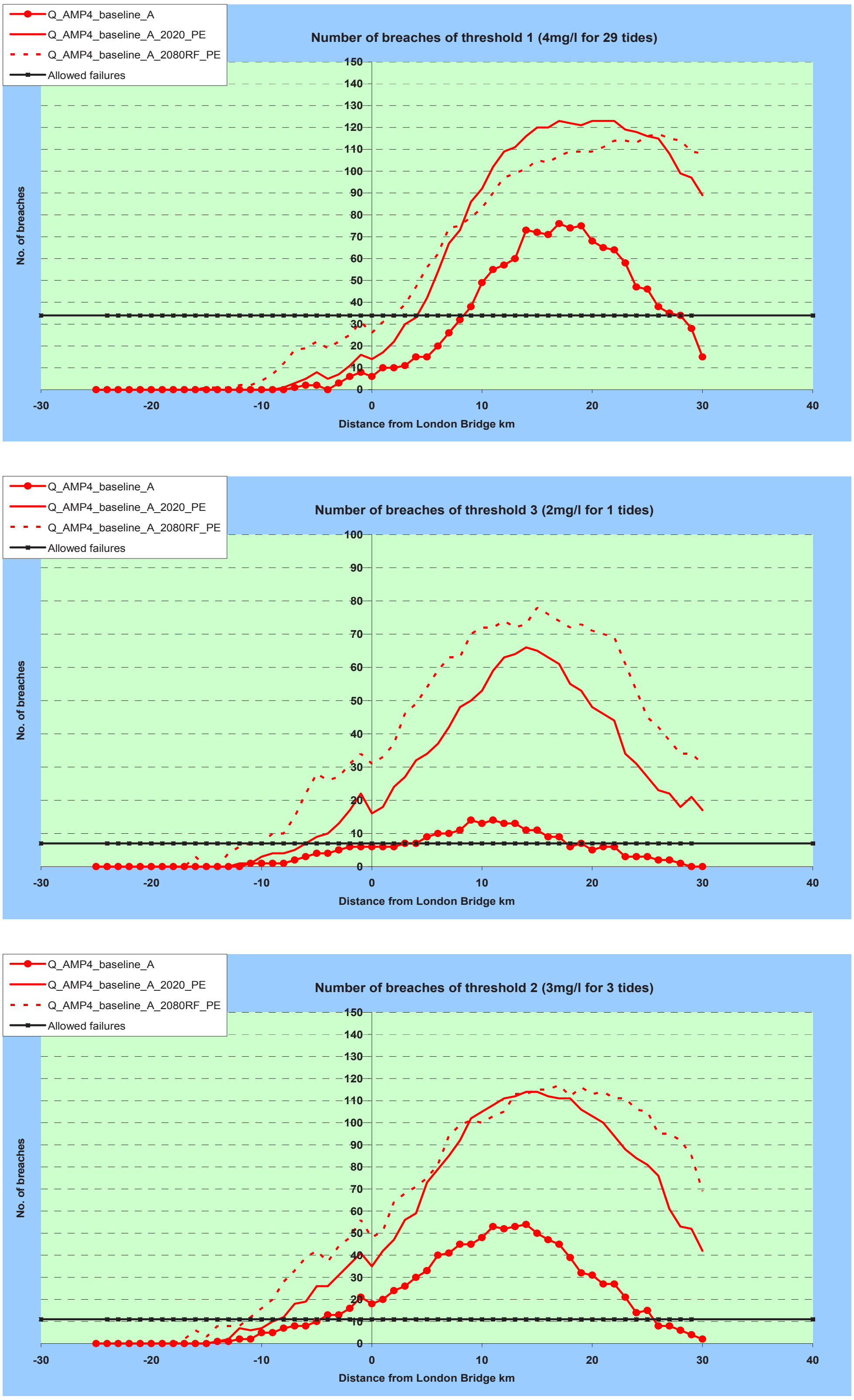
5.3 THE AMP4 BASELINE:

Figure 4.1 shows the result of the various AMP4 baseline runs for all three DO standards. The results show that when the AMP4 baseline was run without climate change impacts and without preceding events (thick, dotted line), the TTQI STW upgrades alone would not be adequate to meet compliance with any of the 3 DO standards in both the upper and middle sections of the Tideway. This was a significant change from the previous TTS modelling Studies which had shown that the AMP4 STW upgrades would result in compliance with the DO standards in the upper Tideway and would only marginally fail in the middle reaches. The change observed in the TTT modelling studies AMP4 baseline is as a result of the various modelling processes that have been incorporated; these include changed DWF inputs as a result of flow and load surveys, input of 2021 population increases and representation of Long Reach and Riverside STW using separate catchment models.

When climate change up to 2020 is included along with preceding events, the level of non-compliance increases with more breaches of all three DO standards. The most significant increase is seen for the 3mg/l and 2mg/l DO standards. This result is because of the poorer quality of estuary water predicted in the lead up to each of the 154 storm events (preceding events) but also the higher river temperatures predicted for 2020 resulting in lower DO saturation and faster reaction rates which deplete DO more rapidly.

It is evident from the AMP4 baseline results that a further improvement is required to reach DO objective compliance; hence, the various proposed TTT CSO solutions were assessed.

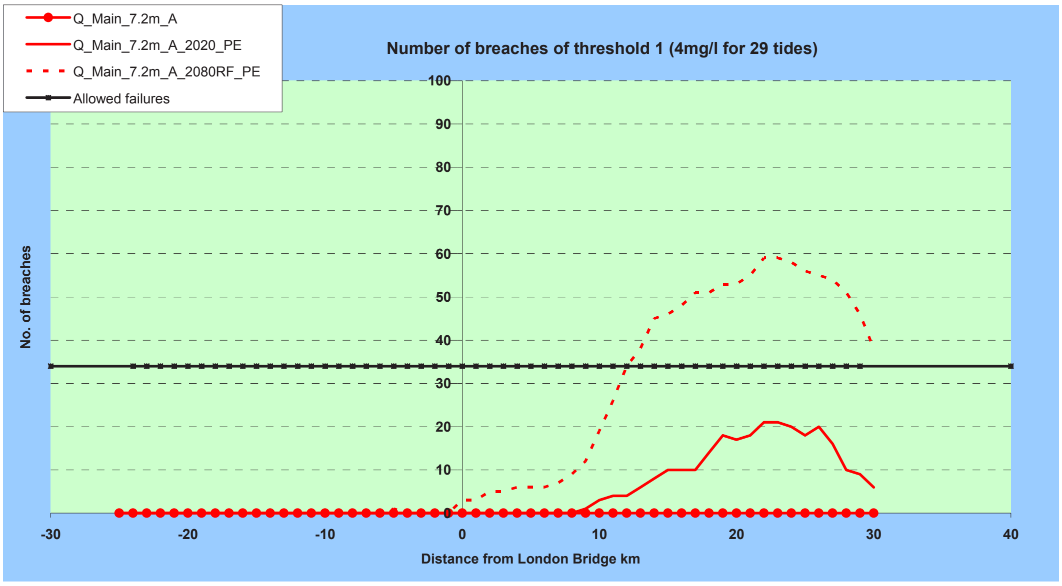
Figure 4.1: Modelling results for the AMP4 baseline – for all three DO standards



5.4 MAIN OPTION 1A; COMPLETE TUNNEL – 7.2M DIAMETER

Modelling option 1a had a significant impact on compliance with the DO standards compared to the AMP4 baseline conditions: The results for the 4mg/l standards are shown in figure 4.2.

