M5 Junction 10 Improvements Scheme

Scheme Hydraulic Modelling Report

TR010063 - APP 9.19

Regulation 5(2)(e)

Planning Act 2008

Infrastructure Planning (Applications: Prescribed Forms and Procedure) Regulations 2009

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Infrastructure Planning

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M5 Junction 10 Improvements Scheme

Development Consent Order 202[x]

9.19 Scheme Hydraulic Modelling Report

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Executive Summary

Gloucestershire County Council faces significant challenges to achieve its vision for economic growth. A Joint Core Strategy (JCS) – a partnership between Gloucester City Council, Cheltenham Borough Council and Tewkesbury Borough Council - was formed to produce a co-ordinated strategic development plan to show how the region will develop during the period up to 2031. This includes a shared spatial vision targeting new homes and new jobs.

An all movements junction has been identified as a key infrastructure requirement to enable the housing and economic development proposed by the Gloucestershire Local Enterprise Partnership's (GFirst LEP's) Strategic Economic Plan and is central to the transport network sought by the council in the adopted Gloucestershire Local Transport Plan.

The M5 Junction 10 Improvement Scheme is made up of the following infrastructure improvements, which can be found in Appendix A:

- An all-movements junction at M5 Junction 10;
- A new West Cheltenham Link Road from Junction 10;
- Dualling of the A4019 to the East of the Link Road;
- A38/A4019 junction improvements at Coombe Hill; and
- Extension to Arle Court Park and Ride interchange.

As part of the options selection and development, the likely impact on flood risk has been considered, specifically on the River Chelt and Leigh Brook. Detailed hydraulic modelling of the without-scheme situation has been undertaken to understand the Baseline flood risk in the area, described in the Baseline Hydraulic Modelling Report (Application document TR010063/APP/9.18).

This report describes the hydraulic modelling of the Scheme, and the Scheme's impact on the Baseline flood risk, and refers back to the Baseline Modelling Report (Application document TR010063/APP/9.18). The Scheme model is based on the M5J10 Baseline model, which itself originated from Environment Agency's middle Chelt model from 2012, as was updated for the Boddington flood map challenge in 2019. The model uses the industry standard ESTRY-TUFLOW software.

The same hydrology study was applied to the Scheme as per the Baseline. A 1% annual exceedance probability event (1 in 100-year return period) flow of 24.5 m^3/s was estimated for the River Chelt at the M5 motorway, and 2.5 m^3/s for the Leigh Brook, again at the M5 motorway. An allowance of +53% in peak flow is included to cover future climate change over the lifetime of the development.

The Scheme is applied to the model as a new 3D surface arising from the highways and earthworks design. Changes are made to various hydraulic structures to reflect the design, such as culvert extentions or ditch realignments. Two primary flood mitigation features are included:

- A large flood storage basin, to be excavated in farmland near the M5 Junction 10, providing some 190,298 m^3 of flood storage.
- 9,162 m^2 compensatory floodplain on a level for level basis created in farmland immediately upstream of the West Cheltenham Link Road, providing 1,513 m^3 replacement storage.

The modelling demonstrates that the Scheme is not at risk of flooding in the design event, and nor does the Scheme increase flood risk to 3rd party receptors. In fact the Scheme reduces flood risk to large areas of land around it, specifically in present day flood events.

This report describes the development and testing of a with-Scheme flood model and assesses the current scheme impact on the Baseline flood risk. Subsequent reports will document:

- The updated Flood Risk Assessment (Application document TR010063/APP/6.15); and
- The Environmental Impact Assessment (Chapter 8 Road Drainage and Water Environment, Application document TR010063/APP/6.6).

List of abbreviations

Abbreviation	Term
ACD	Above chart datum
AEP	Annual Exceedance Probability
AONB	Area of Outstanding Natural Beauty
CBC	Cheltenham Borough Council
CSO	Combined Sewer Overflow
DCO	Development Consent Order
DEFRA	Department for Environment Food and Rural Affairs
DfT	Department for Transport
DMRB	Design Manual for Road and Bridges
DRN	Detailed River Network
EA	Environment Agency
ES	Environmental Statement
GCC	Gloucestershire County Council
HE DDMS	Highways England Drainage Data Management System
HE	Highways England
HIF	Housing Infrastructure Fund
HPC	Highly Parallelised Compute
JCS	Joint Core Strategy
NPPF	National Planning Policy Framework
NPS-NN	National Policy Statement – National Networks
NRW	Natural Resources Wales
NSIP	Nationally Significant Infrastructure Project
QH	Stage-Discharge
RBD	River Basin District
RofSW	Risk of Flooding from Surface Water
RP	Return Period
SRN	Strategic Road Network
SuDS	Sustainable Drainage System
TBC	Tewkesbury Borough Council

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1. Introduction

1.1. Scheme background

1.1.1. Gloucestershire faces significant challenges to achieve its vision for economic growth. The Joint Core Strategy (JCS) is a partnership between Gloucester City Council, Cheltenham Borough Council (CBC) and Tewkesbury Borough Council (TBC) which sets out a strategic planning framework for the three areas. The Adopted JCS 2011-2031 is a coordinated strategic development plan, adopted in December 2017, which shows how the region will develop and includes a shared spatial vision targeting 35,175 new homes and 39,500 new jobs by 2031.

1.1.2. Major development of new housing (c.9,000 homes) and employment land is proposed in the JCS in strategic and safeguarded allocations to the west and north-west of Cheltenham, these being: West Cheltenham (Golden Valley); North West Cheltenham (Elms Park); and safeguard land to the west and the north-west of Cheltenham (all shown in Figure 1 4). The West Cheltenham development, in turn, is linked to wider economic investment, including a government supported cyber business park (Cyber Central UK) adjacent to the Government Communications Headquarters (GCHQ) site in west Cheltenham.

1.1.3. The existing M5 Junction 10 only provides access and egress to and from the north, with no connectivity to M5 south; this causes existing traffic to cross Cheltenham through various routes to access and leave the M5 from the south using other M5 junctions. This contributes significantly to existing traffic flows across Cheltenham, with significant congestion at peak times. To unlock the housing and job opportunities, a highway network is needed that has the capacity to accommodate the increased traffic it will generate, within a sustainable transport context.

1.1.4. Upgrading M5 Junction 10 to an all movements junction has been identified as a key infrastructure requirement to enable the housing and economic development proposed by the JCS and supported in the Gloucestershire Local Enterprise Partnership's (GFirst LEP) Strategic Economic Plan and the transport network sought by GCC in the adopted Gloucestershire Local Transport Plan. Improvements to M5 J10 are critical to maintaining the safe and efficient operation of the junction; and enabling the planned development and economic growth. A bid was submitted in March 2019 to Homes England to the Housing Infrastructure Fund (HIF), wherein an investment case was made for the following infrastructure improvements. Funding was successfully awarded by Homes England in March 2020 for:

- Element 1: Improvements to Junction 10 on the M5 and a new road linking Junction 10 to west Cheltenham.
- Element 2: A38/A4019 Junction Improvements at Coombe Hill.
- Element 3: A4019 widening, east of Junction 10.
- Element 4: An upgrade to Arle Court Park and Ride.

1.1.5. Elements 1 and 3 comprise the M5 Junction 10 Improvements Scheme (the Scheme). The upgrade to Arle Court Park and Ride (now known as the Arle Court Transport Hub) (Element 4) and the junction improvements at Coombe Hill (Element 2) were included as part of the package of improvements funded by Homes England. As they do not form part of the improvement of M5 Junction 10, and are located some distance from the junction, GCC has decided to take these two elements forward as separate packages of work in order to accelerate the programme for these elements, and will deliver them through separate planning strategies.

1.1.6. An application for a Development Consent Order (DCO) under S.22 of the Planning Act 2008 has been submitted for the construction of improvement works to M5 Junction 10, consisting of a new all-movements junction; the widening of the A4019 east of the junction to the Gallagher Retail Park Junction; and a new link road from the A4019 to the B4634. A small section of the A4019 will be realigned to the west of the junction. Consequently, Arle Court Transport Hub received consent in July 2022. Junction improvements at Coombe Hill received consent in April 2023.

1.2. Site location

1.2.1. The M5 links the Midlands with the South West, running from Junction 8 of the M6 at West Bromwich near Birmingham to Exeter in Devon, and linking with the M4 north of Bristol. Junction 10 (of the M5) is located 76 km to the south of Birmingham, 64 km to the north of Bristol, 8 km to the south of Tewkesbury, 6.5km to the north-west of Cheltenham, and 13 km to the north-east of Gloucester.

1.2.2. The junction is in a strategically important location for the region, particularly as northern and western Cheltenham are the sites of a number of large retail parks and employment areas, and the location of planned future housing and nationally significant business development.

1.2.3. The location of M5 Junction 10 is shown in Figure 1. The locations of the infrastructure improvements that make up the M5 Junction 10 Improvements Scheme are illustrated in Figure 2 below.

1.2.4. A geographical summary of the study area is given in Table 1-1.

Table 1-1 - Site location details

Site centroid grid reference	393494, 232220 for the study area
Maximum / minimum elevation	46.28 m AOD / 18.46 m AOD
Study area	7.96 km^2 model domain, 196 ha Scheme
Lead local flood authority	Gloucestershire County
Borough council	Tewksbury County Council
River Basin District	Severn
Management catchment	Severn Vale

1.3. Project Scope

1.3.1. Atkins was appointed by Gloucestershire County Council (GCC) as the designer for the Scheme. The scope was to develop Scheme proposals for the following elements of the Scheme which are related to the changes to the strategic road network (and indicated on Figure 2).

- An all-movements junction at M5 Junction 10 and a new Link Road from Junction 10 (element 1).
- Dualling of the A4019 to the East of the Link Road (element 3).

1.3.2. The overall purpose of the Scheme is to improve the highway network around the existing M5 Junction 10 with an overarching aim to ease traffic congestion and to facilitate development in the area.

1.3.3. The A38/A4019 junction improvements at Coombe Hill; and extension to Arle Court Park and Interchange are geographically located away from the M5 Junction 10 improvements and are within Gloucestershire County Council's (GCC) road network. These elements of the Scheme will not be appraised as part of this flood risk work.

Figure 1 - Location of the Scheme

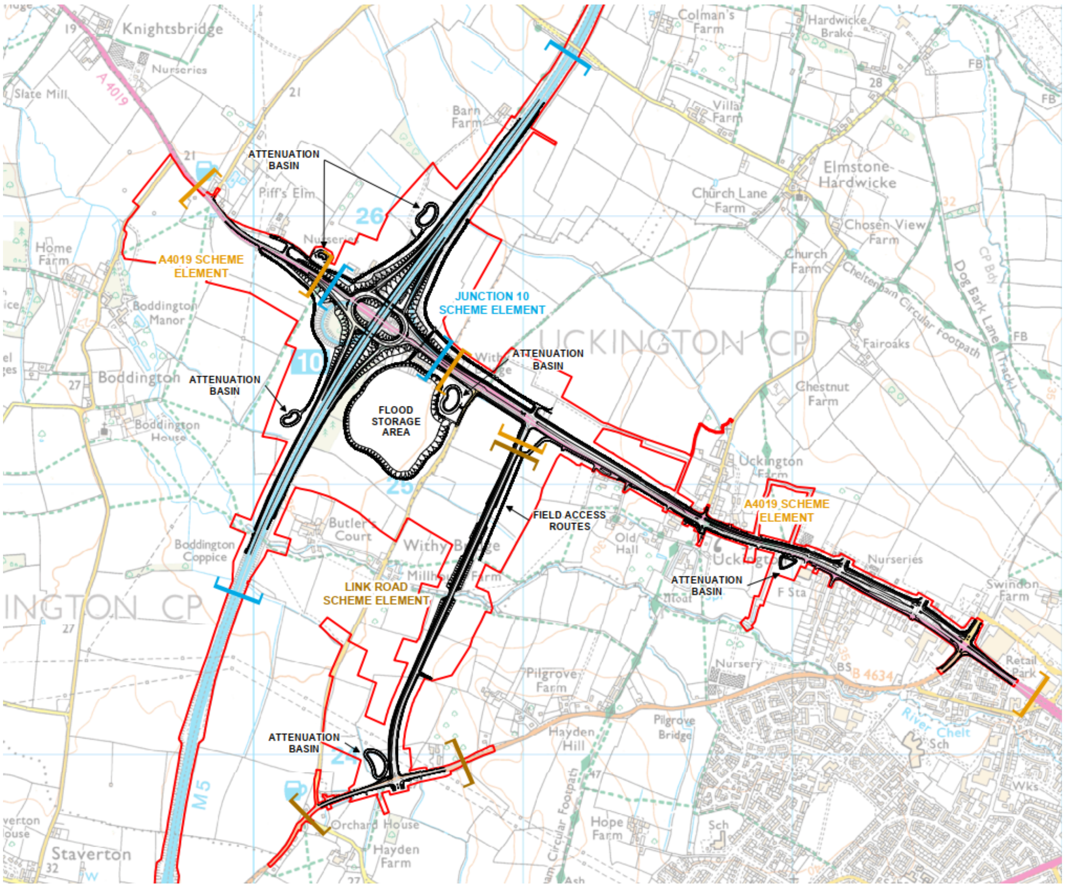


Figure 2 - The M5 Junction 10 Improvements Scheme

The Scheme

1.3.4. The Scheme upgrades the M5 Junction 10 and provides a new link road running south from the A4019 to the B4634 (element 1) and widens the A4019 through Uckington (element 3). Element 2 (A38/A4019 Junction Improvements at Coombe Hill) and Element 4 (Upgrade to Arle Court Park and Ride) are not part of this particular project and are the subject of separate planning applications. The following sections describe the different elements of the Scheme.

M5 Junction 10

1.3.5. The improvements to M5 Junction 10 are to increase the capacity of the junction, and to upgrade the currently northbound only junction to an all-movement junction. To enable travel both south and north on the M5, the two existing Junction 10 exit slip roads will be removed, and four new slip roads will be constructed to provide access and egress to the M5 in all directions.

1.3.6. Two new overbridges will be constructed over the M5, centred either side of the existing overbridge (carrying the A4019 over the M5), which will then be demolished. The new overbridges will create a new elongated shaped roundabout junction over the M5. The A4019 will be realigned to provide an appropriate entry angle to the new roundabout. A dedicated route for cyclists and pedestrians will be provided at grade through the junction (see the section below on the A4019 Widening). Extensions will be required for the Piffs Elm and Leigh Brook culverts, that pass under the M5, as a result of the new slip roads. The planned alignment of the new slip roads means that an extension of the River Chelt culvert under the M5 will not be required.

Link Road

1.3.7. The Link Road (the 'Link Road') will be a new two lane road, with a segregated cycleway and footway, from the B4634 to the A4019. The Link Road is intended to provide greater connectivity between the reconfigured M5 Junction 10 and both the Strategic Allocation, safeguarded land and the proposed Cyber Park.

1.3.8. The Link Road crosses predominantly agricultural land. The design of the Link Road includes flood relief structures across the floodplain to the north of the River Chelt, and a single span bridge over the River Chelt. The current design of this bridge is a structure that will be set back from the riverbanks (by 4 m on each side of the river), and will have a clearance of 2.8 m between the underside of the bridge and the top of the river banks.

1.3.9. To connect the Link Road with the existing A4019 (to the north) and the B4634 (to the south), two new junctions will be constructed:

- A4019 - a four-arm signalised junction with the northern arm providing access to the new developments to the north of the A4019, as safeguarded in the JCS. Pedestrian and cycle access over this junction will be incorporated into the signal phasing for this junction. The DF3 design will identify the requirements for pedestrian and cycle crossings at this location.
- B4634 - a new four arm signalised junction is proposed on the B4634 to connect both the Cyber Park and the Strategic Allocation and safeguarded land to the M5 Junction 10 via the Link Road and the A4019. The location of this junction is close to Hayden Hill Farm on the B4634, approximately 300 m east of the junction for Withybridge Lane.

A4019 Widening

1.3.10. The A4019 links the M5 Junction 10 to north-west Cheltenham. Currently, the A4019 is a dual carriageway over the M5 Junction, returning to single carriageway east of the junction to serve the turning into Withybridge Lane. The A4019 continues eastwards to Cheltenham as a single carriageway, where it ties into an existing dual carriageway at the Gallagher Retail Park.

1.3.11. The section of the A4019 covered by the Scheme runs from just west of the M5 Junction 10 eastwards through to the existing dual carriageway at Gallagher Retail Park.

1.3.12. As part of the highway improvements incorporated into the Scheme, the A4019 will be widened from Withybridge Lane, eastwards through to the Gallagher Retail Park, where the Scheme will tie into the existing dual carriageway. Widening of the A4019 through Uckington will be to the southern side of the A4019. Widening to the east of Uckington will be to the northern side of the A4019.

1.3.13. Two new signalised junctions will be created on the A4019 (between Uckington and the Gallagher Retail Park) as accesses from the A4019 into the future North West Cheltenham Development Area (also referred to as the Elms Park Development site). Changes will also be made (as part of the Scheme) to the layout of the junction of the A4019 with the B4634 at the eastern end of the Scheme (referred to as the Gallagher junction).

1.3.14. For residents and businesses whose current access is directly onto the A4019 (for example those in Uckington, and along the southern side of the A4019 in north-west Cheltenham), short sections of new access roads will be created alongside the widened A4019 to facilitate ease of access both westbound and eastbound.

1.3.15. The Scheme will include a segregated cycleway and footway adjacent to the A4019, which will extend for the full length of the A4019 widening, and will provide connectivity for pedestrians and cyclists between north-west Cheltenham and the junction of the A4019 and Stanboro Lane (west of M5 Junction 10), where it will connect to an existing footway.

1.3.16. Included as part of the proposals are some minor ground raising adjacent to the A4019 at Piffs Elm, immediately west of the M5 Junction 10. This is to prevent the existing localised flooding of the carriageway and the land to the north as described in the Baseline conditions.

1.4. Flood risk scope and context

1.4.1. As part of the sequential testing and options selection, consideration of the likely impact that each option may have on flood risk was made. All options had the potential to increase flood risk where they restrict flood flows or change floodplain dynamics. Further information on this is described in the Preliminary Environmental Assessment of Options Report[1] (PEAOR).

1.4.2. Detailed hydraulic modelling was therefore undertaken to:

- Develop the scheme design, being cognisant of flood risk;
- Demonstrate the impact of the scheme on flood risk; and
- Determine the flood risk to the scheme.

1.4.3. Reporting of flood risk has been separated into stages to enable individual updates and timely delivery throughout the project. This with-Scheme modelling report is described, in the context of the reporting, as:

- a Baseline Hydraulic Modelling Report (Application document TR010063/APP/9.18) describes the development of a flood model for the Baseline associated with the River Chelt and Leigh Brook in the vicinity of the Scheme.
- This **Scheme Hydraulic Modelling Report** reflecting the development and testing of a with-Scheme flood model.
- a Flood Risk Assessment Report (Application document TR010063/APP/6.15) (FRA) documenting the assessment of flood risk for the Scheme in line with regulatory guidelines and requirements.
- a Preliminary Environmental Information Report[2] (PEIR) documenting the interim/early environmental impact assessment specifically here in relation to flood risk.

[1] Gloucestershire County Council (16 December 2019) M5 Junction 10 Improvement, volume 1 – report. Preliminary Environmental Assessment of options Report – Options Identification Stage. GCCM5J10-ATK-EGN-XX-RP-LM-000002 revision C01

[2] Gloucestershire County Council (10 November 2021). M5 Junction 10 improvements Scheme: Preliminary Environmental Information Report, ref CCM5J10-ATK-EGN-ZZ-RP-LM-000012 rev C04. Atkins. Access online https://www.gloucestershire.gov.uk/highways/major-projects-list/m5-junction-10-improvements-scheme/

- The Environmental Statement (ES) (Chapter 8 Road Drainage and Water Environment, Application document TR010063/APP/6.6) documenting the environmental impact assessment specifically here in relation to flood risk.

Purpose of this report

1.4.4. This **Scheme Hydraulic Modelling Report** documents the development of a flood model describing the with-Scheme conditions associated with the River Chelt and Leigh Brook.

1.4.5. The purpose of the Scheme modelling report is to:

- Document the development of a hydraulic model reflecting the design of the Scheme;
- Document the design development in terms of flood risk; and
- Demonstrate, through hydraulic modelling, the predicted flood risk to the Scheme and its impact on flood risk to third parties.

Regulatory review

1.4.6. The Scheme model has been reviewed by the Environment Agency (15 July 2022) to ensure that it meets with their approval, having adhered to their guidelines, and applies and agrees with their local knowledge of the River Chelt. This is important as the model supports a Flood Risk Assessment and Environmental Statement, which in turn supports the planning process on this scheme. GCC, as Lead Local Flood Authority deferred comment to the Environment Agency for both the River Chelt and Leigh Brook. The LLFA has reviewed the flood modelling and assessment at the B3634, at the southern end of the Link Road, as it includes changes to the unnamed Ordinary Watercourse.

1.4.7. Section 9 of this report describes a model handover for regulatory review.

1.4.8. The Environment Agency team shall note that the model build, hydrology, and calibration of the Baseline is described in detail in the Baseline Modelling Report (Application document TR010063/APP/9.18). This Scheme modelling report does not repeat the content of that Baseline report and the reviewer is directed to the Baseline report where clarification is sought.

1.4.9. This report is only intended to describe the Scheme model, describing in general terms, the application of the Scheme design to the model, the inclusion of embedded mitigation, and specifically with respect to changes in flood risk compared to the Baseline model.

1.4.10. Whilst this report describes the Scheme model, its predictions of flood risk and how that differs from the Baseline (Application document TR010063/APP/9.18), the FRA (Application document TR010063/APP/6.15) and ES (Chapter 8 Road Drainage and Water Environment, Application document TR010063/APP/6.6) also cover the impact aspect.

2. Baseline flood information

2.1. The River Chelt catchment

2.1.1. The catchment area of the River Chelt and its tributaries upstream of Boddington is approximately 32 km^2. Figure 3 indicates the catchment draining to the Scheme area.

2.1.2. In its headwaters, the River Chelt's catchment is steep and rural, before it flows into Dowdeswell reservoir, which is managed by Severn Trent Water (STW). The Dowdeswell reservoir drains a catchment of 5 km^2. Its surface area is 0.1 km^2.

2.1.3. The catchment then becomes urbanised as it flows through the town of Cheltenham, which suffered severe flood damage in the summer of 2007. A combined sewer overflow draws in a 11.5 km^2 catchment from the north (and some from the south), from outside the natural watershed, and discharges into the River Chelt at Arle. The steep topography, coupled with high levels of urbanisation in Cheltenham, means that the catchment is highly responsive to high intensity rainfall and peak fluvial flows.

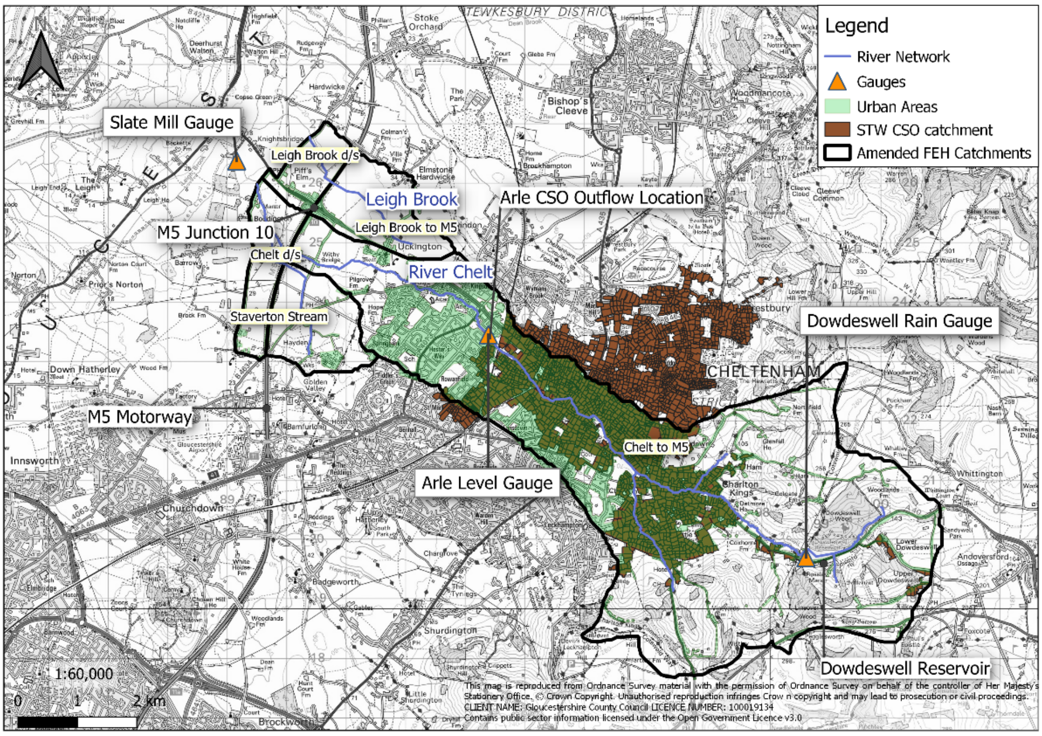
2.1.4. There was one gauging station within the study area on the River Chelt (Slate Mill, NRFA number 54026). However, the Slate Mill gauge was decommissioned and removed in 2010 due to a perceived poor quality of data. In addition to Slate Mill, there is a level only gauge located at Arle.

2.1.5. The Leigh Brook catchment has an area of 9.15 km^2 from its source, approximately 2km upstream of the M5 motorway, to the confluence with the River Chelt. The river is culverted under the M5 motorway and flows westwards, before heading south towards the River Chelt. The Leigh Brook catchment is predominantly rural, although it does contain several roads and villages in its relatively small area. It is situated in the lower reaches of the Chelt and has a shallow bed slope.

2.1.6. West of Cheltenham, both the River Chelt and Leigh Brook catchments are low-lying and rural. Both watercourses are culverted under the existing M5 motorway. Downstream of the M5 motorway, the channel becomes perched on both the Leigh Brook and the River Chelt with raised embankments separating the farmland from the conveyance channels.

2.1.7. The confluence of the River Chelt and Leigh Brook is located immediately upstream of the A38 road, which is approximately 5 km downstream of the M5 Junction 10 Improvement Scheme and approximately 3 km upstream of the River Chelt's confluence with the River Severn at Fletcher's Leap near Wainlode Hill at Hamsfield Ham.

Figure 3 - The Chelt catchment



2.2. Study area

2.2.1. The M5J10 model comprises a study area defined for flood risk, containing:

- The extent of the material works;
- A downstream (outlet) boundary sufficiently remote from the Scheme to ensure any uncertainties would not impact on model predictions of scheme impact or performance; and
- An upstream (inflow) boundary sufficiently close to the Scheme to ensure it represents the contributing watershed without affecting results.

2.2.2. The study area was defined as the 2D model domain, as illustrated in Figure 4 below. The upstream extent is at the roundabout of the B4634 Old Gloucester Road with the A4019 near the retail park at Kingsditch. The domain follows the B4634 south-west towards Hayden, under the M5 motorway, before joining Church Road to Staverton, and then extending due north to Boddington, meeting the A4019 at Piffs Elm/Stanboro Lodge. The boundary then passes north along the B class road towards Hardwicke, crossing the Leigh Brook before turning east and following the watershed close to the C class road to Elmstone Hardwicke along the road named “The Green”. The boundary then continues to follow the catchment boundary of the Leigh Brook, back to the A4019 and B4634 roundabout. No changes to the study area have been made from the Baseline model.

2.3. Existing Baseline modelling

2.3.1. The Baseline flood model was developed from a model of the River Chelt supplied by the Environment Agency. The Baseline Hydraulic Modelling Report (Application document TR010063/APP/9.18) describes how the fluvial systems were numerically modelled using UK standard approaches and following the published guidance of the Environment Agency.

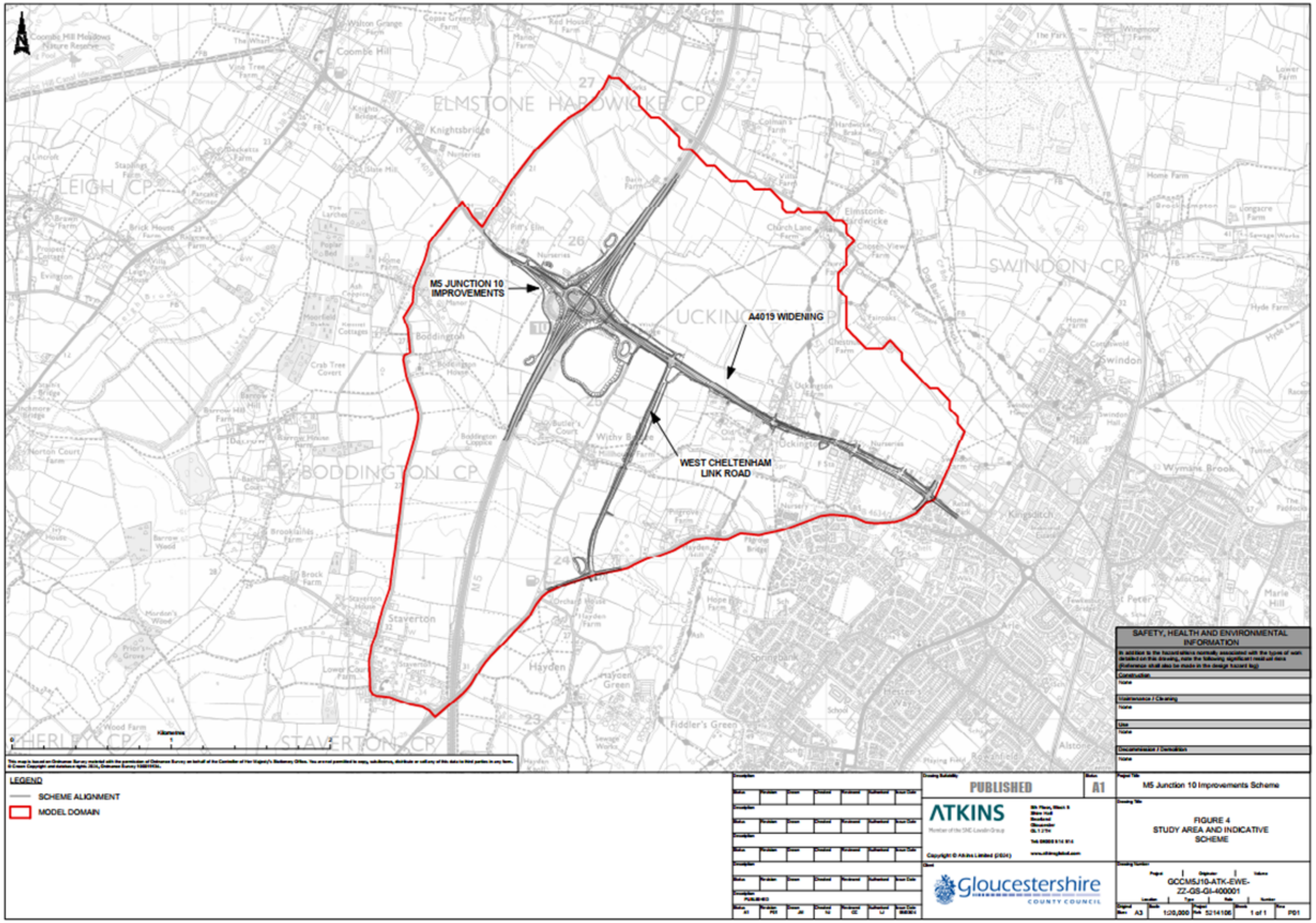
2.3.2. The 1D-2D linked hydraulic model was developed further for the Baseline using the industry standard ESTRY-TUFLOW software. Fundamentally this now fully incorporates the Leigh Brook (and its interactions with the River Chelt) which was modelled in 2D only in the previous hydraulic modelling of this area.

