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Humber Strategy

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Contents

1. Introduction

In the Jacobs (2019) report: “Approach to deriving extreme water levels and waves”, a suite of options for developing the overall modelling of the extreme flood levels across the Humber study area was described. Of the various options the one selected was “3A-predefined combinations”. This was one of the versions of the general approach that uses design events as boundary conditions to the model. The overview of the recommended approach is described by the following steps:

i. Develop, calibrate and verify a **hydrodynamic model** of the study area which will enable water levels to be calculated at all locations with the study area for any combination of boundary conditions.

ii. Undertake a **dependency analysis** to quantify the degree of dependency (from full independent through to fully dependent) between boundaries (river inflow peaks and extreme sea levels).

iii. Based on the FD2308 method, use the dependency analysis to generate a set of **joint probability (JP) scenario tables** for each target AEP – each table contains a set of combinations of boundary AEP which are expected to lead to the target AEP at one or more locations in the study area.

iv. Define ‘design’ **event boundaries** for each river inflow and the sea in terms of flow/level time series and their relative timings together with peak values for the full range of AEPs.

v. Generate and **run hydrodynamic model simulations** for each row in each JP scenarios table (using the standard event boundaries representing the boundary AEPs from the JP scenarios table)

vi. **Extract the maximum water level** at each model node from each simulation (row) within the JP scenarios table for the target AEP. This gives the target AEP water level at the location. Repeat for all target AEPs.

vii. **Verify the extremes** using gauge data and previous extremes results and through assessing the physical plausibility of the results.

viii. **Format extremes into the required deliverables:** spreadsheets, tables, shapefiles and reporting.

Step iv requires the selection of “design” event boundaries for the key rivers. This report provides a review of the design fluvial flood hydrographs considered and makes recommendations as to what would be appropriate to use and if there are aspects that may warrant further work. The review considers the fluvial inflows from the principal catchments draining into the Upper Humber, namely the Ouse, Aire, Don and Trent. Other rivers are either managed by tidal flood gates or enter the Humber further downstream where their effect is considered to have almost negligible effect on the extreme water levels. This follows the approaches taken in earlier modelling of the Humber.

The review concentrates on the suitability of the design flows for the upstream boundaries of Jacobs’ current Humber Strategy model. The joint probability of these major fluvial inflows to the coastal floods and to one another is not the focus of review, and is dealt with elsewhere in the study.

The review is split into the following chapters which deal with each river individually: Chapter 2 – River Ouse, Chapter 3 - River Aire, Chapter 4 - River Don, and Chapter 5 – River Trent.

2. The River Ouse

The source information reviewed:

1) JBA Consulting (2016). Upper Humber Flood Risk Mapping Study – Final Report. Report for the Environment Agency dated August 2016.

2) Mott MacDonald (2018). Ouse and Wharfe Washlands Optimisation Study – Defended and Undefended Flood Modelling for Flood Map Creation. Report for the Environment Agency dated July 2018.

2.1 Upstream model boundary

On the Ouse the location of the current Jacobs Humber Strategy model upstream boundary is Cawood. This is just over 1km downstream of the confluence between the rivers Wharfe and Ouse (Figure 2.1).

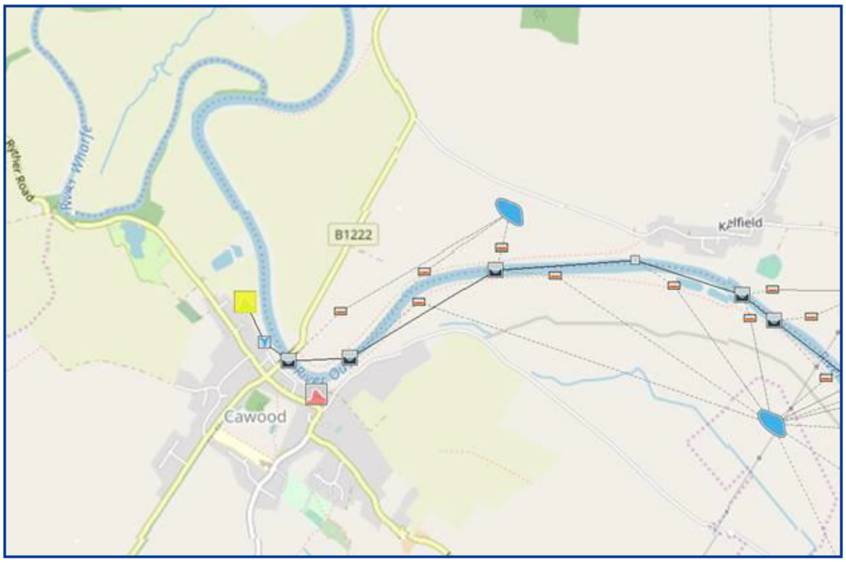

Figure 2.1: Location of the current Jacobs Humber Strategy upstream model boundary

2.2 Upper Humber Flood Risk Mapping Study [UHFRMS] (JBA, 2016)

As well as incorporating the design hydrology of the Ouse, this study also included the design hydrology for the rivers Aire, Don and Trent. Updating of the hydrological inflows was beyond the scope of the project. Instead the inflows were taken from previously developed Environment Agency (EA) models. The report acknowledges that the hydrological methods used to derive these were not particularly comparable with one another and that this was highlighted as a potential area for future development.

The "River Ouse Model Update" (Halcow, 2009) model was used to represent the River Ouse from where the design flows are assumed to have been obtained. This Halcrow model covers the river from the Skelton gauging station in York down to the River Trent confluence. Although the UHFRMS report does not describe this fluvial flood hydrology it does indicate that it provided a peak volumes boundary condition as opposed to a boundary condition that had been established solely on peak flow considerations. Given that that flood risk in the Humber is generally greater for long duration, high volume events would seem to be appropriate; though how this peak-volumes hydrology was established is not described.

The JBA model uses Cawood as the upstream boundary, the same as being used in the current Jacobs model.

The JBA UHFRMS report notes the following general limitations with the fluvial hydrology obtained from the various previous studies:

"*Each of the study watercourses have had their design inflows estimated using a different method (ranging from continuous simulation to more standard FEH methods). These approaches are not necessarily compatible or representative of the same storm (in fact the assumption of a homogeneous storm over a catchment of this size would in itself represent a significant limitation). Moreover, the study area is considered susceptible to both design flow (likely to control the onset of flooding) and design volume (likely to have the greatest influence on maximum flood extents)*".

The JBA report strongly recommends that the fluvial boundary conditions within their model be updated when new model results become available. Plus, it recommends that consideration be given to the dependence of fluvial flood events of adjacent rivers. (This is pertinent to the combined relationship of the Ouse and Wharfe below their confluence where the upstream model boundary is located).

