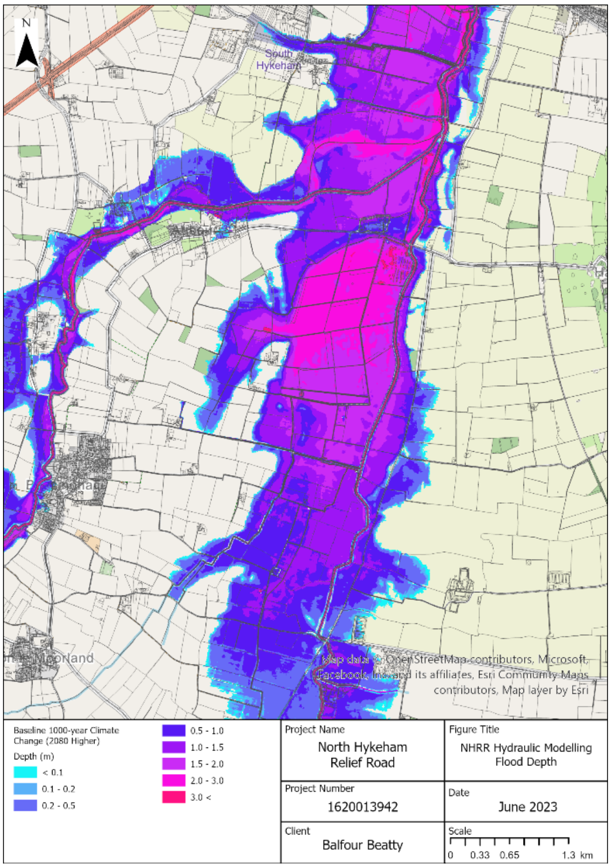


Figure 9-13: 1,000-year plus climate change (2080 Higher) flood depths for the Baseline Scenario

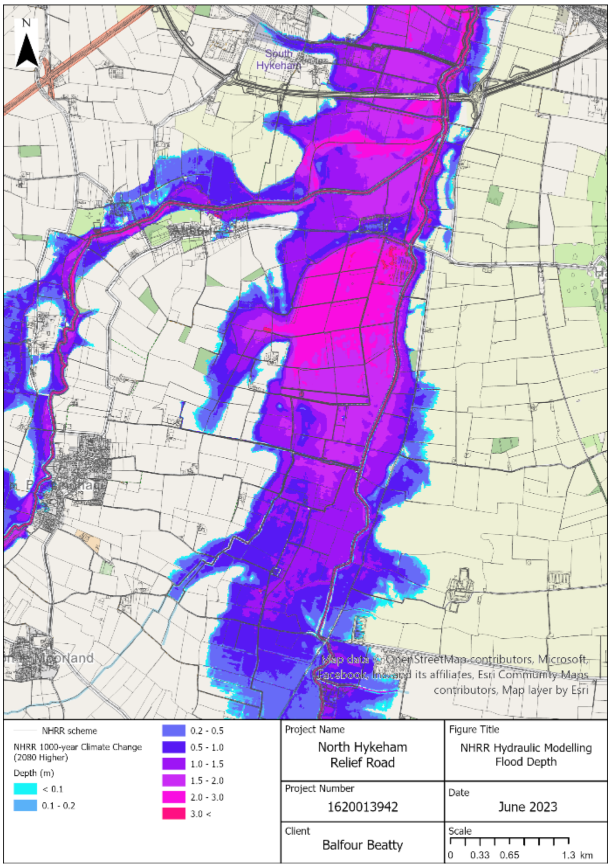


Figure 9-14: 1,000-year plus climate change (2080 Higher) flood depths for the NHRR Scenario

9.3 Flood Velocities

9.3.1 A key aim of the NHRR hydraulic modelling is to assess whether exceedance flow can be conveyed under the NHRR without risk to road users and without exacerbating erosion of the flood-retaining embankments. Flood velocities have been assessed to understand how the NHRR may affect erosion risk to inform scour protection requirements.

9.3.2 The 100-year event flood velocities are not affected by the NHRR scheme. For the 100-year plus climate change (2080 Higher), 1,000-year and 1,000-year plus climate change (2080 Higher) event, the main impact of the NHRR scheme on floodplain velocities is around the NHRR crossing, between the Witham Washland Defence and the Beck.

9.3.3 Figure 9-15 and Figure 9-16 show the flood velocities during the 100-year plus climate change (2080 Higher) event for the Baseline and NHRR scenario respectively. Figure 9-17 shows the flood velocity difference for the 100-year plus climate change (2080 Higher) event between the NHRR scenario and the Baseline Scenario.

9.3.4 Comparison of the velocity mapping shows the impact is limited to the western floodplain. During the baseline scenario, the maximum velocities at the western floodplain are generally below 0.1 m/s and flood waters overtopping the Witham Washland defence pass north unimpeded across the floodplain. During the NHRR scenario, the velocities are simulated to increase compared to the baseline velocities, most significantly around the proposed NHRR wide span bridge. The NHRR crossing prevents the free spread of water across the floodplain. Flood waters are funnelled under the proposed NHRR wide-span bridge. The concentration of flows under the bridge results in increased simulated velocities. The most significant increase in velocities during the 100-year plus climate change (2080 Higher) is on the southern edge of the western NHRR embankment just before the opening to the wide span bridge, increasing to between 0.5 m/s and 0.75 m/s.

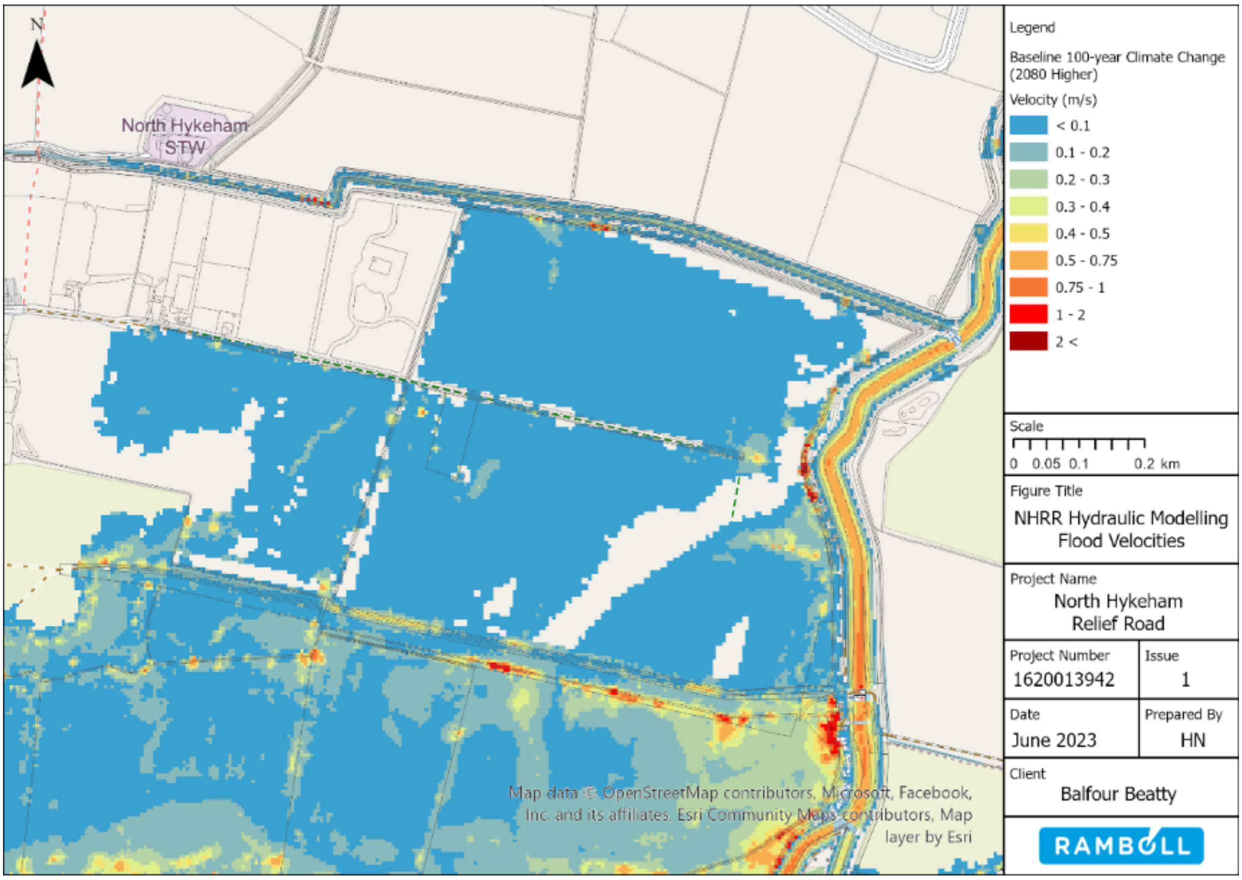


Figure 9-15: 100-year plus climate change (2080 Higher) flood velocities for the Baseline Scenario

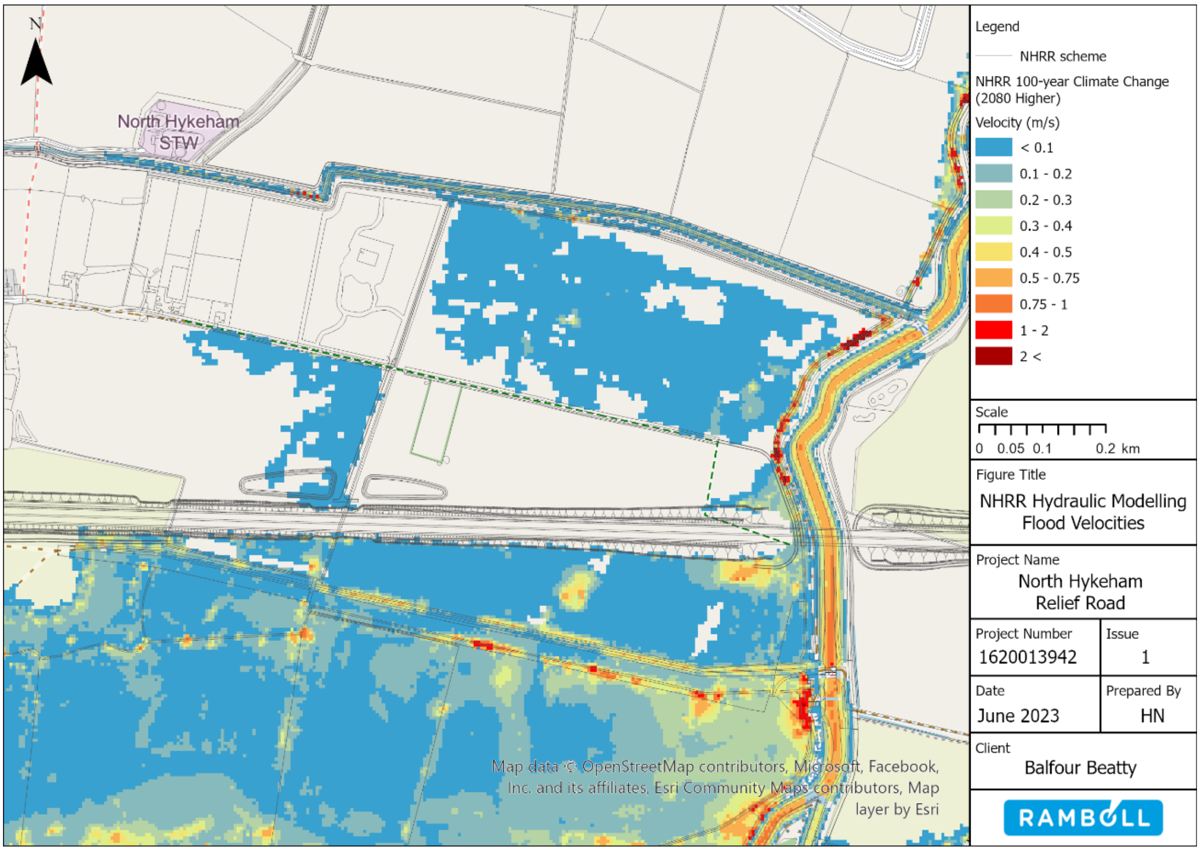


Figure 9-16: 100-year plus climate change (2080 Higher) flood velocities for the NHRR Scenario

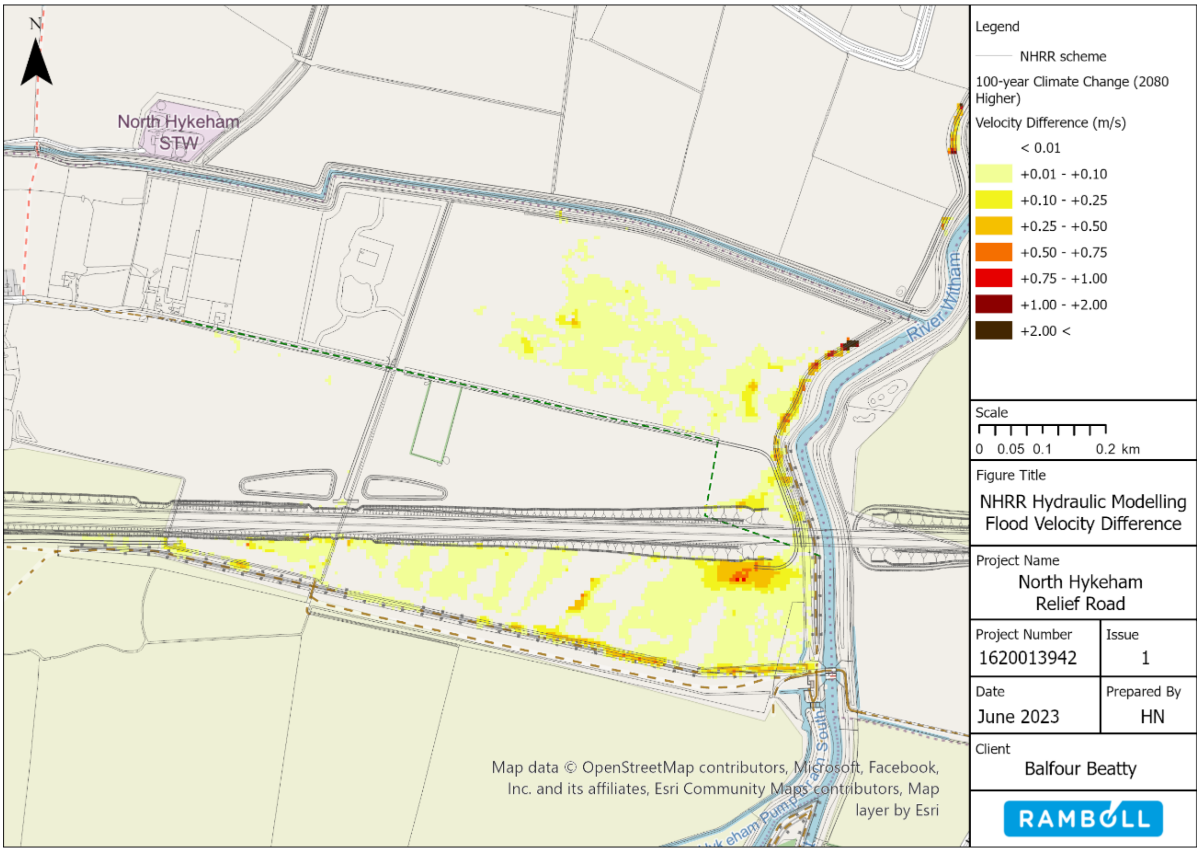


Figure 9-17: 100-year plus climate change (2080 Higher) flood velocity difference between the NHRR Scenario and the Baseline Scenario

9.3.5 Figure 9-18 and Figure 9-19 show the flood velocities during the 1,000-year event for the Baseline and NHRR scenario respectively. Figure 9-20 shows the flood velocity difference for the 1,000-year event between the NHRR scenario and the Baseline Scenario.

9.3.6 During the baseline scenario, the maximum velocities at the western floodplain are generally between 0.1 m/s and 0.3 m/s. During the NHRR scenario, the velocities are simulated to increase compared to the baseline velocities, most significantly to the south of the NHRR embankment where floodwaters overtopping the Witham Washland defence are prevented from spreading north, increasing velocities to between 0.3 m/s and 0.5 m/s. Velocities are simulated to increase to between 0.5 m/s and 0.75 m/s at the wide-span bridge location, where flood flow is concentrated through the opening. The most significant increase in velocities during the 1,000-year event is on the southern edge of the western NHRR embankment just before the opening to the wide span bridge, increasing to between 0.75 m/s and 1 m/s and above.

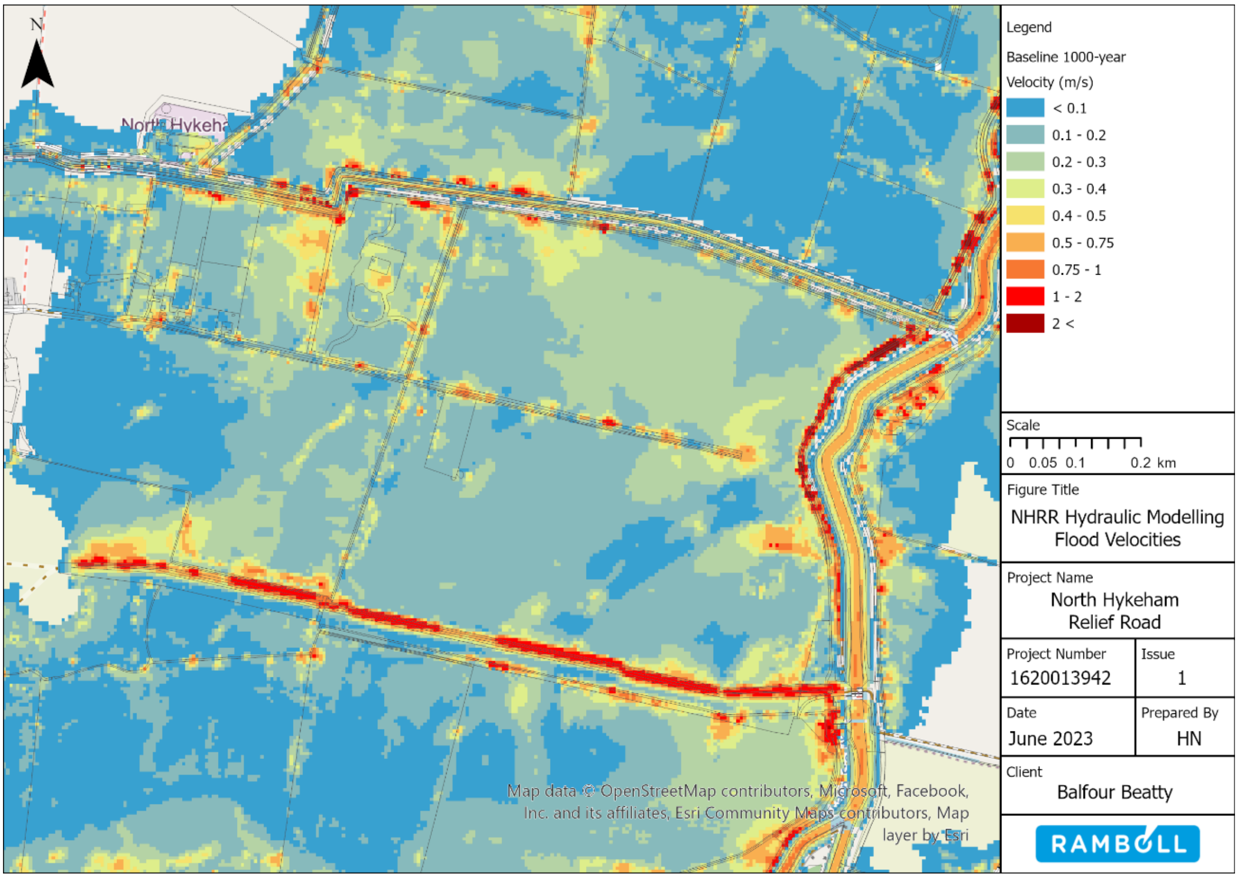


Figure 9-18: 1,000-year flood velocities for the Baseline Scenario

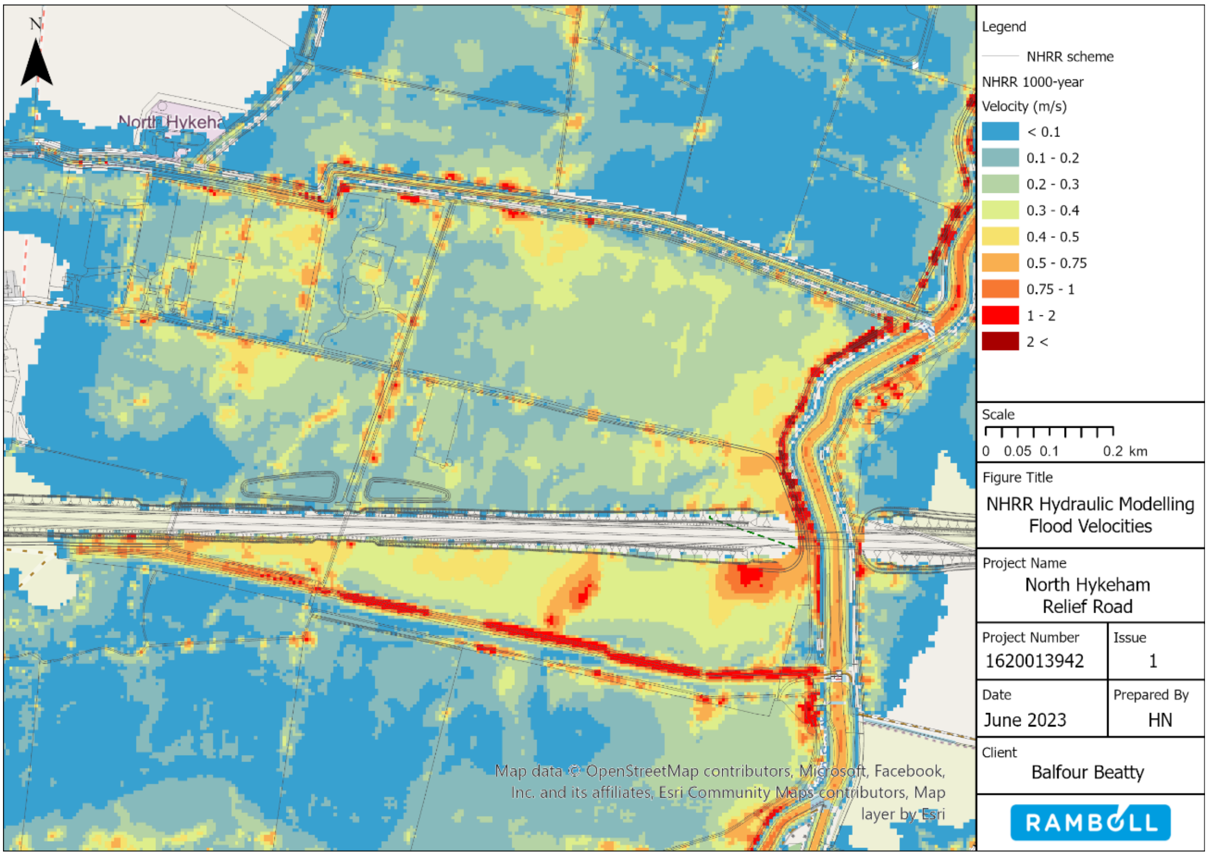


Figure 9-19: 1,000-year flood velocities for the NHRR Scenario

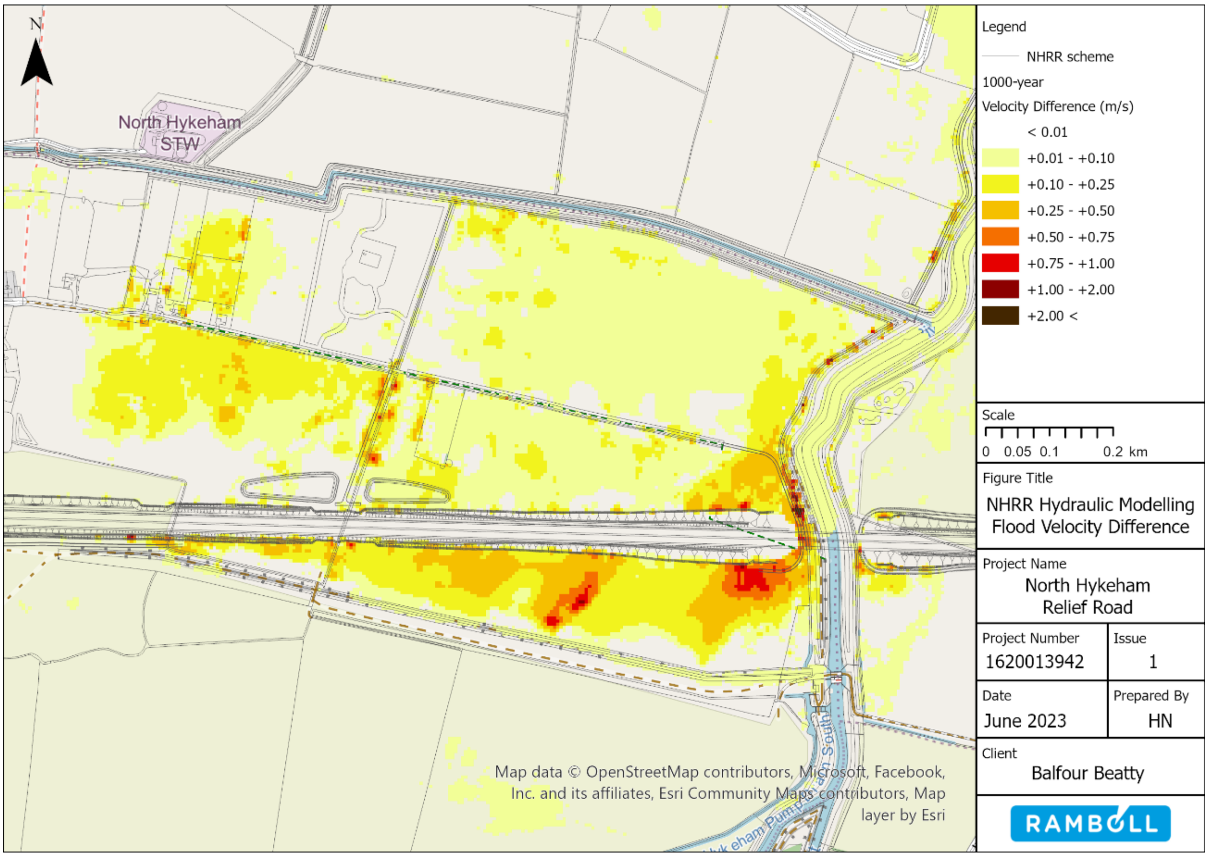


Figure 9-20: 1,000-year flood velocity difference between the NHRR Scenario and the Baseline Scenario

9.3.7 Figure 9-21 and Figure 9-22 show the flood velocities during the 1,000-year plus climate change (2080 Higher) event for the Baseline and NHRR scenario respectively. Figure 9-23 shows the flood velocity difference for the 1,000-year plus climate change (2080 Higher) event between the NHRR scenario and the Baseline Scenario.

9.3.8 During the baseline scenario, the maximum velocities at the western floodplain are generally between 0.1 m/s and 0.4 m/s. During the NHRR scenario, the velocities are simulated to increase compared to the baseline velocities to between 0.3 m/s and 0.75 m/s. Velocities are simulated to increase to over 1 m/s at the wide span bridge location, where flood flow is concentrated through the opening and on the southern edge of the western NHRR embankment just before the opening to the wide-span bridge.

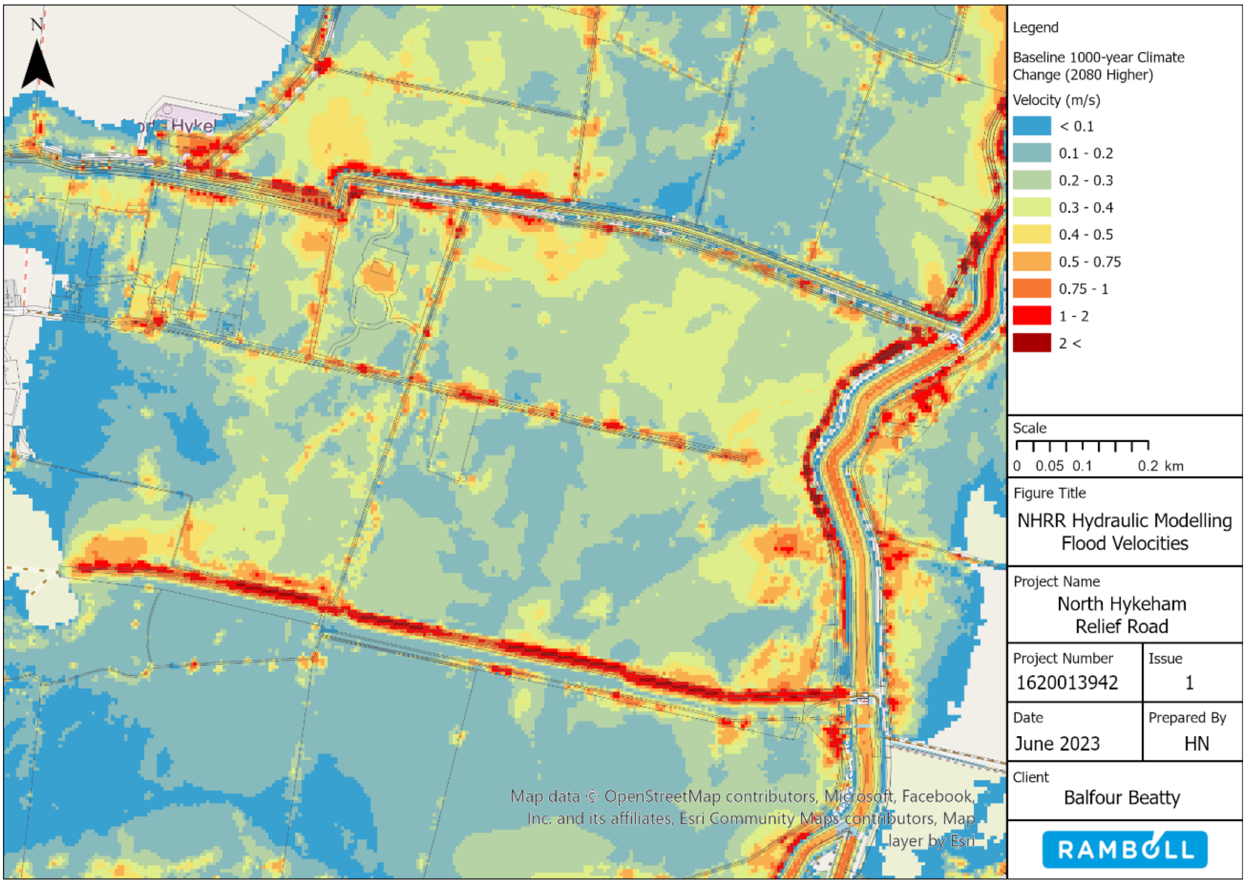


Figure 9-21: 1,000-year plus climate change (2080 Higher) flood velocities for the Baseline Scenario

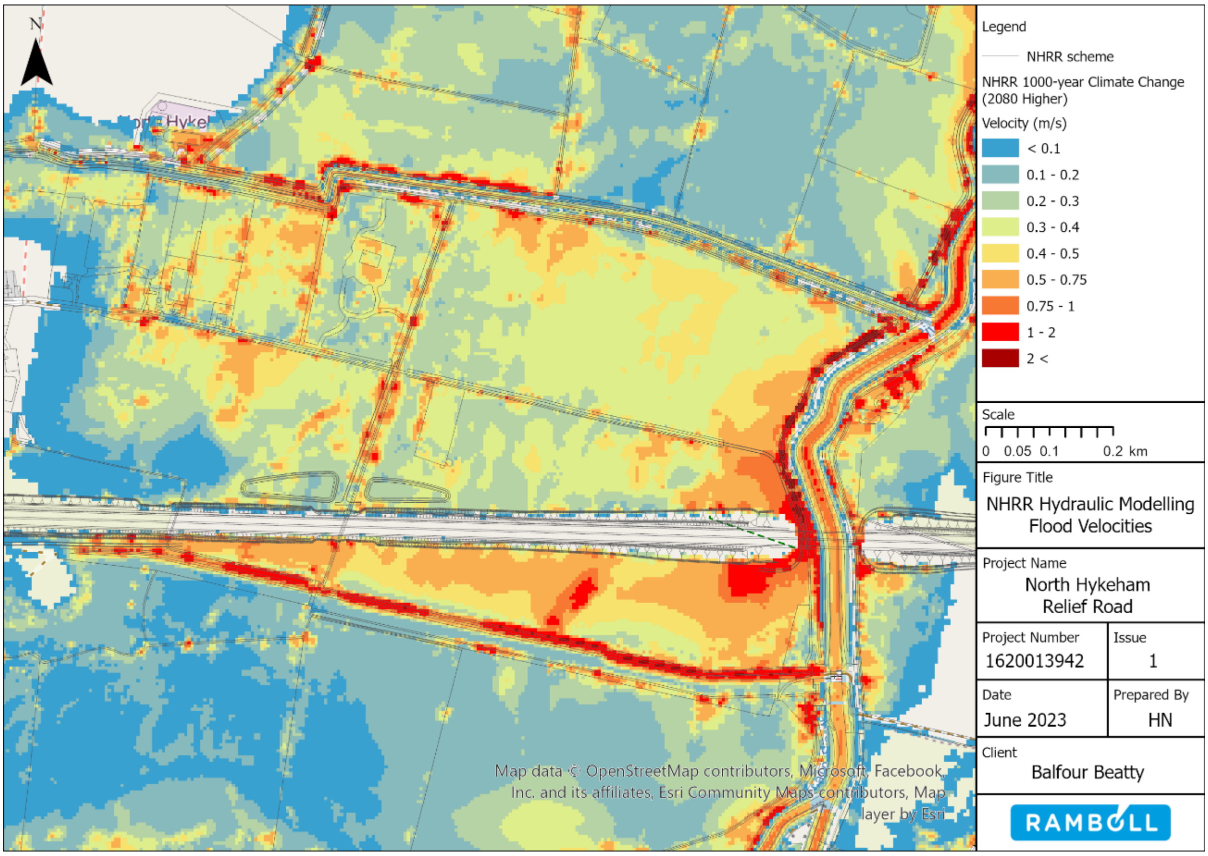


Figure 9-22: 1,000-year plus climate change (2080 Higher) flood velocities for the NHRR Scenario

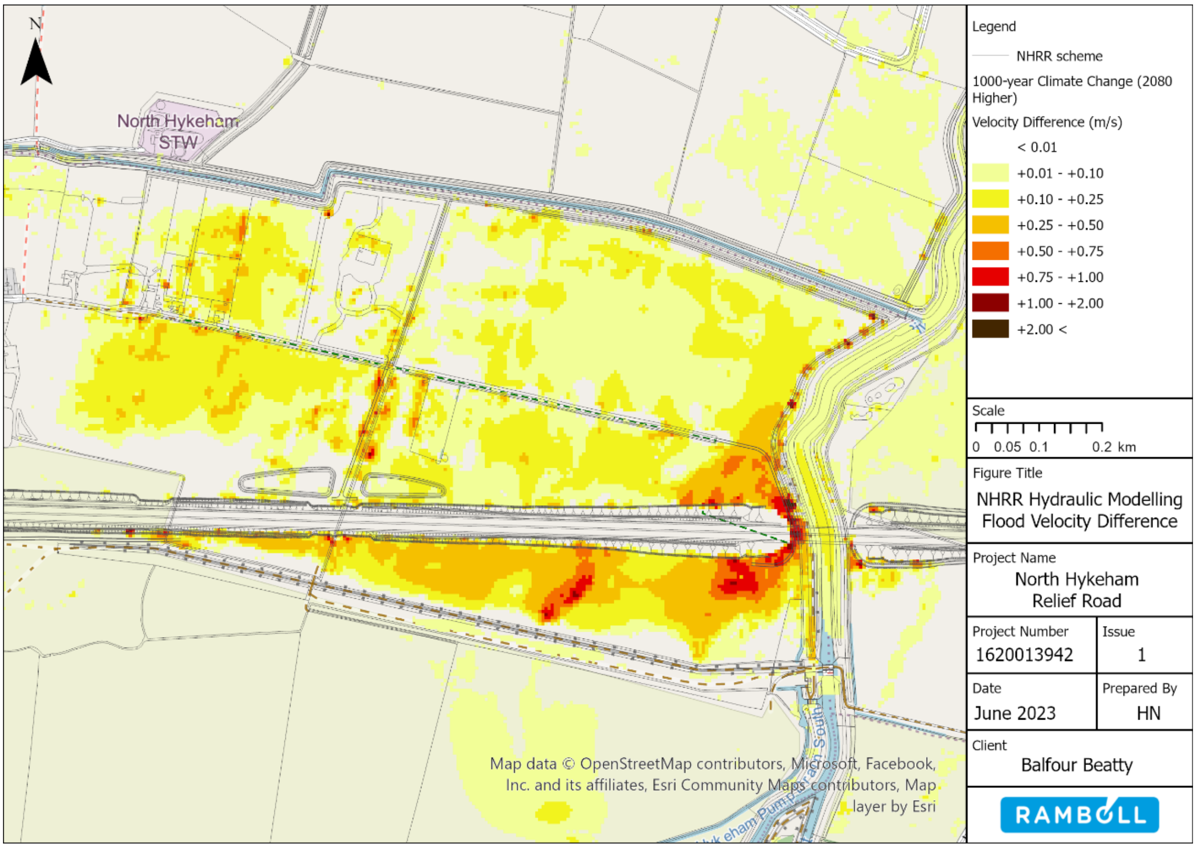


Figure 9-23: 1,000-year plus climate change (2080 Higher) flood velocity difference between the NHRR Scenario and the Baseline Scenario

10. RESULTS – BREACH ANALYSIS

10.1 Breach Analysis

10.1.1 A key aim of the NHRR hydraulic modelling is to assess whether flood defence breach flow can be conveyed under the NHRR without risk to road users and exacerbating erosion of the flood-retaining embankments. Two breach scenarios were assessed:

- Breach of the Witham Washland Defence (FSA); and
- Breach of the River Witham Defence between the River Witham Sluice Gates and the proposed NHRR crossing location (RWUS).

10.1.2 The hydraulic modelling results showed that the NHRR was not simulated to flood and all flows were conveyed under the NHRR during both breach scenarios for all fluvial events simulated. To understand if a breach scenario could exacerbate erosion of the existing flood defences and the NHRR, the flood velocities were assessed.

10.2 Witham Washland Defence Breach (NHRR BREACH FSA)

10.2.1 Figure 10-1, Figure 10-2, Figure 10-3 and Figure 10-4 show the maximum flood velocities during a breach of the Witham Washland Defence during the 100-year, 100-year plus climate change (2080 Higher), 1,000-year and 1,000-year plus climate change (2080 Higher) respectively.

10.2.2 For all events, the velocities at the FSA breach location are over 2 m/s. To the west of the breach, in the area between the NHRR and the Witham Washland Defence, the velocities are generally between 0.4 m/s to 0.75 m/s for the 100-year event, increasing to between 0.5 m/s to 0.75 m/s with areas of 1 m/s to 2 m/s for the higher return period events.

10.2.3 To the east of the breach, the peak velocities are generally between 1 m/s to 2 m/s for all events simulated. The higher velocities simulated follow the main flow pathway of flood waters passing through the breach. Flood waters head towards the NHRR embankment and then pass west towards the wide span bridge opening, passing through to the floodplain to the north where velocities generally decrease.

10.2.4 During the breach scenario, increased velocities are simulated in the IDB drain Hykeham Pump Drain South passing parallel to the river Witham between the Witham Washland defence and the Beck. Velocities along this section of Hykeham Pump Drain South during the NHRR scenario were not simulated to be higher than the Baseline scenario. The higher velocities are linked to the breach of the existing defences and not the inclusion of the NHRR scheme.

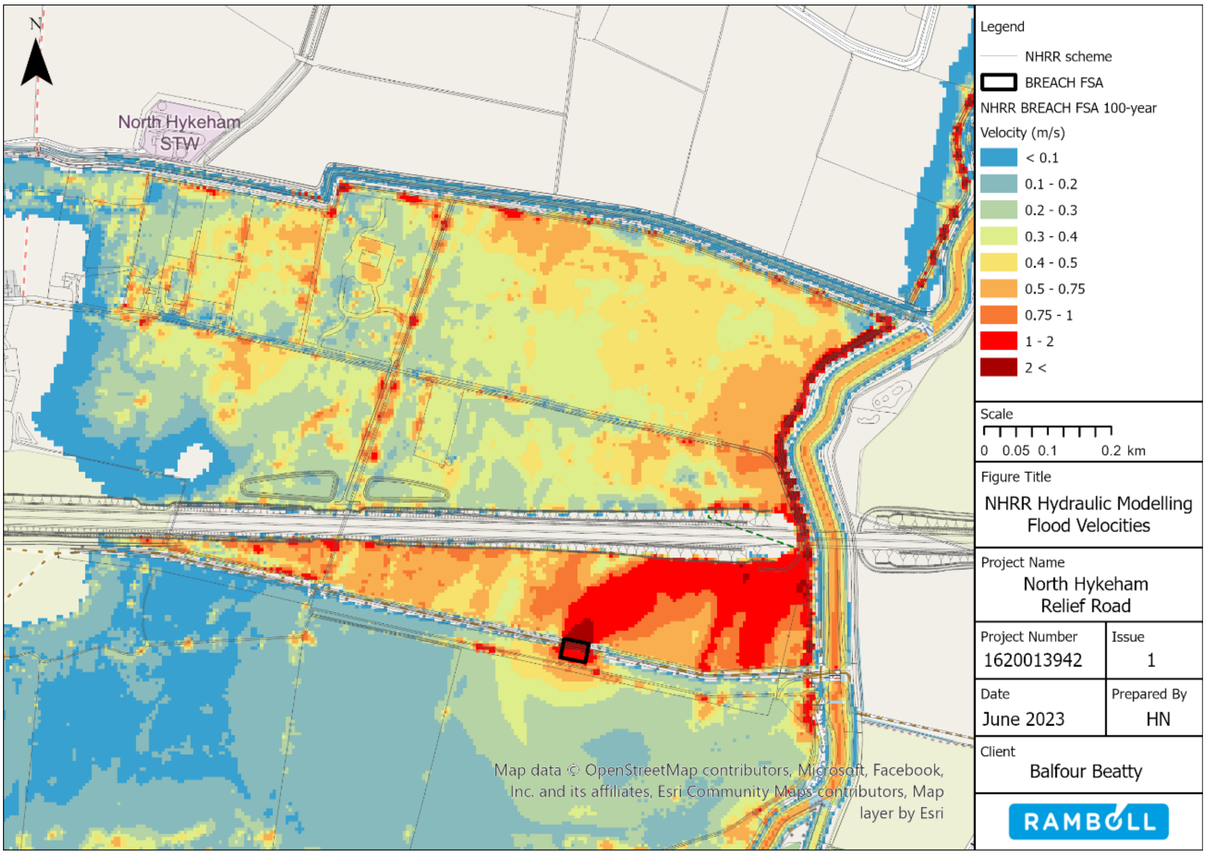


Figure 10-1: 100-year flood maximum velocities for the NHRR BREACH FSA Scenario

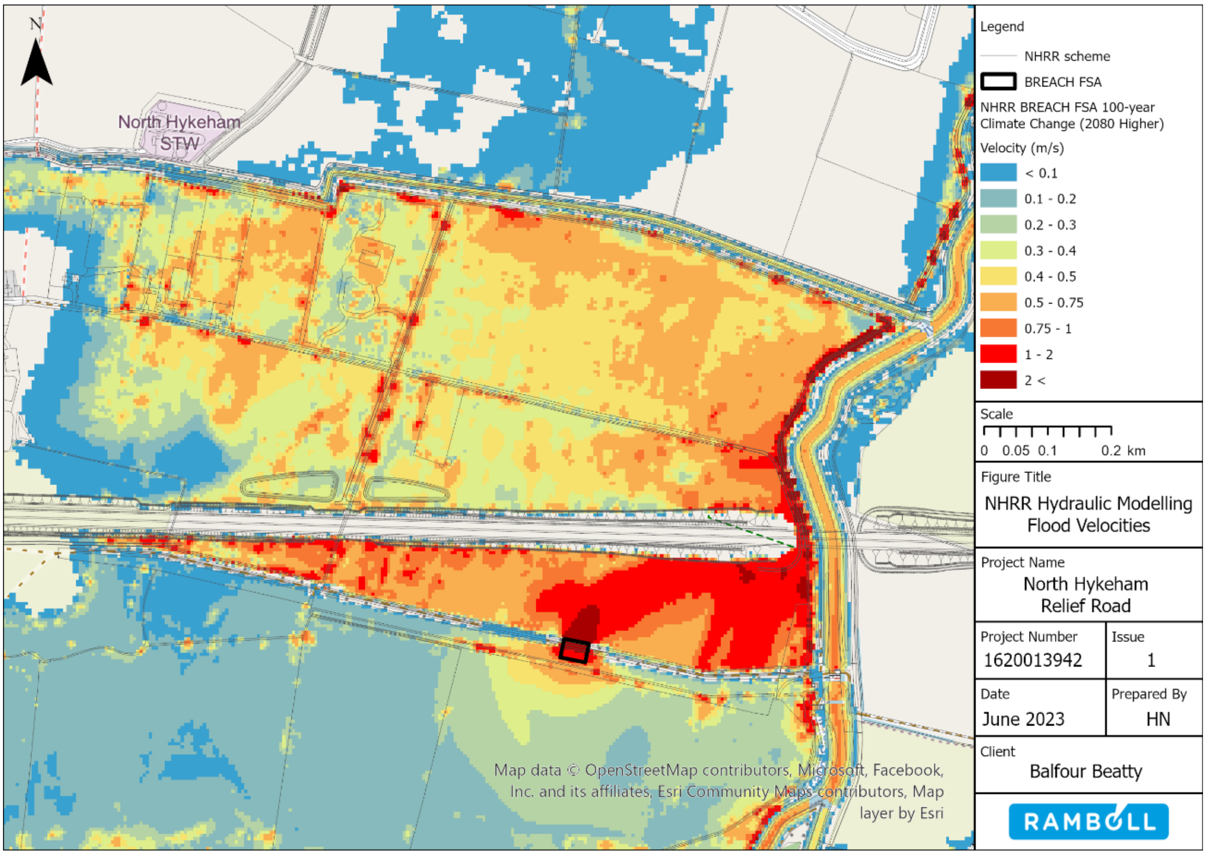


Figure 10-2: 100-year plus climate change (2080 Higher) flood velocities for the NHRR BREACH FSA Scenario

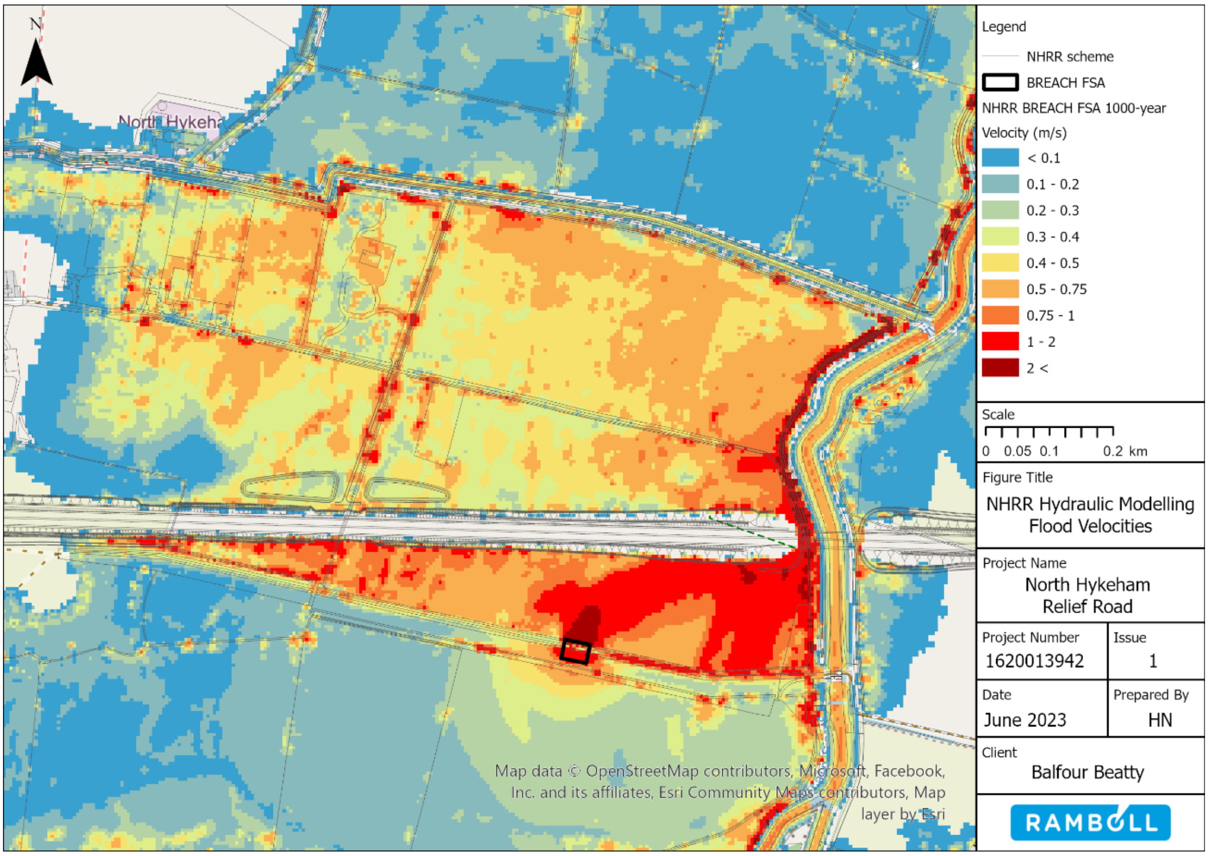


Figure 10-3: 1,000-year flood velocities for the NHRR BREACH FSA Scenario

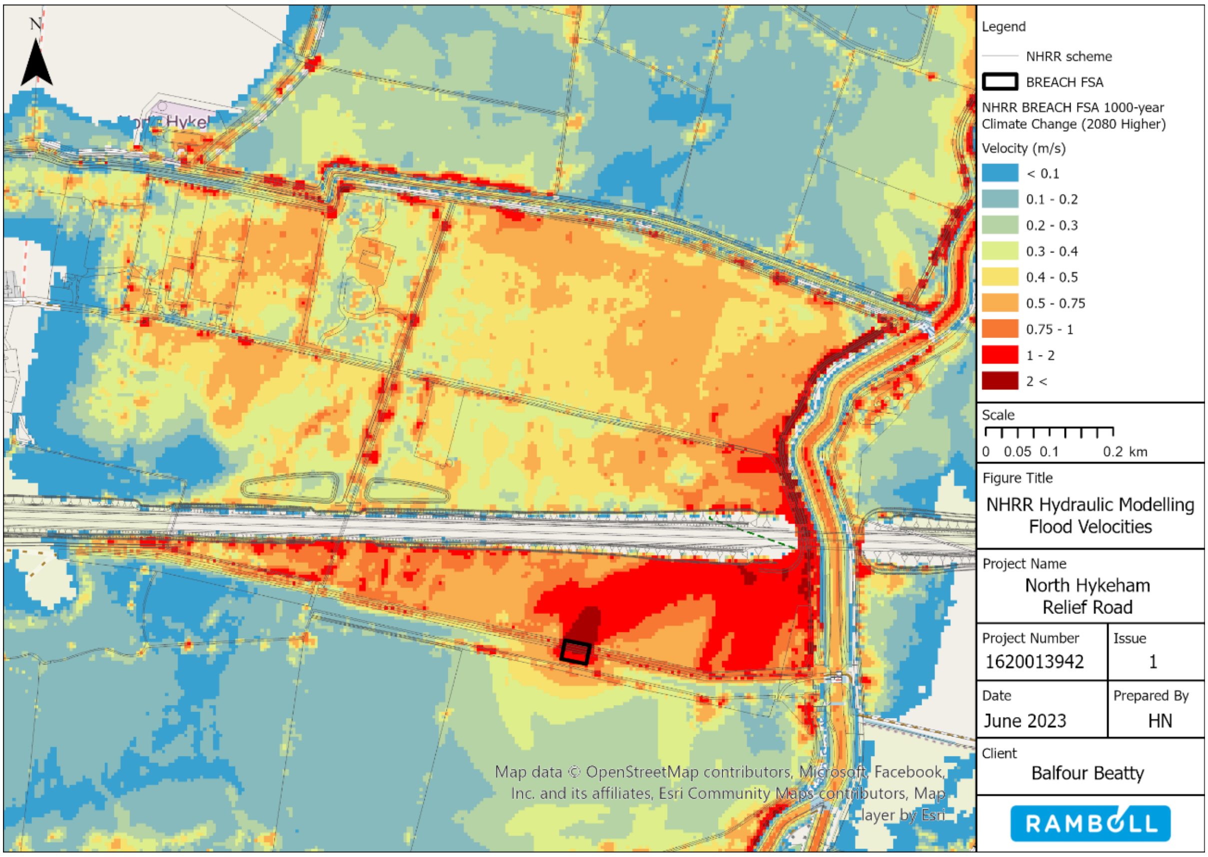


Figure 10-4: 1,000-year plus climate change (2080 Higher) flood velocities for the NHRR BREACH FSA Scenario

10.3 River Witham Defence Breach (NHRR BREACH RWUS)

10.3.1 Figure 10-5, Figure 10-6, Figure 10-7, and Figure 10-8 show the maximum flood velocities during a breach of the River Witham Defence (RWUS) during the 100-year, 100-year plus climate change (2080 Higher), 1,000-year and 1,000-year plus climate change (2080 Higher) respectively.

10.3.2 During the RWUS breach, flood waters pass from the River Witham to the floodplain, into the area between the Witham Washland Defence and the NHRR embankment. The main pathway of flood flows in this area passes north-west towards the wide span bridge opening to fill the floodplain to the north of the NHRR. The River Witham flood gates act to control the water levels in the River Witham at the location of the RWUS breach to not overtop the Witham flood defences. The breach was therefore set to occur when the peak water level is reached upstream of the river Witham flood gate to capture the worst-case impact of a breach occurring when the flood peak reaches the NHRR area.

10.3.3 During the 100-year and 100-year plus climate change (2080 Higher) event, peak velocities at the RWUS breach location are over 2 m/s. Peak velocities in the area around the RWUS breach and at the opening of the wide span bridge are over 2 m/s, reflecting the main pathway of flood flows through the breach. In the area between the Witham Washland Defence and the NHRR, flood velocities decrease towards the west to less than 0.4 m/s for the 100-year event and less than 0.5 m/s for the 100-year plus climate change (2080 Higher) event.