2.3.3. The hydraulic model uses the following input data in addition to that contained in the

Boddington model:

- LiDAR – Composite DTM 2019, 1m resolution;
- Channel cross sections – Environment Agency Middle Chelt Model (2012);
- Channel cross sections – Infomap surveys and Mapping (December 2017) survey of River Chelt near Boddington;
- Channel cross sections – Infomap surveys and Mapping (November 2019) survey of Leigh Brook
- Hydraulic structures – Infomap surveys (November 2019); and
- M5J10 mobile scanning, infill, and aerial survey of critical areas – Atkins (November 2020, with aerial from 2018).

Figure 4 – Study area and indicative Scheme



2.3.4. The Baseline model is driven by hydrology derived using the UK's Flood Estimation Handbook (FEH) and following the Environment Agency Flood Estimation Guidelines[3]. The following input data was applied:

- Recorded rainfall for the Environment Agency Dowdeswell rainfall gauge;
- Recorded stage and flows for the former Environment Agency gauge at Slate Mill;
- Design rainfall parameters from the FEH web service accessed 29 September 2020;
- Catchment descriptors from the FEH web service accessed 29 September 2020;
- Hiflows database version 9, which included data for water year 2019/2020 and was released on 24 September 2020 (this as current at the time of assessment in 2021);
- Combined sewer overflow data from Severn Trent Water for its outfall at Arle;
- ReFH 2.3 software (current at the time of assessment); and
- WINFAP v4 software (current at the time of assessment).

2.3.5. The hydrology and hydraulics were calibrated using event data from:

- 20 July 2007; and
- 13 December 2008.

2.3.6. Data from the now discontinued river flow gauge at Slate Mill was used to calibrate the hydrology alongside the hydraulic model. The hydraulic model was then calibrated with field observations (landowner reports and photographs) and Environment Agency recorded wrack mark data for the River Chelt.

2.3.7. The 1% annual exceedance probability event (1 in 100-year return period) was estimated to generate a peak flow of:

- 24.5 m^3/s in the River Chelt at the M5 motorway; and
- 2.5 m^3/s in the Leigh Brook at the M5 motorway.

2.3.8. The results of the hydraulic modelling demonstrate the Baseline (actual) flood risk in the study area.

1% annual exceedance probability event (1 in 100-year return period)

2.3.9. The results show that flooding occurs on the Leigh Brook floodplain during the 1% annual exceedance probability event (1 in 100-year return period). There is out of bank flooding just west of the upstream point of the Leigh Brook watercourse, resulting in flooding to the properties near Uckington Farm. There is also flooding in the Leigh Brook floodplain just upstream of Barn Farm culvert, under the M5 motorway, as well as downstream of the motorway, continuing west along the watercourse to the downstream model boundary.

2.3.10. More extensive flooding occurs on the Chelt floodplain, compared to lower return periods. Water exits the River Chelt channel at the eastern end of the Chelt floodplain and 8.2 m^3/s passes over Withybridge Lane into the fields east of the motorway. Flooding is largely contained in the Chelt floodplain. No water overtops the A4019 and there is no flow passing under the road through the A4019 culverts.

2.3.11. There is significant flooding held east of the motorway, particularly upstream of the Piffs Elm, River Chelt and Staverton culverts under the M5 motorway. Flows of 18.3 m^3/s pass through the River Chelt culvert under the M5 motorway during this event (1.2 m^3/s more than that in the 4% annual exceedance probability event (1 in 25-year return period)).

2.3.12. Flooding upstream of the Staverton culvert extends south to the upstream point of the Staverton tributary and spreads east to Withybridge lane. Downstream of the Staverton culvert there is further flooding which extends to the confluence between the River Chelt and the Staverton tributary and west up to Boddington Manor. There is also out of bank flooding in the fields to the east of Boddington Manor.

2.3.13. Flooding downstream of Piffs Elm culvert extends west to the downstream boundary at Boddington Lane, where 3.0 m^3/s overtops this road.

[3] Environment Agency (July 2020) Flood estimation guidelines. LT 11832

Design event

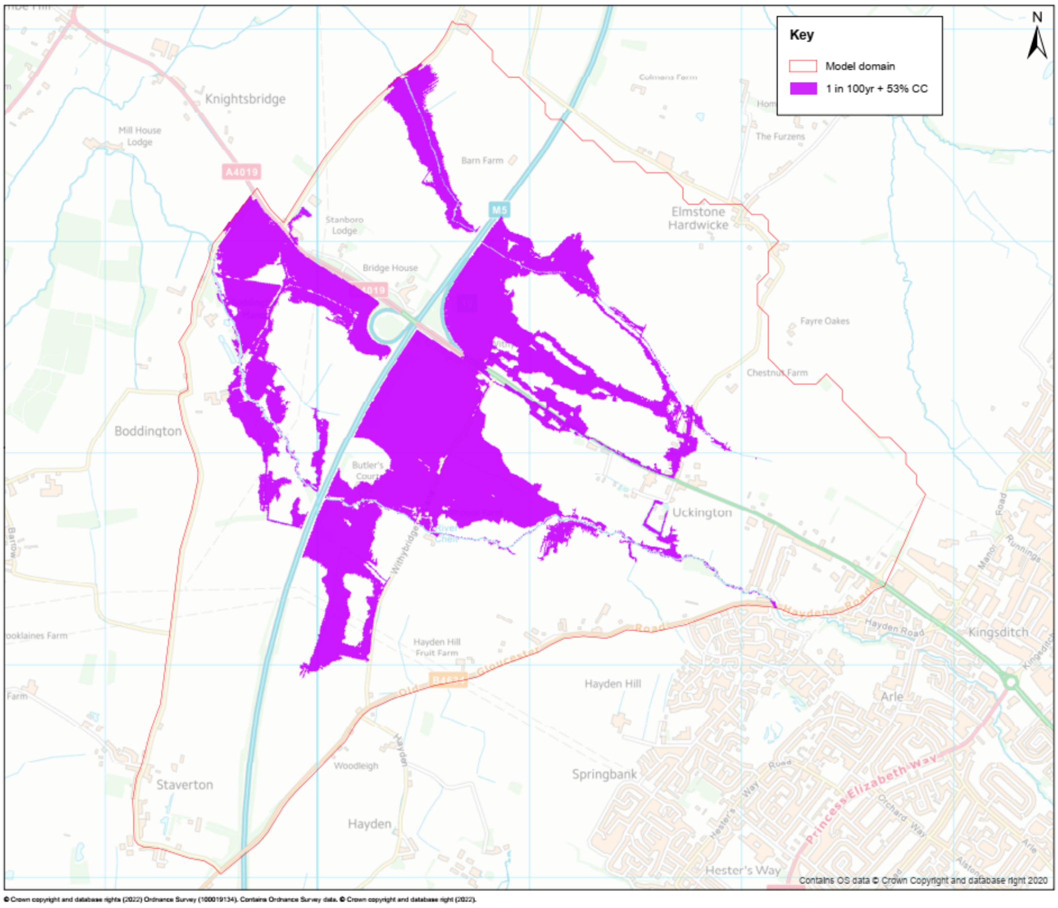
2.3.14. The 1% annual exceedance probability event (1 in 100-year return period) with 53% increase in peak flows to account for future climate change generates a slightly smaller flood extent than the present day 0.1% annual exceedance probability event (1 in 1,000-year return period). This is reflected in the peak flow passing through the River Chelt culvert, being 21.5 m^3/s compared to 21.7 m^3/s.

2.3.15. Perhaps the biggest impact of climate change in the River Chelt catchment at this location is the instigation of flow over the A4019 highway into the catchment of the Leigh Brook. This cross-catchment transfer leads to much greater flooding on the eastern (upstream) side of the M5 motorway at Barn Farm culvert. The occurrence was predicted in the sensitivity testing on both upstream inflow and climate change allowance, even with the lowest change tested (a +20% increase in inflow) causing this impact. The increase in flow from 0 m^3/s in the present day, to 10.3 m^3/s in 100-years' time creates a significant increase in flood risk to the land north of the A4019.

2.3.16. Further details are described in the Baseline Modelling Report (Application document TR010063/APP/9.18).

Figure 5 – Baseline flood extents – design flood

1% annual exceedance probability event (1 in 100-year return period) with 53% climate change uplift



3. Input data

This section of the report describes the data available to inform the Scheme model build.

3.1. Hydrology

3.1.1. The hydrology for the Scheme uses the same inflows as applied to the Baseline model and estimated in 2021. It uses FEH assessments (ReFH2) for five sub catchments, as well as an additional inflow for the Cheltenham CSO. No changes to the hydrology have been made from the Baseline modelling.

3.1.2. The final flow estimates for all design events are provided below in Table 3-1.

Table 3-1 – Flow estimates

Location	Flow m³/s						
	2yr	5yr	10yr	25yr	50yr	100yr	1000yr
River Chelt at M5	8.9	11.9	14.2	17.8	20.9	24.5	37.4
River Chelt downstream M5	0.8	1.0	1.3	1.6	1.9	2.2	3.3
Leigh Brook at M5	0.9	1.2	1.4	1.8	2.1	2.5	3.5
Leigh Brook downstream M5	0.5	0.6	0.7	0.9	1.1	1.3	2.0
Staverton stream	1.5	2.0	2.6	3.0	3.5	4.1	4.3
Arle CSO (provided by STW, scaled by 40%)	No data	2.1	2.4	3.0	3.4	3.9	5.4

3.1.3. Climate change has been accounted for in the model testing as applied to the Baseline, following the Environment Agency's climate change allowance (July 2021)[4]. In summary, the modelling undertaken applies a +53% increase in peak flow for 100-years in the future, in accordance with the Environment Agency guidance (Higher central allowance for the Severn river basin district and Severn Vale management catchment).

3.1.4. A sensitivity test was undertaken using the Upper End (credible maximum) allowance of 94% on peak flow.

3.1.5. The peak flows with climate change allowance are tabulated below.

Table 3-2 – Design flows with climate change allowance

Location	Flow m³/s	
	100yr	100yr + 53% climate change
River Chelt at M5	24.5	37.5
River Chelt downstream M5	2.2	3.4
Leigh Brook at M5	2.5	3.8
Leigh Brook downstream M5	1.3	2.0
Staverton stream	4.1	6.2
Arle CSO	3.9	6.0

3.1.6. The design flood remains the 1% annual exceedance probability event (1 in 100-year return period) with a +53% increase in peak flow for future climate change.

[4] Flood risk assessments: climate change allowances - GOV.UK (www.gov.uk).

3.2. Hydraulic model

3.2.1. Flood modelling for the Scheme used a modification of the Baseline model, which was itself developed from the available Environment Agency models. It is an ESTRY-TUFLOW 1D-2D model.

3.2.2. The Scheme design (highways, structures, earthworks etc) was applied to the Baseline model to reflect the intended changes in topography and water environment. The Scheme input data is tabulated in Table 3-3 below.

3.2.3. The Scheme provides a new elevated roundabout on the A4019 over the M5 motorway with four new slip roads connecting traffic with the M5 motorway below. To provide increase headroom over the motorway, the roundabout and its bridges will be raised. As such, the A4019 is also raised, and regraded, before reconnecting to existing road levels some distance from the motorway. The A4019 is then widened as far as the Gallagher Retail Park at the junction of the B4634 Old Gloucester Road junction. A new junction on the A4019 provides access onto the new West Cheltenham Link Road, which passes south across the River Chelt floodplain, east of the existing Withybridge Lane, to the B4634 near Hayden Hill, south of the River Chelt.

3.2.4. The design information is limited to vertical and horizontal alignments of the Scheme as part of a wider 3D CAD model. The outline design information from Design Fix 3.4 (DF3) as of June 2022 has been used to inform this report.

Table 3-3 Hydraulic model input data

Data	Date	Origin	Source / Drawing
Baseline flood model	February 2021	Atkins	See description in Application document TR010063/APP/9.18
A4019 Dualling 3D CAD model	August 2022, revision P09.1	Atkins	GCCM5J10-ATK-HML-L1_ML_Z-MR-CH-000003
A4019 and Link Road Junction 3D CAD model	August 2022, revision P09.1	Atkins	GCCM5J10-ATK-HML-J2_JN_Z-MR-CH-000003
B4634 and Link Road Junction 3D CAD model	October 2022, revision P07.1	Atkins	GCCM5J10-ATK-HML-J3_JN_Z-MR-CH-000003
Link Road 3D CAD model	June 2022, revision P07.1	Atkins	GCCM5J10-ATK-HML-L2_ML_Z-MR-CH-000003
M5 Junction 10 3D CAD model	October 2022, revision P08.1	Atkins	GCCM5J10-ATK-HML-J1_JN_Z-MR-CH-000003
Access Roads 3D CAD model	October 2022, revision P09.1	Atkins	GCCM5J10-ATK-HML-ZZ_SR-MR-CH-000003
Gallagher Junction 3D CAD model	August 2022, revision P07.1	Atkins	GCCM5J10-ATK-HML-J4_JN-MR-CH-000002

4. Hydraulic method and implementation

4.1.1. This section describes the methods used in the Scheme hydraulic modelling (including post-processing), focusing on non-standard aspects of modelling (rather than a detailed description of every stage of the process or a repeat of procedures that are well documented).

4.2. Hydraulic model build

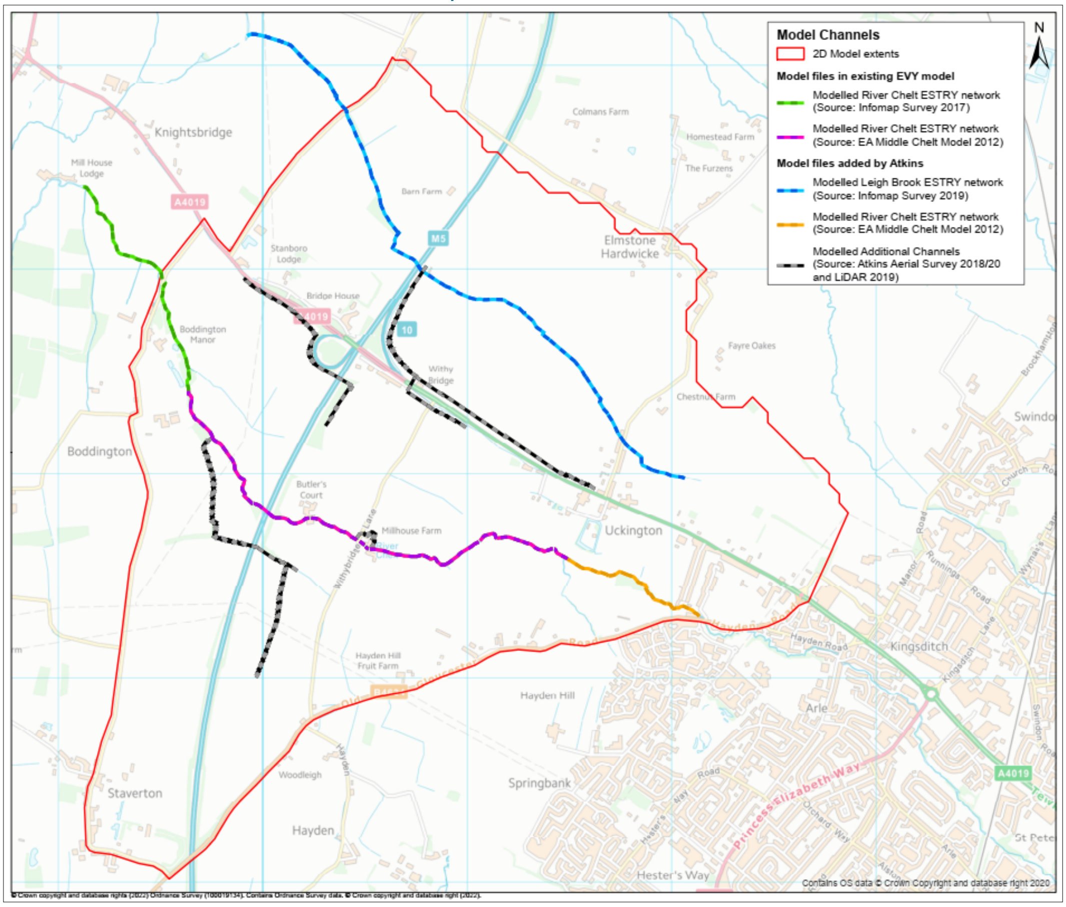
4.2.1. The Scheme model for the M5J10 is a 1D-2D linked model developed from the Baseline model (River Chelt and Leigh Brook). The channels are modelled in 1D ESTRY and the floodplain and surrounding topography in 2D TUFLOW.

Channels

4.2.2. A schematic of the watercourse channels included in the M5J10 model (Baseline and Scheme) is shown in Figure 6. Minor watercourses (field ditches), including the Staverton stream and Piffs Elm channel, have been modelled as Z-line gullies in 2D, with bed levels based on inspection of LiDAR and survey where available. Channels were re-aligned around the scheme surface where applicable, for example where channels are locally diverted to pass around access spurs or moved to suit the new highway embankments.

4.2.3. No changes were made to the representation of the 1D watercourse channels from the Baseline model.

Figure 6 – Schematic of model channels and components



Channel roughness

4.2.4. The 1D channel roughness is applied either through a code in the 1D cross-section file (.csv) which corresponds to a Manning's n value in the TUFLOW Materials File (.tmf), or directly in the attribute in the network line.

4.2.5. No changes were made to the channel roughness coefficients from those included in the Baseline model.

Floodplain representation

Scheme surface

4.2.6. The underlying floodplain was applied as a 2D domain within TUFLOW using the 2019 LIDAR Composite DTM with a 1m resolution consistent with the Baseline model. A TUFLOW grid size of 4m was adopted as with the Baseline model. No changes were made to the underlying 2D domain from the Baseline model.

4.2.7. The Scheme modifies the topography asociated with the motorway junction and the A4019 widening, as well as placing the new West Cheltenham Link Road on an embankment across the River Chelt floodplain. A resulting 3D surface was generated from the 3D CAD model of the Scheme. The new surface has:

- A new grade separate junction over the M5 motorway encompassing two new overbridges for the M5 and associated roundabout;
- An embankment supporting the new southbound off-slip encroaching into the farmland at the existing M5 motorway junction, reflecting the expanse of the junction roundabout;
- An embankment supporting the new southbound on-slip encroaching into Withybridge Gardens at the existing M5 motorway junction, reflecting the expanse of the junction roundabout;
- An embankment supporting the new northbound off-slip encroaching into the farmland at the existing M5 motorway junction, reflecting the expanse of the junction roundabout. The Scheme removes the existing circular on-slip;
- An embankment supporting the new northbound on-slip encroaching into the plant nuseries at the existing M5 motorway junction, reflecting the expanse of the junction roundabout;
- A raised and widened A4019 from the M5 Junction 10 to the Gallagher Retail Park at the B4634 in Uckington, with a cross-roads junction to the West Cheltenham Link Road (south) and spur into future development area (north); and
- The West Cheltenham Link Road raised on an embankment over the River Chelt floodpain, crossing the River Chelt east of Withy Bridge at its high point, before dropping to meet the existing B4634 Old Gloucester Road north of Hayden.

4.2.8. Minor ground raising in the verge alongside to the A4019 immediately west of the M5 Junction 10 at Piffs Elm was included within the model geometry. This is prevents localised flooding of the A4019 carriageway, and the land to the north, as predicted in the Baseline. The verge raising is over some 50m, raising levels by up to 260 mm, with a suggested crest level, with 300mm freeboard, of 21.70m AOD.

Floodplain roughness

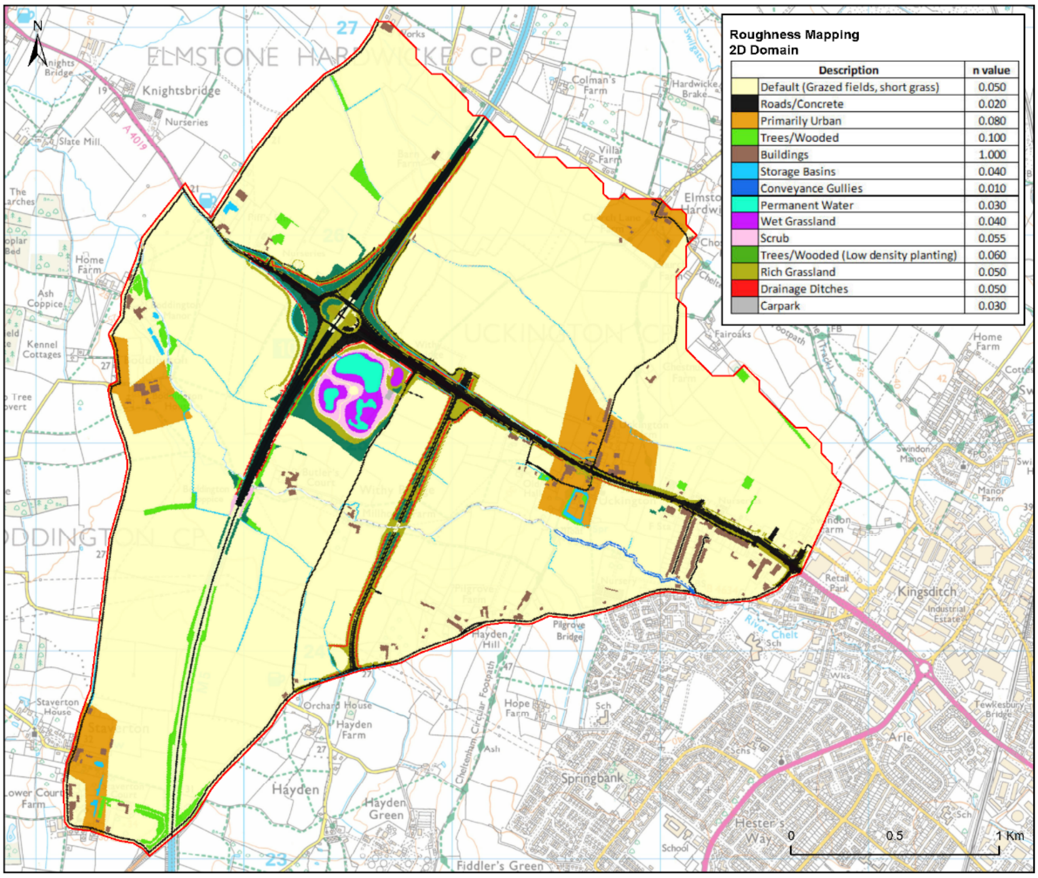
4.2.9. The materials files describing where the Manning roughness values are applied to the 2D domain were updated to reflect the Scheme modifications to topography – noting particularly where farmland or other natural terrain is to be replaced by highway. The proposed landscape design[5] for the Scheme has also been reflected in the 2D surface roughness. Changes to the area of surface materials (and hence roughness coefficient) are shown in Figure 7 below.

4.2.10. No other changes were made to the floodplain roughness coefficients from those included

[5] Atkins (2022) M5 J10 Improvements Scheme - Environmental Master Plan, ref GCCM5J10-ATK-ELS-ZZ-M2-LL-000001

in the Baseline model.

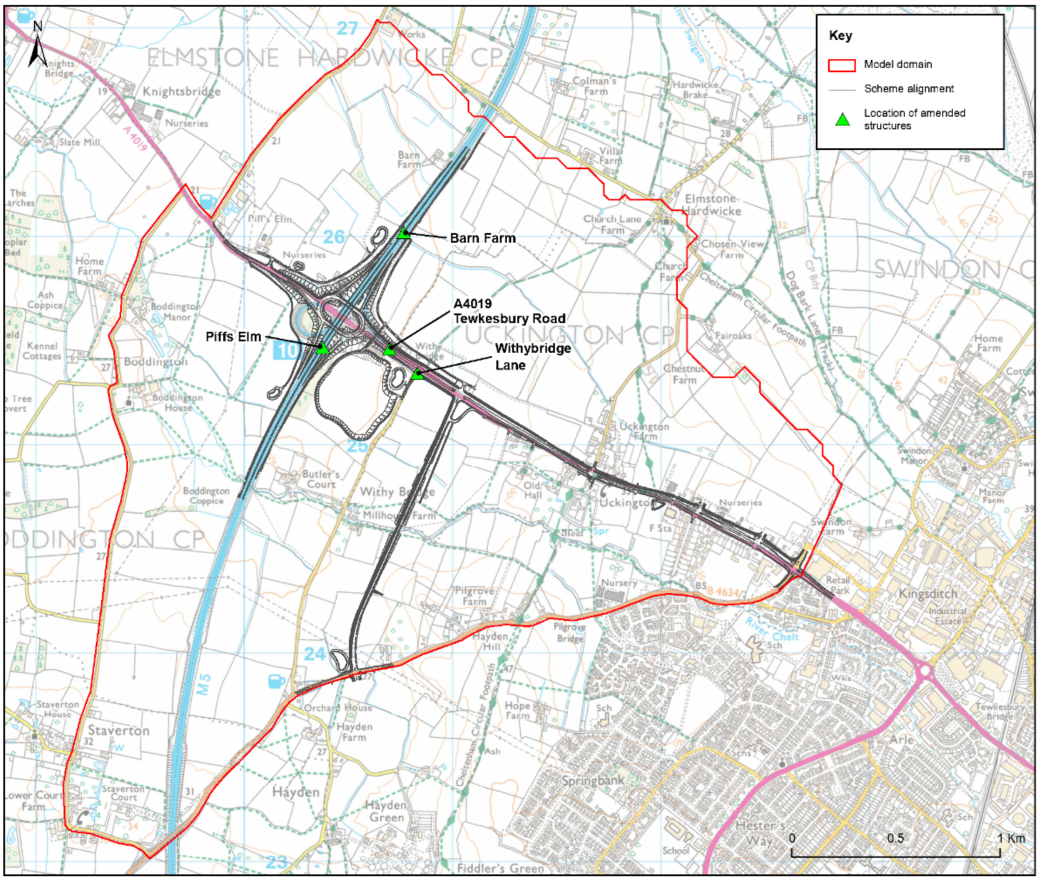
Figure 7 – Changes in surface roughness resulting from the Scheme



Structures

Starting with the Baseline model, changes were made in the Scheme model to either, modify, replace or remove structures as dictated by the Scheme design. The location of these structures are shown in Figure 8 below.

Figure 8 - Plan showing location of structure amendments



Modified and removed structures

4.2.11. Several of the structures included in the Baseline model were modified to reflect the Scheme. One structure included in the Baseline model, the A4019 Tewkesbury Road culvert, was removed as part of the Scheme. These are described below in Table 4-1.

Table 4-1 - Changes made to the Scheme structures

Structure	Baseline model	Scheme model
Piffs Elm culvert Network ID JUNC10	1200 mm diameter pipe culvert. Length 47 m with a gradient of 1 in 138.	Culvert extended to reflect changes to M5 motorway slip roads and widened highway embankment. 53 m long 1200 mm diameter pipe culvert extension on downstream side with a gradient of 1 in 126 to reflect the fixed downstream channel invert. 47.2 m long 1200 mm diameter pipe culvert extension on upstream side with a gradient of 1 in 123 to reflect the fixed upstream channel invert. Total new length 147.2 m

Structure	Baseline model	Scheme model
Barn Farm culvert (Leigh Brook) Network ID's LB_CH18a (left) and LB_CH18b (right)	Twin 1250 mm diameter pipe culverts. Length 53.7 m with gradients of 1 in 145 (left) and 1 in 163 (right).	Both culverts extended to reflect changes to M5 motorway slip roads and widened highway embankment. 7.9 m long 1250 mm diameter pipe culvert extensions on downstream side with gradients of 1 in 395 (left) and 1 in 198 (right) to reflect the fixed downstream channel invert. 8.5 m long 1250 mm diameter pipe culvert extensions on upstream side with gradients of 1 in 845 (left) and 1 in 282 (right) to reflect the fixed upstream channel invert. Total new length 70.1 m
A4019 Tewkesbury Road Network ID's TEWK (twin pipes) and TEWK_2 (inverted triangle chamber)	Inverted triangle chamber leading to twin 750 mm diameter pipe culverts. Total length 88 m with a gradient of 1 in 157.	Removed as part of Scheme.
Withybridge Lane (adjacent to A4019) Network ID's Wbridge_1 (left) and Wbridge_2 (right)	Twin 800 mm diameter pipe culverts. Length 10 m with gradients of 1 in 1 in 83 (left) and 1 in 53 (right).	Both culverts realigned to suit the widened highway embankment and their length set to suit. Total new length 27.5 m with a flat gradient to reflect the existing upstream and downstream channel inverts from LiDAR.

Structures requiring no change

4.2.12. No other changes were made to the other hydraulic structures in the Baseline model. The key structures retained and unchanged in the Scheme model are tabulated below in Table 4-2.

Table 4-2 – Key Baseline structures unchanged by the Scheme

Structure	Baseline model	Scheme model
Staverton culvert Network ID's M5South_1 (left) and M5South_2 (right)	Twin 1000 mm diameter pipes. Length 50 m with gradients of 1 in 625, and 1 in 357.	No changes. Scheme does not require alteration of this culvert.
River Chelt culvert Network ID M5 Culvert	Box culvert with cantilever footway and irregular invert resulting from sedimentation. Length 43.4 m	No changes. Scheme does not require alteration of this culvert.