2.3 Ouse and Wharfe Washlands Optimisation Study (Mott MacDonald, 2018)

One of the aims of the Mott MacDonald (2018) study was to update the design fluvial hydrology on the Ouse and its principal tributary the River Wharfe. This they achieved by two means:

i) Using the findings of the York Detailed Modelling Study[1], which was updated to include the December 2015 flooding, was accepted as proving a suitably updated understanding of the design floods for the Skelton gauge (Ouse @ Skelton, Stn No. 27009) which in turn is the upstream boundary on the Ouse in the Mott MacDonald model.

ii) Undertaking updated flood frequency analysis on the two gauges on the River Wharfe (Wharfe @ Wetherby Flint Mill, Stn No. 27002; Wharfe @ Tadcaster, Stn No. 27089).

Both of these analyses include the extreme flooding experienced in December 2015.

For context it is noted that the flood peaks recorded on the River Wharfe at Flint Mill are approximately two thirds of those recorded at Skelton. So, although the Wharfe catchment (760km^2) is about a quarter of the size of the Ouse at Skelton (3300km^2) the peak flows are much closer than this would suggest.

Table 2 1 is reproduced from the Mott MacDonald report and compares the design peak flows from previous studies for the River Wharfe. A significant increase in the estimated design flows is evident based on their analysis. The report suggests that this is in part due to the longer dataset analysed and in particular to the inclusion of several more recent larger events including the December 2015 extreme flood. The FEH Enhanced Single Site analysis was the favoured method for the estimation of their design flow. (It is noted that only the target gauge annual maximum series were updated to include the December 2015 event and that the pooled gauges were not updated. This could now more easily be achieved since the current Peak Flow dataset is generally updated to 2016-2017. The Mott Macdonald report does not include an equivalent comparison of design peak flows from previous studies for the River Ouse.

[1] This is the name that the Mott Macdonald 2018 report gives it, but no reference was provided. It was later indicated as a component of the existing (Mott Macdonald 2018) study.

Table 4.10: Comparison with previous studies

Study	Halcrow Study	JBA	Bullen	This study
Source	River Ouse Model Update – Summary Report 2009. Obtained from IEDs	Lower Wharfe Washlands Optimisation Study 2008	2000	NA
Flint Mill – QMED	193.5	-		237
Flint Mill – 1 in 100	296.5	-		518
Tadcaster - QMED	193.5	209	194	215
Tadcaster – 1 in 100	296.5	426	297	502

Table 2 1: Comparison of the Mott MacDonald (2018) design flow estimates on the Wharfe to earlier studies. (Reproduced from the Mott MacDonald 2018 report)

Within the Mott MacDonald project much effort was given to refining their model in the washland areas of the Wharfe and Ouse. Detailed representation of the smaller tributaries and washlands downstream of the main inflow points (Skelton on the Ouse and Flint Mill on the Wharfe) was included. This refined representation should allow the main flood waves introduced at the upstream flood boundaries to be more realistically routed down the rivers such that any attenuation or accumulation of additional flow to be more realistically accounted for in the estimate of flows below the Ouse-Wharfe confluence.

The revised design peak flow understanding at the gauged sites was used to scale typical flood hydrograph shapes to provide the design inflow at the upstream boundaries. These shapes were determined from an analysis of historic events. Two principal shapes were identified based upon the 26 December 2015 and the longer duration 26 September 2012 recorded flood hydrographs. The 2012 shape represents a higher volume flood and is described as targeting return period volume flows, whilst the 2015 event is described as targeting return period peak flows. The general flooding is considered susceptible to both design flow (likely to control the onset of flooding) and design volume (likely to have the greatest influence on maximum flood extents).

The smaller tributary catchments downstream of the main inflows were represented by ReFH models and either run with a 26-hour or a 51-hour storm to be appropriate for the 2015 and 2012 scenarios respectively. Table 2 2 explains the setup of the resulting Scenario A and B runs.

Table 4.8: Overview of scenarios for flood mapping

Name	Description	Ouse, Wharfe	Study ReFH catchments	Don, Derwent, Aire GS	Blacktoft
Scenario A	Peak flow scenario	2015 scaled to peak flow for target RP	26 hour storm using target RP	2015 scaled to QMED	2015 stretched to LMED
Scenario B	Volume flow scenario	2012 scaled to peak flow for target RP	51 hour storm using target RP	2012 scaled to QMED	2012 stretched to LMED
Scenario C	Tidal scenario	2012 scaled to QMED	51 hour storm using QMED	2012 scaled to QMED	2012 stretched to target RP

Table 2 2: Overview of scenarios for flood mapping used in the Mott MacDonald (2018) study [Reproduced from the Mott MacDonald 2018 report]

The Mott MacDonald report does consider the coincidence of floods of the same return period occurring on the Ouse and Wharfe. The initial indications suggested that this was not a poor assumption though the analysis was simplistic. We assume that a suitable/typical temporal phasing of the two hydrographs is incorporated in the design model runs as was indicated in the calibration runs.

In the report's recommendations it is suggested there is a need to test the sensitivity of the model to Foss reach inflow representation. It is also recommended that a more sophisticated way of assessing the joint probability of the Wharfe and Ouse flows be considered to gain an improved understand of the fluvial flows downstream of their confluence. These recommendations have not been undertaken in the current Jacobs Humber Strategy modelling.

2.4 River Ouse Summary and Recommendations

The Mott MacDonald (2018) study has incorporated a detailed revision of the peak design flows within their model using data that includes the extreme December 2015 flooding. As such this represents a more up to date understanding of the design peak flows than that used in the JBA (2016) Upper Humber Flood Risk Mapping Study which borrowed analysis based on pre-2009 data.

The Mott MacDonald work suggests a significant increase to design flows on the Wharfe. It is not clear from the reports reviewed what the difference in the design flows at Skelton is.

Explicit representation of the detail of the washlands along the Wharfe and Ouse within the model should allow an improved simulation of the routing of the fluvial floods down to Cawood (the upstream boundary of the Jacobs model).

The use of two design hydrograph shapes (one representing a shape suitable for modelling typical peak flows and the other considered better for representing return period flood volumes) goes some way to investigating the dependence of flood extent upon hydrograph shape (this was an issue flagged in the UMFRMS report as a possible general limitation to their approach).

The Mott MacDonald approach assumes that the same return period event occurs on the Wharfe as that on the Ouse. This understanding could be refined in the future using more sophisticated analysis. The implication of this to the size of the design flow for feeding into the Humber model is unknown and it is recommended that this be considered for future work.

2.4.1 Recommendations

The use of the design hydrographs from the Mott MacDonald (2018) model is recommended within the current Humber Strategy model.