Figure 4.2: Modelling results for the AMP4 baseline – For Option 1a, for the 4mg/l standard.



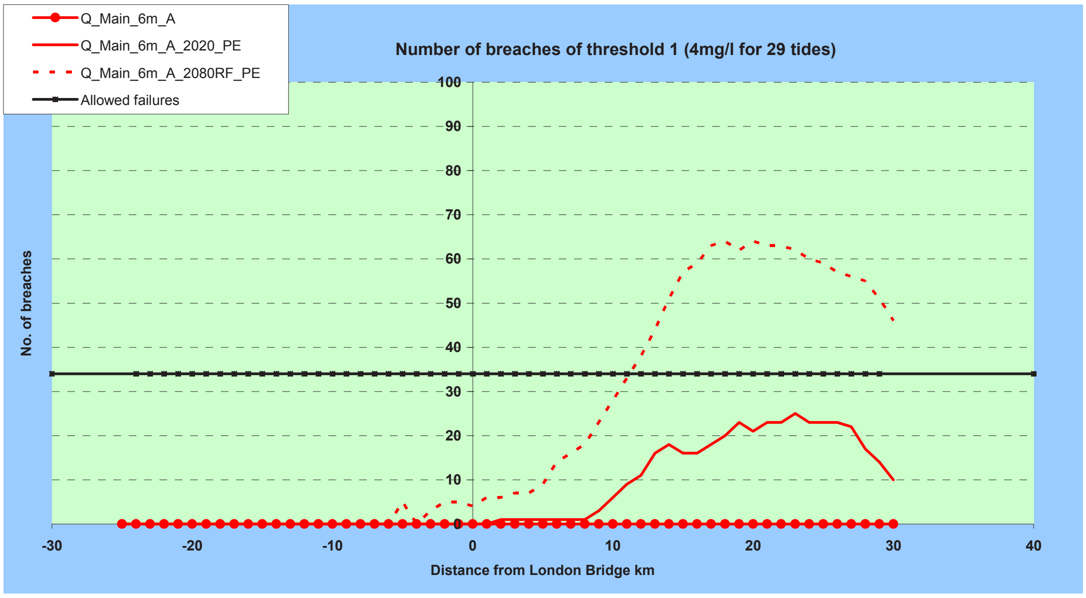
The results show that the solution would meet compliance with all three standards to the point where there is predicted to be no breaches of any of the standards when climate change impacts and preceding events are not included (see think dotted line). When 2020 climate change impacts and preceding events are added to the analysis (solid line – no dots), the solution is still compliant with all three standards with the number of breaches of the 4mg/l well below the allowable failures and with minimal or no breaches of the 3mg/l or 2mg/l standard. The solution 1a is therefore deemed to be compliant.

The solution is non-complaint when the 2080 climate change impacts are considered (dashed line); however as described in section 4.1, the impact of 2080 climate change was not considered as crucial to the compliance assessment for the TTT solution evaluation, henceforth the results of the 2080 climate change are not discussed as a discriminator for the solutions as all solutions would not reach compliance with the overall DO objectives for 2080 climate change predictions. It is important to note however that option 1a (and option 1c) would still be compliant for the 3mg/l and 2mg/l standard when climate change to 2080 is factored in; whereas options 1b, and options 2a-2c fail all three DO standards for 2080 climate change conditions (see sections 4.5 to 4.9)

5.5 VARIANT OPTION 1B; COMPLETE TUNNEL – 6M DIAMETER

As with option 1a, variant option 1b is compliant with all three DO standards when 2020 climate change and preceding events are included (Figure 4.3: solid line – no dots); however, variant option 1b results in an 5 breaches of the 4mg/l and 3mg/l standards and 3 breaches of the 2mg/l standard whereas variant options 1a and 1c have minimal or no breaches of these two standard.

Figure 4.3: Modelling results for option 1b – for the 4mg/l standard



This outcome is as a result of option 1b having a smaller volume and hence a greater number of storm events which 'beat' the tunnel resulting in residual discharge that options 1a and 1c would capture; as described, these additional failures are within the allowable failures and hence option 1b achieves DO objective compliance.