New structures

4.2.13. New structures added as embedded mitigation are described in Section 4.5.

4.3. Inflow boundaries

Upstream boundaries

4.3.1. The inflow points applied to the hydraulic modelling are summarised in Table 4-3, below. No changes were made to the inflow boundaries applied to the Baseline model.

Table 4-3 – Inflow points

Catchment	Catchment area (km^2)	Where inflow is applied in the model	Design flow m^3/s *
River Chelt catchment draining to the M5 motorway	30.59	Applied as a flow time boundary at the upstream boundary of the hydraulic model at the B4634 Old Gloucester Road	37.5
Sub catchment of the River Chelt downstream of the M5 motorway	1.71	Applied as a flow time boundary on the downstream side of the M5 motorway, at the outlet of the motorway culvert	3.4
Leigh Brook catchment draining to the M5 motorway	2.29	Applied as a flow time boundary along the upstream reach of the Leigh Brook between its headwater and the M5 motorway.	3.8
Sub-catchment of the Leigh Brook downstream of the M5 motorway	1.13	Applied as a flow time boundary on the downstream side of the M5 motorway, at the outlet of the motorway culvert	2.0
Staverton stream which flows to the M5 motorway.	2.35	Applied as a flow time boundary into the 2D domain at the mapped upstream point of the tributary. Staverton Stream was not modelled in 1D.	6.2
CSO catchment, which discharges at Arle.	11.50	As a flow-time point discharge at the upstream boundary of the hydraulic model at the B4634 Old Gloucester Road.	6.0

* The design flow being the 1% annual exceedance probability event (1 in 100-year return period) with 53% allowance for future climate change.

4.3.2. Areas draining onto the floodplain have been collected within the model inflows and applied either as the upstream boundaries or on the downstream side of the M5 motorway. This is precautionary as it applies higher flows to the upper lengths of a flow reach.

4.3.3. The locations of these inflow points are shown in Figure 9.

Drainage inputs

4.3.4. The Baseline model does not include for separate road drainage flows within the model boundary, instead the flows are accounted for through the urbanisation elements of the Flood Estimation Handbook.

4.3.5. In a similar manner, changes to the drainage (with new outfalls) as a result of the Scheme are not explicitly modelled as separate inflows. The drainage strategy sees all highway runoff directed to one of a number of drainage attenuation ponds, via both swales and traditional piped drainage. The attenuation ponds then regulate the outflow to a receiving watercourse, based on greenfield runoff in terms of peak flow rates and volumes.

4.3.6. No changes have been made to the hydrology and application of flows from those used in the Baseline model, based on the relative scale of these changes. See Section 4.5 on the drainage strategy as part of the embedded mitigation.

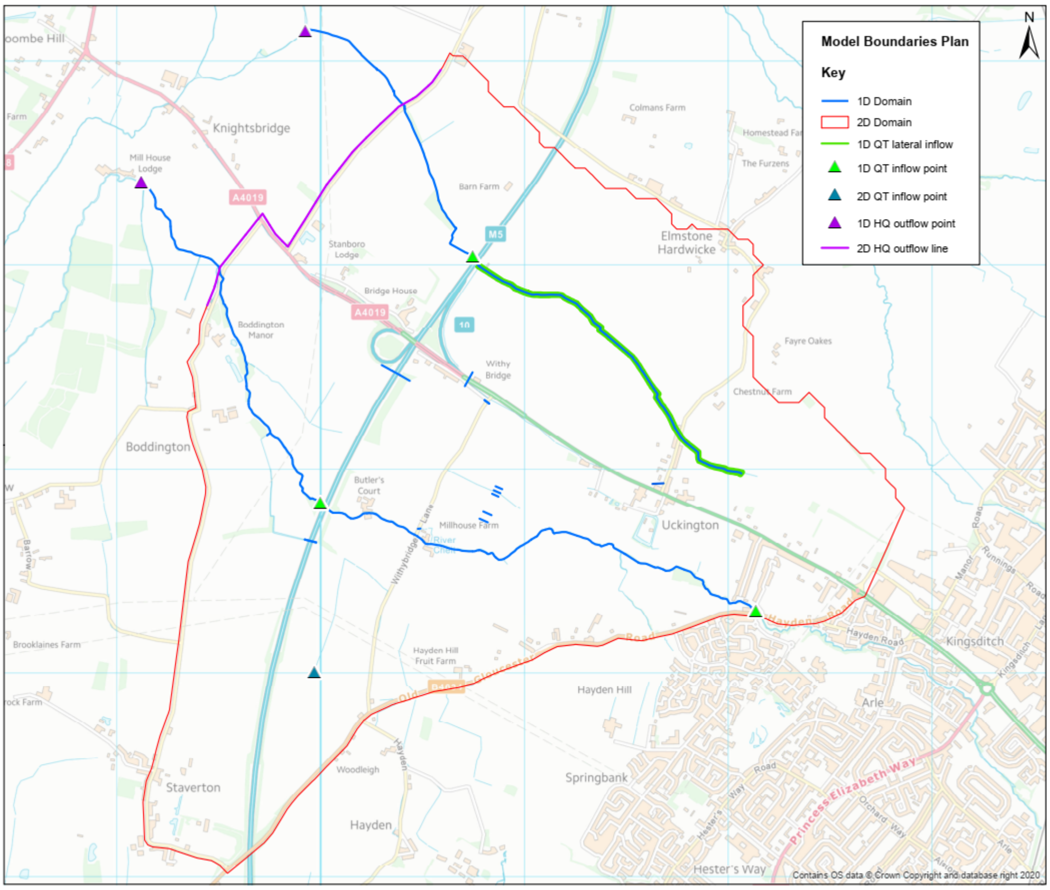
4.4. Downstream Boundary

4.4.1. No changes were made to the downstream boundaries from the Baseline model. These are stage-discharge boundaries in the 1D model and normal flow depths in the 2D model.

4.4.2. The downstream boundaries are set sufficiently remote from the Scheme to not cause an impact on flood levels as was demonstrated by sensitivity testing with the Baseline model; the controlling M5 motorway culverts are well beyond the backwater reach of the downstream boundaries.

4.4.3. The locations of these boundaries are shown in Figure 9.

Figure 9 – Model boundaries



4.5. Embedded mitigation

4.5.1. Without any appropriate embedded mitigation the proposed Scheme would have significant impacts on flood risk to 3rd party land and local infrastructure. Such a scenario was evaluted with the hydraulic model, and is described in Section 6.2.

4.5.2. The guidance is clear that embedded mitigation should be the best practice design approach. Embedded mitigation covers the project design principles adopted to avoid or prevent adverse environmental effects, whereas Essential/Additional mitigation are those measures subsequently required to reduce and, if possible offset likely significant adverse environmental effects in support of the reported significance of effects in the environmental assessment.

4.5.3. Thus, embedded mitigation describes the good-practice measures that would occur without input from the EIA feeding into the design process. It includes actions that would be undertaken to meet other existing legislative requirements, or that are considered to be standard practices or design principles. For example, embedded mitigation could include the appropriate design of river crossings or realignments; and the provision and design of compensatory floodplain storage.

4.5.4. Anything project specific is described as essential (or additional) mitigation – being the extra-over to step away from a significant environmental impact.

4.5.5. For M5 J10 in terms of flooding, the embedded mitigation includes:

- A drainage strategy to limit the peak rate and overall volume of discharge of surface water runoff, and enhance its water quality;
- The new watercourse crossing of the River Chelt being designed to convey the design flow with a minimum 600mm freeboard to soffit;
- The link road including a crossing, or crossings, of the River Chelt floodplain;
- All affected M5 and A4019 watercourse culverts being extended to suit the new roads; and
- Compensatory floodplain or storage being provided to offset the volume of water displaced by the scheme [on a level for level or equivalent basis as appropriate], prior to the removal of any existing floodplain.

4.5.6. These features are described below.

Drainage strategy

4.5.7. A detailed drainage design has been prepared in accordance with the various design standards to manage the risk of flooding of the road itself (i.e. from the scheme's surface, drainage etc.). This is described in the Scheme's drainage strategy[6].

4.5.8. The strategy limits discharges from the new highways such that they do not exceed the present-day runoff rates or volumes, and neither with climate change allowances considered. The Scheme design includes drainage attenuation ponds, fitted with flow controls. Peak runoff from the new paved surfaces is being restricted to the current greenfield runoff: peak outflows will be limited to greenfield runoff rate (QBAR) for events up to the 1% annual exceedance probability event (1 in 100-year return period) with an allowance of 40% applied for climate change (40% being the Environment Agency guidance for climate change impacts on rainfall, as used in drainage design). A volumetric restriction will be applied to control the additional volume of runoff generated.

4.5.9. This will either be applied by reducing all peak flows to no more than the present day mean-annual flood, or providing separate design elements to deal with long term storage.

4.5.10. Under these design rules, the road drainage will not increase the rate or volume of runoff being discharged into the existing watercourses.

4.5.11. The drainage design was applied to the Scheme hydraulic modelling, as detailed below.

[6] Atkins (2021) M5 J10 Improvements Scheme – Drainage strategy report, ref GCCM5J10-ATK-HDG-ZZ-RP-CD-000001

- The attenuation ponds were included in the with-Scheme terrain model, reflecting any changes in ground levels, hence enabling an assessment of their impact on flood risk and their safety from river flooding.
- Discharges from the attenuation ponds were not added to the hydraulic model. With the design standards ensuring no increase in greenfield runoff (rate or volume) modification of the FEH catchments to reflect field scale changes was not necessary. The existing road network is already described by the FEH inflows in the hydrology and Baseline model.

River Chelt bridge

4.5.12. The Scheme requires the addition of a new bridge over the River Chelt, carrying the West Cheltenham Link Road.

4.5.13. Advice from the Environment Agency indicated that a 4 m easement on the south bank and a 2 m easement on the north bank would be acceptable for their regulatory requirements. The proposals comprise a 24 m wide span with the deck soffit set 600 mm above the predicted design flood level of 27.7 m AOD. The abutments are set back from the river banks by 4 m on the north and 8 m on the south, permitting vehicular access under the bridge on both banks.

4.5.14. The new structure was added to the Scheme model to represent the River Chelt bridge. Separate floodplain conveyance features under the West Cheltenham Link Road and are described in the next section below.

Table 4-4 – New bridge structure added to the Scheme model

Structure	Baseline model	Scheme model
West Cheltenham Link Road – River Chelt crossing No Network ID	None. No link road in the Baseline.	Represented in 2D domain only as the proposed soffit level is 600mm above the predicted design flood level. The structure is a ~ 24 m wide opening which is wider than the represented width of the 1D model at this location. Consequently the abutments and the Link Road embankment is represented in the topography of the 2D model.

Chelt floodplain structures

4.5.15. From an early stage of design it was recognised that the West Cheltenham Link Road would need to cross the wide floodplain of the River Chelt. The West Cheltenham Link Road crosses the River Chelt floodplain on the north side of the watercourse, a crossing length of over 200 m from the A4019 in the north to the B4634 in the south. Initial hydraulic modelling predicted a significant impoundment to the east of the link road should no conveyance structures be included.

4.5.16. The results of the Baseline modelling demonstrated that the floodplain accommodates only shallow and slow moving floodwater, with the design flow at typically 200 mm depth of flow running at typically 0.2 m/s. This shallow flooding could readily be conveyed in low height culverts, for example comprising 3 m wide by 1 m high box culvert units.

4.5.17. The Scheme concept was to use multiple span bridges (flexi-arch or similar) or multiple barrel culverts to maintain floodplain connectivity and conveyance. This was developed into a series of 3 m wide box culverts, being suitable for the cranage envisaged for the wider construction (not requiring unique lifting arrangements). Based on the total width of floodplain, and accounting for construction design, 37 separate culverts would be required to cross the floodplain.

4.5.18. The hydraulic design of the crossing was developed concentrating on areas of high flow, depth and velocity across the floodplain. All culverts (aside from the culvert carrying an existing disconnected field ditch) were set with the same invert level, to optimise the construction. This invert level was tested as a variable to optimise the solution. The modelling results indicated that there was a balance between the number and level of culverts, and flood levels upstream of the link road.

4.5.19. The solution implemented 37 culverts. a reduction in this number may be possible at detailed design as the link road design becomes more developed. The setup is as follows (tabulated for the model in Table 4-5 and illustrated in Figure 10):

- 18 nr 3 m wide × 1 m high box culverts, split into two groups of 9 culverts either side of the existing field ditch. All culverts were modelled at around ground level with a constant upstream invert level of 27.1 m AOD and downstream invert level of 27 m AOD.
- A single 6 m wide × 1.35 m high box culvert carrying the existing field ditch, placed on the bed of the existing ditch with an upstream invert level of 26.75 m AOD and a downstream invert level of 26.45 m AOD.
- 18 nr 3 m wide × 1m high box culverts, split into two groups of 9 culverts, with the northernmost culvert approximately 200 m north of the River Chelt. All culverts in this group were modelled at ground level with a constant upstream invert level of 27.1 m AOD and downstream invert level of 27 m AOD.

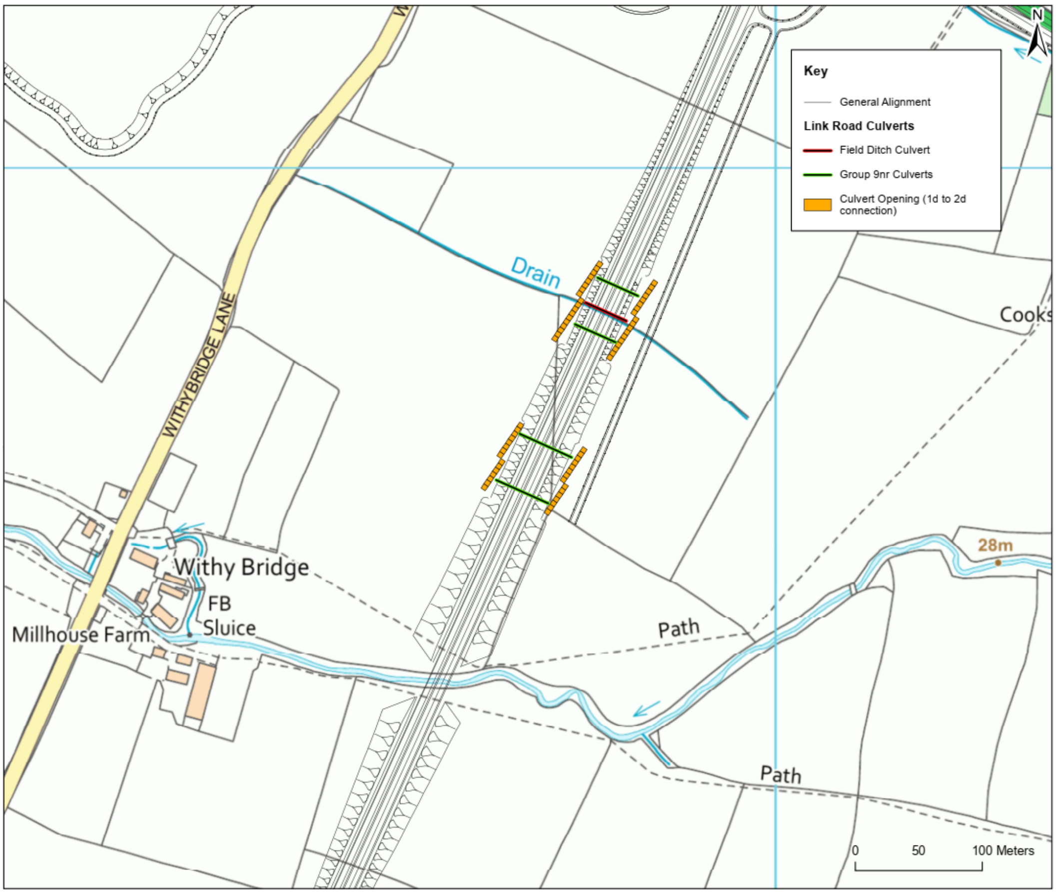
4.5.20. As described above, the culverts were modelled in groups of 9 culverts, whereby a single 1D network line represented 9 culverts, as opposed to a network line for each individual culvert. This approach ensured that an appropriate number of 2D boundary cells could be selected by a collective SX line in the 1D/2D linking of the culvert. This is considered good practice as it helps to eliminate erroneous water levels and flows being applied to a single boundary cell that could affect modelling stability and outputs. If the latter approach were used, where a network line represented only 1 culvert, then the associated SX lines would not be able to select the required number of 2D boundary cells without preventing boundary cells from bordering each other, and therefore blocking flow in some areas.

4.5.21. No culverts were included under the West Cheltenham Link Road on the southern bank of the River Chelt, as no floodplain was predicted here by the Baseline model.

Table 4-5 – New structures added to the Scheme model

Structure	Baseline model	Scheme model
West Cheltenham Link Road – Chelt floodplain culverts Network ID's LR_N_1, LR_N_2, LR_N_3, LR_S_1 and LR_S_2.	None. No link road in the Baseline.	36 nr 3 m wide × 1 m high box culverts set in four groups (each of 9 nr) with upstream invert levels set at 27.10 m AOD and downstream invert levels set at 27.00 m AOD. A single 6 m wide × 1.35 m high box culvert with upstream invert level set at 26.75 m AOD and downstream invert levels set at 26.45 m AOD.

Figure 10 - Setup of Link Road Culverts



Culverts

4.5.22. Four culverts carry watercourses under the existing M5 motorway: the Staverton culvert, River Chelt culvert, Leigh Brook culvert at Barn Farm, and the Piffs Elm culvert collecting overland flow near Withybridge Gardens.

4.5.23. The Scheme requires extension to some of these to maintain their hydraulic connectivity. The culverts will be maintained at their Baseline sizing and extended to suit the existing watercourse levels at either end. This has been described in Section 4.2 above.

Compensatory floodplain storage

4.5.24. Compensatory flood storage works are required where the Scheme would otherwise reduce the available volume of flood storage. CIRIA 624 (Development and flood risk – guidance for the construction industry - Section A.3.3.10, 2004) states that:

"*Compensatory flood storage must become effective at the same point in a flood event as the lost storage would have done (McPherson 2002). It should therefore provide the same volume and be at the same level relative to flood level, as the lost storage. This requirement is often referred to as "level for level" or "direct" compensation*".

4.5.25. Replacement floodplain is required to offset the losses under the footprint of the Scheme. Losses are predicted on both the River Chelt and Leigh Brook floodplains. The hydraulic modelling was used to quantify the losses in terms of plan area and contained volume of floodplain as described by the Baseline model for the design flood event. The Scheme places a total footprint area of 97,630 m^2 into the Baseline 1% annual exceedance probability event (1 in 100-year return period) with climate change floodplain, with a volume of 46,718 m^3 displaced. Note that this does not describe Flood Zone 3 as that omits flooding on the Leigh Brook as an ordinary watercourse. See Table 4-6 for the volumes.

Table 4-6 – Volume of floodwater (Baseline) displaced by the Scheme (m^3)

Event	Drainage Pond east of M5	River Chelt east of M5	River Chelt west of M5	Link Road	Leigh Brook east of M5	Leigh Brook west of M5	Total
2yr	0	0	0	0	0	0	**-**
5yr	0	5	0	0	0	0	**5**
10yr	0	85	0	0	0	0	**85**
25yr	0	703	3	31	0	1	**738**
50yr	78	5279	1237	349	0	2	**6,945**
100yr	153	15591	1494	563	6	8	**17,815**
100yrCC	910	28934	1668	909	14241	56	**46,718**
1,000yr	1159	30040	1687	972	19727	61	**53,646**

4.5.26. The total volume of floodwater displaced by the Junction 10 improvements in the River Chelt floodplain amounts to 31,512 m^3 during the design event (910 m^3 + 28,934 m^3 + 1668 m^3), covering losses in the Chelt floodplain (south of the A4019 catchment divide). Some 153,573 m^3 flood water retained from the Leigh Brook (not going over or under the A4019) increases the storage requirement as described below under the heading of 'River Chelt floodplain'.

4.5.27. The 909 m^3 for the West Cheltenham link road is described separately in the next section headed 'West Cheltenham Link Road', and has been dealt with separately from the main River Chelt floodplain.

4.5.28. The impact on the Leigh Brook is described first, below.

1) Leigh Brook floodplain

4.5.29. The total volume of floodwater displaced by the Junction 10 improvements in the Leigh Brook floodplain amounts to 14,297 m^3 during the design event (14,241 m^3 + 56 m^3).

4.5.30. The Scheme severs the overland flow from the River Chelt across the A4019, and through its culverts, which generates much of this calculated displacement in the Leigh Brook catchment. This cross-catchment transfer passes over 153,573 m^3 of floodwater to the Leigh Brook during the Baseline design event. It leads to much greater flooding on the eastern (upstream) side of the M5 motorway at Leigh Brook culvert, with a peak flow of 10.3 m^3/s passing over the road, inundating a length of highway of 135 m with a peak depth of 500 mm. A peak flow of ~ 1.6 m^3/s is also predicted to pass through the twin A4019 culverts in the baseline event.

4.5.31. As the Scheme reduces flooding in the Leigh Brook besides the M5 motorway (by preventing overtopping of the A4019), the total volume of floodwater then displaced is far less than the 14,297 m^3 described above (14,241m^3 + 56m^3). Hydraulic testing of the Baseline model with the A4019 overtopping removed demonstrated that the amount of flooding accommodated on the two fields next to the A4019 and M5 motorway, in the Leigh Brook floodplain, significantly reduced from 92,021 m^3 to only 27,415 m^3 (during the design event). Of this remaining 27,415 m^3, only 1,693 m^3 would be displaced under the footprint of the Scheme.

4.5.32. Given the substantial reduction in flood risk to the Leigh Brook caused by severance of the A4019 flow path (92,021 m^3 – 27,415 m^3 = 64,606 m^3 reduction), despite a minor loss (1,693 m^3) of resulting floodplain from the Scheme, no compensatory floodplain has been provided for the Leigh Brook. The severance of floodplain is dealt with in the River Chelt floodplain, described below.

2) River Chelt floodplain

4.5.33. The total volume of floodwater displaced by the Junction 10 improvements in the River Chelt floodplain amounts to 31,512 m^3 during the design event, covering losses in the Chelt floodplain (south of the A4019 catchment divide). Some 153,573 m^3 of floodwater retained from the Leigh Brook (not going over or under the A4019) is also considered in the storage requirement.

4.5.34. Hence the Scheme has been designed to manage:

- 31,512 m^3 River Chelt floodwater displaced by the Scheme; and
- 153,573 m^3 floodwater retained from the Leigh Brook.

4.5.35. It should be noted that the majority of this is only required at the design event when floodwaters would overtop the A4019 highway in the Baseline conditions. Up until this event, the A4019 causes no severance of flow other than the minor flows that pass through the twin 750 diameter culverts in the Baseline. These culverts will be removed and flows redirected onto the River Chelt floodplain (into the flood storage area) in the Scheme. Hence at the 1% annual exceedance probability event (1 in 100-year return period) a volume of only 17,238 m^3 is required.

4.5.36. The majority of the River Chelt floodplain is generated from an overland flow leaving the River Chelt some 650 m upstream of Withy Bridge, where high flows overtop the right (north) river bank. Ground levels fall away from the River Chelt at this location: there is a 4 m drop in ground levels between the River Chelt to where it ponds near the M5 motorway at Withybridge Gardens.

4.5.37. As indicated in Figure 11, the topography directs the overland flow to the M5 junction 10, where it drains through Piffs Elm culvert. Once floodwaters arrive in this location, there is no other flow path back to the River Chelt. The Baseline hydraulic modelling predicts a 3 m drop in peak flood levels between the fields where the River Chelt banks overtop and Withybridge Gardens.

4.5.38. The primary mechanism of flooding, and cause of floodplain generation, arises from water flowing out of and away from the River Chelt.

4.5.39. Figure 12 indicates the velocity vectors during the peak of the design event. These vectors evidence the direction of flow away from the River Chelt, and at the peak of the event over the A4019.

Figure 11 – Existing ground levels near M5 J10 and Withybridge Gardens

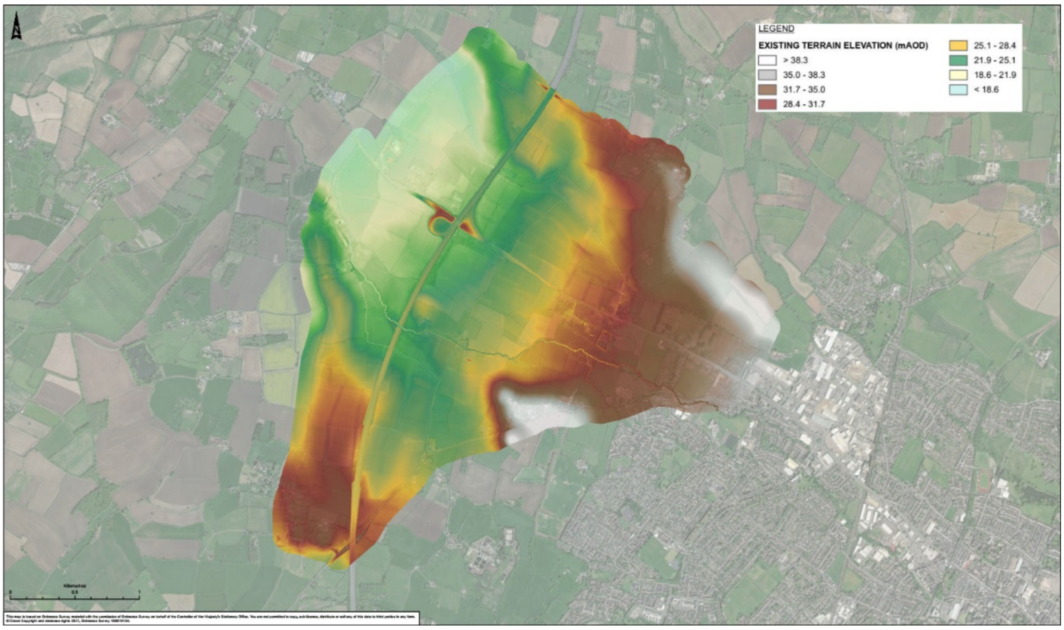
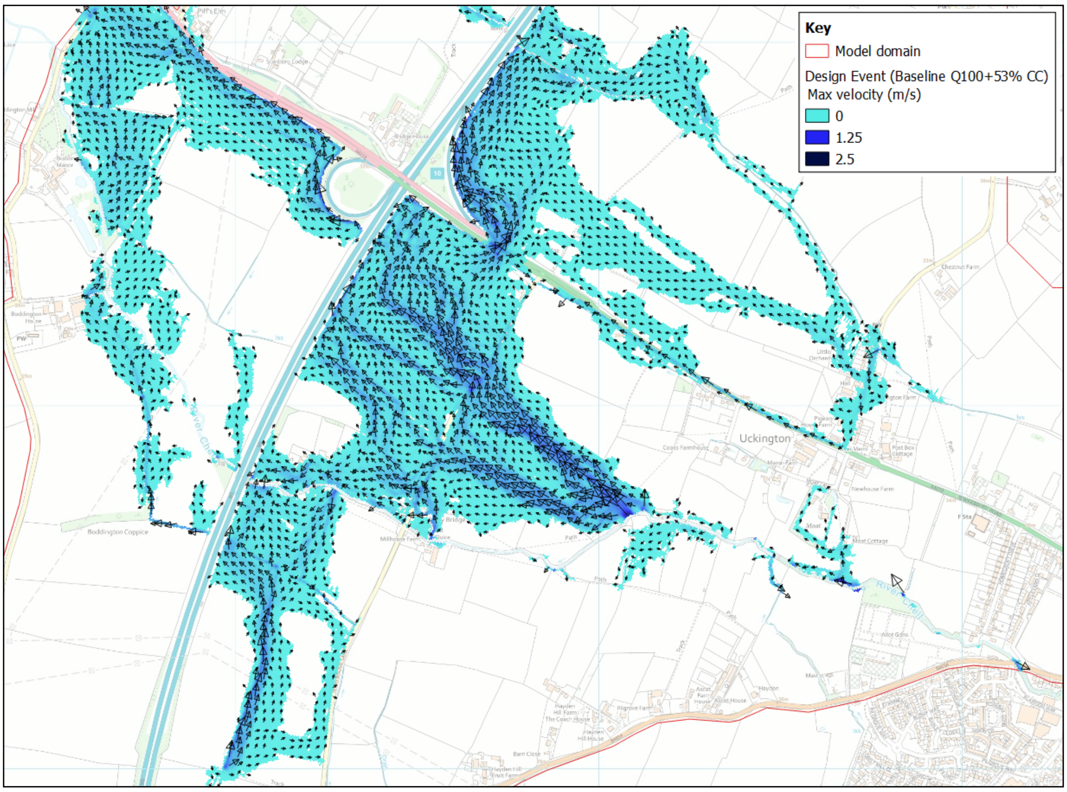


Figure 12 – Flood extent with velocity vectors during design event



4.5.40. In such circumstances, a level for level approach to replacement of floodplain is not appropriate. Provision of compensatory volume at differing ground levels would have no impact on flows or flood levels in the River Chelt and only increase the amount of land required by the Scheme.

4.5.41. During early consultation the Environment Agency agreed that compensatory floodplain for the junction improvement works, including A4019 could be provided on a total volume basis, as opposed to level for level. Compensatory floodplain will thus be provided in the fields to the east (upstream) of the M5 motorway, immediately south of the A4019, where floodwaters accumulate in the Baseline. This will retain the same volume of water leaving the River Chelt and not displace it elsewhere, and fundamentally not change how water passes on to the floodplain.

4.5.42. The Scheme thus provides a new flood storage feature by excavation of a wetland bowl. The flood storage will drain through the Piffs Elm culvert and hence a minimum water level similar to the invert of the east extension to the existing Piffs Elm culvert (22.76 m AOD). Additional excavation below this level may be provided for biodiversity and amenity, enabling a permanent body of water to be retained. A ground investigation for the Scheme indicated very low permeablilty of this underlying strata with little or no infiltration and likewise groundwater intrusion. The permanent water, as dead storage, was not included in the hydraulic model as would not influence the results.