The Mott MacDonald study supplied two sets of design hydrology so that the effects of a longer duration flood with greater flood volume (Scenario B) could be assessed against a more typical shape (Scenario A). The model sensitivities to these two scenarios appears not to be reported in the report reviewed, however the Humber Strategy model in-channel results are unlikely to be sensitive to the assumed inflow Scenario (A or B) due to overtopping of defences upstream of the model inflow and within the Humber Strategy model. It is therefore recommended that the current Jacobs Humber Strategy modelling adopts the more conservative Scenario B design inflows for the design EWL simulations.

The model inflows applied in the Humber Strategy modelling are shown graphically and tabulated in Section 4.5 and Appendix C respectively of the Humber 2100+ Extreme Water Levels modelling report (document number ENV0000300C-CH2-ZZ-3A0-RP-HY-0010).

2.4.2 Potential additional work

The significance to the design flows downstream of the Wharfe-Ouse confluence of better understanding the joint probability of the upstream Wharfe and Ouse flood flows is not known. The conservative assumption to date seems to have been to adopt the same return period event occurring on each. Although some initial simplistic analysis suggests this assumption may be reasonable, consideration of a more sophisticated joint probability analysis would provide an improved understanding of the importance to the predicted downstream design flows. To progress the current project, the Mott Macdonald conservative approach is considered appropriate.

3. The River Aire

The source information reviewed:

1) JBA Consulting (2016). Upper Humber Flood Risk Mapping Study – Final Report. Report for the Environment Agency dated August 2016.

2) JBA Consulting (2017). Northern Forecasting Package Lower Aire Model – Final Report v1.0. Report for the Environment Agency dated July 2017.

3.1 Upstream model boundary

On the Aire the location of the current Jacobs Humber Strategy model upstream boundary is the Beale Weir. This is also the location of the Aire @ Beale Weir gauging station (Stn No. 27003). This is 4km downstream of Knottingley, and about 19km upstream of the Aire confluence with the Ouse. Unfortunately the high flow record at this station is not considered to be good enough for inclusion in the Peak Flows dataset and is understood to not provide reliable estimates of flood flows.

3.2 Upper Humber Flood Risk Mapping Study [UHFRMS] (JBA, 2016)

As well as incorporating the design hydrology of the Aire, this study also included the design hydrology for the rivers Ouse, Don and Trent. However, updating of the hydrological inflows was beyond the scope of the project. Instead the inflows were taken from previously developed Environment Agency (EA) models. The report acknowledges that the hydrological methods used to derive these were not particularly comparable with one another and that this was highlighted as a potential area for future development.

For the Aire the inflows were extracted from the Lower Aire FRMS 2012 model, (Black and Veatch, 2012) and were used as input at the upstream boundary (Beale Weir). Although the UMFRMS report does not describe this fluvial flood hydrology it does indicate that it provided a peak flows boundary condition as opposed to a boundary condition that had been established on peak flood volumes. Given that that flood risk in the Humber is generally greater for long duration, high volume events this use of a peak flows boundary would seem to be a potential limitation.

During the UHFRMS project the inflows from the River Aire 2012 model were found to inaccurately represent the falling limb of the fluvial hydrograph at the 0.5% and 0.1% AEP events. Flows on this limb were found to plateau at such a high level that overtopping of the downstream defences continued indefinitely: a factor exacerbated by the long run times required for the Upper Humber study. Whilst the reasons for this were not investigated in detail, it appeared to be due to the scaling of inflows applied to the River Aire model. To improve this, without remodelling the whole of the upstream River Aire (which would have been required to fully appreciate the draining of the washlands), an approach was adopted to better represent the falling limb using volume analysis of design ReFH hydrographs to provide a plausible receding limb leaving the design peaks unaffected.

The JBA report notes the following general limitations with the fluvial hydrology:

"*Each of the study watercourses have had their design inflows estimated using different a different method (ranging from continuous simulation to more standard FEH methods). These approaches are not necessarily compatible or representative of the same storm (in fact the assumption of a homogeneous storm over a catchment of this size would in itself represent a significant limitation). Moreover, the study area is considered susceptible to both design flow (likely to control the onset of flooding) and design volume (likely to have the greatest influence on maximum flood extents)*".

The UHFRMS report strongly recommends that the fluvial boundary conditions within their model be updated when new model results become available. Plus, it recommends that consideration be given to the dependence of fluvial flood events of adjacent rivers. (Although the UHFRMS does not describe the derivation of the design hydrology used, it is observed that this issue of dependence may be a pertinent issue for the Aire since immediately above the Calder-Aire confluence both rivers are served by good high flow monitoring, and these may well be the best source of design hydrology down at Beale Weir suggesting their statistical dependence will be an issue for consideration).

3.3 Northern Forecasting Package Lower Aire Model - Final Report v1.0 (JBA, 2017)

The Environment Agency had previously created flood maps of the Lower Aire but the hydrology and modelling methodology used in those previous studies was considered to be outdated. Hence the aim of this study was to update the understanding of the flood risk via, amongst other things, calculating an up-to-date set of fluvial inflows for the model.

The method used to achieve this was to follow a distributed approach in which suitable inflow hydrographs were created for the Aire and Calder upstream boundaries at Swillington and Methley that could then be routed through the hydraulic model to define design conditions along the Lower Aire (downstream of the Aire and Calder confluence). Although minor inflows from the small tributaries along the model reach are included they introduce a near negligible flow compared to the two main rivers.

The FEH Statistical method was used to estimate the design flows at the gauging stations. Pooled (enhanced single-site) and single-site analysis were compared together with seeking to incorporate longer-term flood history. The gauging stations used are: River Calder@Methley Bridge gauge (Stn No 27079) which is also the location of the model upstream boundary. The Methley gauge is a Peak Flows gauge with flow data suitable for pooling with about 30 years of data. It is located a short distance upstream of the confluence with the Aire (Figure 4.2).

Figure 1-1; Lower Aire study extent (Swillington to Fairburn)