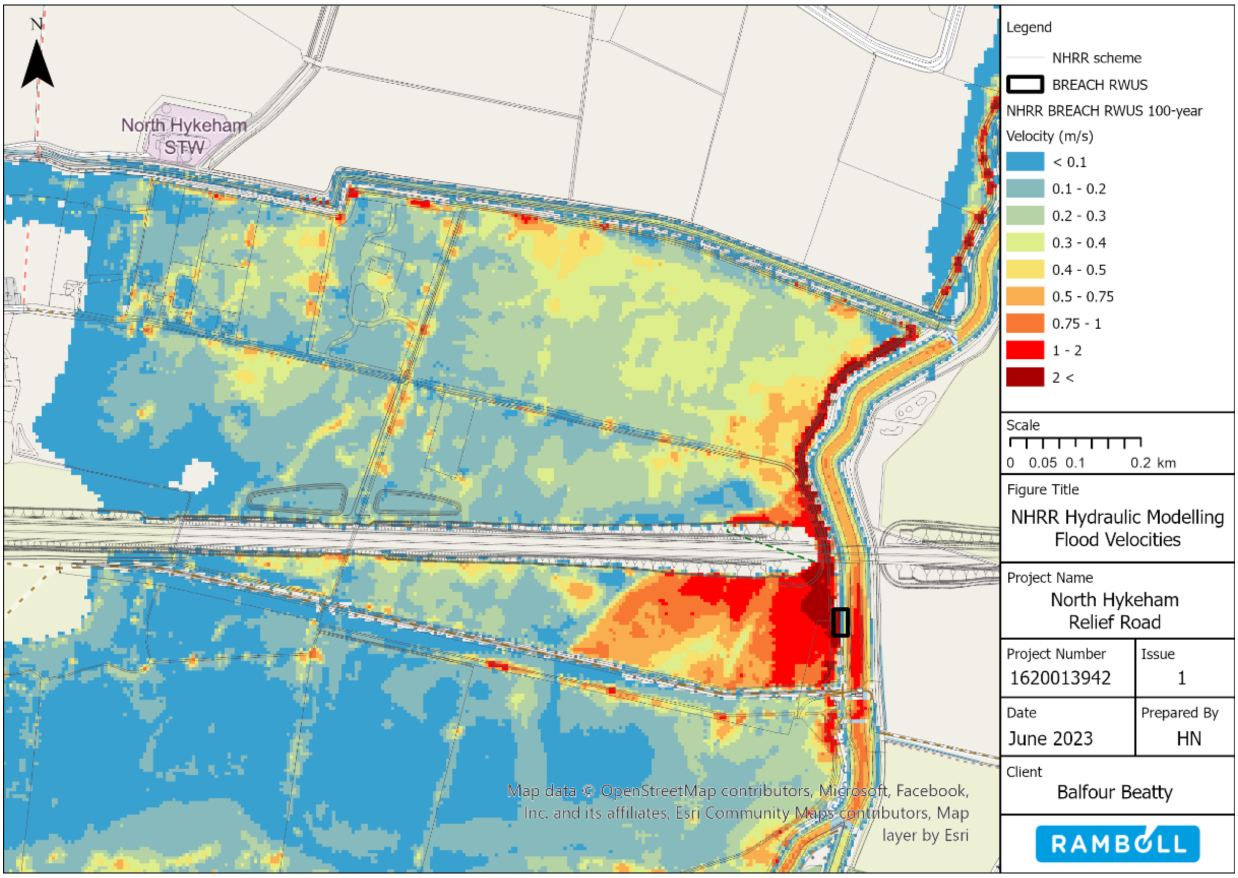


Figure 10-5: 100-year flood velocities for the NHRR BREACH RWUS Scenario

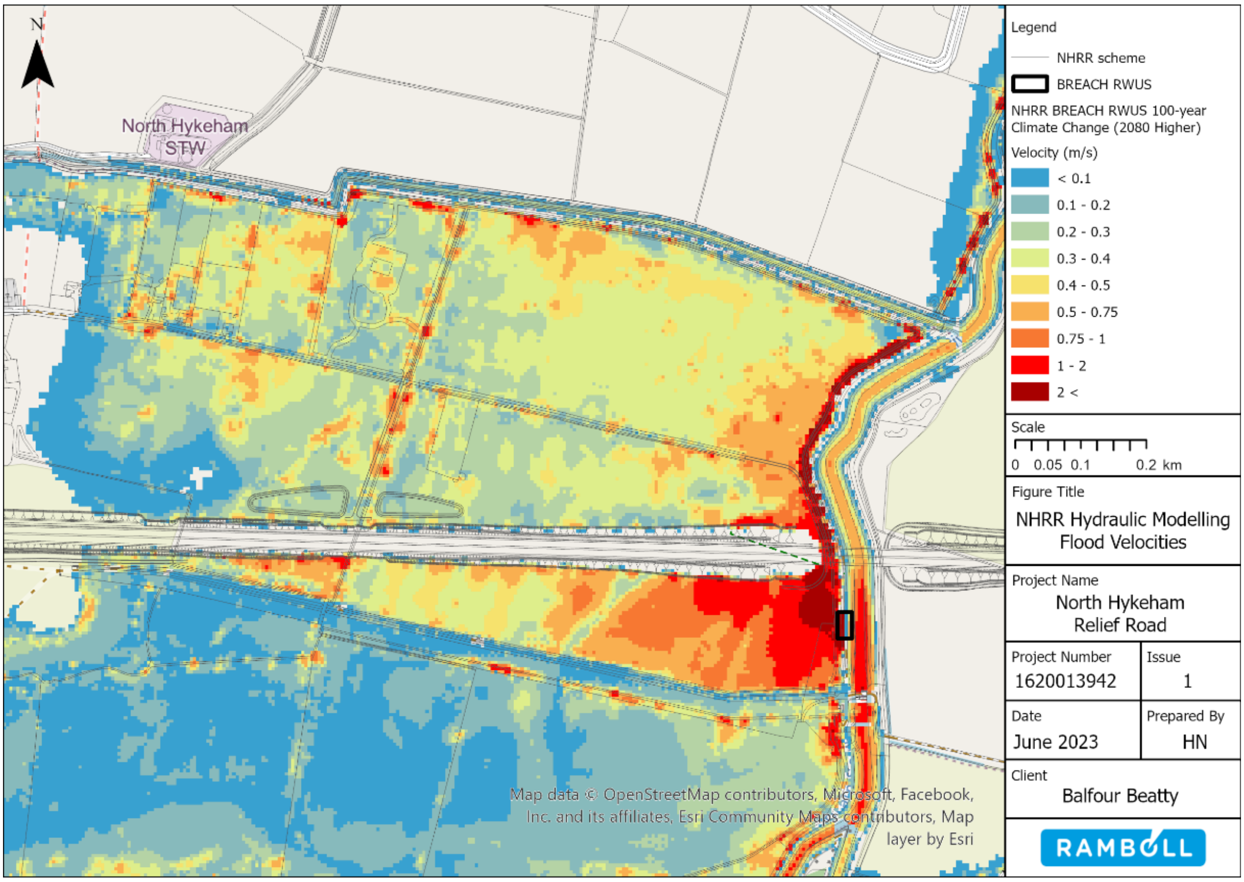


Figure 10-6: 100-year plus climate change (2080 Higher) flood velocities for the NHRR BREACH RWUS Scenario

10.3.4 During the 1,000-year and 1,000-year plus climate change (2080 Higher) event, the impact of the RWUS breach on flood velocities to the floodplain around the NHRR is minimal. This is because the floodplain around the NHRR is already significantly flooded when the RWUS breach occurs. At the start of the RWUS breach, there is not a significant difference between the water levels in the River Witham and the water levels in the floodplain around the NHRR and to cause a significant impact to velocities. The velocities for the RWUS breach scenarios and the NHRR scenarios for the 1,000-year and 1,000-year plus climate change events are therefore very similar.

10.3.5 The RWUS breach also simulated increased velocities along the IDB drain Hykeham Pump Drain South passing parallel to the river Witham between the Witham Washland Defence and the Beck. This is linked to the breach of the defence and not the inclusion of the NHRR because the velocities simulated at Hykeham Pump Drain South during the NHRR scenario were comparable to the velocities simulated during the Baseline scenario.

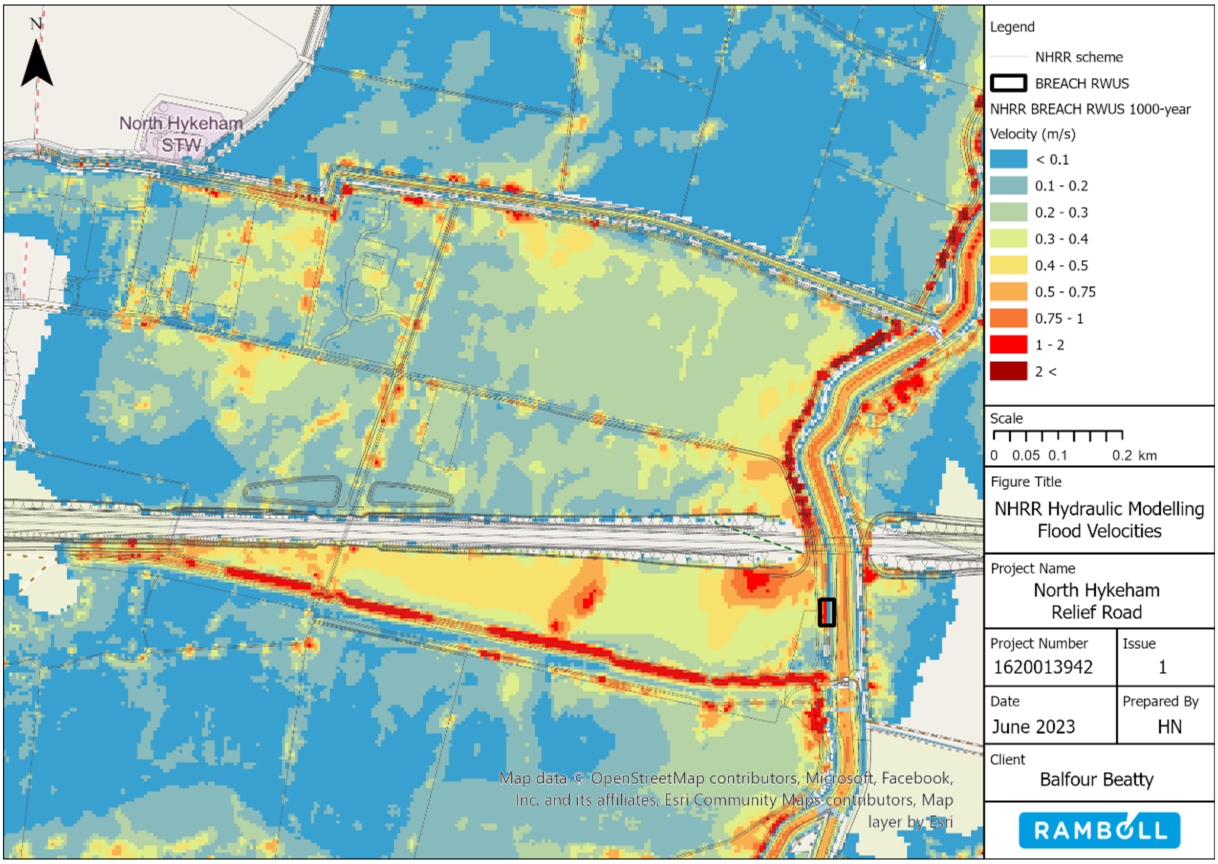


Figure 10-7: 1,000-year flood velocities for the NHRR BREACH RWUS Scenario

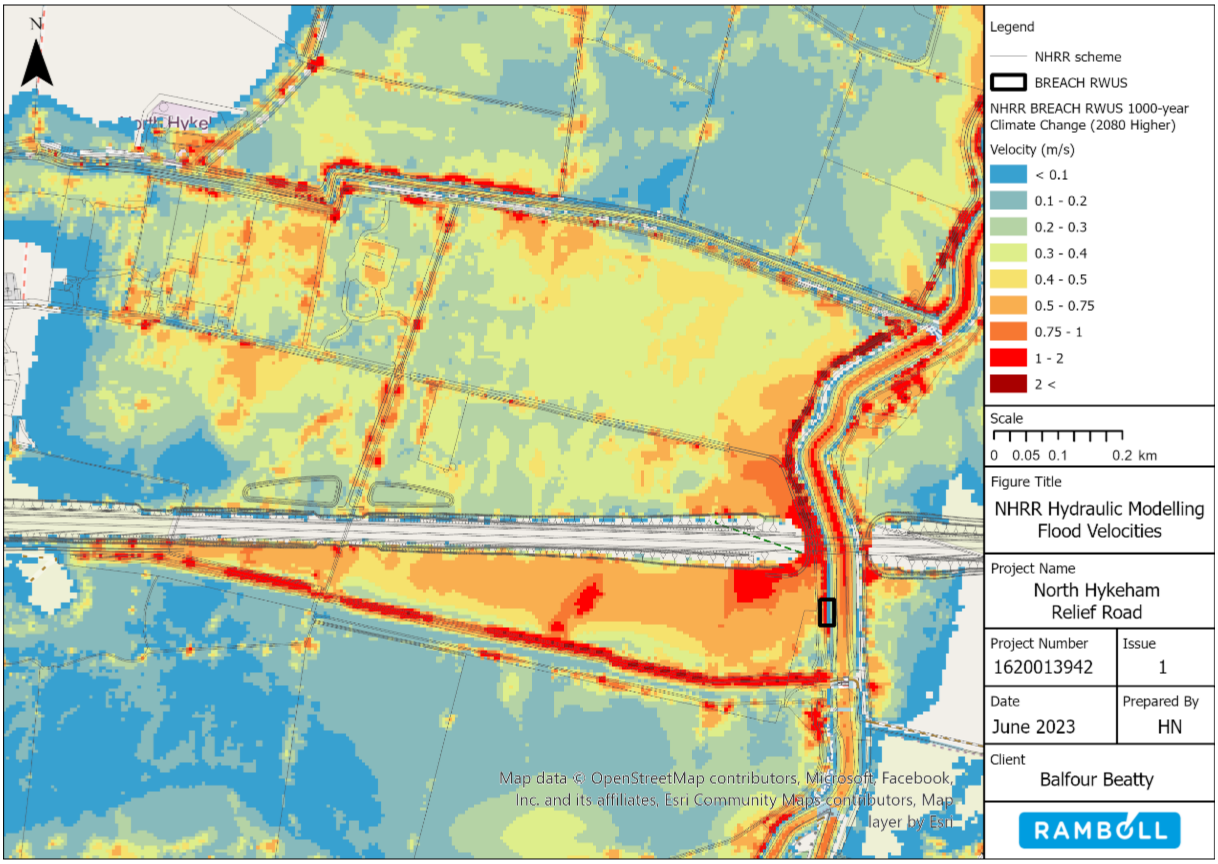


Figure 10-8: 1,000-year plus climate change (2080 Higher) flood velocities for the NHRR BREACH RWUS Scenario

11. LIMITATIONS

11.1 Limitations

11.1.1 During any hydraulic modelling study, there will always be associated limitations, for example with uncertainty, data availability etc. The representation of any complex system by a model requires several assumptions to be made. In the case of the hydraulic modelling prepared by Ramboll for this report, it has been assumed that:

- Cross sections accurately represent the shape and variation of the river.
- Model parameters have been determined appropriately.
- Design flows are an accurate representation of a given return period.
- The surveyed cross sections of hydraulic structures and units used to represent them in the model adequately represent the situation.
- LiDAR accurately reflects bank heights and that the filtered LIDAR has appropriately removed the influence of vegetation along the banks.

11.1.2 The accuracy of hydraulic models is heavily dependent on the accuracy of the hydrological and topographic data on which they are based.

11.1.3 While every effort has been made to accurately reflect the situation on the ground and estimate appropriate model parameters, these can never be completely certain. Therefore, assumptions are made as part of the modelling process. Sensitivity tests have been carried out to highlight the sensitivity of the model.

11.1.4 The model has been built for the purpose of flood risk mapping. It has been optimised for high flows and would need adapting to be suitable to be used for more low flows.

11.1.5 The methodologies adopted were informed by best practice and use of available data. Whilst the modelling approaches are deemed suitable and acceptable, there will always be future improvements and updates that can be made.

12. CONCLUSIONS

12.1 Summary

12.1.1 Lincolnshire County Council, as Highway Authority, is seeking to obtain planning permission for the NHRR, which will complete the last section of the ring road around Lincoln, linking the A15, Lincoln Eastern Bypass (LEB), with the A46, Western Bypass. Ramboll were commissioned by Balfour Beatty Construction to undertake an FRA for the NHRR. This work has included hydraulic modelling of the River Witham.

12.1.2 The Existing EA hydraulic modelling for the area is a 1D-2D Infoworks RS model. Following consultation and agreement with the EA, Ramboll converted the existing Infoworks RS model to an ESTRY-TUFLOW model to assess the impacts of the NHRR scheme.

12.1.3 Consultation with the EA and key stakeholders identified that the main concern relating to flood risk is how the NHRR scheme could impact existing flood risk management arrangements. Specifically, assessing the potential impact to/from the proposed NHRR structure should the flood defences fail or be overtopped in an exceedance event. The two aims for this study were to:

- Assess the impact to/from the proposed NHRR structure should the existing flood storage embankment and flood levees fail or be overtopped in an exceedance event; and
- Assess the impact of the NHRR on existing flood risk at the river Witham floodplain.

12.2 Results – Flood Risk

12.2.1 The 100-year event flood extent, depths and velocities are not significantly affected by the NHRR scheme as the 100-year flood does not interact with the NHRR scheme. The existing flood defences operating in the vicinity of the NHRR crossing retain the 100-year event within the River Witham and the various flood storage areas.

12.2.2 The impact of the NHRR scheme on flood risk during the 100-year plus climate change (2080 Higher) event is limited to the floodplain upstream and downstream of the NHRR crossing. The NHRR scheme acts to prevent the spread of flood water overtopping the Witham Washland defence, reducing the flood extent north of the NHRR crossing and increasing the flood extent to the south, in the area between the NHRR crossing and the Witham Washland defence. Flood depths to the north of the NHRR crossing are reduced by between 50 mm to 100 mm while flood depths to the south, in the area between the NHRR crossing and the Witham Washland defence, increase by between 20 mm to 200 mm.

12.2.3 The water accumulating between the NHRR crossing and the Witham Washland defence during the 100-year plus climate change (2080 Higher) event passes north between the NHRR embankment and the existing river Witham defence under the proposed wide-span bridge. The water then spreads to the floodplain north of the NHRR crossing and into the IDB drain Hykeham Pump Drain South running parallel to the river Witham. The additional water fills the IDB Hykeham Pump Drain South up to Meadow Lane during the NHRR scenario compared to the baseline scenario, where flood waters filled the Hykeham Pump Drain South up to the Beck.

12.2.4 The impact of the NHRR scheme on the flood extent of the 1,000-year event and the 1,000-year event plus climate change (2080 Higher) is limited to the area around the NHRR crossing. The NHRR scheme acts to prevent the spread of water across the floodplain, resulting in a reduction in the NHRR scenario flood extent. Upstream and downstream of the NHRR crossing, the changes in flood extents are very small, limited to the slight variations at the edges of the floodplain.

12.2.5 The NHRR scheme acts to prevent the spread of flood water overtopping the Witham Washland defence. This results in a reduction to the flood depths north of the NHRR crossing of between 20 mm to 50 mm during the 1,000-year and 1,000-year plus climate change (2080 Higher) event. During the 1,000-year event, an increase in flood depths is simulated to the south in the area between the NHRR crossing and the Witham Washland defence by between 50 mm to 100 mm near the river Witham to between 100 mm to 200 mm further west. During the 1,000-year event plus climate change (2080 Higher) event, the increase in the flood depths to the south in the area between the NHRR crossing and the Witham Washland defence is simulated to be between 100 mm to 200 mm near the river Witham to between 200 mm to 500 mm further west.

12.2.6 The 1,000-year event plus climate change (2080 Higher) event simulates an increase in flood depth of between 50 mm to 100 mm in the Witham Washland storage area, which is less than a 5% increase of the baseline flood depth. An increase of between 20 mm to 50 mm in flood depth is simulated to the Brant Washland storage areas which, for much of this area, equates to an increase of less than 2% of the baseline flood depth.

12.2.7 For the 100-year plus climate change (2080 Higher), 1,000-year and 1,000-year plus climate change (2080 Higher) event, the main impact of the NHRR scheme on floodplain velocities is around the NHRR crossing, between the Witham Washland Defence and the Beck. During the baseline scenario, flood waters overtopping the Witham Washland defence pass north unimpeded across the floodplain. During the NHRR scenario, the NHRR crossing prevents the free spread of water across the floodplain, leading to an accumulation of flood waters in the area between the NHRR and the Witham Washland defence which are then funnelled under the proposed NHRR wide-span bridge. The accumulation of flood waters and the concentration of flows under the wide-span bridge results in an increase in simulated velocities.

12.2.8 During the 100-year plus Climate Change (2080 Higher) event baseline scenario, the most significant increase in velocities was simulated on the southern edge of the western NHRR embankment just before the opening to the wide span bridge, increasing to between 0.5 m/s and 0.75 m/s. During the 1,000-year event, the NHRR scenario velocities are simulated to increase compared to the baseline velocities to the south of the NHRR embankment to between 0.3 m/s and 0.5 m/s. Velocities are simulated to increase to between 0.5 m/s and 0.75 m/s at the wide span bridge location, and up to between 0.75 m/s to 1 m/s and above on the southern edge of the western NHRR embankment just before the opening to the wide span bridge. During the 1,000-year plus climate change (2080 Higher) event, the NHRR scenario velocities to the south of the NHRR embankment are simulated to increase compared to the baseline velocities to between 0.3 m/s and 0.75 m/s. Velocities are simulated to increase to over 1 m/s at the wide span bridge location.

12.3 Results – Breach Analysis

12.3.1 The hydraulic modelling results showed that the NHRR was not simulated to flood and all flows were conveyed under the NHRR during the two breach scenarios for all fluvial events simulated. To understand if a breach scenario could exacerbate erosion of the existing flood defences and the NHRR, the flood velocities were assessed.

12.3.2 During the FSA breach, the velocities for all events at the FSA breach location are over 2 m/s. To the west of the FSA breach, in the area between the NHRR and the Witham Washland Defence, the velocities are generally between 0.4 m/s to 0.75 m/s for the 100-year event, increasing to between 0.5 m/s to 0.75 m/s with areas of 1 m/s to 2 m/s for the higher return period events. To the east of the breach, the peak velocities are generally between 1 m/s to 2 m/s for all events simulated. The higher velocities simulated follow the main flow pathway of flood waters passing through the breach. Flood waters head towards the NHRR embankment and then pass west towards the wide span bridge opening, passing through to the floodplain to the north where velocities generally decrease.

12.3.3 During the RWUS breach, flood waters pass from the river Witham into the floodplain, filling the area between the Witham Washland Defence and the NHRR embankment. The main pathway of flood flows in this area passes north-west towards the wide span bridge opening to fill the floodplain to the north of the NHRR.

12.3.4 During the 100-year and 100-year plus climate change (2080 Higher) event, peak velocities at the RWUS breach location and at the opening of the wide span bridge are over 2 m/s, reflecting the main pathway of flood flows through the breach. In the area between the Witham Washland Defence and the NHRR, flood velocities decrease towards the west to less than 0.4 m/s.

12.3.5 During the 1,000-year and 1,000-year plus climate change (2080 Higher) event, the impact of the RWUS breach on flood velocities to the floodplain around the NHRR is minimal because the floodplain around the NHRR is already significantly flooded when the RWUS breach occurs. At the start of the RWUS breach, the water level in the floodplain and the River Witham are similar therefore, a hydraulic jump that would cause a significant increase in velocities is not created during the RWUS breach for the 1000-year and 1000-year plus climate change (2080 Higher) events. The velocities for the RWUS breach scenarios and the NHRR scenarios for the 1,000-year and 1,000-year plus climate change events are therefore very similar.

12.3.6 Both the FSA and RWUS breach scenarios simulated increased velocities along the IDB drain Hykeham Pump Drain South passing parallel to the river Witham between the Witham Washland Defence and the Beck. This is linked to the breach of the defence and not the inclusion of the NHRR because the velocities simulated at Hykeham Pump Drain South during the NHRR scenario were similar to the velocities simulated during the Baseline scenario.

12.4 Conclusions

12.4.1 The NHRR was not simulated to flood under any model scenario or fluvial event. All flows were simulated to be conveyed under the NHRR, either under the proposed wide span bridge connecting the west and east NHRR embankments or through culvert allowing the continued conveyance of IDB drain Green Lane Drain. The main impact to flood risk of the NHRR scheme is to the floodplain around the NHRR crossing. Upstream and downstream of the NHRR crossing, the changes in flood extents are very small, limited to the slight variations at the edges of the flood extents.

12.4.2 The hydraulic modelling results show that a breach of the Witham Washland defence and the river Witham defence results in increased flood velocities to the floodplain around the NHRR crossing, noticably in the area between the NHRR and the Witham Washland defence and the opening allowing flood flows under the wide span bridge to the north. It will be important that the NHRR design includes the appropriate protection to mitigate possible erosion of both the NHRR design and to the existing flood defences.

12.5 Recommendations

12.5.1 The NHRR design should consider the inclusion of appropriate protection to mitigate possible erosion of both the NHRR design and the existing flood defences during overtopping and defence failure events.

12.5.2 To improve the NHRR hydraulic modelling 1D Mass Balance, further action should be taken to address the 1D ESTRY model instabilities at the downstream boundary for the extreme return period events (1000-year and 1000-year plus climate change (2080 Higher)).

12.5.3 At detailed design stage, if the EA hydraulic model is available, the NHRR hydraulic model should consider using the EA's updated hydrological approach for consistency and better comparability.

12.5.4 The flood modelling results should be compared with the updated EA hydraulic model for the Witham when this becomes available.

APPENDIX 1
EA MEETING MINUTES

RAMBOLL

ENVIRONMENT
& HEALTH

MINUTES OF MEETING

Project name	**T0126 MCHW Review and Update Drainage**
Project no.	**16200xxxx**
Subject	**Water Environment**
Meeting date	**20/05/2022**
Location	**Online**
Meeting no.	**1**
Taken by	**Steve Cox**
Participants	Adam Lakin (AL) – Bentley Project Management on behalf of Lincolnshire County Council Andy Marginson (AM) – Ramboll, Structures Lead Gareth Dickinson (GD) – Balfour Beatty, Design Manager John Ray (JR) – Environment Agency, Flood Risk Senior Advisor Steve Cox (SC) – Ramboll, Water Environment Lead
Absent	-
Copy to	All above

DRAFT

Minutes of Meeting

Nº.	Item	Action by
1	Meeting was called to ensure engagement with the EA at an early stage in order to understand the EA's main concerns and requirements with regard to the water environment, particularly flood risk.	
2	JR's team will do the permitting with regard to the NHRR bridges and structures around the washlands.	
3	JR will be key EA contact for flood risk. The EA Sustainable Places team will be involved with respect to water quality and groundwater.	
4	All parties keen for regular liaison as the design progresses. GD to suggest a schedule for meetings with JR and his team. JR suggested a small technical group could be put together.	GD
5	JR noted that the impacts of the scheme may be greater for the Internal Drainage Board (IDB). Key contact for the IDB is Guy Hird. AL noted that the IDB have provided specific information on their requirements. IDB ditches will need to be continued under/through the new NHRR embankment. There are IDB channels on either side of the River Witham embankment paralleling the river.	
6	JR described the current flood storage arrangement just south (upstream) of the scheme. There are raised defences along the banks of the River Witham and a raised defence perpendicular to the Witham on the west side. This latter defence creates a flood storage area. There is a control structure on the Witham adjacent to the perpendicular defence. If Lincoln is expected to flood the side gates are opened to allow water to flood into the storage area. If the river keeps rising then the control structure can be raised to further reduce flood risk.	

	The storage area has sufficient volume for it to be classified under the Reservoirs Act. The embankment retaining the storage area is designed for a 1% AEP flood. This embankment is designed to withstand overtopping and includes a concrete capping beam. The river embankments were raised in the early 1990s. They are subject to vegetation growth and burrowing animals which may have reduced their ability to withstand a breach/erosion. During a flood in November 2019 the storage area reached ~80% full. The max water depth in the storage area is only around 1.5 m. There is a further embankment running east-west along a ditch further downstream (and north of the proposed NHRR). This may retain some additional floodwater.	
7	Key considerations which will need to be demonstrated to the EA concern what happens when the flood storage embankment fails or, more likely, overtops in an exceedance event. • Does the water get trapped behind the proposed NHRR? • Might the embankment be eroded and/or the river embankments affecting their integrity? • Can the exceedance and breach flow be conveyed under the NHRR without risk to road users and exacerbating erosion of the flood retaining embankments? • How many / what size of flood conveyance culverts will be required through the NHRR embankment? JR noted that constructing a complex hydraulic model of the NHRR may not be necessary to answer the above questions. It may be sufficient to do empirical calculations demonstrating sufficient conveyance of flow through the NHRR. The recently completed Lincoln Eastern Bypass (LEB) included a bridge over the River Witham further downstream. JR envisaged a similar design for the proposed NHRR bridge. While the impacts of the NHRR bridge do of course need to be considered, they are not likely to be the main focus with regard to flood risk impacts. Residential estates in North Hykeham are slightly raised and the EA are confident that these are not currently at risk of fluvial flooding. There is only one property in the 0.1% AEP flood zone downstream of the storage area (the IDB depot). The reservoir embankment is inspected (as required by the Reservoirs Act). The inspector is David Rebollo from Mott MacDonald.	
8	AL noted that farmland severed by the NHRR may need to be reconnected and underpasses may be an option. The underpasses could also have a dual purpose of conveying flood flows.	

	JR noted that the road would not need to be too high above existing ground level for flood resilience but could of course be higher if required for other reasons.	
9	Compensatory storage. JR stated that because of the topography, the floodplains are passive (only in play if major incident) such that developments make no material difference to flood storage. There would therefore be no requirement to provide compensatory storage. Similarly, compensatory storage was not required for the LEB. JR considered that one design option could be for the road embankment to deliberately retain floodwater and create additional storage.	
10	The current hydraulic model for the area is the Upper Witham Infoworks model (2015). It is a 1D/2D model. Infoworks was chosen in 2006 as the favoured software but it is recognised that this is now not the case. The d/s boundary is in the centre of Lincoln at the confluence with the River Till. The current model contains a notable 0.5 m error at the downstream boundary. An update of the Upper Witham model is to be commissioned but there have been some delays appointing one of the three framework consultants so the update has not yet commenced. JR is still hopeful that the update can be completed in the autumn of 2022. If necessary, JR can point out the main errors in the existing model. The model (current and to be updated) covers a very large area – most of the Upper Witham to near Grantham. JR noted that this would be a much larger area/model than would be needed for assessing the impacts of the NHRR. The downstream flow restriction is primarily where the A1434 crosses the Witham in the Bracebridge area of Lincoln. The EA model update will: • Convert the model to Flood Modeller Pro (FMP) • Automate the control structures • Incorporate some survey that has already been undertaken from the storage area to the downstream boundary. The EA will ask the framework consultant undertaking the update to revisit the flows in the model but not necessarily update them. JR noted that if the reservoir engineer requires that the 1-in-10,000 year event or the Probable Maximum Flood (PMF) (i.e. the limit of the credible worst case) dictates the design, then changes to flow during more frequent events will be relatively small and immaterial in comparison.	
11	Tidal influence. JR noted this was at most a few millimetres and was built into the downstream boundary of the model where there is a sluice to retain water	

	to enable navigation. Tidal influence would not need to be considered in any modelling for the NHRR.	
12	NHRR Programme. BB/Ramboll surveys are due to commence in the next two to three months, with the hydraulic modelling programmed to start around September 2022. The modelling for the NHRR, and the EIA which relies on it, will need to be complete by ~April 2023 in order to meet the autumn 2023 target date for planning submission.	
13	GD said that BB/Ramboll would produce a Design Input Plan. Workshop perhaps. Set out the parameters at the beginning of the project so all parties know what is required, thereby reducing the likelihood of late requests which are difficult to accommodate.	GD
14	Groundwater. A brief discussion was held around groundwater and the presence of the Source Protection Zone (SPZ) to the east on the limestone geology. The LEB also crosses the SPZ and includes a large basin adjacent to the roundabout between Branston and Canwick. It is not known whether this is a soakaway or whether it discharges to a small surface water stream. GD noted that he has the detailed drainage drawings for the LEB and would provide these to SC. The water utility provider in the area is Anglian Water.	GD

APPENDIX 2
MOTTMAC INFOWORKS 2015 HYDRAULIC MODELLING REPORTS



Upper Witham Model Improvements Study

Hydrology Report

July 2015

Environment Agency

Mott MacDonald

Upper Witham Model Improvements Study

Hydrology Report

July 2015

Environment Agency

Mott MacDonald, Demeter House, Station Road, Cambridge CB1 2RS, United Kingdom
T +44 (0)1223 463500 **F** +44 (0)1223 461007 **W** www.mottmac.com

Mott MacDonald

Issue and revision record

Revision	Date	Originator	Checker	Approver	Description
A	02/03/2015	Mary Jeddere-Fisher			Work in Progress For Discussion Purposes First Issue
B	15/05/2015	Mary Jeddere-Fisher	Sarah Sims	Sun Yan Evans	Second Issue
C	10/07/2015	Mary Jeddere-Fisher	Sun Yan Evans	Sun Yan Evans	Third Issue

Information Class: Standard

Contents

Figures

Tables

Glossary

AEP	Annual Exceedance Probability
AMAX	Annual Maximum Series of Flow Data
BFIHOST	Base Flow Index estimated from soil type
BL	Baseflow Lag
BR	Baseflow Recharge
Cini	Initial Soil Moisture
DPLBAR	Mean Drainage Path Length (km)
EA	Environment Agency
FARL	Flood Attenuation due to Reservoirs and Lakes
FEH	Flood Estimation Handbook
IDB	Internal Drainage Board
L-CV	Moment of Coefficient of Variance
LMED	Median Annual Peak Level
L-SKEW	Moment of Skewness
POT	Peaks Over Threshold
QMED	Median Annual Peak Flow
ReFH	Revitalised FSR/FEH Flood Hydrograph
SAAR	Standard Annual Rainfall (mm)
SPRHOST	Standard Percentage Runoff
TBR	Tipping Bucket Rainfall
Tp	Time-to-peak
URBEXT2000	Index of urban and suburban extent

Executive Summary

Mott MacDonald has been commissioned by the Environment Agency to review and update the Upper Witham Infoworks RS model.

The Hydrology Report describes the derivation of design hydrology for fluvial inflows, which have formed the boundary conditions for the hydraulic model for assessing the flood risk within the Upper Witham Catchment.

Hydrological Modelling Approach

The hydrological analysis carried out in this study serves two separate purposes:
1. To derive hydrological flows for a catchment wide study of the Upper Witham
2. To derive hydrological flows for the individual catchments of Witham Brook, Mow Beck and Barrowby Stream

A catchment wide hydrological approach has been taken for the Upper Witham – Grantham (South Witham to Claypole) and Upper Witham – Lincoln (Claypole to downstream of Lincoln) models , with the focus on providing appropriate inflows for the hydraulic model, using available data to improve estimates across all sub catchments. To this aim, flow estimation points have been identified along the main rivers, upstream of any washlands, at the following locations:
- Colsterworth,
- Saltersford,
- Claypole,
- Brant Broughton,

At each of these locations, Flood Frequency Analysis using the FEH Statistical method has been carried out to derive target peak flows for the design events. Upstream of these locations scaling to reconcile distributed ReFH flows with the target peak flows has been undertaken.

Downstream of Claypole, Brant Broughton, and the Till Washlands, flood frequency analysis for the purpose of target peak flow estimation is not suitable due to the influence of the washlands on the hydrological response of the catchment. Flood Frequency Analysis at North Hykeham (downstream of the River Witham and River Brant washlands), and on the River Till, upstream of the washlands, has been carried out. However this is for information purposes only, and it is not the intention for these values to be used as target peak flows.

ReFH Hydrological inflows downstream of Claypole, Brant Broughton and on the River Till have therefore not been scaled, but the ReFH model parameters have been enhanced through donor transfer.

A number of IDB pumped catchments surround Lincoln. The hydraulic model represents these catchments predominantly in 2D or in some locations using 1D storage areas. The model represents the attenuation and storage of these catchments. Therefore the standard ReFH hydrograph inflows, enhanced through donor transfer, have been distributed along the drain network with no scaling applied.

The washlands were designed using a coincident peak assumption as part of the hydrological analysis. Therefore to remain consistent with the previous analysis and definition of the standard of protection that the washlands provide, the same assumption has been used for the timing and phasing of the hydrological inflows in this study.

Urban ReFH methods have been used to derive hydrological inflows for the Witham Brook and Mow Beck & Barrowby Stream catchment-specific models due to the urban nature of the catchments.

Final Derived Flows and Hydrological Model Parameters

The table below gives a summary of the target flows derived as part of the assessment.

Table 1.1: Summary of Target Peak Flows at Flow Estimation Points

							Flows (m^3/s)
AEP (%)	Colsterworth	Saltersford	Claypole	River Brant at Brant Broughton	Witham Brook	Mow Beck	Barrowby Stream
50%	5.89	7.71	16.5	9.76	1.69	2.09	1.39
20%	8.84	11.33	23.76	13.76	2.27	2.78	1.86
10%	10.72	13.65	28.55	16.20	2.77	3.37	2.25
5%	12.49	15.88	33.00	18.45	3.35	4.06	2.71
4%	13.13	16.65	34.49	19.13	3.55	4.30	2.87
3.33%	13.55	17.19	35.48	19.72	3.73	4.51	3.01
2%	14.90	18.81	38.78	21.37	4.28	5.17	3.44
1.33%	15.96	20.05	41.09	22.64	4.77	5.74	3.83
1%	16.73	20.97	42.90	23.52	5.15	6.19	4.13
0.5%	20.14	24.98	50.49	27.91	6.20	7.43	4.95
0.1%	32.75	39.48	77.55	42.75	9.56	11.36	7.58

Storm duration sensitivity analysis has been carried out and the following conclusions can be drawn from this exercise:

- For the Upper Witham – Grantham: model the 10 hour storm duration is estimated to be most critical along the majority of the watercourses, and has therefore been used for all design runs.
- For the Upper Witham – Lincoln: model the 10 hour storm duration is estimated to be critical along Boultham Catchwater and the 40 hour storm duration along the majority of the remaining water courses. In consultation with the EA both storm durations have been used for the design runs in the Lincoln model.

Hydrograph shape has been derived in two separate ways:

1. At Claypole analysis has been undertaken of the AMAX hydrograph series from 1983 through to 2012 to derive a representative hydrograph, based on observed data for Claypole, and used as the inflow at Claypole in the Upper Witham – Lincoln model.
2. The remaining inflow hydrographs have been derived using ReFH units, with the ReFH model parameters, Tp, Cini, BL and BR enhanced through donor transfer. Donor correction factors have been estimated by using an average of the correction factors derived over the three winter events (Cini,

BL and BR) and from all 4 events (Tp) at each of the gauging stations, as part of the calibration/verification hydrological analysis.

1 Introduction

1.1 Background

The Environment Agency (EA) commissioned Mott MacDonald in December 2014 to carry out model updates for 5 models that the EA holds for the Upper Witham catchment in line with the EA's medium term plan to review and update strategic models every 5 years. These are:

- 2007 Upper Witham Flood Map Improvements Model
- 2009 Upper Witham Strategy model
- 2009 Witham Brook Model
- 2009 Skellingthorpe Drain Mode
- 2009 Mow Beck & Barrowby Stream Model

The aim of the project is to ensure that flood modelling outputs, including flood extents, are reliable and based on the latest available data.

The history/chronology of the model development in the Upper Witham is complex, therefore the study has been split into four critical stages:

1. Review of existing hydraulic models
2. Review of existing hydrological analysis
3. Update of hydrological analysis
4. Update of existing hydraulic models, and provision of flood levels and extents

This report covers the third stage and is for the purpose of updating the hydrological analysis carried out on the Upper Witham catchment. A detailed review of the previous hydrological analysis was provided as part of stage 2, which also provided recommendations for the hydrological update. A review of the available data was presented, this is repeated in Section 2 for ease of reference.

1.2 Study Area

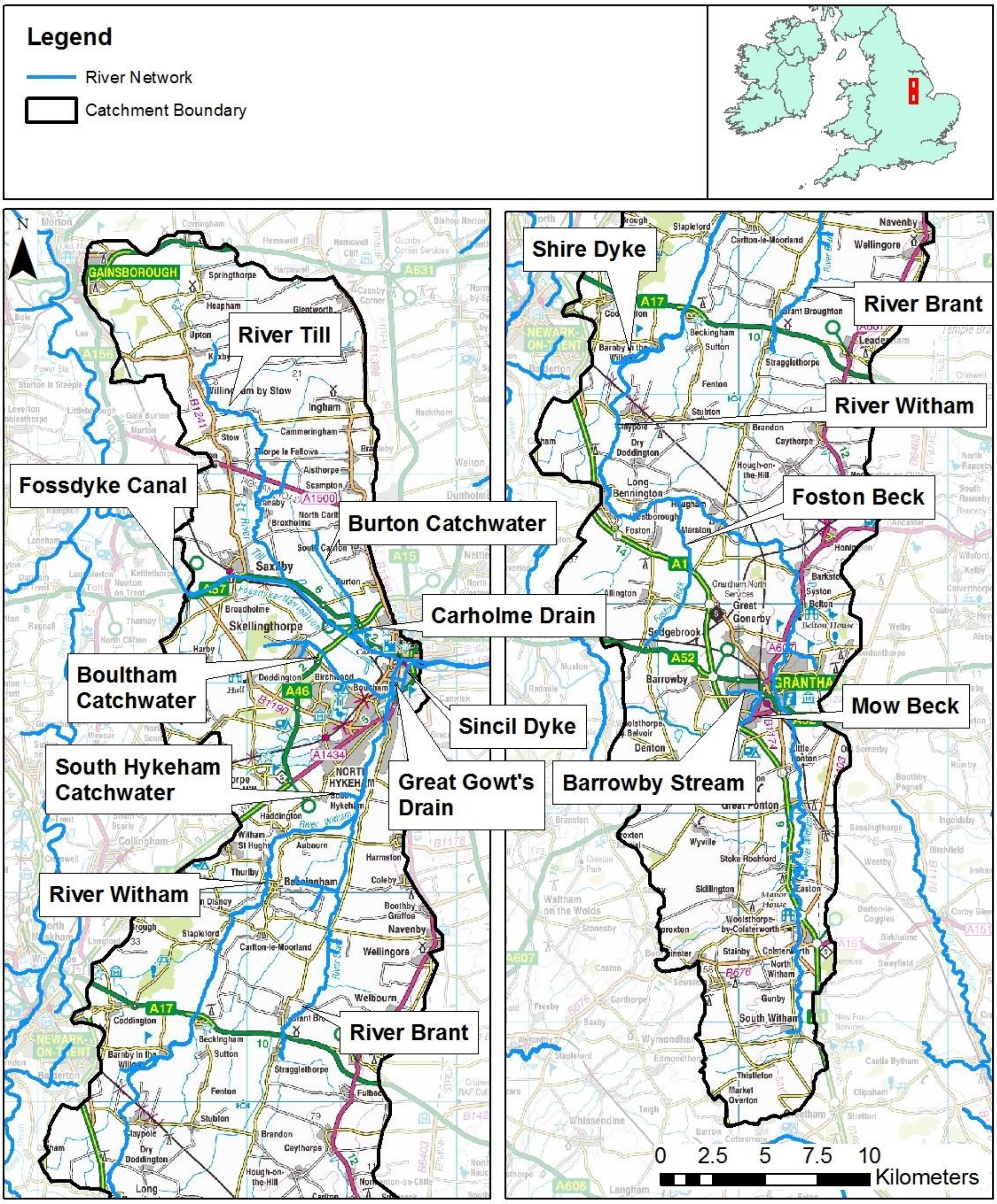
The study area extends from South Witham (NGR SK919197) to Stamp End Sluice (NGR SK983 711), a catchment area of 830km^2, and includes all main river watercourse tributaries as follows:

- Mow Beck
- Barrowby Stream
- Witham Brook
- Foston Beck
- Shire Dyke
- River Brant
- Skinnard Dyke
- Cardinal Dyke
- South Hykeham Catchwater
- Boultham Catchwater
- Skellingthorpe Drain
- Sincil Dyke
- Great Gowt's Drain

- Fossdyk Canal to Torksey Lock
- Burton Catchwater
- Carholme Drain
- River Till
- Cricket Till

Figure 1.1 shows the extent of the study area, and the key watercourses included.

Figure 1.1: Study Area



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The main towns in the Upper Witham catchment are:

- Grantham
- Lincoln
- North Hykeham

Of particular note within the Upper Witham catchment are a series of washlands on the Rivers Witham, Brant and Till designed to protect Lincoln against a flood with an annual exceedance probability (AEP) of 1%. The presence of the washlands changes the hydrological response of the catchment. In previous studies the area was split at Claypole into the Upper Witham – Grantham and Upper Witham – Lincoln sub models.

1.3 Software

The software used as part of the hydrological update are listed below:

- ArcGIS: 10.1
- MapINFO: 10
- FEH: Version 3
- HiFLOWS database v.3.3.4
- WINFAP: Version 3.0.003
- ISIS v 3.7

2 Data Availability

2.1 Summary of Existing Hydrological Analysis

Table 2.1 summarises the hydrological analysis which has previously been carried out for the Upper Witham catchment.

Table 2.1: Summary of Existing Hydrological Analysis

Study	Study Type	Source	Date	Comments
Upper Witham Flood Map Improvements	Catchment Wide Strategic Flood Risk Mapping Study	Faber Maunsell	2007	Used Hydrometric data available up till 2005
Skellingthorpe Beck – Addendum to Witham Catchment Flood Map Improvements	Flood map Improvements and Map Areas benefiting from defences study	Faber Maunsell	2009	Used Hydrometric data available up till 2005
Witham Brook - Addendum to Witham Catchment Flood Map Improvements	Flood map Improvements and Map Areas benefiting from defences study	Faber Maunsell	2009	Used Hydrometric data available up till 2005
Mow Beck & Barrowby Stream – Phase 2 of Witham Catchment Flood Map Improvements Study	Flood map Improvements and Map Areas benefiting from defences study	Faber Maunsell	2009	
Foston Beck at Allington	Rating Review	JBA	Feb 2013	Draft Report
Brant Broughton	Rating Review	JBA	Feb 2013	Draft Report
Cringle Brook	Rating Review	JBA	Oct 2012	Final Report
Honington Beck	Rating Review	JBA	Mar 2013	Draft Report

Source: Mott MacDonald and Environment Agency

2.2 Flow and Level Data

Table 2.2 summarised the flow and level data available for the study, and Figure 2.1, the location of the flow and level gauges. Figure 2.2 provides more detail of the level gauges within Lincoln.

Table 2.2: Summary of Available Flow and Level Data

Data	Source	Date	Comments
Flow Data			
Claypole GS	Witham Flood Map Improvements Study	1960 - 1980	AMAX Data
	EA	1980 - 2014	15 Minute Data
Cringle Brook GS	EA	1980 - 2014	15 Minute Data
Colsterworth GS	Witham Flood Map Improvements Study	1979 – 1980	AMAX Data

Data	Source	Date	Comments
	EA	1980 - 2014	15 Minute Data
Honington Beck GS	EA	1984 - 2014	15 Minute Data
Saltersford GS	Witham Flood Map Improvements Study	1969 - 1984	AMAX Data
	EA	1985 - 2014	15 Minute Data
Allington GS	EA	1988 - 2014	15 Minute Data
Brant Broughton GS	EA	1991 - 2014	15 Minute Data
North Hykeham GS	EA	1999 - 2014	15 Minute Data
Level Data			
North Witham	EA	1999 - 2014	15 Minute Data
Colsterworth GS	EA	1980 - 2014	15 Minute Data
Cringle Brook GS	EA	1980 - 2014	15 Minute Data
Saltersford upstream 2	EA	2003 - 2014	15 Minute Data
Saltersford GS	EA	1985 - 2014	15 Minute Data
Spittlegate Mill Downstream	EA	2002 – 2004 and 2006 – 2014	15 Minute Data
Mow Beck	EA	2007 - 2014	15 Minute Data
Harrowby Mill	EA	2002 – 2014	15 Minute Data
Belton	EA	2000 – 2002 and 2007 – 2013	15 Minute Data
Honington Beck GS	EA	1984 - 2014	15 Minute Data
Hougham	EA	2000 – 2002 and 2007 – 2013	15 Minute Data
Allington GS	EA	1988 - 2014	15 Minute Data
A1 Culvert (Foston Beck)	EA	2000 – 2002 and 2006 – 2013	15 Minute Data
Claypole GS	EA	1980 - 2014	15 Minute Data
Beckingham Bridge	EA	2003 - 2014	15 Minute Data
Aubourn Weir	EA	1993 - 2013	15 Minute Data
Brant Broughton GS - Upstream	EA	1991 - 2014	15 Minute Data
Brant Broughton - Downstream	EA	1998 - 2014	15 Minute Data
Horseshoe Bridge	EA	1996 - 2014	15 Minute Data
Brant Control Sluice	EA	1998 – 2014	15 Minute Data
Brant Control Washland Level	EA	1998 – 2014	15 Minute Data
Witham Washland Sluice – Upstream	EA	1998 – 2014	15 Minute Data
Witham Washland Sluice – Washland	EA	1999 and 2002 – 2014	15 Minute Data
Witham Washland Sluice - Downstream	EA	1998 – 2014	15 Minute Data

Data	Source	Date	Comments
North Hykeham GS	EA	1993 - 2014	15 Minute Data
Bracebridge	EA	1993 - 2014	15 Minute Data
Bargate	EA	1996 - 2014	15 Minute Data
Skellingthorpe	EA	2000 – 2013	15 Minute Data
Willingham Bridge	EA	2002 - 2014	15 Minute Data
Squires Bridge	EA	1996 - 2014	15 Minute Data
Till Wash Ultrasonic Level	EA	2001 – 2003 and 2005 - 2008	15 Minute Data
Till Sluice Upstream	EA	1996 – 1999 and 2002 – 2014	15 Minute Data
Till Sluice Downstream	EA	1999 - 2014	15 Minute Data
Odder Bridge	EA	1981 – 1985 and 2001 - 2014	15 Minute Data
Burton Marina	EA	2002 - 2014	15 Minute Data
Fossdyke Golfcourse	EA	1993 - 2014	15 Minute Data
Fossdyke Waterways	EA	1993 - 2014	15 Minute Data
Brayford Pool	EA	1993 - 2014	15 Minute Data
Great Gowt Sluice - Upstream	EA	2000 - 2014	15 Minute Data
Great Gowt Sluice - Downstream	EA	2000 - 2014	15 Minute Data
Monson Street	EA	1998 – 2014	15 Minute Data
Stamp End - Upstream	EA	1998 - 2014	15 Minute Data
Stamp End - Downstream	EA	1998 - 2014	15 Minute Data

Source: Mott MacDonald and Environment Agency

Figure 2.1: Location of Flow and Level Gauges

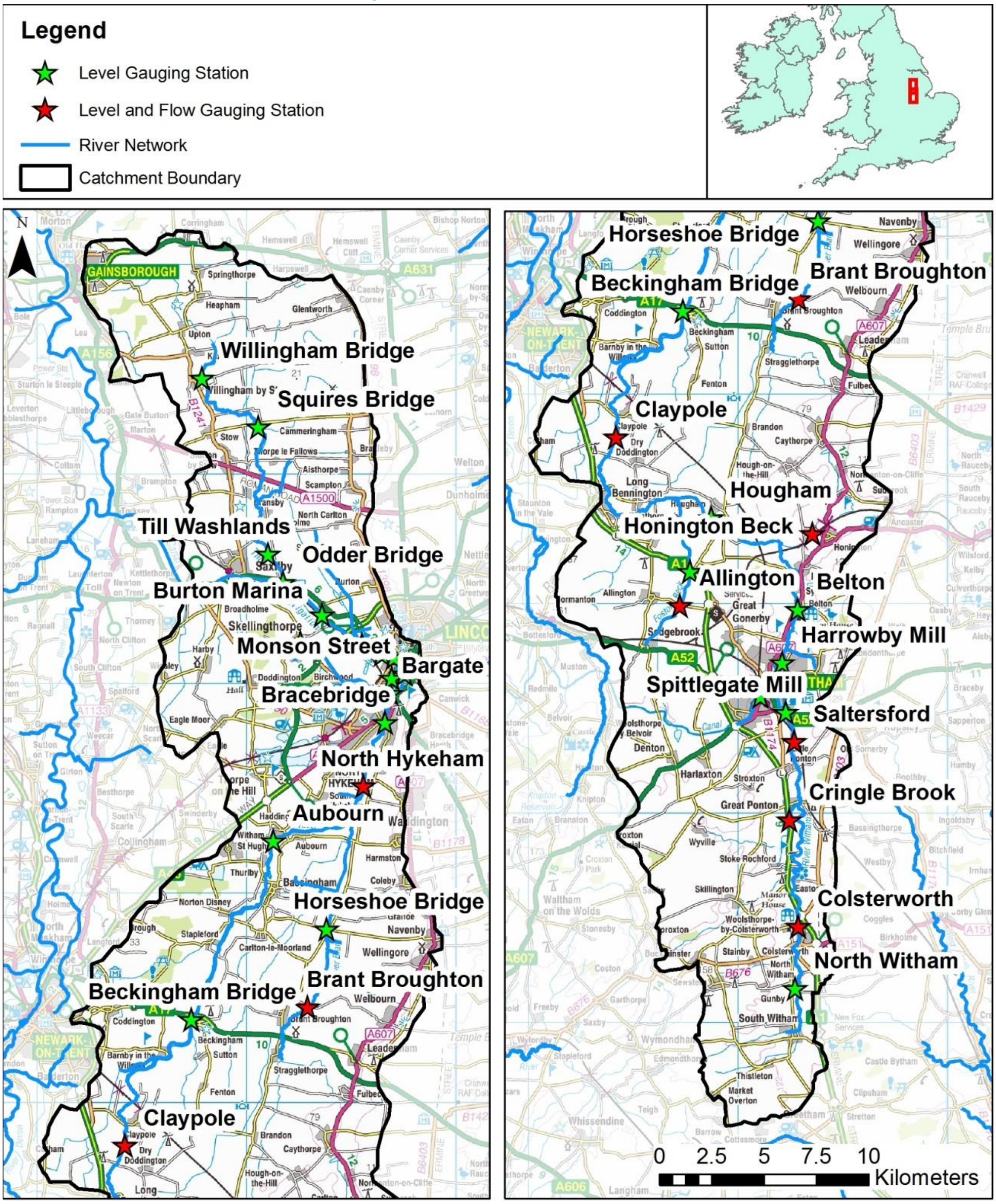

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Figure 2.2: Location of Flow and Level Gauges – Lincoln

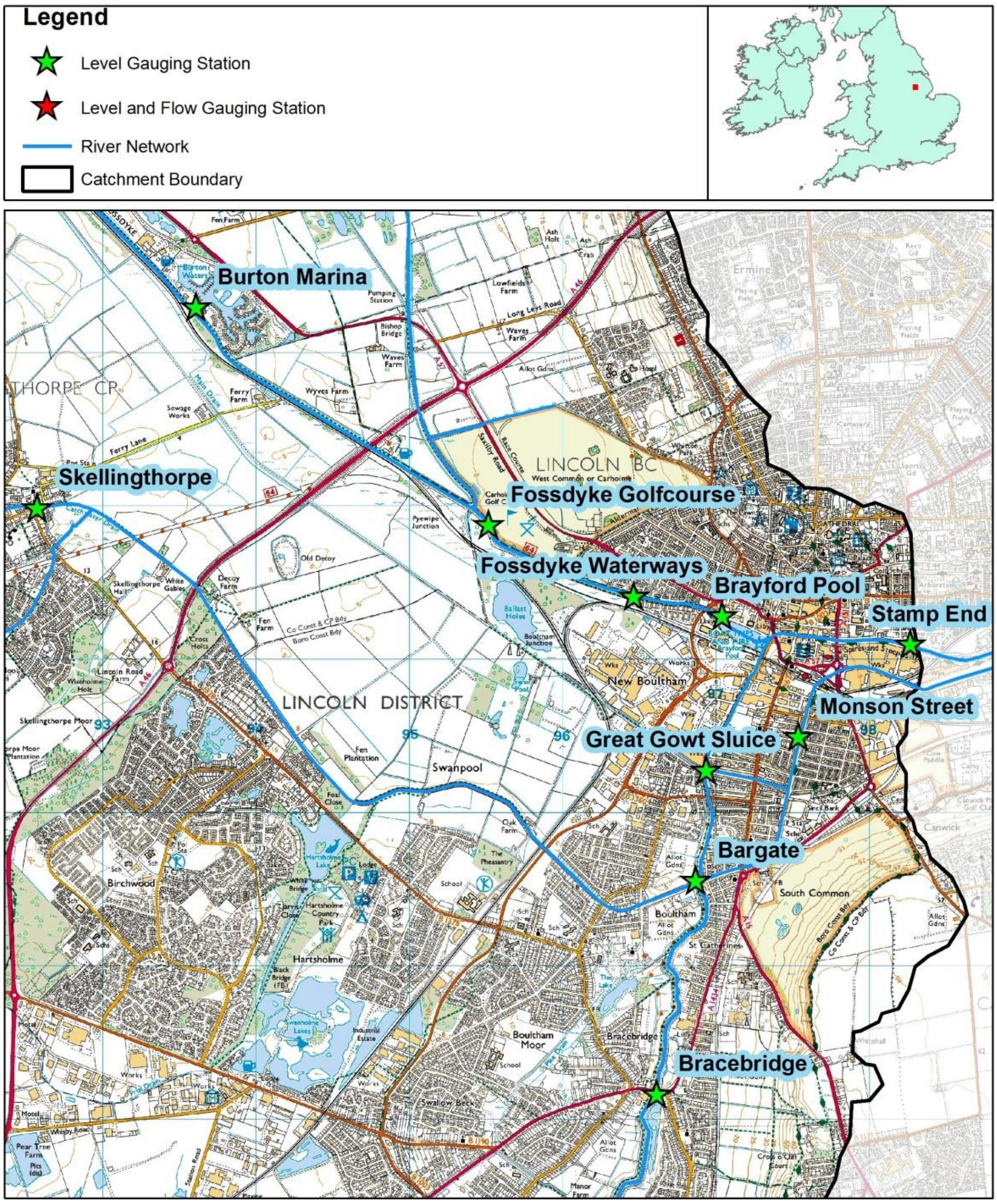


Figure 2.3 and Figure 2.4 detail the data availability for each month of each water year at the flow and level gauges respectively.

Figure 2.3: Data Availability per Month at Flow Gauging Stations

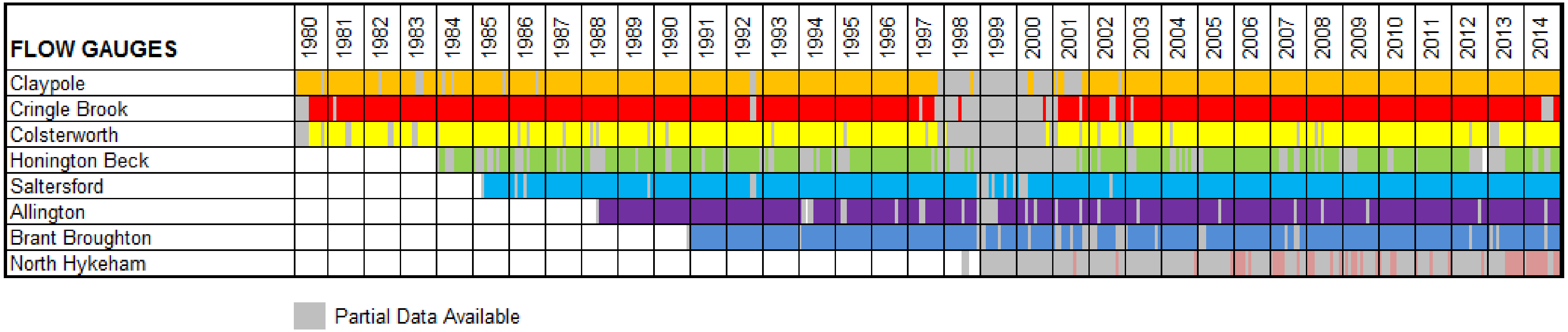
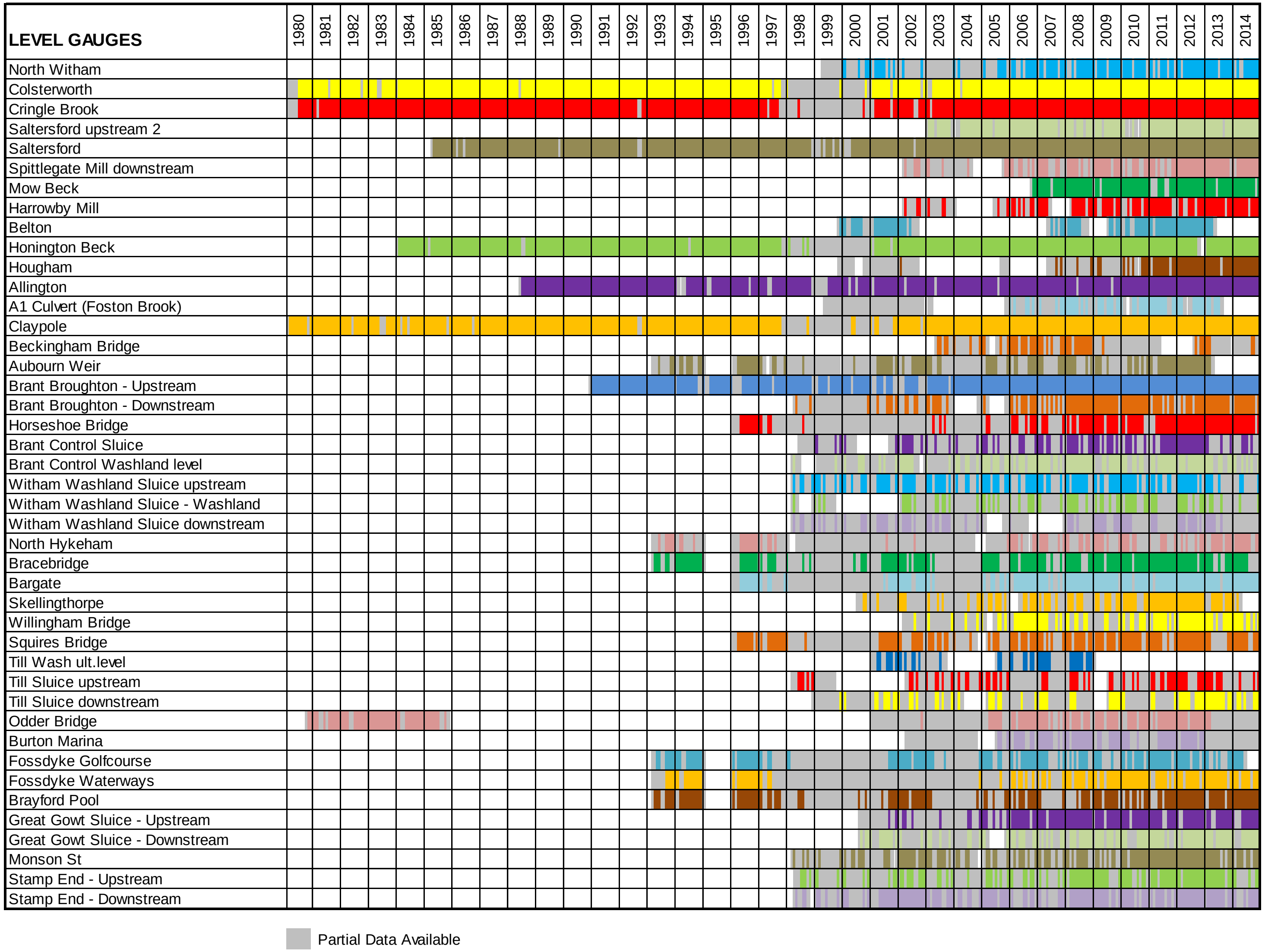


Figure 2.4: Data Availability per Month at Level Gauging Stations



2.3 Rainfall Data

Table 2.2 summarised the rainfall data available for the study and Figure 2.5 the location of the rainfall gauges.