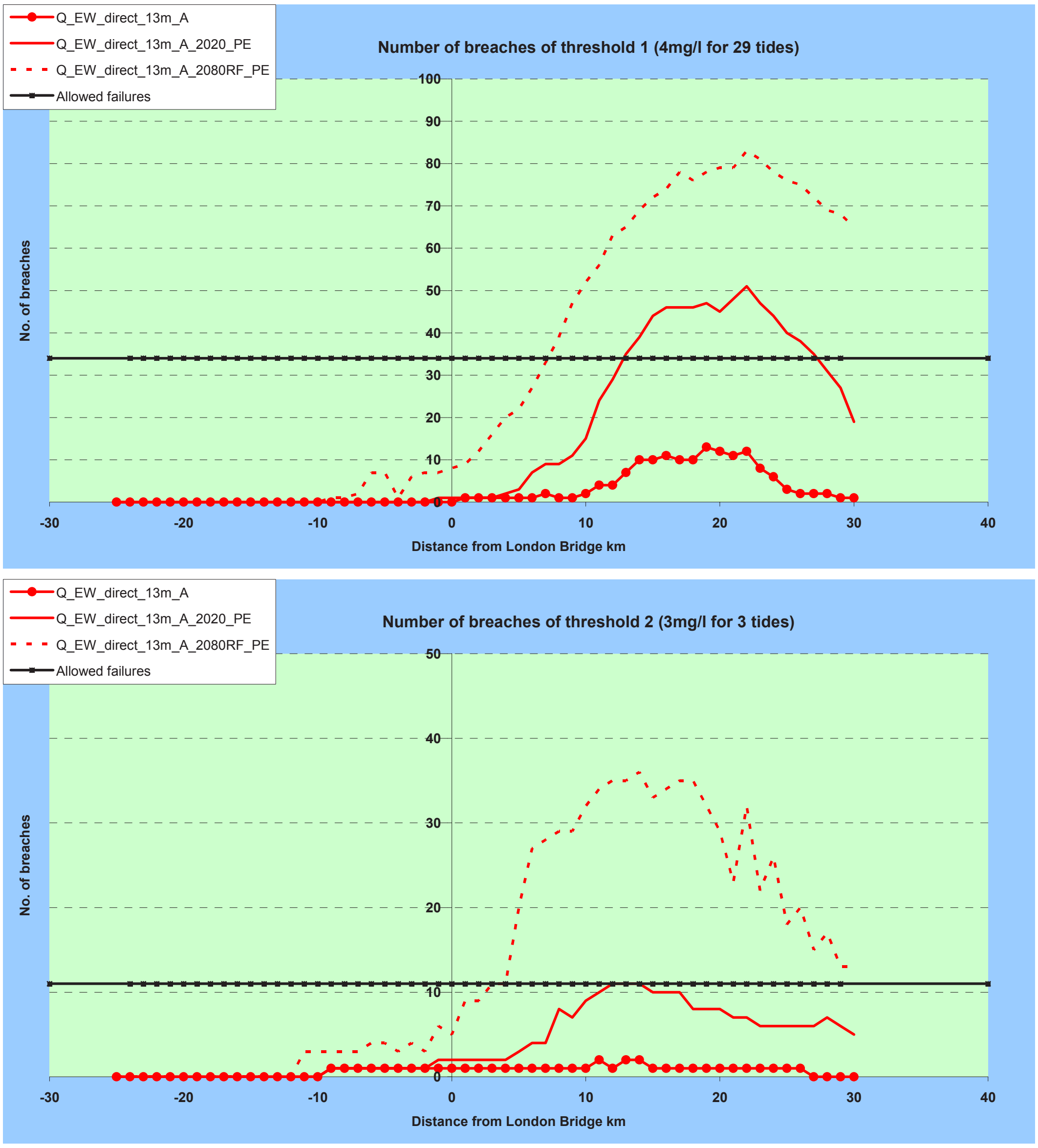
5.6 VARIANT OPTION 1C; COMPLETE TUNNEL – DIRECT ABBEY MILLS LINK

Because variant option 1c has the same dimensions as the component parts of option 1a (but with a different configuration for Abbey mills interception) it achieves the same level of compliance as option 1a; this solution is therefore compliant with the DO objectives along with option 1a and 1b.

5.7 MAIN OPTION 2A; EAST-WEST TUNNEL: DIRECT ABBEY MILLS LINK – 13M

All three of the two-part, East-West tunnel options are non compliant with the DO objectives when the 2020 climate change impacts and preceding events are included. Figure 4.4 shows that main option 2a with the large diameter Eastern link tunnel from Abbey Mills to Beckton fails the 4mg/l standard and is only just compliant with the 3mg/l standard (solid line with no dots on both graphs)

Figure 4.4: Modelling results for Option 2a – for the 4mg/l and 3mg/l standards



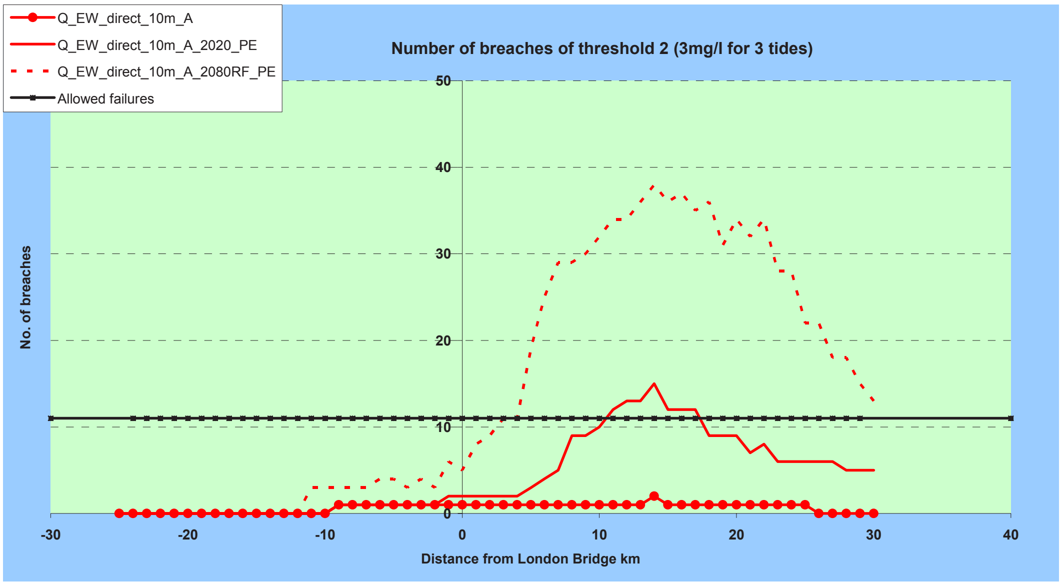
The failure to meet compliance is as a result of the section of Tideway between Heathwall and Abbey Mills where the CSOs are not intercepted for this option. These CSOs still spill during the 154 storm events and as such impact on compliance of all three standards. The main option 2a passes the 2mg/l and 3mg/l standards but on the basis of failing the 4mg/l standard, remains non-compliant with the overall DO objective.

The impact of climate change to 2080 is that option 2a is unable to meet compliance with any of the DO standards.

5.8 VARIANT OPTION 2B; EAST-WEST TUNNEL: DIRECT ABBEY MILLS LINK – 10M

The level of compliance of the variant option 2b is almost identical to the main option 2a for the 4mg/l standard, being non compliant for this DO standard; however, figure 4.5 shows that unlike option 2a, option 2b is non compliant for the 3mg/l standard.

Figure 4.4: Modelling results for Option 2b – for the 3mg/l standard



This variation in performance for option 2b is due to the smaller volume of the eastern link tunnel between Abbey Mills and Beckton. Although Beckton STW has been increased to 2700Ml/d to accommodate tunnel pump out whilst filling, this increased capacity is not quite adequate to make up for the reduced tunnel volume over option 1a. At the time of the modelling result write up, it is considered that 2700Ml/d is the maximum hydraulic capacity that could be treated at Beckton with the current limitation of the Northern Outfall Sewer that brings incoming effluent for treatment. As with option 2a, option 2b passes the 2mg/l standard but fails the DO objective overall.

5.9 Variant Option 2c; East-West tunnel: Abbey Mills link via Charlton.

The performance of the variant option 2c is virtually identical to option 1a in that it fails the 4mg/l standard and marginally complies with the 3mg/l standard. As with both options 2a and 2b, option 2c passes the 2mg/l standard.

The modelling results show that in terms of water quality objectives alone, there is no additional benefit to extending the Eastern link tunnel to pick up the Charlton CSO; however, it is acknowledged that the other objectives of the study rely on spill frequency which is reduced by picking up the Charlton CSO.

5.10 Compliance of the East-West tunnel options

It is important to note at this stage that the modelling results for all of the TTT solutions have used the same starting assumptions for the TTQI STW upgrades to ensure a consistent AMP4 baseline for solution performance comparison (with the exception of Beckton FFT which needs to differ in order to treat the differing tunnel pumpout rates and volumes.). Whilst it hasn't been tested specifically for the purposes of the TTT option assessment, it is possible that option 2a and its variant options could move closer to compliance if the TTQI STW improvements were further tightened. It is acknowledged however, that the proposed TTQI upgrades represent a significant improvement to the current conditions and it would be difficult to realistically improve these further for some sites given the land availability and planning restrictions.