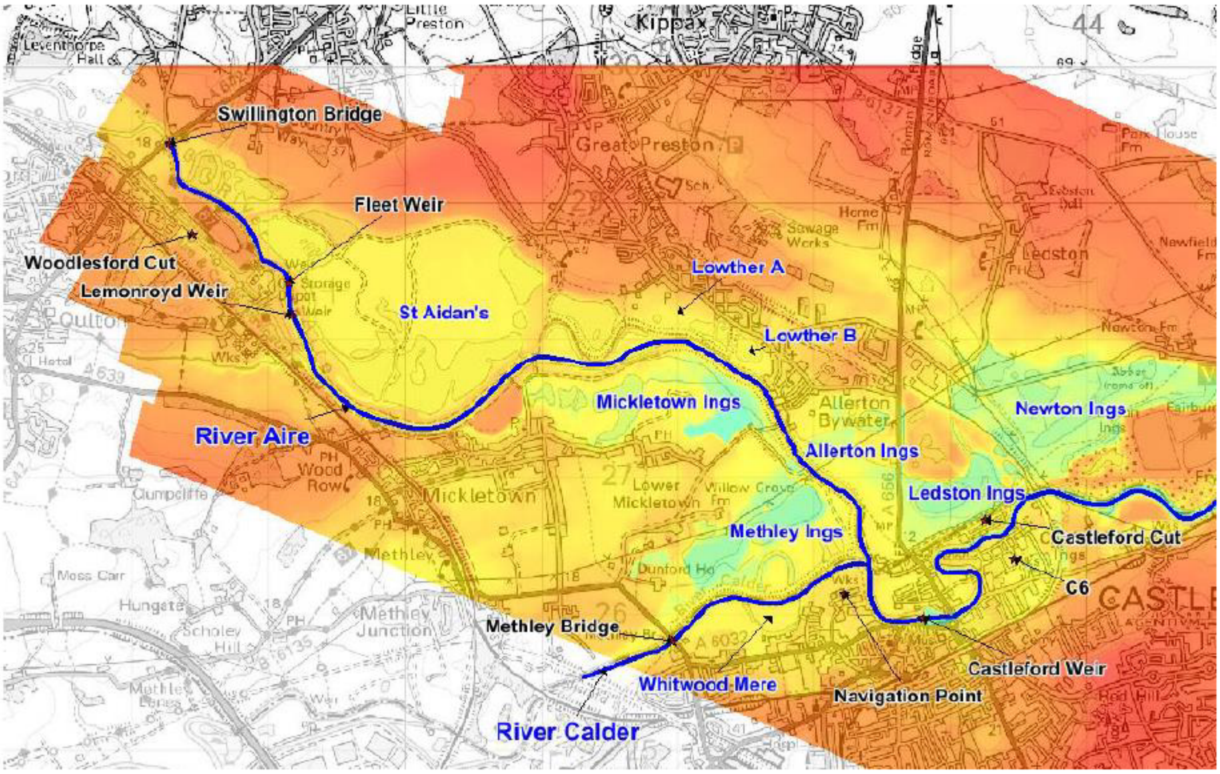

Figure 3.1: Lower Aire upstream extent of the model showing the location of the gauging stations with respect to the Aire-Calder confluence [Reproduced from the JBA 2017 report]

Similarly, on the Aire the Lemonroyd gauge (Stn No. 27080) (also with a record of over 30 years of good quality flood data), was used to estimate the peak design flows used as inflow for the Swillington upstream flow boundary. A correction was needed for the post-2012 Lemonroyd flow estimates to account for the impact of the St Aidan's flood basin (see Figure 4.2).

For context it is noted that the flood peaks recorded on the River Calder (Methley) tend to be slightly larger than those recorded for the same event on the River Aire (Lemonroyd). Plus the Aire tends to peak on average about 5 hours earlier than the Calder.

Hydrograph shapes were derived from the averaging of observed events and then scaled to match the estimated peak flows. The resulting design hydrographs were checked against the results of a frequency analysis of annual maximum volumes over a range of durations since receptors within and beyond the washlands are likely to be sensitive to flooding from high volume events. The reports suggest that there was promising agreement, though the details of this analysis were not available to review.

Finally, a joint probability analysis of events along the Aire and Calder was undertaken to provide a range of potential design event combinations that could give the T-year event downstream of the confluence. Based on this and allowing for a typical 5 hour lag between the Aire and Calder peaks, the Lower Aire design flows can be obtained from the model along the reach below the Aire-Calder confluence.

This approach to representing the design hydrology makes an allowance for the level of dependence between the flood events on the Aire and Calder. The application of the method is also able to explicitly account for the opening of the St Aidan's flood basin in 2012 which was described as adding significantly to the available flood storage volume.

3.4 River Aire Conclusions and Recommendation

The recent JBA (2017) study presents a thorough and detailed analysis of the Lower Aire design flows. The flows extracted from the model at Beale Weir (the upstream flow boundary for the current Jacobs Humber Strategy) allows for both the impact of the St Aidan's flood basin (established in 2012), and for the joint probability characteristics of the flows on the upstream Calder and Aire rivers at their confluence. The analysis also represents an update in terms of length of records used and in doing so includes the extreme December 2015 flood event within the analysis.

3.4.1 Recommendations

It is recommended that the recent JBA (2017) design hydrology is accepted and incorporated into the current Jacobs Humber Strategy model.

The model inflows applied in the Humber Strategy modelling are shown graphically and tabulated in Section 4.5 and Appendix C respectively of the Humber 2100+ Extreme Water Levels modelling report (document number ENV0000300C-CH2-ZZ-3A0-RP-HY-0010).

4. The River Don

The source information reviewed:

3) JBA Consulting (2016). Upper Humber Flood Risk Mapping Study – Final Report. Report for the Environment Agency dated August 2016.

4) JBA Consulting (2017). Don Catchment Model: Hydrology Report (Revised Draft Report). Report for the Environment Agency dated February 2017.

5) Flood estimates at Doncaster derived by the FEH statistical method, and Archers method hydrograph profiles, both derived for this study.

4.1 Upstream model boundary

On the Don the location of the current Jacobs Humber Strategy model upstream boundary is the Don at Doncaster. The minor inflows of the EaBeck (joining the Don several kilometres downstream of Doncaster), and the River Went (joining the Don 15km downstream of Doncaster) are not included as model inflows as these watercourses have downstream tidal structures, and so their inflows do not contribute to peak flows in the model.

4.2 Upper Humber Flood Risk Mapping Study [UHFRMS] (JBA, 2016)

As well as incorporating the design hydrology of the Don, this study also included the design hydrology for the rivers Ouse, Aire and Trent. However, updating of the hydrological inflows was beyond the scope of the UHFRMS project. Instead the inflows were taken from previously developed Environment Agency (EA) models. The report acknowledges that the hydrological methods used to derive these were not particularly comparable with one another and that this was highlighted as a potential area for future development.

The design flows used in the UHFRMS model were obtained from the Lower Don Flood Risk Management Study (JBA Consulting, 2009). The previous Don FRMS report (JBA 2009) indicates the Continuous Simulation (CS) modelling used in that study was developed in approximately 2000. Although the UHFRMS report does not describe the derivation of the hydrology it does indicate that a peak volumes boundary condition was used as opposed to a boundary condition that had been established solely on peak flow considerations. Given that flood risk in the Humber is generally greater for long duration, high volume events this would seem to be appropriate and one that a continuous simulation style of approach could lend itself to. However, how this peak-volumes hydrology was actually established is not described in the UHFRMS report and not been covered in this high level review.

The UHFRMS report notes the following general limitations with the fluvial hydrology:

"*Each of the study watercourses have had their design inflows estimated using different a different method (ranging from continuous simulation to more standard FEH methods). These approaches are not necessarily compatible or representative of the same storm (in fact the assumption of a homogeneous storm over a catchment of this size would in itself represent a significant limitation). Moreover, the study area is considered susceptible to both design flow (likely to control the onset of flooding) and design volume (likely to have the greatest influence on maximum flood extents)*".