4.5.43. The flood storage accommodates the volume of River Chelt floodwater displaced by the Scheme, being 31,512 m^3 in the design event. The full sizing also provides storage for the floodwater prevented for acessing the Leigh Brook floodplain, being 153,573 m^3. However, the maximum storage required is not required to be the sum of these, as the relative timing of the inflows, outflows and overflows mean that the total volume cannot be combined (superposition of total volume is not appropriate). There is a 4 to 5 hour delay between the peak of flooding on the River Chelt and Leigh Brook floodplains predicted by the Baseline model, with the peak stage related displacement being instantaneous at the height of the event, and the flow over the A4019 being transitional over a period of time. Summation to obtain 185,085 m^3 would overestimate the volume required.

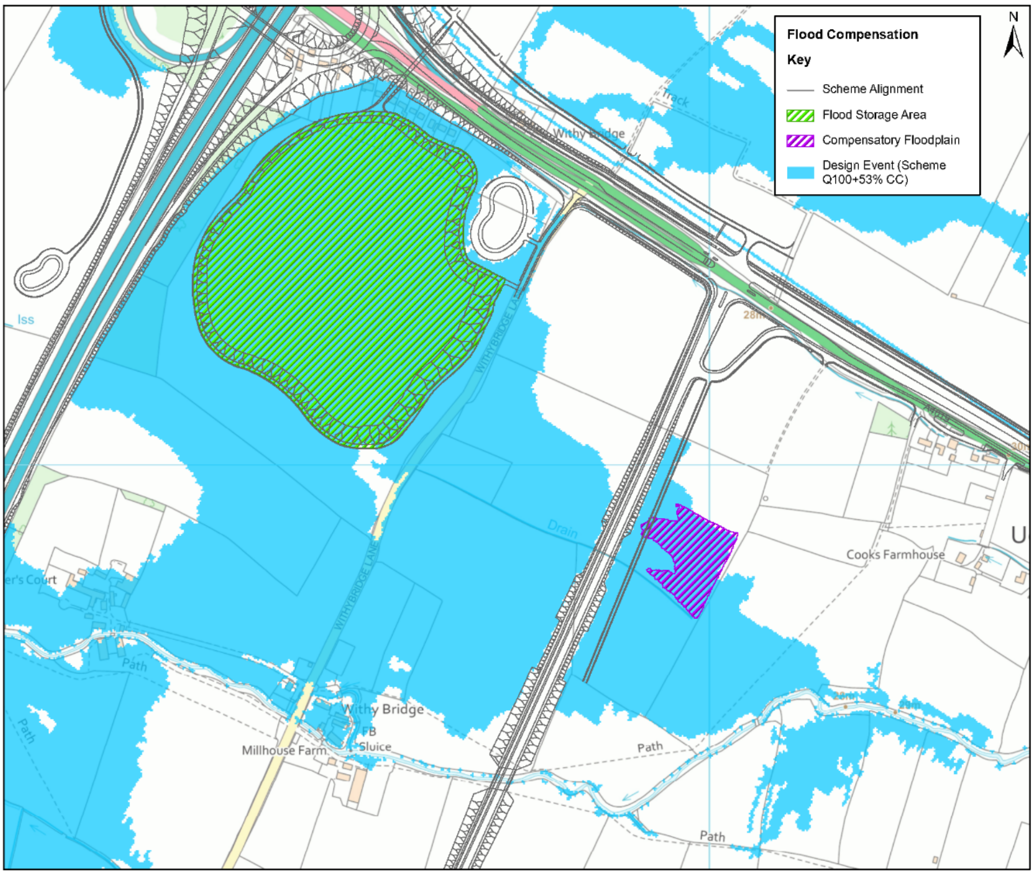
4.5.44. The flood storage was developed through an iterative approach using the hydraulic model to ensure no detriment to 3rd party receptors. Tests were undertaken with different sized wetlands storage, varying the plan area and perimeter, side slopes and precise location in the same location.

- Where the model predicted flood levels would reduce, the wetland storage was too large but could be optimized (made smaller);
- Where the model predicted flood levels would increase and affect 3rd parties, then the wetland storage was too small; and
- Where the model predicted flood levels would increase but not affect 3rd parties, then the wetland storage was acceptable but could be further optimized (made larger).

4.5.45. The resulting outline design was proven in the model. It includes for side slopes around the wetland of 1 in 3, with a 118,801 m^2 organic planform that could include bays, inlets and islands. See Figure 13. The design provides a total excavation below existing ground level (and hence storage volume) of 190,298 m^3 (to Piffs Elm culvert invert level). This is an excavated depth of ~1.5 m along the western perimeter and ~3 m along the eastern perimeter. This provides an oversized flood storage volume compared to the over-calculated losses, being a precautionary approach whilst the design develops.

4.5.46. It is recognised that the detailed design could increase the storage requirement compared to the current over-calculated 185,085 m^3, or reduce the volume provision within the same identified area below 190,298 m^3. Hence the oversizing of this storage area has been adopted and the modelling should be updated as the detailed design progresses.

Figure 13 – Flood storage area



4.5.47. Further details on the performance of the storage is discussed in Section 6.

3) West Cheltenham Link Road

4.5.48. The total volume of floodwater displaced by the West Cheltenham Link Road amounts to

909 m^3 during the design event, covering losses in the Chelt floodplain not counted by the improvements at Junction 10.

4.5.49. During the early consultation, the Environment Agency requested that compensatory floodplain for the West Cheltenham Link Road be provided on a level for level basis. Compensatory floodplain for the West Cheltenham Link Road will thus be provided in the fields to the east (upstream) of the Link Road, adjacent to the existing floodplain (overland flow path).

4.5.50. A level for level assessment was applied to quantify the incremental losses for a range of flood events between the present-day threshold event (4% annual exceedance probability event (1 in 25-year return period)) and the design event. It should be noted that levels of the overland flow vary across the Baseline floodplain and hence a level for level replacement is not straight forward. An approach was developed to assess the frequency of flooding and then apply a level-for-level assessment as described in CIRIA 624:

- The hydraulic model was used to calculate the volume lost for a range of return periods;
- Volumes for each flood frequency band were calculated, giving a frequency volume relationship;
- The corresponding volumes were reprovided for each flood frequency band, setting back the existing flood contours into dry land. Hence a dry land would be excavated to flood to a given depth band, providing the same displaced volume over a new area;
- A CAD/GIS approach was used to shape the storage area; and,
- This shape was incorporated into the hydraulic model and tested (validated) for a range of return periods.

4.5.51. The losses and replacement of floodplain is quantified in Table 4-7 below.

Table 4-7 – Reprovision of storage in the compensatory floodplain

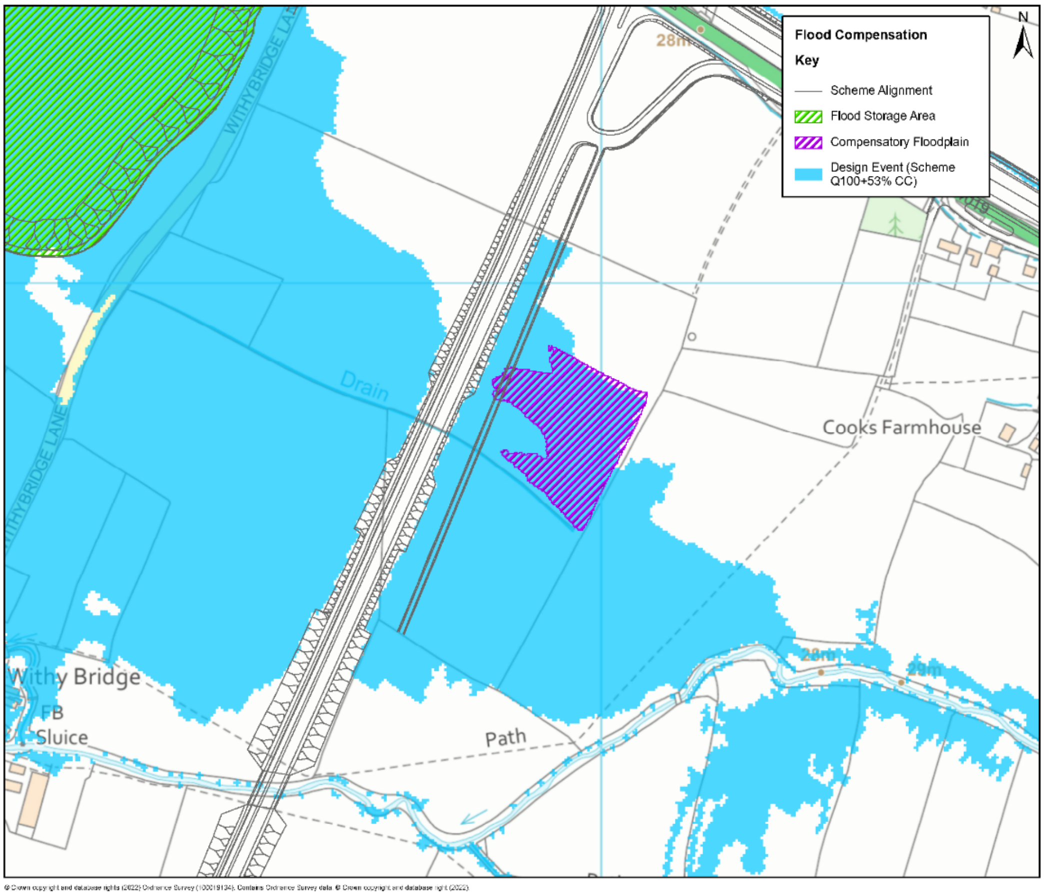
Return period (years)	Volume lost at relief road (m^3)	Volume provided at storage area (m^3)	Difference (m^3)
Onset of flooding at relief road	-	-	-
25	31	405	+374
50	349	866	+517
100	563	1086	+523
100 plus climate change (53%)	909	1456	+547
1000	972	1513	+541
Total volume displaced/re-provided	**972**	**1513**	**541**

4.5.52. The scheme design ensures the hydraulic connectivity of the floodplain across and along the West Cheltenham Link Road such that the new floodplain can be inundated when required to do so.

4.5.53. The new floodplain (see Figure 14) has a plan area of 9,162 m2 and a total excavation below existing ground level of 2775 m3, providing some 1,456 m3 replacement storage at the design event.

4.5.54. Further details on the performance of the storage is discussed in Section 6.

Figure 14 – Link Road floodplain compensation



4.6. Additional mitigation

4.6.1. Additional measures would be required to manage/mitigate any unacceptable consequences, although as documented in this report and the FRA (Application document TR010063/APP/6.15), no significant effects are predicted. If found to be required during future development of the Scheme, additional flood mitigation might include for additional compensatory floodplain to offset the hydraulic impacts (afflux) of the West Cheltenham Link Road crossing.

4.6.2. The land predicted to incur increased flooding is bounded by the Order limits although the change in flood risk is described in the FRA (Application document TR010063/APP/6.15), as being no change or a non-material increase in flood risk. The Scheme thus balances the sustainability of further excavation to provide extra flood storage with the magnitude of detriment and vulnerability of the receptors: the permanent scale, cost and impact of additional excavation for flood storage would be significant when compared the temporary impact of the additional floodwater.

4.6.3. The significance of a change in predicted flood level was discussed with the Environment Agency in the early consultation. It was agreed that:

- ±10 mm should be used to highlight a change in flood risk. The ±10 mm was based on DMRB LA113 which suggests that level of change is negligible. This was also supported by Natural Resources Wales (NRW) guidance note 028 which suggested flood risk should be reported to two decimal places. It is noted that other schemes across England use a higher tolerance for change, being 20 mm or even 50 mm.
- Any change in flood risk to property in excess of +10 mm would be mitigated.
- On agricultural land, any material increase in flood risk could be mitigated, or agreements accepting the change set in place with the landowners.

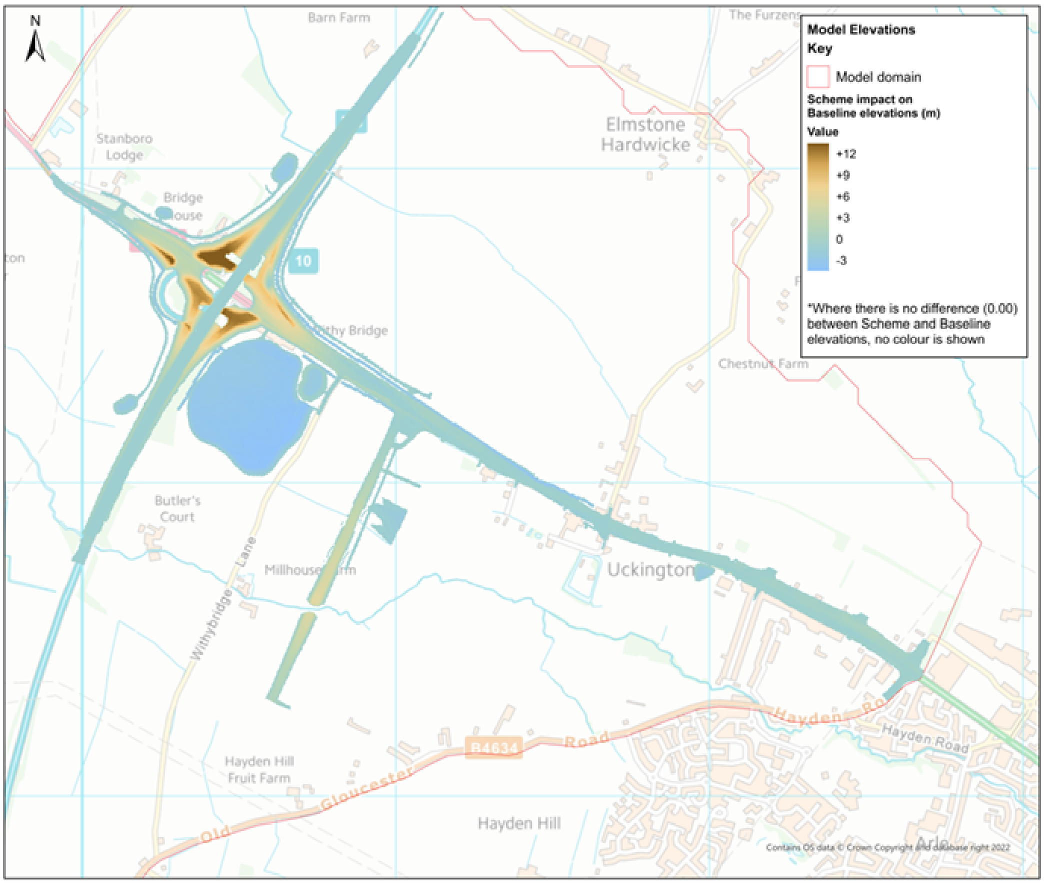
4.7. The resulting scheme

4.7.1. The resulting Scheme surface and hydraulic features for flood modelling are indicated below in Figure 15.

Figure 15 – Scheme surface

4.7.2. The changes in ground levels arising from this shceme are shown as a difference grid in Figure 16

Figure 16 – Changes in ground levels as a result of scheme construction



4.8. Modelling assumptions made

4.8.1. As with the Baseline model, no critical modelling assumptions were made. All relevant data has been obtained and used.

4.8.2. Those modelling assumptions not deemed critical to the project (and as applied to the Baseline model) are:

- The application of inflows in the upstream end of a flow reach is precautionary but is applicable for the design of a highway scheme;
- Manning's roughness values appertaining to an autumn/spring condition are used for the design event. It is assumed that winter conditions would result in an increased channel conveyance; and
- The additional crossings over the mill leat at Millhouse Farm are not critical to hydraulic performance, with the Withybridge Road crossing included as the smallest on that reach.

4.8.3. The specific assumptions relating to the Scheme modelling are:

- Culvert extensions will be made with invert levels fixed by the existing culvert inlet/outlet levels, and the invert levels in the existing watercourse feeding/receiving them.

5. Scheme model proving

This section discusses run performance, sensitivity analysis and the implications of this in the context of this project. This section is important to provide confidence in the model results generated, particularly where vulnerable receptors may be affected.

5.1. Calibration and validation

5.1.1. The Scheme model relies on the same calibration work undertaken for the Baseline model. Given the nature of the Scheme model (a future change) no calibration has been undertaken on the Scheme model.

5.2. Sensitivity analysis

5.2.1. Sensitivity testing was previously undertaken previously to support confidence in the Baseline model.

5.2.2. Informal tests with the Baseline model included:

- Sensitivity to flow using design flows from a range of estimation techniques;
- Sensitivity to structure dimensions and levels; and
- Sensitivity to downstream boundary location and stage-discharge data.

5.2.3. Formal tests were undertaken with the Baseline model on:

- Sensitivity to channel and floodplain roughness;
- Sensitivity to structure coefficients including structure blockage;
- Sensitivity to downstream boundary;
- Sensitivity to upstream boundary;
- Sensitivity to flow using the credible maximum climate change allowance;
- Sensitivity to computational timestep;
- Sensitivity to TUFLOW hardware configuration and solver; and
- Sensitivity to TUFLOW software version.

5.2.4. Sensitivity testing has also been undertaken on the Scheme model to help understand the possible changes to the predicted impact of the Scheme caused by uncertainty in various model parameters.

5.2.5. Informal tests with the Scheme model were undertaken during the design development and iterations, including sensitivity to structure dimensions and levels.

- Formal tests were undertaken with the Scheme model using the present day 1% annual exceedance probability event (1 in 100-year return period) to establish:
- Sensitivity to partial blockage of the new link road culverts; and
- Sensitivity to partial blockage of the Piffs Elm culvert being the key outlet of the flood storage area.

5.2.6. The December 2014 National Policy Statement for National Networks[7] (NPS-NN) sets out the need for, and Government's policies to, deliver development of Nationally Significant Infrastructure Projects (NSIPs) on the national road and rail networks in England. It provides planning guidance for promoters of nationally significant infrastructure projects on the road and rail networks, and the basis for the examination by the Examining Authority and decisions by the Secretary of State.

5.2.7. The NPS-NN requires taking into account the potential impacts of climate change using the latest UK Climate Projections over the estimated lifetime of the new infrastructure. Similar to the Environment Agency guidance, the policy requires demonstration that there are no critical features of the design of the Scheme which may be seriously affected by more radical changes to the climate beyond that projected in the latest set of UK climate

[7] Department for Transport (December 2014) National Policy Statement for National Networks. Reference ID P2689507 12/14

projections. Any potential critical features should be assessed taking account of the latest credible scientific evidence (e.g. by referring to additional credible maximum scenarios such as from the Intergovernmental Panel on Climate Change or Environment Agency). Hence, the National Policy Statement for National Networks refers back to the Environment Agency guidance for definition of the Upper End climate change allowance.

5.2.8. Thus, as a NSIP, there was a need to assess the flood risk from a credible maximum climate change scenario, and so a sensitivity test to flow using the Upper End climate change allowance was undertaken; this was a +94% increase in peak flow. It should be noted that this test was to assess how sensitive the Scheme might be to large-scale changes in the climate and help design in future adaptation measures as may be required over its lifetime. This was not a test to evaluate the impact of the Scheme on 3rd party receptors at the Upper End scenario, but only to evaluate the risk on the Scheme at the Upper End scenario.

5.2.9. No sensitivity testing was undertaken on the Scheme model for the upstream or downstream boundaries, as it was proven that the results of the Baseline were insensitive to those parameters and hence would be similar for the Scheme model.

Results reporting

5.2.10. The results have been documented in this report at the same key locations as the Baseline to reflect maximum flooded depths (being more tangible than absolute flood levels) and peak flows at key locations. However, where ground levels are changing as a result of the Scheme, peak flood levels (m AOD) have also been reported. These key locations are described below in Table 5-1 and Table 5-2, and shown on Figure 17.

5.2.11. The results are compared against the Scheme results to establish both the impact on how the Scheme may perform, and the importance of future maintenance.

5.2.12. The full results are contained in the hydraulic model files. Flood depth difference mapping for the climate change sensitivity test is included in Appendix B.1.

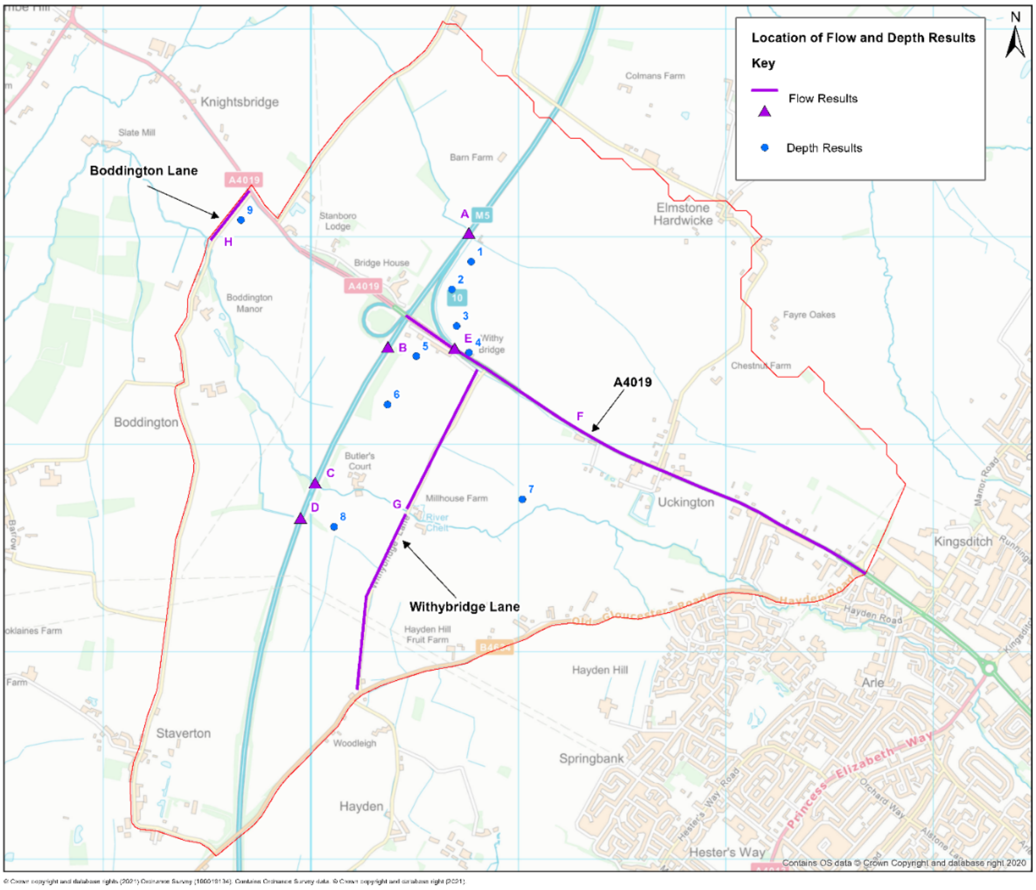
Table 5-1 – Key locations for reporting flood depth or level

Point	Location
1	Leigh Brook, nr Barn Farm culvert
2	Leigh Brook, nr existing slip road north
3	Leigh Brook, nr existing slip road south
4	North of A4019, nr existing slip road and Withy Bridge
5	South of A4019, Withybridge Gardens
6	West of Withybridge Lane, north of Butlers Court
7	East of Withybridge Lane, eastern end of River Chelt floodplain
8	Nr Staverton culvert, south of Butlers Court
9	Boddington Lane, north of Boddington Manor

Table 5-2 – Key locations for reporting flow

Point	Location
A	Leigh Brook through Barn farm culvert under M5 motorway
B	River Chelt through Piffs elm culvert under M5 motorway
C	River Chelt culvert under M5 motorway
D	Staverton culvert under M5 motorway
E	Flow through the A4019 culvert
F	Flow over the top of the A4019 highway
G	Flow passing over the length of Withybridge Lane
H	River Chelt flow passing over Boddington Lane

Figure 17 – Location of points for result reporting



Sensitivity to structure blockage

5.2.13. A sensitivity test was undertaken to consider blockage of the new West Cheltenham Link Road structures.

5.2.14. The new link road crossing over the River Chelt is relatively large (with a span far greater than the watercourse itself). Blockage of this structure was not applied since early testing identified that it would have little impact on the results. Furthermore, a full blockage of that structure is unlikely.

5.2.15. The link road culverts are similar and reasonably large, being 3 m wide and 1 m tall, across a floodplain with a typical flow depth of 200 mm and flow velocity of 0.2 m/s during the 1% annual exceedance probability event (1 in 100-year return period). The overland flows presents a low energy system and the risk of waterborne debris likely to block the culverts is low.

5.2.16. Instead of a uniform blockage on each of the 37 culverts, the sensitivity test was applied by partly blocking 9 culverts, being ~25% of the overall number of barrels. This was applied to the culvert group immediately south of the field ditch (see Figure 10), as this is where the largest depths and velocities are concentrated and therefore the location where a blockage would be most likely to occur and have the most impact. It was not considered realistic to assume a blockage of all 37 culverts. The blockage applied to these 9 culverts was 20%, based on a considered portion of each culvert likely to block, given their 3m width.

5.2.17. A second test was undertaken with the Piffs Elm culvert. This culvert is the single outlet for the flood storage area and will need to be kept free of debris to allow that facility to drain after a flood event. This test was undertaken to demonstrate the impact of a blockage and hence any need for a maintenance plan. The same test as applied for the Baseline was undertaken, being a 90% blockage – reflective of the likelihood of the 1.2 m diameter culvert to block and as applied in the Baseline testing. This test was applied assuming no blockage of the link road structures.

Blockage of the West Cheltenham Link Road

5.2.18. The results indicate that partial blockage of the link road culverts has little to no impact on the scheme model results. Partial blockage of the link road culverts resulted in no change to reported peak depths, or flood extents compared to when no blockage was applied to these culverts.

5.2.19. The only minor differences in results were upstream of the link road, where depths were marginally higher during the blockage simulation due to the blockage (in north group 2) holding more water east of the link road.

5.2.20. There is also a very minor difference in flows over Withybridge Lane, where flows are 0.1 m^3/s less in the blockage simulation. This is likely due to more water being held east of the link road in this simulation.

Selected point results are tabulated below, in

5.2.21. Table 5-3 & Table 5-4, to give an indication of the scale of change, comparing with the present day 1% annual exceedance probability event (1 in 100-year return period). The location of these points are shown in Figure 17.

Table 5-3 – Sensitivity of Scheme flood depths to blockage of the link road structures

1% annual exceedance probability event (1 in 100-year return period)
Levels quoted to nearest 10 mm which conceals the nominal changes in predicted depth.

Location	With blockage depth (m)	Without blockage depth (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00
3 Leigh Brook nr A4019	0.00	0.00
4 A4019	0.00	0.00
5 Withybridge Gardens	1.00	1.00
6 north of Butlers court	0.71	0.71
7 Eastern end of River Chelt floodplain	0.18	0.18
8 nr Staverton culvert	0.30	0.30
9 Boddington Lane	0.41	0.41

Table 5-4 – Sensitivity of Scheme flood flows to blockage of the link road structures

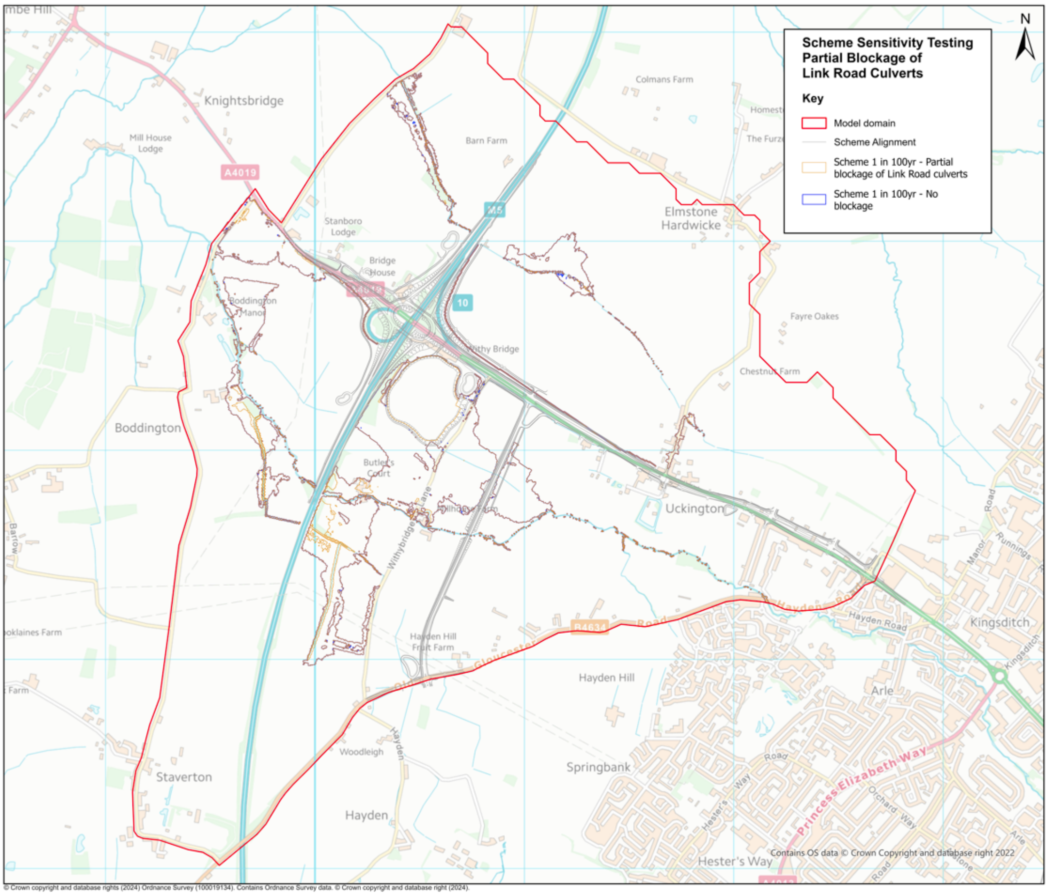
1% annual exceedance probability event (1 in 100-year return period)

Location	With blockage flow (m^3/s)	Without blockage flow (m^3/s)
A Barn farm culvert	2.2	2.2
B Piffs elm culvert	1.7	1.7
C River Chelt culvert	18.3	18.3
D Staverton culvert	2.7	2.7
E A4019 culvert	0.0	0.0
F A4019 over the top	0.0	0.0
G Withybridge Lane	8.1	8.2
H Boddington Lane (nr downstream boundary)	1.6	1.6

5.2.22. The resulting flood extent map (comparing with the present day 1% annual exceedance probability event (1 in 100-year return period)) is shown as

5.2.23. Figure 18.Figure 21

Figure 18 – Sensitivity of flood extent to blockage of the link road structures



Blockage of Piffs Elm culvert

5.2.24. Given the importance of the Piffs Elm culvert, the results have also been compared to the Baseline; the Baseline with the Piffs Elm culvert blocked by the same amount (90%). In the Baseline conditions, excess floodwater is, instead, able to pass over and under the A4019 into the Leigh Brook catchment: with Scheme, the flow path over and under the A4019 is removed.