Table 2.3: Summary of Available Rainfall Data

Data	Source	Date	Comments
Snitterby School Lane	EA	1973 – 1979 and 2011 – 2014	Daily Rainfall Totals
Halton Fen	EA	1963 – 1976 and 2001 – 2014	Daily Rainfall Totals
Witham St Hughes	EA	1970 – 1976 and 2008 – 2014	Daily Rainfall Totals
Brant Broughton	EA	1963 – 2014	Daily Rainfall Totals
Brant Broughton	EA	1987 – 2014	Tipping Bucket Data
Normanby by Stow	EA	1980 – 2014	Daily Rainfall Totals
Coates Hall	EA	1980 – 2014	Daily Rainfall Totals
Riseholme	EA	1963 – 1993 and 2001 – 2014	Daily Rainfall Totals
Lincoln	EA	1995 – 2014	Daily Rainfall Totals
Navenby	EA	1972 – 2014	Daily Rainfall Totals
Walcot	EA	1976 – 1981 and 1998 – 2014	Daily Rainfall Totals
Wing Water Treatment Works	EA	1983 – 2014	Daily Rainfall Totals
Wing Water Treatment Works	EA	2003 – 2014	Tipping Bucket Data
Gunthorpe Hall	EA	1964 – 2014	Daily Rainfall Totals
Welby	EA	1985 – 2014	Daily Rainfall Totals
Grimsthorpe Castle	EA	1996 - 2014	Daily Rainfall Totals
Upton	EA	1978 – 1984 and 1987 – 2014	Tipping Bucket Data
Toft Newton	EA	1987 – 2014	Tipping Bucket Data
South Witham	EA	1978 – 1984 and 1987 – 2014	Tipping Bucket Data
Till Washland	EA	1999 -2008 and 2011 – 2014	Tipping Bucket Data
Canwick	EA	2011 – 2014	Tipping Bucket Data
Short Ferry	EA	2011 – 2014	Tipping Bucket Data
Ruskington	EA	1978 – 2014	Tipping Bucket Data
Osbournby	EA	2000 – 2014	Tipping Bucket Data
Baunston	EA	1985 – 2014	Tipping Bucket Data
Ropsley	EA	1984 – 2008 and 2011 – 2014	Tipping Bucket Data
Saltersford	EA	1987 – 1994 and 1998 – 2003 and 2006 – 2014	Tipping Bucket Data
Wickenby	EA	2002 – 2014	Tipping Bucket Data
Corby Glen	EA	1985 – 2014	Tipping Bucket Data

Source: Mott MacDonald and Environment Agency

Figure 2.5: Location of Rainfall Gauges

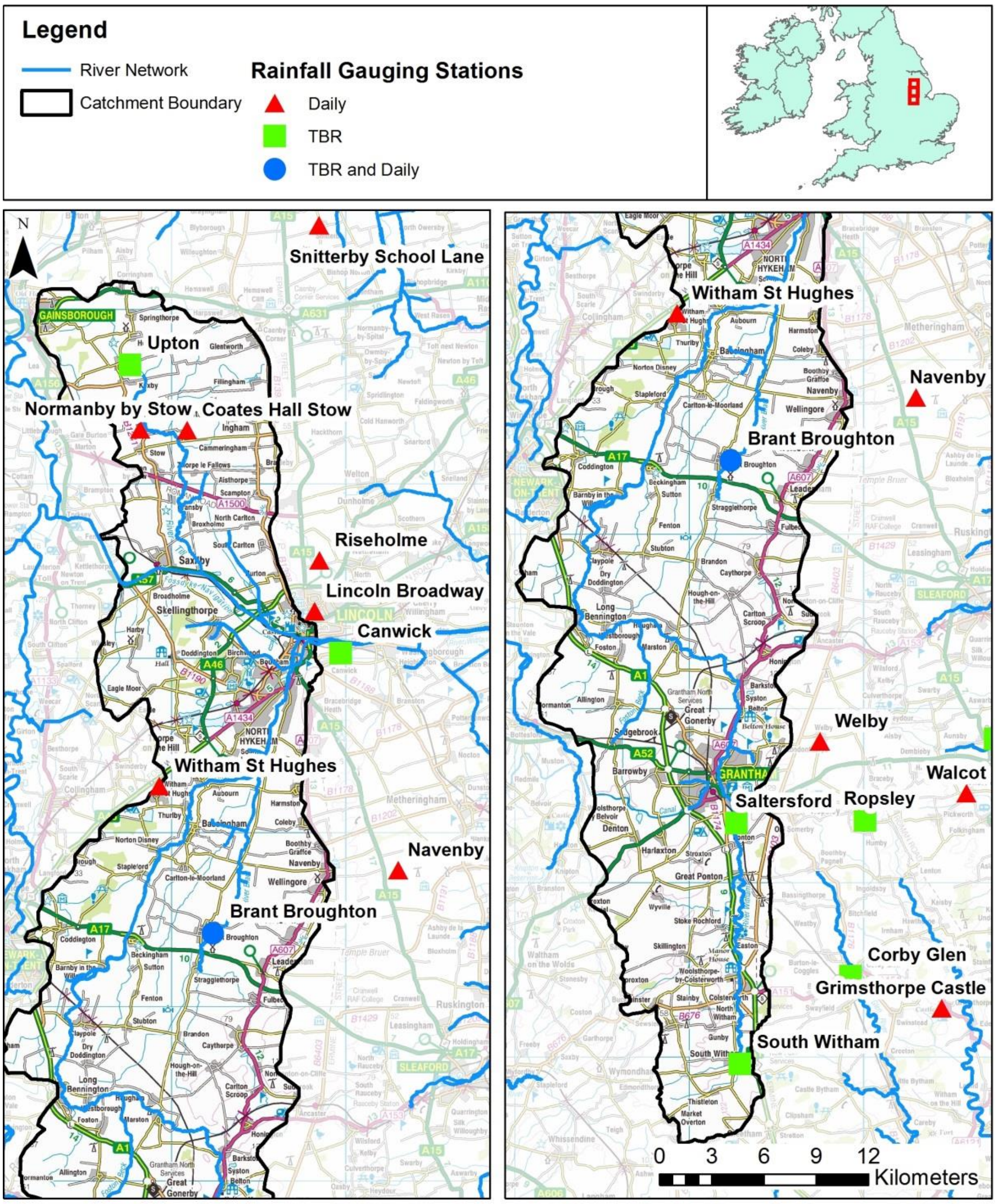


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Figure 2.6 and Figure 2.7 detail the data availability for each month of each water year at the tipping bucket and daily rainfall gauges respectively.

Figure 2.6: Rainfall Data Availability per Year at Daily Total Rainfall Gauges

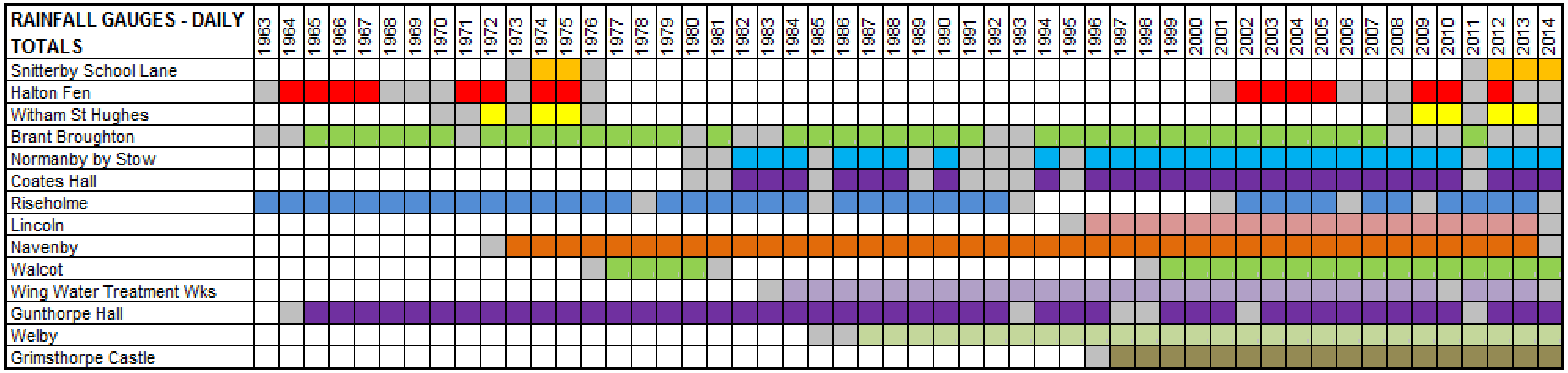
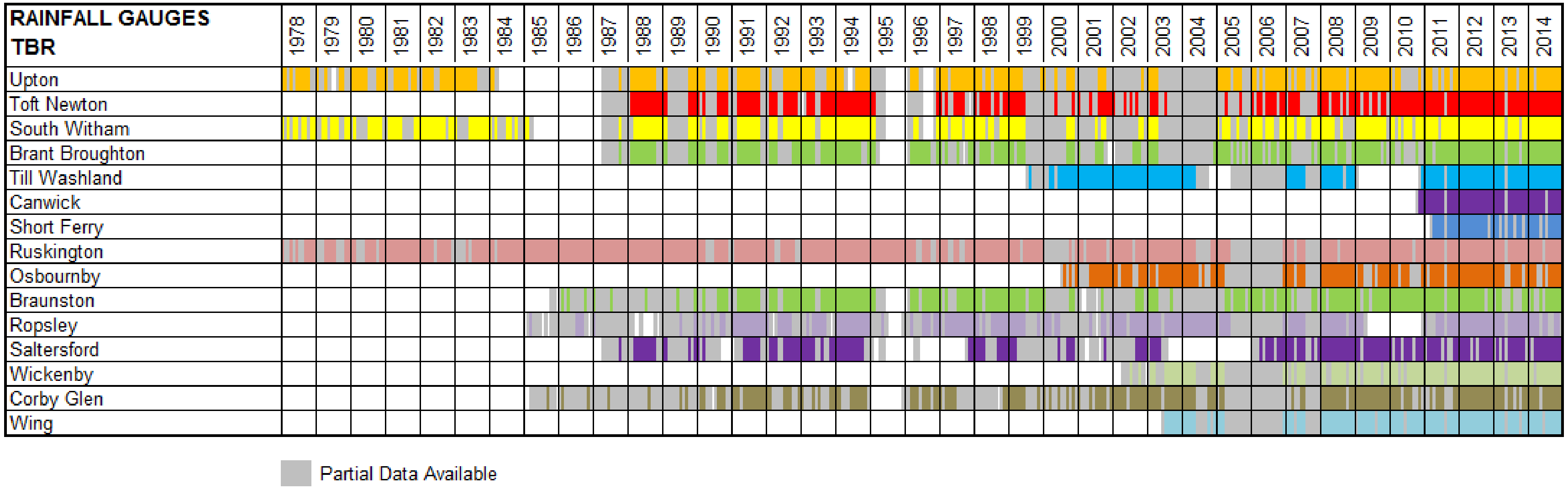


Figure 2.7: Rainfall Data Availability per Month at Tipping Bucket Rainfall Gauges



Source: Mott MacDonald.

3 Hydrological Modelling Approach

The hydrological analysis carried out in this study serves two separate purposes:

1. To derive hydrological flows for a catchment wide study of the Upper Witham.
2. To derive hydrological flows for the individual catchments of Witham Brook, Mow Beck and Barrowby Stream

Chapters 4 to 9 of this report cover the first purpose of deriving hydrological inflows for the catchment wide study, and Chapter 10 the second purpose of the catchment specific hydrological inflows for Witham Brook, Mow Beck and Barrowby Stream.

3.1 Hydrological Modelling Approach for Catchment Wide Study

The hydrological response of the Upper Witham Catchment is significantly influenced by the washlands located on the River Brant, River Witham and River Till upstream of Lincoln. This has the effect of splitting the overall catchment into two distinct regions:

- Upstream of the washlands – In particular upstream of Claypole on the River Witham
- Downstream of the washlands

To reflect the two distinct regions, the hydraulic model has been split at Claypole. The upper model (Upper Witham – Grantham) focusses on the upstream catchment of the River Witham from South Witham, through Grantham and to Claypole. The lower model (Upper Witham – Lincoln) focusses on the River Witham downstream of Claypole (incorporating the River Witham washlands), River Brant and River Till (with their associated washlands), and the smaller tributaries of Burton Catchwater, Boultham Catchwater and Skellingthorpe Drain.

A catchment wide hydrological approach has been taken, with the focus on providing appropriate inflows for the hydraulic model extents using available data to improve estimates across all sub catchments. Target flow estimation points have been identified along the main rivers, upstream of any washlands, at the following locations:

- Colsterworth
- Saltersford
- Claypole
- Brant Broughton

At each of these locations, flood frequency analysis using the FEH Statistical method has been carried out to derive target peak flows for the design events (Section 6). Scaling to reconcile distributed ReFH flows with the target peak flows has been undertaken. The scaling factors are described in Section 9.1. Upstream of these locations, ReFH inflow hydrographs have been scaled to the target peak flows.

The ReFH parameters of time-to-peak, baseflow lag and baseflow recharge have been improved through simulation of calibration events, and applied using donor transfer to ungauged catchment inflows for the calibration and design events. This is detailed in Section 8.2.

Downstream of Claypole, Brant Broughton, and the Till Washlands, flood frequency analysis for the purpose of target peak flow estimation was not suitable due to the influence of the washlands on the hydrological response of the catchment. Flood frequency analysis at North Hykeham (downstream of the River Witham and River Brant washlands) and at River Till at Washlands have been carried out. However these are for information purposes only and these values were not used as target peak flows (Section 6.4 and 6.6). Transfer of scaling factors from the Grantham model (upstream of Claypole) to the Lincoln model has not been undertaken as no coherent trend in the scaling factors was found for the Grantham model, and therefore transfer of the scaling factors would not be defendable. ReFH Hydrological inflows downstream of Claypole on the River Witham, downstream of Brant Broughton and on the River Till, Burton Catchwater and Boultham Catchwater have therefore not been scaled, but the ReFH model parameters have been enhanced through donor transfer.

A number of IDB pumped catchments surround Lincoln. The hydraulic model represents these catchments in 2D, with the IDB drains enforced into the model, and abstraction units used to represent the pumps. The model represents the attenuation and storage of these catchments, with the abstraction units controlling the flow between the IDB catchment and the main river network. Samuels trapezoidal unit hydrographs have therefore not been used for these pumped catchments as this would double-count the attenuation. Standard ReFH triangular unit hydrographs, enhanced through donor transfer, have therefore been distributed along the drain network.

The washlands were designed using a coincident peak assumption as part of the hydrological analysis, therefore to remain consistent with the previous analysis and definition of the standard of protection that the washlands provide, the same assumption has been used for the timing and phasing of the hydrological inflows in this study (Section 9.2). This choice of hydrograph phasing is not representative of a typical storm over the Upper Witham catchment, where historic data suggests that the Brant peaks earlier than the River Witham at Claypole, and the River Till peaks after Claypole (for example in the November 2012 event).

3.2 Hydrological Modelling Approach for Witham Brook, Mow Beck and Barrowby Stream Catchment Specific Models

The Upper Witham Model Improvement Study also incorporates two smaller models of Witham Brook and Mow Beck & Barrowby Stream, which both join the River Witham in Grantham.

Hydrological analysis specific to these two catchments, as opposed to a catchment wide approach, is also required. These are both heavily urbanised catchments, and therefore an Urban ReFH method, implemented using the ISIS Urban ReFH boundary, has been adopted as being most suitable for deriving design hydrological inflows (Section 10). The Urban ReFH method has been reviewed following comparison of the modelled flood extents against anecdotal evidence and found to provide sensible flood extents. These Urban ReFH inflows have been applied o the two catchment specific models only. For the catchment wide study, the inflows representing the Witham Brook and Mow Beck & Barrowby Stream catchments have been derived as summarised in Section 3.1 to ensure consistency across the catchment wide study.

4 Catchment Characteristics

4.1 Catchment Overview

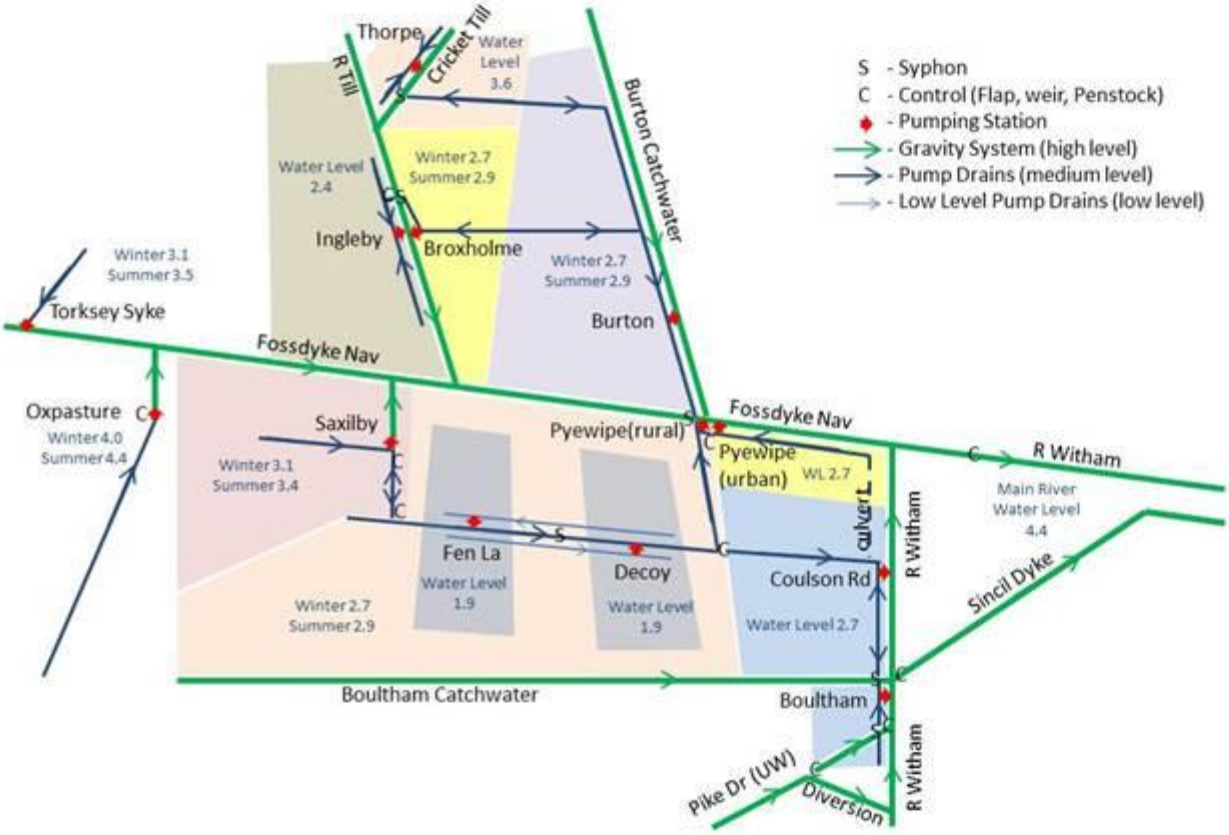
The geology of the catchment of the Upper Witham consists of clay and limestone. Downstream of Grantham the catchment is predominantly clay. There are some superficial deposits of Boulder Clay in the headwaters and gravel terrace deposits in the valleys. The mixed geology is confirmed by BFIHOST and SPRHOST values, which indicate some degree of groundwater influence (the BFIHOST value for the Witham at North Hykeham is 0.49).

The catchment is largely rural, although Grantham and Lincoln are significant urban areas. The catchment at North Hykeham is 559km^2 and as such, smaller urban areas are unlikely to play a significant role in determining fluvial flood risk and they typically account for a small proportion of the overall catchment.

The washlands, located on the River Witham, Brant and Till have a significant impact on the flood levels within Lincoln, as they offer considerable storage during flood events. There are also a number of drainage ditches, canals and other artificial influences which will alter both storage potential and timing of peak flows.

The IDB pumped catchments, surrounding Lincoln, are characterised by a series of low and medium level drains, connected to each other via Syphons, and control structures, and the main rivers by a series of pumping stations. Figure 4.1 provides a summary of the interconnectivity of the IDB pumped catchments.

Figure 4.1: Summary of IDB Catchment Interconnectivity



Source: Upper Witham Internal Drainage Board

Rainfall is generally low with a Standard Annual Average Rainfall (SAAR) of around 600mm.

4.2 Sub-Catchment Delineation

The catchment delineation has been governed by the following key concepts:

- Focus on areas of interest – principally the main river,
- Location of Gauging stations,
- Sub-catchment characteristics.

Sub-catchment delineation initially used digitised FEH catchments to identify approximate catchment boundaries. These have subsequently been refined through discussion with the Environment Agency's Asset Performance team, using knowledge from the Upper Witham IDB. The study area generally shows minimal elevation change, with a number of artificial features such as canals.

The finalised catchment delineation is shown in Figure 4.2. The resulting catchment delineation is similar to that of the Faber Maunsell (2007) study, although the number of sub-catchments has been substantially reduced, from 61 to 22. The number of separate inflow locations however is 87, enabling a detailed representation of the inflow contribution from each part of the catchment.

The majority of the inflows have been applied as lateral inflows, distributed along the length of the catchment they represent.

Point inflows have been used to represent the flow from the following tributaries:

- Mow Beck and Barrowby Stream
- Witham Brook
- Honington Beck

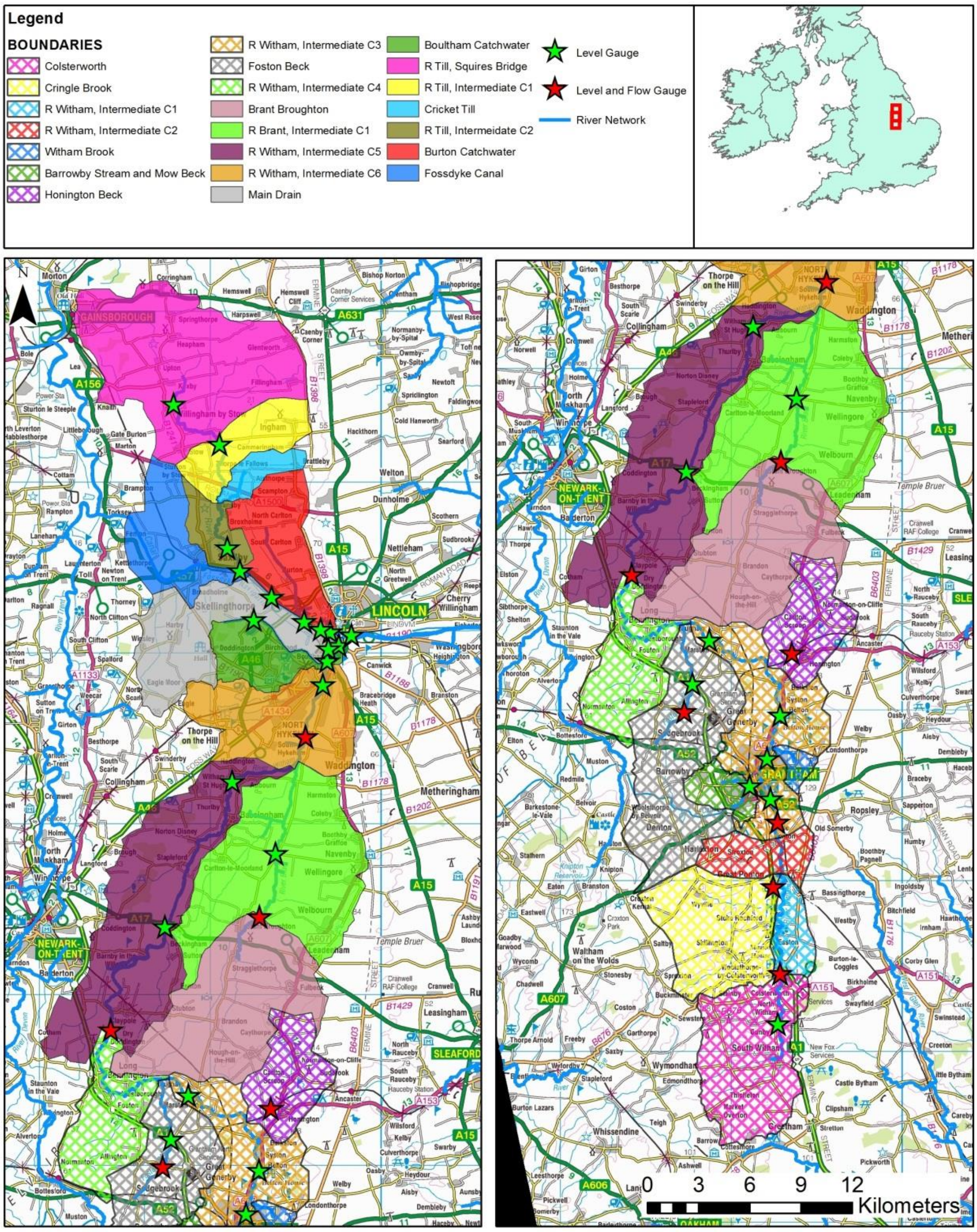
For the Upper Witham – Lincoln model, the inflow at Claypole has been represented as a point inflow.

The IDB pumped catchments have been represented as follows:

- Pike Drain – Proportion of the “River Witham Intermediate C6” catchment applied as a point inflow to the 2D domain at the upstream limit of the modelled drain.
- Main Drain (comprising of the region between Boultham Catchwater and Fossdyke Canal) – Inflow derived for the whole catchment and divided according to area weighting, and IDB catchment delineation. Applied either as 1D inflows to storage areas, or where representation is in 2D, as point inflows to the drain network.
- Burton IDB Catchment – Proportion of the “Burton Catchwater” catchment applied as a point inflow to the drain in the 2D domain.
- Ingleby, Broxholme and Thorpe IDB Catchments – Combined as part of “River Till Intermediate C2” and applied as 1D inflows to storage areas.

Details of the inflow locations and their respective weightings have been provided in the Hydraulic Modelling report in Figures C.1 and C.2, and Tables C.2 and C.3.

Figure 4.2: Revised Catchment Delineation



Source: Mott MacDonald. This map is reproduced by permission of Ordnance Survey on behalf of The Controller Of Her Majesty's Stationary Office. Environment Agency 100026380, 2015.

4.3 Catchment Characteristics

The finalised catchment characteristics for the 22 inflows are presented in Appendix A. In cases where little or no change occurred to the FEH catchment boundary, then FEH descriptors were used directly.

In the case where boundaries changed significantly or intervening characteristics were required, then the finalised catchment characteristics were derived through area weighting. DPLBAR was calculated using FEH equation 5.7.1 for the intermediate catchments.

A summary of the key catchment characteristics is provided in Table 4.1.

Table 4.1: Summary of Key Catchment Descriptors

Catchment ID (Used in Model)	Catchment	AREA (km^2)	BFIHOST	DPLBAR (km)	FARL	SAAR (mm)	SPRHOST (%)	URBEXT 2000
Colsterworth	River Witham upstream of Colsterworth GS	50.09	0.656	7.41	0.993	641	22.63	0.026
Cringle_Br	Cringle Brook	44.93	0.849	8.33	0.934	655	11.65	0.005
RW_US_CB	R Witham Intermediate C1 (Cringle Brook – Colsterworth GS)	11.24	0.75	3.99	0.994	646	16.62	0.021
RW_US_Salt	R Witham Intermediate C2 (Saltersford – Cringle Brook)	15.65	0.794	4.51	0.973	646	14.43	0.012
Witham_Br	Witham Brook	3.76	0.607	2.10	1	618	26.69	0.232
MowBeck_BS	Barrowby Stream and Mow Beck	9.86	0.567	4.69	1	607	32.01	0.222
HoningtonBr	Honington Beck	24.9	0.592	5.74	0.977	597	28.97	0.012
RW_US_FB	R Witham Intermediate C3 (Foston Beck – Saltersford GS)	49.3	0.632	8.47	0.974	618	25.71	0.038
RW_US_CP	R Witham Intermediate C4 (Claypole – Foston Beck)	30.89	0.25	6.55	0.975	562	51.53	0.029
Foston_Beck	Foston Beck	60.83	0.464	10.43	0.969	597	37.74	0.337
Witham_US_Brant	R Witham Intermediate C5 (River Brant – Claypole)	89.01	0.411	11.68	0.978	564	40.34	0.011
Witham_US_BC	R Witham Intermediate C6 (River Brant - Boultham Catchwater)	45. 14	0.436	8.06	0.979	596	38.37	0.068
Brant_GS_US	River Brant upstream of Brant Broughton GS	65.68	0.369	8.54	0.995	574	45.2	0.007
Brant_GS_DS	R Brant Intermediate C1 (Brant Broughton –	81.14	0.364	11.10	0.997	579	44.4	0.01

Catchment ID (Used in Model)	Catchment	AREA (km^2)	BFIHOST	DPLBAR (km)	FARL	SAAR (mm)	SPRHOST (%)	URBEXT 2000
	Confluence with River Witham)							
Boultham	Boultham Catchwater	18.07	0.446	4.88	0.882	600	35.33	0.149
Main_Drain	Main Drain	41.44	0.439	12.6	0.93	596	36.5	0.017
RT_US_SQB	River Till upstream of Squires Bridge	85.78	0.339	9.08	0.992	592	41.99	0.018
RT_US_CT	River Till Intermediate C1 (Squires Bridge – Confluence with Cricket Till)	20.82	0.364	5.31	0.993	592	41.28	0.016
Cricket Till	Cricket Till	7.94	0.368	1.6	1	590	40.02	0
RT_US_FD	R Till Intermediate C2 (Cricket Till – Confluence with Fossdyke Canal)	141.51	0.405	3.81	0.992	597	41.76	0.019
Burton	Burton Catchwater	30.91	0.457	8.24	0.938	593	36.94	0.013
FD_US_RT	Fossdyke Canal Upstream of River Till	27.44	0.347	6.14	1	595	43.95	0.030

Source: FEH CD-ROM

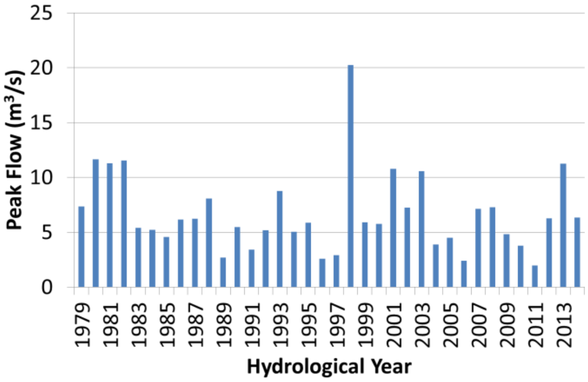
The same catchment areas and characteristics have been used for Witham Brook and Mow Beck & Barrowby Stream hydrological analysis for the stand-alone models as for the catchment wide model.

5 Derivation of Index Flood

5.1 Derivation of QMED at Gauged Target Flow Estimation Points

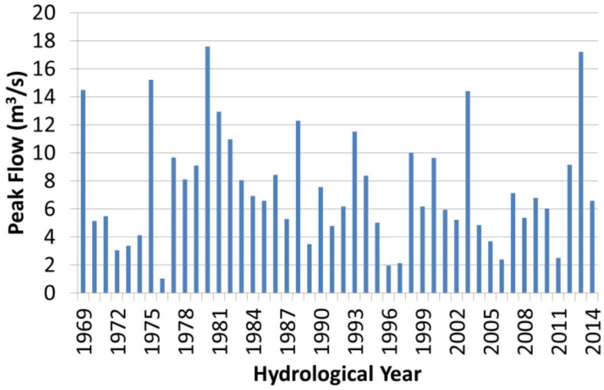
QMED has been derived at the gauged target flow estimation points along the River Witham using observed AMAX data. Figure 5.1 to Figure 5.4 show the observed AMAX data at Colsterworth, Saltersford, Claypole and North Hykeham respectively. Table 5.1 provides the derived QMED values at the gauging stations. The AMAX series used is provided in Appendix B.

Figure 5.1: Observed AMAX data at Colsterworth Gauging Station



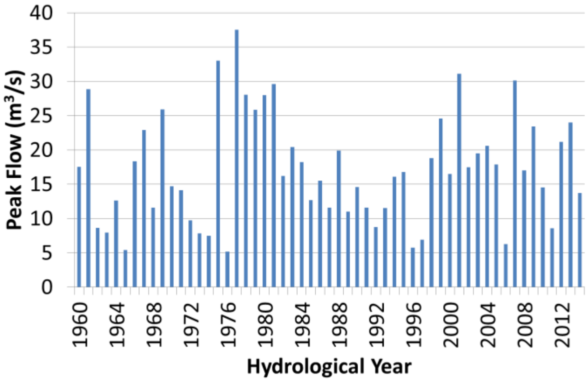
Source: Mott MacDonald

Figure 5.2: Observed AMAX data at Saltersford Gauging Station



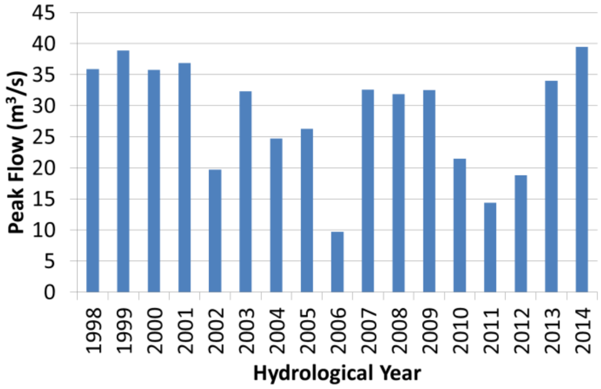
Source: Mott MacDonald

Figure 5.3: Observed AMAX data at Claypole Gauging Station



Source: Mott MacDonald

Figure 5.4: Observed AMAX data at North Hykeham Gauging Station



Source: Mott MacDonald

Table 5.1: Summary of Observed QMED at Gauged Target Flow Estimation Points

Gauging Station	Observed QMED	Number of Years of Data	Comments
Colsterworth	5.89	35	Increase of 1.7% from 2007 Study[(2)]
Saltersford	6.57[(1)]	45	Concerns over data at Saltersford due to blockage at Stilling Well. 2007 study discarded AMAX series after 1995, and had QMED value of 8m^3/s.
Claypole	16.50	54	Increase of 1.2% from 2007 Study[(2)]
North Hykeham	32.30[(1)]	16	Peak Flows limited to around 40m^3/s due to Washlands. Concerns over accuracy of ultrasonic gauge.
Brant	9.76	24	Uses updated JBA rating. 2007 study used value of 23.74m^3/s, calculated using data transfer from River Stour at Kedington. There was previously low confidence in the rating curve and therefore observed data was not used. The rating curve has been updated and is considered suitable for use.

Source: Mott MacDonald.

(1) These QMED values have not been taken forward due to concerns with the observed data. Final QMED values provided in Table 5.5.

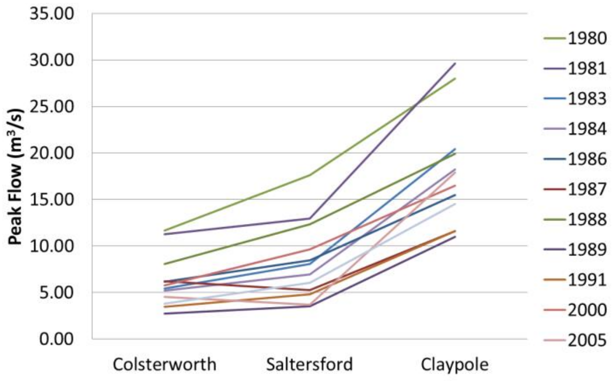
(2) Rating analysis at Colsterworth and Claypole (Chapter 6) does not affect QMED values

There is low confidence in the observed QMED at both Saltersford and North Hykeham, this is discussed below.

Saltersford Gauging Station

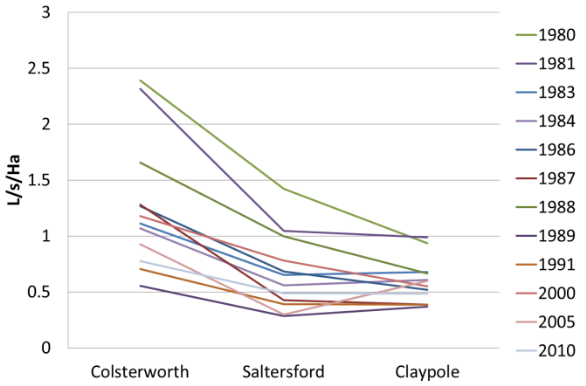
At Saltersford a blockage to the stilling well has been recorded, and the 2007 study discarded all data post 1995. As part of this study analysis of the flows at Colsterworth, Saltersford and Claypole for concurrent AMAX events has been undertaken to see if the data at Saltersford is thought to be reliable. Figure 5.5 and Figure 5.6 show a comparison of the peak flows, and specific runoff at the three gauging stations. This data is provided in tabular form in Appendix C.

Figure 5.5: Comparison of Peak Flow



Source: Mott MacDonald

Figure 5.6: Comparison of Specific Runoff



Source: Mott MacDonald

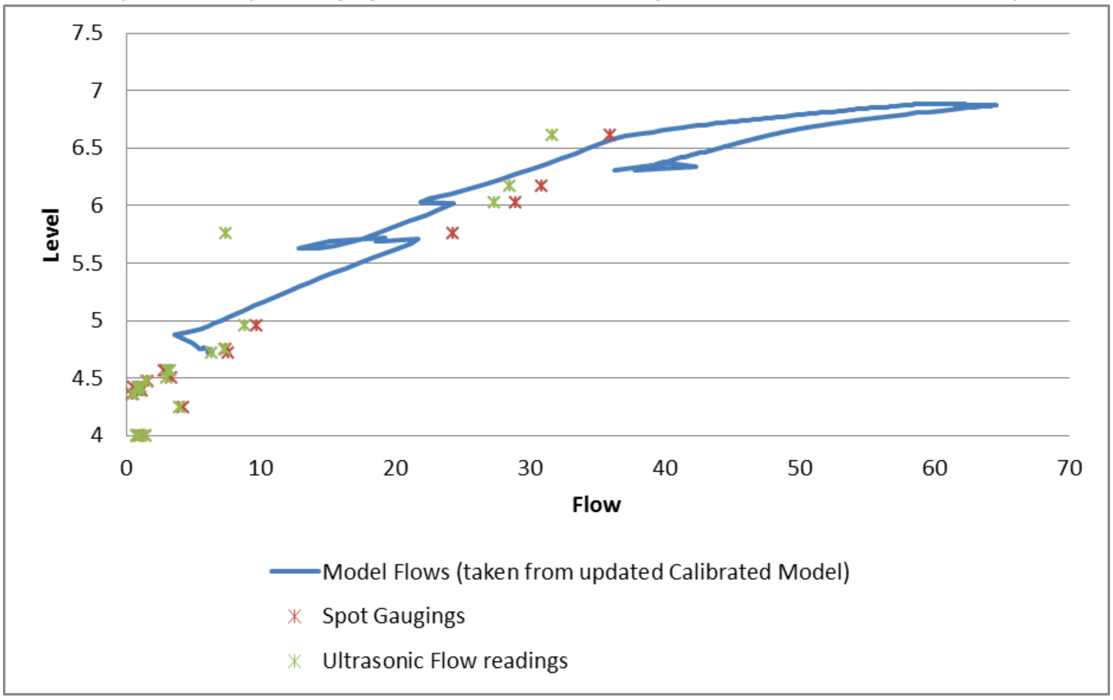
This analysis shows that there are some inconsistencies in the data (particularly in 1981, 1986 and 1987). The data is therefore not considered suitable for QMED calculation, and the gauging station has been considered as an ungauged site for QMED derivation.

Out of the 36 years of concurrent data available at the three gauging stations (from 1979 – 2014), only 12 of the recorded AMAX events were concurrent events at all three gauging stations. When assessing the number of concurrent events between Colsterworth and Claypole over the same period, there are 16 events.

North Hykeham Gauging Station

At North Hykeham gauging station there is concern that the ultrasonic flow gauge may be underestimating flows. A comparison between spot gauging flows, ultrasonic flow readings (at the time of the spot gaugings) and modelled flows (influenced by opening and closing of washland gates) is provided in Figure 5.7.

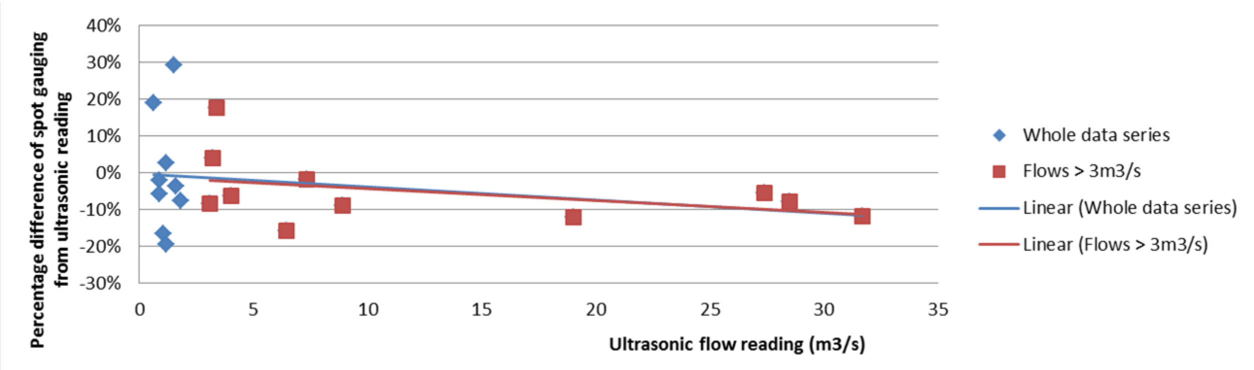
Figure 5.7: Comparison of Spot Gaugings, Ultrasonic Flow Readings and Modelled Flows at North Hykeham



Source: Mott MacDonald

This shows that the ultrasonic flow reading is consistently under reading the flows. A comparison of the difference in recorded flows has therefore been undertaken and is given in Figure 5.8. A best fit line has also been added to the graph. This has been calculated for all flows, and flows above $3m^3/s$ to understand whether the low flow spot gaugings (which show the most scatter) are having a large influence on the line of best fit.

Figure 5.8: Comparison of Spot Gaugings and Ultrasonic Flow Readings at North Hykeham



Source: Mott MacDonald

The analysis shows that the percentage difference between the spot gauging and ultrasonic reading increases with increasing flow. The line of best fit calculated using the full data and the flows >3m^3/s is very similar. The calculate relationship between the ultrasonic flow reading and the estimated true flow is:

$$Q_{REAL} = \frac{Q_{ULTRASONIC}}{1 - 0.0032Q_{ULTRASONIC} - 0.01}$$

Revising the observed AMAX using this relationship gives a revised QMED of 36.9m^3/s. The data used in this analysis, and regression statistics are provided in Appendix D.

QMED transfer has also been considered for this location due to the uncertainty in the observed flows. This is detailed in Section 5.2, along with a final conclusion for the QMED value at North Hykeham.

5.2 Derivation of QMED at Ungauged Target Flow Estimation Points

QMED estimates at the Till Washlands, Saltersford and North Hykeham have been derived using the ungauged approach including donor adjustment. The catchment characteristics of a number of nearby catchments have been compared against those of the target catchments for use as donor sites. For each potential donor both the original QMED transfer method (as detailed in FEH Volume 3), and the revised (2008) transfer method incorporating the distance adjustment ratio have been used, which is the method recommended in OI_197_08.

5.2.1 River Till Upstream of Washlands

Table 5.2 details the suitable donor sites for the River Till at Washlands, and the corresponding transferred QMED values. The donor sites were selected by reviewing the catchment descriptors of sites within the Upper Witham Catchment and the sites suggested as potential donors by the WINFAP FEH software, to identify sites with similar catchment characteristics.

Table 5.2: Donor Sites for River Till Flow Estimation Point

	Station	Area (km^2)	SAAR	BFI	SPR	FARL	Distance between Catchments (km)	Observed QMED at Donor Sites (m^3/s)	QMED Catchment Descriptors (Urban Adjusted)(m^3/s)	QMED Transferred to Target Site (m^3/s) Without Distance	QMED Transferred to Target Site (m^3/s) With Distance
Target Site	River Till Upstream of Washlands	114	592	0.345	41.82	0.993			13.61		
Donor Sites	Foston Beck@ Allington	40	608	0.516	35.35	0.953	51	4.41	3.3	18.18	14.27
	Brant @ Brant Broughton	66	574	0.369	45.2	0.995	37	9.76	7.26	18.3	14.53
	28024 (Wreake @ Syston Mill)	417	634	0.403	41.93	0.953	70	34.39	37.73	12.4	13.47

The proposed donor is the River Brant, as it has the most similar BFIHOST value. Foston Beck has a BFIHOST value, which although is within the recommended ± 0.18, differs by 0.17 from that at the target site, and therefore is not considered the most suitable donor site. Wreake @ Syston Mill has a BFIHOST which only differs from that at the target site by 0.06; however the site is more distant from the target site than Brant Broughton and on a different watercourse.

There is a fairly large difference between the donored QMED when considering distance compared to not considering distance. This is due to the donor site being up to 37km away from the target site. POT analysis has therefore been carried out using the Till Washland Ultrasonic Level Gauge data for the full water years of 2001, 2002, 2006, 2007 and 2008. The LMED value derived using POT, with a threshold of 5.0mAOD, was 5.71mAOD. The updated calibrated model has then been used to provide an estimate of QMED from LMED, giving a value of 17.5m^3/s. This value is fairly similar to that calculated using Brant Broughton as a donor, without considering distance. It is recommended that a value of 17.5 m^3/s is used for QMED. The data used in the POT analysis and in estimating QMED from the derived LMED value (including the QH relationship taken from node RT02109) are provided in Appendix E.

5.2.2 River Witham at Saltersford

Table 5.3 details the suitable donor sites for the River Witham at Saltersford, and the corresponding transferred QMED values.

Table 5.3: Donor Sites for River Witham at Saltersford Flow Estimation Point

	Station	Area (km²)	SAAR	BFI	SPR	FARL	Distance between Catchments (km)	Observed QMED at Donor Sites (m³/s)	QMED Catchment Descriptors (Urban Adjusted) (m³/s)	QMED Transferred to Target Site (m³/s) Without Distance	QMED Transferred to Target Site (m³/s) With Distance
Target Site	River Witham @ Saltersford	124	646	0.761	16.58	0.973			4.43		
Donor Sites	River Witham @ Claypole	300	615	0.592	28.49	0.975	8.5	16.5	16.86	4.34	4.4
	River Witham @ Colsterworth	49	641	0.656	22.63	0.993	4.9	5.89	3.38	7.71	5.75

Both donor sites are suitable for transferring to Saltersford, however the BFIHOST value at Colsterworth provides a better match to that at Saltersford. Saltersford lies between Colsterworth and Claypole, and therefore in order to provide consistency along the watercourse for deriving target peak flows, the derived QMED at Saltersford should be between the observed QMED's at Colsterworth and Claypole.

The observed QMED at Colsterworth is 5.89m³/s. If Claypole is used as a donor site, QMED at Saltersford would be less than the upstream observed QMED at Colsterworth. Therefore it is recommended that Colsterworth is used as the donor site without considering distance, giving a final derived QMED value of 7.71 m³/s at Saltersford.

5.2.3 River Witham at North Hykeham

Only Claypole was considered as a donor site for North Hykeham as it is both on the water course and closest to the target site. Table 5.4 details the QMED transfer process for North Hykeham.

Table 5.4: Donor Sites for River Witham at North Hykeham Flow Estimation Point

	Station	Area (km²)	SAAR	BFI	SPR	FARL	Distance between Catchments (km)	Observed QMED at Donor Sites (m³/s)	QMED Catchment Descriptors (Urban Adjusted) (m³/s)	QMED Transferred to Target Site (m³/s) Without Distance	QMED Transferred to Target Site (m³/s) With Distance
Target Site	River Witham @ North Hykeham	559	596	0.494	35.27	0.984			36.06		
Donor Sites	River Witham @ Claypole	300	615	0.592	28.49	0.975	10	16.5	16.86	35.28	35.76

The donor transfer from Claypole provides fairly similar QMED value to the analysis carried out on the observed data in section 5.1 (QMED value of 36.9m^3/s). It is therefore recommended that the value of 36.9m^3/s is used as this is based on observed data, and supported by the donor transfer analysis, and the catchment descriptor derived QMED value.

5.3 Summary of QMED values at Flow Estimation Points

Table 5.5 provides a summary of the final derived QMED values at each of the flow estimation points, and the method used to derive these values.

Table 5.5: Summary of QMED Values at Flow Estimation Points

Flow Estimation Point	Derived QMED (m^3/s)	Methodology Used
River Witham at Colsterworth	5.89	Observed QMED from AMAX
River Witham at Saltersford	7.71	Donor Transfer from Colsterworth, not using distance
River Witham at Claypole	16.5	Observed QMED from AMAX
River Witham at North Hykeham	36.9	Ultrasonic Flow Readings, adjusted due to ultrasonic gauge under-reading flows
River Till upstream of Washlands	17.5	POT Analysis
River Brant at Brant Broughton	9.76	Observed QMED from AMAX

Source: Mott MacDonald

6 Flood Frequency Analysis

Flood frequency analysis has been carried out on the River Witham at Colsterworth, Saltersford, Claypole, North Hykeham, River Till upstream of the washlands and River Brant at Brant Broughton. The analysis has been reported in the following order as the analysis at some of the stations feeds into the analysis at subsequent stations:

- Colsterworth Gauging Station
- Claypole Gauging Station
- Saltersford Gauging Station
- North Hykeham Gauging Station
- River Brant Gauging Station
- River Till upstream of Washlands.

6.1 Flood Frequency Analysis at Colsterworth Gauging Station

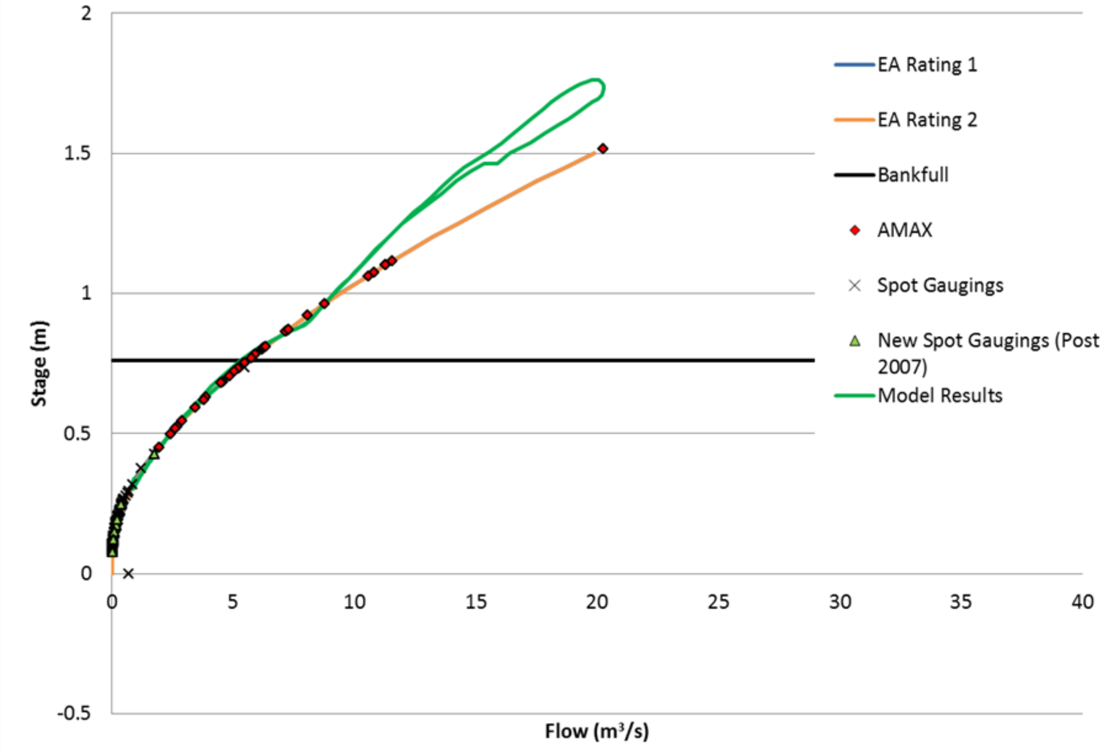
Single site and pooled analysis (enhanced and non-enhanced) have been carried out at Colsterworth gauging station. For comparison, a lumped ReFH assessment has also been undertaken. No refinement to the ReFH parameters was considered at this stage.

A hybrid estimate of the 0.5%, 0.2% and 0.1% AEP events has been undertaken. This uses the ReFH ratio of Q0.1%/Q1%, in order to estimate the 0.1%AEP event for the statistical method (the Q0.5%/Q1% ReFH ratio is used for the 0.5% AEP event, and the Q0.2%/Q1% ReFH ratio for the 0.2% AEP event).

Rating Curve Review

Whilst carrying out the analysis at Colsterworth it was noted that the model was producing a different flow/stage relationship than that suggested by the EA Rating curve, particularly for flows that were out of bank. Figure 6.1 compares the EA rating against the model results and available spot gaugings.

Figure 6.1: Comparison of Model Results (updated calibrated model) against EA Rating and Spot Gaugings at Colsterworth (UWE14603)



Source: Mott MacDonald

The gauging station is located within a series of 3 embankments, leading to significant backing up of flow upstream of each embankment. The modelled flows represent this, and suggest a reduced flow estimate for the larger AMAX events. Due to the differences in flow estimates for the larger AMAX events, the subsequent single site flood frequency analysis has been carried out for both the existing AMAX data (calculated from the EA Rating 2), and a revised AMAX series calculated using the model data. A summary of all the AMAX data used in the analysis is given in Appendix B.

Single Site Analysis

Single site analysis has been carried out using both the existing AMAX data and the revised AMAX data. Figure 6.2 and Figure 6.3 respectively show the flood frequency curves generated for each set of AMAX data.