The UHFRMS report strongly recommends that the fluvial boundary conditions within their model be updated when new model results become available.

4.3 Don Catchment Model: Hydrology Report (JBA, 2017)

This report describes the recent work to refine the hydrology of the Don catchment using CS. It builds upon the previous flood mapping study undertaken by JBA in 2004 which was also based on CS. The motivation for using a CS approach is justified in the following:

"At 1256km² (at Doncaster) the Don is a large catchment by UK standards. It is also complicated. It encompasses a range of catchment sizes and responses, multiple reservoirs, controlled and uncontrolled flood storage (on-line and off-line), raised embankments and flood locked tributaries. All this confounds traditional flood estimation methods and makes CS the only robust alternative".

In the updated JBA work the rivers across the Don basin have been represented by calibrated PDM rainfall-runoff models that have used long stochastic rainfall series (5000-years long) to simulate plausible long-term flow sequences along the length of the rivers. From these flow sequences likely flood events (>QMED) were selected and routed through appropriate hydraulic models to gain long-term synthetic annual maximum series from which design flows and levels could be derived. In doing this detailed approach there have been checks upon the performance of the stochastic rainfall against the FEH13 depth-duration-frequency rainfall estimates, and flood frequency curve checks against recorded flow data. The approach also included the explicit inclusion and simulation of reservoir storage across the headwaters of the basin which was shown capable of exerting a significant influence on downstream flood frequency depending on assumed antecedent reservoir levels.

The coverage of the model allows the supply of synthetic flood hydrology for the Don at Doncaster.

Since the earlier work in 2004 the Don catchment has experienced the exceptional flood of 26 June 2007 (Figure 4.1), and this has been incorporated in to the understanding of the design flows during the recent work.

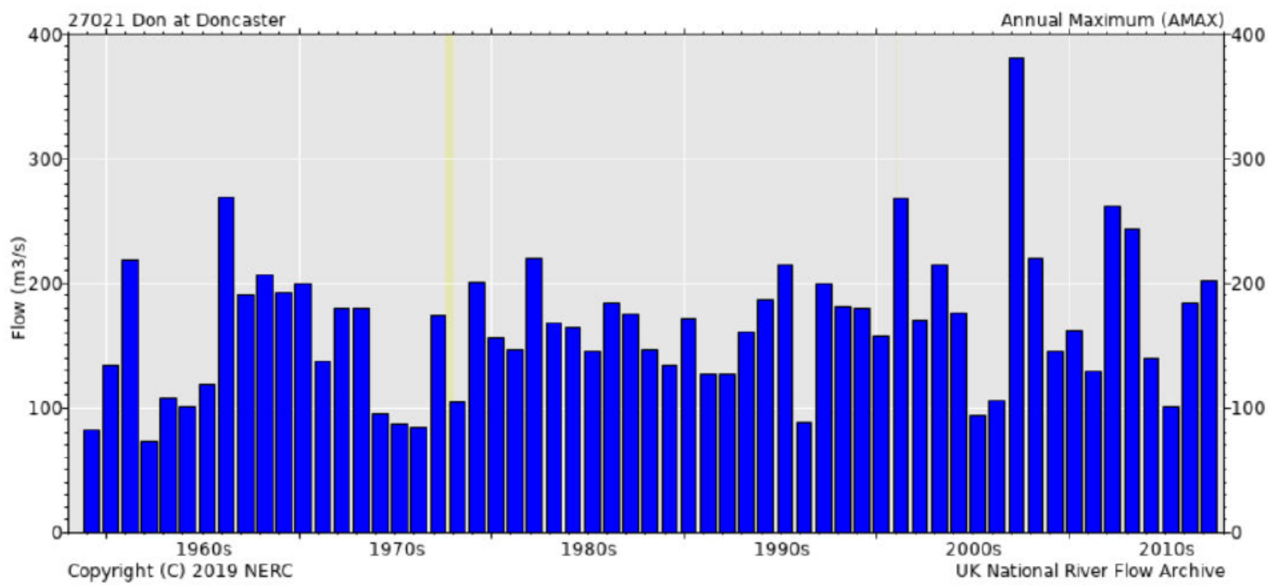

Figure 4.1: Peak Flows annual maximum series for the Don @ Doncaster showing the exceptional size of the June 2007 event

The pertinent key finding for the design flows at Doncaster (Don @ Doncaster, Stn No. 27021) was that the estimated 100-year flow had dropped from 310m³/s to 288 m³/s (-7%)[2], but that lesser return periods are closer. Although perhaps counter intuitive that the design flow reduces after the inclusion within the thinking of the extreme June 2007 event. This was explained as being due to an improved representation of the Middle Don via the use of lateral catchment inflows rather than a simplistic application of a 1.4 rainfall factor (as done earlier) to account for unrepresented areas of the catchment. This is visually summarised in Figure 4.2 where

[2] This was reported as -9% in the report but has been corrected to -7% in this review.

the blue line is the update compared to the older CS grey curve. The red crosses are the Gringorten plotting positions of the annual maximum series which are shown to largely fall within the 90 percentile and 10 percentile confidence levels of the updated blue curve.

Figure 6-9: Flood frequency curves and observed AMAX at Doncaster

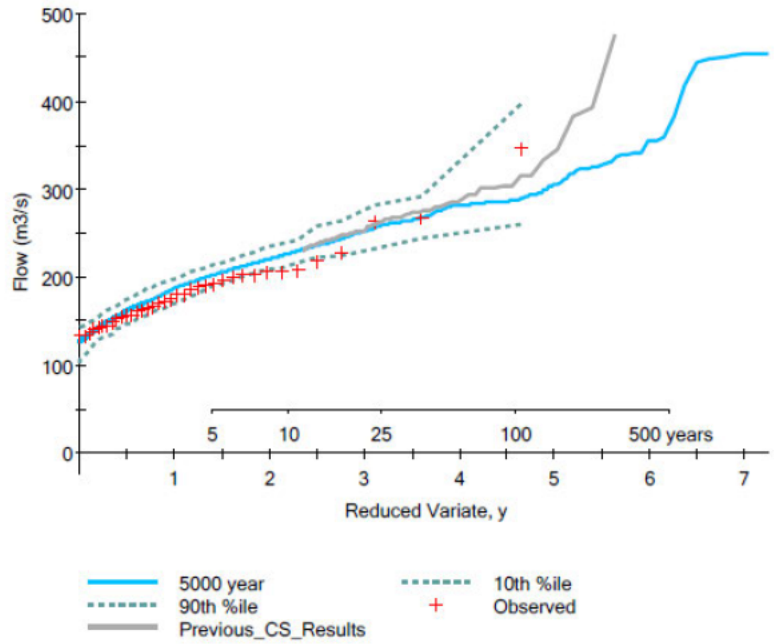

Figure 4.2: The revised flood frequency curve for the Don @ Doncaster [Reproduction of Figure 6-9 from JBA (2017)]

No information is given on what a design event hydrograph shape should look like. This is unsurprising given one of the potential benefits of CS is that a very large number of plausible events are simulated from which the simulated level (or flood extent or volume or flow) can be assessed on a target-site-by-target-site basis without recourse to imposing a fixed "design event" concept on the analysis.