5.11 PREDICTED NUMBER OF FISH KILLS EVENTS FOR THE COST BENEFIT ANALYSIS

In using the 4mg/l standard as an indication of the frequency of events which may lead to fish kill events, the following approximate estimation of such events for each solution is included in table 4.2, including a comparison against the AMP4 baseline. These figures formed the basis of the water quality and fisheries analysis for the Cost Benefit Studies. For simplicity of reporting the modelling studies, if a solution is considered non compliant with the DO objective it is considered that it cannot achieve sustainability of fish populations (See section 2).

Figure 4.4: Modelling impacts on Fish population sustainability

Option	**Fish Sustainability?**	**Frequency of potential fish kill events**
AMP4baseline	No	Approximately 2 a year
Main option 1a	***Yes***	***Less than once a year***
Variant option 1b	Yes	*Less than once a year nut slightly more frequently than option 1a*
Variant option 1c	Yes	*Less than once a year*
Main option 2a	***No***	**Approximately 1 a year**
Variant option 2b	No	Approximately 1 a year
Variant option 2c	No	Approximately 1 a year

6 TTT SOLUTIONS; SPILL FREQUENCY ANALYSIS

In order to provide approximate estimates of the frequency of residual tunnel option spills for the other objectives analysis, the modelling group undertook a separate spill frequency analyses.

It is important to note at this stage that the residual spills for the east west tunnel options (option 2a and its variants) are based on those lengths of the Tideway that have CSOs intercepted. For the area of the Tideway between Heathwall and Abbey Mills, the frequency of spills will remain as it is for the base case.

To obtain an idea of the average number of spills per year, it would be necessary to run all 34 years of event data as a single time series through each sewerage catchment model. This was not achievable within the time constraints of the TTT modelling assessment. It was possible however, to make use of the preceding event modelling which used a simplified model of the sewerage catchment model for each of the solution options and AMP4 baseline as detailed in the report *TTT: Thames Tideway Project - Quests modelling results Report, Dec 200*6. As this process used a simplified methodology, all 34 years (both summer and winter events) could be run through the simplified model relatively quickly for each solution and the AMP4 baseline. Using the model outputs it was possible to define an approximate frequency of residual spills from each solution, on average, each year. The residual spills are calculated from several defined sub-catchments, which were created to lump together several CSOs, which were individually modelled in the sewerage network models. It is acknowledged that this methodology is a crude simplification of London's sewerage network owing to the complexity of how London's sewers are interconnected with trunk sewers; nevertheless, it provides a good estimation of the CSO sub-catchment spill frequency and the simplified model calibrated well against the sewerage network model predictions for 7 rainfall events, which were checked for comparison (Note that variant options 1c and 2c were not modelled as they were predicted give the virtually similar results as their respective main options 1a and 2a, as was the case for the DO estuary modelling).

The results show that there would be an average of approximately 40-107 spills per year with the AMP4 baseline in place. The variation quoted is not a variation in spills over different years, but a reflection that there is a variation in the frequency of each modelled CSO sub-catchment within a given year. In assessing the number of residual spills from each of the options, the CSO which spills the most frequently within a given year has been selected to give the maximum expected spills which would occur on average per year. The frequency of predicted AMP4 baseline spills reduces to an average of 3-4 per year with option 1a, and to 9 for the smaller volume option 1b. Options 2a and 2c would give 9 spills with option 2b giving similar results per year on average. Note again, that for the CSO sub-catchments not intercepted for options 2a and 2b the residual spills remain the same as for the AMP4 baseline.

Although it was considered that there was not sufficient time to run all 34 years of data through the complete solution models using Thames Water's sewerage network model, a single year was selected and the entire year of rainfall was simulated using the sewerage network models for each solution and the AMP4 baseline. The results showed a similar pattern to the average annual spill analysis using all 34 years of event data from the simplified model. Options 1a and 1c resulted in one residual spill for this particular year, whilst the smaller volume tunnel spilled on 3 occasions. For option 2a and its variants, the western tunnel sections of all 3 options spilt twice, whilst for the eastern tunnel, options 2a and 2c had one residual spill whereas the smaller option 2b had 5 residual spills.

In terms of percentage of annual CSO discharge intercepted and treated, on average over the 34 years, options 1a and 1c treat the vast majority of discharges at 94%, whereas option 1b would treat 89% of all CSO discharges. The three East-West tunnel options would each intercept and treat only 72% of the total CSO discharges.

7 WATER FRAMEWORK DIRECTIVE (WFD) COMPLIANCE

As part of the TTT assessment, compliance checks against the draft Water draft Framework Directive DO standards for estuaries has been undertaken. This check was undertaken as indication of how well the solutions would perform against the draft WFD standards; however, The WFD assessment has not been used to determine overall solution compliance as the TTSS DO objectives have been developed specifically for the Thames Tideway and as such are considered most suitable for the purposes of the TTT solution.

The UK WFD Technical Advisory Group report (2006) sets out standards for transitional and coastal waters to meet the Water Framework Directive. These can be split into two types of standard:

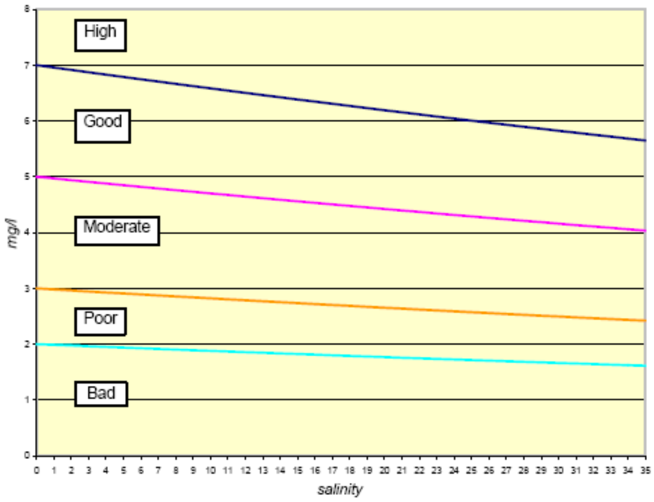
1. Annual 5-percentile standards – the concentrations that should be bettered for 95% of the time as summarised in Figure 7.1 (TAG 2006). To achieve good status the annual 5-percentile must be between 4.0 and 5.7mg/l varying with salinity.

2. Intermittent standards - to protect against more extreme events dissolved oxygen should not fall below 2mg/l at the freshwater end of the estuary for more than one 6-hour tidal cycle over a 6-year period.