5.2.25. The results indicate that firstly, as expected, blockage (90%) of Piffs Elm culvert reduces the peak flow through this structure in both the Baseline and with-Scheme simulations. Partial blockage of this structure reduced peak flow from 3.0 m^3/s to 0.2 m^3/s in the Baseline, and from 1.7 m^3/s to 0.2 m^3/s with-Scheme. Consequently, depths upstream of this structure also increase in both simulations. Near Withybridge Gardens, depths in the Baseline increase from 0.811 m to 1.135 m; at the same location in the Scheme, which is within the flood storage area, depths increase from 0.999 m to 1.205 m. It should be noted that this was insufficient to fill the flood storage area.

5.2.26. Blockage of Piffs Elm culvert does not impact the peak flows passing through the River Chelt and Staverton culverts, under the motorway, in the Baseline or Scheme simulation. However due to the reduced flow through Piffs Elm culvert when a blockage is applied, the amount of floodwater reaching the River Chelt floodplain west (downstream) of the M5 motorway is reduced in both the Baseline and with-Scheme simulations. This is reflected in the peak flow passing over Boddington Lane at the model's downstream boundary; peak flows over this road are reduced from 3.0 to 0.2 m^3/s when blockage is applied to the Baseline simulation, and similarly from 1.6 to 0.2 m^3/s when blockage is applied to the with-Scheme simulation.

5.2.27. Selected point results are tabulated below in Table 5-5 and Table 5-6 to give an indication of the scale of change, comparing with the present day 1% annual exceedance probability event (1 in 100-year return period). The location of these points are shown in Figure 17.

Table 5-5 – Sensitivity of Scheme flood depths to blockage of the Piffs Elm culvert

1% annual exceedance probability event (1 in 100-year return period)

Location	Baseline without blockage (m)	Baseline with blockage (m)	Scheme without blockage (m)	Scheme with blockage (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00	0.00	0.00
3 Leigh Brook nr A4019	0.00	0.00	0.00	0.00
4 A4019	0.00	0.00	0.00	0.00
5 Withybridge Gardens	0.81	1.14	1.00	1.21
6 north of Butlers court	0.14	0.43	0.71	0.92
7 Eastern end of River Chelt floodplain	0.18	0.18	0.18	0.18
8 nr Staverton culvert	0.31	0.31	0.30	0.30
9 Boddington Lane	0.43	0.37	0.41	0.36

Table 5-6 – Sensitivity of Scheme flood flows to blockage of the Piffs Elm culvert

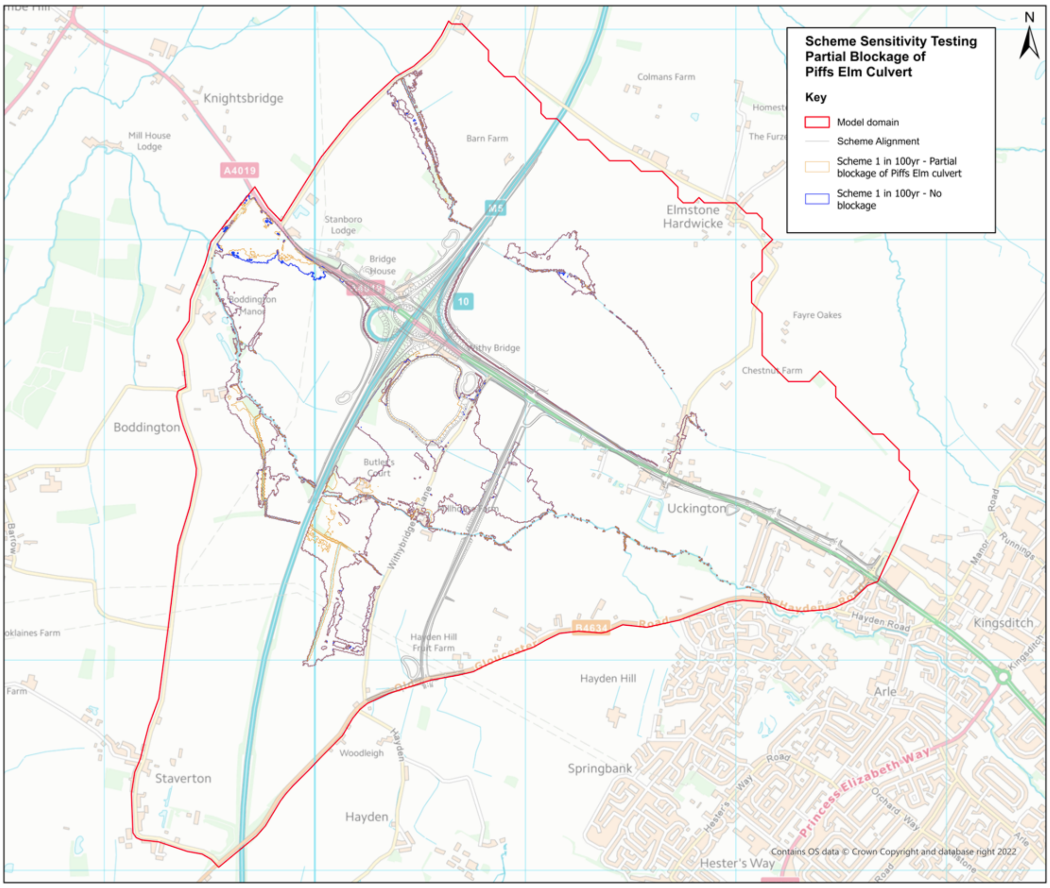
1% annual exceedance probability event (1 in 100-year return period)

Location	Baseline without blockage (m^3/s)	Baseline with blockage (m^3/s)	Scheme without blockage (m^3/s)	Scheme with blockage (m^3/s)
A Barn farm culvert	2.2	2.6	2.2	2.2
B Piffs elm culvert	3.0	0.2	1.7	0.2
C River Chelt culvert	18.3	18.3	18.3	18.3
D Staverton culvert	2.7	2.7	2.7	2.7
E A4019 culvert	0.0	0.0	0.0	0.0
F A4019 over the top	0.0	0.0	0.0	0.0
G Withybridge Lane	8.2	8.2	8.2	8.1
H Boddington Lane (nr downstream boundary)	3.0	0.2	1.6	0.2

5.2.28. The resulting flood extent map (comparing with the present day 1% annual exceedance probability event (1 in 100-year return period)) is shown as

5.2.29. Figure 19.

Figure 19 – Sensitivity of flood extent to blockage of Piffs Elm culvert



Sensitivity to flow using the Credible Maximum climate change allowance

5.2.30. A sensitivity test was undertaken on the climate change allowance by applying the Upper End uplift on the 1% annual exceedance probability event (1 in 100-year return period). For the River Chelt and its tributaries, the Upper End scenario requires a +94% increase in peak flow.

5.2.31. Changes were made to reflect this Upper End scenario by stretching the peak flows, as with the Higher Central allowance, used for the design flood.

Table 5-7 – Peak flows with different climate change allowances

	Peak 100yr flow m^3/s			
	Present day (+0%)	Central (+37%)	Higher Central (+53%)	Upper End (+94%)
River Chelt at M5	24.5	33.6	37.5	47.5
River Chelt downstream M5	2.2	3.0	3.4	4.3
Leigh Brook at M5	2.5	3.4	3.8	4.9
Leigh Brook downstream M5	1.3	1.8	2.0	2.5
Staverton stream	4.1	5.6	6.3	8.0
Arle CSO	4.0	5.5	6.1	7.8

5.2.32. The results in Table 5-7 indicate that the model results are sensitive to the impacts of climate change. Adding increasing climate change allowances to the model has the biggest impact in the study area upstream of the M5 motorway on the Leigh Brook floodplain, compared to impacts seen elsewhere in the study area. There is very little flooding in the present day and Central (+37%) climate change allowance simulations between the A4019 and Leigh Brook watercourse, but flood extents in the Higher Central (+53%) and Upper End (+94%) climate change simulations extend from the A4019 to north of the watercourse and from The Green road at Uckington to the fields east of the motorway.

5.2.33. In the Baseline event there is overtopping of the A4019 during all climate change events, whereas the Scheme raises this road and therefore no scheme events lead to overtopping of this road. Even in the highest climate change allowance event (+94%), no flows overtop the A4019.

5.2.34. Adding climate change allowances to the model results in further out of bank flooding along the River Chelt, both upstream and downstream of the M5 motorway. In the Upper End (+94%) climate change simulation flooding reaches the properties around Moat Lane, which does not occur during any other simulations. There is also a significant increase in flooding in the Upper End (+94%) climate change simulation west of the M5 motorway, just upstream of Boddington Manor. This appears due to the increase in flows through the River Chelt culvert under the M5 motorway; present day results record flows of 18.3 m^3/s passing through this structure whereas the Upper End simulation records flows of 23.6 m^3/s.

5.2.35. Selected point results are tabulated below in Table 5-8 and Table 5-9 to give an indication of the scale of change, comparing with the present day 1% annual exceedance probability event (1 in 100-year return period). The location of these points are shown in Figure 17.

Table 5-8 – Sensitivity of Scheme flood depths to climate change

1% annual exceedance probability event (1 in 100-year return period)

Location	Present day (0%) (m)	Central (37%) (m)	Higher Central (53%) (m)	Upper End (94%) (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00	0.00	0.03
3 Leigh Brook nr A4019	0.00	0.00	0.00	0.01
4 A4019	0.00	0.00	0.00	0.00
5 Withybridge Gardens	1.00	2.02	2.45	3.22
6 north of Butlers court	0.71	1.73	2.16	2.93
7 Eastern end of River Chelt floodplain	0.18	0.24	0.26	0.29
8 nr Staverton culvert	0.30	0.39	0.43	0.53
9 Boddington Lane	0.41	0.45	0.46	0.48

Table 5-9 – Sensitivity of Scheme flood flows to climate change

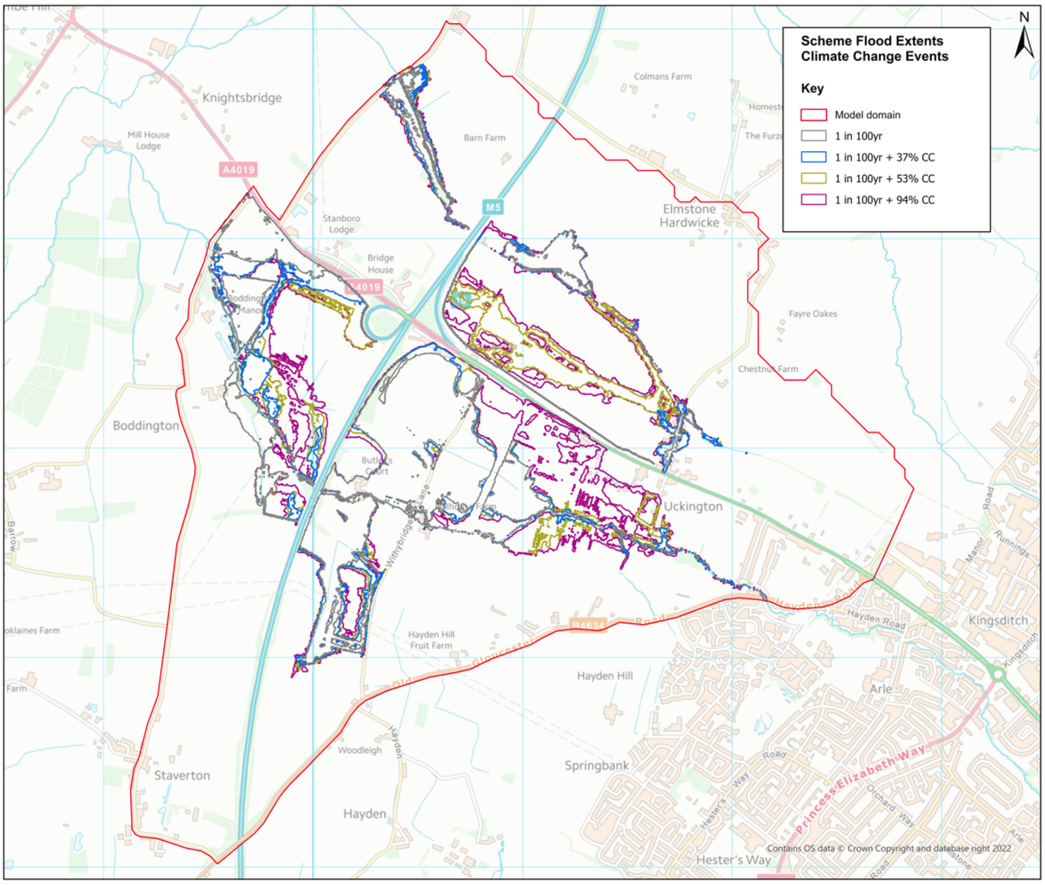
1% annual exceedance probability event (1 in 100-year return period)

Location	Present day (0%) (m^3/s)	Central (37%) (m^3/s)	Higher Central (53%) (m^3/s)	Upper End (94%) (m^3/s)
A Barn farm culvert	2.2	2.9	3.2	4.0
B Piffs elm culvert	1.7	3.1	3.3	3.6
C River Chelt culvert	18.3	20.8	21.5	23.6
D Staverton culvert	2.7	2.8	2.8	2.9
E A4019 culvert	0.0	0.0	0.0	0.0
F A4019 over the top	0.0	0.0	0.0	0.0
G Withybridge Lane	8.2	16.8	20.6	28.7
H Boddington Lane (nr downstream boundary)	1.6	4.3	5.3	7.1

5.2.36. The resulting flood extent map (comparing different climate change allowances) is shown as Figure 20.

5.2.37. The Impact of the Scheme, compared to the Baseline was evaluated for the Upper end (+94% flow) climate change scenario.

Figure 20 – Sensitivity of Scheme flood extent to climate change



Sensitivity to Climate change using the Credible Maximum climate change allowance

5.2.38. The NNPS which asks for demonstration that there are no critical features of the design of new national networks infrastructure which may be seriously affected by more radical changes to the climate beyond that projected in the latest set of UK climate projections.

5.2.39. Hence a similar comparison to the above was made in accordance with the Environment Agency guidance on assessing credible maximum scenarios for NSIPs. As a sensitivity test it assesses how sensitive the Scheme is to changes in the climate for a worst case future scenarios, and can help to ensure that the development can be adapted to large-scale climate change over its lifetime.

5.2.40. The Impact of the Scheme, compared to the Baseline, was evaluated for the Upper end (+94% flow) climate change scenario on top of the present day 1% annual exceedance probability event (1 in 100-year return period).

5.2.41. The modelling identified that the credible maximum scenario would create additional detriment with the Scheme in place, with this affecting the farmland around the flood storage area and the link road. The flood extent increases compared to baseline with water ponding upstream of the link road which is predicted to overtop near the junction with the A4019. This introduces a new flow path that flows in parallel with the A4019 westwards where it merges with the water ponding in the storage area.

5.2.42. It was not surprising that additional detriment was predicted. The higher flood levels arising from higher flood flows means that the Scheme displaces additional floodwater that is not accommodated in the flood storage area. Furthermore, the 36 culverts included under the Link Road were sized and numbered to account for the design flow: with more overland flow, additional culverts would be required. It should be noted that despite the higher flood levels in the credible maximum event, the floodwater was not predicted to reach the soffit of the Link Road culverts.

5.2.43. Adaptation measure are available to the Scheme should the future climate risk become greater than those being applied to the design event. These might include:

- Adding extra culverts under the link road to collect the larger overland flow;
- Enlarging the flood storage area and/or enlarging the Piffs Elm culvert under the M5 motorway; and
- Enlarging the Uckington roadside ditch to collect the increased flows into this drainage channel.

5.3. Run parameters

5.3.1. The same version of the TUFLOW software was applied to the Scheme modelling as was used for the Baseline, specifically build 2020-01-AB-iSP-w64.

5.3.2. The TUFLOW model was applied using the heavily parallelised compute option (HPC) to speed up run times in combination with GPU hardware.

5.3.3. Standard run parameters have been adopted within the model run, with sensitivity analysis undertaken on key factors during the Baseline modelling.

5.3.4. A timestep of 1 second was applied to both the 1D and 2D models.

5.4. Run performance

5.4.1. The TUFLOW models were simulated using GPU hardware in addition to the HPC software. This is the same approach as applied in the Baseline model.

The mass balance for the revised model is comfortably within recommended bounds (1%) as indicated in

5.4.2. Table 5-10.

Table 5-10 – Scheme model numerical errors

	1% AEP	0.1% AEP	1% AEP+CC53
Volume Error	-0.00%	-0.00%	-0.00%
Final Cumulative ME	-0.00%	0.02%	-0.00%

5.4.3. ESTRY and TUFLOW both generate check, warning, and error messages during both the pre-processing and computation stage. Check messages are notes which are generated to cross check model input data. Check messages generated during the model runs were examined and found to be non-critical.

5.4.4. No warning messages were recorded during the computational stage which gives further confidence that the model is running in a stable manner.

6. With-Scheme model results

This section describes the results and highlight what they show, including any new understanding derived through undertaking the project.

6.1. Production of flood extents

6.1.1. Mapping of the results has been undertaken to provide flood extents and depth grids to demonstrate the flood risk. The Scheme results from the M5J10 model have been plotted for the key design events:

- The threshold event when notable flooding commences at Junction 10. See Section 6.4.
- 1% annual exceedance probability event (1 in 100-year return period) – a River Chelt flow of 18.3 m^3/s at the M5 motorway. See Section 6.5 below and in 0 of this report.
- 1% annual exceedance probability event (1 in 100-year return period) with 53% allowance for climate change giving 21.5 m^3/s at the M5 motorway. See Section 6.6 below and in 0 to this report. This shows the impact of a 53% increase in peak flow, as a result of climate change, on the 1% annual exceedance probability event (1 in 100-year return period).
- 0.1% annual exceedance probability event (1 in 1,000-year return period) – a River Chelt flow of 21.7 m^3/s at the M5 motorway. See Section 6.7 below and in 0 of this report.

6.1.2. The full set of model results are contained in the model files. Flood mapping for all return periods simulated are included in 0.

6.1.3. It should be noted that the results tabulated in this report are based on the peak stage/flows from a 100-hour simulation period which allows for peak levels to fall in the Scheme arrangement. Those described in the Baseline Modelling report (Application document TR010063/APP/9.18) were described for a 50-hours simulation period, and hence do not match those in this report at certain locations.

6.1.4. Two artificial scenarios were also tested to help demonstrate the performance of the embedded mitigation measures. These tests considered the scheme with no mitigation in place:

- No floodplain storage or compensation and no link road culverts; and
- All conveyance structures included, but no floodplain storage or compensation.

6.2. Scheme without embedded mitigation

6.2.1. It is assumed that the Scheme without embedded mitigation would have an adverse impact on flood risk. The Scheme model was tested to validate this assumption, and demonstrate the need for mitigation.

6.2.2. The model was thus tested without either any compensatory floodplain or storage, nor without conveyance structures through the West Cheltenham Link Road. The test does include for the displacement of water cause by the footprint of the earthworks (including the severance of flows over the A4019 into the Leigh Brook and the link road embankment), and the extension to the M5 motorway and A4019 culverts to account for the proposed highway improvements.

6.2.3. The results indicate that the Scheme would cause widespread detriment if embedded mitigation were not included. The biggest impact of not including embedded mitigation would be in the River Chelt floodplain, upstream (east) of the M5 motorway. Since there would be no conveyance structures through the Link Road to pass flows under the highway embankment, floodwater would be held back against the Link Road resulting in an increase in Baseline levels of up to 0.750 m. With-Scheme water levels would increase enough to overtop the northern end of the Link Road (where it joins the A4019). This would result in more flooding in the with-Scheme simulation from west of the Link Road to west of Withybridge Lane, and increased depths in the with-Scheme simulation in the fields east of the M5 motorway (0.830 m) compared to Baseline (0.811 m).

6.2.4. The omission of conveyance structures through the Link Road would result in increased flows passing through the River Chelt culvert under the M5 motorway; peak flows increase from 18.3 m^3/s in the Baseline to 19.1 m^3/s with-Scheme. Higher flows in the River Chelt upstream of the culvert would also results in more flooding around Millhouse Farm and upstream of the Staverton culvert.

6.2.5. The increase in flood levels near Withybridge Gardens in the with-Scheme simulation would minorly increase the peak flow passing under the M5 motorway through Piffs Elm culvert. Peak flows through this structure would increase from 3.0 m^3/s in the Baseline to 3.1 m^3/s with-Scheme. However, there is a reduction to flood levels downstream (west) of the M5 motorway, extending from the outfall of Piffs Elm culvert to the fields upstream of the model's downstream boundary at Boddington Lane. However, the Scheme without embedded mitigation is predicted to increase flooding near Boddington Manor.

6.2.6. The Scheme without embedded mitigation has minimal impact on flood levels across the Leigh Brook floodplain, both upstream and downstream of the motorway. It does not change peak flows through the Barn Farm culvert, which carries the Leigh Brook watercourse under the motorway.

6.2.7. Selected point results are tabulated below in Table 6-1 and Table 6-2 to give an indication of the flooding. The location of these points are shown in Figure 17 above.

Table 6-1 –Baseline and Scheme (without-mitigation) depths

1% AEP event (1 in 100-year return period)

Location	Baseline depth (m)	Scheme depth (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00
3 Leigh Brook nr A4019	0.00	0.00
4 A4019	0.00	0.00
5 Withybridge Gardens	0.81	0.83
6 north of Butlers court	0.14	0.13
7 Eastern end of River Chelt floodplain	0.18	0.18
8 nr Staverton culvert	0.30	0.32
9 Boddington Lane	0.43	0.43

Table 6-2 – Baseline and Scheme (without-mitigation) flows

1% AEP event (1 in 100-year return period)

Location	Baseline flow (m^3/s)	Scheme flow (m^3/s)
A Barn farm culvert	2.2	2.2
B Piffs elm culvert	3.0	3.1
C River Chelt culvert	18.3	19.1
D Staverton culvert	2.7	2.7
E A4019 culvert	0.0	0.0
F A4019 over the top	0.0	0.0
G Withybridge Lane	8.2	7.3
H Boddington Lane (nr downstream boundary)	3.0	3.0

The resulting flood extent map (comparing to the Baseline) is shown as Figure 21. A difference grid (Scheme - Baseline) is shown in Figure 22.

Figure 21 – Flood extents for the Baseline and Scheme (without-mitigation)

at the 1% AEP event (1 in 100-year return period)

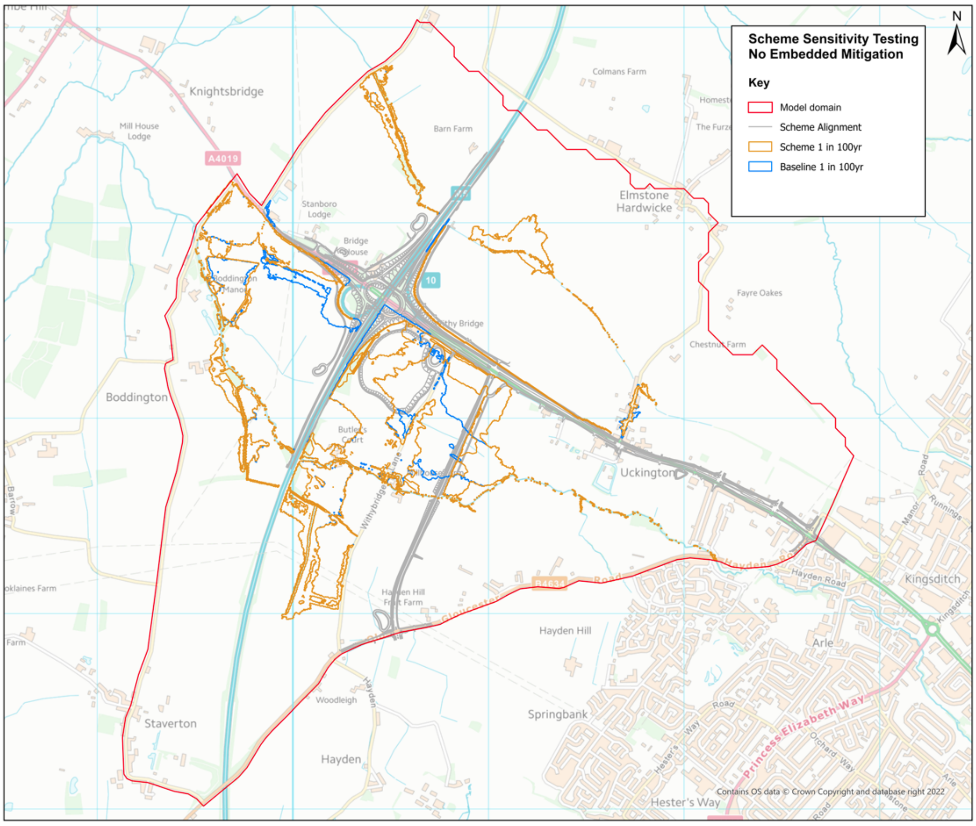
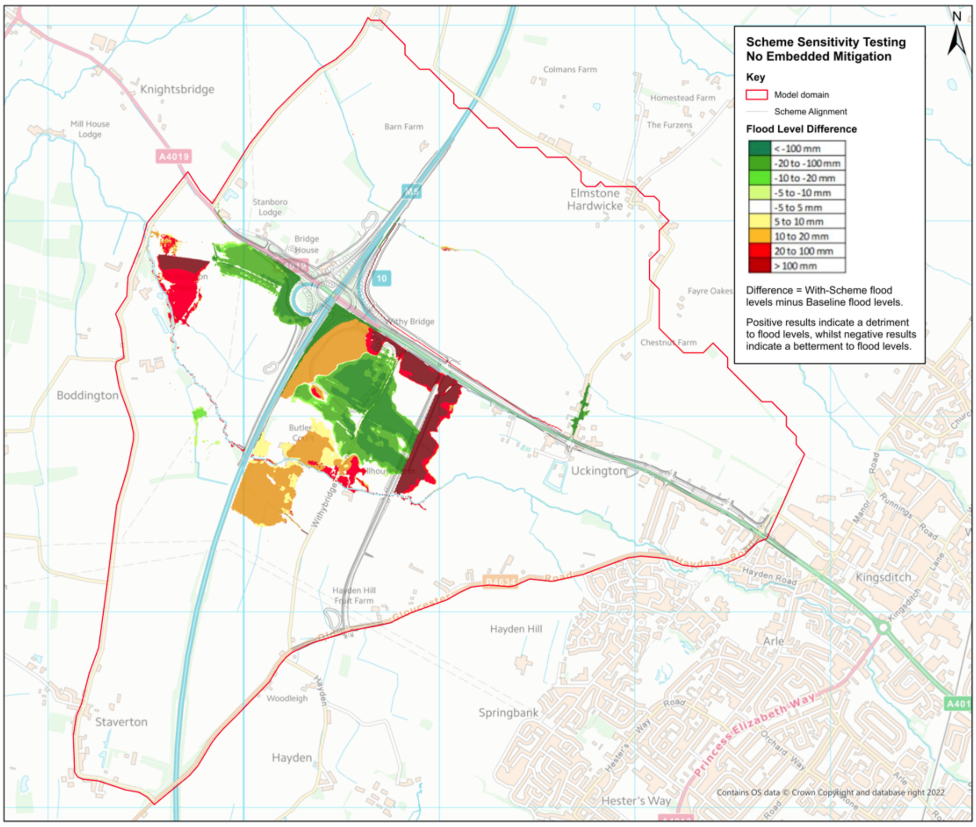


Figure 22 – Scheme impact without mitigation on flood level

at the 1% AEP event (1 in 100-year return period)



6.3. Scheme with no flood storage or floodplain compensation

6.3.1. In addition to testing the Scheme model without any embedded mitigation, the Scheme model was also tested with part of the embedded mitigation included; being the Link road culverts and River Chelt crossing. For this test, neither the compensatory floodplain nor storage was included.

6.3.2. The results indicate that the Scheme would cause extensive detriment to flood levels in the fields east of the M5 motorway, near Withybridge Gardens, where compensatory floodplain or storage is not included as embedded mitigation. At this location, flood depths in the Baseline are 0.811 m whilst the Scheme would increase depths to 0.944 m. Similarly, north of Butlers Court, depths of 0.140 m in the Baseline would increase to 0.238 m with-Scheme.

6.3.3. Peak flows through Piffs Elm culvert would be increased from 3.0 m^3/s in the Baseline to 3.1 m^3/s with-Scheme. However, the scheme was predicted to result in a reduction to flood levels downstream of this structure, west of the M5 motorway.

6.3.4. Across the Leigh Brook catchment, there would be very little change in flood extents, depths and flows both upstream and downstream of the M5 motorway.

6.3.5. Selected point results are tabulated below in Table 6-3 and Table 6-4 to give an indication of the flooding. The location of these points are shown in Figure 17 above.

Table 6-3 –Baseline and Scheme (with part mitigation) depths
1% AEP event (1 in 100-year return period)

Location	Baseline depth (m)	Scheme depth (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00
3 Leigh Brook nr A4019	0.00	0.00
4 A4019	0.00	0.00
5 Withybridge Gardens	0.81	0.94
6 north of Butlers court	0.14	0.24
7 Eastern end of River Chelt floodplain	0.18	0.18
8 nr Staverton culvert	0.30	0.30
9 Boddington Lane	0.43	0.44†

† change is 2 mm, from 433.3 mm (433 mm) to 435.8 mm (436 mm)

Table 6-4 –Baseline and Scheme (with part mitigation) flows
1% AEP event (1 in 100-year return period)

Location	Baseline flow (m^3/s)	Scheme flow (m^3/s)
A Barn farm culvert	2.2	2.2
B Piffs elm culvert	3.0	3.1
C River Chelt culvert	18.3	18.3
D Staverton culvert	2.7	2.7
E A4019 culvert	0.0	0.0
F A4019 over the top	0.0	0.0
G Withybridge Lane	8.2	8.2
H Boddington Lane (nr downstream boundary)	3.0	3.1

6.3.6. The resulting flood extent map (comparing to the Baseline) is shown in Figure 23. A difference grid (Scheme - Baseline) is shown in Figure 24.