Apart from the Gringorten plotting positions of the annual maximum series, no other means of establishing a flood frequency relationship at the Don @ Doncaster gauging station was included in the report. In a more targeted flood study for Doncaster it would be expected that the standard FEH statistical methods of Single Site and Enhance Single Site analysis would be presented (as a minimum for context). Also, a flood chronology may offer a valuable longer-term historic perspective (assuming the scale of any changes over time does not invalidate such an approach). Without these to set context and compare to it is difficult to finalise an opinion as to the robustness of the design flood hydrology given in this report. (It is noted that the revision of the CS method has already resulted in a large change to the previous version for flood events rarer than the 200-year event. Could a further revision result in another significant change?). However, the comparison given in Figure 4.2 does suggest a more conventional relationship for the rarest events than the old analysis.

4.4 FEH statistical estimate and Archers hydrograph profile derived for this study

In addition to the above review of previous River Don CS flood estimates:

- The Environment Agency has expressed reservations regarding outputs of the most recent Don Continuous Simulation Modelling (CSM) hydrology (JBA, 2017), as the return period estimated for the 2007 event based on this hydrology is considered to be too high. This conclusion is based on internal Environment Agency discussions (the Environment Agency does not have a report detailing/supporting this opinion).
- Instead of applying the most recent Don CS results (JBA 2017) for other flood risk studies in the area, the Environment Agency currently applies results of the previous Don CS hydrology. We understand this is the same as applied in the Don FRMS study, JBA 2009.
- The previous Don FRMS report (JBA 2009) indicates the CS modelling used in that study was developed in approximately 2000.
- The Environment Agency is working with the Don CS modelling team to try and resolve identified shortcomings in the latest Don CS flood estimates.

Whilst utilising the latest Don CS inflows in the Humber EWL modelling would expediate the Humber EWL project, it is possible the design inflows would differ in peak flow and/or volume compared to estimates linked more directly to the flow data (e.g. FEH statistical method applied at Don@Doncaster, and Archer's[3] design hydrograph profiles). Given the limited confidence in the Don CS flood estimates, the following validation work was undertaken to reduce the uncertainties.

- Derivation of a flood frequency curve at Doncaster and an Archers design hydrograph profile. This will provide the context needed to evaluate whether to apply the most recent Don CS hydrology (JBA 2017) in the Humber EWL modelling. Alternatively, it may be preferable to apply the derived flood frequency curve at Doncaster and an Archers design hydrograph profile.

The flood frequency curve derived by the FEH statistical method and Archers design hydrograph profiles at the Don@Doncaster are reported in Appendix A. Peak flows at the Don@Doncaster derived by the FEH statistical method and by the most recent Don CS hydrology (JBA 2017) are compared in Table 4 1. Design event volumes derived by the two methods are compared in Table 4 2.

Table 4 1 shows that for all events except the 1000 year return period event the FEH statistical approach derives greater peak flows than the CS method. Table 4 2 shows that for all but the 1000 year return period event the Archer's method derived hydrographs provide a more conservative estimate of total volume of the main flood peak.

[3] Archer D et al (2000)., The Synthesis of Design Flood Hydrographs, CIWEM/ICE Water Environment 2000: Flood warning and Management, ICE London

	Peak flow (cumecs)		
Return period (years)	CS Derived flows (JBA 2017) at Humber model upstream extent	Peak flood estimates at Doncaster derived by FEH statistical method (2019)	Ratio of PG GEV to CS peak flows (i.e. ratio of upstream model inflows)
2	151.0	167.57	1.11
5	-	218.85	-
10	227.9	250.01	1.10
20	250.128	278.17	1.11
50	288.008	312.02	1.08
75	300.819	326.09	1.08
100	303.271	335.64	1.11
200	316.584	357.93	1.13
500	-	385.08	-
1000	503.041	404.35	0.80

Table 4 1: Peak flows derived by CS (JBA 2017) and the FEH statistical method (this study - Humber EWLs, 2019)

	Hydrograph volume (10^6 m^3)		
Return period (years)	Archers	CS (JBA 2017)	Ratio (Archers/CS)
2	39	35	1.11
10	59	41	1.42
20	65	44	1.48
50	73	59	1.23
75	76	59	1.29
100	79	65	1.21
200	84	69	1.21
1000	95	122	0.78

Table 4 2: Comparison of Hydrograph Volumes (at Humber EWL project River Don upstream model inflow)

4.5 River Don Summary and Recommendations

The provided report does not supply a clear understanding of what hydrological approach was used in the Upper Humber Flood Risk Mapping Study (2016), though it is speculated that it may have been based on the earlier (2000) version of the CS modelling.

The more recent (2017) CS work identified a weakness in the previous work which has been rectified via the inclusion of lateral catchments. Conceptually this is a better form of the model and is thought to result in an improved flood frequency relationship for the rarest events of 100 years and rarer.

Since the earlier work in 2000 the Don catchment has experienced the exceptional flood of 26 June 2007. This has been incorporated in to the understanding of the design flows in the more recent work.

Good agreement exists between the revised flood frequency curve for the Don at Doncaster and the plotting positions of the gauge's annual maximum series. A key finding for the design flows at Doncaster was that the estimated 100-year flow has dropped from 310m^3/s to 288 m^3/s (-7%), but that lesser return periods are little changed. For rarer events than the 100-year event the reductions are more significant.

No information regarding the design shape of the hydrograph was supplied in either of the previous study reports and this has therefore not been reviewed.

4.5.1 Recommendations

The extreme flows derived during this study by the FEH statistical method and Archers method hydrographs are recommended, as these are more directly linked to gauged flow data at Doncaster than the CS design hydrographs. These design hydrographs have higher peaks and volumes than the CS hydrographs, except for the 1000 year event. Design hydrographs derived by the two methods are compared in Appendix A.

The CS flows indicate a steepening of the flood frequency curve between 200yrs and 1000yrs, which is not apparent in the new statistical flood frequency curve (1000yr:200yr ratio is 1.13 for new FEH statistical estimates, and 1.59 for CS estimates). This could be due to, for example, poor CS model performance (the highest recorded event - 2007 event - is overestimated at Doncaster in the CS calibration by 19%) or reservoir storage within the upstream catchment no longer providing significant attenuation for the largest 1000yr event, which is not captured in the FEH statistical estimates. The estimation of highest flows is therefore particularly uncertain.