Figure 7.1: Extracts from UK Technical Advisory Group report (2006)

Dissolved oxygen standards for transitional and coastal waters			
	Freshwater	Marine	Description
5-percentile (mg/l)			
High	7	5.7	Protects all life-stages of salmonid fish
Good	5 - 7	4.0 – 5.7	Resident salmonid fish
Moderate	3 - 5	2.4 – 4.0	Protects most life-stages of Non-salmonid adults
Poor	2 - 3	1.6 – 2.4	Resident non-salmonid fish, Poor survival of salmonid fish
Bad	2	1.6	No salmonid fish. Marginal survival of resident species

Figure 1: Variation of oxygen standards with salinity



Standards for action on intermittent discharges		
	Minimum dissolved oxygen (mg/l)	Return period (years)
Good	2	1 in 6
Moderate	2	1 in 3

7.1 ANNUAL 5-PERCENTILE STANDARDS

To assess compliance of a TTT solution with the annual 5-percentiles, a typical year (1986) based on dew point temperature and daily river flows at Teddington was selected for analysis. The estuary model was run for the seven month summer period (April to October) using the STW and river quality agreed for the dry weather component of the solution to be tested, with four storm events (3rd August 1986, 22nd August 1986, 25th August 1986 and 13th September 1986) which occurred in this year from 154 events used in the CTP. The storm loads are different for each of the model runs.

The dissolved oxygen standards vary with salinity as shown in Figure 6.1. Model predictions of average salinity for the baseline model run were converted into distance down the estuary to plot the Annual 5-percentile oxygen versus distance along the Tideway. For each cell a 7 months time-series of output was produced and the 8.6-percentile oxygen calculated and compared to the Annual 5-percentile standard for each model cell.

7.2 WATER FRAMEWORK DIRECTIVE (WFD) COMPLIANCE RESULTS

For the intermittent discharge standard, the 'good' status has a similar return period to that of the 2mg/l standard used in the CTP. As all solutions are deemed complaint for the CTP 2mg/l standard, they are also compliant with the intermittent discharge standard.

For the 5-percentile standard analysis, the 1986 results are shown in Figures 6.2 and 6.3.

Figure 7.2 1986 Water Framework Directive Standards

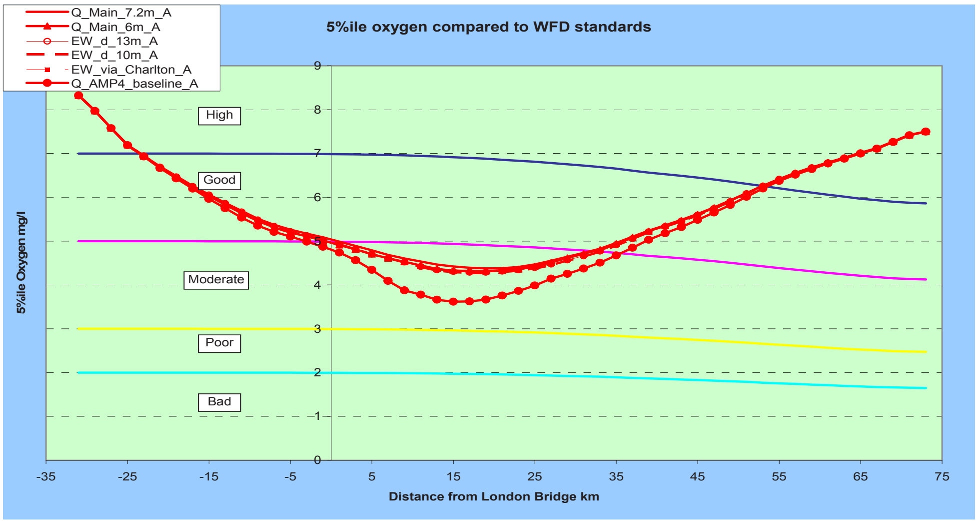
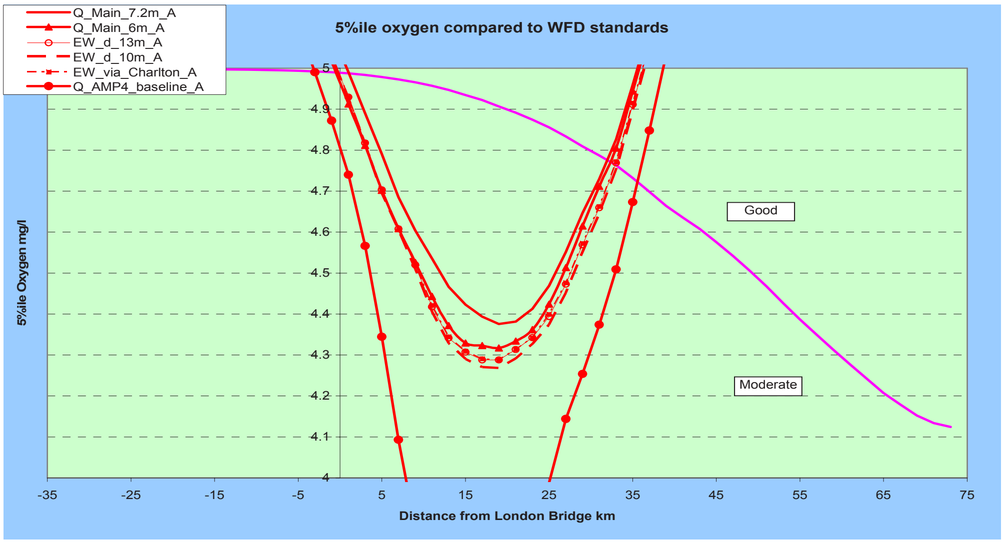