Figure 23 – Flood extents for the Baseline and Scheme (with part mitigation)

1% AEP event (1 in 100-year return period)

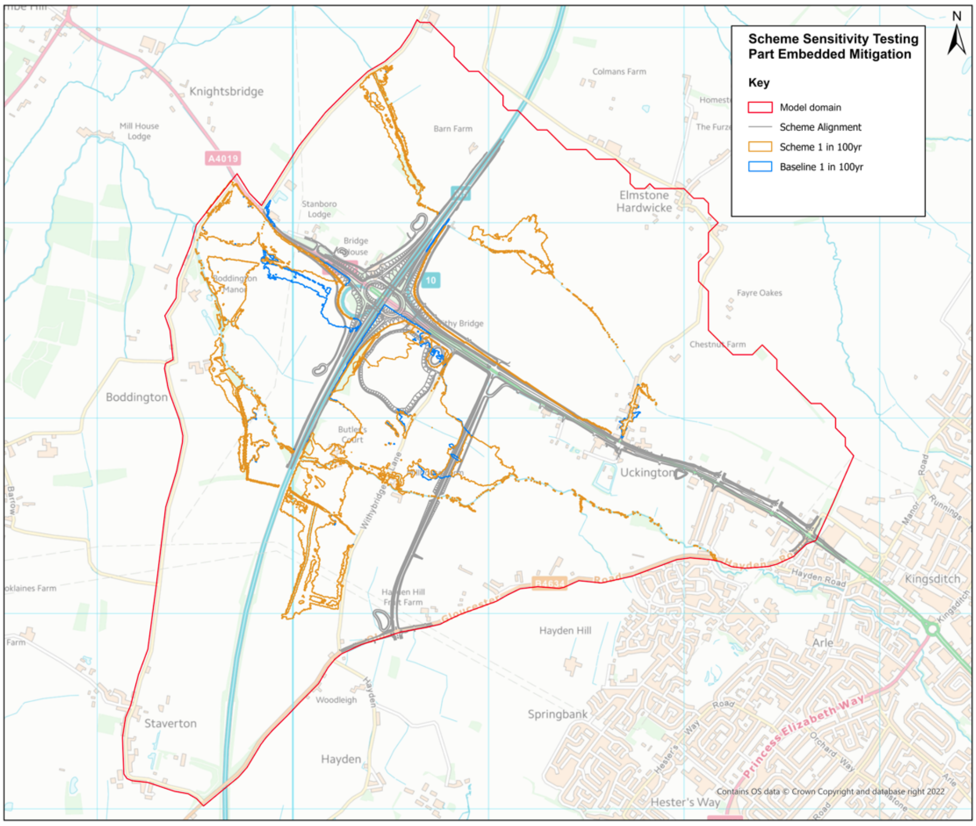
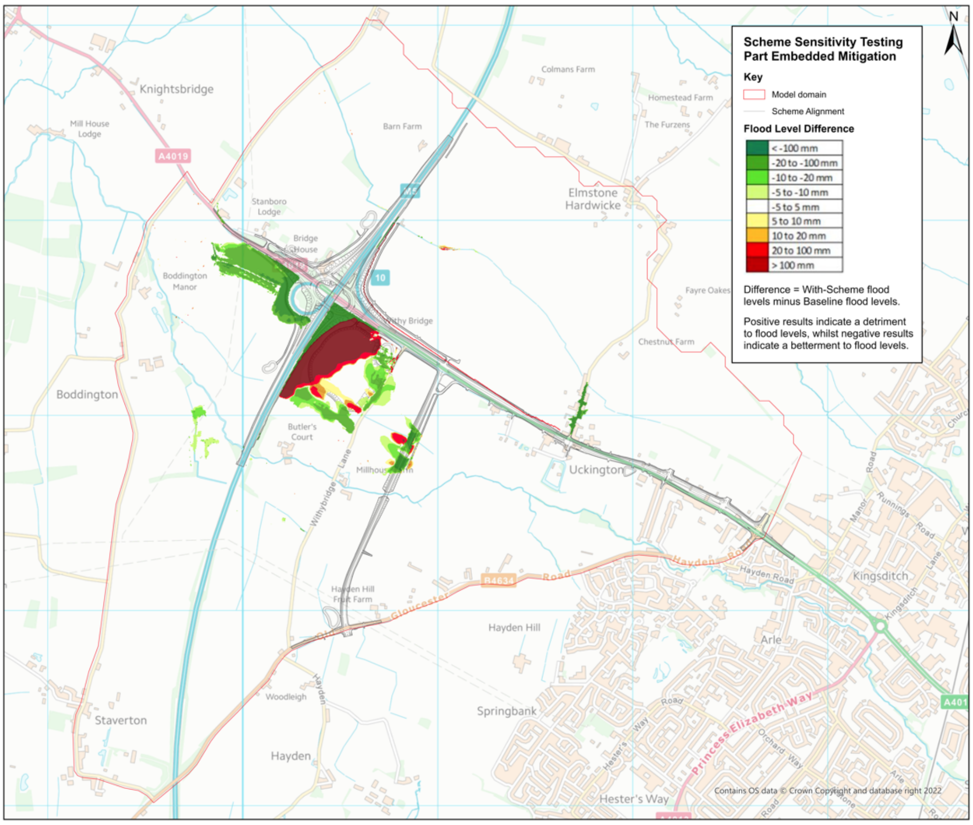


Figure 24 – Scheme impact with part mitigation on flood level

1% AEP event (1 in 100-year return period)



6.4. Threshold event

6.4.1. The threshold event has been defined here as the event which causes notable flooding of the farmland on the eastern (upstream) side of the M5 motorway.

6.4.2. The Baseline modelling indicates that whilst flooding does occur between Withybridge Lane (Millhouse Farm) and the M5 motorway at the 10% annual exceedance probability event (1 in 10-year return period), large area flooding only initiates once the River Chelt banks are overtopped upstream. The Scheme flood extents do not differ from the Baseline flood extents at the 10% annual exceedance probability event (1 in 10-year return period).

6.4.3. The riverbanks are predicted to overtop in the Baseline at the 5% annual exceedance probability event (1 in 20-year return period) with the resulting overland flow flooding as far as Withybridge Lane. Floodwater in this event was not predicted to reach the M5 motorway.

6.4.4. At the 5% annual exceedance probability event (1 in 20-year return period) flows reach the fields to the east of the M5 motorway in both Baseline and Scheme, via the existing ditch/realigned ditch alongside the motorway leading to Piffs Elm. With the Scheme present, some of this flow spreads across the flood storage area albeit with shallow depths of inundation.

6.4.5. During a 4% annual exceedance probability event (1 in 25-year return period) flows pass across the fields and arrive at the M5 motorway. In the Baseline, this floodwater accumulates as permitted by the terrain. The Scheme model has this overland flow captured in the flood storage basin, spreading wider than in the Baseline, but contained inside the designated flood storage area.

6.4.6. As intended, in the Scheme simulation, water enters the flood storage area by the M5 motorway and results in deeper flooding as a result of excavated (reduced) ground levels. Flood depths in the storage area south of Withybridge Gardens increase from 0.030 m in the Baseline to 0.094 m with-Scheme. At the southern end of the storage area, north of Butlers Court, flooding does not occur in neither the Baseline nor Scheme.

6.4.7. Across the Leigh Brook catchment, there is very little change in flood extents, depths and flows both upstream and downstream of the M5 motorway.

6.4.8. Selected point results are tabulated below in 6-5 and 6-6 to give an indication of the flooding. The location of these points are shown in Figure 17 above.

Table 6-5 – 4% AEP event (1 in 25-year return period) Baseline and Scheme depths

Location	Baseline depth (m)	Scheme depth (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00
3 Leigh Brook nr A4019	0.00	0.00
4 A4019	0.00	0.00
5 Withybridge Gardens	0.03	0.09
6 north of Butlers court	0.00	0.00
7 Eastern end of River Chelt floodplain	0.01	0.01
8 nr Staverton culvert	0.03	0.02
9 Boddington Lane	0.12	0.13

Table 6-6 – 4% AEP event (1 in 25-year return period) Baseline and Scheme flows

Location	Baseline flow (m^3/s)	Scheme flow (m^3/s)
A Barn farm culvert	1.5	1.5
B Piffs elm culvert	0.1	0.0
C River Chelt culvert	17.1	17.1
D Staverton culvert	2.4	2.4
E A4019 culvert	0.0	0.0
F A4019 over the top	0.0	0.0
G Withybridge Lane	1.6	1.6
H Boddington Lane (nr downstream boundary)	0.0	0.0

6.4.9. The resulting flood extent map (comparing to the Baseline) is shown as Figure 25. A difference grid (Scheme - Baseline) is shown in Figure 26.

Piffs Elm – west of the M5 motorway

6.4.10. There is a reduction in peak flow through Piffs Elm culvert, under the M5 motorway due to water being held in the flood storage area: the model predictions reducing from 90 l/s in the Baseline to 30 l/s with-Scheme.

6.4.11. The reduction in peak flow through Piffs Elm culvert results in a decrease in flood levels downstream of Piffs Elm culvert. This is a function of the flood storage and the drainage through Piffs Elm; the full volume of the displaced floodwater at this event (scheme footprint amounting to some 703 m^3) is drained through the culvert. Whilst the culvert extension reduces the flow for a given headwater, the stored volume then drains over a longer period of time.

Figure 25 – Baseline and Scheme flood extents for the 4% AEP event (1 in 25-year return period)

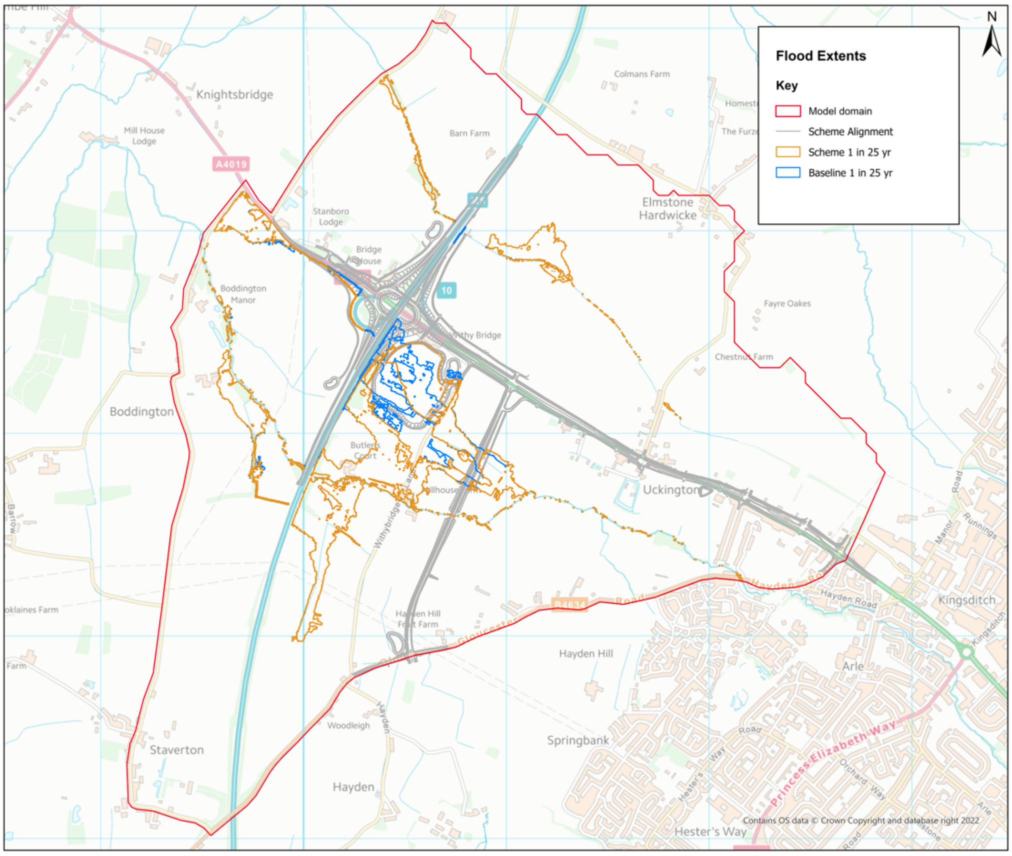


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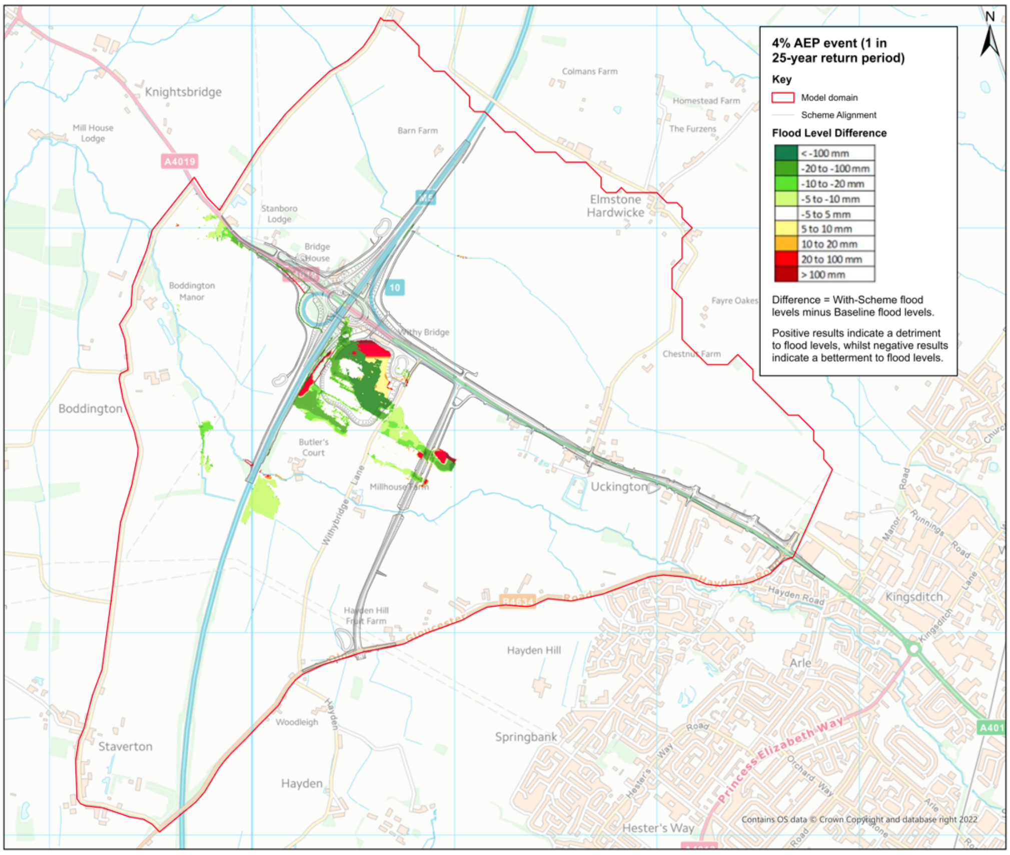
Figure 26 – Scheme impact on flood level at the 4% AEP event (1 in 25-year return period)



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6.5. 1% AEP event (1 in 100-year return period)

6.5.1. The Scheme results generally show no significant difference to Baseline flood extents in the Leigh Brook catchment, upstream and downstream of the motorway, for the 1% annual exceedance probability event (1 in 100-year return period).

6.5.2. At Uckington, west of the headwaters of the Leigh Brook, a new roadside drainage ditch as part of the Scheme is predicted to reduce flood levels by around 100 mm and thus reducing flood risk to the properties as it collects floodwater that ponds in the local road.

6.5.3. There is a minor isolated increase in flood levels in the farmland upstream of Barn Farm culvert, where peak flood levels are predicted to increase by between 10-30 mm – there appears to be no hydraulic reason for this and may be a model anomaly. Baseline flows through Barn Farm culvert, which carries the Leigh Brook under the M5 motorway, are unaffected by the Scheme during the 1 in 100-year event. Peak flow predictions through this culvert, for both Baseline and Scheme, are 2.2 m^3/s.

6.5.4. In the Chelt catchment, there are some changes to flood extents upstream and downstream of the M5 motorway. Existing flooding has been removed within the proposed Scheme footprint; at the proposed motorway junction, the A4019 widening and the West Cheltenham Link Road (by virtue of the raised ground levels).

6.5.5. There is a reduction in flood levels upstream of the M5 motorway embankment, south of the A4019, resulting from excavated (reduced) ground levels where the flood storage area is proposed. There is no impact on peak flows through the River Chelt culvert during the 1 in 100 year event; peak flow through this structure is 18.3 m^3/s in both the Baseline and with Scheme.

6.5.6. The Scheme results show a widespread reduction in flood levels downstream of the motorway embankment, south of the A4019. The peak flow through Piffs Elm culvert is reduced from 3.0 m^3/s in the Baseline to 1.7 m^3/s with Scheme, resulting in less extensive flooding predicted downstream of the Piffs Elm culvert, extending west to Boddington Road. Flood levels immediately downstream of the Piffs Elm culvert are reduced from the Baseline by around 120 mm, and flood levels west of this are also reduced.

6.5.7. There is a modification in flood extents immediately upstream and downstream of the proposed West Cheltenham Link Road, which comprises of increases and decreases in flooding associated with the proposed link road culverts.

6.5.8. Selected point results are tabulated below in Table 6-7 and Table 6-8, to give an indication of the flooding. The location of these points are shown in Figure 17 above.

Table 6-7 – 1% AEP event (1 in 100-year return period) Baseline and Scheme depths

Location	Baseline depth (m)	Scheme depth (m)
1 Leigh Brook nr Barn Farm culvert	0.00	0.00
2 Leigh Brook existing slip road	0.00	0.00
3 Leigh Brook nr A4019	0.00	0.00
4 A4019	0.00	0.00
5 Withybridge Gardens	0.81	1.00
6 north of Butlers court	0.14	0.71
7 Eastern end of River Chelt floodplain	0.18	0.18
8 nr Staverton culvert	0.30	0.30
9 Boddington Lane	0.43	0.41

Table 6-8 – 1% AEP event (1 in 100-year return period) Baseline and Scheme flows (m^3/s)

Location	Baseline flow (m^3/s)	Scheme flow (m^3/s)
A Barn farm culvert	2.2	2.2
B Piffs elm culvert	3.0	1.7
C River Chelt culvert	18.3	18.3
D Staverton culvert	2.7	2.7
E A4019 culvert	0.0	0.0
F A4019 over the top	0.0	0.0
G Withybridge Lane	8.2	8.2
H Boddington Lane (nr downstream boundary)	3.0	1.6

6.5.9. The resulting flood extent map (comparing to the Baseline) is shown as Figure 27. A difference grid (Scheme - Baseline) is shown in Figure 28.

Piffs Elm – west of the M5 motorway

6.5.10. There is a reduction in peak flow through Piffs Elm culvert, under the M5 motorway, the model predictions reducing from 3.0 m^3/s in the Baseline to 1.7 m^3/s with-Scheme. This results in a decrease in flood levels and flood extents downstream of Piffs Elm culvert.

6.5.11. The reduction in peak flow through Piffs Elm culvert means that less farmland is flooded on the west side of the M5 motorway, although the duration of shallow flooding is increased. This is a function of the flood storage and it draining through Piffs Elm; the full volume of the displaced floodwater (scheme footprint amounting to some 15,744 m^3) is drained through the culvert. Whilst the culvert extension reduces the flow for a given headwater, the stored volume then drains over a longer period of time.

6.5.12. A combination of reducing the flow through Piffs Elm culvert and the localised raising of verge levels between the watercourse and the highway prevents flooding of the A4019 in the with scheme case. The area is at risk during the baseline scenario.

6.5.13. The impact on duration is relative to the capacity of the roadside ditch downstream of the M5 motorway. The existing roadside ditch collects water from the Piffs Elm culvert and the A4019 highway and conveys it west to the Leigh Brook at Knightsbridge. The capacity of this ditch is unclear, with numerous abandoned field access crossings reducing the capacity below that of the ditch in isolation. The ditch itself is over 1 m deep, with 1.2 m base width. Using a 0.060 Manning's roughness and a 1 in 200 bedslope (as with the wider floodplain) a channel capacity of 1.7 m^3/s might be expected. The flow through Piffs Elm culvert exceeds 1.7 m^3/s for approximately 11 hours in the Baseline, but does not exceed 1.7 m^3/s in with-Scheme scenario.

6.5.14. The access crossings over this ditch will reduce the ditch capacity with the effect that floodwater is forced onto the adjacent farmland, south of the ditch. The A4019 highway is raised higher than the land opposite. Basic modelling of this ditch suggests that it could convey up to 0.5 m^3/s before being surcharged by the field crossings. Under such conditions, the duration of flow through Piffs Elm culvert over 0.5 m^3/s increases from approximately 11 hours in the Baseline to approximately 21.5 hours with-Scheme. This is an increase of 10.5 hours. However, the resulting flooding is less extensive and less deep than in the Baseline.

6.5.15. The Scheme is addressing this change through consultations with the landowner, with a view that an agreement is made, balancing the betterment of shallower flooding, less often with the increase in flooded duration.

Figure 27 – Baseline and Scheme flood extents

1% AEP event (1 in 100-year return period)

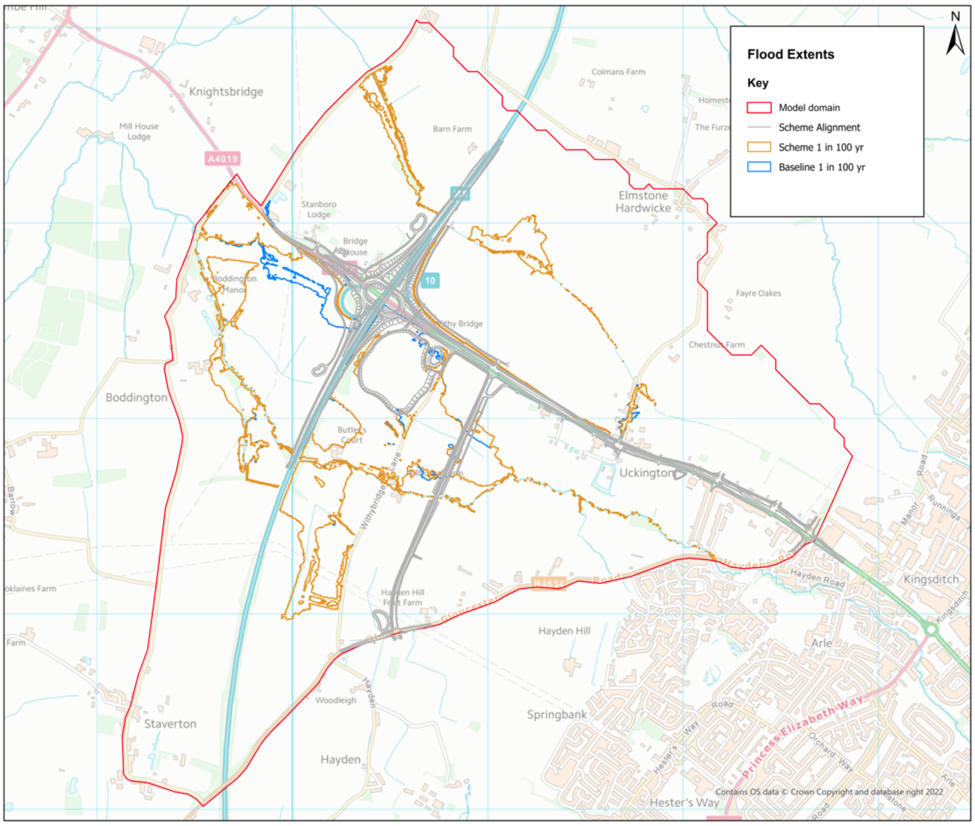
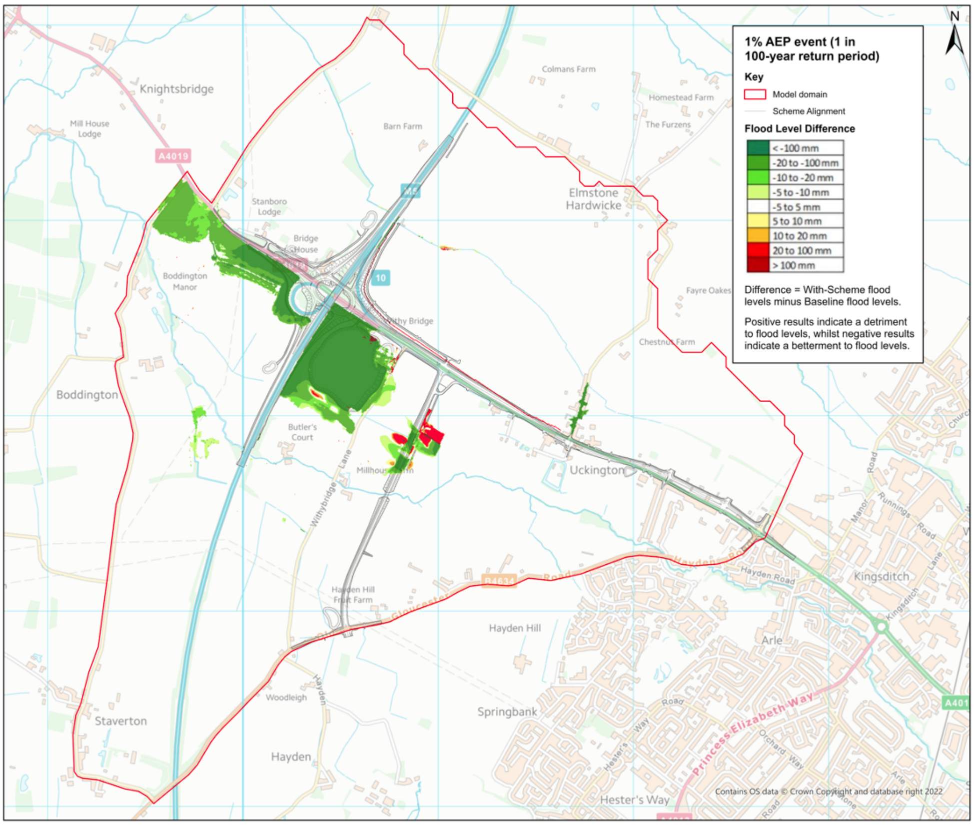


Figure 28 – Scheme impact on flood level

1% AEP event (1 in 100-year return period)



6.6. Design event - climate change impacts

6.6.1. Climate change was applied by stretching the inflow hydrographs such that the peak flow was increased by 53%.

6.6.2. The flood extent from the 1% annual exceedance probability event (1 in 100-year return period) with 53% increase in peak flows to account for future climate change is marginally smaller than the present day 0.1% annual exceedance probability event (1 in 1,000-year return period).

6.6.3. During the Baseline modelling, the biggest impact of climate change in the River Chelt catchment at this location was the instigation of flow over the A4019 highway into the catchment of the Leigh Brook. However, the Scheme reduces flood risk north of the A4019 by severing the flow path over the A4019, and also removing the small twin culverts under the A4019 road. Raising of the A4019 road to suit the new M5 motorway junction prevents the flow path from developing and instead retains the water in the fields to the south of it. This results in a widespread reduction in Baseline flood levels across the Leigh Brook floodplain; flood levels have reduced on average by over 0.5 m, both upstream and downstream of the motorway.

6.6.4. The biggest impact of severing the overland flow across the A4019 into the Leigh Brook floodplain is seen alongside the motorway embankment, where areas with Baseline flood depths of >0.75 m no longer flood. There is consequently a reduction in peak flow through Barn Farm culvert, under the M5 motorway, the predictions reducing flow from 9.4 m^3/s in the Baseline to 3.2 m^3/s with-Scheme. This results in decreased flood levels downstream of the M5 motorway and a reduction in out of bank flooding which continues west to the model's downstream boundary.

6.6.5. The raising of the A4019 in the with-Scheme model retains more water in the Chelt floodplain (which would have previously entered the Leigh Brook catchment). As intended, water enters the flood storage area by the M5 motorway and results in deeper flooding as a result of excavated (reduced) ground levels. Flood levels at the location of the flood storage area south of Withybridge Gardens reduce from 25.37 m AOD in the Baseline to 25.24 m AOD with Scheme. At the southern end of the storage area, north of Butlers Court, similarly peak flood levels reduce from 25.38 m AOD in the Baseline to 25.24 m AOD with Scheme.

6.6.6. The maximum depth of flooding in the storage area, south of Withybridge Gardens, is predicted to be 2.45 m with Scheme. Prior to the excavation, the Baseline model predicted a maximum depth of 1.43 m in this area. At the southern end of the storage area, north of Butlers Court, the Baseline flood depth was 0.72 m: this rises with the depth of excavation to 2.16 m with Scheme. The flood storage will provide an area of temporarily deep water. The hazards presented by this will be addressed through the detailed design. There is no increase in the actual flood level.

6.6.7. New flooding is predicted on the compensatory floodplain, upstream of the proposed West Cheltenham Link Road, with up to 250 mm depth of floodwater predicted to inundate this area. Increases and decreases in flood levels are predicted both upstream and downstream of the proposed link road culverts.

6.6.8. Selected point results are tabulated below in Table 6-9 and Table 6-10 to give an indication of the flooding. The location of these points are shown in Figure 17 above.

6.6.9. The resulting flood extent map (comparing to the Baseline) is shown as Figure 29. A difference grid (Scheme - Baseline) is shown in Figure 30.

Piffs Elm – west of the M5 motorway

6.6.10. There is a reduction in peak flow through Piffs Elm culvert, under the M5 motorway, during the design event with the model predictions reducing from 3.7 m^3/s in the Baseline to 3.3 m^3/s with-Scheme. This results in a decrease in flood levels and flood extents downstream of Piffs Elm culvert. The scheme also prevents flows overtopping the A4019 near Elmstone Business Park, which occurs in the Baseline.