The model inflows applied in the Humber Strategy modelling are shown graphically and tabulated in Section 4.5 and Appendix C respectively of the Humber 2100+ Extreme Water Levels modelling report (document number ENV0000300C-CH2-ZZ-3A0-RP-HY-0010).

4.6 Consideration of November 2019 River Don flood event

Further to the above assessment, during this study there was significant flooding in the River Don catchment in November 2019. This event was apparently an event of similar size as (or slightly larger than) the AMAX1 2007 event at Doncaster. The below considers how this event fits with the FEH statistical flood estimates at Doncaster derived for this study.

4.6.1 Probability of largest floods experienced based on current flood frequency curve

Prior to the November 2019 event, the 2007 event was the highest peak in the Doncaster Gauging Station 60-years period of record. The FEH statistical estimate indicates a return period of approx. 500 years for this event. Whilst this is a high return period, within the longer record, it is not implausible, as follows:

In context of the gauged record (not including the 2019 event):

Probability of 1 of 500 year return event in a 60 year record = 11%

In context of longer term flood history data (not including the 2019 event):

Probability of 4 events exceeding the 100 year flood in 200 year record = 9%

However, including the additional recent large 2019 event, these probabilities reduce to 5% and 4% respectively, i.e. less likely.

4.6.2 Maximum likelihood estimate of return period of the 2007 event (and the November 2019 large event) based on longer term flood history

A search of the British Hydrological Society Chronology of British Hydrological Events database indicates up to five events (including the 2007 and 2019 events) exceeding the 100 year return period may have occurred in the past 200 years (Appendix A).

If the 2007 event and the similar sized 2019 event were the 2 largest events in the previous 200 years, a maximum likelihood estimate of their return period would be 100 years (it is difficult to rank historic events before gauged records - if any of the historic events were larger than the 2007 and 2019 events, this return period would reduce, and so 100 years is considered an upper estimate).

The impact of assigning a 100 year return period to the 2007 event rather than the current Flood Frequency Curve estimate of 500 years, increases the 100 year flood estimate by approximately 15%. The single site Flood Frequency Curve at Doncaster 80% upper confidence limit is slightly above this estimate (i.e. the 100 year peak flow is slightly higher than the 2007 event), as illustrated in Figure 4.3.

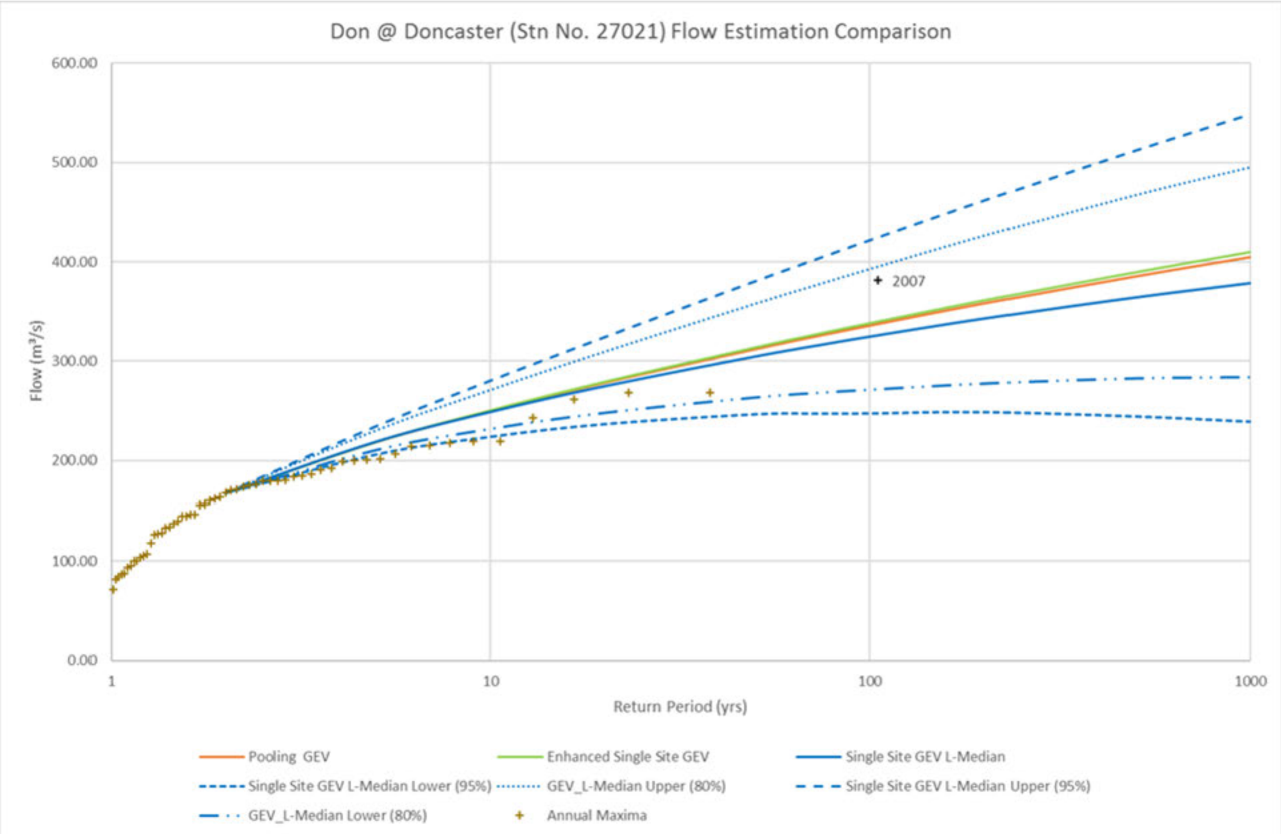

Figure 4.3: Flood Frequency Curves at the Don@Doncaster derived by the FEH statistical method for this study

4.6.3 Interpretation for Humber EWLs project

The assessment in Sections 4.6.1 and 4.6.2 assumes a stationary climate, and therefore a stationary Flood Frequency Curve. Alternatively, the two large recent events (2007 and 2019) may be considered as possible realisations of a changed climate (i.e. consistent with the projected increase in flood peaks due to climate change), and this is accounted for with the proposed 15% to 20% climate change uplifts to be applied in the 2021 flood estimates for the Humber EWLs study.

This is consistent with an initial assessment by CEH of the 2019 event [redacted] which concludes:

"It will no doubt take time for an attribution [i.e. attributing the recent extreme event to climate change] to be published for this flood event. But what we can say with some certainty is that there has been an increasing trend in flooding over the last four or five decades in parts of northern Britain and this is at least consistent with what we may expect in a warming world."