Figure 6.2: Single Site Analysis at Colsterworth Gauging Station using Existing AMAX Data

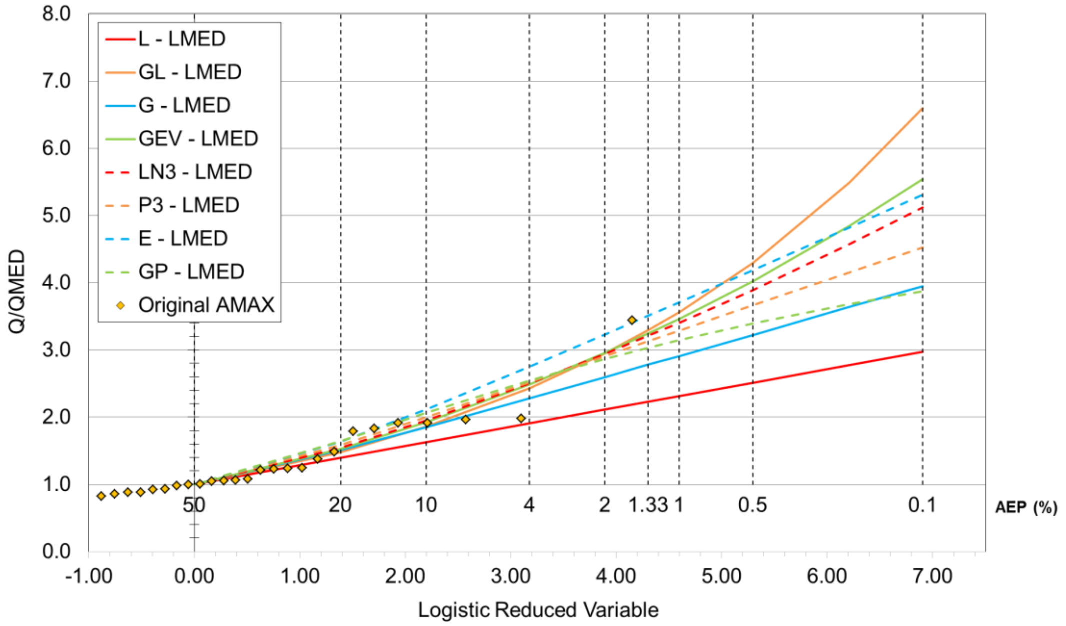
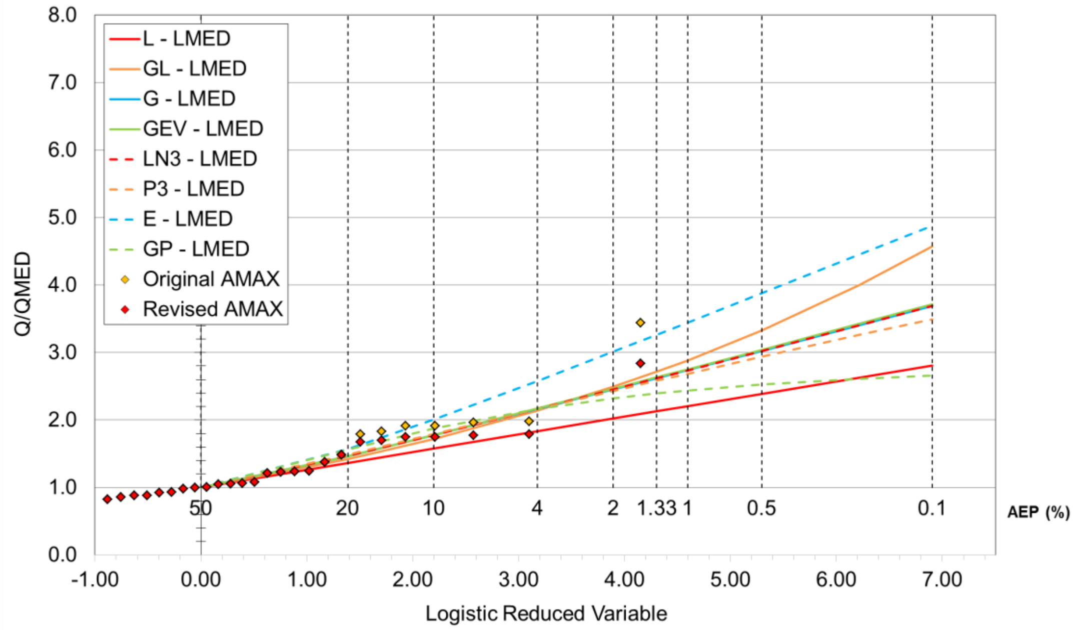


Figure 6.3: Single Site Analysis at Colsterworth Gauging Station using Revised AMAX Data



Source: WINFAP-FEH Software

In both cases the GL curve gives a suitable match to the observed AMAX series.

Enhanced Single Site and Pooled Analysis

Both Enhanced Single Site and Pooled Analysis were carried out at Colsterworth.

A pooling group was created using the WINFAP-FEH Software. The initial pooling group is provided in Table 6.1. The pooling group was reviewed for short records and for catchments with descriptors such as BFIHOST that may unduly influence the final pooled growth curves. No changes were made to the initial pooling group.

Table 6.1: Initial/Final Pooling Group – Colsterworth Gauging Station

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	BFIHOST	Comment
33032 (Heacham @ Heacham)	0.235	44	0.461	0.315	0.099	1.129	0.968	
33054 (Babingley @ Castle Rising)	0.345	36	1.129	0.214	0.069	0.985	0.906	
26003 (Foston Beck @ Foston Mill)	0.354	52	1.739	0.243	-0.015	0.291	0.88	
36003 (Box @ Polstead)	0.445	49	3.841	0.31	0.109	0.762	0.554	
36007 (Belchamp Brook @ Bardfield Bridge)	0.602	48	4.628	0.384	0.129	1.93	0.523	
34005 (Tud @ Costessey Park)	0.648	51	3.146	0.281	0.181	1.144	0.598	
37003 (Ter @ Crabbs Bridge)	0.66	48	4.991	0.248	-0.037	0.815	0.461	
36004 (Chad Brook @ Long Melford)	0.678	45	4.938	0.306	0.199	1.523	0.44	
37016 (Pant @ Copford Hall)	0.718	47	8.502	0.285	0.049	0.093	0.404	
30004 (Lymn @ Partney Mill)	0.768	50	6.778	0.236	0.059	0.754	0.568	
34012 (Burn @ Burnham Overy)	0.778	46	1.024	0.226	-0.137	1.574	0.965	
Weighted Means								
Enhanced Single Site				0.267	0.088			
Pooling Group Only				0.278	0.065			
Heterogeneity score								
Enhanced Single Site	3.31							
Pooling Group Only	3.155							

Figure 6.4 and Figure 6.5 provides the growth curves generated from the enhanced single site analysis, using the original AMAX and the revised AMAX respectively. Figure 6.6 provides the growth curves generated from the pooled analysis.

Figure 6.4: Enhanced Single Site Analysis at Colsterworth Gauging Station using Original AMAX data

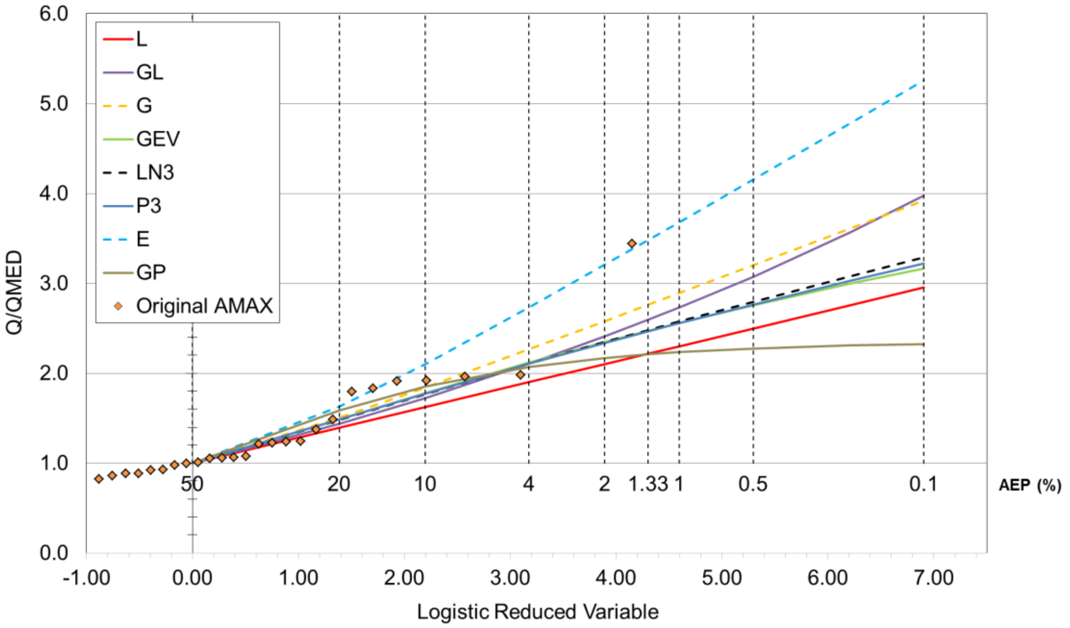
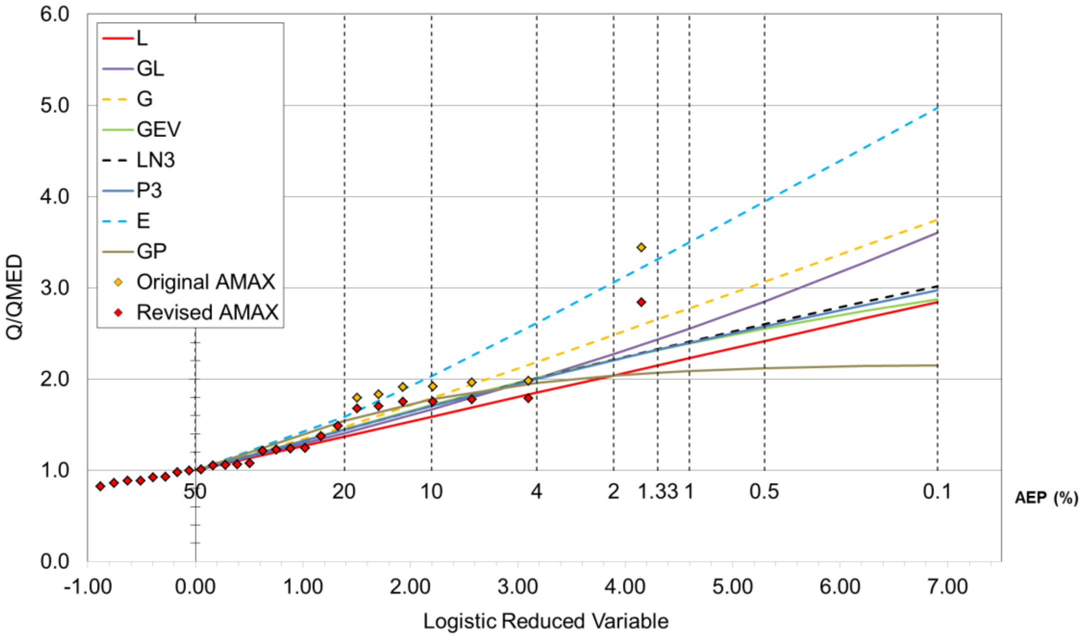
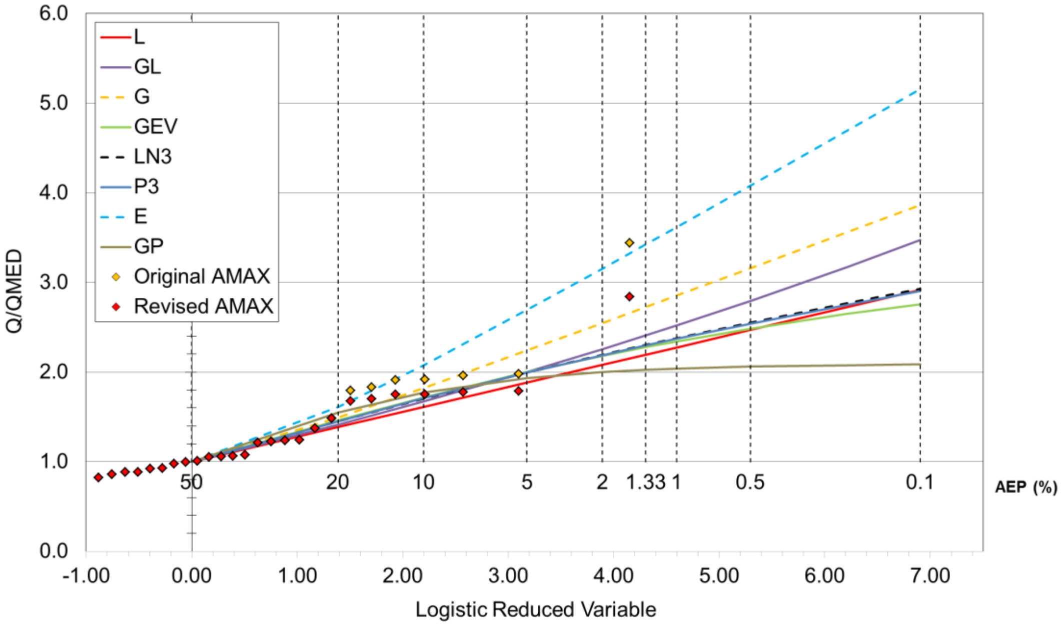


Figure 6.5: Enhanced Single Site Analysis at Colsterworth Gauging Station using Revised AMAX data



Source: WINFAP-FEH Software

Figure 6.6: Pooled Analysis at Colsterworth Gauging Station



Source: WINFAP-FEH Software

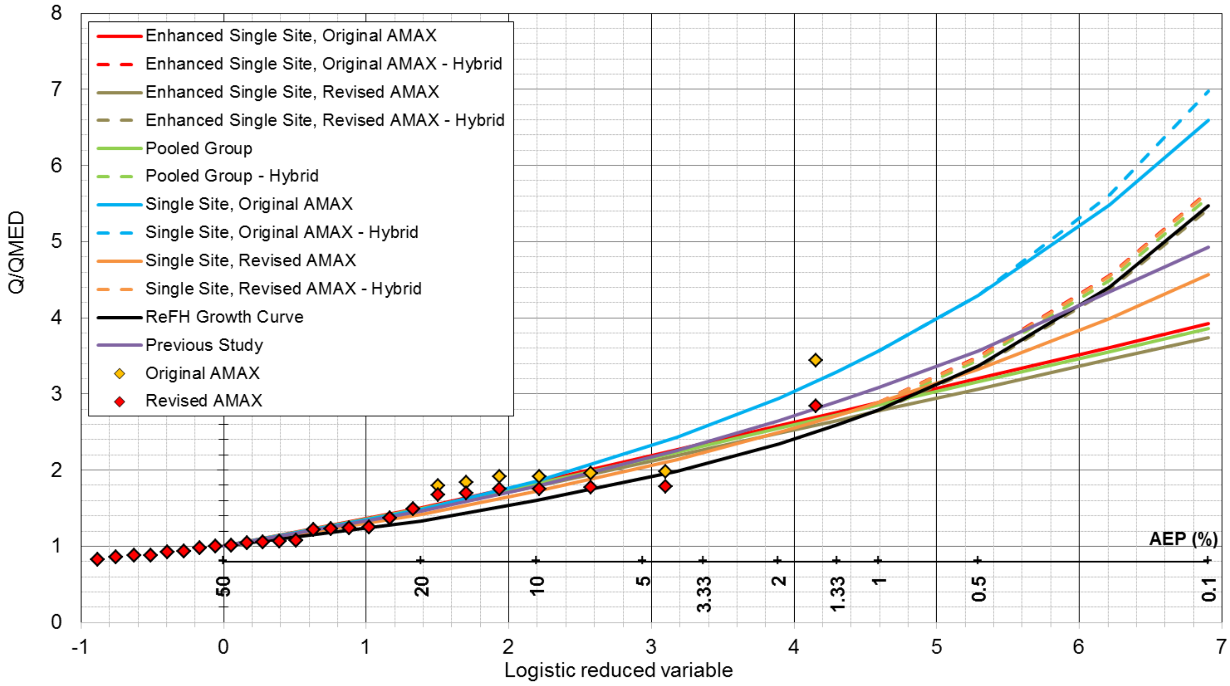
In all 3 figures the majority of the flood frequency curves tend to underestimate the observed AMAX data, particularly the larger events, between an AEP of 20% and 4%. There is some concern that the catchments used in the pooling group may be drawing down the enhanced single site curves. Formation of a homogenous pooling group proved difficult for this site and it may be that the pooled catchments do not adequately represent the type of conditions expected on the Upper Witham.

The enhanced single site growth curves are fairly comparable between the analysis with the original AMAX and the revised AMAX data, with the revised AMAX enhanced single site being slightly lower than with the original AMAX data.

Comparison of Growth Curves

An overall comparison of the best fitting growth curves from each methodology, and against a ReFH growth curve and the growth curve used in the previous 2007 study is provided in Figure 6.7. The growth factors calculated using the Hybrid methodology for the larger AEP events have been included using dashed lines.

Figure 6.7: Comparison of Best Fitting Growth Curves at Colsterworth Gauging Station



Source: WINFAP-FEH Software

The single site growth curve using the revised AMAX data matches very closely with the enhanced single site and pooled growth curves. The final choice of growth curve depends on which AMAX series is to be adopted, with the single site growth curves both providing suitable growth curves for their respective AMAX series. It is important that the growth curves derived along the River Witham for target peak flow estimation are consistent with each other. Table 6.2 provides a summary of the growth factors for the curves presented in Figure 6.7, and the associated z-scores (goodness of fit test) where applicable.

Table 6.2: Summary of Growth Factors at Colsterworth Gauging Station

Annual Exceedence Probability	Single Site - GL (Original AMAX)	Single Site - GL (Revised AMAX)	Enhanced Single Site (Original AMAX)	Enhanced Single Site (Revised AMAX)	Pooled Group	ReFH Growth Curve	Previous Study
50%	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20%	1.48	1.42	1.51	1.48	1.50	1.33	1.47
10%	1.86	1.72	1.84	1.79	1.82	1.60	1.79
4%	2.43	2.14	2.27	2.19	2.24	1.98	2.26
2%	2.95	2.49	2.58	2.48	2.55	2.34	2.66
1.33%	3.30	2.72	2.76	2.65	2.73	2.59	2.90
1%	3.56	2.89	2.89	2.78	2.85	2.79	3.09
0.5%	4.30	3.33	3.20	3.07	3.16	3.37	3.57

Annual Exceedence Probability	Single Site - GL (Original AMAX)	Single Site - GL (Revised AMAX)	Enhanced Single Site (Original AMAX)	Enhanced Single Site (Revised AMAX)	Pooled Group	ReFH Growth Curve	Previous Study
0.2%	5.49	3.99	3.61	3.45	3.56	4.40	
0.1%	6.60	4.57	3.92	3.74	3.86	5.47	4.93
0.5% (Hybrid)	4.30	3.48	3.49	3.35	3.44		
0.2% (Hybrid)	5.61	4.55	4.55	4.37	4.49		
0.1% (Hybrid)	6.97	5.65	5.66	5.43	5.58		
Z – score			-0.11	-0.024	0.0774		

In discussion with the Environment Agency, it has been agreed to use the average of the Enhanced Single Site (Original AMAX) and Enhanced Single Site (Revised AMAX) growth curves. The reasons for this are:

- The model rating is based on limited information – therefore average of original and revised AMAX is reasonable.
- The April 1998 event did not cause significant flooding in the Upper Witham, and therefore to ensure that the growth curve passes through this event (using a single site analysis, or custom growth curve) may be placing too much emphasis on the April 1998 event, which is not backed up by anecdotal evidence.
- Enhanced single site analysis incorporates the April 1998 event, but in addition the pooling group data.

Final growth curve and target peak flows are detailed in Table 6.14 and Table 6.15 respectively.

6.2 Flood Frequency Analysis at Claypole Gauging Station

Single site and pooled analysis (enhanced and non-enhanced) have been carried out at Claypole gauging station. For comparison, a lumped ReFH assessment has also been undertaken. No refinement to the ReFH parameters was considered at this stage.

A hybrid estimate of the 0.5%, 0.2% and 0.1% AEP events has been undertaken. This uses the ReFH ratio of Q0.1%/Q1%, in order to estimate the 0.1%AEP event for the statistical method (the Q0.5%/Q1% ReFH ratio is used for the 0.5% AEP event, and the Q0.2%/Q1% ReFH ratio for the 0.2% AEP event).

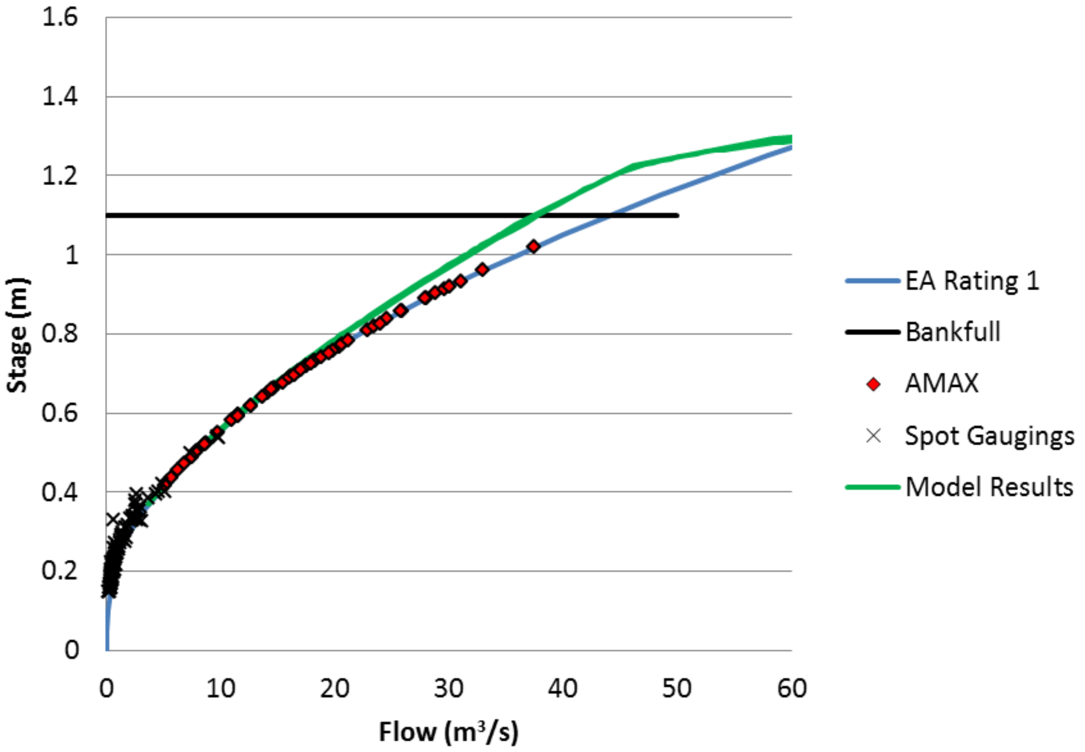
AMAX and Rating Curve Review

Whilst carrying out the analysis at Claypole it was noted that:

- The model (updated calibrated model – node UWC_6163) produces a different flow/stage relationship than that suggested by the EA rating curve, particularly for flows that were out of bank.
- The level series at Claypole for April 1998 looks erroneous/suspicious, with the peak of the event chopped off, and therefore is not identified as an AMAX event at Claypole, even though it was the largest recorded event at Colsterworth, Cringle Brook and Allington within the Upper Witham catchment since records began at these stations.

Figure 6.8 compares the EA rating against the model results and available spot gaugings.

Figure 6.8: Comparison of Model Results against EA Rating and Spot Gaugings.at Claypole

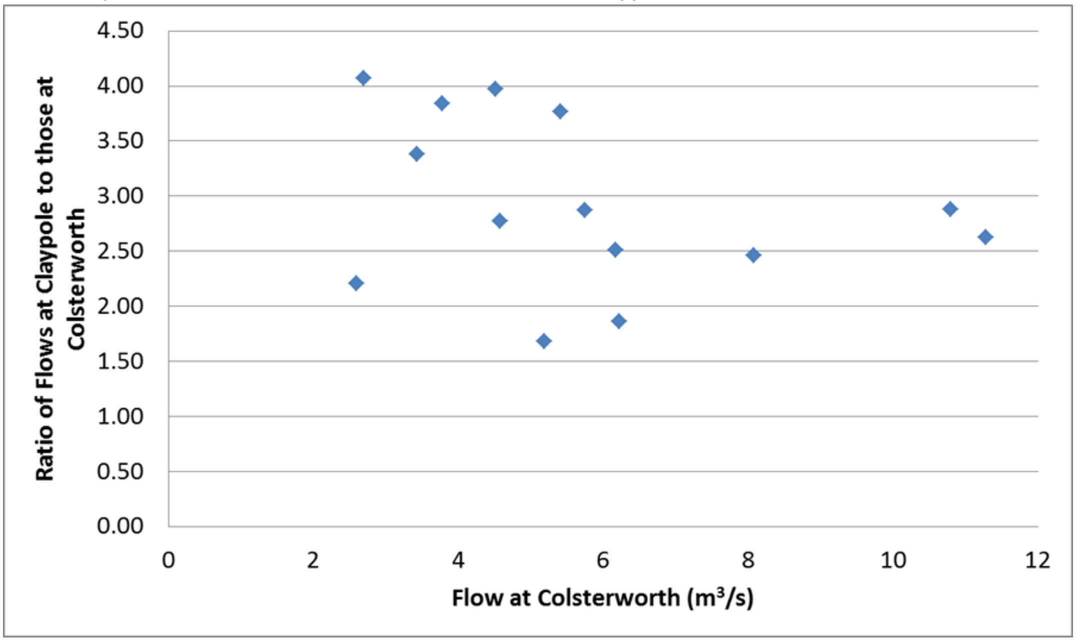


Source: Mott MacDonald

Due to the differences in flow estimates for the larger AMAX events, the subsequent single site flood frequency analysis has been carried out for both the existing AMAX data (calculated from the EA Rating 1), and a revised AMAX series calculated using the model data. A summary of all the AMAX data used in the analysis is given in Appendix B.

To provide an estimate of the April 2008 flow, the ratio of observed flows between Claypole and Colsterworth for concurrent events was calculated. These are plotted in Figure 6.9.

Figure 6.9: Comparison of Ratio of Observed Flows Between Claypole and Colsterworth for Concurrent Events.



Source: Mott MacDonald

Due to the high scatter in the ratios, it was agreed in consultation with the Environment Agency that the data for April 2008 would be considered missing, rather than used to provide an estimate of the flow at Claypole based on this analysis.

Single Site Analysis

Single site analysis has been carried out using both the existing AMAX data and the revised AMAX data. Figure 6.10 and Figure 6.11 respectively show the flood frequency curves generated for each set of AMAX data.

Figure 6.10: Single Site Analysis at Claypole Gauging Station using Existing AMAX Data.

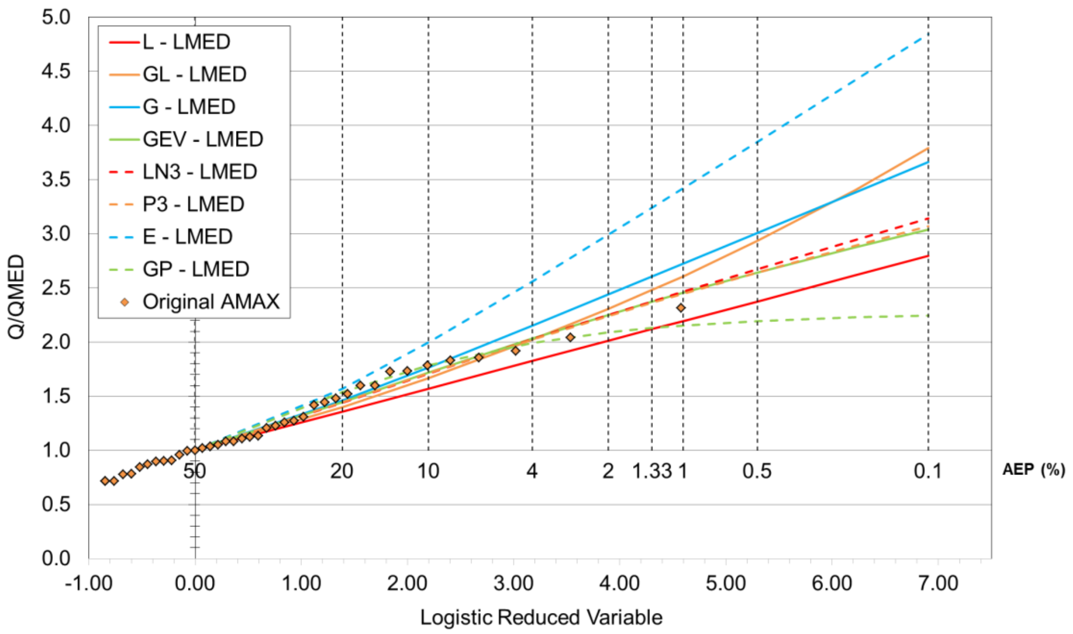
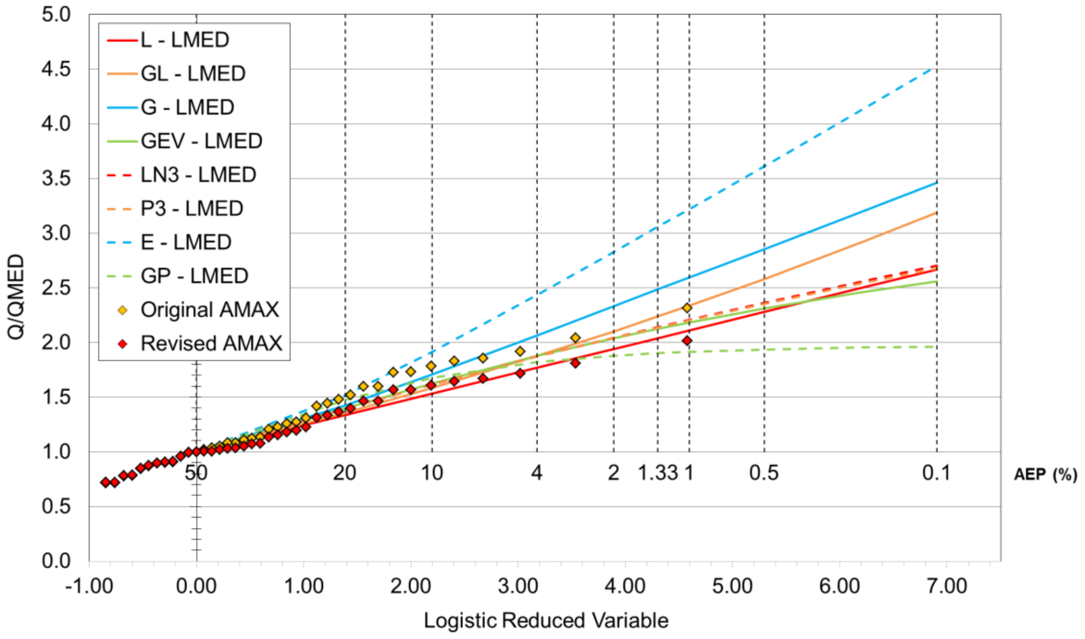


Figure 6.11: Single Site Analysis at Claypole Gauging Station using Revised AMAX Data



Source: WINFAP-FEH Software

In the single site analysis with original AMAX data, the General Logistic (GL) growth curve fits the data fairly well, with the exception of the largest event. In the single site analysis with the revised data, the majority of the growth curves overestimate flow when compared to the observed data. It should be kept in mind that one of the largest events on the catchment upstream of Claypole – particularly at Colsterworth, Cringle Brook and Foston Beck, has not been included in this analysis and therefore if a reliable flow estimate for the April 1998 event existed, and was used, this may increase the growth factors derived from single site analysis.

The growth curves are all fairly low, with the 1%AEP growth factor being typically between 2 and 2.5. This suggests that there is a reasonable amount of storage upstream of Claypole that is attenuating the flow during large events. This has been confirmed following model runs with large areas of floodplain inundated from Marston down to Claypole, particularly for the more extreme events.

Enhanced Single Site and Pooled Analysis

Both Enhanced Single Site and Pooled Analysis were carried out at Claypole.

A pooling group was created using the WINFAP-FEH Software. The pooling group was reviewed for short records and for catchments with descriptors such as BFIHOST that may unduly influence the final pooled growth curves.

Two sites were removed from the pooling group (33021 – Rhee and 33005 Bedford Ouse), and two sites (37005 – Colne and 25005-Leven) were added. Rhee was removed as it has a fairly high BFIHOST (0.715 compared to 0.592 at the subject site) and 4 AMAX events with flows at or under 1m^3/s, compared to a QMED of 8.27 m^3/s. Bedford Ouse was removed as it is an old data set, with the last recorded data in 1978, and has a year with a low AMAX event. While the final pooling group is still heterogenous, the H2 statistic has substantially lowered (from 4.89 to 2.68). The final pooling group is provided in Table 6.3

Table 6.3: Final Pooling Group – Claypole Gauging Station

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
22006 (Blyth @ Hartford Bridge)	0.398	52	52.546	0.319	0.289	1.832	
~~33021 (Rhee @ Burnt Mill)~~	~~0.474~~	~~50~~	~~8.274~~	~~0.264~~	~~-0.13~~	~~1.871~~	Site Removed
~~33005 (Bedford Ouse @ Thornborough Mill)~~	~~0.52~~	~~28~~	~~21.8~~	~~0.178~~	~~-0.112~~	~~2.264~~	Site Removed
40005 (Beult @ Stilebridge)	0.553	42	42.099	0.227	0.218	1.06	
37010 (Blackwater @ Appleford Bridge)	0.563	50	12.195	0.277	0.044	1.303	
33019 (Thet @ Melford Bridge)	0.623	52	7.826	0.265	0.126	0.456	
14001 (Eden @ Kemback)	0.659	39	40.417	0.176	0.032	1.368	
31005 (Welland @ Tixover)	0.685	50	37.42	0.292	0.248	0.33	
54041 (Tern @ Eaton Upon Tern)	0.715	40	11.77	0.203	0.132	0.629	
53008 (Avon @ Great Somerford)	0.742	49	36.405	0.254	0.207	0.039	
28024 (Wreake @ Syston Mill)	0.768	42	34.388	0.307	0.393	2.111	
25005 (Leven @ Leven Bridge)	0.776	48	43.54	0.241	0.269	0.626	Site Added
37005 (Colne @ Lexden)	0.802	52	12.556	0.258	0.06	1.247	Site Added
Weighted Means							
Enhanced Single Site				0.245	0.148		
Pooling Group Only				0.258	0.184		
Heterogeneity score							
Enhanced Single Site	2.68						
Pooling Group Only	2.502						

Figure 6.12 and Figure 6.13 provides the growth curves generated from the enhanced single site analysis using the original AMAX data and revised AMAX data respectively. Figure 6.14 provides the growth curves generated from the pooled analysis.

Figure 6.12: Enhanced Single Site Analysis at Claypole Gauging Station using Original AMAX Data

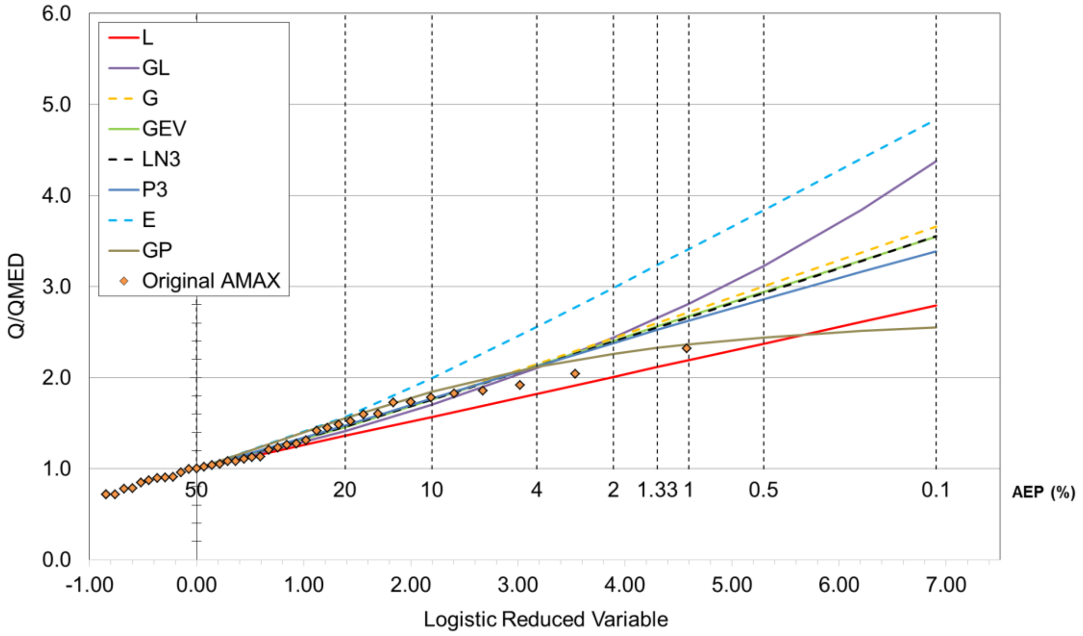


Figure 6.13: Enhanced Single Site Analysis at Claypole Gauging Station using Revised AMAX Data

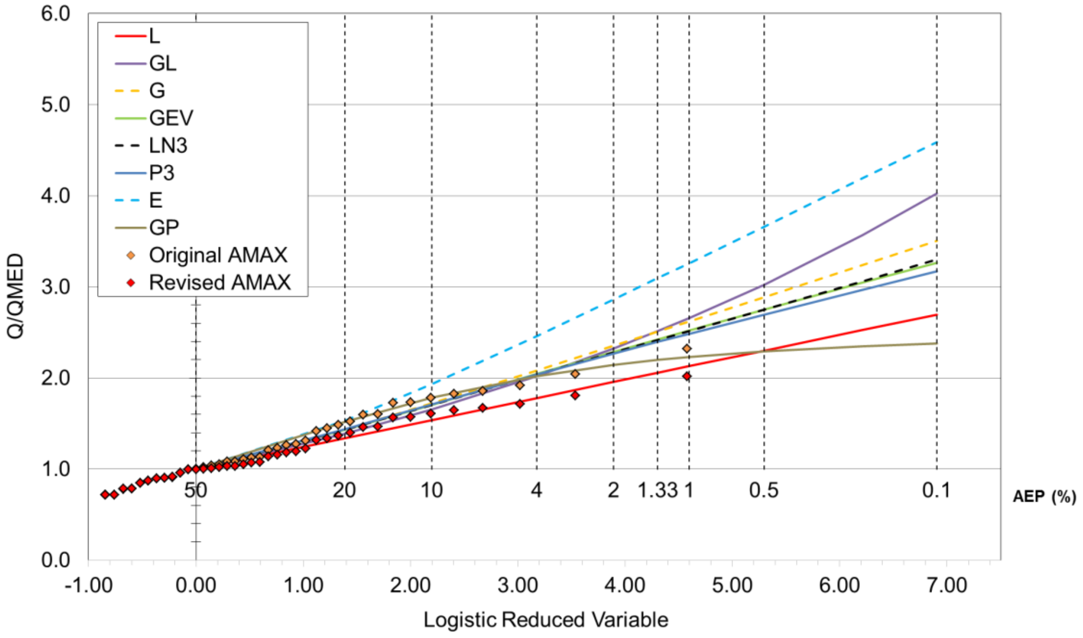
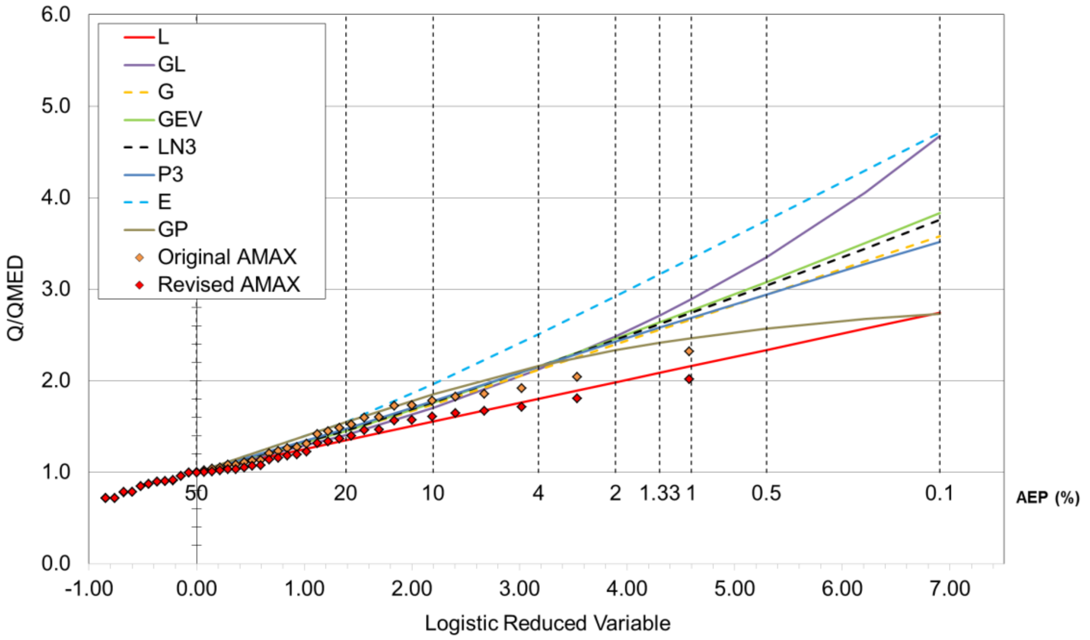


Figure 6.14: Pooled Analysis at Claypole Gauging Station



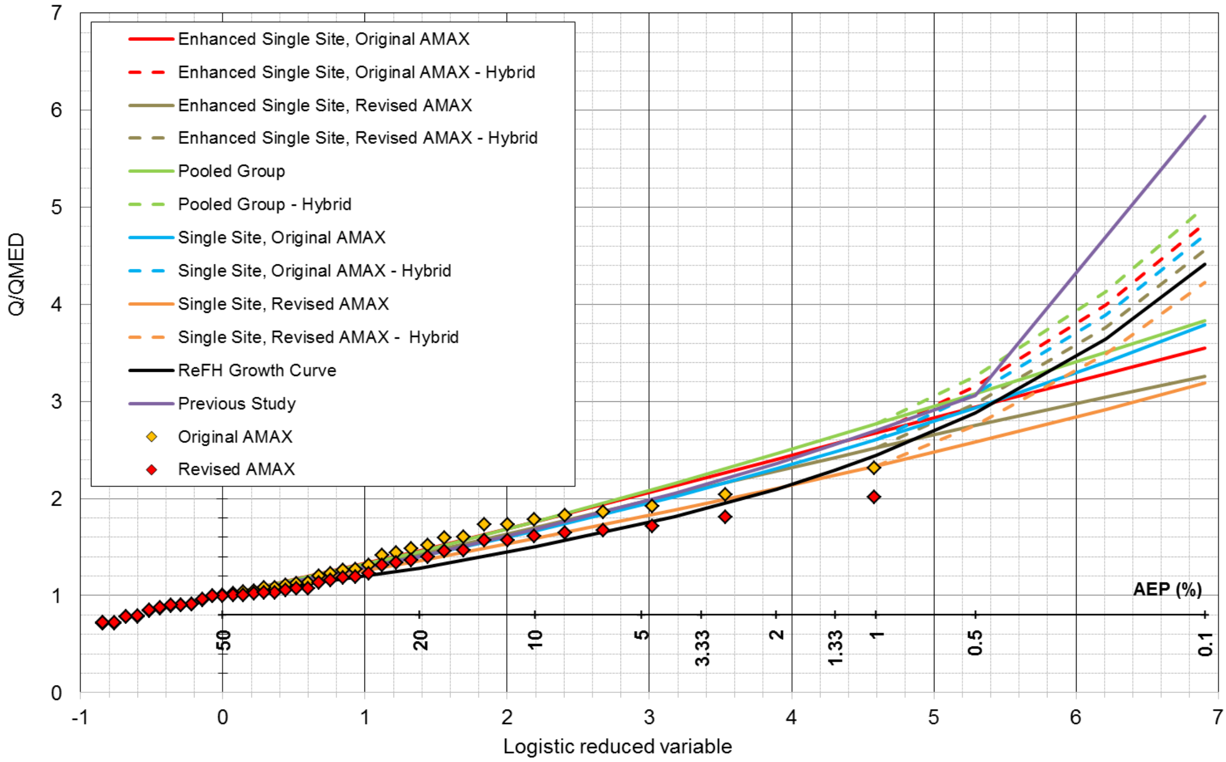
Source: WINFAP-FEH Software

The pooled growth curves all lie (with the exception of the Logistic growth curve) above the observed data. When the pooling group is enhanced with the flow series at Claypole, the growth curves are pulled down slightly, and fit the observed data better.

Comparison of Growth Curves

An overall comparison of the best fitting growth curves from each methodology, and against a ReFH growth curve and the growth curve used in the previous 2007 study is provided in Figure 6.15. The growth factors calculated using the Hybrid methodology for the larger AEP events have been included using dashed lines.

Figure 6.15: Comparison of Best Fitting Growth Curves at Claypole Gauging Station



Source: WINFAP-FEH Software

The comparison of all growth curves shows that the single-site growth curve using the revised AMAX data gives lower growth factors than the other methodologies, and although this appears to match the observed data the best, it should be remembered that one of the larger events on this catchment (April 1998) has been omitted from the analysis.

Table 6.4 provides a summary of the growth factors for the curves presented in Figure 6.7 and the associated z-scores (goodness of fit test) where applicable.

Table 6.4: Summary of Growth Factors at Claypole Gauging Station

Annual Exceedence Probability	Single Site (Original AMAX)	Single Site - GL (Revised AMAX)	Enhanced Single Site (Original AMAX)	Enhanced Single Site (Revised AMAX)	Pooled Group	ReFH Growth Curve	Previous Study
50%	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20%	1.40	1.36	1.46	1.43	1.45	1.28	1.40
10%	1.67	1.59	1.76	1.70	1.76	1.51	1.68
4%	2.02	1.88	2.13	2.04	2.16	1.81	2.06
2%	2.31	2.10	2.41	2.29	2.46	2.09	2.36

Annual Exceedence Probability	Single Site (Original AMAX)	Single Site - GL (Revised AMAX)	Enhanced Single Site (Original AMAX)	Enhanced Single Site (Revised AMAX)	Pooled Group	ReFH Growth Curve	Previous Study
1.33%	2.48	2.24	2.56	2.42	2.64	2.29	2.56
1%	2.61	2.34	2.68	2.52	2.77	2.44	2.70
0.5%	2.93	2.58	2.94	2.75	3.08	2.88	3.06
0.2%	3.40	2.92	3.29	3.05	3.50	3.64	
0.1%	3.79	3.19	3.55	3.26	3.83	4.41	5.94
0.5% (Hybrid)	3.07	2.76	3.15	2.97	3.26		
0.2% (Hybrid)	3.89	3.49	3.99	3.76	4.13		
0.1% (Hybrid)	4.71	4.22	4.83	4.56	5.00		
Z-score			-0.31	-0.498	-0.909		

In discussion with the Environment Agency, it has been agreed to use the average of the Enhanced Single Site (Original AMAX) and Enhanced Single Site (Revised AMAX) growth curves. The reasons for this are:

- Model rating is based on limited information – Therefore average of original and revised AMAX is reasonable.
- No reliable estimates of the April 1998 flow are available, and therefore since this event has been omitted from the single site analysis, using the single site analysis on it's own would not be recommended.

Final growth curve and target peak flows are detailed in Table 6.14 and Table 6.15 respectively.

6.3 Flood Frequency Analysis at Saltersford Gauging Station

The observed data at Saltersford has been considered to be unsuitable for use due to a blockage of the stilling well (Section 5.1), therefore only pooled analysis has been conducted at this location.

A hybrid estimate of the 0.5%, 0.2% and 0.1% AEP events has been undertaken. This uses the ReFH ratio of Q0.1%/Q1%, in order to estimate the 0.1%AEP event for the statistical method (the Q0.5%/Q1% ReFH ratio is used for the 0.5% AEP event, and the Q0.2%/Q1% ReFH ratio for the 0.2% AEP event).

Pooled Analysis

Pooled Analysis was carried out at Saltersford gauging station.

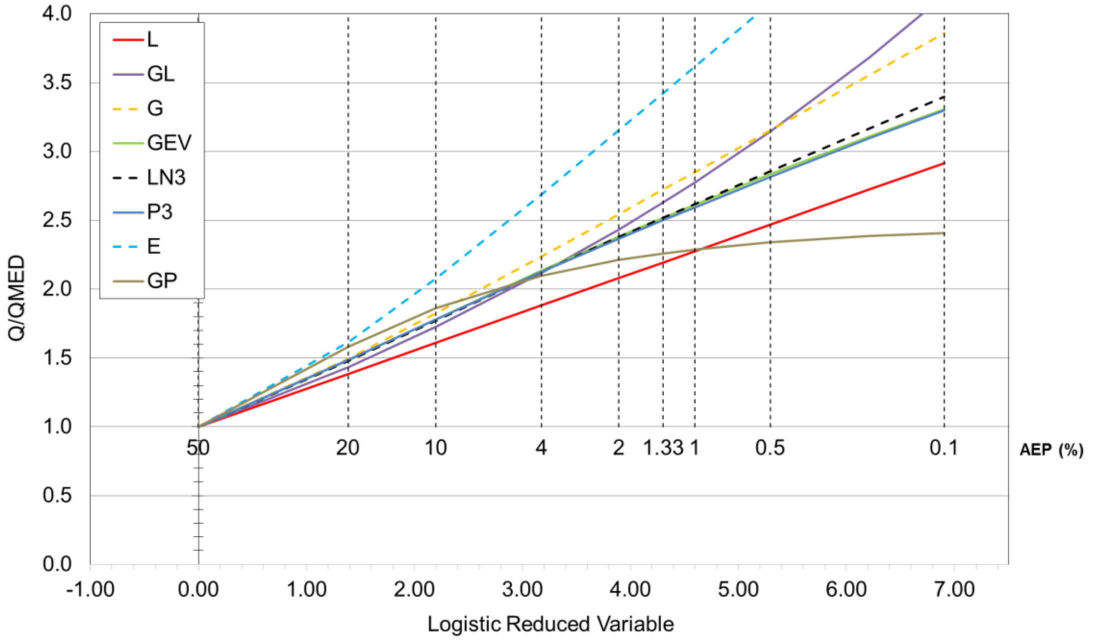
A pooling group was created using the WINFAP-FEH Software. The pooling group was reviewed for short records and for catchments with descriptors such as BFIHOST that may unduly influence the final pooled growth curves. The initial pooling group was strongly heterogeneous, however following a review of the pooling group it was decided that no changes were necessary or led to an improvement of the pooling group. The final pooling group is provided in Table 6.5.

Table 6.5: Final Pooling Group – Saltersford Gauging Station

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
35008 (Gipping @ Stowmarket)	0.272	46	12.762	0.296	0.108	0.563	
33018 (Tove @ Cappenham Bridge)	0.36	48	16.939	0.27	0.183	0.149	
37020 (Chelmer @ Felsted)	0.367	42	13.018	0.332	0.216	0.607	
36005 (Brett @ Hadleigh)	0.445	48	11.523	0.298	0.153	0.232	
37014 (Roding @ High Ongar)	0.464	49	10.756	0.246	-0.152	1.776	
39025 (Enborne @ Brimpton)	0.471	45	16.8	0.204	0.148	2.784	
38004 (Rib @ Wadesmill)	0.488	53	11.798	0.313	0.163	0.294	
54036 (Isbourne @ Hinton on the Green)	0.513	39	13.924	0.329	0.368	1.214	
54040 (Meese @ Tibberton)	0.524	39	4.736	0.238	0.3	2.668	
33051 (Cam @ Chesterford)	0.524	43	8.129	0.248	-0.108	0.777	
21027 (Blackadder Water @ Mouth Bridge)	0.556	32	40.298	0.321	0.268	0.666	
34012 (Burn @ Burnham Overy)	0.569	46	1.024	0.226	-0.137	1.015	
Weighted Means							
Pooling Group Only				0.277	0.124		
Heterogeneity score							
Pooling Group Only	5.04						

Figure 6.16 provides the growth curves generated from the pooled analysis.

Figure 6.16: Pooled Analysis at Saltersford Gauging Station



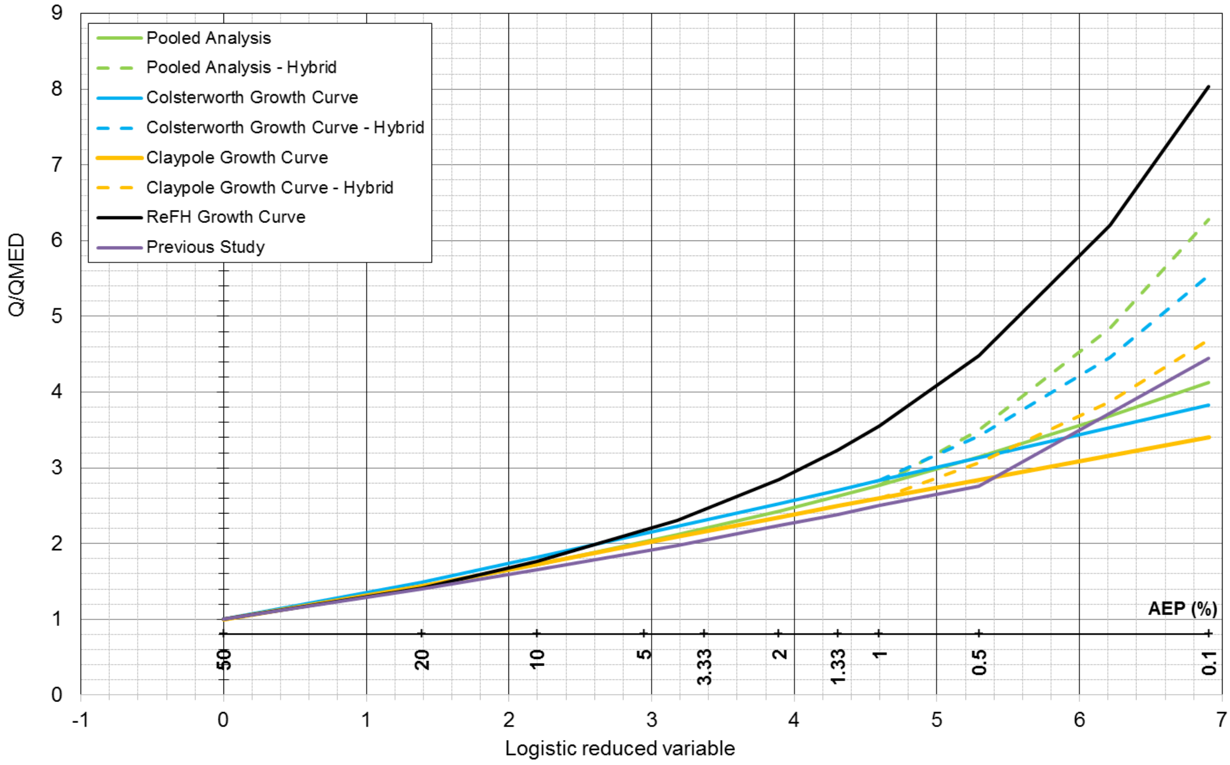
Source: WINFAP-FEH Software

The growth curve indicated to be the best fit was the General Logistic growth curve (z-score of 0.285).

Comparison of Growth Curves

As there is very little data to inform the choice of growth curve at Saltersford, the pooled General Logistic curve has been compared against the chosen growth curves upstream at Colsterworth and downstream at Claypole, ReFH growth curve, and the growth curve used in the previous study. This comparison is shown in Figure 6.17. The growth factors calculated using the Hybrid methodology for the larger AEP events have been included using dashed lines.

Figure 6.17: Comparison of Pooled Growth Curves at Saltersford against those Upstream and Downstream at Colsterworth and Claypole



Source: WINFAP-FEH Software

The comparison of all growth curves shows that the pooled growth curve lies very close to the growth curve chosen at Colsterworth, and for the largest events lies above that at Colsterworth. In order to ensure consistency along the watercourse, the average of the chosen growth curves at Claypole and Colsterworth has been used at Saltersford. This approach was discussed and agreed with the Environment Agency.

Table 6.6 provides a summary of the growth factors for the curves presented in Figure 6.17, and the final chosen growth curve.

Table 6.6: Summary of Growth Factors at Saltersford Gauging Station

Annual Exceedence Probability	Pooled Analysis - GL	Colsterworth Growth Curve	Claypole Growth Curve	ReFH Growth Curve	Previous Study	Chosen Growth Curve
50%	1.00	1.00	1.00	1.00	1.00	1.00
20%	1.43	1.49	1.44	1.41	1.40	1.47
10%	1.72	1.82	1.73	1.77	1.65	1.77
4%	2.12	2.23	2.09	2.31	1.98	2.16
2%	2.43	2.53	2.35	2.85	2.24	2.44
1.33%	2.63	2.71	2.49	3.24	2.39	2.60
1%	2.77	2.83	2.60	3.55	2.50	2.72
0.5%	3.14	3.14	2.85	4.48	2.76	2.99
0.2%	3.68	3.53	3.17	6.20		3.35
0.1%	4.13	3.83	3.40	8.04	4.45	3.62
0.5% (Hybrid)	3.50	3.42	3.06			3.24
0.2% (Hybrid)	4.85	4.46	3.88			4.17
0.1% (Hybrid)	6.28	5.55	4.70			5.12

6.4 Flood Frequency Analysis at North Hykeham Gauging Station

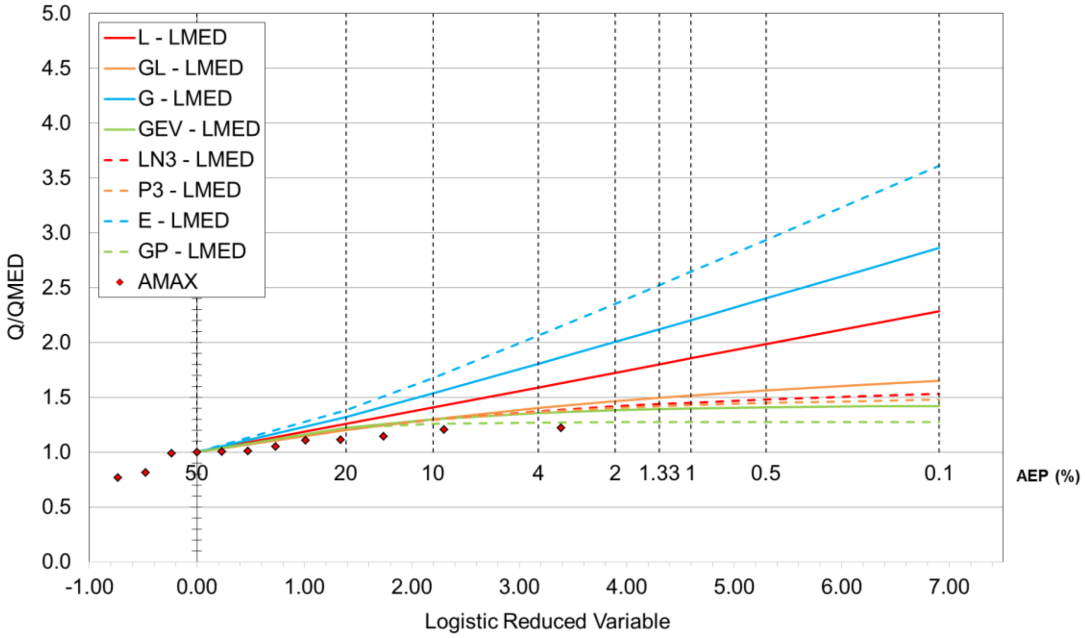
Single site and pooled analysis (enhanced and non-enhanced) have been carried out at North Hykeham gauging station. For comparison, a lumped ReFH assessment has also been undertaken. No refinement to the ReFH parameters was considered at this stage.

A hybrid estimate of the 0.5%, 0.2% and 0.1% AEP events has been undertaken. This uses the ReFH ratio of Q0.1%/Q1%, in order to estimate the 0.1%AEP event for the statistical method (the Q0.5%/Q1% ReFH ratio is used for the 0.5% AEP event, and the Q0.2%/Q1% ReFH ratio for the 0.2% AEP event).