Table 6-9 – 1% AEP event (1 in 100-year return period) with climate change Scheme depths

Location	Baseline depth (m)	Scheme depth (m)
1 Leigh Brook nr Barn Farm culvert	0.71	0.00
2 Leigh Brook existing slip road	0.75	0.00
3 Leigh Brook nr A4019	0.23	0.00
4 A4019	0.25	0.00
5 Withybridge Gardens	1.43	2.45
6 north of Butlers court	0.72	2.16
7 Eastern end of River Chelt floodplain	0.26	0.26
8 nr Staverton culvert	0.43	0.43
9 Boddington Lane	0.47	0.46

Table 6-10 – 1% AEP event (1 in 100-year return period) with climate change Scheme flows

Location	Baseline flow (m^3/s)	Scheme flow (m^3/s)
A Barn farm culvert	9.4	3.2
B Piffs elm culvert	3.7	3.3
C River Chelt culvert	21.5	21.5
D Staverton culvert	2.8	2.8
E A4019 culvert	1.6	0.0
F A4019 over the top	10.3	0.0
G Withybridge Lane	20.6	20.6
H Boddington Lane (nr downstream boundary)	5.9	5.3

6.6.1. The reduction in peak flow through Piffs Elm culvert means that less farmland is flooded on the west side of the M5 motorway. The results indicates that both depth and frequency of flooding is reduced as a result of the upstream flood storage, although the duration of shallow flooding is increased. This is a function of the flood storage and the drainage through Piffs Elm; the full volume of the displaced floodwater (scheme footprint and A4019 overtopping (amounting to some 155,118 m^3) is drained through the culvert. Whilst the culvert extension reduces the flow for a given headwater, the stored volume then drains over a longer period of time.

6.6.2. Local verge raising downstream of Piffs Elm culvert between the watercourse and the highway prevents flooding of the A4019 in the with Scheme case. The highway is at risk during the baseline scenario.

6.6.3. At the assumed ditch capacity of 1.7 m^3/s for the watercourse downstream of Piffs Elm, the duration of flow through the culvert increases from approximately 17 hours in the Baseline to approximately 28 hours with-Scheme (an increase of 11 hours despite the peak flow being reduced by 0.4 m^3/s). Similarly, applying a crossing capacity of 0.5 m^3/s, the duration of flow through Piffs Elm culvert over 0.5 m^3/s increases from approximately 18 hours in the Baseline to approximately 45 hours with-Scheme. This is an increase of 27 hours.

Figure 29 – Flood extents for the 1% AEP event (1 in 100-year return period) with climate change

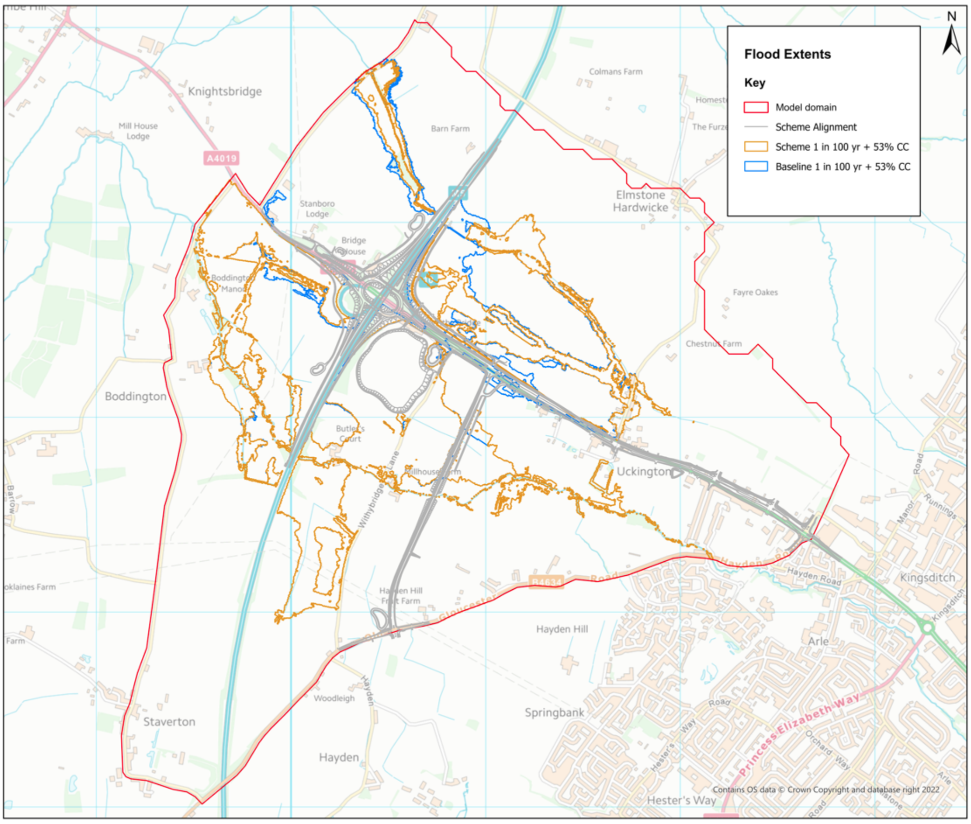
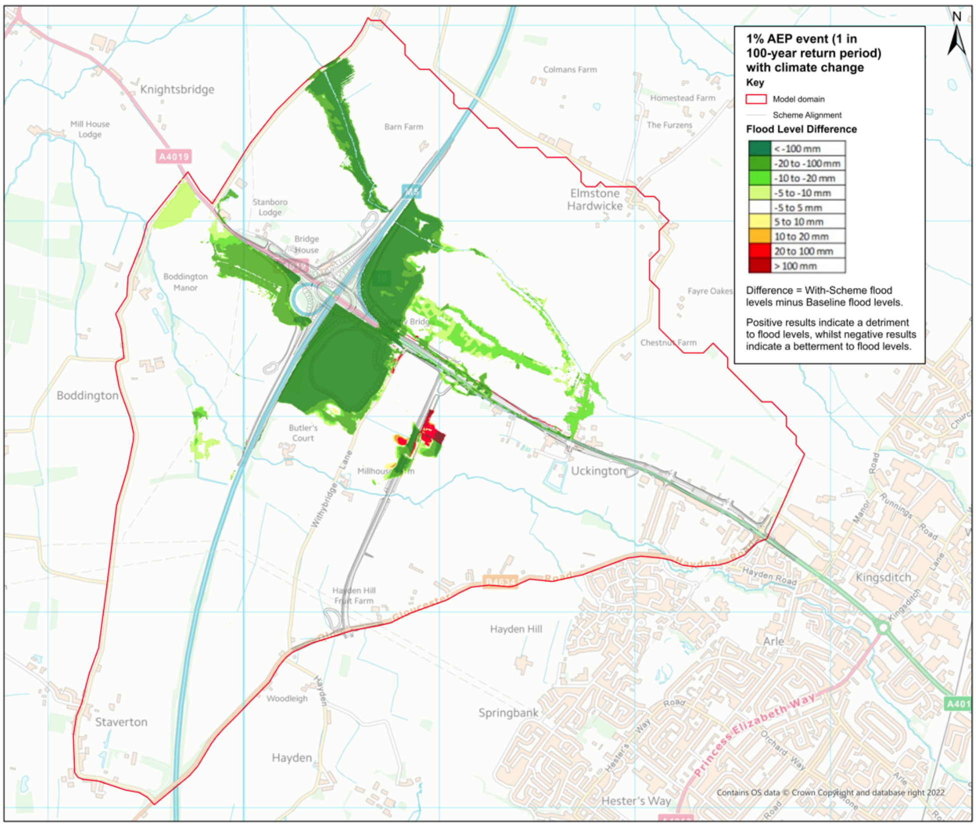


Figure 30 – Scheme impact on flood level at the 1% AEP event with climate change



6.6.1. Peak stage on the farmland drops by 10 mm near the downstream boundary, opposite the Old Spot public house, resulting in a reduction of flooded extent. Flood levels here are regulated by Boddington Lane, which is elevated above the floodplain; the impacts slightly further east, closer to the M5 motorway, are more notable with no flooding predicted.

6.6.2. The Scheme is addressing the adverse effects of an increase in flooded duration through consultations with the landowner, with a view that an agreement is made, balancing the betterment of no flooding, or less flooding and less often, with the increase in flooded duration.

6.7. 0.1% AEP event (1 in 1,000-year return period)

6.7.1. The residual risks of the extreme event (0.1% annual exceedance probability event (1 in 1,000-year return period) as defined in the NPPF) are of deeper flooding and higher velocities in the river and on the floodplain. This event has been simulated in the Baseline and Scheme hydraulic model.

6.7.2. The hydraulic modelling demonstrates that the Scheme itself does not become flooded from the watercourse or overland flow during this extreme event. The 0.1% annual exceedance probability event (1 in 1,000-year return period) is only marginally bigger than the 1% annual exceedance probability event (1 in 100-year return period) with 53% allowance for climate change.

6.7.3. The most significant difference between Scheme and Baseline flood extents is found in the Leigh Brook catchment, upstream of the M5 motorway. During the extreme event, the Scheme continues to sever the flow path over the A4019 and retains water in the fields south of it. This results in a widespread reduction in Baseline flood levels across the Leigh Brook floodplain, both upstream (east) and downstream (west) of the M5 motorway.

6.7.4. There is a reduction in peak flows through Barn Farm culvert, under the M5 motorway, the predictions reducing flow from 10.2 m^3/s in the Baseline to 3.4 m^3/s with-Scheme. This results in decreased Baseline flood levels downstream of the M5 motorway and a reduction in out of bank flooding which continues west to the model's downstream boundary.

6.7.5. The raising of the A4019 in the with-Scheme model retains more water in the Chelt floodplain (which would have previously entered the Leigh Brook catchment). This results in a 230 mm increase in flood levels upstream of the M5 motorway embankment although this does not cause any notable widening of the existing flood extents (see figures below). Increases in flood levels are most significant in the fields between the motorway and Withybridge Lane, where the proposed flood compensatory area is to be located.

6.7.6. As intended, water enters the flood storage area by the M5 motorway and results in deeper flooding as a result of excavated (reduced) ground levels - although flood levels here are predicted to rise locally by 230 mm in this event. Flood depths in the storage area south of Withybridge Gardens increase (as a result of ground lowering) from 1.47 m in the Baseline to 2.86 m with Scheme, and at the southern end of the storage area, north of Butlers Court, from 0.76 m in the Baseline to 2.57 m with Scheme, assuming the invert of the storage area not below the invert of the extended Piffs Elm culvert..

6.7.7. New flooding is predicted on the compensatory floodplain, upstream of the proposed West Cheltenham Link Road and increases and decreases in flood levels are predicted both upstream and downstream of the proposed link road culverts.

6.7.8. There is a reduction in peak flow through Piffs Elm culvert, under the M5 motorway, predictions reducing from 3.7 m^3/s in the Baseline to 3.3 m^3/s with-Scheme. This results in a decrease in flood levels and flood extents downstream of Piffs Elm culvert. The scheme also prevents flows overtopping the A4019 near Elmstone Business Park, which occurs in the Baseline.

6.7.9. Local verge raising downstream of Piffs Elm culvert between the watercourse and the highway prevents flooding of the A4019 in the with scheme case. The area is at risk during the baseline scenario.

6.7.10. Selected point results are tabulated below in Table 6-11 and Table 6-12 to give an indication of the flooding. The location of these points are shown in Figure 17 above.

Table 6-11 – 0.1% AEP event (1 in 1,000 year return period) Baseline and Scheme depths

Location	Baseline depth (m)	Scheme depth (m)
1 Leigh Brook nr Barn Farm culvert	1.05	0.00
2 Leigh Brook existing slip road	1.08	0.01
3 Leigh Brook nr A4019	0.43	0.00
4 A4019	0.29	0.00
5 Withybridge Gardens	1.47	2.86
6 north of Butlers court	0.76	2.57
7 Eastern end of River Chelt floodplain	0.26	0.26
8 nr Staverton culvert	0.45	0.45
9 Boddington Lane	0.47	0.47

Table 6-12 – 0.1% AEP event (1 in 1,000-year return period) Baseline and Scheme flows

Location	Baseline flow (m^3/s)	Scheme flow (m^3/s)
A Barn farm culvert	10.2	3.4
B Piffs elm culvert	3.7	3.3
C River Chelt culvert	21.7	21.7
D Staverton culvert	2.8	2.8
E A4019 culvert	1.6	0.0
F A4019 over the top	13.3	0.0
G Withybridge Lane	22.4	22.4
H Boddington Lane (nr downstream boundary)	6.4	5.9

6.7.11. The resulting flood extent map (comparing to the Baseline) is shown as Figure 31. A difference grid (Scheme - Baseline) is shown in Figure 32.

Figure 31 – Baseline and Scheme flood extents for the 0.1% AEP event

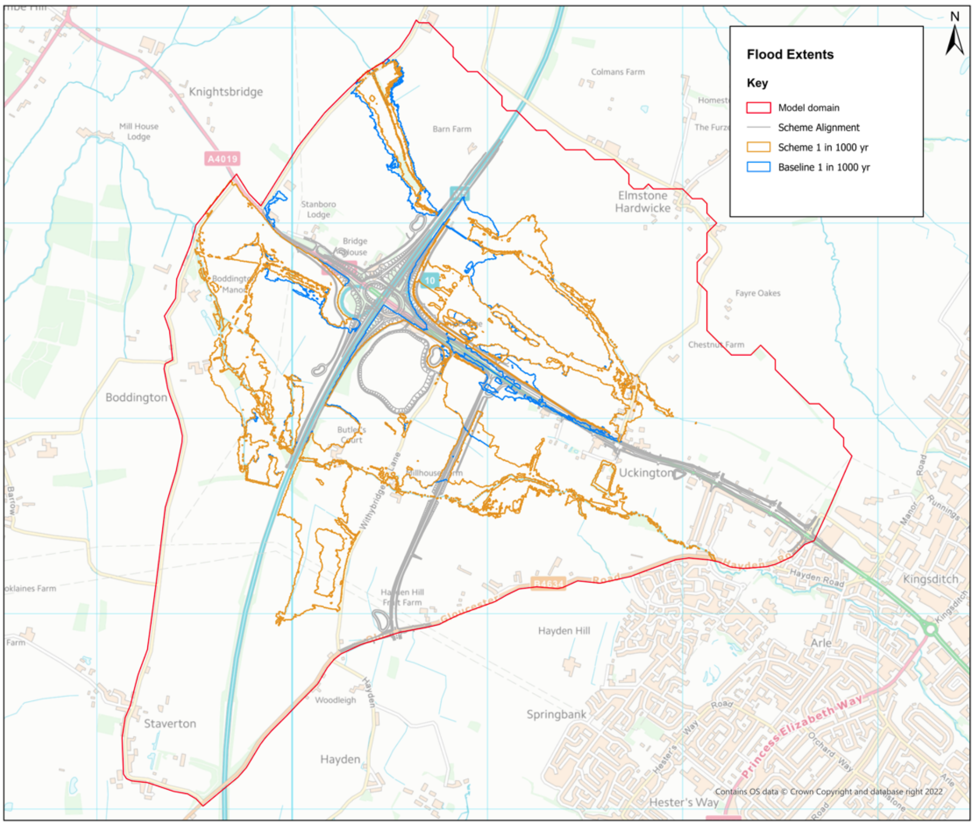
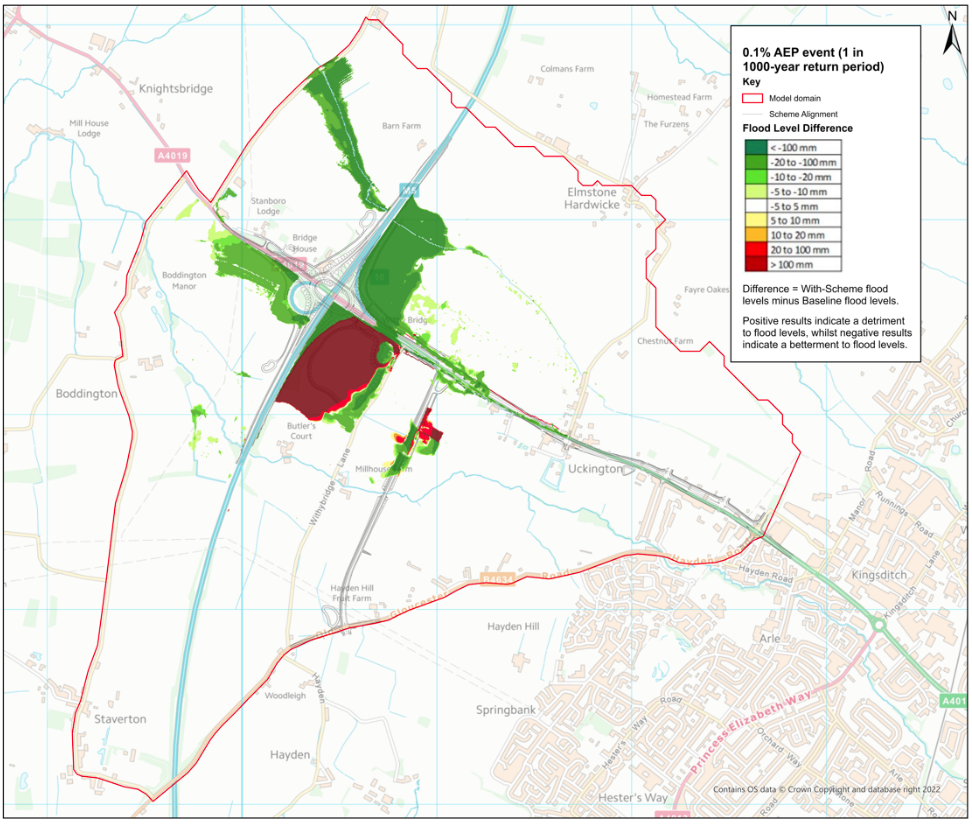


Figure 32 – Scheme impact on flood level at the 0.1% AEP event (1 in 1,000-year return period)



7. Assumptions and limitations

7.1.1. This section highlights the limitations of the modelling approach used and any restrictions that might apply to the specific model that was constructed.

7.2. Assumptions

7.2.1. The application of climate change factors to the M5J10 model assume a 53% uplift to the peak flow passing into the M5J10 model domain, with the inflow hydrographs being predicted by the River Chelt model stretched accordingly. There is no current guidance from the Environment Agency on how to apply the uplifts to flow (peak flow or full flood hydrograph).

7.3. Limitations

7.3.1. The model is limited by its study area, which includes the positioning of upstream and downstream boundaries sufficiently remote from the site of interest to ensure uncertainty and instability do not affect predictions for scheme design or flood risk impact assessment.

7.3.2. It is difficult to select a grid size which is suitable for both the River Chelt and Leigh Brook watercourses, and provides acceptable model run times. The grid size (4m) of the 2D domain may be deemed too coarse to accurately define some sections of the Leigh Brook. However, the Leigh Brook is represented in 1D and does not rely on the 2D grid to represent in-channel conveyance. Therefore, the grid size is deemed to be suitable to inform this study.

7.3.3. The model is a fluvial model and does not reflect surface water flooding caused by direct rainfall or other overland flow.

7.4. Future improvements

7.4.1. The Scheme model includes improvements already made to the Baseline model, as documented and issued to the Environment Agency in March 2022.

7.4.2. Improvements can be made to how the hydrological boundaries are applied to the 1D network of the Leigh Brook and have been trialled within the model. Currently the hydrological inputs to the model upstream of the M5 on the Leigh Brook are all applied as a lateral inflow which results in a small flow being applied to the upstream boundary of the model. Increasing the flow applied to the first section of the Leigh Brook to account for the catchment naturally draining to the upstream boundary of the model removes the influence of negative depths on peak flow. It should be noted that these negative depths do not propagate to the next cross-section downstream. These changes to the model result in subtle differences to the flood extents of the Leigh Brook between Uckington and the M5, although no changes are predicted downstream of the M5 or within the River Chelt catchment.

7.4.3. The junction design has developed since the modelling and initial version of the report was prepared, and now includes for a bat and equestrian underpass (culvert), under the A4019 on the east of Junction 10. This large culvert is set above the 1% annual exceedance probability event (1 in 100-year return period) with future climate change and show will not impact the results described in this report. However, it may convey more extreme events and pass some floodwater into the Leigh Brook catchment.

8. Summary and recommendations

8.1.1. The preliminary design of the M5 Junction 10 improvements scheme (new highway embankments, culverts and culvert extensions, and compensatory floodplain) has been applied to the Baseline hydraulic model of the River Chelt and Leigh Brook. This model was developed using ESTRY-TUFLOW and the Baseline calibrated to the July 2007 flood.

8.1.2. The Baseline hydrology has been applied to the model. At the 1% annual exceedance probability event (1 in 100-year return period), flow at the M5 motorway for the River Chelt of 24.5 m^3/s was estimated, and 2.5 m^3/s for the Leigh Brook.

8.1.3. The Scheme has been tested against the Higher Central climate change allowance as its "design flow", being +53% on peak flow, or a peak flow of 37.5 m^3/s in the River Chelt. The Upper End (credible maximum) scenario of +94% on peak flow was applied as a sensitivity test in the design.

8.1.4. Sensitivity tests were undertaken on structure parameters, including blockage.

8.1.5. The predictions from the Scheme flood model indicate that for the 1% annual exceedance probability event (1 in 100-year return period):

- Peak flood levels drop over much of the study area, as the large flood storage area attenuates water, despite no severance of water into the Leigh Brook during this event;
- the displacement of flood water by the Link Road is offset by the new compensatory floodplain; and
- flows passing downstream along the River Chelt valley are marginally reduced with a reduction in flow passing through Piffs Elm culvert.

8.1.6. The impacts of climate change on the 1% annual exceedance probability event (1 in 100-year return period) are notable, with the Scheme severing flows over the A4019 from the River Chelt into the Leigh Brook.

- Peak flood levels drop over much of the study area, as the large flood storage area attenuates water, including the large Baseline volume passing into the Leigh Brook in this event;
- the displacement of flood water by the Link Road is offset by the new compensatory floodplain; and
- flows passing downstream along the River Chelt valley are significantly reduced with a reduction in flow passing through both the Piffs Elm and Barn Farm culverts.

8.1.7. The modelling demonstrates that the Scheme is not at risk of flooding in the design event, and nor does the Scheme increase flood risk to 3rd party receptors.

8.2. Recommendations

8.2.1. It is recommended that the Scheme model be maintained with the developing design of the M5 Junction 10 improvements, to inform and guide the detailed design work.

8.2.2. A flood risk assessment will be required to support the environmental impact assessment as delivered through an Environmental Statement.

9. Model handover

9.1.1. A model handover spreadsheet is included as Appendix D, listing the required files or model run names for each design and sensitivity model run.

9.1.2. The Scheme model was reviewed by the Environment Agency. in June 2022, to ensure that it meets with their approval, having adhered to their guidelines. The model has been used to prepare a Flood Risk Assessment in support of the planning process on this scheme.

9.1.3. The model handover comprises the ESTRY-TUFLOW model files akin to an Environment Agency Product 7 delivery.

9.1.4. The review team shall note that the underlying model originates from the March 2022 Baseline model. The Baseline was reviewed by the Environment Agency in April 2021 and again in March 2022. All matters recommended to that Baseline model were implemented.

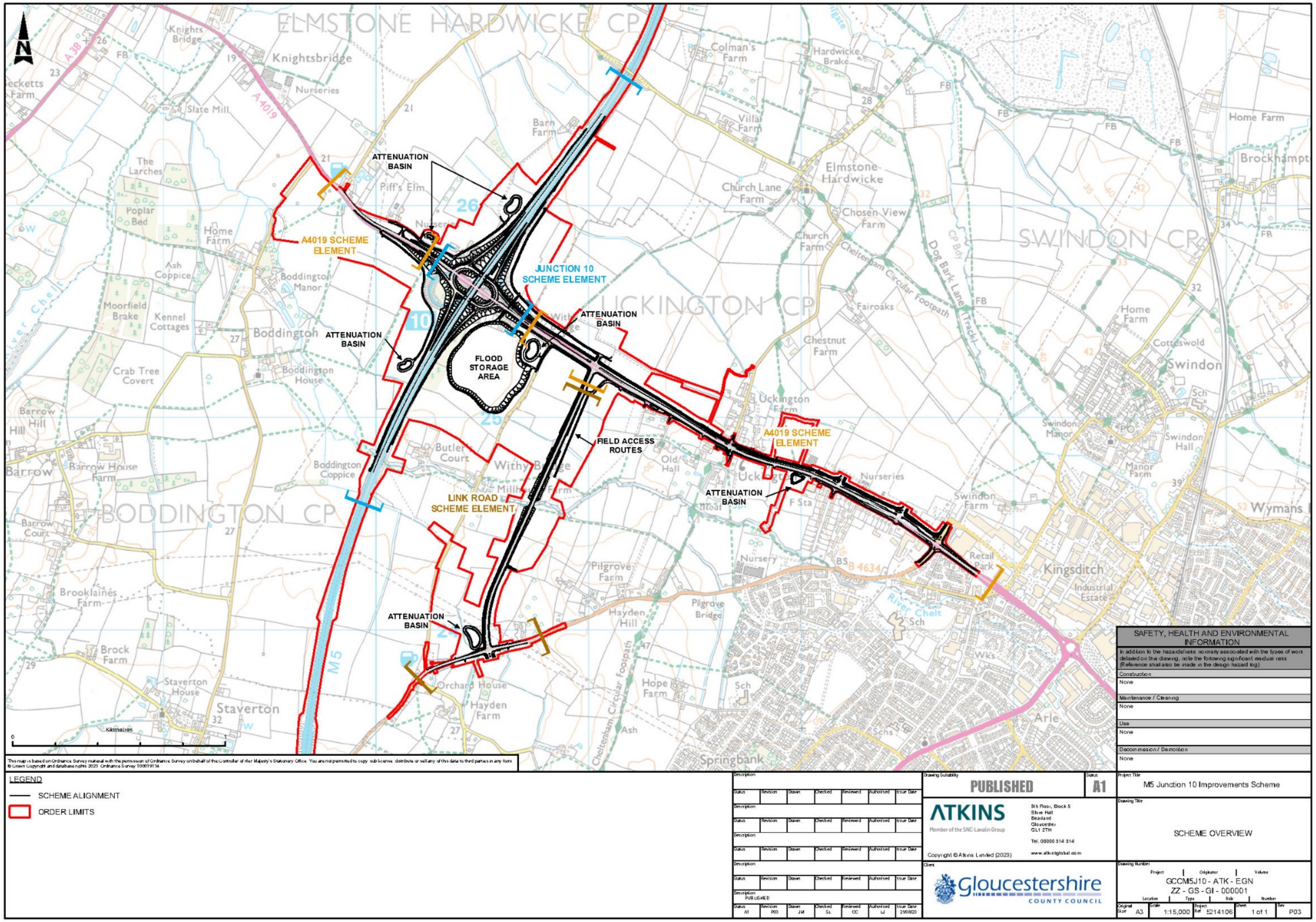
9.1.5. The study area for the Scheme model (as was the Baseline model) covers the extent of the proposed changes to the existing motorway junction, the proposed new link road, and the proposed widening of the existing A4019 road. The model domain for the M5J10 covers an area greater than and enclosing the predicted impact area. Model results upstream of Uckington, or downstream of Boddington are of no consequence to the Scheme and are omitted from this study/deliverable – although they may here provide the boundary conditions to the model. In this context, those boundary conditions are proven to be sufficiently remote from the Scheme to negate any uncertainty in the boundary conditions.

9.1.6. This report is intended only as a description of the Scheme model, describing in general terms the build and performance of the model. Specifically, this report documents changes made to the Baseline model and the predicted changes in flood risk when compared to the Baseline model. Further detail on the impacts is given in the Flood Risk Assessment and Environmental Statement.