We therefore propose to retain the flood estimates derived for this study by the FEH statistical method, and consider the recent 2007 and 2019 extreme events as possible realisations of a changed climate.

5. The River Trent

The source information reviewed:

3) JBA Consulting (2016). Upper Humber Flood Risk Mapping Study – Final Report. Report for the Environment Agency dated August 2016.

4) Mott Macdonald (2013). Tidal Trent Modelling and Mapping Study. Report for the Environment Agency dated December 2013.

5.1 Upstream model boundary

On the Trent the location of the current Jacobs Humber Strategy model upstream boundary is the Trent at the North Muskham gauging station.

The inflows from watercourses between the Trent at North Muskham and the confluence of the Trent with the Humber are not included as these inflows are either insignificant compared to the Trent flows or the watercourses have downstream tidal structures, and so their inflows do not contribute to peak flows in the model. Flows at Gainsborough are therefore essentially the flows at North Muskham routed hydraulically to Gainsborough.

5.2 Upper Humber Flood Risk Mapping Study [UHFRMS] (JBA, 2016)

As well as incorporating the design hydrology of the Trent, this study also included the design hydrology for the rivers Ouse, Don and Aire. However, updating of the hydrological inflows was beyond the scope of the project. Instead the inflows were taken from previously developed Environment Agency (EA) models. The report acknowledges that the hydrological methods used to derive these were not particularly comparable with one another and that this was highlighted as a potential area for future development.

For the Trent the inflows were extracted from the Tidal Trent Modelling and Mapping Study, Mott Macdonald 2013, and were used as input at the upstream Trent model boundary (at North Muskham gauging station). These design inflows are discussed further in Section 5.3.

The JBA report notes the following general limitations with the fluvial hydrology:

"*Each of the study watercourses have had their design inflows estimated using different a different method (ranging from continuous simulation to more standard FEH methods). These approaches are not necessarily compatible or representative of the same storm (in fact the assumption of a homogeneous storm over a catchment of this size would in itself represent a significant limitation). Moreover, the study area is considered susceptible to both design flow (likely to control the onset of flooding) and design volume (likely to have the greatest influence on maximum flood extents)*".

The UHFRMS report strongly recommends that the fluvial boundary conditions within their model be updated when new model results become available.

5.3 Tidal Trent Modelling and Mapping Study, Mott Macdonald 2013

5.3.1 FEH statistical method

The Tidal Trent Modelling and Mapping Study (Mott Macdonald 2013) derives a flood frequency curve at North Muskham by the FEH statistical method. This application of the FEH statistical method is considered not to apply best practice, as follows:

- Despite a relatively long period of good quality recorded flows available at North Muskham (43 years of AMAX data from 1969 to 2011 considered by the National Rivers Flow Archive to be suitable for QMED estimation and for inclusion in pooling groups), the study derived a QMED estimate at North Muskham by the catchment descriptor donor transfer method, using the Nottingham gauge (approximately 40km upstream) as a donor (without applying the distance adjustment to the donor adjustment). This resulted in a QMED estimate approximately 4% higher than that derived from AMAX records at Morth Muskham (470 cumces compared to 453 cumecs). The preference for a donor adjusted catchment descriptor estimate is unusual as the subject site is well gauged. The only stated justification for adopting the higher donor adjusted value was "*in consultation with the EA*". The current QMED value derived from AMAX records published on the National Rivers Flow Archive website is 438 cumecs (approximately 7% lower than the Mott Macdonald 2013 estimate).
- Single site and (ungauged) pooled growth curves were derived at North Muskham and Nottingham gauging stations. Both pooled growth curves include more than one gauge on the same river (i.e. increasing the weight of the growth curve of rivers with more than one representation in the pooling group). Goodness of fit measures are not provided in the report for the pooled growth curves. The report shows that for both North Muskham and Nottingham the pooled growth curve lies within the confidence intervals of the single site growth curve, but the percentile of the confidence intervals is not stated in the report.
- For both sites, composite growth curves were constructed which applied the pooling group growth curve for return periods up to 5 years and the single site growth curve for 10 year and higher return periods. This again is an odd choice as the single site growth curve is usually considered reliable up to approximately half the subject site record length (i.e. up to approximately the 25 year return period at North Muskham), and a pooled growth curve would be preferred for higher return periods. The only stated justification for this choice was "*in consultation with the EA*" and "*to provide a better fit to observed data*" (to ensure the resulting growth curve fitted the AMAX records plotted using the Gringorten plotting position i.e. an overfit to the AMAX dataset).
- Given the good quality peak flow data at North Muskham, developing an Enhanced single Site growth curve would be appropriate, and would probably yield a growth curve between the single site and ungauged pooled growth curves.
- The composite growth curves at Nottingham and North Muskham were similar (all growth factors within 3%). Despite the derivation of a growth curve at the North Muskham site, the study applied growth factors for Nottingham at North Muskham. The only stated justification for this choice was "*in consultation with the EA*". It is possible this choice was made as the Nottingham growth factors are mostly slightly higher than the North Muskham growth factors (which would provide slightly more conservative flood estimates, but this is not a valid reason).

5.3.2 Flood hydrograph profile

The Mott Macdonald 2013 study applied the 1986 flood event hydrograph profile at North Muskham (scaled to match design flood peaks) as a representative flood hydrograph profile at North Muskham. This event was chosen as it was considered representative/average. Whilst this is considered reasonable, there is variation in historic hydrograph profiles at North Muskham, and the sensitivity of model outputs to hydrograph volume could be tested by scaling the hydrograph time base by e.g. +/- 25%.

5.4 River Trent Conclusions and Recommendation

The FEH statistical estimates of the Mott Macdonald 2013 study are considered likely to overestimate peak floods at North Muskham, as:

- The derived QMED value is approximately 7% higher than an updated value
- The single site growth curve applied in the study for return periods 10 years and higher has growth factor approximately 25% higher than that of the pooled growth curve for the 100 year return period event.

5.4.1 Recommendations

It is recommended that the Mott Macdonald 2013 design flood estimates at North Muskham and design hydrograph profiles are applied in the Humber EWL study with the following sensitivity tests, for e.g. the 100 year return period fluvial event:

- Design inflows adjusted by - 25% (Mott Macdonald 2013 flood estimates are considered likely to be overestimates)
- Design hydrograph time base adjusted by +/- 25%

The model inflows applied in the Humber Strategy modelling are shown graphically and tabulated in Section 4.5 and Appendix C respectively of the Humber 2100+ Extreme Water Levels modelling report (document number ENV0000300C-CH2-ZZ-3A0-RP-HY-0010).

Appendix A. River Don FEH statistical method peak flood estimates and Archer's hydrograph derivation

Please see attached document: *River Don - Flood estimation audit trail_Chkd_Revd_v4.docx*