Single Site Analysis

Single site analysis has been carried out using the observed AMAX series (from the ultrasonic flow gauge, adjusted using relationship derived from spot-gauging data (5.2.3)). Figure 6.18 shows the flood frequency curves generated.

Figure 6.18: Single Site Analysis at North Hykeham Gauging Station.



Source: WINFAP-FEH Software

The single site analysis shows some very low growth curves. This is due to the influence of the Washlands attenuating the peak flows.

Enhanced Single Site and Pooled Analysis

Both Enhanced Single Site and Pooled Analysis were carried out at North Hykeham.

A pooling group was created using the WINFAP-FEH Software. The pooling group was reviewed for short records and for catchments with descriptors such as BFIHOST that may unduly influence the final pooled growth curves. Although the pooling group was heterogeneous, the review did not identify any sites which should be removed. The final pooling group is provided in Table 6.7

Table 6.7: Final Pooling Group – North Hykeham Gauging Station

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
27087 (Derwent @ Low Marishes)	1.221	23	14.699	0.149	0.26	1.601	
54016 (Roden @ Rodington)	1.327	51	14.077	0.173	0.042	0.232	
33019 (Thet @ Melford Bridge)	1.406	52	7.826	0.265	0.126	0.96	
33034 (Little Ouse @ Abbey Heath)	1.441	43	16.995	0.235	-0.003	0.309	
33021 (Rhee @ Burnt Mill)	1.497	50	8.274	0.264	-0.13	1.53	
54012 (Tern @ Walcot)	1.54	53	35.576	0.154	-0.003	0.228	
40005 (Beult @ Stilebridge)	1.544	42	42.099	0.227	0.218	0.928	
54020 (Perry @ Yeaton)	1.929	49	10.569	0.157	-0.016	0.31	
43009 (Stour @ Hammoon)	1.969	44	111.285	0.188	0.063	0.563	
204001 (Bush @ Seneirl Bridge)	2.03	40	62.337	0.094	0.172	1.205	
33005 (Bedford Ouse @ Thornborough Mill)	2.052	28	21.8	0.178	-0.112	1.132	
31005 (Welland @ Tixover)	2.165	50	37.42	0.292	0.248	1.612	
Weighted Means							
Enhanced Single Site				0.19	0.042		
Pooling Group Only				0.193	0.068		
Heterogeneity score							
Enhanced Single Site	4.14						
Pooling Group Only	3.89						

Figure 6.19 and Figure 6.20 provides the growth curves generated from the enhanced single site analysis and pooled analysis respectively.

Figure 6.19: Enhanced Single Site Analysis at North Hykeham Gauging Station

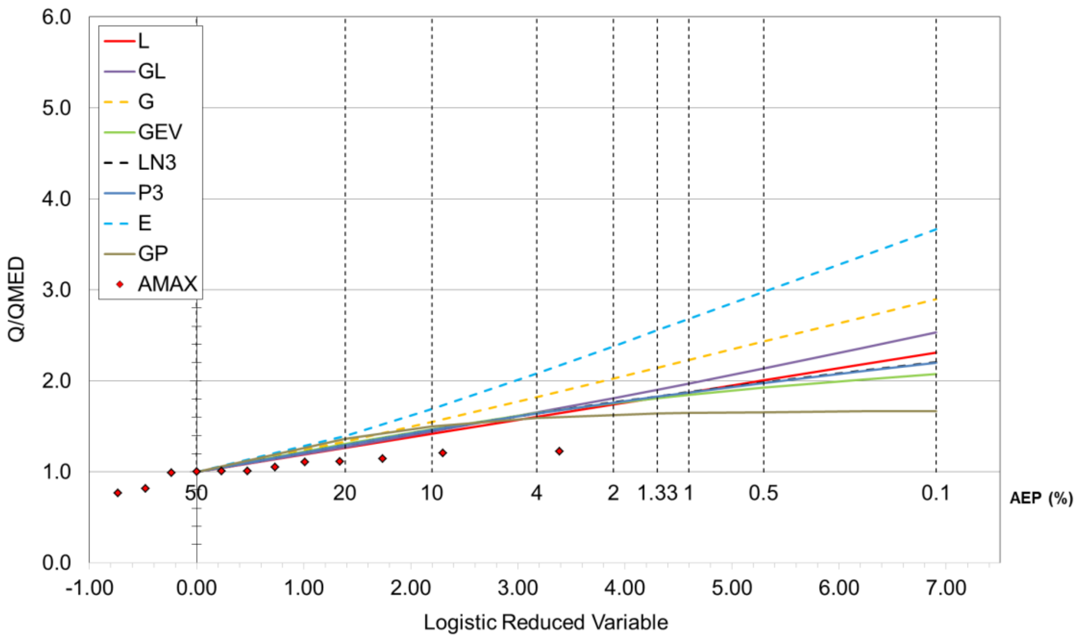
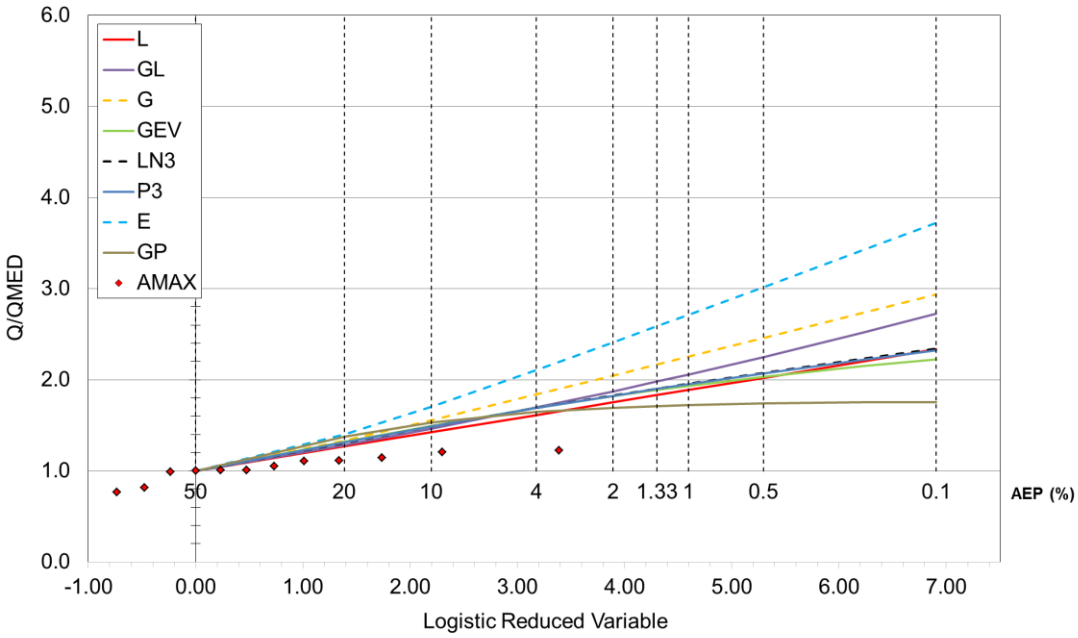


Figure 6.20: Pooled Analysis at North Hykeham Gauging Station



Source: WINFAP-FEH Software

The enhanced single site and pooled growth curves all lie significantly above the observed data. This is due to the attenuation and storage from the washlands not being represented within the catchment characteristics, and therefore the pooling group not reflecting this.

Due to the significance of the washlands on attenuating the flow, it has been decided that calculating peak flow estimates for North Hykeham for the purpose of target peak flow estimation is not suitable, since it does not capture the large increases in volume for very little or no increase in water levels, dependant on the operation of the washlands during each event.

Table 6.8 provides growth factors and the associated z-scores (goodness of fit test) where applicable. There has been no attempt, as part of the hydraulic modelling, to scale model inflows to ensure that these flow estimates are met. The final modelled flows through North Hykeham have also been added to the graph for comparison purposes.

Table 6.8: Summary of Growth Factors and Peak Flow Estimates at North Hykeham Gauging Station – Not for use as Target Peak Flows

Annual Exceedence Probability	Single Site Growth Factor (GP)	Peak Flows Estimate (from Single Site – GP) (m^3/s)	Pooled Group Growth Factor (GL)	Peak Flows Estimate (from Pooled – GL) (m^3/s)	ReFH Growth Curve	ReFH Flow Estimate (m^3/s)
50%	1.00	36.90	1.00	36.90	1.00	47.87
20%	1.23	45.24	1.29	47.42	1.26	60.54
10%	1.26	46.53	1.46	54.02	1.48	70.64
4%	1.27	46.94	1.70	62.55	1.75	83.90
2%	1.27	46.97	1.87	69.08	2.01	96.21
1.33%	1.27	47.01	1.98	73.03	2.19	104.64
1%	1.27	47.01	2.06	75.87	2.32	111.26
0.5%	1.27	47.01	2.25	82.95	2.71	129.86
0.2%	1.27	47.01	2.51	92.77	3.38	161.88
0.1%	1.27	47.01	2.73	100.59	4.05	193.91
0.5% (Hybrid)	1.49	54.87	2.40	88.55		
0.2% (Hybrid)	1.85	68.40	2.99	110.38		
0.1% (Hybrid)	2.22	81.93	3.58	132.22		
Z-score			0.8			

6.5 Flood Frequency Analysis at Brant Broughton Gauging Station

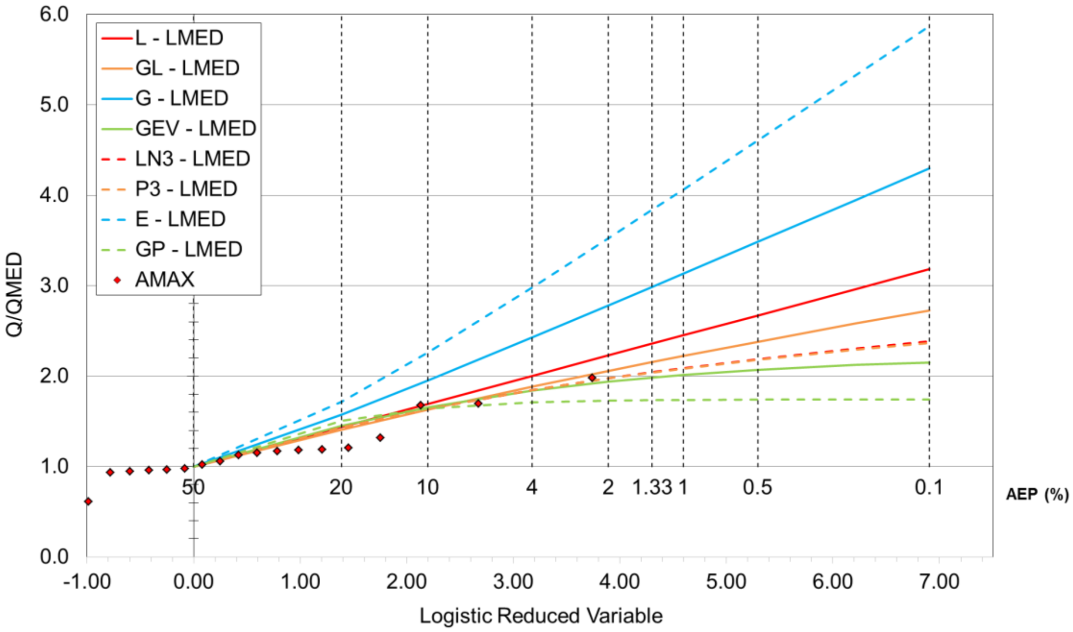
Single site and pooled analysis (enhanced and non-enhanced) have been carried out at Brant Broughton gauging station. For comparison, a lumped ReFH assessment has also been undertaken. No refinement to the ReFH parameters was considered at this stage. The AMAX data that has been used has been derived from the updated JBA rating (February 2013) for Brant Broughton.

A hybrid estimate of the 0.5%, 0.2% and 0.1% AEP events has been undertaken. This uses the ReFH ratio of Q0.1%/Q1%, in order to estimate the 0.1%AEP event for the statistical method (the Q0.5%/Q1% ReFH ratio is used for the 0.5% AEP event, and the Q0.2%/Q1% ReFH ratio for the 0.2% AEP event).

Single Site Analysis

Single site analysis has been carried out. Figure 6.21 shows the flood frequency curves generated.

Figure 6.21: Single Site Analysis at Brant Broughton Gauging Station



Source: WINFAP-FEH Software

The GL curve gives the best match to the data, particularly for the higher events. All the growth curves pass above the observed data around the 20% AEP event.

Enhanced Single Site and Pooled Analysis

Both Enhanced Single Site and Pooled Analysis were carried out at Brant Broughton.

A pooling group was created using the WINFAP-FEH Software. The initial and final pooling groups are provided in Table 6.1. The pooling group was reviewed for short records and for catchments with descriptors such as BFIHOST that may unduly influence the final pooled growth curves. One site was removed, Roding @ High Ongar, and replaced with Roding @ Rodington. Roding @ High Ongar was removed as there are 4 recorded AMAX events with peak flows of 1m^3/s or less, compared to a QMED of 10.7m^3/s. These low events are not consistent with the AMAX series found on the same watercourse at

Rodington, where the smallest AMAX event has a flow of 4.74m^3/s compared to a QMED of 14m^3/s. Therefore the site at Rodington was replaced with that at High Ongar.

Table 6.9: Initial/Final Pooling Group – Brant Broughton Gauging Station

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
33029 (Stringside @ Whitebridge)	0.822	47	2.673	0.245	-0.108	0.752	
34005 (Tud @ Costessey Park)	1.404	51	3.146	0.281	0.181	0.809	
33057 (Ouzel @ Leighton Buzzard)	1.644	31	7.741	0.269	0.214	1.997	
33011 (Little Ouse @ County Bridge Euston)	1.785	51	3.88	0.309	0.016	0.893	
37003 (Ter @ Crabbs Bridge)	1.862	48	4.991	0.248	-0.037	0.282	
54020 (Perry @ Yeaton)	1.87	49	10.569	0.157	-0.016	1.566	
33032 (Heacham @ Heacham)	1.883	44	0.461	0.315	0.099	1.062	
43014 (East Avon @ Upavon)	1.908	41	3.616	0.206	0.051	0.784	
33054 (Babingley @ Castle Rising)	1.92	36	1.129	0.214	0.069	0.417	
26003 (Foston Beck @ Foston Mill)	1.994	52	1.739	0.243	-0.015	0.111	
~~37014 (Roding @ High Ongar)~~	~~2.001~~	~~49~~	~~10.756~~	~~0.246~~	~~-0.152~~	~~2.169~~	Removed
33007 (Nar @ Marham)	2.069	29	3.527	0.226	0.021	1.156	
54016 (Roden @ Rodington)	2.081	51	14.077	0.173	0.042	1.114	Added
Weighted Means							
Enhanced Single Site				0.287	0.025		
Pooling Group Only				0.241	0.041		
Heterogeneity score							
Enhanced Single Site	2.8						
Pooling Group Only	2.86						

Figure 6.22 and Figure 6.23 provides the growth curves generated from the enhanced single site analysis and pooled analysis.

Figure 6.22: Enhanced Single Site Analysis at Brant Broughton Gauging Station

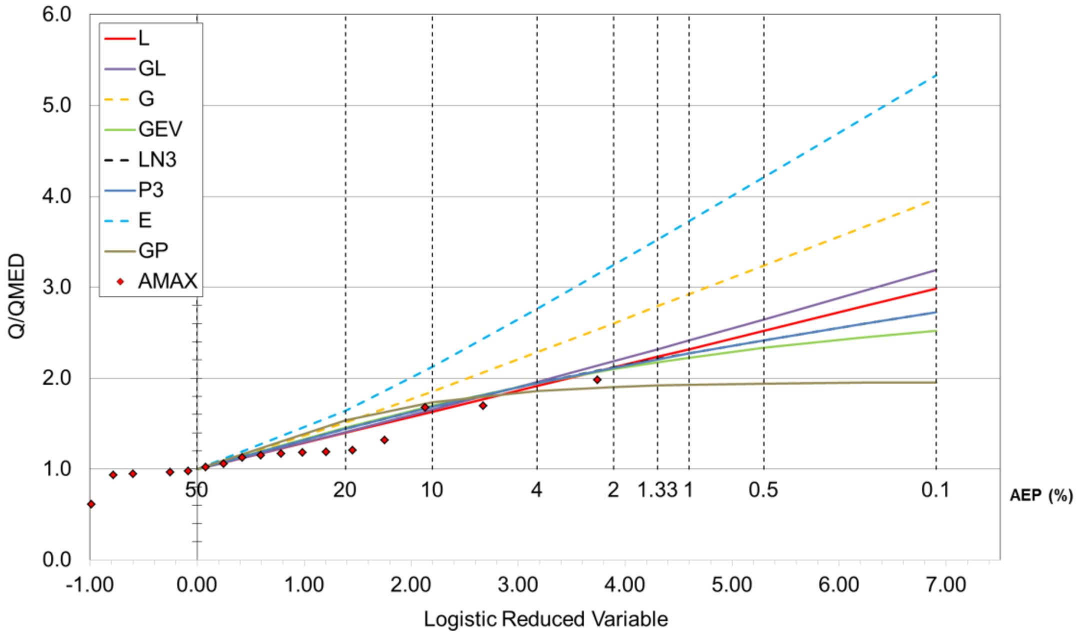
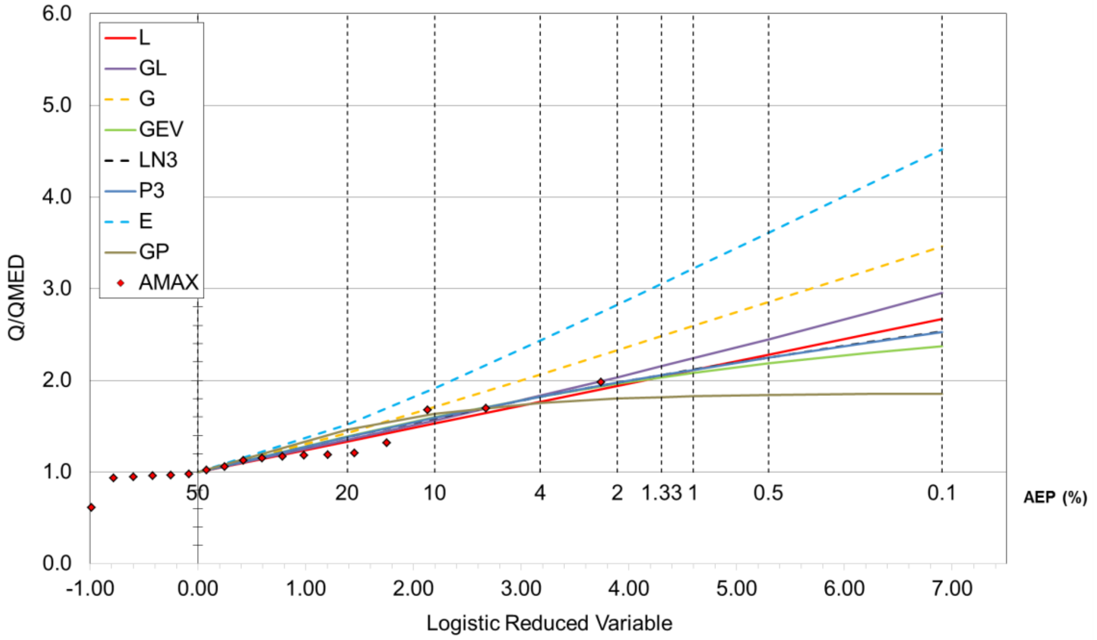


Figure 6.23: Pooled Analysis at Brant Broughton Gauging Station



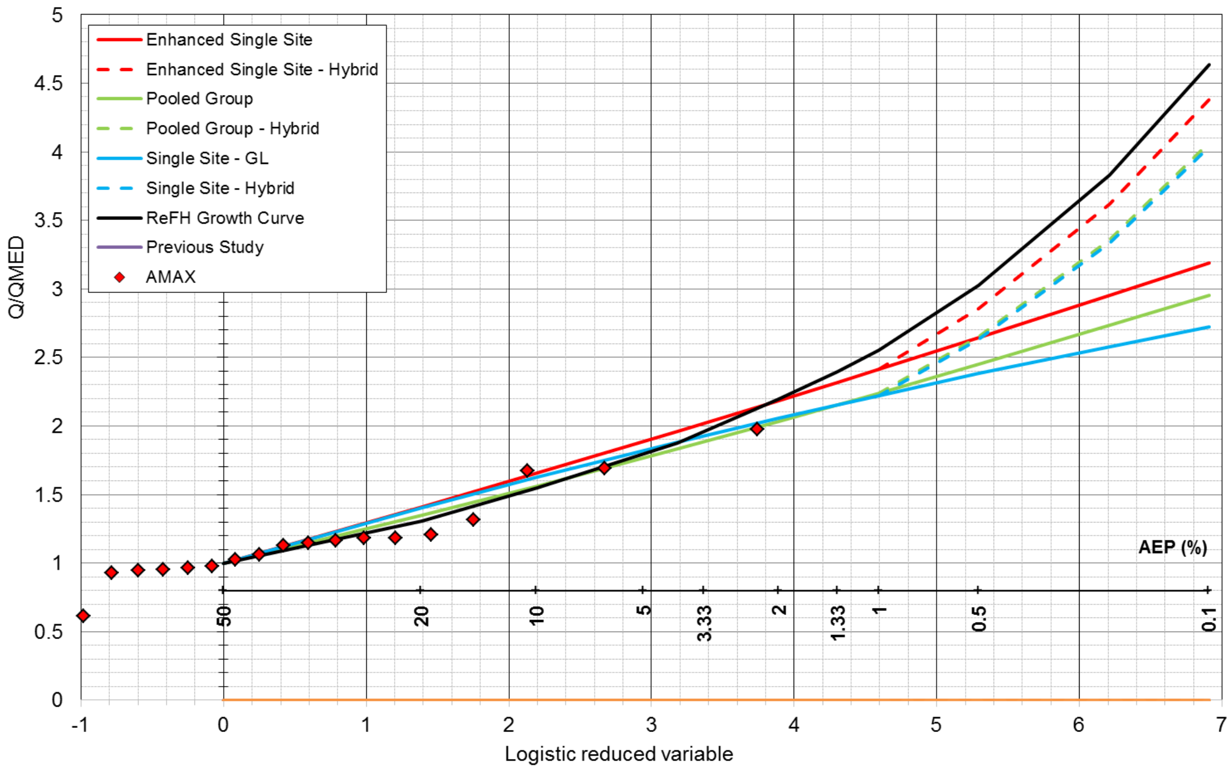
Source: WINFAP-FEH Software

Both the enhanced single site and pooled analysis match the largest 3 events well, but like the single site analysis pass above the smaller events (around 20% AEP).

Comparison of Growth Curves

An overall comparison of the best fitting growth curves from each methodology, and against a ReFH growth has been carried out, this is provided in Figure 6.24. The growth factors calculated using the Hybrid methodology for the larger AEP events have been included using dashed lines.

Figure 6.24: Comparison of Best Fitting Growth Curves at Brant Broughton Gauging Station



Source: WINFAP-FEH Software

All three growth curves, and the ReFH growth curve are very similar up to 2%AEP event. Unusually the enhanced single site is greater than both the pooled and single site curves (although very similar to the single site for the 50% to 10% AEPs. This is due to the enhanced single site method applying comparatively more weighting to the coefficient of variation (L-CV) moment from the subject sight, than to the L-skewness moment from the subject site. The subject site has a high L-CV (compared to the remaining pooling group members) and a low L-SKEW.

The enhanced pooling group therefore has an overall L-CV that is closer to the subject site, but an L-SKEW closer to the pooling group value. The result is that for higher frequency events the enhanced single site growth curve follows the single site growth curve, however for lower frequency events, the enhanced single site growth curves has a similar gradient to the pooled growth curve – giving an overall higher growth curve.

Table 6.10 provides a summary of the growth factors for the curves presented in Figure 6.24 and the associated z-scores (goodness of fit test) where applicable.

Table 6.10: Summary of Growth Factors at Brant Broughton Gauging Station

Annual Exceedence Probability	Single Site - GL	Enhanced Single Site - GL	Pooled Group - GL	ReFH Growth Curve
50%	1.00	1.00	1.00	1.00
20%	1.41	1.41	1.35	1.31
10%	1.63	1.66	1.56	1.55
4%	1.88	1.96	1.83	1.88
2%	2.06	2.19	2.03	2.19
1.33%	2.16	2.32	2.15	2.40
1%	2.22	2.41	2.24	2.55
0.5%	2.38	2.64	2.45	3.02
0.2%	2.58	2.95	2.73	3.83
0.1%	2.72	3.19	2.96	4.64
0.5% (Hybrid)	2.63	2.86	2.65	
0.2% (Hybrid)	3.33	3.62	3.36	
0.1% (Hybrid)	4.04	4.38	4.06	
Z-score		0.10	0.19	

The data record at Brant is only 24 years, and therefore it is recommended that the Enhanced single site growth curve is used at Brant Broughton.

6.6 Flood Frequency Analysis at River Till Washlands

The observed data at River Till Washlands has been considered to be unsuitable for use due to the limited data available, and due to the station being beset with problems, therefore only pooled analysis has been conducted at this location.

A hybrid estimate of the 0.5%, 0.2% and 0.1% AEP events has been undertaken. This uses the ReFH ratio of Q0.1%/Q1%, in order to estimate the 0.1%AEP event for the statistical method (the Q0.5%/Q1% ReFH ratio is used for the 0.5% AEP event, and the Q0.2%/Q1% ReFH ratio for the 0.2% AEP event).

Pooled Analysis

Pooled Analysis was carried out at River Till Washlands Site.

A pooling group was created using the WINFAP-FEH Software. The pooling group was reviewed for short records and for catchments with descriptors such as BFIHOST that may unduly influence the final pooled growth curves. Stringside, Roden, Nar and East Avon were all removed due to very high BFIHOST values compared to that for the River Till. Despite these changes, the pooling group is still strongly heterogeneous, indicating that there is a reasonable spread in the individual growth curves. Several alternative pooling groups were considered. The initial pooling group is provided in Table 6.11 and the final pooling group is provided in Table 6.12.

Table 6.11: Initial Pooling Group – River Till at Washlands

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
33029 (Stringside @ Whitebridge)	0.969	47	2.673	0.245	-0.108	0.734	Station removed
54016 (Roden @ Rodington)	1.641	51	14.077	0.173	0.042	1.182	Station removed
54020 (Perry @ Yeaton)	1.646	49	10.569	0.157	-0.016	1.072	
33057 (Ouzel @ Leighton Buzzard)	1.739	31	7.741	0.269	0.214	1.835	
34005 (Tud @ Costessey Park)	1.814	51	3.146	0.281	0.181	0.703	
33011 (Little Ouse @ County Bridge Euston)	1.869	51	3.88	0.309	0.016	0.804	
40005 (Beult @ Stilebridge)	1.978	42	42.099	0.227	0.218	0.831	
33019 (Thet @ Melford Bridge)	2.059	52	7.826	0.265	0.126	0.335	
33007 (Nar @ Marham)	2.1	29	3.527	0.226	0.021	1.146	Station removed
33021 (Rhee @ Burnt Mill)	2.101	50	8.274	0.264	-0.13	1.093	
203019 (Claudy @ Glenone Bridge)	2.179	41	34.081	0.128	0.269	1.804	
43014 (East Avon @ Upavon)	2.22	41	3.616	0.206	0.051	0.462	Station removed

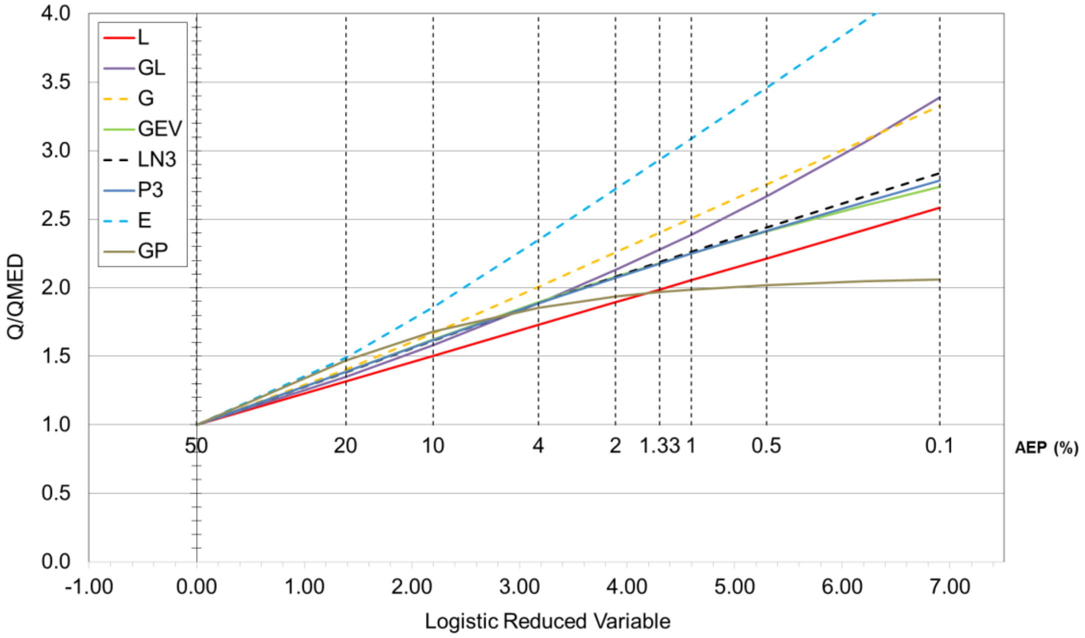
Table 6.12: Revised Pooling Group – River Till at Washlands

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
54020 (Perry @ Yeaton)	1.646	49	10.569	0.157	-0.016	0.747	
33057 (Ouzel @ Leighton Buzzard)	1.739	31	7.741	0.269	0.214	0.558	
34005 (Tud @ Costessey Park)	1.814	51	3.146	0.281	0.181	0.719	
33011 (Little Ouse @ County Bridge Euston)	1.869	51	3.88	0.309	0.016	0.911	
40005 (Beult @ Stilebridge)	1.978	42	42.099	0.227	0.218	0.831	

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	Comment
33019 (Thet @ Melford Bridge)	2.059	52	7.826	0.265	0.126	0.699	
33021 (Rhee @ Burnt Mill)	2.101	50	8.274	0.264	-0.13	0.692	
203019 (Claudy @ Glenone Bridge)	2.179	41	34.081	0.128	0.269	1.484	
37003 (Ter @ Crabbs Bridge)	2.236	48	4.991	0.248	-0.037	0.216	Station added
15008 (Dean Water @ Cookston)	2.285	53	26.832	0.132	0.059	1.092	Station added
54040 (Meese @ Tibberton)	2.349	39	4.736	0.238	0.3	2.373	Station added
Weighted Means							
Pooling Group Only				0.229	0.106		
Heterogeneity score							
Pooling Group Only	5.86						

Figure 6.25 provides the growth curves generated from the pooling group.

Figure 6.25: Revised Pooling Group Analysis at River Till Washlands



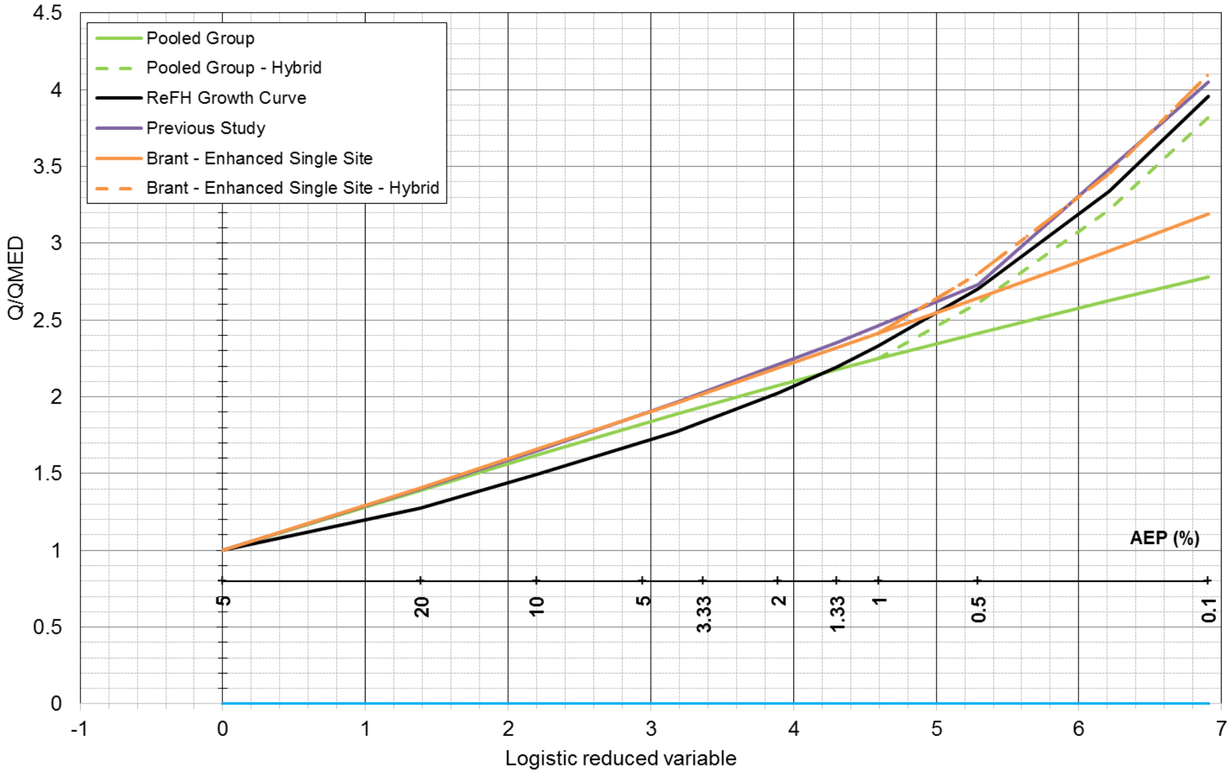
Source: WINFAP-FEH Software

The growth curve indicated to be the best fit was the Pearson Type III growth curve (Z-score of -0.87).

Comparison of Growth Curves

There is very little data to inform the choice of growth curve at the River Till Washlands, however Brant Broughton was found to be a suitable donor site for QMED, and therefore Figure 6.26 compares the growth curve derived from the pooling analysis, the chosen growth curve for the River Brant, the ReFH growth curve and that used in the previous study. The growth factors calculated using the Hybrid methodology for the larger AEP events have been included using dashed lines.

Figure 6.26: Comparison of Pooled Growth Curve at Till Washland against ReFH, Previous Study, and Growth Curve Derived at Brant Broughton



Source: WINFAP-FEH Software

Table 6.13 provides a summary of the growth factors for the curves presented in Figure 6.26.

Table 6.13:   Summary of Growth Factors at River Till Washlands

Annual Exceedence Probability	Pooled Analysis – P3	Brant, Enhanced Single Site	ReFH Growth Curve	Previous Study
50%	1.00	1.00	1.00	1.0
20%	1.39	1.41	1.27	1.4
10%	1.62	1.66	1.49	1.6
4%	1.89	1.96	1.77	2.0

Annual Exceedence Probability	Pooled Analysis – P3	Brant, Enhanced Single Site	ReFH Growth Curve	Previous Study
2%	2.07	2.19	2.03	2.2
1.33%	2.18	2.32	2.20	2.4
1%	2.25	2.41	2.33	2.5
0.5%	2.42	2.64	2.70	2.7
0.2%	2.63	2.95	3.34	
0.1%	2.78	3.19	3.96	4.1
0.5% (Hybrid)	2.61	2.86		
0.2% (Hybrid)	3.22	3.62		
0.1% (Hybrid)	3.82	4.38		

The growth curves are all fairly similar. Initially it was recommended that the growth curve derived at Brant Broughton is used at Till Washlands due to the similarity of the catchments, and being within the same overall catchment, however following initial model runs, it was identified that there was more attenuation on the River Till, than on the River Brant, particularly for the larger events, due to a number of embanked roads. The flood response on these two tributaries therefore, although similar for smaller events, is very different for larger, out of bank events. In consultation with the Environment Agency, it was agreed that the River Till would be treated as per the other tributaries in the Upper Witham – Lincoln model, with ReFH hydrographs applied directly with no scaling. The derived peak flows, from FEH Statistical Analysis at River Till upstream of Washlands, have therefore not been used as target peak flows in the hydraulic modelling.

6.7 Summary of Selected Growth Curves

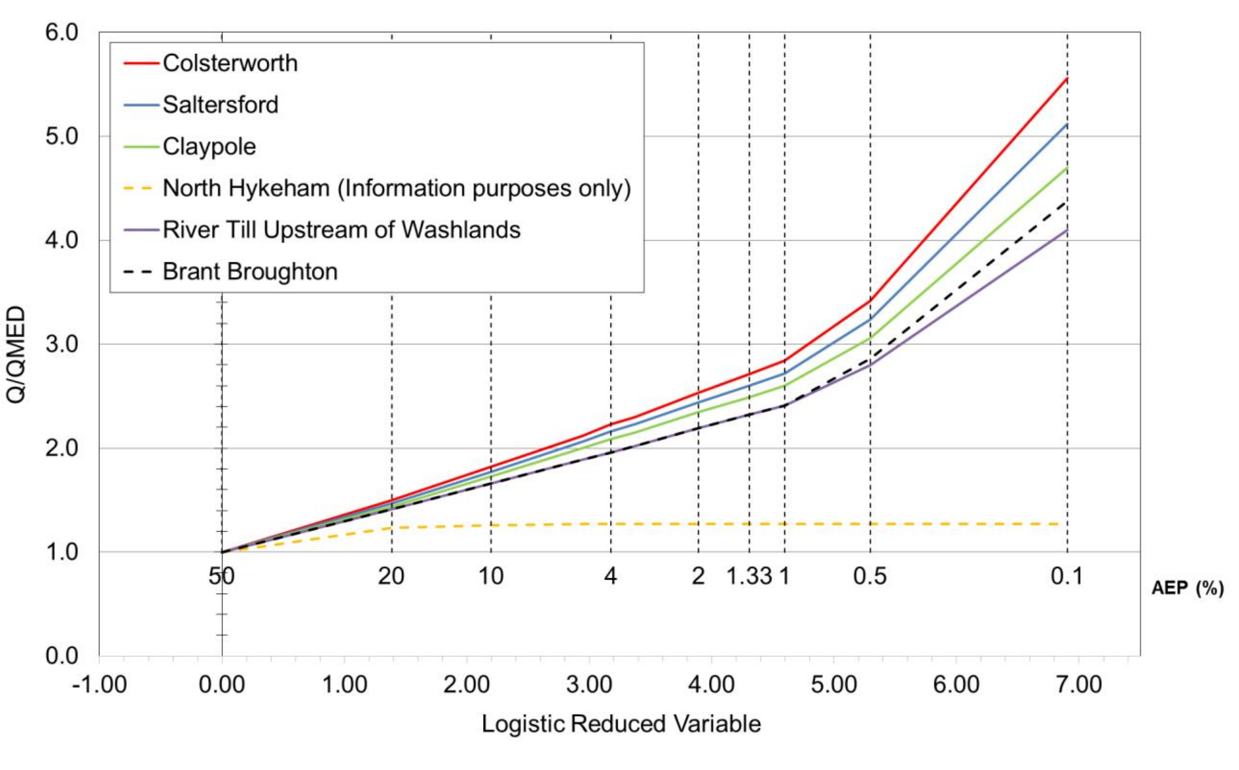
The growth curves selected from the above analysis at the flow estimation points are tabulated in Table 6.14 and shown in Figure 6.27.

Table 6.14: Summary of Growth Factors at Flow Estimation Points

						Growth Factor
AEP (%)	Colsterworth	Saltersford	Claypole	North Hykeham (FOR INFORMATION PURPOSES ONLY)	River Till upstream of Washlands (FOR INFORMATION PURPOSES ONLY)	Brant Broughton
50%	1	1.00	1	1.00	1.00	1.00
20%	1.5	1.47	1.44	1.23	1.41	1.41
10%	1.82	1.77	1.73	1.26	1.66	1.66
5%	2.12	2.06	2.00	1.27	1.89	1.89
4%	2.23	2.16	2.09	1.27	1.96	1.96
3.33%	2.3	2.23	2.15	1.27	2.02	2.02

2%	2.53	2.44	2.35	1.27	2.19	2.19
1.33%	2.71	2.60	2.49	1.27	2.32	2.32
1%	2.84	2.72	2.6	1.27	2.41	2.41
0.5%	3.42	3.24	3.06	1.27	2.86	2.86
0.1%	5.56	5.12	4.7	1.27	4.38	4.38

Figure 6.27: Growth Curves at Flow Estimation Points



Source: Mott MacDonald

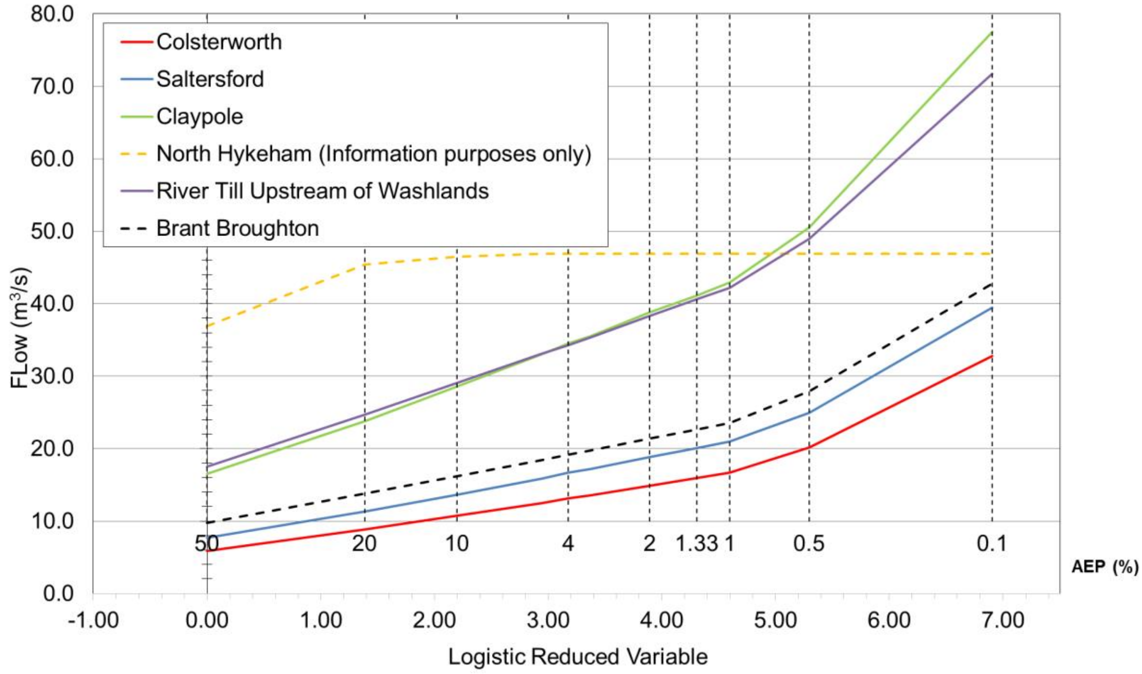
6.8 Summary of Target Peak Flows

Target peak flows have been calculated at the flow estimation points and are tabulated in Table 6.15 and shown in Figure 6.28.

Table 6.15: Summary of Target Peak Flows at Flow Estimation Points

						Flows (m^3/s)
AEP (%)	Colsterworth	Saltersford	Claypole	North Hykeham (FOR INFORMATION PURPOSES ONLY)	River Till upstream of Washlands (FOR INFORMATION PURPOSES ONLY)	River Brant at Brant Broughton
50%	5.89	7.71	16.5	36.9	17.5	9.76
20%	8.84	11.33	23.76	45.39	24.68	13.76
10%	10.72	13.65	28.55	46.49	29.05	16.20
5%	12.49	15.88	33.00	46.86	33.08	18.45
4%	13.13	16.65	34.49	46.86	34.30	19.13
3.33%	13.55	17.19	35.48	46.86	35.35	19.72
2%	14.90	18.81	38.78	46.86	38.33	21.37
1.33%	15.96	20.05	41.09	46.86	40.60	22.64
1%	16.73	20.97	42.90	46.86	42.18	23.52
0.5%	20.14	24.98	50.49	46.86	49.00	27.91
0.1%	32.75	39.48	77.55	46.86	71.76	42.75

Figure 6.28: Target Peak Flows at Flow Estimation Points



Source: Mott MacDonald

A comparison has been made between the revised peak flows, and those derived as part of the 2007 Upper Witham Flood Map Improvements study. The percentage difference in the flows is provided in Table 6.16.

Table 6.16: Comparison Between Revised Peak Flows and 2007 Upper Witham Peak Flows

AEP (%)	Change in Flows between 2007 Upper Witham Study and Current Analysis				
	Colsterworth	Saltersford	Claypole	Brant Broughton	River Till Upstream of Washlands
50%	2%	-4%	1%	-59%	23%
20%	4%	1%	4%	-58%	25%
10%	3%	3%	4%	-58%	25%
4%	0%	5%	3%	-58%	23%
2%	-3%	5%	1%	-58%	22%
1.33%	-5%	5%	-1%	-58%	22%
1%	-6%	5%	-2%	-58%	21%
0.5%	-3%	13%	1%	-55%	29%
0.1%	15%	11%	-20%	-51%	33%

Flows at Colsterworth and Saltersford and Claypole are similar to the previous study, with the exception of the 0.1% AEP, where the Hybrid ReFH method has been used consistently across the sites as part of this study. In the 2007 study, the FEH statistical method was used to derive the 0.1% AEP flows for Colsterworth and Saltersford, and the ReFH method used at Claypole.

Flows at Brant Broughton are around 58% lower than the previous study. This is due to the revised rating curve, derived by JBA, being used to update the AMAX series, and subsequent QMED value. The 2007 study derived QMED using donor transfer as there was low confidence in the rating at the time of the study.

Flows at River Till upstream of the washlands have been increased by around 25%. This is due to an increase in the chosen QMED value from $13.8m^3/s$ to $17.03m^3/s$. QMED was derived in the 2007 study using data transfer from Kym @ Hail Weston. POT analysis has been used as part of this study to drive QMED value, and this value is supported by data transfer from Brant Broughton.

Following the hydraulic modelling a comparison has also been carried out between the target peak flows and the modelled peak flows. This is given in Table 6.17.

Table 6.17: Comparison of Target Peak Flows at Flow Estimation Points against Modelled Peak Flows (Defended)

AEP (%)	Colsterworth (m^3/s)		Saltersford (m^3/s)		Claypole (m^3/s)		North Hykeham (FOR INFORMATION PURPOSES ONLY) (m^3/s)		River Till upstream of Washlands (FOR INFORMATION PURPOSES ONLY) (m^3/s)		River Brant at Brant Broughton (m^3/s)	
	Target	Model	Target	Model	Target	Model	Target	Model	Target	Model	Target	Model
50%	5.89	5.87	7.71	7.83	16.50	16.61	36.9	40.45	17.50	18.12	9.76	9.74
20%	8.84	8.81	11.33	11.24	23.76	24.71	45.39	49.70	24.68	21.33	13.76	13.90
10%	10.72	10.70	13.65	13.55	28.55	28.45	46.49	50.99	29.05	23.16	16.20	16.24
5%	12.49	12.50	15.88	15.74	33.00	31.34	46.86	51.49	33.08	25.67	18.45	18.42
4%	13.13	13.14	16.65	16.52	34.49	34.55	46.86	51.57	34.30	26.38	19.13	19.27
3.33%	13.55	13.50	17.19	17.03	35.48	36.72	46.86	51.51	35.35	26.99	19.72	19.68
2%	14.90	14.94	18.81	18.84	38.78	37.60	46.86	51.71	38.33	29.81	21.37	21.49
1.33%	15.96	15.93	20.05	20.21	41.09	38.06	46.86	51.66	40.60	31.82	22.64	22.80
1%	16.73	16.66	20.97	21.15	42.90	40.13	46.86	51.7	42.18	32.30	23.52	23.80
0.5%	20.14	20.16	24.98	25.04	50.49	50.49	46.86	51.65	49.00	32.86	27.91	25.76
0.1%	32.75	32.69	39.48	39.68	77.55	72.53	46.86	51.79	71.76	33.32	42.75	42.27

For the undefended model, the modelled peak flows through Till upstream of the Washlands and North Hykeham area given in Table 6.18.

Table 6.18: Modelled Peak Flows for Undefended Model at North Hykeham and River Till upstream of Washlands

AEP (%)	North Hykeham Modelled Peak Flow (m^3/s)	River Till upstream of Washlands Modelled Peak Flow (m^3/s)
1%	50.91	35.19
0.1%	61.94	60.98

Source: Mott MacDonald

The modelled peak flows match the target peak flows well at all locations where the target peak flows were used to inform the scaling of the ReFH hydrographs.

The final modelled flow for the 50% AEP is 9.6% greater than the peak flow estimate. However the modelled growth factors match the single site growth factors (to 2 decimal places). The modelled peak flows for AEPs between 2% and 0.1% are sensitive to the exact time of opening/closing of the washland gates, therefore the peak flows do not necessary increase with decreasing AEP. The peak flows from the undefended model at North Hykeham show an increase in the flows over the defended model, however the modelled peak flows are still lower than those predicted by the pooled analysis at this site.

At the River Till upstream of the washlands, the modelled flows are lower than the target peak flows (with the exception of the 50% AEP), and with very little increase in flows between the lower frequency events. The undefended model shows peak flows more similar to the target peak flows, particularly for the 0.1% AEP, suggesting that the influence of the washlands extends upstream of the washlands.

7 Calibration and Verification Events

7.1 Event Selection

Four events have been selected by the Environment Agency for the calibration and verification of the Upper Witham model, and following review of the available data during these events they have been considered appropriate to use. The events that have been used for calibration are:

- November 2000
- June 2007
- January 2008

The event that have been used for verification is:

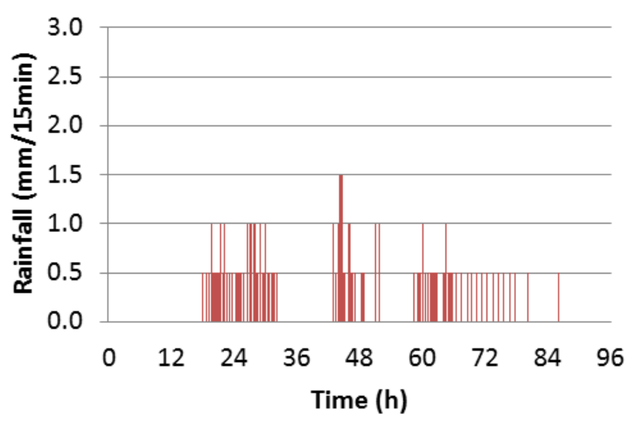
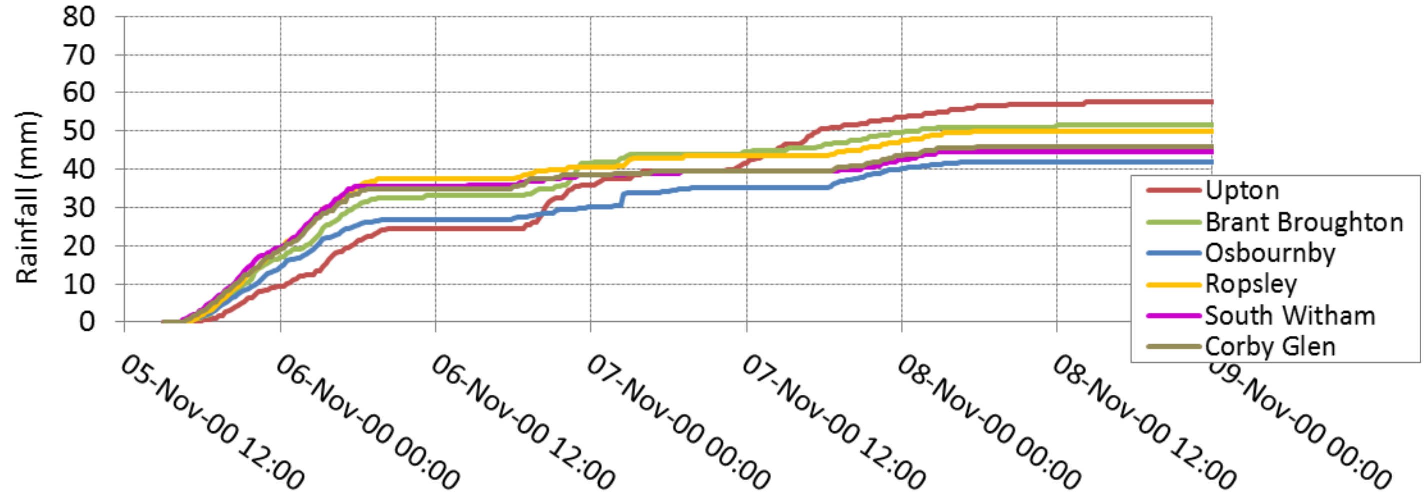
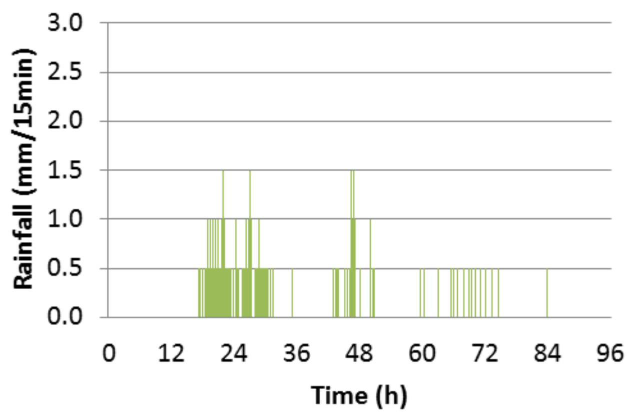
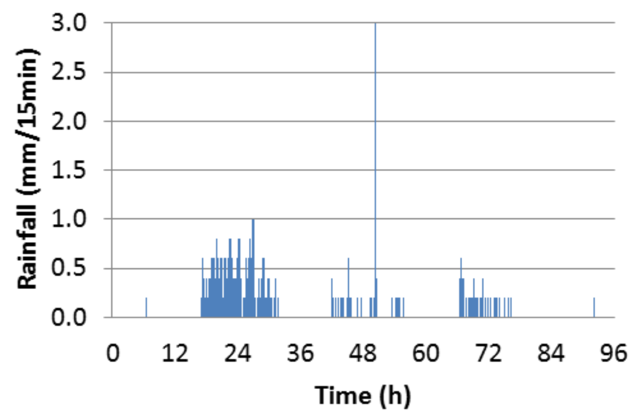
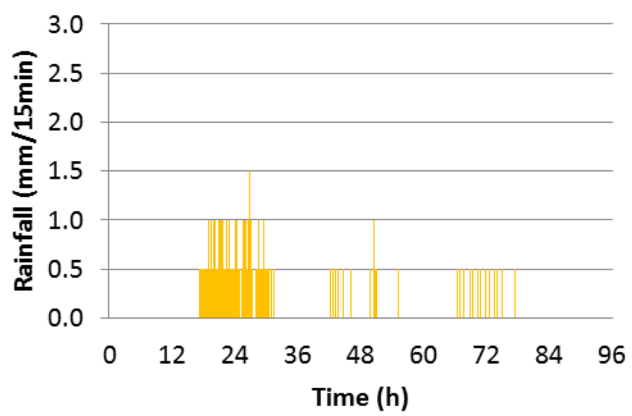
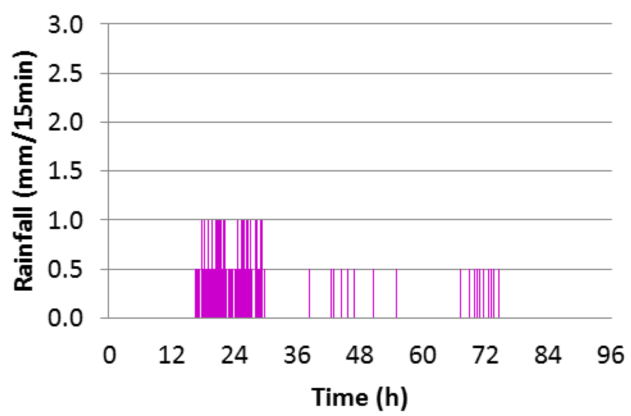
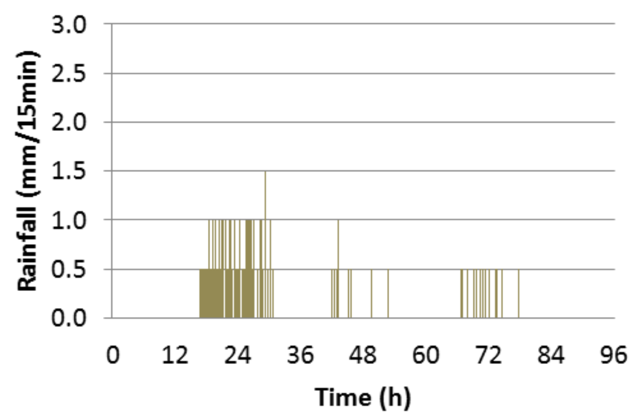
- November 2012

7.2 Review of Available Data

7.2.1 Rainfall Data

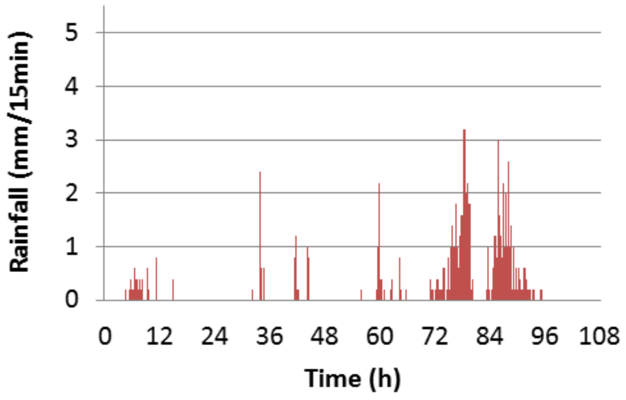
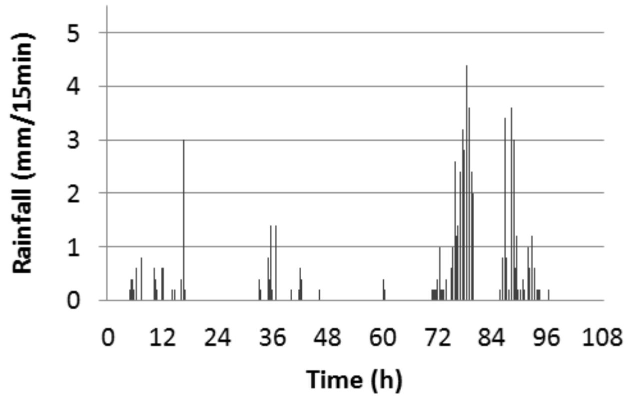
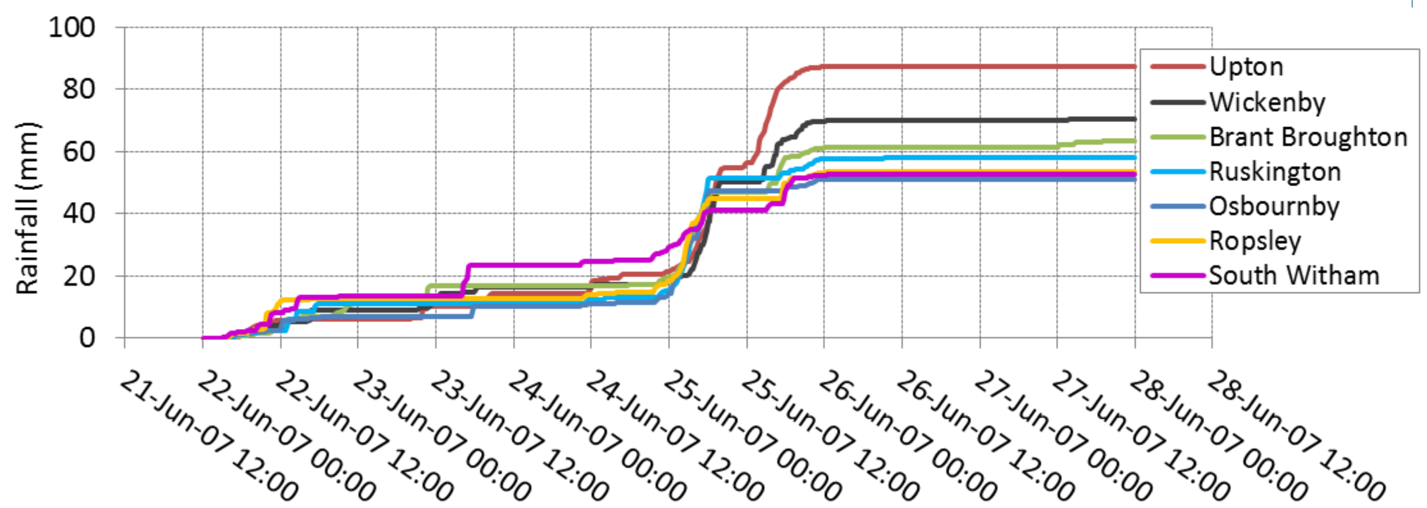
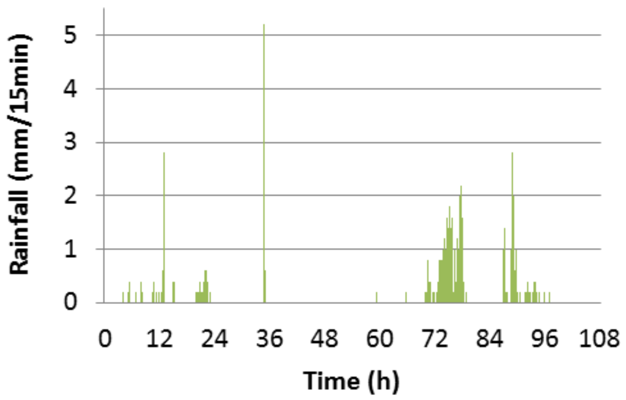
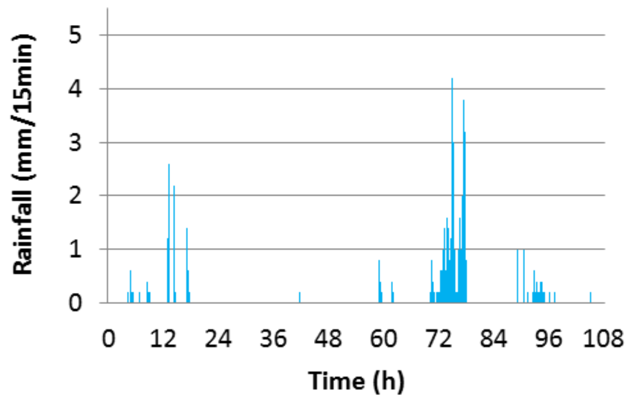
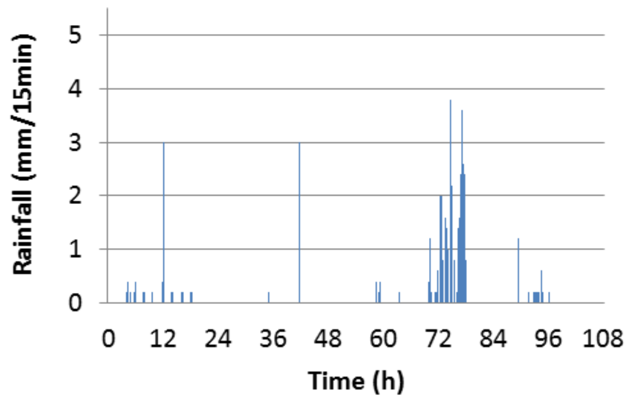
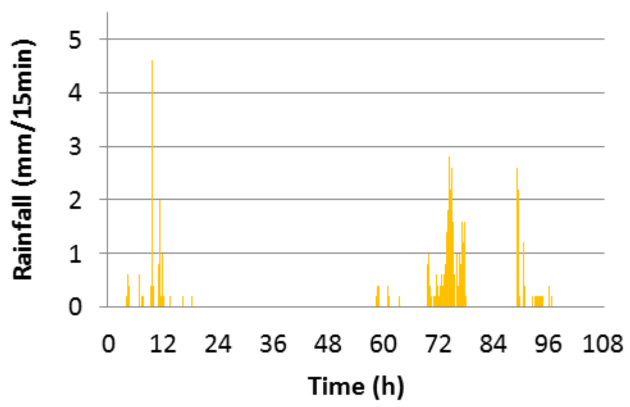
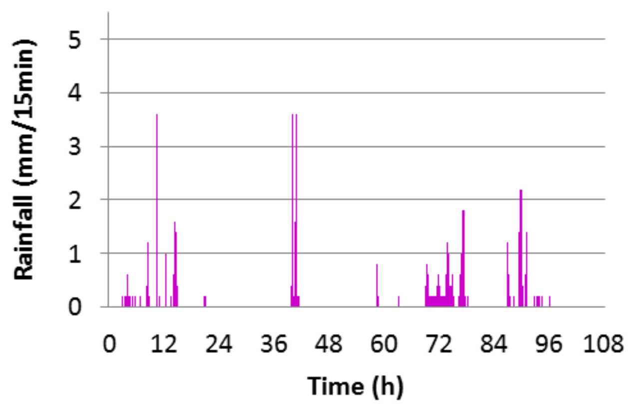
The rainfall data for each event has been provided in Table 7.1 to Table 7.4 along with some key comments from the analysis.