Figure 7.3 1986 Water Framework Directive Standards 4 to 5mg/l

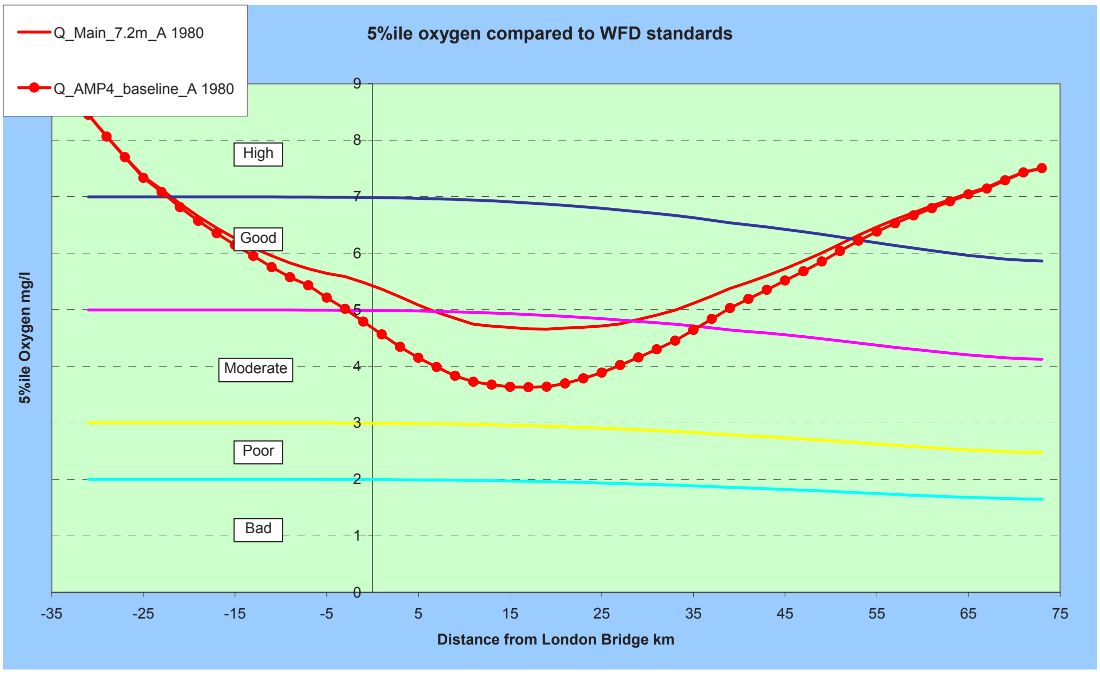


Figures 6.2 and 6.3 demonstrate that the AMP4 Baseline and Main 7.2m tunnel achieve 'Good' status in the freshwater and tidal reaches, and 'Moderate' status in the middle reaches. The Main 7.2m tunnel solution increases the 5-percentile oxygen but much of the middle reaches of the Tideway remains in the 'Moderate' zone.

Figure 6.3 shows the difference between the solutions is small. These are highlighted by focussing on the 4 to 5mg oxygen. The larger tunnels (6m and 7.2m) have slightly higher 5-percentile oxygen than the East-West tunnels. The 13m East-West tunnel is very similar to the via Charlton tunnel, and both have a higher 5-percentile oxygen than the 10m tunnel.

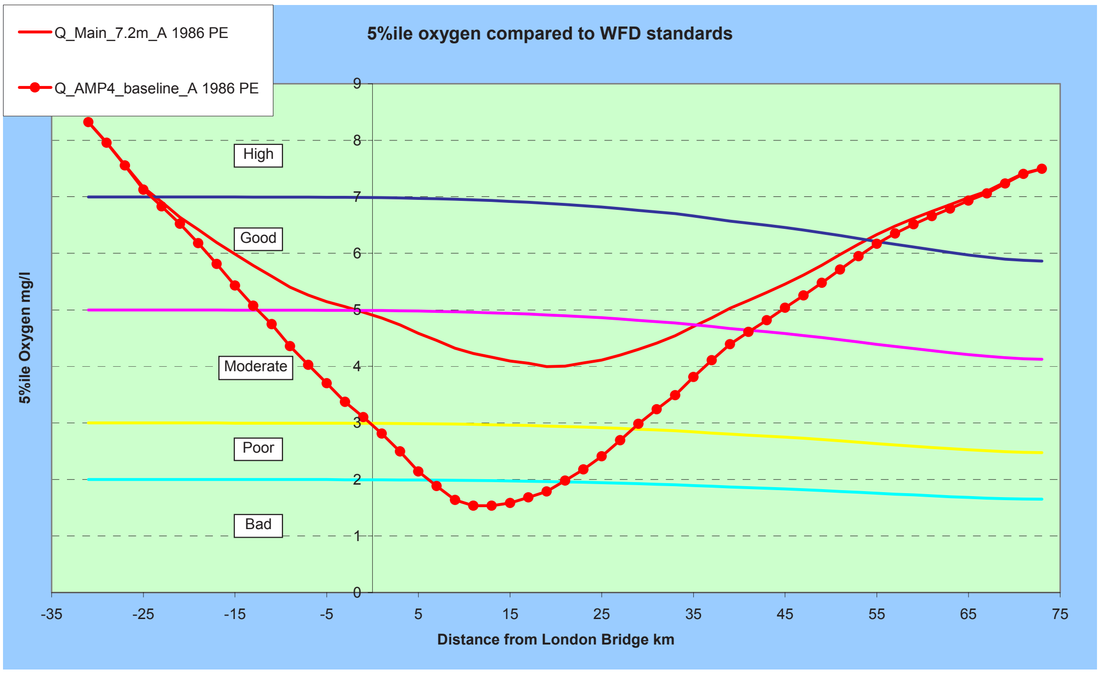
Another year (1980) was run to assess the variation from year to year and the results for the AMP4 Baseline and Main 7.2m tunnel are shown in Figure 6.4. The 1980 results are slightly higher for the tunnel than the baseline and achieve 'Moderate' status.

Figure 7.4 1980 Water Framework Directive Standards



Preceding events and 2020's climate change were also added to the 1980-year analysis. The results show that the even with the TTQI STW upgrades in place, the estuary is predicted to be in the 'poor' category when climate change is in place and combined with all the storm events that take place in during the summer assessment period (figure 6.6). The impact of the tunnel solution however is to return the Tideway to a moderate status which underlines the importance of a solution to achieving future water quality standards once the WFD DO standards are agreed and finalised.

Figure 6.6 1980 Water Framework Directive Standards with preceding events and 2020's climate change



8 CONCLUSIONS

Over the course of 2006, a comprehensive analysis has been undertaken of the various TTT solutions.

The following conclusions can be drawn from the TTT modelling assessment:

- The future 2021 AMP4 baseline with the various TTQI upgrades in place will not meet compliance with the DO objectives, failing all three DO standards unless a CSO solution is implemented in tandem; this is the case whether climate change impacts and preceding events are included or not.

- Only the main tunnel Option 1a and its variant options 1b and 1c can meet all three DO standards and hence reach compliance with the DO objectives for the proposed solutions up to 2021 when climate change for 2020s is included. As a result, only option 1a and it variants can be judged to achieve fish population sustainability.

- Significantly, for options 1a and 1c there are minimal or no predicted breaches of the 3mg/l or 2mg/l standards. Variant option 1b results in an additional 5 breaches of the 4mg/l standard and results in 5 breaches of the 3mg/l standard and 3 breaches of the 2mg/l standard when compared to options 1a and 1c as a result of its smaller storage volume; but as described, this is within the allowable failures and hence achieves DO objective compliance

- Options 2a, 2b and 2c all fail the DO objective; however option 2a and its variant option 2c only fail on one of the three standards, whereas option 2b fails on two DO standards.

- Whilst it hasn't been tested specifically for the purposes of the TTT option assessment, it is possible that option 2a and its variant options could move closer to compliance if the TTQI STW improvements were further tightened. It is acknowledged however, that the proposed TTQI upgrades represent a significant improvement to the current conditions and it would be difficult to realistically improve these further for some sites given the land availability and planning restrictions.

- The modelling results show that in terms of water quality objectives alone, there is no additional benefit to extending the Eastern link tunnel to pick up the Charlton CSO, acknowledging that the other objectives of the study rely on spill frequency which is reduced by picking up the Charlton CSO.

- None of the proposed TTT solutions will achieve the DO objective compliance when climate change impacts up to 2080 are factored into the assessment; however, it is acknowledged that this would be likely to occur even if all CSO discharges were removed and hence is not a discriminator between options for the TTT assessments.