Table 7.1: Summary of Rainfall Data for November 2000 Event

Upton	Wickenby	Cumulative Rainfall	
	Not Available		
Brant Broughton	**Canwick**	**Ruskington**	**Osbournby**
	Not Available	Not Available	
Saltersford	**Ropsley**	**South Witham**	**Corby Glen**
Not Available			
Comments	Storm tracking northwards, with initially high rainfall at South Witham and Ropsley, but intensity of rainfall heading northwards towards Upton Fairly uniform rainfall distribution across catchment.		

Source: EA Rainfall Data

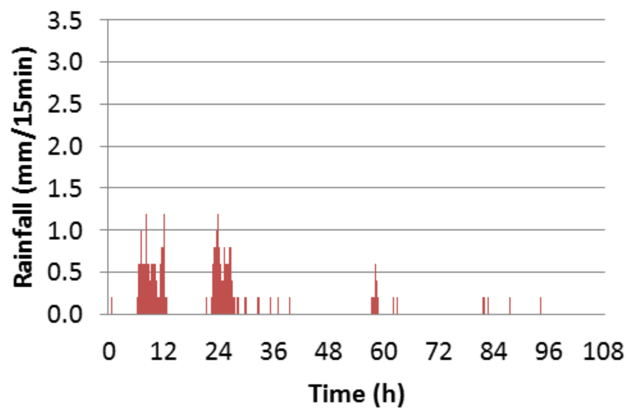
Table 7.2: Summary of Rainfall Data for July 2007 Event

Upton	Wickenby	Cumulative Rainfall	
			
Brant Broughton	**Canwick**	**Ruskington**	**Osbournby**
	Not Available		
Saltersford	**Ropsley**	**South Witham**	**Corby Glen**
Not Available			Not Available
Comments	Storm tracking northwards, with initially high rainfall at South Witham, but intensity of rainfall increasing northwards towards Upton. Large difference in rainfall distribution across the catchment Main rainfall period starts 70 hours into the event. Calibration run includes the smaller precursor event to ensure that the remaining storage capacity within the catchment after the initial rainfall is correctly represented.		

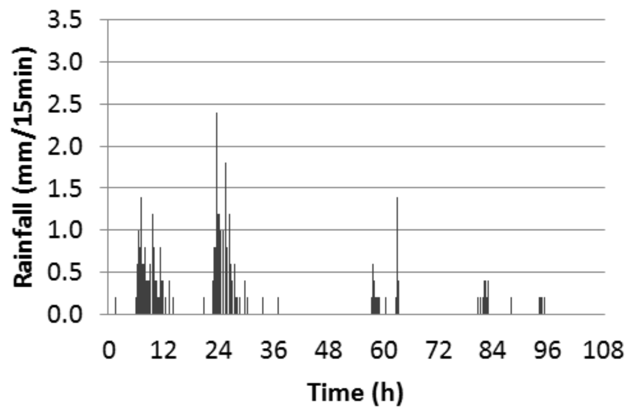
Source: EA Rainfall Data

Table 7.3: Summary of Rainfall Data for January 2008 Event

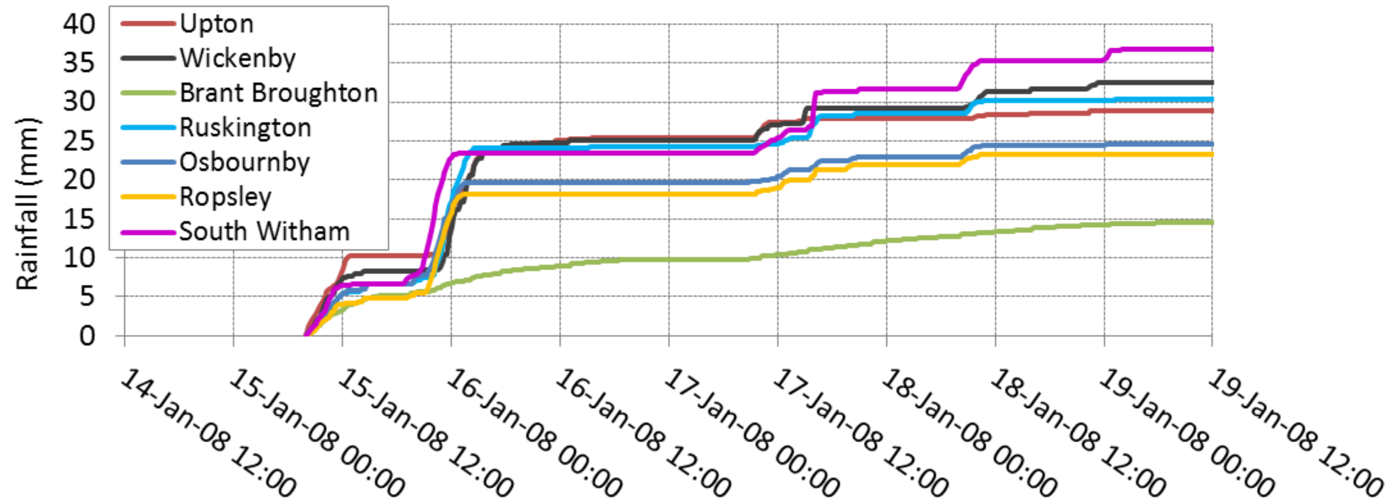
Upton



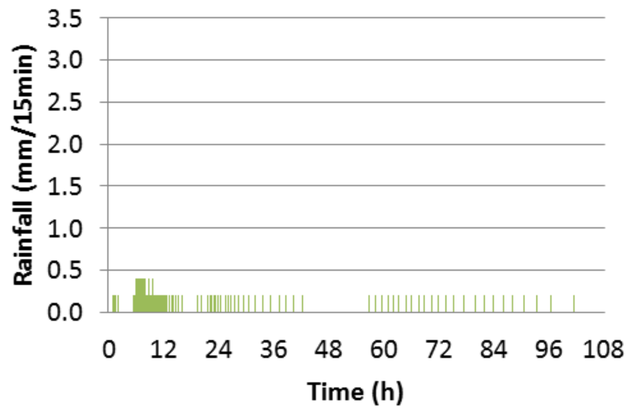
Wickenby



Cumulative Rainfall



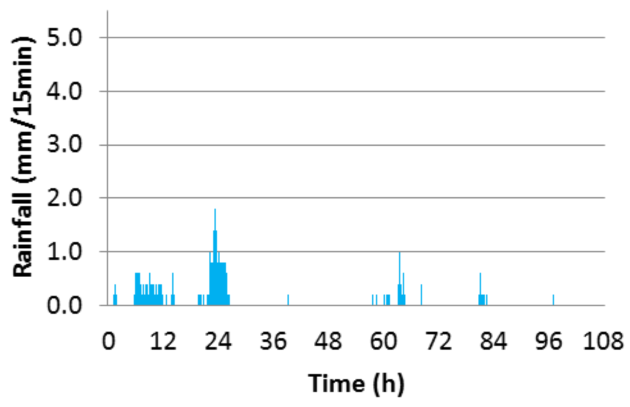
Brant Broughton



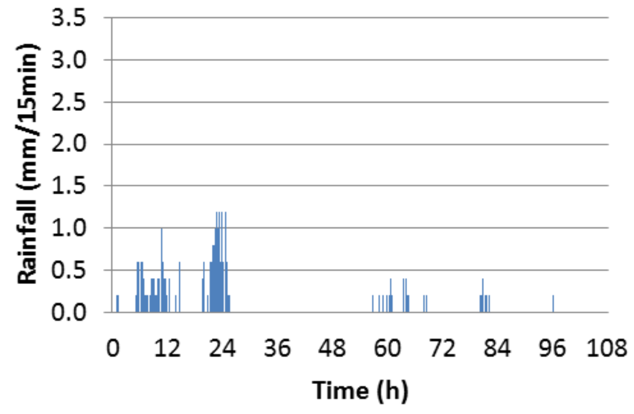
Canwick

Not Available

Ruskington



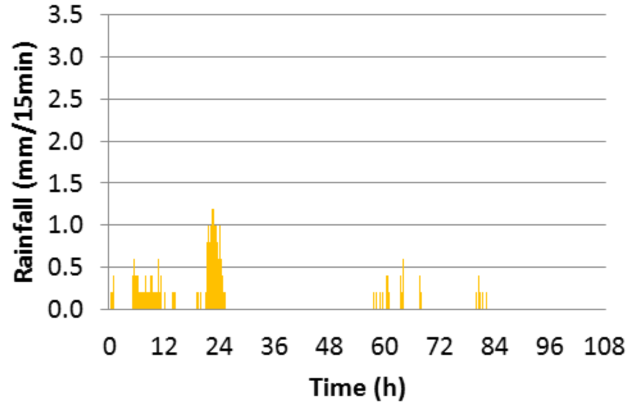
Osbournby



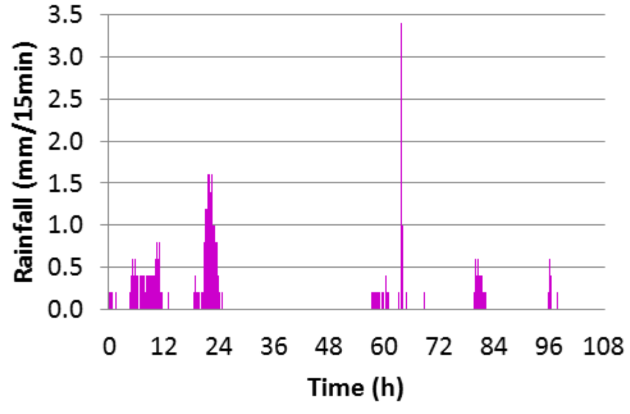
Saltersford

Not Available

Ropsley



South Witham



Corby Glen

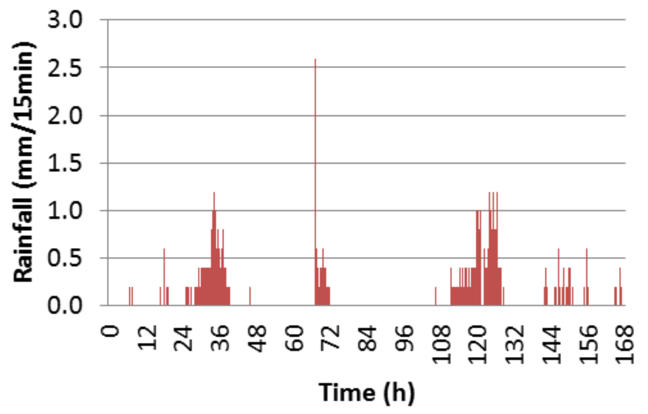
Not Available

Comments	
	Storm tracking southwards, with initially high rainfall at Upton at approximately 6 hours into the event but highest intensities in South Witham later in the event (24 hours). Data at Brant Broughton Suspect Fairly big difference in rainfall distribution across the catchment, with lower rainfall in the middle of the catchment (Ropsley and Osbournby)

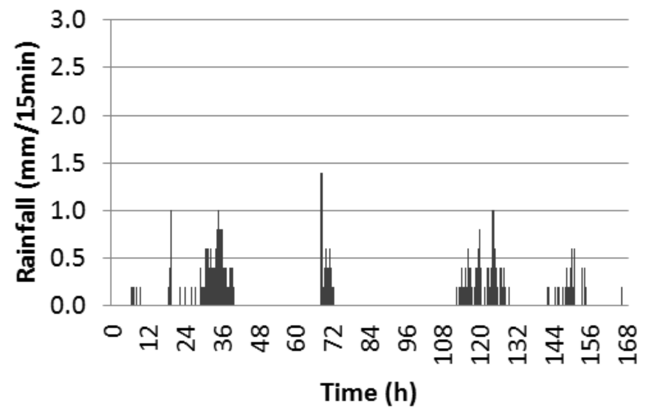
Source: EA Rainfall Data

Table 7.4: Summary of Rainfall Data for November 2012 Event

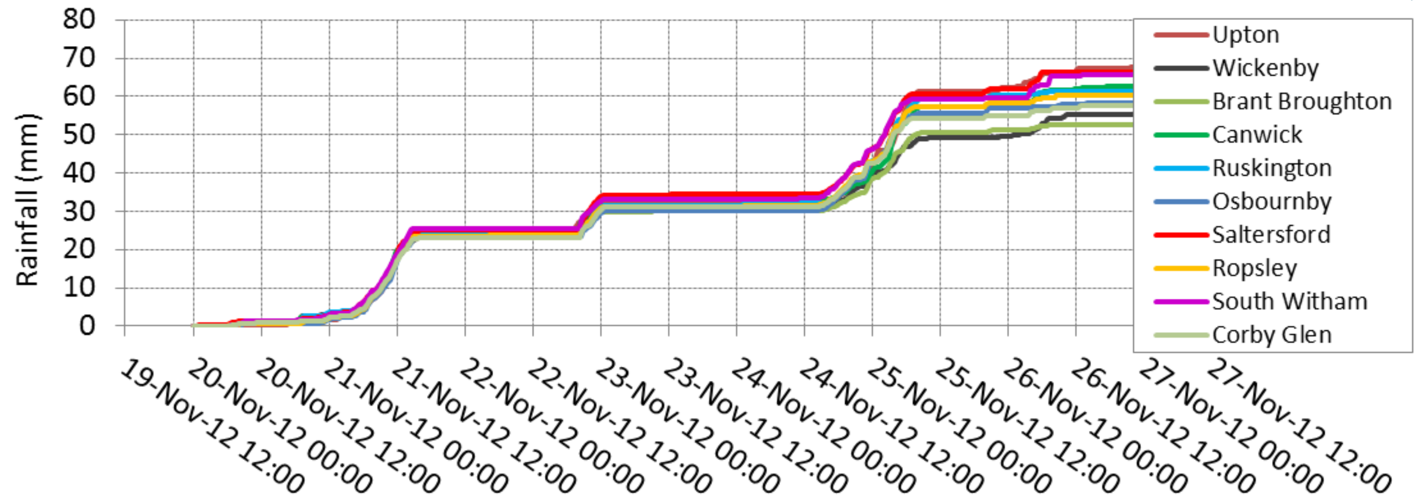
Upton



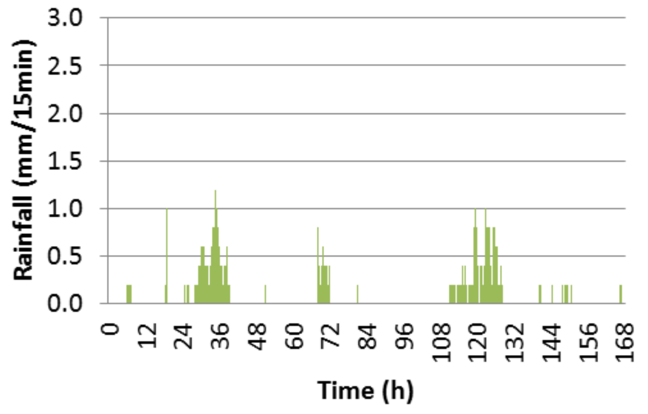
Wickenby



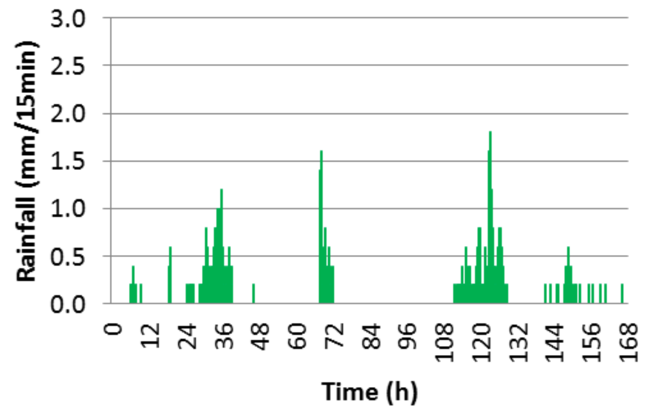
Cumulative Rainfall



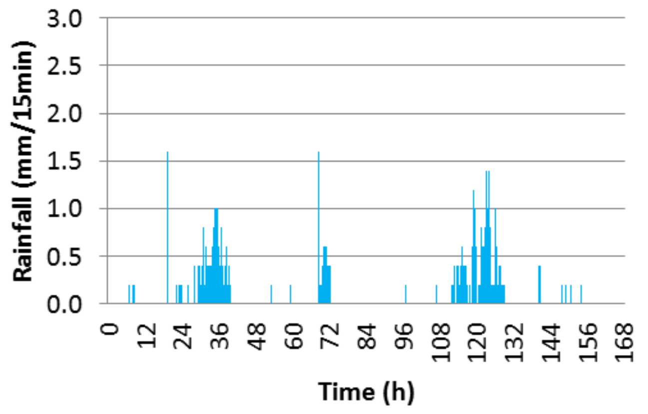
Brant Broughton



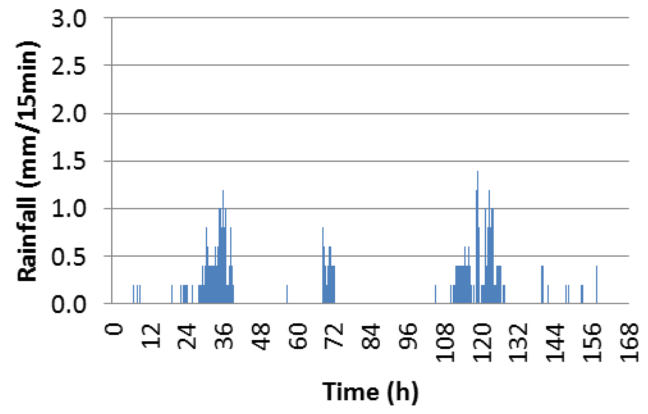
Canwick



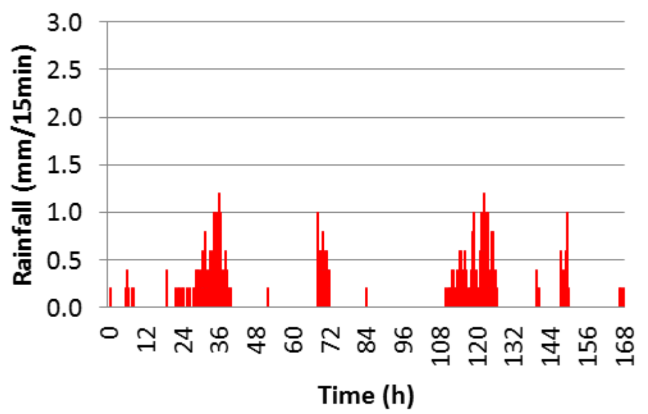
Ruskington



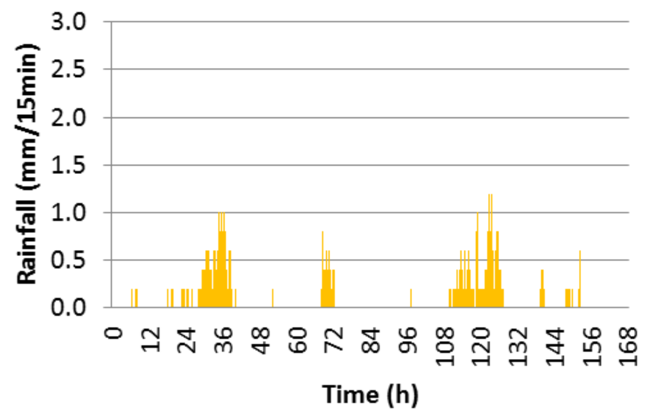
Osbournby



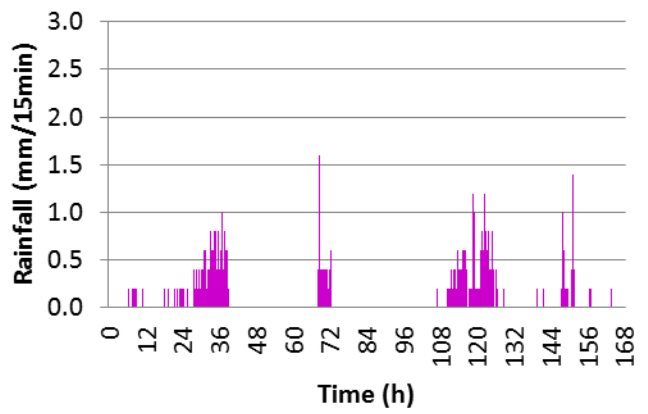
Saltersford



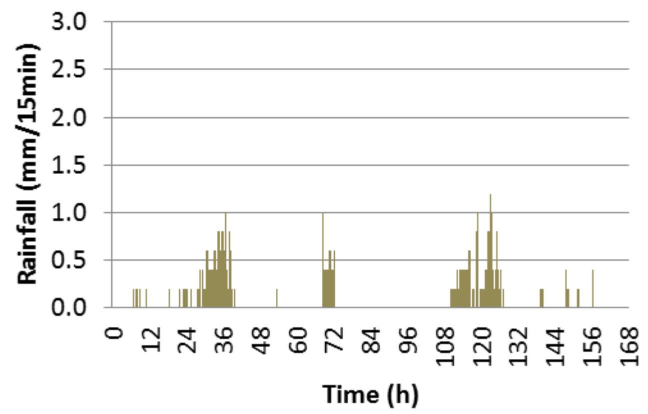
Ropsley



South Witham



Corby Glen



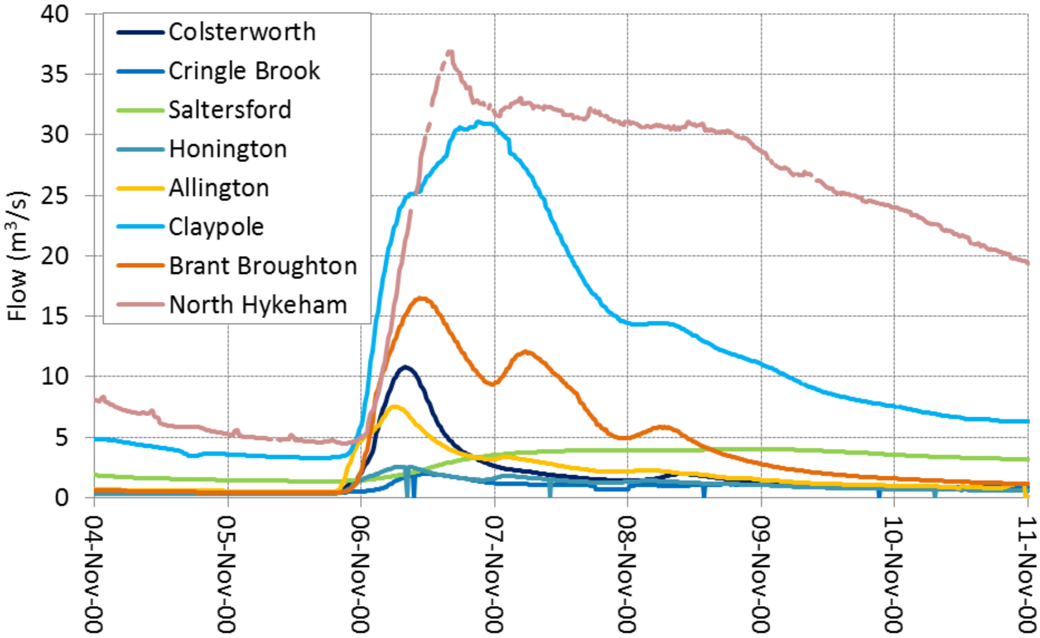
Comments	Storm tracking northwards, with initially high rainfall at South Witham, but the location with the highest intensity of rainfall heading northwards towards Upton. Fairly uniform rainfall distribution, particularly during first two peaks of rainfall (36 and 72 hours)

Source: EA Rainfall Data

7.2.2 Flow Data

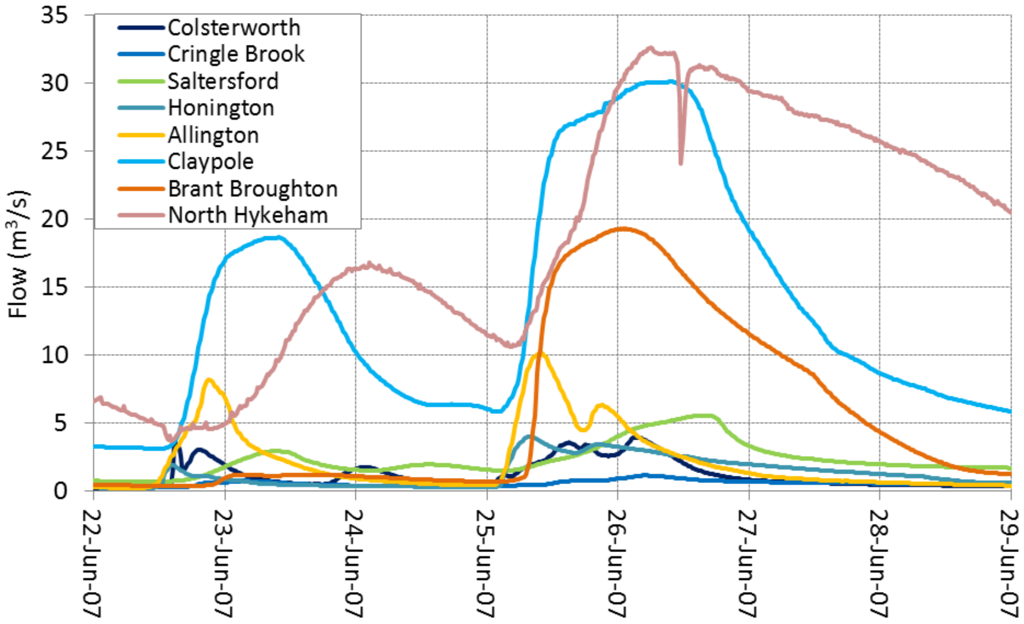
Flow data for each of the events has been reviewed and the flow hydrographs, with the exception of North Hykeham an ultrasonic flow gauge, calculated from stage data using the most recent approved rating curves. The resulting hydrographs are provided in Figure 7.1 to Figure 7.4.

Figure 7.1: Flow Hydrographs for November 2000 Event



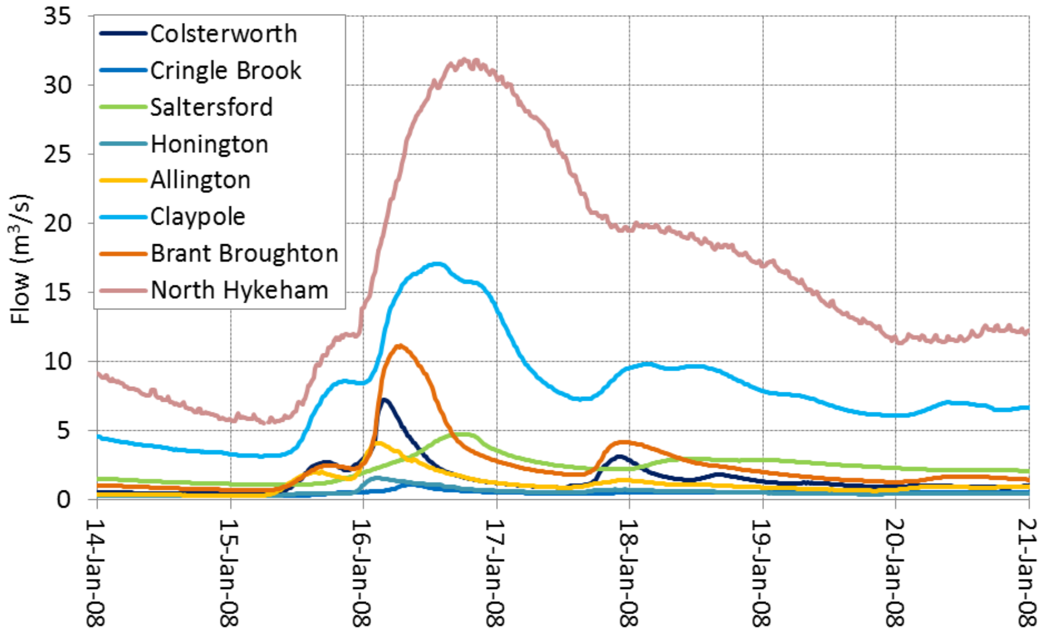
Source: EA Flow Data

Figure 7.2: Flow Hydrographs for June 2007 Event



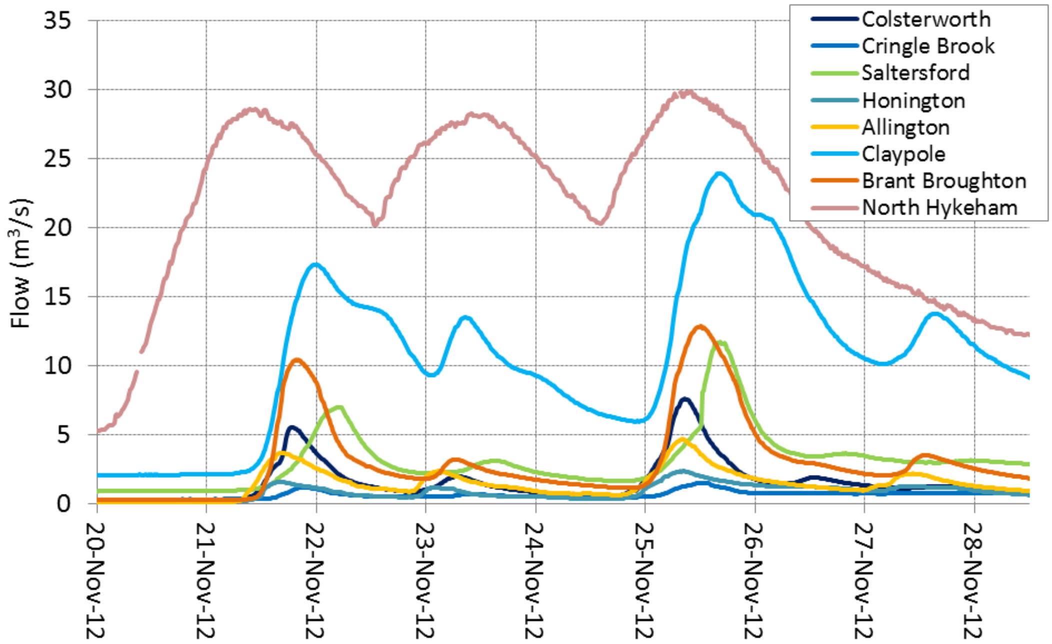
Source: EA Flow Data

Figure 7.3: Flow Hydrographs for January 2008 Event



Source: EA Flow Data

Figure 7.4: Flow Hydrographs for November 2012 Event



Source: EA Flow Data

The data at Saltersford is not considered reliable, particularly for the first three events. The hydrograph shape is very different from those both upstream and downstream, with the peak of the event occurring well after the peak at Colsterworth, or even for some events, Claypole. This is considered to be due a blockage of the intake for the stilling well.

7.2.3 Level Data

Table 7.5 details the gauges for which level data is available for each calibration/verification event.

Table 7.5: Summary of Level Gauge Data Available during Calibration/Verification Events.

Gauging Station	November 2000	June 2007	January 2008	November 2012
North Witham	Yes	No	No	No
Colsterworth	Yes	Yes	Yes	Yes
Cringle Brook	Yes	Yes	Yes	Yes
Saltersford	Suspect	Suspect	Suspect	Yes
Spittlegate Mill	No	Yes	Yes	Yes
Harrowby Mill	No	Yes	Yes	Yes
Belton	No	Yes	Yes	Yes
Allington	Yes	Yes	Yes	Yes
Hougham	Suspect	Yes	Suspect	Suspect (peak

Gauging Station	November 2000	June 2007	January 2008	November 2012
				missing)
Claypole	Yes	Yes	Yes	Yes
Willingham Bridge	No	No	Yes	Yes
Squires Bridge	Yes	Yes	Yes	Yes
Till Sluice upstream	No	No	Yes	Yes
Till Sluice downstream	Yes	No	Yes	Yes
Odder Bridge	Yes	Yes	Yes	Yes
Burton Marina	No	Suspect	Suspect	Yes
Fossdyke Golfcourse	Yes	Yes	Yes	Yes
Fossdyke Waterways	Yes	Yes	Yes	Yes
Brayford Pool	Suspect	Suspect	Suspect	Suspect
Stampend Sluice upstream	Suspect	Yes	Yes	Yes
Monson St	Yes	Yes	Yes	Yes
Great Gowt Sluice downstream	Yes	Yes	Yes	Yes
Great Gowt Sluice - upstream	Yes	Yes	Yes	Yes
Bargate	Yes	Yes	Yes	Yes
Skellingthorpe	Yes	Yes	Yes	Yes
Bracebridge	Yes	Yes	Yes	Yes
North Hykeham	No	Yes	Yes	Yes
Witham Washland Sluice downstream	Yes	Yes	Yes	Yes
Witham Washland Sluice upstream	Yes	No	Yes	Yes
Aubourn Weir	Yes	Yes	Yes	Yes
Beckingham Bridge	No	Yes	Datum Shift?	Yes
Claypole	Yes	Yes	Yes	Yes
Brant Control Sluice	No	Yes	Yes	Yes
Brant Control Washland level	Yes	Yes	Yes	Yes
Horseshoe Bridge	Yes	Yes	Yes	Yes
Brant Broughton	Yes	Yes	Yes	Yes

Source: Mott MacDonald

7.3 Estimation of Time to Peak

The time to peak for each of the flow gauging stations, with the exception of Saltersford and North Hykeham, have been calculated from the rainfall and flow data using lag analysis (FEH Equation 4.2.9). In addition the time to peak at Squires Bridge – River Till has also been calculated from the level data as there are no flow gauging stations along the River Till . Saltersford and North Hykeham have been excluded due to the concerns over the level gauge at Saltersford and due to the timing of peaks typically more influence by storage and the operation of the Washlands at North Hykeham. The derived time-to peak values (Tp) are presented in Table 7.6.

Table 7.6: Summary of Observed Time to Peak during Calibration and Verification Events

Location	Catchment Descriptor Derived Time to Peak (Hours)	Rainfall Gauges used in Analysis	Observed Time to Peak (Hours)				
			November 2000	June 2007	January 2008	November 2012	Derived Donor Correction Factor
Colsterworth GS	8.9	South Witham (2000, 2007, 2008), Ropsley (2012)	6.9	5.4	7.2	6.5	0.73
Honington Beck GS	5.9	Brant (2000), Ropsley (2007, 2008, 2012)	5.7	4.4	4.3	6.1	0.87
Allington GS	7.9	Brant (2000, 2007), Ropsley (2008, 2012)	4.6	4.9	4.1	6.1	0.63
Claypole GS	17.3	Brant (2000, 2007, 2012), Ropsley (2008)	11.5	10.8	10.4	11.5	0.64
Brant Broughton GS	10.3	Brant (2000, 2007, 2012), Ropsley (2008)	8.1	7.5	6.2	8.6	0.74
Squires Bridge GS	13.1	Upton (All years)	9.1	12.2	11.4	10	0.81

Source: Mott MacDonald

The observed time-to peaks are very similar across the events, and are less than that derived from catchment descriptors at all the gauging stations. The ratio of the average of the observed Tp over the catchment descriptor derived Tp has been used as a donor correction factor for ungauged catchments in both the calibration/verification inflows and in deriving design inflows. Donor catchments have been selected based on similar catchments characteristics. Final values for design events, including which station is used as a donor for each sub-catchment, are provided in Section 8.

7.4 Optimisation of ReFH Model Parameters

The initial catchment wetness (Cini), Baseflow Lag (BL), and Baseflow Recharge (BR) parameters within the ReFH Model have been optimised using lumped ReFH to the gauges for each of the calibration and verification events. Observed rainfall has been used at each gauging station (with the exception of Squires Bridge where only level data is available), and the ReFH Model parameters varied until a good match was found between the observed flows, and those derived through the ReFH Model, with most attention on matching peak flows and hydrograph volumes during the peak of an event. Table 7.7 presents the default values (derived from catchment descriptors) and the optimised values for each of the events.

Table 7.7: Optimisation of ReFH Parameters for Calibration/Verification Events

Gauging Station	Parameter	Default Value	November 2000	June 2007	January 2008	November 2012	Derived Donor Correction Factor (Average of Winter Events)
Colsterworth	Cini	84	150	60	100	110	1.4
	BL	63	70	63	63	63	1
	BR	4.49	0.75	0.8	0.8	0.8	0.5
Claypole	Cini	103	70	60	45	55	0.6
	BL	76	68.3	70	80	80	1
	BR	1.33	2	2	2.2	2	1.6
Honington Beck	Cini	106	45	25	47	43	0.4
	BL	53	65	60	65	65	1.2
	BR	1.3	3.1	4.5	3	2.8	2.3
Allington	Cini	119	64	75	42	45	0.4
	BL	56	65	65	65	65	1.2
	BR	1.15	2.4	2.4	2.1	2.35	2
Brant Broughton	Cini	126	126	25	80	105	0.8
	BL	49	56	35	54	54	1.1
	BR	0.80	0.8	4	1	0.85	1.1

Source: Mott MacDonald

With the exception of Cini, which would be expected to vary from event to event, the other parameters are fairly consistent across the 4 events, particularly for the 3 winter events. Two significant outliers are Brant Broughton and Honington Beck during the June 2007 event, where the observed flow at these gauging stations suggests a very large volume of water for the amount of recorded rainfall, only replicated by the ReFH model if high baseflow recharge values are used.

Analysis of the rainfall data surrounding these two catchments for the June 2007 event was carried out, with daily rainfall totals at the tipping bucket gauging stations compared against those at the daily rainfall stations. This is provided in Table 7.8.

Table 7.8: Summary of Daily Rainfall Totals during the June 2007 event near Honington and Brant Broughton

Rainfall Station	Station type	Total Rainfall on 24th June 2007 (mm)	Total Rainfall on 25th June 2007 (mm)
Brant Broughton	Tipping Bucket	30.4	14.4
Ruskington	Tipping Bucket	40.6	6.4
Ropsley	Tipping Bucket	32	8.8
Osbournby	Tipping Bucket	37.2	3.8

Rainfall Station	Station type	Total Rainfall on 24th June 2007 (mm)	Total Rainfall on 25th June 2007 (mm)
Welby	Daily Total	43	17.6
Navenby	Daily Total	33.5	11.1
Walcot	Daily Total	34.7	4

Source: Mott MacDonald

The data shows that the observed rainfall at Welby station was 35% and 29% greater than that observed at Brant Broughton and Ruskington respectively. This suggests that there may have been some localised heavy rain over the catchments of Honington and Brant during the event. The analysis in Table 7.7 was carried out for the June 2007 event (for Honington and Brant only) using a combination of the rainfall profiles at Brant and Ruskington, with the Ruskington rainfall being used on the 24th June, and Brant Broughton rainfall on the 25th June.

Percentage runoff calculations were also carried out for this event and are given in Table 7.9. This analysis confirmed the decision to not use Brant Broughton or Ruskington Rainfall Stations on their own, as to match these greater than 100% runoff would be required.

Table 7.9: Percentage Runoff Calculations for June 2007 (Honington and Brant Catchments)

Rainfall Station	Percentage Runoff – Honington Catchment	Percentage Runoff – Brant Broughton Catchment
Brant Broughton	107%	60%
Ruskington	105%	59%
Combination of Brant and Ruskington	87%	49%

Source: Mott MacDonald

For the calibration, verification and design events, the average of the optimised parameters over the three winter events at each gauging station has been used to enhance the design ReFH hydrographs. The June 2007 event was not used in enhancing the design ReFH hydrographs as there is reduced confidence in the derived parameters during this event due to the uncertainty in the observed rainfall. Final donor correction values, and the respective donor catchment for each ungauged catchment are provided in Section 8 and used for both calibration and design events.

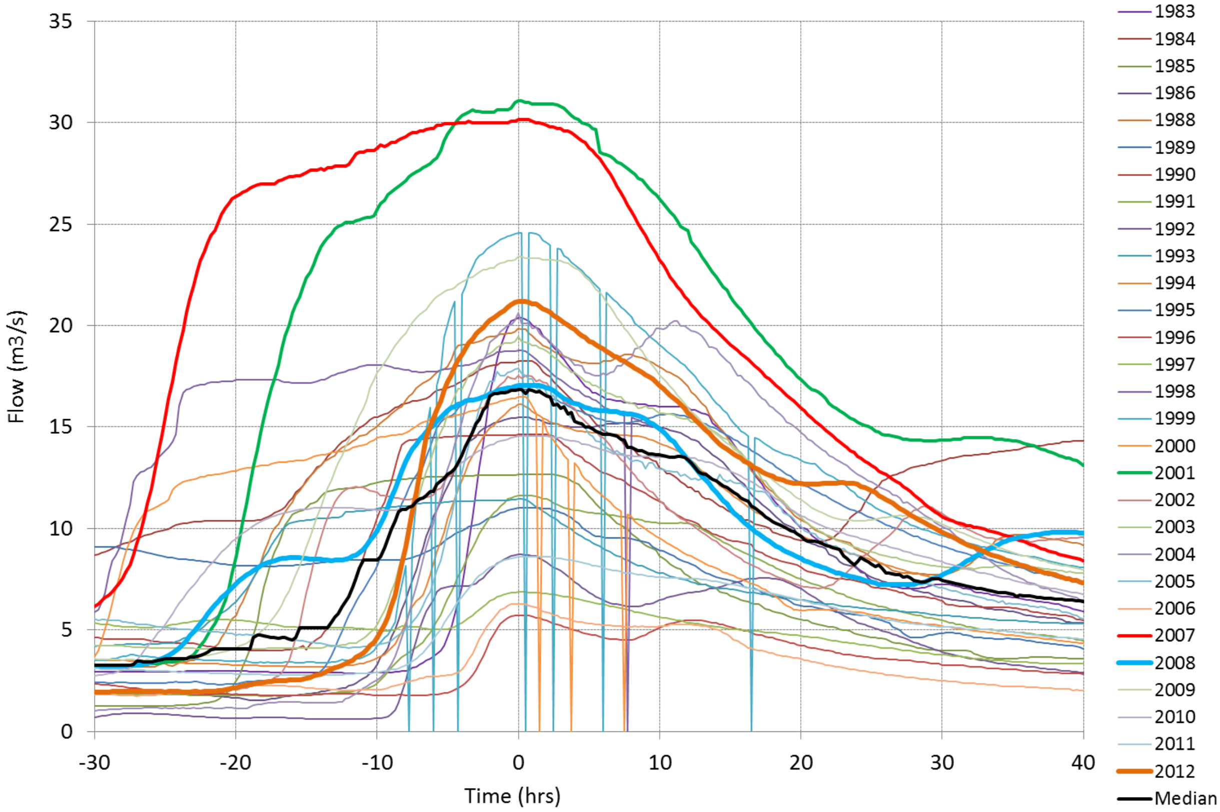
The only exception to this is for the June 2007 calibration event. Due to the significant difference in optimised Baseflow Lag at Brant Broughton and Honington in the June 2007 event compared to the average of the Winter events, the donor correction factor derived for Honington during the winter events has been applied to the two ungauged catchments upstream of the River Brant Confluence with the River Witham (RW_US_Brant and RB_DS_GS). This gives a donor correction value of 2.3 compared to 1.1 for Brant Broughton (average of winter events), used during the remaining 3 events and for the design runs, or compared to 5, derived solely from the June 2007 event at Brant Broughton.

8 Derivation of Design Hydrograph Shape

8.1 Hydrograph Shape Analysis

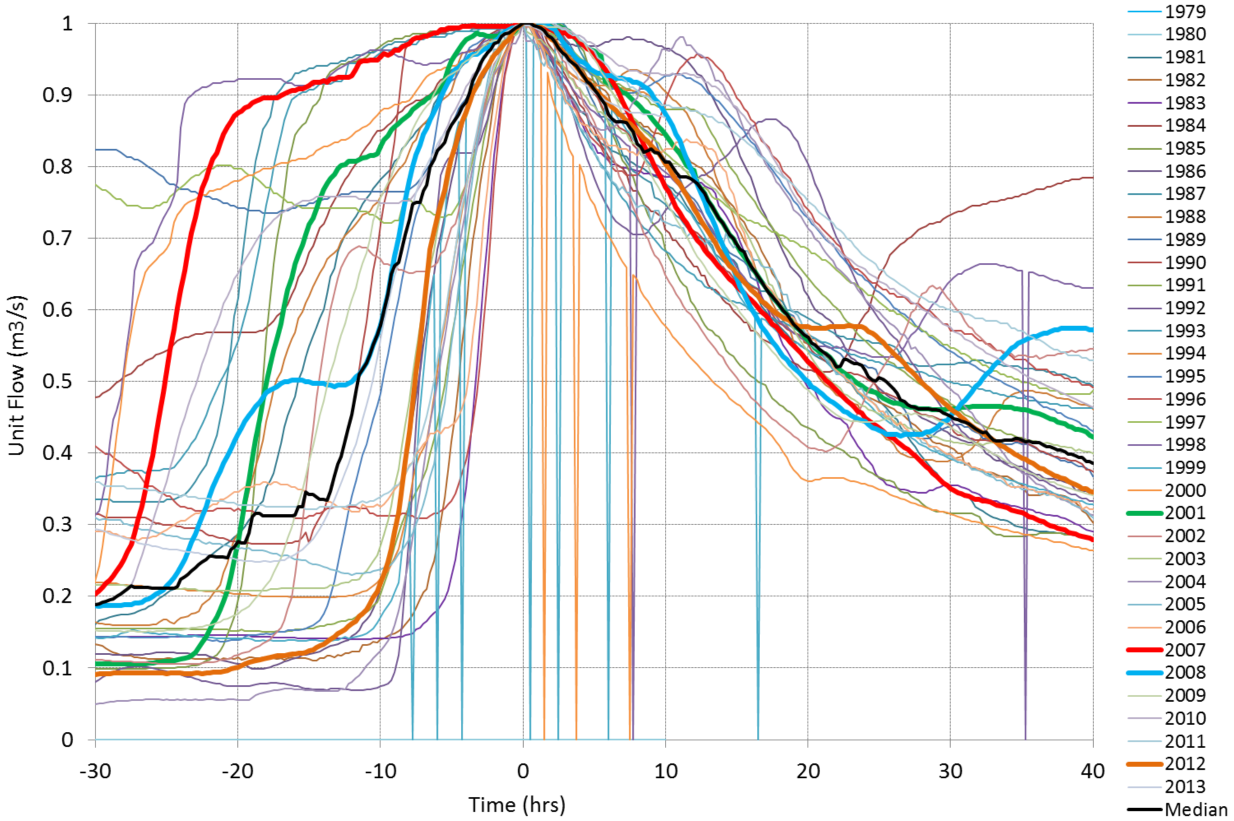
Hydrograph shape analysis has been carried out at Claypole. This has involved selecting each of the flow hydrographs corresponding to AMAX events, standardising the hydrograph to give a peak of 1, and aligning them so the peaks all coincide at t=0. Figure 8.1 shows the non-standardised hydrographs and Figure 8.2 the standardised hydrographs. In each the 4 chosen calibration/verification events have been highlighted in bold. The median of all the hydrographs has also been added in black.

Figure 8.1: Hydrograph Analysis at Claypole Gauging Station – Non-Standardised Hydrographs



Source: Mott MacDonald

Figure 8.2: Hydrograph Analysis at Claypole Gauging Station –Standardised Hydrographs

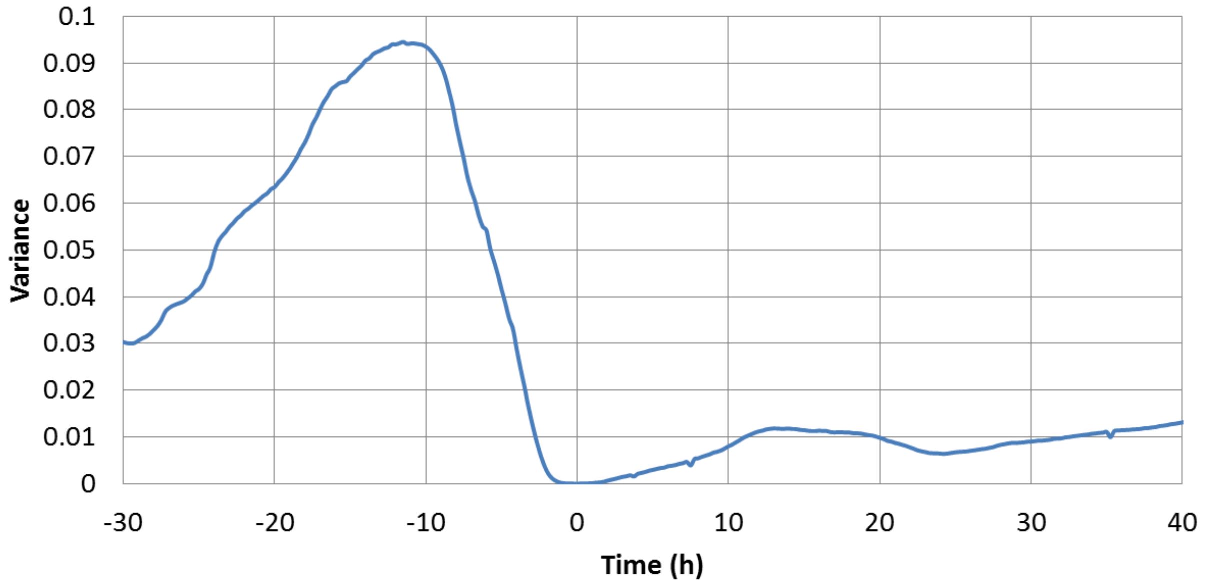


Source: Mott MacDonald

The analysis shows all the main events (highlighted in bold) have very similar falling limbs to the median hydrograph profile. On the rising limb, the June 2007 and November 2000 (water year 2001) events have a significantly earlier rising than the median, indicating a long duration event, with a lot of volume.

The variance of the standardised hydrographs has also been calculated and is given in Figure 8.3. This confirms the small spread in the falling limbs, but highlights that the greatest variance occurs on the rising limb, just prior to the peak of the hydrographs, at around -10 hours.

Figure 8.3: Variance in Standardised Hydrographs at Claypole Gauging Station



Source: Mott MacDonald

In discussion with the Environment Agency it was agreed that the standardised November 2000 event hydrograph would be used as a design hydrograph for the main model inflow in the Upper Witham – Lincoln model. This has been scaled up to match the target peak flow calculated for Claypole. This event provides one of the larger hydrograph volumes, being larger than the median, however not as conservative as the June 2007 event, which when scaled up to the 0.1%AEP target flow, would represent a highly conservative estimate of volume. The ordinates of the dimensionless hydrograph are provided in Appendix F.

8.2 Optimisation of ReFH Model Parameters

The ReFH model parameters, Tp, BL, and BR have been optimised as part of the derivation of calibration and verification hydrological inflows as detailed in Section 7. These optimised values, taken for Tp as an average across all 4 events, and for BL and BR, as an average across the three winter events has been used as donors for enhancing the ReFH hydrographs for the design runs. Where the baseflow recharge donor correction factor is in excess of 2, care has been taken to ensure that the ReFH units are not erroneously creating volume. Donor site have been chosen based on having similar catchment characteristics, using the same method as that used for QMED transfer. Table 8.1 summarises the donor correction factors to be used for each parameter for each catchment.

Table 8.1: Summary of Donor Correction Factors for ReFH Inflow Hydrographs

Model ID	Catchment	Donor Correction Factor				Donor Catchment
		Time To Peak	Baseflow Lag	Baseflow Recharge	Cini	
Colsterworth	River Witham upstream of Colsterworth GS	0.73	1	0.5	1.4	Colsterworth Gauging Station
Cringle_Br	Cringle Brook					
RW_US_CB	River Witham Intermediate C1 (Cringle Brook – Costerworth GS)					
RW_US_Salt	River Witham Intermediate C2 (Saltesford – Cringle Brook)					
Witham_Br	Witham Brook	0.87	1.2	2.3	0.4	Honington Beck
MowBeck_BS	Barrowby Stream and Mow Beck upstream					
HoningtonBr	Honington Beck					
RW_US_FB	River Witham Intermediate C3 (Foston Beck – Saltersford GS)					
RW_US_CP	River Witham Intermediate C4 (Claypole – Foston Beck)	0.63	1.2	2	0.4	Allington Gauging Station
Foston_Beck	Foston Beck					
Witham_US_Brant	River Witham Intermediate C5 (River Brant – Claypole)	0.74	1.1	1.1	0.8	Brant Broughton Gauging Station
Witham_US_BC	River Witham Intermediate C6 (River Brant - Boultham Catchwater)					
Brant_GS_US	River Brant upstream of Brant Broughton GS					
Brant_GS_DS	River Brant Intermediate C1 (Brant Broughton – Confluence with River Witham)					
Boultham	Boultham Catchwater	0.77	1.1	1.1	0.8	Average of Brant Broughton and Squires Bridge for Tp, Brant Broughton for BL, BR and Cini
Main_Drain	Main Drain					
RT_US_SQB	River Till upstream of Squires Bridge	0.81	1.1	1.1	0.8	Squires Bridge for Tp, Brant Broughton for BL, BR and Cini
RT_US_CT	River Till Intermediate C1 (Squires Bridge – Confluence with Cricket Till)					
Cricket Till	Cricket Till					
RT_US_FD	River Till Intermediate C2 (Cricket Till – Confluence with Fossdyke Canal)					
Burton	Burton Catchwater					
FD_US_RT	Fossdyke Canal Upstream of River Till					

Source: Mott MacDonald

8.3 Storm Duration Analysis

Storm duration analysis has been carried out at Claypole using a lumped ReFH unit. Using the optimised values of Tp, BL, and BR as derived above, it was found that the peak flows were not sensitive to storm duration. For the 1%AEP event the peak flow estimates were within $1m^3/s$ (with a maximum of $77m^3/s$) for storm durations varying from 29 hours to 49 hours.

Due to the insensitivity of the peak flows to storm duration, it was agreed with the EA that sensitivity testing would be carried out on the 1% AEP event. This event has been run for the following storm durations:

- Upper Witham – Grantham model:
  - 10hrs
  - 20hrs
  - 40hrs
- Upper Witham – Lincoln model:
  - 10hrs
  - 40hrs
  - 60hrs

The standardised June 2007 hydrograph chosen for Claypole has also been scaled with respect to time for each of the three storm durations to ensure that the volume represented by the hydrograph is appropriate for each storm duration run. The hydrograph ordinants are provided in Appendix F.

The results and analysis of the storm duration sensitivity tests are provided in Appendix G.

From the analysis it was agreed with the Environment Agency to run the Upper Witham - Grantham model for the 10 Hour storm duration, and the Upper Witham – Lincoln model for the 10 Hour and 40 Hour storm durations.

9 Reconciliation of Target Peak Flows with Design Inflow Hydrographs

9.1 Scaling of Hydrograph Inflows

Table 9.1 details which hydrograph inflows have been scaled to ensure that the target peak flow calculated using flood frequency analysis are attained along the River Witham and Brant.

Table 9.1: Summary of Catchment Inflows Scaled to Attain Target Peak Flow Estimations

Model	Target Peak Flow Estimation Site	Catchment Inflows Scaled to Ensure Peak Flows are Achieved
Upper Witham Grantham	Colsterworth Gauging Station	River Witham Upstream of Colsterworth
	Saltersford Gauging Station	Cringle Brook, River Witham Intermediate C1, River Witham Intermediate C2
	Claypole Gauging Station	Witham Brook, Barrowby Stream and Mow Beck, Honington Beck, River Witham Intermediate C3, River Witham Intermediate C4, Foston Beck, River Witham Intermediate C5
Upper Witham – Lincoln	Claypole Gauging Station	Main Inflow on River Witham at Claypole
	Brant Broughton Gauging Station	River Brant upstream of Brant Broughton

Source: Mott MacDonald

The catchments not listed above have not had their inflows scaled as due to the presence of the washlands, the critical factor becomes the volume within the hydrograph, rather than the peak flow.

Table 9.2 details the scaling factors used for each region. Different scaling factors were applied for the 10 Hour and 40 Hour storm duration model runs upstream of Brant Broughton. The other regions all fell into the Upper Witham – Grantham model which was only run for the 10 hour storm duration.

Table 9.2: Scaling Factors Applied to ReFH Hydrograph Inflows

	10 Hour Storm Duration			10 Hour Storm Duration	40 Hour Storm Duration
AEP	Upstream of Colsterworth	Colsterworth to Saltersford	Saltersford to Calypole	Upstream of Brant Broughton	
50%	0.95	1.40	1.16	1.04	0.94
20%	1.09	1.65	1.41	1.10	1.02
10%	1.14	1.50	1.50	1.08	1.00
5%	1.15	1.35	1.55	1.05	0.97
4%	1.16	1.34	1.66	1.04	0.97

AEP	Upstream of Colsterworth	Colsterworth to Saltersford	10 Hour Storm Duration Saltersford to Calypole	10 Hour Storm Duration	40 Hour Storm Duration
				Upstream of Brant Broughton	
3.3%	1.15	1.32	1.85	1.02	0.95
2%	1.13	1.32	1.93	0.98	0.92
1.3%	1.10	1.30	1.80	0.95	0.89
1%	1.08	1.26	1.71	0.92	0.87
0.5%	1.12	1.20	1.60	0.91	0.85
0.1%	1.37	1.15	1.05	0.88	0.84

Source: Mott MacDonald

9.2 Timing/Phasing of Hydrograph Inflows

In the Upper Witham – Grantham model there are no changes to the timing or phasing of hydrograph inflows, unless the target flows become difficult to attain without ensuring that peak flows from tributaries coincide with those along the River Witham.

In the Upper Witham – Lincoln model the hydrograph inflows have been phased to ensure peak coinciding with peak at:

- Confluence of River Brant with River Witham
- Confluence of Boultham Catchwater with River Witham,
- Confluence of River Till with Fossdyke Canal
- Confluence of Burton Catchwater with Fossdyke Canal
- Confluence of Fossdyke Canal with River Witham

This is consistent with the methodology used when designing the washlands, and determining the level of protection that they offer Lincoln. Table 9.3 provides the phasing adjustments.

Table 9.3: Summary of Phasing Adjustments for Upper Witham – Lincoln Model

Inflow	QT Hydrograph shifted to ensure peak occurs at time:	Time delay applied to ReFH Hydrograph (same for all storm durations) (Hours)
Claypole	10H: 15 Hours 40H: 30 Hours 60H: 40 Hours	
Witham_US_Brant		5.5
Brant_GS_US		9.5
Brant_GS_DS		9.5
Witham_US_BC		17.0
Boultham		15.0
Main_Drain		6.0

Inflow	QT Hydrograph shifted to ensure peak occurs at time:	Time delay applied to ReFH Hydrograph (same for all storm durations) (Hours)
Burton		12.0
RT_US_CT		15.0
Cricket Till		17.0
RT_US_FD		12.5
FD_US_RT		13.0

Source: Mott MacDonald

10 Witham Brook and Mow Beck & Barrowby Stream

The hydrological inflows for the Witham Brook and Mow Beck & Barrowby Stream catchment specific models have been derived separately. Both of these catchments are heavily urbanised with URBEXT2000 values of 0.23 and 0.22 respectively. With limited observed data available on both catchments (problems have been reported for the level gauge on Mow Beck), the Urban version of ReFH has been used. This method divides the catchment into a paved region, and undeveloped region. The undeveloped region is treated as per the normal ReFH methodology, whilst the paved region has a percentage runoff set to 70%.

Infoworks RS does not currently implement the Urban ReFH model, therefore all analysis for these two catchments has been undertaken using ISIS software, and the resulting inflow hydrographs copied across to Infoworks and applied as flow-time boundaries.

The parameters used in the Urban ReFH for each catchment are as follows:

Table 10.1: Urban ReFH Parameters for Witham Brook and Mow Beck & Barrowby Stream

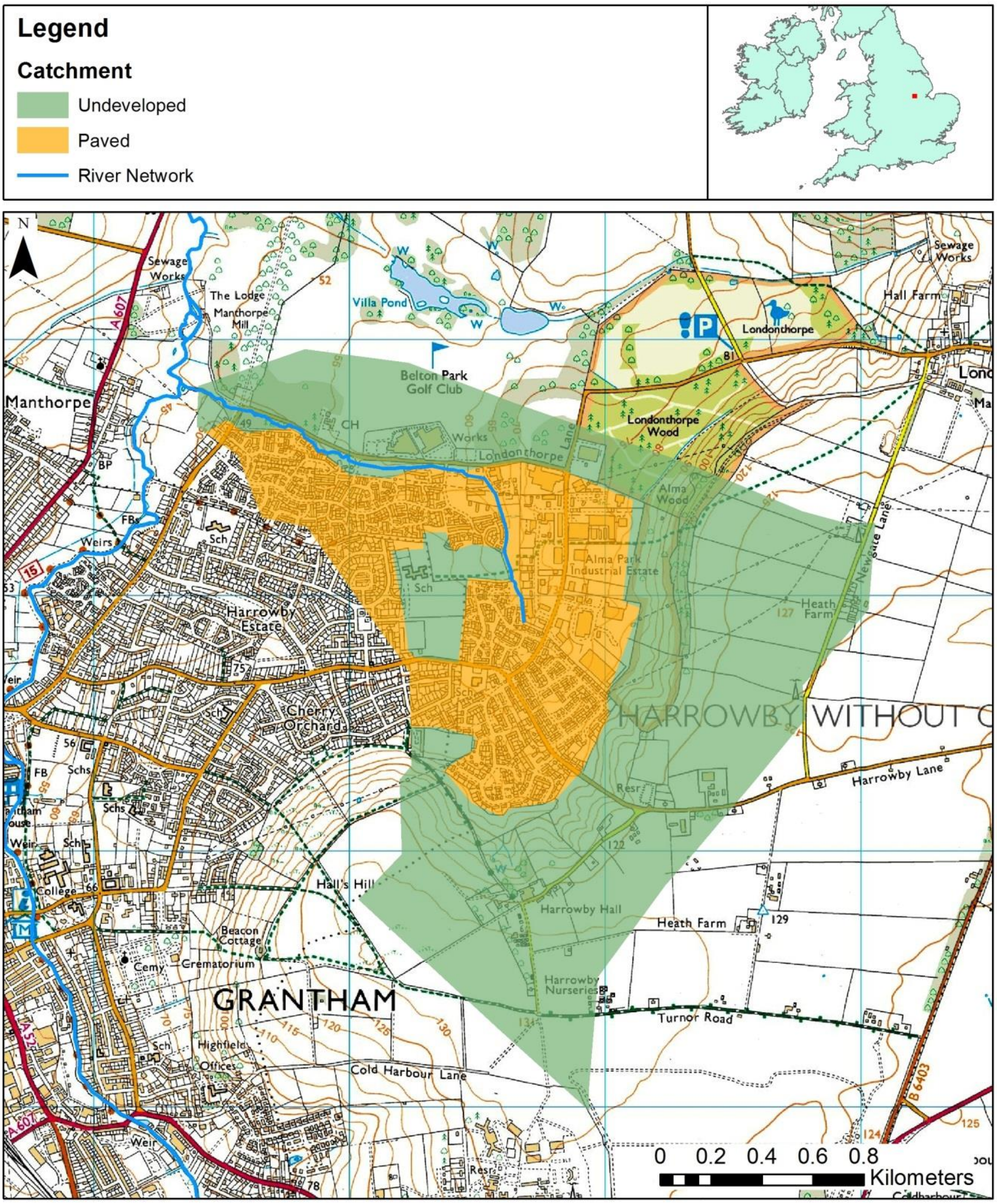
Catchment	Undeveloped Area	Paved Area	Storm Duration	Time Step
Witham Brook	2.43	1.33	4.75	0.25
Mow Beck & Barrowby Stream	5.48	3.71	5.75	0.25

Source: Mott MacDonald

All paved area is assumed to drain into the catchment as no sewer plans or records have been reviewed as part of this study, and assuming that the whole catchment drains towards the two watercourses provides a conservative estimate of the overall contributing catchment. The paved area draining away from the watercourse has therefore been set to 0.

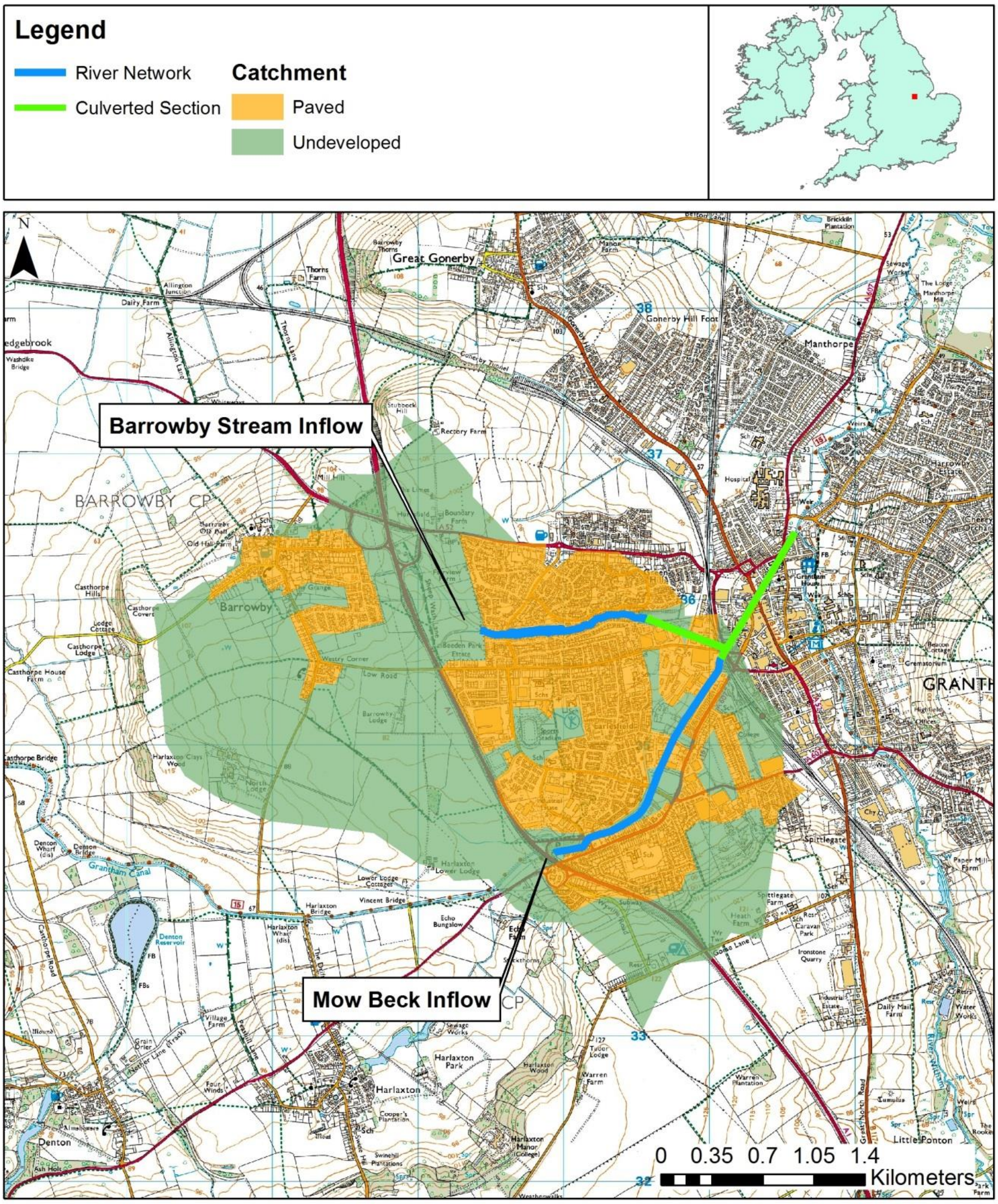
Figure 10.1 and Figure 10.2 shows how the catchments have been split up into undeveloped and paved areas for the Witham Brook and Mow Beck & Barrowby Stream catchments respectively.

Figure 10.1: Paved and Undeveloped Regions of Witham Brook Catchment



Source: Mott MacDonald. This map is reproduced by permission of Ordnance Survey on behalf of The Controller Of Her Majesty's Stationary Office.

Figure 10.2: Paved and Undeveloped Regions of Mow Beck and Barrowby Stream Catchment



Source: Mott MacDonald. This map is reproduced by permission of Ordnance Survey on behalf of The Controller Of Her Majesty's Stationary Office. © Crown Copyright. All rights reserved. Environment Agency 100026380, 2015.

The storm duration has been calculated as the critical storm duration for the lumped ReFH catchment. All other parameters have been left as default.

For Witham Brook a single inflow has been used at the upstream extent of the Witham Brook model. For Mow Beck & Barrowby Stream the flows have been derived for the catchment as a whole (with an area of 9.19km^2), and have been split between the two watercourses according to catchment area (60% to Mow Beck, and 40% to Barrowby Stream). The overall catchment for Mow Beck & Barrowby Stream has been taken as the catchment upstream of the Mow Beck-Grantham and Barrowby Stream-Grantham culvert inlets, similar to the previous hydrological analysis carried out on the catchment. This method assumes that flow originating from the small area downstream of the culvert inlets would be passed forward, through the urban drainage system prior to the arrival of the peak from the upstream catchment.

Table 10.2 and Table 10.3 summarise the peak flows calculated for Witham Brook and Mow Beck & Barrowby Stream respectively, comparing them against the standard ReFH model and flows derived in the previous study. For Witham Brook, two sets of flows calculated during the previous study are presented.

Table 10.2: Peak Flow Comparisons on Witham Brook

				Peak Flows (m^3/s)
AEP	Urban ReFH	Standard ReFH	Previous Study (Lumped Catchment Approach)	Previous Study (Revised Hydrology using Pooling Group derived for Mow Beck and Barrowby Stream)
50%	1.69	0.75	0.21	0.62
20%	2.27	1.01	0.32	1.28
10%	2.77	1.23	0.56	1.59
5%	3.35	1.46	N/A	1.91
4%	3.55	1.54	0.58	2.02
3.33%	3.73	1.61	N/A	N/A
2%	4.28	1.83	0.72	2.38
1.33%	4.77	2.02	0.87	2.62
1%	5.15	2.18	0.93	2.79
0.5%	6.20	2.63	1.31	3.24
0.1%	9.56	4.26	3.44	4.52

Source: Mott MacDonald and Addendum to Witham Catchment Flood Map Improvement Volume 2 Hydraulic Modelling Report

Table 10.3: Peak Flow Comparisons on Mow Beck & Barrowby Stream

	Peak Flows, Mow Beck (m^3/s)			Peak Flows, Barrowby Stream (m^3/s)		
AEP	Urban ReFH	Standard ReFH	Previous Study (FEH Statistical – Pooling Group)	Urban ReFH	Standard ReFH	Previous Study (FEH Statistical – Pooling Group)
50%	2.09	0.92	0.27	1.39	0.62	0.91
20%	2.78	1.24	0.65	1.86	0.82	1.85
10%	3.37	1.48	0.82	2.25	0.99	2.33
5%	4.06	1.75	0.93	2.71	1.16	2.68
4%	4.30	1.83	0.98	2.87	1.22	2.81
3.33%	4.51	1.91		3.01	1.28	
2%	5.17	2.17	1.14	3.44	1.44	3.29
1.33%	5.74	2.38	1.2	3.83	1.59	3.51
1%	6.19	2.56	1.31	4.13	1.70	3.7
0.5%	7.43	3.06	1.42	4.95	2.04	4.04
0.1%	11.36	4.85	1.74	7.58	3.23	5.01

Source: Mott MacDonald and Addendum to Witham Catchment Flood Map Improvement Volume 2 Hydraulic Modelling Report

For Witham Brook, the Urban ReFH method produces flows around twice those of the revised hydrology in the previous study. The hydrology in the previous study was revised as the 0.1%AEP flows were not producing flooding to the extent observed during the June 2007 event, even with a 50% blockage simulated at the industrial estate culvert. Even when the 0.1% (original lumped catchment approach) with 100% runoff was used, giving a peak flow of 7.08m^3/s (without blockage) this did not provide the flood extents that were observed. The Urban ReFH method is therefore considered the most suitable approach for this watercourse.

For Mow Beck and Barrowby Stream, the Urban ReFH is producing flows up to 3 times larger than the FEH Statistical method in the previous study. The above discussion on Witham Brook suggests the FEH Statistical method adopted in the previous study for Witham Brook, which was the same pooling group as derived for Mow Beck and Barrowby Stream may be underestimating the flows along Witham Brook, and therefore the same could be true for Mow Beck and Barrowby Stream.

It is recommended that the Urban ReFH method is used as a starting point for Mow Beck and Barrowby Stream and that the approach is reviewed following hydraulic modelling to ensure that the modelled extents are consistent with any available flood history along the watercourses.

11 Assumptions and Limitations

The final design flows derived as part of this study are subject to a number of assumptions and limitations. The key assumptions and limitations are provided below:

- Availability and reliability of observed level and flow data,
  - The level gauge at Claypole did not pick up the April 1998 event – this has been considered as missing for flood frequency analysis purposes.
  - The level gauge at Saltersford has a blocked stilling well intake, and therefore the data has not been used for deriving QMED at this location.
  - Problems recorded with level gauges at Till Washlands, and Mow Beck.
  - Lack of flow data downstream of the washlands limits being able to verify the flows.
  - No data is available on IDB pump discharged during historic events. This limits confidence in the estimated volume of IDB catchment inflows.
- Reliability of rating curves,
  - The most recent approved ratings have been adopted for deriving AMAX data, however at Colsterworth and Claypole it was noted that particularly for out of bank flows, the model results were not consistent with the approved ratings. In these locations an average of the EA rating derived AMAX series, and model rating derived AMAX series were adopted for flood frequency analysis at these locations.
- Catchment wide hydrological assessment has been focussed on the River Witham, therefore the storm durations and reconciliation of flows to target peak flows has not been used to optimise flows for the minor tributaries, in particular Cringle Brook and Foston Beck. The ReFH models for these tributaries have however been improved through donor transfer.
- Limited flow data was available for the River Till, Boultham Catchwater, Burton Catchwater, Witham Brook, Mow Beck and Barrowby Stream for deriving design inflows.

12 Conclusions and Recommendations

12.1 Conclusions

Design flow estimates have been derived at Colsterworth, Saltersford, Claypole, and Brant Broughton. These have been calculated using the FEH Statistical Method, with the Hybrid ReFH approach used for the 0.2% and 0.1% AEP events. These design flow estimates have been used as target flows for the Upper Witham – Grantham and Upper Witham – Lincoln models, with ReFH inflows scaled accordingly.

Downstream of the target flow location, no flood frequency analysis for the purpose of target flow estimation has been possible due to the significant influence of the Witham, Brant and Till Washlands on attenuating floods through Lincoln. For these catchments, no scaling of the ReFH inflow hydrographs has been carried out and inflows from tributaries have been phased to ensure coincident peaks along the main River Witham. This is consistent with the methodology used during the design of the washlands.

At the upstream limit of the Upper Witham – Lincoln model, a standardised hydrograph profile, taken from the November 2000 event, scaled to the derived target flow for Claypole has been used as the design inflow for the catchment upstream of Claypole.

The ReFH model parameters, Time to Peak, Baseflow Lag and Baseflow Recharge have been optimised at each of the gauged locations for the four calibration and verification events. These optimised parameters have then been used to enhance the ReFH model at the ungauged catchments for design and calibration events.

For the catchment specific models of Witham Brook, Mow Beck & Barrowby Stream, the Urban ReFH model has been used to derive design inflows. The resulting flood outlines have then been discussed with the Environment Agency and Upper Witham IDB, to ensure that the derived flows are suitable, given the limited hydrometric data available.

12.2 Recommendations

It is recommended that as additional data is collected within the Upper Witham Catchment, and following significant events, the analysis carried out in this study, including the optimisation of the ReFH model parameters, is reviewed and updated accordingly.

In addition if any further rating reviews are undertaken, and result in significant changes to the existing ratings, then AMAX data should be updated and the resulting flood frequency analysis revised.

Additional reliable flow gauging is recommended on:

- River Till, upstream of the washlands: There is limited confidence in the flows derived for this catchment,
- River Witham at Saltersford: Although a flow gauge exists, the stilling pipe has been blocked and therefore current flow recordings are unreliable. This is a key gauge for understanding the flows through Grantham

- Mow Beck & Barrowby Stream and Witham Brook: to improve confidence on the flows and resulting flood levels through Grantham.

Recording of levels and pumped volumes from the IDB pumped catchments (particularly Coulson road, Fossdyke Delph and Decoy) during flood events would also be beneficial in improving the understanding of the runoff within the catchments and the volumes pumped from the IDB catchments into the main rivers.

Appendices

Appendix A. Revised Catchment Descriptors

Table A.1: FEH Catchment descriptors for inflow locations

	River Witham upstream of Colsterworth GS	Cringle Brook	R Witham Intermediate C1 (Cringle Brook – Costerworth GS)	R Witham Intermediate C2 (Saltesford – Cringle Brook)	Witham Brook	Barrowby Stream and Mow Beck upstream	Honington Beck	R Witham Intermediate C3 (Foston Beck – Saltersford GS)	R Witham Intermediate C4 (Claypole – Foston Beck)	Foston Beck	R Witham Intermediate C5 (River Brant – Claypole)	R Witham Intermediate C6 (River Brant - Boultham Catchwater)	River Brant upstream of Brant Broughton GS	R Brant Intermediate C1 (Brant Broughton – Confluence with River Witham)	Boultham Catchwater	Main Drain	River Till upstream of Squires Bridge	River Till Intermediate C1 (Squires Bridge – Confluence with	Cricket Till	R Till Intermediate C2 (Cricket Till – Confluence with Fossdyke Canal)	Burton Catchwater	Fossdyke Canal Upstream of River Till
	Colsterworth	Cringle_Br	RW_US_CB	RW_US_Salt	Witham_Br	MowBeck_BS	HoingintonBr	RW_US_FB	RW_US_CP	Foston_Beck	Witham_US_Brant	Witham_US_BC	Brant_GS_US	Brant_GS_DS	Boultham	Main_Drain	RT_US_SQB	RT_US_CT	Cricket Till	RT_US_FD	Burton	FD_US_RT
AREA	50.09	44.93	11.24	15.65	3.76	9.86	24.9	49.3	30.89	60.83	89.01	45.14	65.68	81.14	18.07	41.44	85.78	20.82	7.94	11.51	30.91	27.44
ALTBAR	123	128	119	120	90	81	63	100	86	67	69	56	32	26	15	11	20	20	9	17	20	10
ASPBAR	79	85	72	81	325	104	284	69	28	353	41	10	340	326	57	360	190	199	132	184	251	147
ASPVAR	0.28	0.35	0.2	0.23	0.59	0.39	0.08	0.12	0.14	0.35	0.16	0.14	0.32	0.28	0.31	0.2	0.17	0.18	0.37	0.16	0.54	0.15
BFIHOST	0.656	0.849	0.75	0.794	0.607	0.567	0.592	0.632	0.25	0.464	0.411	0.436	0.369	0.364	0.446	0.439	0.339	0.364	0.368	0.405	0.457	0.347
DPLBAR	7.41	8.33	3.99	4.514	2.1	4.69	5.74	8.466	6.553	10.43	11.682	8.062	8.54	11.104	4.88	12.6	9.08	5.309	1.6	3.81	8.24	6.14
DPSBAR	22.3	33.2	44.85	33.682	49.7	36.4	36.1	31.573	15.51	28.7	7.208	21.146	18.4	13.876	10	6.4	11.1	12.619	4.5	5.324	19.5	6.5
FARL	0.993	0.934	0.994	0.973	1	1	0.977	0.974	0.975	0.969	0.978	0.979	0.995	0.997	0.882	0.93	0.992	0.993	1	0.992	0.938	1
FPEXT	0.1239	0.0834	0.1101	0.0925	0.0193	0.0719	0.1096	0.1013	0.1403		0.2337	0.2894	0.2804	0.4026	0.3907	0.7866	0.2816	0.3026	0.9213	0.3999	0.4498	0.6523
FPDBAR	0.675	0.361	0.62	0.485	0.141	0.398	0.563	0.591	0.789		1.51	1.952	1.418	2.613	3.146	7.558	1.454	1.705	11.737	3.561	5.364	7.212
FPLOC	1.167	1.151	1.159	1.204	0.675	0.915	0.861	0.961	0.805		0.689	0.679	0.824	0.795	0.81	0.913	0.898	0.869	0.932	0.796	0.825	0.819
LDP	14.34	15.44	22.27	26.17	3.75	9.34	11.11	44.17	53.33	20.35	78.5	85.78	16.33	27.3	12	21.12	17.88	22.65	3.14	32.7	16.37	9.4
PROPWET	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.14	0.27	0.25	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
RMED-1H	12.1	11.4	11.9	11.6	10.8	10.2	10.6	11.2	10.9	10.3	10.8	10.8	10.4	10.7	11.2	11.1	11.3	11.2	11	11.2	11.2	11.1
RMED-1D	32.4	33	32.5	32.7	31.9	31.5	30.7	32.1	31.7	31.3	31.5	31.4	30.9	31.1	31.7	30.1	28.4	28.3	27.5	28.3	28.8	28.2
RMED-2D	42.5	42.3	42.4	42.2	41.1	40.2	41.9	41.7	41.1	40.2	40.7	40.6	40.7	40.4	39.5	38.5	36.8	36.7	36.3	36.7	37.1	36.9
SAAR	641	655	646.01	646	618	607	597	618	562	597	564	596	574	579	600	596	592	592	590	597	593	595
SAAR4170	649	656	650	652	648	626	627	644	632	614	620	615	606	604	600	594	619	621	617	617	622	601
SPRHOST	22.63	11.65	16.62	14.43	26.69	32.01	28.97	25.71	51.53	37.74	40.34	38.37	45.2	44.4	35.33	36.5	41.99	41.28	40.02	41.76	36.94	43.95
URBCONC1990	0.415	-999999	0.408	-999999	0.669	0.716	0.37	0.669	0.626	-999999	0.601	0.625	-999999	-999999	0.757	0.639	0.568	0.573	0.581	0.608	0.514	0.783
URBEXT1990	0.0063	0.0014	0.0051	0.0035	0.1067	0.1253	0.0117	0.0237	0.0187	0.0045	0.0161	0.0157	0.0045	0.0044	0.1201	0.0181	0.023	0.0242	0.0265	0.024	0.0082	0.0376
URBLOC1990	0.764	-999999	1.016	-999999	1.059	0.858	0.986	0.696	0.876	-999999	1.028	0.971	-999999	-999999	0.715	0.879	1.271	1.114	1.625	1.061	0.603	0.608
URBCONC2000	0.704	0.658	0.698	0.66	0.802	0.875	0.807	0.82	0.81	-0.02105	0.799	0.807	0.636	0.708	0.882	0.82	0.784	0.766	-999999	0.794	0.76	0.915
URBEXT2000	0.0261	0.0052	0.0214	0.012	0.2322	0.2222	0.0121	0.038	0.029	0.33741	0.011	0.068	0.0071	0.01	0.1492	0.0166	0.0175	0.016	0	0.019	0.0126	0.0303
URBLOC2000	1.001	0.699	1.138	1.224	0.849	0.837	1.412	0.792	0.942	0.33127	1.085	1.056	0.747	0.97	0.714	0.518	1.481	1.282	-999999	1.122	0.469	0.592
C	-0.0224	-0.02122	-0.02209	-0.0215	-0.01948	-0.02043	-0.01846	-0.02069	-0.02086	0.20909	-0.02072	-0.02026	-0.01861	-0.01872	-0.02117	-0.02182	-0.02278	-0.02299	-0.02345	-0.02288	-0.02306	-0.0227
D1	0.35832	0.35344	0.3564	0.35455	0.3458	0.34426	0.31735	0.34535	0.34035	0.30291	0.33145	0.32528	0.31261	0.30955	0.30428	0.28654	0.27616	0.27579	0.26325	0.27381	0.27723	0.26548
D2	0.33149	0.31999	0.33227	0.32453	0.32722	0.31479	0.37831	0.33385	0.33573	2.44511	0.33585	0.33242	0.35802	0.33633	0.25537	0.2781	0.31142	0.30639	0.30492	0.30325	0.28055	0.29885
D3	0.22963	0.2459	0.23237	0.23845	0.2207	0.21972	0.18221	0.22347	0.21834	-0.02	0.21733	0.21485	0.19824	0.20936	0.21724	0.24872	0.26302	0.26483	0.27127	0.26485	0.25914	0.26842
E	0.30605	0.30453	0.30542	0.30475	0.30178	0.30317	0.30026	0.3035	0.30324	0.302	0.30337	0.30339	0.30124	0.30247	0.30751	0.30724	0.30109	0.30234	0.30936	0.30363	0.30812	0.3088
F	2.47138	2.47193	2.47306	2.47141	2.46442	2.44316	2.47834	2.46764	2.4617	0.374	2.47171	2.48481	2.4916	2.51042	2.55542	2.55054	2.55269	2.55105	2.54838	2.55108	2.54976	2.55017
C(1 km)	-0.021	-0.02	-0.02	-0.02	-0.019	-0.019	-0.02	-0.02	-0.022	0.187	-0.019	-0.02	-0.018	-0.019	-0.021	-0.021	-0.024	-0.024	-0.023	-0.021	-0.022	-0.022
D1(1 km)	0.353	0.353	0.353	0.339	0.345	0.345	0.33	0.31	0.313	0.303	0.314	0.319	0.296	0.314	0.317	0.31	0.272	0.265	0.26	0.304	0.311	0.275
D2(1 km)	0.341	0.313	0.313	0.313	0.33	0.33	0.364	0.385	0.372	2.471	0.266	0.254	0.334	0.262	0.254	0.263	0.302	0.305	0.312	0.265	0.261	0.273
D3(1 km)	0.245	0.242	0.242	0.244	0.22	0.22	0.182	0.203	0.23		0.205	0.186	0.216	0.207	0.19	0.196	0.263	0.27	0.272	0.214	0.218	0.261
E(1 km)	0.305	0.302	0.302	0.301	0.303	0.303	0.302	0.302	0.304		0.305	0.305	0.302	0.306	0.307	0.308	0.309	0.311	0.309	0.307	0.31	0.307
F(1 km)	2.475	2.478	2.478	2.464	2.444	2.444	2.451	2.444	2.452		2.524	2.557	2.54	2.526	2.555	2.541	2.547	2.54	2.549	2.558	2.552	2.556

Source: FEH CD-ROM

Appendix B. AMAX Data

Table B.1: Summary of AMAX Data Used in Study (Red values are where changes have been made from the original AMAX as part of this study)

Water Year	Colsterworth				Saltersford			Claypole				Cringle Brook			Allington			Honington Beck			North Hykeham				Brant Broughton		
	Date	Level	Flow	Revised Flow	Date	Level	Flow	Date	Level	Flow	Revised Flow	Date	Level	Flow	Date	Level	Flow	Date	Level	Flow	Date	Level	Flow	Revised Flow	Date	Level	Flow
1960								30/01/1960	Not Available	17.55	16.69																
1961								04/12/1960	Not Available	28.88	25.99																
1962								06/01/1962	Not Available	8.63	8.63																
1963								30/03/1963	Not Available	7.93	7.90																
1964								05/03/1964	Not Available	12.63	12.63																
1965								29/09/1965	Not Available	5.38	5.38																
1966								10/12/1965	Not Available	18.32	17.35																
1967								15/05/1967	Not Available	22.93	21.22																
1968								11/07/1968	Not Available	11.61	11.61																
1969					16/05/1969	Not Available	14.48	03/11/1968	Not Available	25.90	23.63																
1970					12/04/1970	Not Available	5.14	13/04/1970	Not Available	14.72	14.72																
1971					24/01/1971	Not Available	5.47	24/01/1971	0.65	14.11	14.11																
1972					07/03/1972	Not Available	3.05	08/03/1972	0.55	9.71	9.71																
1973					28/06/1973	Not Available	3.38	20/06/1973	0.50	7.82	7.82																
1974					09/02/1974	Not Available	4.13	09/02/1974	0.49	7.46	7.46																
1975					09/03/1975	Not Available	15.20	09/03/1975	0.96	33.03	29.19																
1976					11/12/1975	Not Available	1.04	01/12/1975	0.42	5.16	5.16																
1977					25/02/1977	Not Available	9.66	11/02/1977	1.02	37.53	32.56																
1978					06/05/1978	Not Available	8.11	05/05/1978	0.89	28.06	25.34																
1979	29/12/1978	0.88	7.33	7.33	08/04/1979	Not Available	9.07	01/02/1979	0.86	25.86	23.60																
1980	15/08/1980	1.12	11.66	10.51	15/08/1980	Not Available	17.58	15/08/1980	0.89	27.99	25.29																
1981	27/04/1981	1.10	11.28	10.30	27/04/1981	Not Available	12.93	27/04/1981	0.91	29.60	26.59	27/04/1981	0.62	2.08													
1982	26/06/1982	1.12	11.55	10.45	26/06/1982	Not Available	10.96	07/03/1982	0.69	16.20	16.20	26/06/1982	0.61	1.98													
1983	01/06/1983	0.75	5.42	5.42	01/06/1983	Not Available	8.05	01/06/1983	0.77	20.40	19.09	21/05/1983	0.62	2.05													
1984	31/01/1984	0.73	5.20	5.20	31/01/1984	Not Available	6.92	29/01/1984	0.73	18.20	17.28	02/02/1984	0.46	1.17				30/01/1984	0.57	3.02							
1985	21/01/1985	0.69	4.58	4.58	23/03/1985	0.73	6.57	22/01/1985	0.62	12.70	12.70	23/03/1985	0.49	1.33				23/11/1984	0.45	1.86							

Water Year	Colsterworth				Saltersford			Claypole				Cringle Brook			Allington			Honington Beck			North Hykeham				Brant Broughton		
	Date	Level	Flow	Revised Flow	Date	Level	Flow	Date	Level	Flow	Revised Flow	Date	Level	Flow	Date	Level	Flow	Date	Level	Flow	Date	Level	Flow	Revised Flow	Date	Level	Flow
1986	10/01/1986	0.80	6.17	6.17	10/01/1986	0.80	8.43	10/01/1986	0.68	15.50	15.50	17/04/1986	0.55	1.62				10/01/1986	0.41	1.49							
1987	07/04/1987	0.80	6.23	6.23	08/04/1987	0.67	5.26	08/04/1987	0.60	11.60	11.60	07/04/1987	0.53	1.55				12/02/1987	0.31	0.81							
1988	24/01/1988	0.92	8.08	8.08	24/01/1988	0.94	12.30	24/01/1988	0.76	19.90	18.66	24/01/1988	0.57	1.73				24/01/1988	0.53	2.55							
1989	05/04/1989	0.53	2.70	2.70	06/04/1989	0.57	3.49	07/04/1989	0.58	11.00	11.00	05/04/1989	0.32	0.65	07/04/1989	0.53	2.15	07/04/1989	0.27	0.57							
1990	08/02/1990	0.75	5.47	5.47	08/02/1990	0.77	7.54	01/03/1990	0.66	14.60	14.60	08/02/1990	0.45	1.10	28/02/1990	0.66	3.06	28/02/1990	0.38	1.25							
1991	28/02/1991	0.59	3.43	3.43	28/02/1991	0.64	4.79	28/02/1991	0.60	11.60	11.60	28/02/1991	0.39	0.85	28/02/1991	0.56	2.39	30/09/1991	0.39	1.36					28/02/1991	0.76	5.96
1992	23/09/1992	0.73	5.19	5.19	09/01/1992	0.71	6.17	23/09/1992	0.53	8.74	8.74	23/09/1992	0.40	0.89	09/01/1992	0.36	1.03	23/09/1992	0.40	1.39					09/01/1992	0.32	0.91
1993	13/01/1993	0.96	8.75	8.75	14/01/1993	0.91	11.50	07/12/1992	0.59	11.50	11.50	14/01/1993	0.57	1.74	13/01/1993	0.85	4.56	03/10/1992	0.51	2.38					13/01/1993	0.97	9.08
1994	26/02/1994	0.72	5.05	5.05	05/01/1994	0.80	8.35	13/12/1993	0.69	16.10	16.10	05/01/1994	0.58	1.81	26/02/1994	0.66	3.05	15/09/1994	0.51	2.39					12/12/1993	1.02	9.54
1995	26/01/1995	0.78	5.86	5.86	26/01/1995	0.66	5.02	27/12/1994	0.70	16.80	16.07	26/01/1995	0.56	1.67	26/01/1995	1.10	6.48	26/01/1995	0.65	3.93					26/01/1995	1.21	11.38
1996	12/02/1996	0.52	2.60	2.60	10/01/1996	0.46	1.95	12/02/1996	0.44	5.73	5.73	26/02/1996	0.25	0.47	12/02/1996	0.42	1.38	26/02/1996	0.22	0.33					26/02/1996	0.38	1.40
1997	09/07/1997	0.54	2.89	2.89	27/06/1997	0.48	2.11	29/06/1997	0.47	6.88	6.88	27/06/1997	0.30	0.59	27/06/1997	0.26	0.49	28/06/1997	0.43	1.65					31/08/1997	0.38	1.41
1998	10/04/1998	1.52	20.24	16.70	11/04/1998	0.86	10.00	03/01/1998	0.74	18.80	MISSING	10/04/1998	0.86	3.84	10/04/1998	1.64	10.42	10/04/1998	0.86	6.64	12/04/1998	6.33	35.90	41.73	10/04/1998	1.17	10.99
1999	16/01/1999	0.78	5.92	5.92	16/01/1999	0.71	6.17	26/12/1998	0.84	24.60	22.56	26/12/1998	0.64	2.20	10/03/1999	1.15	6.75	10/03/1999	0.73	4.83	10/03/1999	6.49	38.90	45.88	10/03/1999	1.23	11.55
2000	03/04/2000	0.77	5.74	5.74	04/04/2000	0.85	9.64	04/04/2000	0.70	16.50	16.50	04/04/2000	0.50	1.37	03/04/2000	0.85	4.51	20/09/2000	0.45	1.87	04/04/2000	6.33	35.80	41.60	04/04/2000	1.01	9.40
2001	06/11/2000	1.08	10.79	10.01	19/07/2001	0.70	5.95	06/11/2000	0.93	31.10	27.69	18/07/2001	0.79	3.28	18/07/2001	1.28	7.65	06/11/2000	0.93	7.81	06/11/2000	6.43	36.90	43.10	06/11/2000	1.66	16.52
2002	26/01/2002	0.87	7.22	7.22	27/01/2002	0.66	5.20	22/10/2001	0.72	17.50	16.67	26/01/2002	0.49	1.30	22/10/2001	0.94	5.29	21/10/2001	0.35	1.04	23/10/2001	5.48	19.70	21.35	26/01/2002	0.55	3.22
2003	16/10/2002	1.06	10.55	10.29	16/10/2002	1.00	14.40	22/12/2002	0.75	19.50	18.32	30/12/2002	0.55	1.61	22/12/2002	0.82	4.33	29/12/2002	0.40	1.42	30/12/2002	6.27	32.30	36.93	30/12/2002	1.10	10.34
2004	31/01/2004	0.63	3.87	3.87	01/02/2004	0.65	4.84	10/08/2004	0.77	20.60	19.29	31/01/2004	0.42	0.95	13/08/2004	0.89	4.90	13/08/2004	0.89	7.09	01/02/2004	5.90	24.70	27.32	31/01/2004	1.07	9.98
2005	24/10/2004	0.68	4.51	4.51	24/10/2004	0.58	3.68	24/10/2004	0.72	17.90	16.99	24/10/2004	0.41	0.92	23/10/2004	0.84	4.50	23/10/2004	0.48	2.07	25/02/2005	5.11	26.30	29.28	24/10/2004	1.23	11.53
2006	11/03/2006	0.50	2.41	2.41	23/05/2006	0.50	2.38	22/05/2006	0.46	6.29	6.29	22/05/2006	0.39	0.84	30/12/2005	0.41	1.34	25/09/2006	0.23	0.41	23/05/2006	4.96	9.69	10.11	30/12/2005	0.34	1.08
2007	20/07/2007	0.86	7.14	7.14	21/07/2007	0.75	7.11	26/06/2007	0.92	30.10	26.97	05/07/2007	0.47	1.23	25/06/2007	1.61	10.12	25/06/2007	1.31	14.88	26/06/2007	6.62	32.60	37.32	26/06/2007	1.87	19.30
2008	16/03/2008	0.87	7.27	7.27	07/06/2008	0.67	5.36	16/01/2008	0.71	17.00	16.25	16/03/2008	0.47	1.22	16/01/2008	0.80	4.10	16/01/2008	0.56	2.83	16/01/2008	6.22	31.90	36.40	16/01/2008	1.19	11.19
2009	02/11/2008	0.70	4.84	4.84	02/11/2008	0.74	6.76	10/02/2009	0.82	23.40	21.58	16/02/2009	0.46	1.16	10/02/2009	0.94	5.35	10/02/2009	0.72	4.70	11/02/2009	6.25	32.50	37.19	10/02/2009	1.25	11.75
2010	16/01/2010	0.62	3.78	3.78	16/01/2010	0.70	6.02	16/01/2010	0.66	14.50	14.50	16/01/2010	0.44	1.07	15/01/2010	0.55	2.34	16/01/2010	0.38	1.26	17/01/2010	5.81	21.50	23.47	22/01/2010	0.99	9.23
2011	09/11/2010	0.45	1.95	1.95	09/11/2010	0.50	2.49	26/02/2011	0.52	8.60	8.60	26/02/2011	0.27	0.53	26/02/2011	0.48	1.77	04/10/2010	0.40	1.42	27/02/2011	5.22	14.40	15.29	26/02/2011	0.52	2.75
2012	29/04/2012	0.81	6.27	6.27	30/04/2012	0.83	9.14	07/07/2012	0.78	21.20	19.78	29/04/2012	0.47	1.20	06/07/2012	1.48	9.08	29/04/2012	0.79	5.66	07/07/2012	5.85	18.80	20.30	29/04/2012	1.65	16.33
2013	27/01/2013	1.10	11.26	9.87	27/01/2013	1.08	17.20	25/11/2012	0.83	24.00	22.04	24/12/2012	0.60	1.93	27/01/2013	0.95	5.38	25/11/2012	0.86	6.76	26/11/2012	6.38	34.00	39.17	25/11/2012	1.36	12.84
2014	28/10/2013	0.81	6.33	6.33	28/10/2013	0.73	6.57	26/01/2014	0.64	13.70	13.70	01/02/2014	0.43	1.01	06/01/2014	0.67	3.12	26/01/2014	0.32	0.86	27/01/2014	5.58	39.50	46.73	06/01/2014	1.00	9.32

Source: EA AMAX Data

Appendix C. Concurrent Event Analysis for Saltersford Gauging Station

Table C.1 provides the data used to generate Figure 5.5 and Figure 5.6, comparing the peak flows and specific runoff of concurrent AMAX events at Colsterworth, Saltersford and Claypole.

Table C.1: Summary of AMAX Data for Concurrent Events at Colsterworth, Saltersford and Claypole Gauging Stations

	Peak Flow Recorded at:			Specific Runoff at:		
Water Year	Colsterworth (m^3/s)	Saltersford (m^3/s)	Claypole (m^3/s)	Colsterworth (L/s/Ha)	Saltersford (L/s/Ha)	Claypole (L/s/Ha)
1980	11.66	17.58	27.99	2.39	1.42	0.93
1981	11.28	12.93	29.60	2.31	1.05	0.99
1983	5.42	8.05	20.40	1.11	0.65	0.68
1984	5.20	6.92	18.20	1.07	0.56	0.61
1986	6.17	8.43	15.50	1.27	0.68	0.52
1987	6.23	5.26	11.60	1.28	0.43	0.39
1988	8.08	12.30	19.90	1.66	1.00	0.66
1989	2.70	3.49	11.00	0.55	0.28	0.37
1991	3.43	4.79	11.60	0.70	0.39	0.39
2000	5.74	9.64	16.50	1.18	0.78	0.55
2005	4.51	3.68	17.90	0.92	0.30	0.60
2010	3.78	6.02	14.50	0.78	0.49	0.48

Appendix D. Regression Analysis at North Hykeham Gauging Station

Regression analysis was carried out at North Hykeham gauging station to compare the ultrasonic flow records against spot gaugings. The data used is provided in Table D.1.

Table D.1: Summary of Spot Gauging Data and Concurrent Ultrasonic Gauge Readings at North Hykeham Gauging Station

Date and Time of Spot Gauging	Spot Gauged Flow (m^3/s)	Ultrasonic Recorded Flow (m^3/s)
29.07.1999 08:02	0.529	0.63
31.03.2000 08:24	1.465	1.18
31.03.2000 09:45	1.177	1.52
13.06.2000 12:40	1.981	1.83
26.07.2000 08:10	0.888	0.87
26.07.2000 09:34	0.935	0.88
31.10.2000 10:34	21.625	19.00
17.01.2001 09:52	4.301	4.03
04.07.2001 13:16	0.599	0.97
24.07.2001 12:42	2.864	3.37
08.08.2001 09:47	3.076	3.20
22.01.2004 12:06	7.474	7.34
19.01.2005 10:34	1.68	1.62
26.06.2007 10:42	35.985	31.70
14.12.2011 09:59	1.14	1.17
01.05.2012 13:52	24.338	7.51
25.11.2012 15:00	28.979	27.40
21.12.2012 12:28	30.901	28.50
17.12.2013 11:00	1.245	1.04
22.01.2014 12:54	7.643	6.43
20.11.2014 13:26	3.386	3.10
24.11.2014 13:07	9.778	8.91

Linear Regression analysis was carried out on the percentage difference between the spot gauged flow, and the ultrasonic recorded flow. This was carried out on two sets of data:

1. The whole data set
2. Spot gaugings which were in excess of $3m^3/s$

The derived relationship between the spot gauged flow and ultrasonic recorded flow, along with the corresponding R^2 value is provided below.

Whole data set

$$Q_{SPOT\ GAUGE} = \frac{Q_{ULTRASONIC}}{1 - 0.0035Q_{ULTRASONIC} - 0.0037}$$

$R^2 = 0.0816$

Spot gaugings in excess of $3m^3/s$.

$$Q_{SPOT\ GAUGE} = \frac{Q_{ULTRASONIC}}{1 - 0.0032Q_{ULTRASONIC} - 0.01}$$

$R^2 = 0.1539$

In both cases the R^2 value is not very high due to the high scatter of results near the lower spot-gaugings. The equation derived using the spot gaugings in excess of $3m^3/s$ has been used to estimate AMAX data as detailed in Section 5.1, however the final derived QMED value from the revised AMAX has also been compared against QMED derived using donor transfer to ensure that the final value is sensible.

Appendix E. POT Analysis at River Till at Washlands

POT analysis has been carried out at the River Till at Washlands site, using level data from 2001, 2002, 2006, 2007 and 2008. A threshold value of 5.0mAOD was used. Table E.1 provides the POT data series.

Table E.1: POT Data Series at River Till at Washlands

Date	Level (mAOD)	Rank
30/10/2000	5.59	7
06/11/2000	5.81	3
26/11/2000	5.00	18
01/01/2001	5.03	14
24/01/2001	5.47	8
04/02/2001	5.61	6
07/04/2001	5.01	16
13/07/2001	6.00	1
27/10/2001	5.06	13
29/07/2002	5.18	11
27/08/2002	5.06	12
13/07/2007	5.29	9
21/07/2007	5.62	5
27/07/2007	5.02	15
12/01/2008	5.26	10
15/01/2008	5.79	4
20/01/2008	5.91	2
01/05/2008	5.01	17

Source: EA Data

The median annual maximum flood level (LMED) has been estimated from this data series using FEH Equation 3.2.1:

$$LMED = wL_i + (1 - w)L_{i+1}$$

Where L_i is the ith ranked flood level (i determined by the number of years of data available), and w is a weighting dependant on the number of years data available.

For 5 years of data, the FEH handbook gives:

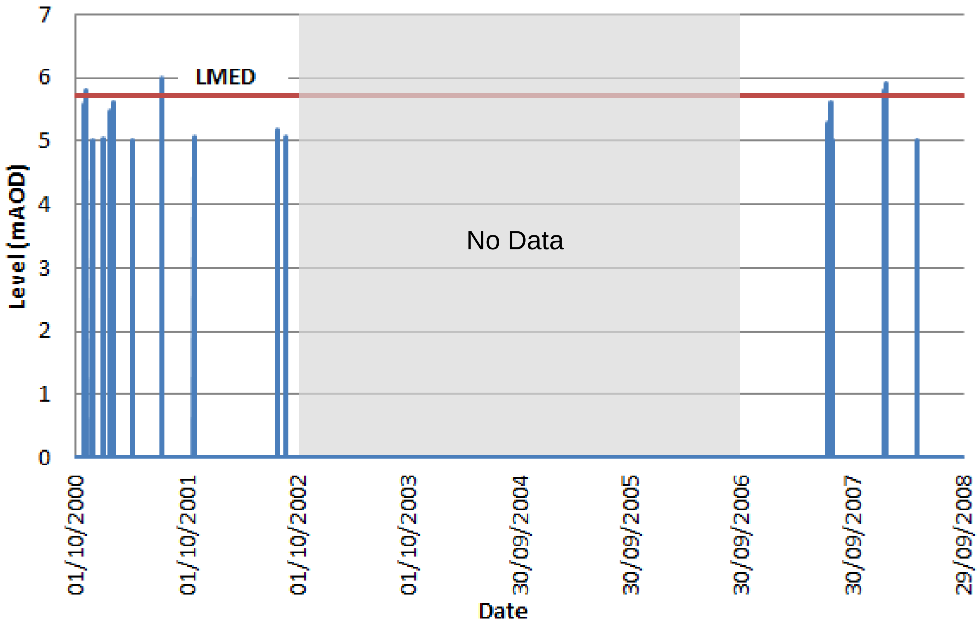
$$i = 4, w = 0.509$$

Therefore:

$$LMED = 0.509 * 5.79 + (1 - 0.509) * 5.62 = 5.71mAOD$$

Figure E.1 shows the POT series, with the derived LMED value

Figure E.1: POT series at River Till at Washlands

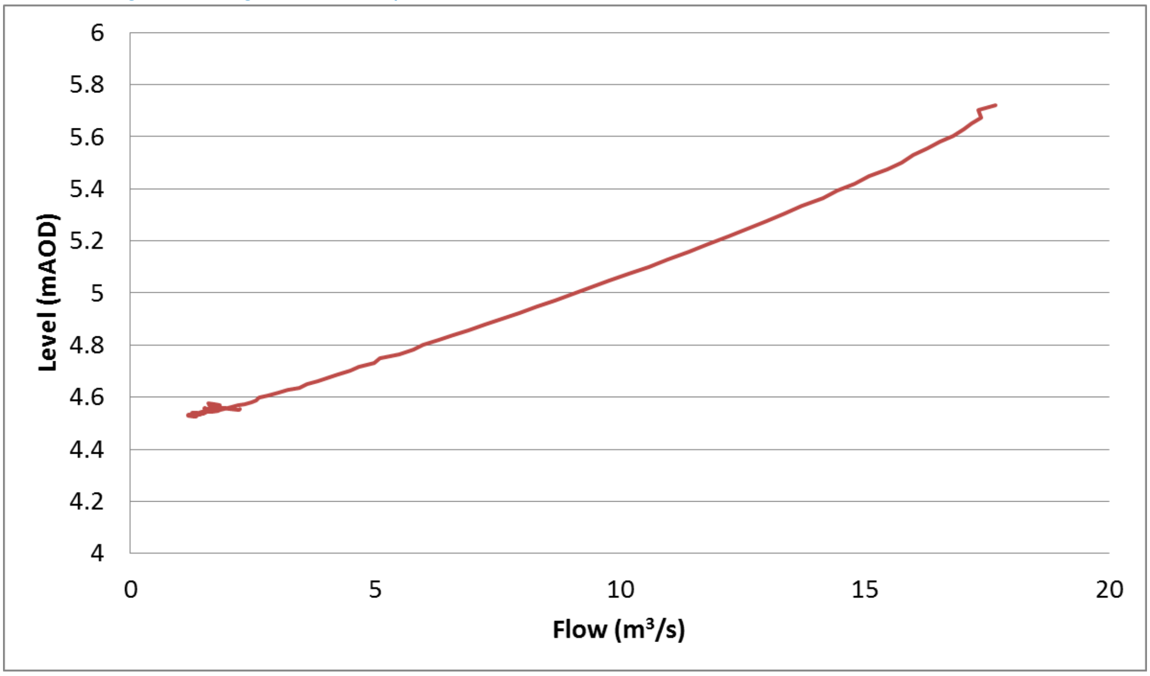


Source: Mott MacDonald

QMED has then been estimated from the LMED value using a stage discharge relationship extracted from the hydraulic model. The stage discharge relationship used is shown in Figure E.2. The Till washlands open at roughly a level of 5.8mAOD, and therefore the stage discharge relationship is valid up to this level, and in particular at the LMED level of 5.71mAOD.

The stage-discharge relationship gives a flow value of 17.5m^3/s for the LMED level of 5.71mAOD. Giving an estimated QMED value of 17.5 m^3/s.