- The modelling results for the TTT assessment have demonstrated a greater level of robustness as they have included changes to the modelling process which show that compliance with the DO objectives can still be met from a considerably worse baseline than was the case during the TTSS studies

- Options 1a and 1c would result in the lowest residual spills, with a predicted 3-4 spills per year on average. Option 1b results in 9 spills on average per year based on the most frequently spilling CSO. Options 2a, 2b and 2c would result in 9 residual spills (based on the most frequently spilling CSO) on average per year from the CSOs intercepted, but would spill as frequently as the baseline for those CSOs not intercepted.

- In terms of percentage of annual CSO discharge intercepted and treated, on average over the 34 years, options 1a and 1c treat the vast majority of discharges at 94%, whereas option 1b would treat 89% of all CSO discharges. The three East-West tunnel options would each intercept and treat only 72% of the total CSO discharges.

- A method has been derived for the testing compliance against draft WFD DO standards. Modelling to date has shown little difference between solution performances, with all solutions deemed complaint for the intermittent discharge standard. For the 5-percentile DO standard, all solutions performed similarly improving the reliance in the Tideway achieving 'moderate status' as it would be predicted to do with the just the TTQI upgrades in place. If climate change and preceding events are included, the future baseline would result in a 'poor' categorisation for the Tideway without a CSO solution in place; modelling for a single option (1a) showed that the Tideway would return to moderate status if a solution of this magnitude were applied

9 REFERENCES

- TTSS - The preparation and application of the modelling Framework for the Compliance Testing of Options: Audit Report, Sept 2003.
- TTSS – Objectives Working Group Report: Vol 2, modelling Study, Feb 2005
- TTT - Thames Tideway Quests model Calibration and Verification report, Dec 2006.
- TTT - Thames Tideway Project: Quests modelling results Report, Dec 2006

10 APPENDIX 1

Network Model Improvements

The network macro models of the Beckton, Crossness, Mogden, Riverside and Long Reach sewer catchments along with the modelling package Infoworks were used to assess the flows and water quality of sewerage arriving at each sewerage treatment works (STW) and the 57 combined sewer outfalls to the river.

The Beckton, Crossness and Mogden sewer models uses the enhanced models used in the Phase 1 and Phase 2 Thames Tideway Strategic Study (TTSS) (February 2005), with additional updates and improvements described later in this section.

Riverside and Long Reach sewer models were not used in the February 2005 TTSS reported, instead daily STW records, were used to assess flow contribution from the works. For the TTT 2006 study, the available Riverside and Long Reach macro models were included to provide improved hourly flows to the works, and from the storm tanks during the 154 compliance-testing events.

Hydraulic and water quality data from the predicted Combined Sewer Overflows (CSOs) for the future 2021 AMP4 baseline were provided to WRc for impact assessment using their Quest river models; this also included input data for flow to treatment, flow to storm tanks and flow from storm tanks (where modelled) at the five STWs from the Infoworks simulation of the various storm events. This was repeated for each of the solution models, which were developed to represent each of the six TTT options to be assessed.

Improvements and updates included into the network model are detailed in the following points and table:

The Population was calibrated to reflect 2021 projected average dry weather flows (DWF) as follows. Model population was increased on the same pro rata basis across all subcatchments. No account to concentrate population to areas with known large development was made due to time constraints on the modeling assessment.

Catchment	**Average 2021 DWF (ML/d)**
Beckton	1344
Crossness	597
Mogden	560
Riverside	187
Long Reach	104

Storm tank volumes at the works were updated to reflect latest operational survey information of storm tanks as follows:

Catchment	Storm Tank Volume (m^3)
Crossness	79,308
Mogden	96,640
Riverside	20,790
Long Reach	14,000

All CSOs were checked to ensure there was no discharge during DWF, and reflect existing CSOs performance. Amendments were updated into the model to reflect this where required (e.g. Canning Town PS now decommissioned, weirs discharging to Holloway SRS increased for Option 2a, 2b and 2c where the increased base wastewater flows were causing short daily spills).

The Beckton network model was updated along with the real time controls (RTC) to reflect new flow to full treatment (FTFT) at Beckton, which varied with solution options as follows:

		Beckton
Run No.	Option	FFT
1	AMP4 baseline	1800
2	Option 1a	2336
3	Option 1b	2105
4	Option 1c	2336
5	Option 2a	1998.3
6	Option 2b	2700
7	Option 2c	1998.3

The WQ loading factor applied to discharges from the Crossness model has been removed. During the re-verification exercise of the Crossness model as a result of the flow and load surveys, it was determined that the flow monitoring apparatus at the Crossness STWs was not calibrated appropriately, and therefore a earlier base-flow correction factor applied to Infoworks flow from Crossness was no longer necessary.

New solution models and RTC were created for Option 1a, 1b, 1c, 2a, 2b and 2c as per details from the Thames Water emerging solutions group paper.

Pumps for solution options were rated to empty the tunnel in 2 days, and RTC for tunnel pumps were written to start emptying the tunnel once capacity at the STW becomes available.

All solutions where created to provide the storage capacity to the first spill point using Infoworks Total Storage Graph function for tunnel volume, as detailed in the table below:

Description	First Spill Point Invert (m AD)
Option 1a	- 4.46 mAD
Option 1b	- 4.46 mAD
Option 2a	Western Tunnel = - 4.46 mAD Eastern Tunnel = 1.13 mAD
Option 2b	Western Tunnel = - 4.46 mAD Eastern Tunnel = 1.13 mAD
Option 2c	Western Tunnel = - 4.46 mAD Eastern Tunnel = 1.13 mAD

The CSOs were categorised according to environmental impact and frequency of operation as described below.

Category	**Description**
1	CSOs that operate frequently and have an adverse environmental impact
2	CSOs that do not operate frequently but have an adverse environmental impact
3	CSOs which have no significant environmental impact

4	CSOs that operate frequently but do not have an adverse environmental impact

Intercepted CSOs to each of the solution models were updated as per table below, using details from the emerging solutions group paper.