Figure E.2: Stage-Discharge Relationship at River Till at Washlands



Source: Mott MacDonald

Mott MacDonald

Appendix F. Claypole Dimensionless Hydrograph Ordinates

Table F.1: Dimensionless Hydrograph Ordinates for Claypole

Time Ordinate (Hr)				
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
-30.00	-18.00	-27.00	-34.50	0.11
-29.75	-17.85	-26.78	-34.21	0.11
-29.50	-17.70	-26.55	-33.93	0.11
-29.25	-17.55	-26.33	-33.64	0.11
-29.00	-17.40	-26.10	-33.35	0.11
-28.75	-17.25	-25.88	-33.06	0.11
-28.50	-17.10	-25.65	-32.78	0.11
-28.25	-16.95	-25.43	-32.49	0.11
-28.00	-16.80	-25.20	-32.20	0.11
-27.75	-16.65	-24.98	-31.91	0.11
-27.50	-16.50	-24.75	-31.63	0.11
-27.25	-16.35	-24.53	-31.34	0.11
-27.00	-16.20	-24.30	-31.05	0.11
-26.75	-16.05	-24.08	-30.76	0.11
-26.50	-15.90	-23.85	-30.48	0.11
-26.25	-15.75	-23.63	-30.19	0.11
-26.00	-15.60	-23.40	-29.90	0.11
-25.75	-15.45	-23.18	-29.61	0.11
-25.50	-15.30	-22.95	-29.33	0.11
-25.25	-15.15	-22.73	-29.04	0.11
-25.00	-15.00	-22.50	-28.75	0.11
-24.75	-14.85	-22.28	-28.46	0.11
-24.50	-14.70	-22.05	-28.18	0.11
-24.25	-14.55	-21.83	-27.89	0.11
-24.00	-14.40	-21.60	-27.60	0.11
-23.75	-14.25	-21.38	-27.31	0.11
-23.50	-14.10	-21.15	-27.03	0.11
-23.25	-13.95	-20.93	-26.74	0.12
-23.00	-13.80	-20.70	-26.45	0.12
-22.75	-13.65	-20.48	-26.16	0.13
-22.50	-13.50	-20.25	-25.88	0.14
-22.25	-13.35	-20.03	-25.59	0.14
-22.00	-13.20	-19.80	-25.30	0.15
-21.75	-13.05	-19.58	-25.01	0.16
-21.50	-12.90	-19.35	-24.73	0.17
-21.25	-12.75	-19.13	-24.44	0.18
-21.00	-12.60	-18.90	-24.15	0.19
-20.75	-12.45	-18.68	-23.86	0.21
-20.50	-12.30	-18.45	-23.58	0.23
-20.25	-12.15	-18.23	-23.29	0.25
-20.00	-12.00	-18.00	-23.00	0.28
-19.75	-11.85	-17.78	-22.71	0.30

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
-19.50	-11.70	-17.55	-22.43	0.33
-19.25	-11.55	-17.33	-22.14	0.36
-19.00	-11.40	-17.10	-21.85	0.39
-18.75	-11.25	-16.88	-21.56	0.42
-18.50	-11.10	-16.65	-21.28	0.45
-18.25	-10.95	-16.43	-20.99	0.47
-18.00	-10.80	-16.20	-20.70	0.50
-17.75	-10.65	-15.98	-20.41	0.52
-17.50	-10.50	-15.75	-20.13	0.54
-17.25	-10.35	-15.53	-19.84	0.56
-17.00	-10.20	-15.30	-19.55	0.58
-16.75	-10.05	-15.08	-19.26	0.61
-16.50	-9.90	-14.85	-18.98	0.63
-16.25	-9.75	-14.63	-18.69	0.64
-16.00	-9.60	-14.40	-18.40	0.66
-15.75	-9.45	-14.18	-18.11	0.68
-15.50	-9.30	-13.95	-17.83	0.69
-15.25	-9.15	-13.73	-17.54	0.71
-15.00	-9.00	-13.50	-17.25	0.72
-14.75	-8.85	-13.28	-16.96	0.73
-14.50	-8.70	-13.05	-16.68	0.74
-14.25	-8.55	-12.83	-16.39	0.75
-14.00	-8.40	-12.60	-16.10	0.77
-13.75	-8.25	-12.38	-15.81	0.78
-13.50	-8.10	-12.15	-15.53	0.78
-13.25	-7.95	-11.93	-15.24	0.79
-13.00	-7.80	-11.70	-14.95	0.80
-12.75	-7.65	-11.48	-14.66	0.80
-12.50	-7.50	-11.25	-14.38	0.80
-12.25	-7.35	-11.03	-14.09	0.81
-12.00	-7.20	-10.80	-13.80	0.81
-11.75	-7.05	-10.58	-13.51	0.81
-11.50	-6.90	-10.35	-13.23	0.81
-11.25	-6.75	-10.13	-12.94	0.81
-11.00	-6.60	-9.90	-12.65	0.81
-10.75	-6.45	-9.68	-12.36	0.82
-10.50	-6.30	-9.45	-12.08	0.82
-10.25	-6.15	-9.23	-11.79	0.82
-10.00	-6.00	-9.00	-11.50	0.83
-9.75	-5.85	-8.78	-11.21	0.84
-9.50	-5.70	-8.55	-10.93	0.84
-9.25	-5.55	-8.33	-10.64	0.85
-9.00	-5.40	-8.10	-10.35	0.86

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
-8.75	-5.25	-7.88	-10.06	0.86
-8.50	-5.10	-7.65	-9.78	0.86
-8.25	-4.95	-7.43	-9.49	0.87
-8.00	-4.80	-7.20	-9.20	0.87
-7.75	-4.65	-6.98	-8.91	0.88
-7.50	-4.50	-6.75	-8.63	0.88
-7.25	-4.35	-6.53	-8.34	0.89
-7.00	-4.20	-6.30	-8.05	0.89
-6.75	-4.05	-6.08	-7.76	0.89
-6.50	-3.90	-5.85	-7.48	0.90
-6.25	-3.75	-5.63	-7.19	0.90
-6.00	-3.60	-5.40	-6.90	0.91
-5.75	-3.45	-5.18	-6.61	0.91
-5.50	-3.30	-4.95	-6.33	0.92
-5.25	-3.15	-4.73	-6.04	0.94
-5.00	-3.00	-4.50	-5.75	0.95
-4.75	-2.85	-4.28	-5.46	0.96
-4.50	-2.70	-4.05	-5.18	0.96
-4.25	-2.55	-3.83	-4.89	0.97
-4.00	-2.40	-3.60	-4.60	0.98
-3.75	-2.25	-3.38	-4.31	0.98
-3.50	-2.10	-3.15	-4.03	0.98
-3.25	-1.95	-2.93	-3.74	0.99
-3.00	-1.80	-2.70	-3.45	0.98
-2.75	-1.65	-2.48	-3.16	0.98
-2.50	-1.50	-2.25	-2.88	0.98
-2.25	-1.35	-2.03	-2.59	0.98
-2.00	-1.20	-1.80	-2.30	0.98
-1.75	-1.05	-1.58	-2.01	0.98
-1.50	-0.90	-1.35	-1.73	0.99
-1.25	-0.75	-1.13	-1.44	0.99
-1.00	-0.60	-0.90	-1.15	0.99
-0.75	-0.45	-0.68	-0.86	0.99
-0.50	-0.30	-0.45	-0.58	0.99
-0.25	-0.15	-0.23	-0.29	1.00
0.00	0.00	0.00	0.00	1.00
0.25	0.15	0.23	0.29	1.00
0.50	0.30	0.45	0.58	1.00
0.75	0.45	0.67	0.86	1.00
1.00	0.60	0.90	1.15	1.00
1.25	0.75	1.13	1.44	1.00
1.50	0.90	1.35	1.73	1.00
1.75	1.05	1.58	2.01	1.00

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
2.00	1.20	1.80	2.30	1.00
2.25	1.35	2.03	2.59	1.00
2.50	1.50	2.25	2.88	1.00
2.75	1.65	2.48	3.16	0.99
3.00	1.80	2.70	3.45	0.99
3.25	1.95	2.93	3.74	0.99
3.50	2.10	3.15	4.03	0.98
3.75	2.25	3.38	4.31	0.98
4.00	2.40	3.60	4.60	0.97
4.25	2.55	3.83	4.89	0.97
4.50	2.70	4.05	5.18	0.97
4.75	2.85	4.28	5.46	0.96
5.00	3.00	4.50	5.75	0.96
5.25	3.15	4.73	6.04	0.96
5.50	3.30	4.95	6.33	0.95
5.75	3.45	5.18	6.61	0.92
6.00	3.60	5.40	6.90	0.92
6.25	3.75	5.63	7.19	0.91
6.50	3.90	5.85	7.48	0.91
6.75	4.05	6.08	7.76	0.91
7.00	4.20	6.30	8.05	0.90
7.25	4.35	6.53	8.34	0.90
7.50	4.50	6.75	8.63	0.90
7.75	4.65	6.98	8.91	0.89
8.00	4.80	7.20	9.20	0.89
8.25	4.95	7.43	9.49	0.88
8.50	5.10	7.65	9.78	0.88
8.75	5.25	7.88	10.06	0.88
9.00	5.40	8.10	10.35	0.87
9.25	5.55	8.33	10.64	0.86
9.50	5.70	8.55	10.93	0.86
9.75	5.85	8.78	11.21	0.85
10.00	6.00	9.00	11.50	0.85
10.25	6.15	9.23	11.79	0.84
10.50	6.30	9.45	12.08	0.83
10.75	6.45	9.68	12.36	0.82
11.00	6.60	9.90	12.65	0.82
11.25	6.75	10.13	12.94	0.81
11.50	6.90	10.35	13.23	0.80
11.75	7.05	10.58	13.51	0.80
12.00	7.20	10.80	13.80	0.80
12.25	7.35	11.03	14.09	0.78
12.50	7.50	11.25	14.38	0.77

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
12.75	7.65	11.48	14.66	0.76
13.00	7.80	11.70	14.95	0.75
13.25	7.95	11.93	15.24	0.74
13.50	8.10	12.15	15.53	0.74
13.75	8.25	12.38	15.81	0.73
14.00	8.40	12.60	16.10	0.72
14.25	8.55	12.83	16.39	0.71
14.50	8.70	13.05	16.68	0.71
14.75	8.85	13.28	16.96	0.70
15.00	9.00	13.50	17.25	0.69
15.25	9.15	13.73	17.54	0.68
15.50	9.30	13.95	17.83	0.67
15.75	9.45	14.18	18.11	0.67
16.00	9.60	14.40	18.40	0.66
16.25	9.75	14.63	18.69	0.65
16.50	9.90	14.85	18.98	0.65
16.75	10.05	15.08	19.26	0.64
17.00	10.20	15.30	19.55	0.63
17.25	10.35	15.53	19.84	0.63
17.50	10.50	15.75	20.13	0.62
17.75	10.65	15.98	20.41	0.61
18.00	10.80	16.20	20.70	0.61
18.25	10.95	16.43	20.99	0.60
18.50	11.10	16.65	21.28	0.59
18.75	11.25	16.88	21.56	0.59
19.00	11.40	17.10	21.85	0.58
19.25	11.55	17.33	22.14	0.57
19.50	11.70	17.55	22.43	0.57
19.75	11.85	17.78	22.71	0.56
20.00	12.00	18.00	23.00	0.56
20.25	12.15	18.23	23.29	0.55
20.50	12.30	18.45	23.58	0.55
20.75	12.45	18.68	23.86	0.54
21.00	12.60	18.90	24.15	0.54
21.25	12.75	19.13	24.44	0.54
21.50	12.90	19.35	24.73	0.53
21.75	13.05	19.58	25.01	0.53
22.00	13.20	19.80	25.30	0.52
22.25	13.35	20.03	25.59	0.52
22.50	13.50	20.25	25.88	0.51
22.75	13.65	20.48	26.16	0.51
23.00	13.80	20.70	26.45	0.51
23.25	13.95	20.93	26.74	0.50

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
23.50	14.10	21.15	27.03	0.50
23.75	14.25	21.38	27.31	0.49
24.00	14.40	21.60	27.60	0.49
24.25	14.55	21.83	27.89	0.49
24.50	14.70	22.05	28.18	0.49
24.75	14.85	22.28	28.46	0.48
25.00	15.00	22.50	28.75	0.48
25.25	15.15	22.73	29.04	0.48
25.50	15.30	22.95	29.33	0.47
25.75	15.45	23.18	29.61	0.47
26.00	15.60	23.40	29.90	0.47
26.25	15.75	23.63	30.19	0.47
26.50	15.90	23.85	30.48	0.47
26.75	16.05	24.08	30.76	0.47
27.00	16.20	24.30	31.05	0.47
27.25	16.35	24.53	31.34	0.46
27.50	16.50	24.75	31.63	0.46
27.75	16.65	24.98	31.91	0.46
28.00	16.80	25.20	32.20	0.46
28.25	16.95	25.43	32.49	0.46
28.50	17.10	25.65	32.78	0.46
28.75	17.25	25.88	33.06	0.46
29.00	17.40	26.10	33.35	0.46
29.25	17.55	26.33	33.64	0.46
29.50	17.70	26.55	33.93	0.46
29.75	17.85	26.78	34.21	0.46
30.00	18.00	27.00	34.50	0.46
30.25	18.15	27.23	34.79	0.46
30.50	18.30	27.45	35.08	0.46
30.75	18.45	27.68	35.36	0.46
31.00	18.60	27.90	35.65	0.46
31.25	18.75	28.13	35.94	0.46
31.50	18.90	28.35	36.23	0.47
31.75	19.05	28.58	36.51	0.47
32.00	19.20	28.80	36.80	0.47
32.25	19.35	29.03	37.09	0.47
32.50	19.50	29.25	37.38	0.47
32.75	19.65	29.48	37.66	0.47
33.00	19.80	29.70	37.95	0.47
33.25	19.95	29.93	38.24	0.47
33.50	20.10	30.15	38.53	0.47
33.75	20.25	30.38	38.81	0.46
34.00	20.40	30.60	39.10	0.46

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
34.25	20.55	30.83	39.39	0.46
34.50	20.70	31.05	39.68	0.46
34.75	20.85	31.28	39.96	0.46
35.00	21.00	31.50	40.25	0.46
35.25	21.15	31.73	40.54	0.46
35.50	21.30	31.95	40.83	0.46
35.75	21.45	32.18	41.11	0.46
36.00	21.60	32.40	41.40	0.46
36.25	21.75	32.63	41.69	0.45
36.50	21.90	32.85	41.98	0.45
36.75	22.05	33.08	42.26	0.45
37.00	22.20	33.30	42.55	0.45
37.25	22.35	33.53	42.84	0.45
37.50	22.50	33.75	43.13	0.44
37.75	22.65	33.98	43.41	0.44
38.00	22.80	34.20	43.70	0.44
38.25	22.95	34.43	43.99	0.44
38.50	23.10	34.65	44.28	0.44
38.75	23.25	34.88	44.56	0.43
39.00	23.40	35.10	44.85	0.43
39.25	23.55	35.33	45.14	0.43
39.50	23.70	35.55	45.43	0.43
39.75	23.85	35.78	45.71	0.43
40.00	24.00	36.00	46.00	0.42
40.25	24.15	36.23	46.29	0.42
40.50	24.30	36.45	46.58	0.42
40.75	24.45	36.68	46.86	0.42
41.00	24.60	36.90	47.15	0.41
41.25	24.75	37.13	47.44	0.41
41.50	24.90	37.35	47.73	0.41
41.75	25.05	37.58	48.01	0.41
42.00	25.20	37.80	48.30	0.41
42.25	25.35	38.03	48.59	0.41
42.50	25.50	38.25	48.88	0.40
42.75	25.65	38.48	49.16	0.40
43.00	25.80	38.70	49.45	0.40
43.25	25.95	38.93	49.74	0.40
43.50	26.10	39.15	50.03	0.39
43.75	26.25	39.38	50.31	0.39
44.00	26.40	39.60	50.60	0.39
44.25	26.55	39.83	50.89	0.39
44.50	26.70	40.05	51.18	0.39
44.75	26.85	40.28	51.46	0.39

			Time Ordinate (Hr)	
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
45.00	27.00	40.50	51.75	0.39
45.25	27.15	40.73	52.04	0.38
45.50	27.30	40.95	52.33	0.38
45.75	27.45	41.18	52.61	0.38
46.00	27.60	41.40	52.90	0.38
46.25	27.75	41.63	53.19	0.38
46.50	27.90	41.85	53.48	0.38
46.75	28.05	42.08	53.76	0.38
47.00	28.20	42.30	54.05	0.38
47.25	28.35	42.53	54.34	0.37
47.50	28.50	42.75	54.63	0.37
47.75	28.65	42.98	54.91	0.37
48.00	28.80	43.20	55.20	0.37
48.25	28.95	43.43	55.49	0.37
48.50	29.10	43.65	55.78	0.37
48.75	29.25	43.88	56.06	0.37
49.00	29.40	44.10	56.35	0.37
49.25	29.55	44.33	56.64	0.36
49.50	29.70	44.55	56.93	0.36
49.75	29.85	44.78	57.21	0.36
50.00	30.00	45.00	57.50	0.36
50.25	30.15	45.23	57.79	0.36
50.50	30.30	45.45	58.08	0.36
50.75	30.45	45.68	58.36	0.36
51.00	30.60	45.90	58.65	0.36
51.25	30.75	46.13	58.94	0.36
51.50	30.90	46.35	59.23	0.35
51.75	31.05	46.58	59.51	0.35
52.00	31.20	46.80	59.80	0.35
52.25	31.35	47.03	60.09	0.35
52.50	31.50	47.25	60.38	0.35
52.75	31.65	47.48	60.66	0.35
53.00	31.80	47.70	60.95	0.34
53.25	31.95	47.93	61.24	0.34
53.50	32.10	48.15	61.53	0.34
53.75	32.25	48.38	61.81	0.34
54.00	32.40	48.60	62.10	0.34
54.25	32.55	48.83	62.39	0.33
54.50	32.70	49.05	62.68	0.33
54.75	32.85	49.28	62.96	0.33
55.00	33.00	49.50	63.25	0.33
55.25	33.15	49.73	63.54	0.33
55.50	33.30	49.95	63.83	0.33

		Time Ordinate (Hr)		
Original Nov 2000 Event	Scaled for 10 Hour Storm Duration	Scaled for 40 Hour Storm Duration	Scaled for 60 Hour Storm Duration	Non-dimensionalised flow ordinate
55.75	33.45	50.18	64.11	0.32
56.00	33.60	50.40	64.40	0.32
56.25	33.75	50.63	64.69	0.32
56.50	33.90	50.85	64.98	0.32
56.75	34.05	51.08	65.26	0.32
57.00	34.20	51.30	65.55	0.31
57.25	34.35	51.53	65.84	0.31
57.50	34.50	51.75	66.13	0.31
57.75	34.65	51.98	66.41	0.31
58.00	34.80	52.20	66.70	0.31
58.25	34.95	52.43	66.99	0.30
58.50	35.10	52.65	67.28	0.30
58.75	35.25	52.88	67.56	0.30
59.00	35.40	53.10	67.85	0.30
59.25	35.55	53.33	68.14	0.30
59.50	35.70	53.55	68.43	0.30
59.75	35.85	53.78	68.71	0.29
60.00	36.00	54.00	69.00	0.29

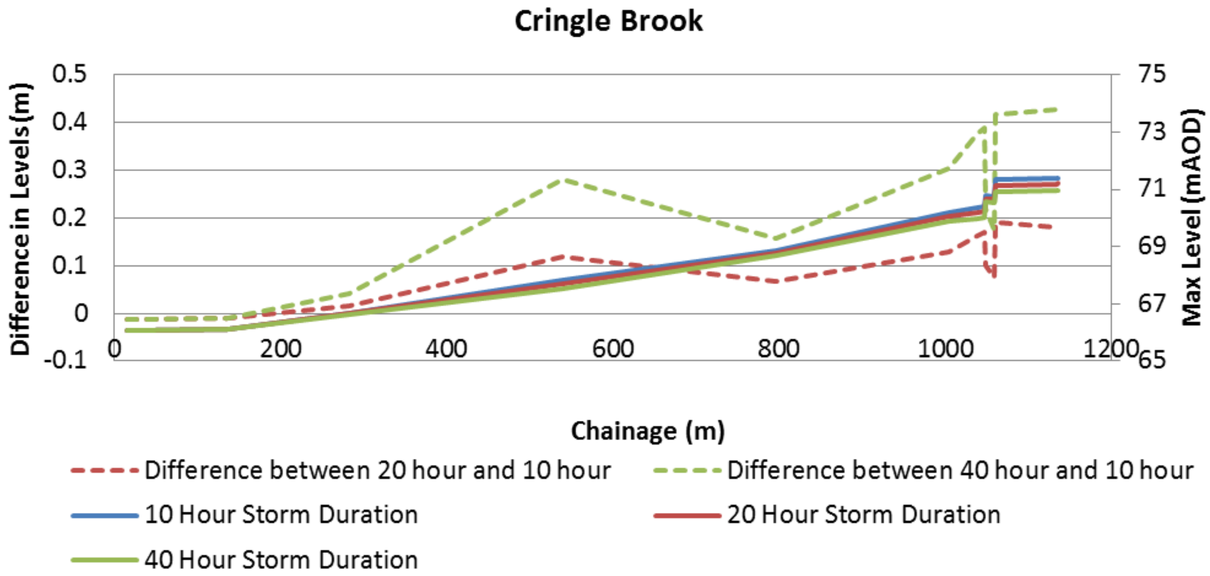
Appendix G. Storm Duration Sensitivity Analysis

G.1 Upper Witham Grantham Model

Peak level comparison and flood extent comparison was carried out for the 10, 20 and 40 hour storm duration runs for the Upper Witham – Grantham model.

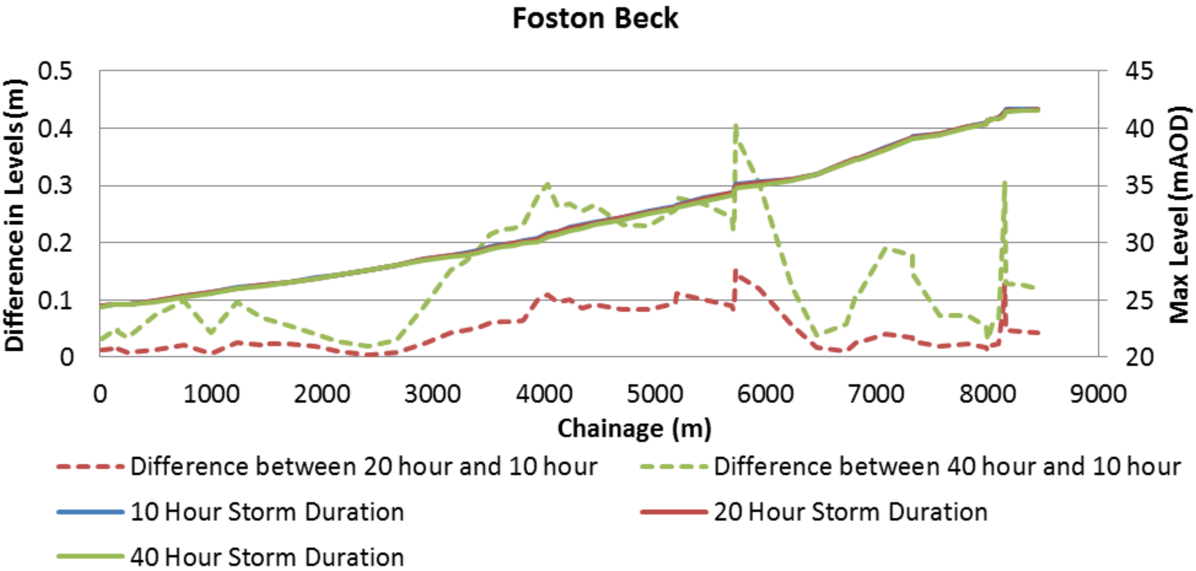
Figure G.1 to Figure G.3 compare the peak levels for Cringle Brook, Foston Beck and the River Witham upstream of Claypole, with the difference between the 20 and 40 hours, compared to the 10 hour storm duration also plotted. Table G.1 details the number of sections for which each storm duration provides the maximum level, the median error of the non-best sections (difference in levels between the overall maximum level across all 3 storm durations and the level modelled for that specific storm duration) and the maximum error of the non-best sections.

Figure G.1: Peak Level Comparison on Cringle Brook for 10H, 20H, and 40H Storm Duration runs (1%AEP)



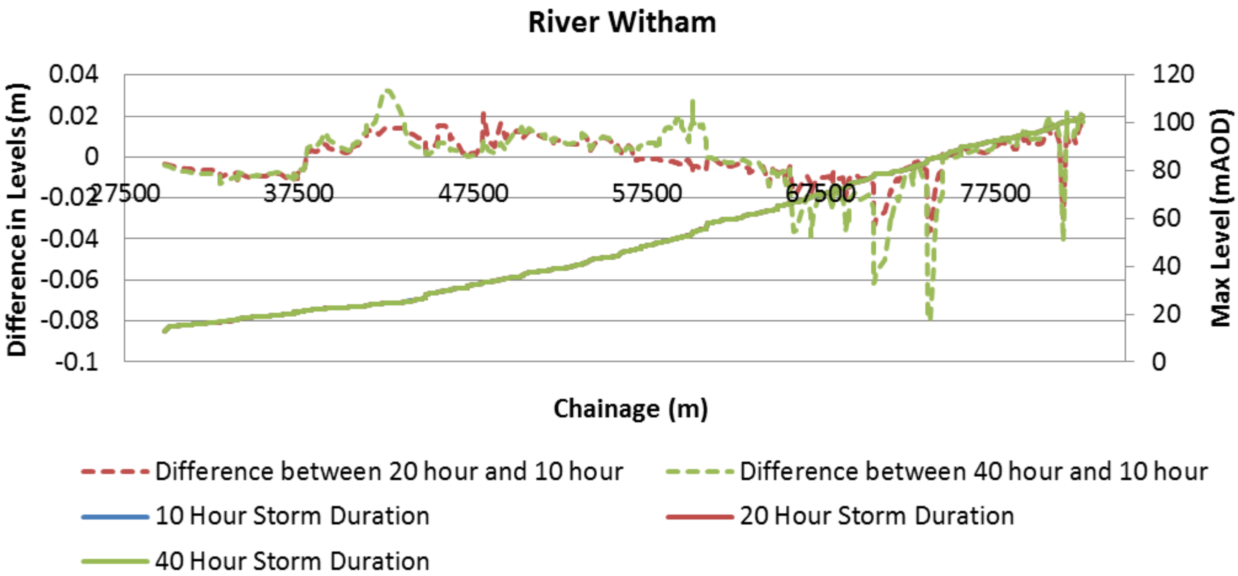
Source: Mott MacDonald

Figure G.2: Peak Level Comparison on Foston Beck for 10H, 20H, and 40H Storm Duration runs (1%AEP)



Source: Mott MacDonald

Figure G.3: Peak Level Comparison on River Witham, Upstream of Claypole for 10H, 20H, and 40H Storm Duration runs (1%AEP)



Source: Mott MacDonald

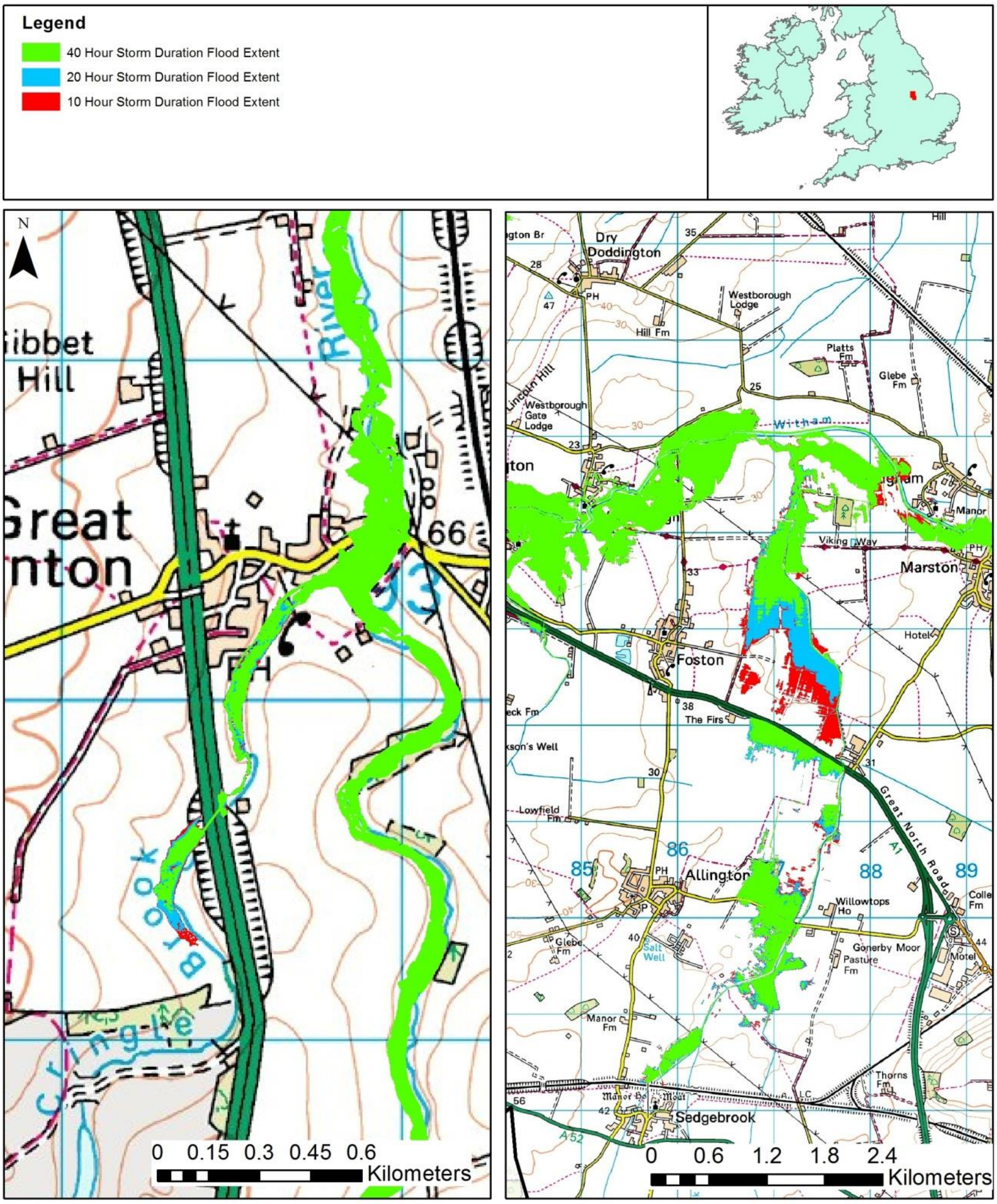
Table G.1: Upper Witham – Grantham Storm Duration Sensitivity Analysis

	Storm Duration		
	10 Hour	20 Hour	40 Hour
Number of sections for which each storm duration provides the maximum modelled levels	315	183	139
Median error of non-best sections	0.006m	0.008m	0.008m
Maximum error of non-best sections	0.080m	0.191m	0.435m

Source: Mott MacDonald

Figure G.4 compares the flood extents for each of the three storm durations, focussing on Foston Beck and Cringle Brook where the largest differences are seen

Figure G.4: Comparison of Flood Extents for Storm Duration Sensitivity on Upper Witham – Grantham Model



Source: Mott MacDonald. This map is reproduced by permission of Ordnance Survey on behalf of The Controller Of Her Majesty's Stationary Office. © Crown Copyright. All rights reserved. Environment Agency 100026380, 2015.

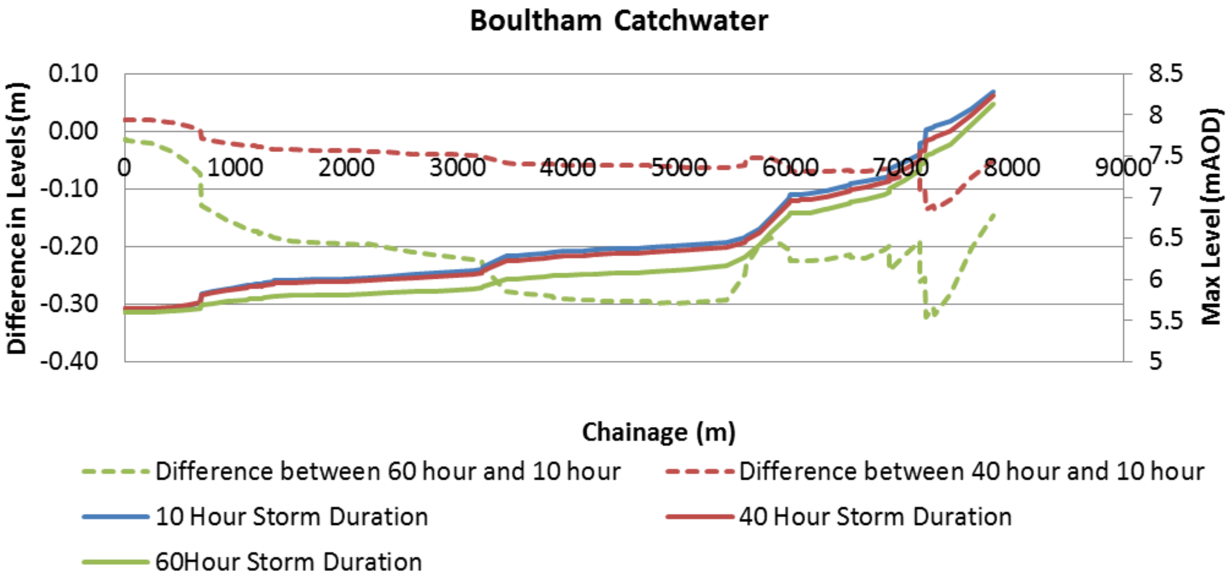
The 10 hour storm duration is critical for the majority of the sections, and also minimises the error with the remaining sections, therefore the 10 hour storm duration has been used for the design runs.

G.2 Upper Witham Lincoln Model

Peak level comparison and flood extent comparison was carried out for the 10, 40 and 60 hour storm duration runs for the Upper Witham – Lincoln model.

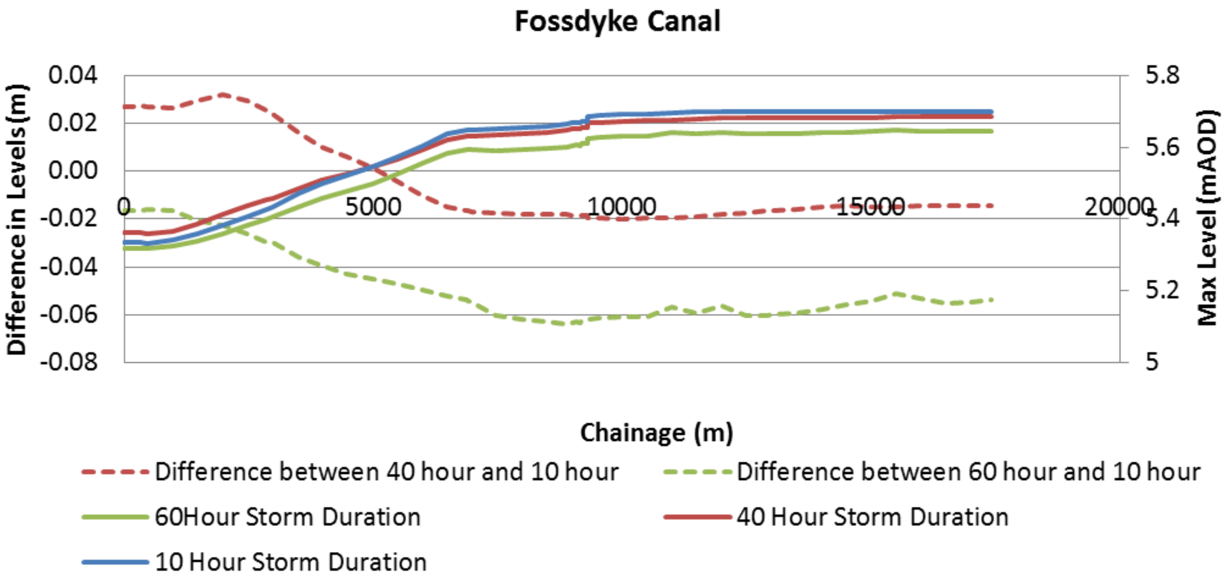
Figure G.5 to Figure G.10 compare the peak levels for each tributary in the Upper Witham – Lincoln model, with the difference between the 40 and 60 hours, compared to the 10 hour storm duration also plotted.

Figure G.8: Peak Level Comparison on Boultham Catchwater for 10H, 40H, and 60H Storm Duration runs (10%AEP)



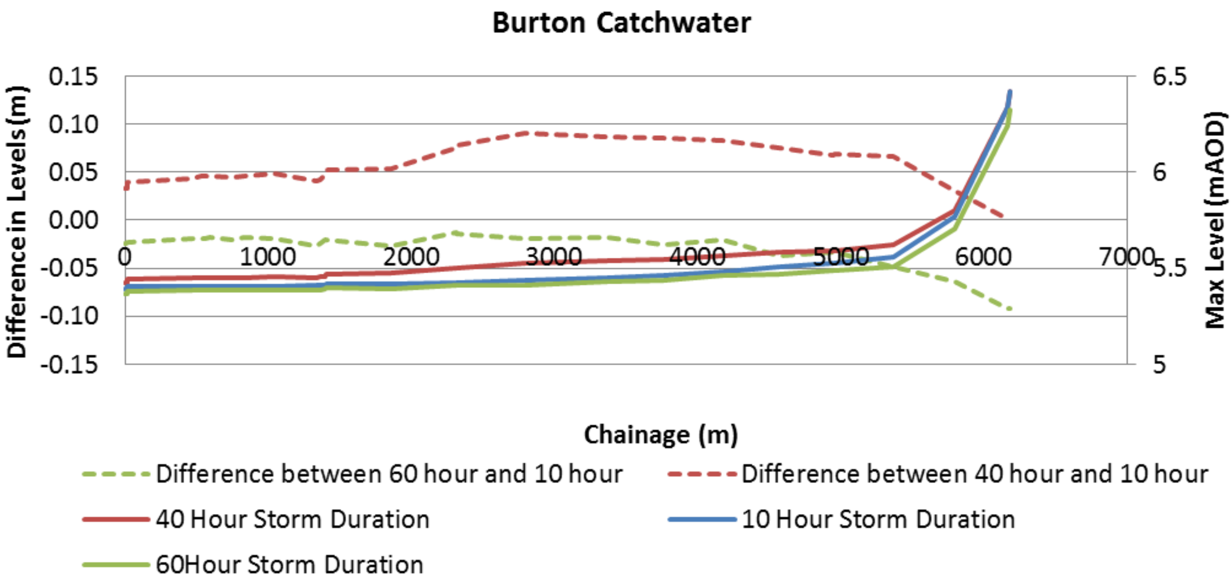
Source: Mott MacDonald

Figure G.9: Peak Level Comparison on Fossdyke Canal for 10H, 40H, and 60H Storm Duration runs (10%AEP)



Source: Mott MacDonald

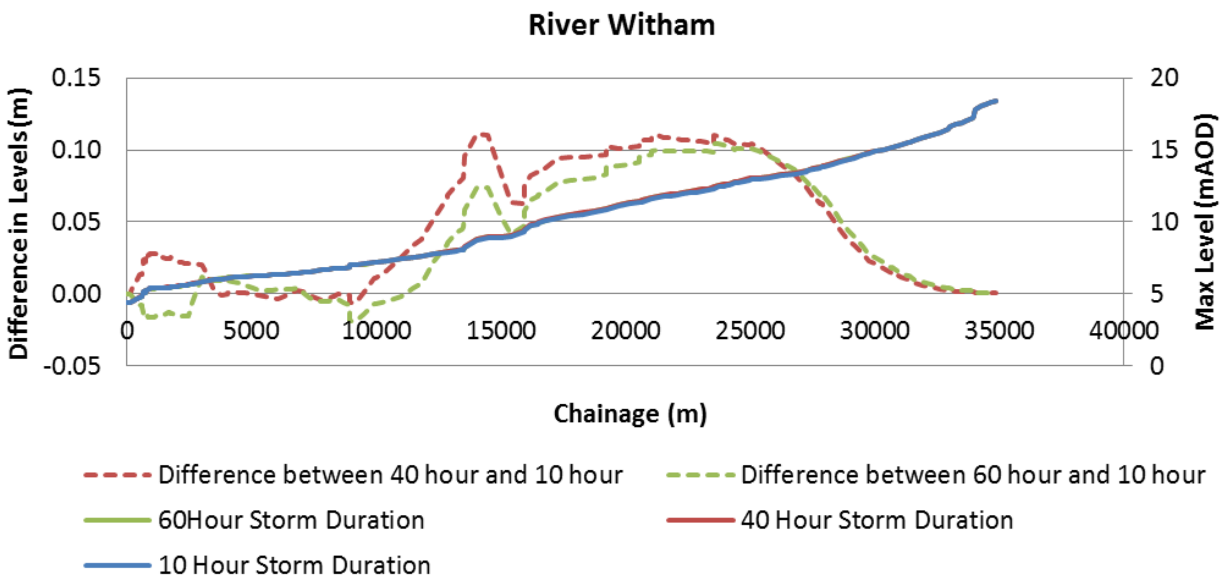
Figure G.10: Peak Level Comparison on Burton Catchwater for 10H, 40H, and 60H Storm Duration runs (10%AEP)



Source: Mott MacDonald

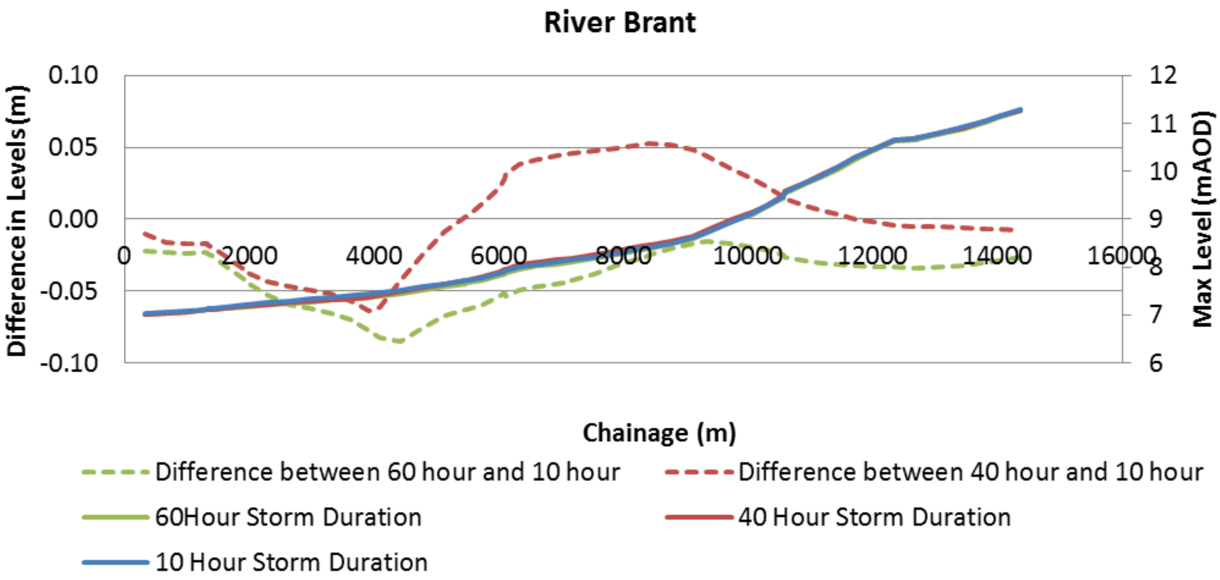
Table G.2 details the number of sections for which each storm duration provides the maximum level, the median error of the non-best sections (difference in levels between the overall maximum level across all 3 storm durations, and the level modelled for that specific storm duration), and the maximum error of the non-best sections.

Figure G.5: Peak Level Comparison on River Witham, downstream of Claypole for 10H, 40H, and 60H Storm Duration runs (10%AEP)



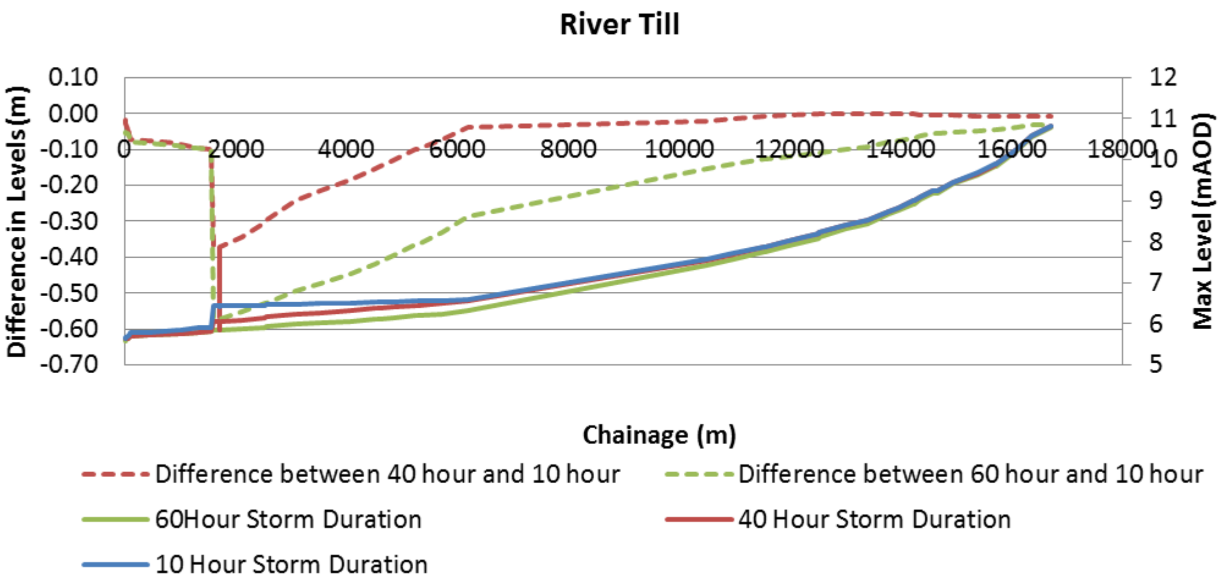
Source: Mott MacDonald

Figure G.6: Peak Level Comparison on River Brant for 10H, 40H, and 60H Storm Duration runs (10%AEP)



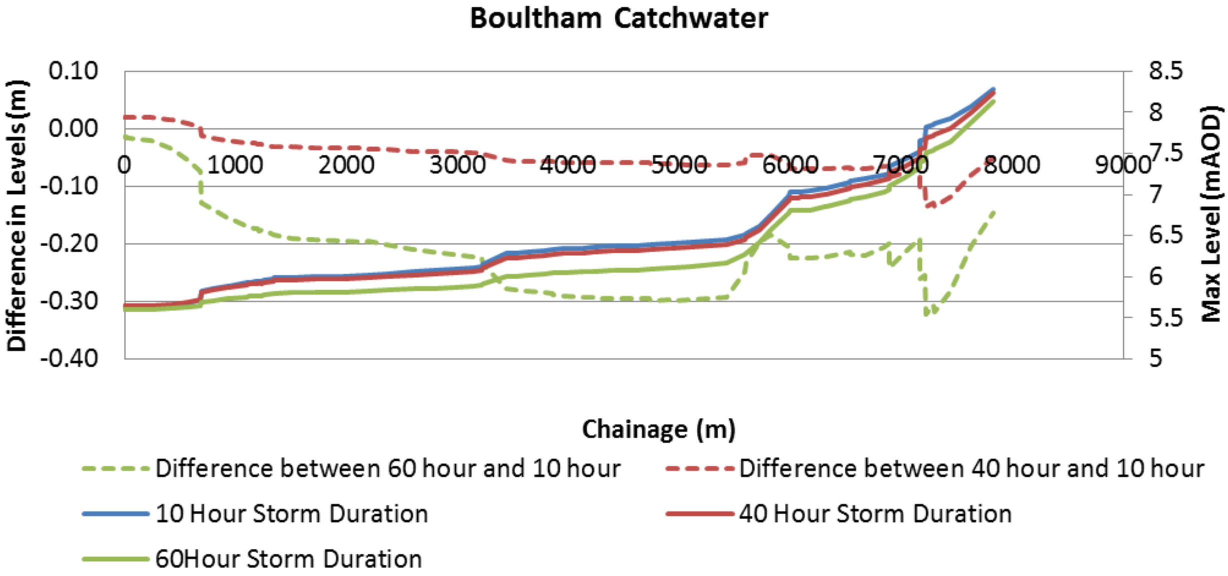
Source: Mott MacDonald

Figure G.7: Peak Level Comparison on River Till for 10H, 40H, and 60H Storm Duration runs (10%AEP)



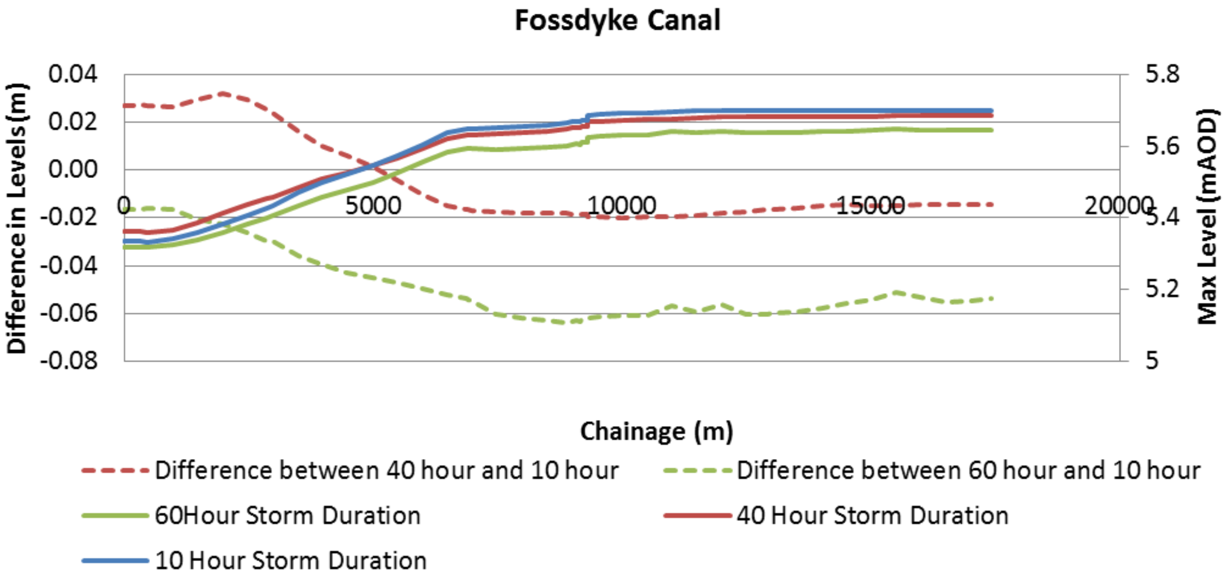
Source: Mott MacDonald

Figure G.8: Peak Level Comparison on Boultham Catchwater for 10H, 40H, and 60H Storm Duration runs (10%AEP)



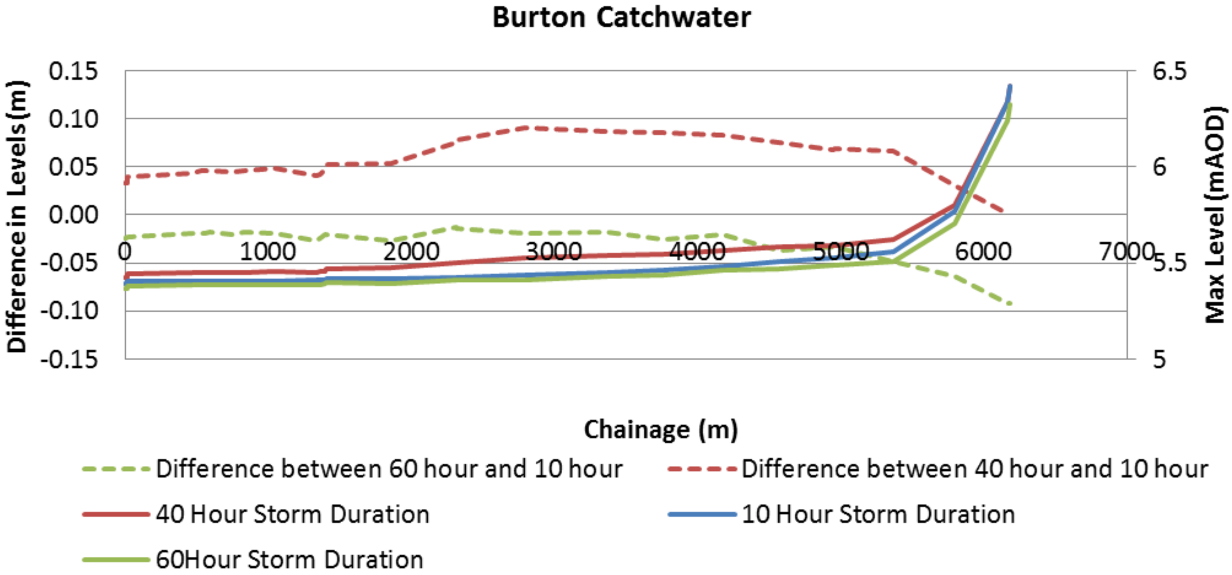
Source: Mott MacDonald

Figure G.9: Peak Level Comparison on Fossdyke Canal for 10H, 40H, and 60H Storm Duration runs (10%AEP)



Source: Mott MacDonald

Figure G.10: Peak Level Comparison on Burton Catchwater for 10H, 40H, and 60H Storm Duration runs (10%AEP)



Source: Mott MacDonald

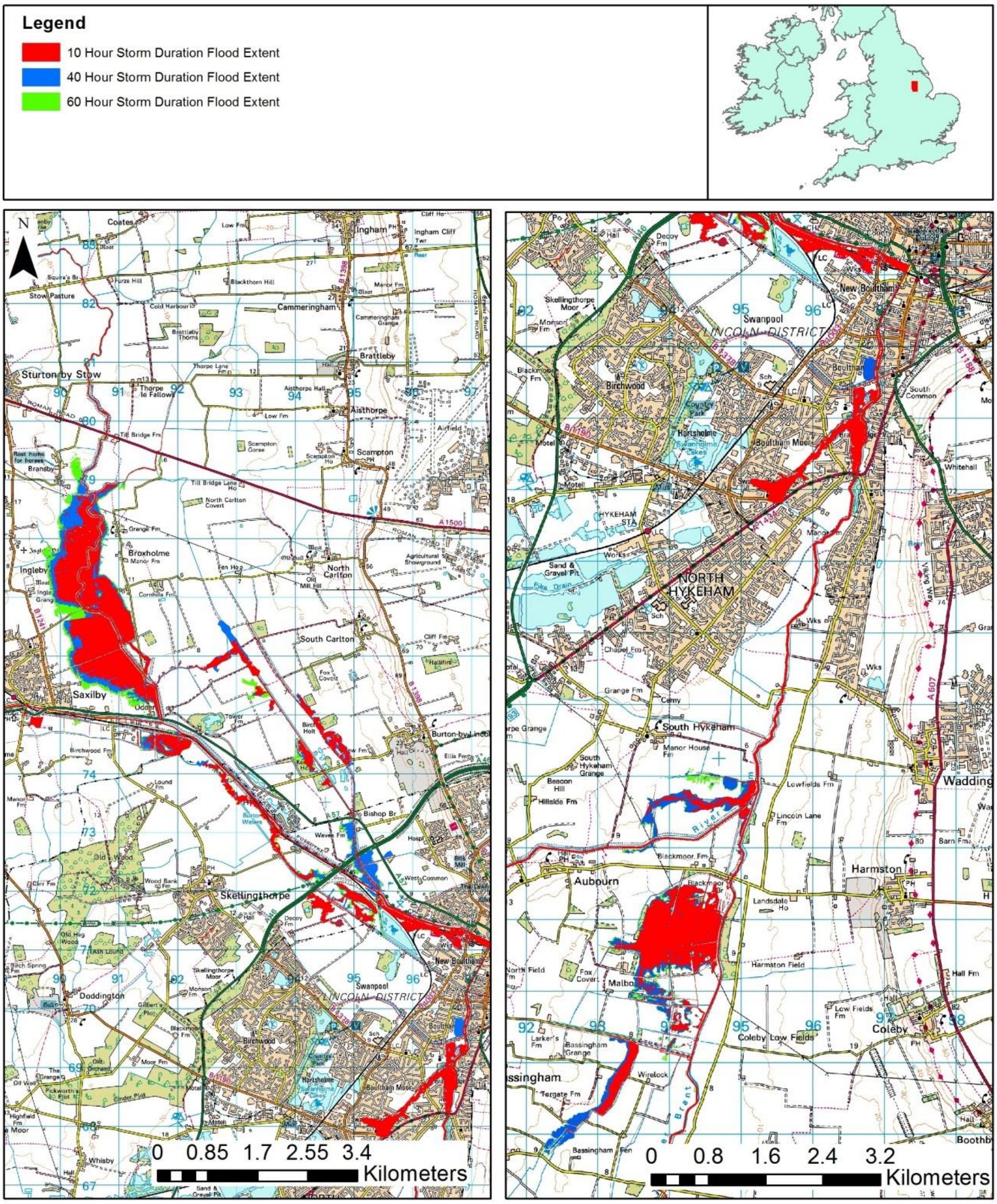
Table G.2: Upper Witham – Lincoln Storm Duration Sensitivity Analysis

			Storm Duration
	10 Hour	40 Hour	60 Hour
Number of sections for which each storm duration provides the maximum modelled levels	225	341	78
Median error of non-best sections	0.027m	0.018m	0.054m
Maximum error of non-best sections	0.111m	0.567m	0.573m

Source: Mott MacDonald

Figure G.11 compares the flood extents for each of the three storm durations, focussing on the River Till washlands, and River Witham Washlands.

Figure G.11: Comparison of Flood Extents for Storm Duration Sensitivity on Upper Witham – Lincoln Model



Source: Mott MacDonald. This map is reproduced by permission of Ordnance Survey on behalf of The Controller Of Her Majesty's Stationary Office. © Crown Copyright. All rights reserved. Environment Agency 100026380, 2015.

The 40 hour storm duration is critical for the majority of the sections. The 10 hour storm duration is critical for Boultham Catchwater.

The 10 hour storm duration appears at first, from the peak water level analysis, to be critical for the River Till, however this is primarily due to the time delay in washland gates opening and the effect of the gate opening being seen in lowering water levels upstream. For the shorter storm durations, the hydrograph has a much steeper rising limb, allowing a greater increase in flows, and corresponding water level to pass down the river in the same time than the longer storm durations. The flood extents along the Till however show that the largest flood extents are from the 60 hour storm duration model run in the washlands.

In consultation with the Environment Agency, the 10 hour and 40 hour storm durations have been run for the Upper Witham – Lincoln model.

APPENDIX 3
EA 2018 WITHAM CHANNEL SURVEY