Description	EA Category	Intercepted CSOs in Option 1a, 1b & 1c	Intercepted CSOs in Option 2a & 2b	Intercepted CSOs in Option 2c
Acton Storm Water Outfall	Cat 1	Intercepted	Intercepted	Intercepted
LL1 (Main Line)-Chiswick Eyot		Not Intercepted	Not Intercepted	Not Intercepted
Stamford Brook, East Branch	Cat 2	Intercepted	Intercepted	Intercepted
West Putney Storm Relief	Cat 1	Intercepted	Intercepted	Intercepted
Hammersmith Pumping Station	Cat 1	Intercepted	Intercepted	Intercepted
NW Storm Relief	Cat 2	Intercepted	Intercepted	Intercepted
LL1 SW Outlet at Hammersmith (Brooke Lane)	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
LL No.1 Putney Bridge Storm	Cat 1	Intercepted	Intercepted	Intercepted
Frogmore SRS (Bell Lane Creek)	Cat 1	Intercepted	Intercepted	Intercepted
Frogmore SRS (River Wandle)	Cat 1	Intercepted	Intercepted	Intercepted
Falcon Brook Relief	Cat 3	Intercepted	Intercepted	Intercepted
Jews Row Outlet	Cat 1	Intercepted	Intercepted	Intercepted
Falcon Brook Pumping Station	Cat 1	Intercepted	Intercepted	Intercepted
Lots Road Pumping Station	Cat 1	Intercepted	Intercepted	Intercepted
Church Street Sewer	Cat 2	Intercepted	Intercepted	Intercepted
Queen Street Sewer	Cat 2	Intercepted	Intercepted	Intercepted
Smith Street Main Line Outlet	Cat 2	Intercepted	Intercepted	Intercepted
Smith Street Relief	Cat 2	Intercepted	Intercepted	Intercepted
Ranelagh Main Line (inclds Sloane St, Ranelagh & KSP SRS)	Cat 1	Intercepted	Intercepted	Intercepted
Western P/S (U/S of P Stn)	Cat 1	Intercepted	Intercepted	Intercepted
Western P/S (Stn to River)	Cat 1	Intercepted	Intercepted	Intercepted
KSP Main Line	Cat 2	Intercepted	Not Intercepted	Not Intercepted
Clapham Storm Relief	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Brixton Storm Relief	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Grosvenor Ditch	Cat 2	Intercepted	Not Intercepted	Not Intercepted
Horseferry Road	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Wood Street	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Regent Street	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Northumberland Street	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Savoy Street	Cat 2	Intercepted	Not Intercepted	Not Intercepted

Description	EA Category	Intercepted CSOs in Option 1a, 1b & 1c	Intercepted CSOs in Option 2a & 2b	Intercepted CSOs in Option 2c
Essex Street	Cat 2	Intercepted	Not Intercepted	Not Intercepted
Blackfriars Bridge (Fleet)	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Paul's Pier Wharf	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
London Bridge	Cat 4	Not Intercepted	Not Intercepted	Not Intercepted
Shad Thames Pumping Station	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Battle Bridge	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Beer Lane	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Hermitage Dock	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Nightgale Hermitage Dock (Wapping Dock)	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Cole Stairs Outlet	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Bell Wharf Outlet	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
NE Storm Relief – Shadwell	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Ratcliffe Cross	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Holloway Storm Relief Sewer	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Blackwall Sewer (Diversion)	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Deptford Storm Overflow	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Deptford Storm Discharge Culvert	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Blackwall Basin	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Isle of Dogs Pumping Station	Cat 4	Not Intercepted	Not Intercepted	Not Intercepted
Abbey Mills Pumping Station from STATION F	Cat 1	Intercepted	Intercepted	Intercepted
Abbey Mills Pumping Station from STATION A	Cat 1	Intercepted	Intercepted	Intercepted
River Lea, Canning Town PS	Cat 4	Not Intercepted	Not Intercepted	Not Intercepted
Charlton Storm Relief	Cat 1	Intercepted	Not Intercepted	Intercepted
Earl Storm Relief	Cat 1	Intercepted	Not Intercepted	Not Intercepted
Heathwall Pumping Station	Cat 1	Intercepted	Intercepted	Intercepted
South West Storm Relief	Cat 1	Intercepted	Intercepted	Intercepted
Wick Lane (into River Lea)	Cat 2	Intercept Via Abbey Mills outfalls	Intercept Via Abbey Mills outfalls	Intercept Via Abbey Mills outfalls
Wick Lane (into River Lea)	Cat 2	Intercept Via Abbey Mills outfalls	Intercept Via Abbey Mills outfalls	Intercept Via Abbey Mills outfalls
Henley Road Outfall	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted
Iron Gate	Cat 3	Not Intercepted	Not Intercepted	Not Intercepted

The changes to the modelling process had the impact of increasing the frequency of storm flow inputs into the Estuary model and spills from the model thereby increasing the confidence in the performance of a solution option to capture all major rainfall events.

In Summary, the following starting assumptions and process for baseline and solutions in Infoworks were used:

- Water quality (WQ) runs were undertaken for Beckton, Crossness and Long Reach models. Hydraulic (flow) runs were undertaken for Mogden and Riverside models.
- All WQ runs applied default water quality parameters as recommended by the Infoworks software, no adjustments were made to default parameters.
- Each compliance rainfall event includes a 2 weeks DWF initialization file to simulate the start up quality in the sewers. All DWF initialization files apply start flow and water quality condition at 8am, which reflects the sewers at peak diurnal conditions (worst case conditions).
- Each rainfall event was simulated for an additional 48 hrs or 72 hrs after the storm depending on storm intensity and duration, to ensure that the pumps empty the tunnel at the end of simulation.
- The solution tunnel and storm tanks were assumed empty at the start of each of the 154 rainfall events.
- No allowances were made for consecutive storm events and partially full solution tunnel or storm tanks during events (although this quality impact was included in the estuary CTP modeling – see preceding events section)
- Solution tunnel pumps will start emptying the tunnel once available capacity to accommodate the pumped flow becomes available. This applies to the full solution tunnel and Eastern tunnel.
- Western tunnel pumps will start emptying the tunnel once there is capacity in receiving low-level sewers in Beckton and Crossness.
- Standalone solution models were used for Option 1a, 1b & 1c utilising selected inflow and water quality data from base case (no solution) runs as CSO and STW inputs.
- Full solution models (includes Beckton and Crossness catchment) were used for Option 2a and 2b.
- A standalone solution model was used for Option 2c, utilising inflow and water quality date from Option 2a as CSO and STW inputs.
- All base case (no solution) runs excluded tide files at the outfalls. This is acceptable as the majority of outfalls would be intercepted, and hence would have a free discharge into the solution tunnel.
- All solution models applied tide files to the solution outfalls. A constant tide file was used for all solution outfalls based on existing data from the Tower Pier tidal gauge. Real tide data were available for rainfall events from 1990 to 2002. For all events from 1971 to 1989, a standard tide profile was used. All missing data in the existing tide files were interpolated.

Network model Limitations

- The models used are macro (planning) models. The models are set up to include and model all flows in the catchments, and have all the main trunk sewers, bifurcations and storm discharge points. However, because of the size of the catchments and sewers, only limited verification in the trunk sewers has been possible and extensive local catchment details were not included.

- RTC at Beckton and Crossness which control how incoming sewer flows are split between arrival at the STWs and discharge via CSOs are based on current understanding of prescribed operating practices, but does not necessarily reflect the “real operation conditions”, for example the RTC waits until flows are less than peak DWF to divert flows back to Beckton from Abbey Mills, however in reality this may not be the case. Operations may divert flow back earlier. RTC divert flows to the river once FTFT is met at the works, but operations may choose to sustain the full treatment flow and surcharge the trunk sewers for some duration before diversion to river. It is necessary to include a generic RTC in the modelling for such a klarge number of simulations.

- For partial solutions – Option 2a, 2b and 2c, it was necessary to modify the weir levels at Holloway Storm Relief Sewer to ensure that the model does not discharge DWF to the CSO due to increased population. This should be recognized as a weakness of the partial solution models.

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