Appendices

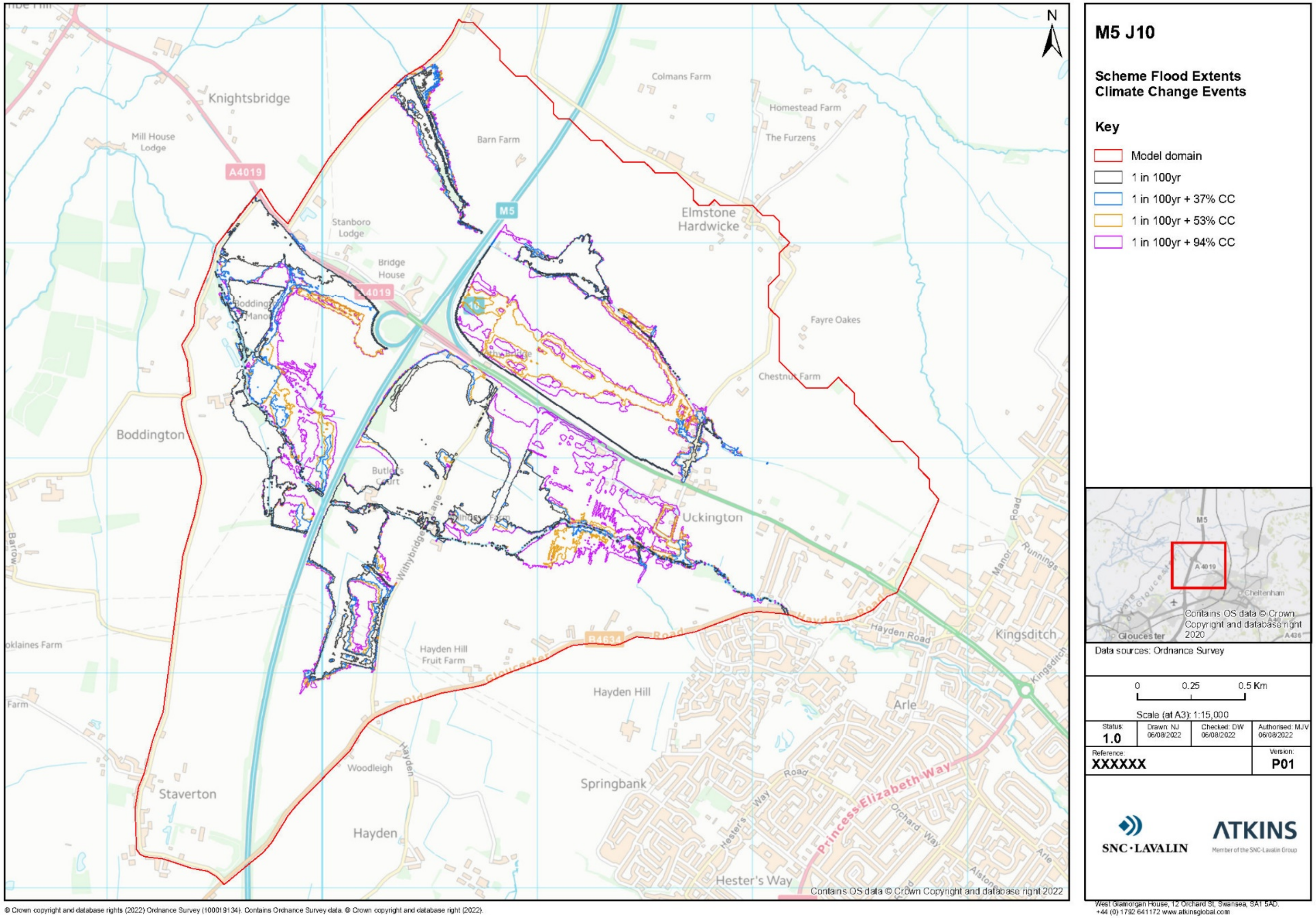
Appendix A. Scheme drawing

AtkinsRéalis Gloucestershire COUNTY COUNCIL



Appendix B. Sensitivity test results

B.1. Sensitivity to credible maximum climate change


N
Knightsbridge
Boddington
Uckington
Elmstone Hardwicke
Staverton
Hayden
Springbank
Kingsditch
Arle
Hester's Way
Hayden Hill
M5
A4019
B4634
Contains OS data © Crown Copyright and database right 2022
M5 J10
Scheme Flood Extents
Climate Change Events
Key
Model domain
1 in 100yr
1 in 100yr + 37% CC
1 in 100yr + 53% CC
1 in 100yr + 94% CC
Contains OS data © Crown Copyright and database right 2020
Data sources: Ordnance Survey
0
0.25
0.5 Km
Scale (at A3): 1:15,000
Status: 1.0
Drawn: NJ 06/08/2022
Checked: DW 06/08/2022
Authorised: MJV 06/08/2022
Reference: XXXXXX
Version: P01
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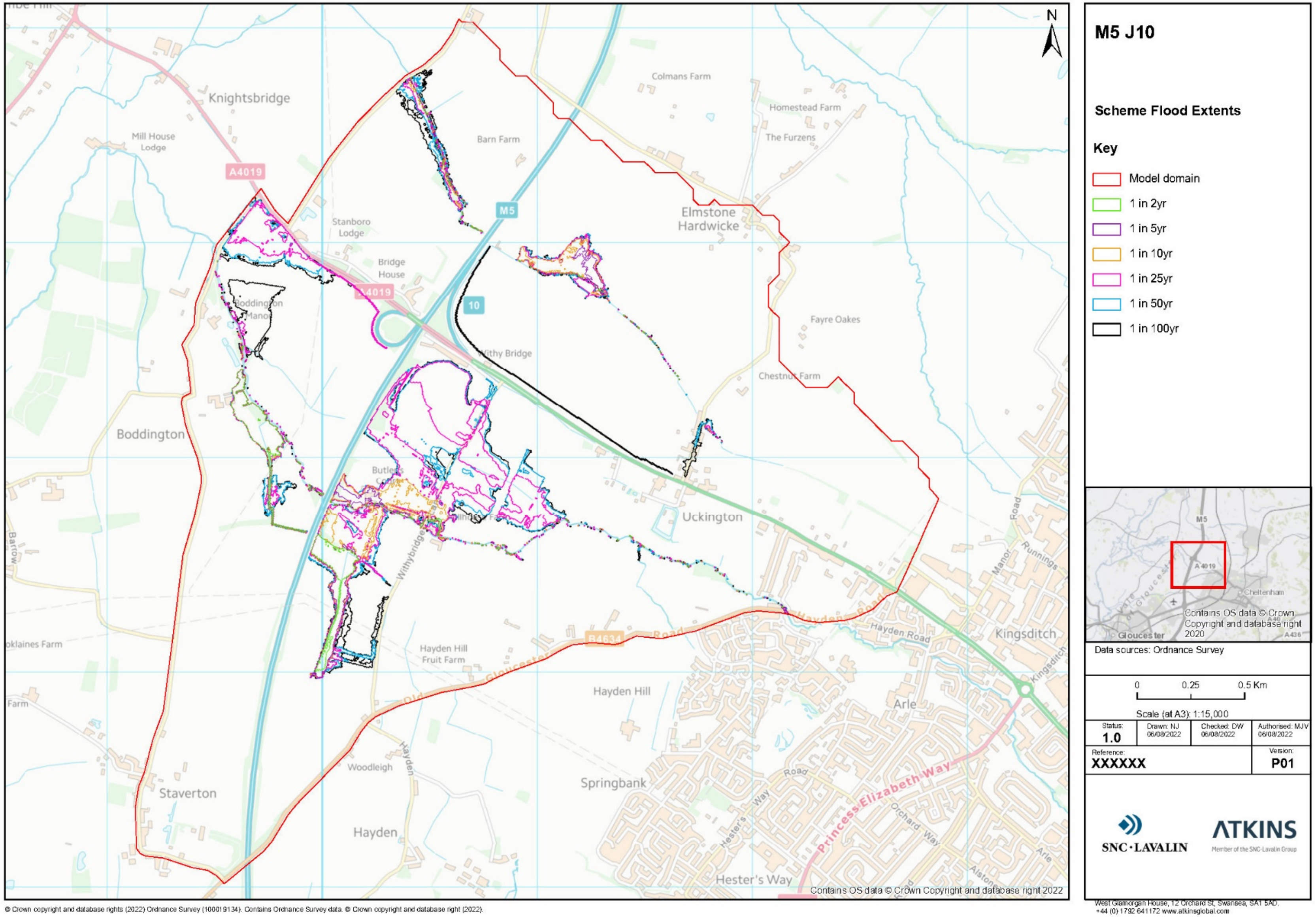
Appendix C. With Scheme model results

Flood extent maps and depth difference grids for the Scheme design events.

C.1. All events 50% AEP to 1% AEP

Encompassing the:

- 50% annual exceedance probability event (1 in 2-year return period)
- 20% annual exceedance probability event (1 in 5-year return period)
- 10% annual exceedance probability event (1 in 10-year return period)
- 4% annual exceedance probability event (1 in 25-year return period)
- 2% annual exceedance probability event (1 in 50-year return period)
- 1% annual exceedance probability event (1 in 100-year return period)


M5 J10
Scheme Flood Extents
Key
Model domain
1 in 2yr
1 in 5yr
1 in 10yr
1 in 25yr
1 in 50yr
1 in 100yr
Knightsbridge
Mill House Lodge
A4019
Stanboro Lodge
Bridge House
Boddington Manor
Barn Farm
Colmans Farm
Homestead Farm
The Furzens
Elmstone Hardwicke
M5
10
Fayre Oakes
Withy Bridge
Chestnut Farm
Boddington
Uckington
Hayden Hill Fruit Farm
B4634
Hayden Road
Kingsditch
Hayden Hill
Arle
Woodleigh
Staverton
Springbank
Hayden
Princess Elizabeth Way
Hester's Way
Contains OS data © Crown Copyright and database right 2022
Contains OS data © Crown Copyright and database right 2020
Data sources: Ordnance Survey
0 0.25 0.5 Km
Scale (at A3): 1:15,000
Status: 1.0
Drawn: NJ 06/08/2022
Checked: DW 06/08/2022
Authorised: MJV 06/08/2022
Reference: XXXXXX
Version: P01
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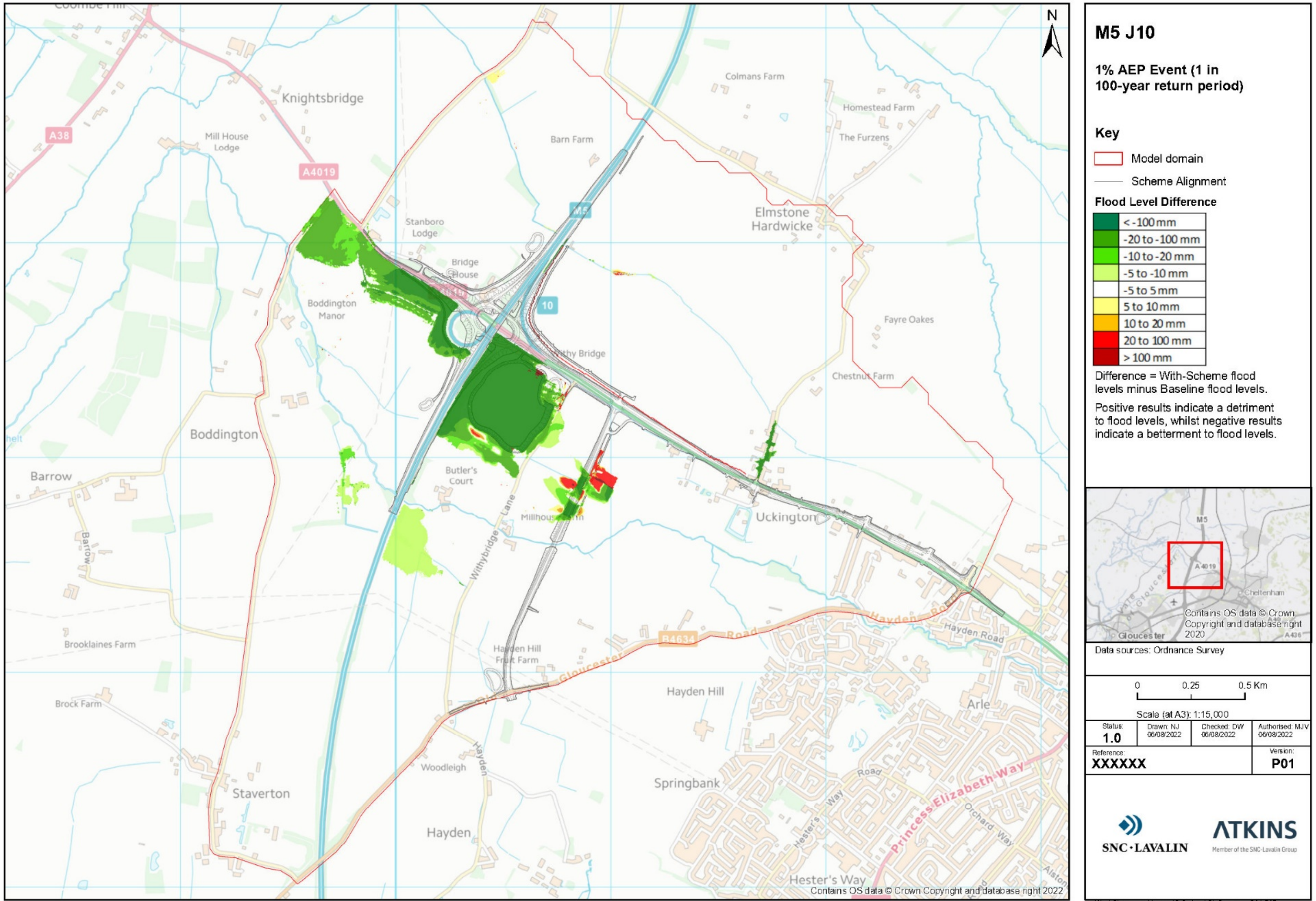
C.2. 1% AEP event (1 in 100-year return period)

Flood depth difference grid (Scheme – Baseline)



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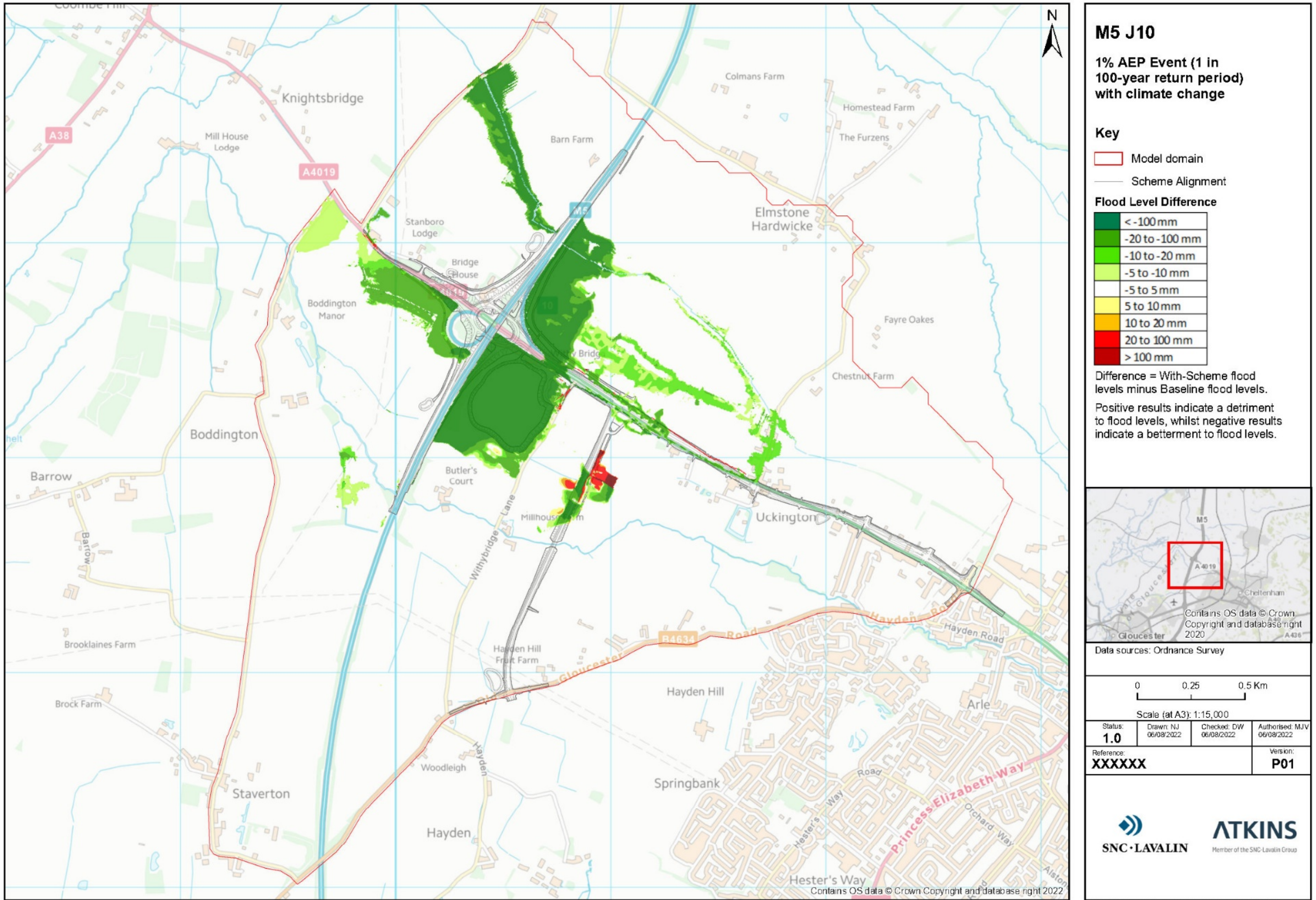
C.3. 1% AEP event (1 in 100-year return period) with climate change

Flood depth difference grid (Scheme – Baseline)



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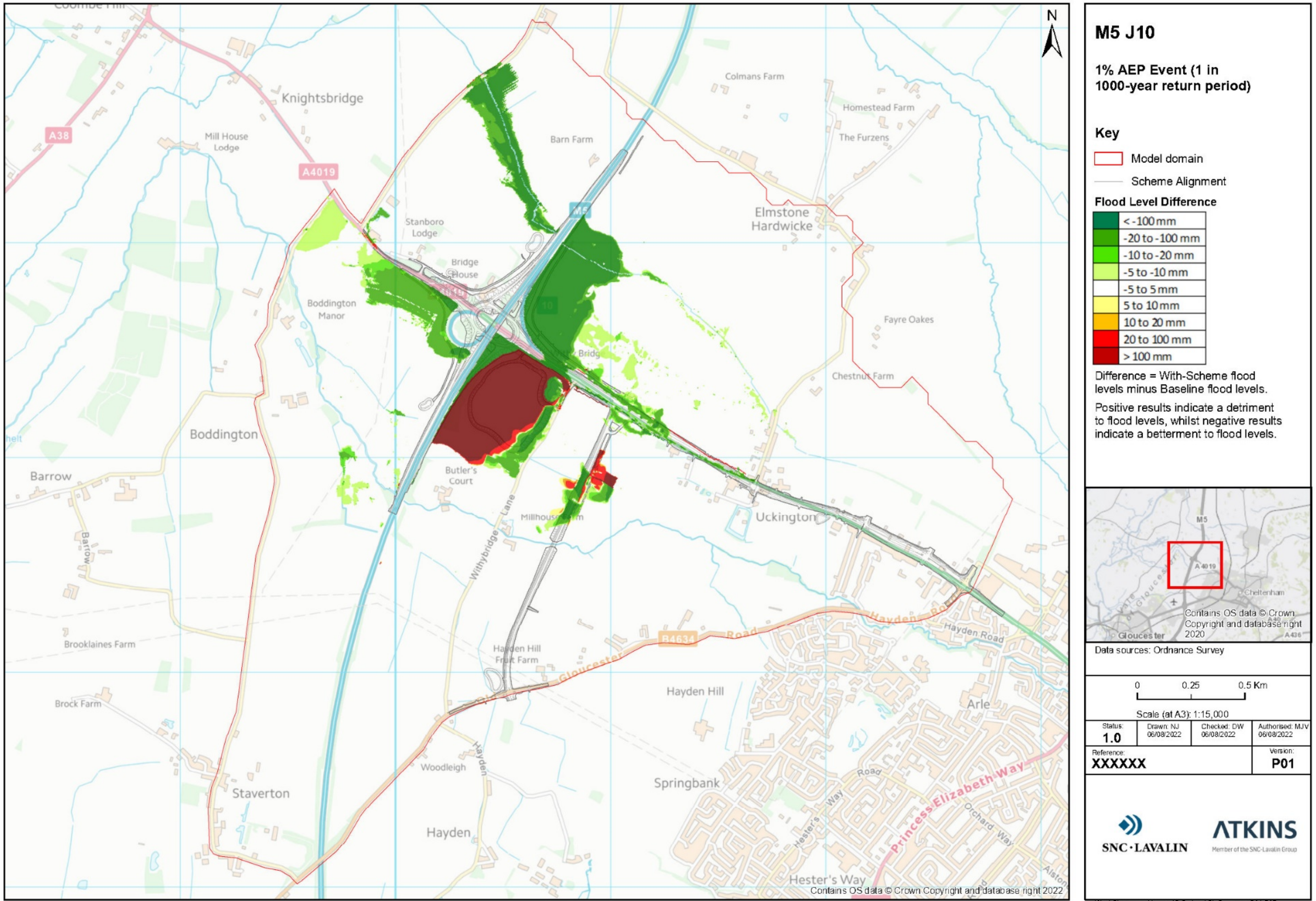
C.4. 0.1% AEP event (1 in 1000-year return period)

Flood depth difference grid (Scheme – Baseline)


M5 J10
1% AEP Event (1 in 1000-year return period)
Key
Model domain
Scheme Alignment
Flood Level Difference
< -100 mm
-20 to -100 mm
-10 to -20 mm
-5 to -10 mm
-5 to 5 mm
5 to 10 mm
10 to 20 mm
20 to 100 mm
> 100 mm
Difference = With-Scheme flood levels minus Baseline flood levels.
Positive results indicate a detriment to flood levels, whilst negative results indicate a betterment to flood levels.
Contains OS data © Crown Copyright and database right 2020
Data sources: Ordnance Survey
0
0.25
0.5 Km
Scale (at A3): 1:15,000
Status: 1.0
Drawn: NJ 06/08/2022
Checked: DW 06/08/2022
Authorised: MJV 06/08/2022
Reference: XXXXXX
Version: P01
SNC·LAVALIN
ATKINS
Knightsbridge
Mill House Lodge
A38
A4019
Colmans Farm
Homestead Farm
The Furzens
Barn Farm
Elmstone Hardwicke
Stanboro Lodge
Bridge House
Boddington Manor
Fayre Oakes
Chestnut Farm
Boddington
Barrow
Butler's Court
Uckington
Brooklaines Farm
Brock Farm
Hayden Hill
Arle
Woodleigh
Staverton
Springbank
Hayden
Hayden Road
Princess Elizabeth Way
Hester's Way
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Appendix D. Model logs

D.1. Model log

Date	Model version	Detail	OneNote Links (further info)
13/03/2021	v5	Model timestep changed from 0.5 to 1 second (to reduce run time), TUFLOW software version changed from 2018 to 2020 (to use most current version at time)	
15/04/2021	v6	Trimmed Leigh Brook XS data in csv's to match channel width in GIS (as per 2d_bc and 2d_code files) - in order to address EA review comment about differing widths.	
20/05/2021	v6	Extensions to existing culverts involving amendments to culvert length and invert levels: Piffs Elm (ID: JUNC 10), A4019 (TEWK), Withybridge (WBridge_1 and WBridge_2) and Barn Farm culverts (LB_CH18a and LB_CH18b). Culvert extensions included as separate nwk lines (i.e. 3 parts: original baseline culvert, west extension and east extension). A419 culvert re-aligned - now perpendicular to A4019. Wbridge twin culverts moved south.	2021 08 12 Scheme Model - Changes to Structures
20/05/2021	v6	Updates to ditches - realigned/moved to accommodate new surface and IL's adjusted according to culvert extensions or LiDAR	
04/06/2021	v7	After testing, settled on 37 culverts under Link Road *(1d_nwk_LinkRoad_Cul_L_Scheme_010.shp)*	2021 10 28 LR Culverts Setup
10/06/2021	v7	Ditch added at Uckington to pick up flow path which then goes through proposed spur road as open channel (in reality would be culverted)	
28/06/2021	v7	Received most up to date CAD model from highways of proposed surface - DF2.3 (*m5j10_df_2_3_surface.asc*)	
16/07/2021	v7	After testing, settled on wetland compensation surface V06-1. Invert level of 22.76 to match upstream IL of Piffs Elm Culvert (allows drainage) - *Compensation_Version6_Option1.asc*	
27/07/2021	v7	Ditches amended following DW internal check - some ditch z lines were not crossing cross hairs of model grid cells, corrected in order to create continuous flow path. Ditch z point elevations were also checked and revised where necessary using Atkins aerial survey and/or existing Lidar.	
09/08/2021	v7	After testing, settled on link road level-for-level compensation surface v06 (*LR_Reprovision_All_v6.asc*)	2021 08 09 Link Road Compensation Test V08
12/08/2021	v7	Added embankment (with z-line) north of link road level-for-level surface to prevent flooding moving into north field (*2d_zsh_LR_Comp_North_Wall_Scheme_001-L.shp*)	
09/11/2021	v7	Channel added connecting wetland to inlet of Piffs Elm (found embankment was sat between in model) - *2d_zsh_Wetland_Join_Scheme_001-L.shp*	
10/11/2021	v8	Baseline updates applied to Scheme model (Mill house farm - 30/09/2021 in BL model log and Staverton ditch - 18/10/2021 and 29/10/2021)	
19/11/2021	v8	Trimmed 4x Leigh Brook XS data - 2.83.csv, 2.70.csv, 2.68u.csv, 2.67d.csv	
19/11/2021	v8	2D material files amended to reflect scheme surface	
09/12/2021	v9	New topo survey added to model - M5J10Topo.asc	
14/12/2021	v9	Received most up to date CAD model from highways of proposed surface - DF3 (m5j10_df_3_surface.asc)	2021 12 14 Scheme Surface DF3
04/01/2022	v9	Link Road culvert testing - v09 19 culverts under LR (removed whole of south group)	2022 01 04 Scheme results - reducing LR culverts v09
10/01/2022	v9	Link Road culvert testing - v10 28 culverts under LR (removed half of south group)	2022 01 10 Scheme results - reducing LR culverts v10
10/01/2022	v9	LR culverts lengths reduced to suit DF3 surface (north group culverts now 35m (was 55m), south group culverts now 45m (was 65m))	
10/01/2022	v9	Tests removing A4019 culvert in Scheme. Kept in for this version of Scheme	2022 01 10 Scheme results - removing A4019 culvert
17/01/2022	v9	Tests to slow flow through Piffs Elm culvert - reduced size of culvert from 1.2 to 0.9 (test only at this stage)	2022 02 02 Scheme Tests at Piffs Elm cont'd
20/01/2022	v9	Tests to trim Uckington ditch - now starting west of Pigeon Farm (test only at this stage)	
02/02/2022	v9	Tetss to add culvert connecting The Green with Uckington ditch. Settled on 300mm dia for this version of Scheme	2022 02 02 Uckington ditch culvert tests Q100+CC53%
09/02/2022	v9	Tests to resize wetland (version 7.2)	2022 02 14 Wetland V07-2
17/02/2022	v9	Final scheme simulations for DF2 complete - 37 LR culverts, Uck culvert 300mm dia, A4019 culverts included, wetland v6-1	2022 02 17 Final scheme results DF2
01/03/2022	v10	Updated chelt crossing opening through LR (previously 40m cut out from LR surface, updated to approx. 26m)	2022 03 01 New Chelt Crossing Alignment
29/03/2022	v10	Received updated highways surface (DF3.3)	2022 03 29 Updated Highways Surface (DF3.3)
29/03/2022	v10	Updated wetland surface (V8.1)	2022 03 29 Updated Wetland Surface (V8.1)
25/04/2022	v10	Culverts under A4019 removed	2022 04 04 Scheme v10 - with & without A4019 culverts
19/05/2022	v10	Received updated highways surface (DF3.4)	
07/06/2022	v10	LR comp surface V7 added to model (MI/Proposed/LR_Reprovision_v7.asc)	
07/07/2022	v10	2D roughness files in model updated to reflect landscape design	2022 05 19 Environment design DR3.4
18/07/2022	v10	Drainage pond surface added to model (MI/Proposed/Ponds.asc)	
26/07/2022	v10	Piffs Elm alterations to extensions and roughness	2022 07 25 Final Scheme Model Updates
19/04/2023	v11	Verge raising (using thin z-line) of 30-50mm over some 50m to prevent detriment on A4019 and fields to north	2023 04 24 Glass Wall Tests - 50m and 25m

D.2. Model files description

Model Simulations

	GIS Filename	Model File Type	1 in 2yr	1 in 5yr	1 in 10yr	1 in 20yr	1 in 25yr	1 in 50yr	1 in 100yr	1 in 1000yr	1 in 100yr+37%CC (Central)	1 in 100yr+53%CC (Higher Central)	1 in 100yr+94%CC (Upper End)	ST01 Scheme without embedded mitigation	ST02 Scheme with part embedded mitigation	ST03 Link Road culverts with part blockage	ST04 Piffs Elm culvert with part blockage	TUFLOW File	Description
1	1d_nwk_Chelt_Trunc-A_L_002.shp	River Chelt 1d network																TCF	Truncated River Chelt network line based on EVY's original file
2	1d_nwk_Chelt_Trunc-A_L_002_Extended.shp	River Chelt 1d network																TCF	River Chelt network line based on EVY's original file - extended to reach updated downstream boundary location
3	1d_nwk_Chelt_EA_ln_002.shp	River Chelt 1d network																TCF	Upstream River Chelt network line, extracted from EA Middle Model (2012) files to replace 2d gully line from Old Gloucester Road to EVY Chelt files
5	1d_nwk_CheltStructures_v14-Trunc_A_L_004.shp	River Chelt 1d structures network																TCF	River Chelt structures network line based on EVY's original file
6	1d_nwk_LB_Atkins_Trunc_ln_scheme_004.shp	Leigh Brook 1d network																TCF	Truncated Leigh Brook network line based on Infomap 2019 survey. Amended to suit scheme
7	1d_nwk_LB_Atkins_Trunc_ln_002_Extended.shp	Leigh Brook 1d network																TCF	Leigh Brook network line based on Infomap 2019 survey - extended to reach updated downstream boundary location
8	1d_nwk_MCH_Cul_014_L_Scheme_014.shp	M5 Structures 1d network																TCF	M5 Structures file updated using Infomap 2019 survey and Highways England PI reports where required. Amended to reflect scheme V10
9	1d_nwk_MCH_Cul_014_L_Scheme_014_Block.shp	M5 Structures 1d network																TCF	Piffs Elm culvert blockage sensitivity test
10	1d_nwk_LinkRoad_Cul_L_Scheme_010.shp	Link Road culverts 1d network																TCF	Proposed Link Road Culverts network lines. Amended to reflect scheme V10
11	1d_nwk_LinkRoad_Cul_L_Scheme_010_Block.shp	Link Road culverts 1d network																TCF	Proposed Link Road culverts blockage sensitivity test
12	1d_nwk_Uck_Pipe_003.shp	Uckington ditch culvert 1d network																TCF	New (proposed) roadside drainage ditch at Uckington
13	1d_xs_Chelt_v10-Trunc_A_L_006.shp	River Chelt 1d XS																TCF	River Chelt XS based on EVY's original file
14	1d_xs_Chelt_v10-Trunc_A_L_Extended.shp	River Chelt 1d XS																TCF	River Chelt XS based on EVY's original file, extended to reach updated downstream boundary location
15	1d_xs_Chelt_EA_L_001.shp	River Chelt 1d XS																TCF	River Chelt XS's extracted from EA Middle Model (2012) files
16	1d_xs_CheltStructures_v01-Trunc_A_L.shp	River Chelt Structures 1d XS																TCF	River Chelt structures XS's based on EVY's original file
17	1d_XS_CheltStructure_Atkins_ln_001.shp	River Chelt Structure 1d XS																TCF	River Chelt structure XS's (under M5) based on Infomap 2019 survey
18	1d_XS_LB_Atkins_Trunc_Scheme_ln_004.shp	Leigh Brook 1d XS																TCF	Leigh Brook XS's based on Infomap 2019 survey. Amended to suit scheme
19	1d_XS_LB_Atkins_ln_001_Extended.shp	Leigh Brook 1d XS																TCF	Leigh Brook XS's based on Infomap 2019 survey
20	1d_XS_LBStructures_Atkins_Trunc_ln_001.shp	Leigh Brook Structures 1d XS																TCF	Leigh Brook structures XS's based on Infomap 2019 survey
21	1d_bc_Trunc_bndy_001_Extended.shp	1D HQ Point Boundaries																TCF	Downstream HQ boundaries for 1D sections of River Chelt and Leigh Brook
22	1d_bc_Trunc_FEH_Scheme_004.shp	1D QT Point Inflow																TCF	1D QT Point Inflows for River Chelt upstream, River Chelt downstream, Leigh Brook downstream and CSO catchments. Amended to suit scheme
23	1d_bc_Trunc_FEH_Scheme_R_003.shp	1D QT Polygon Inflow																TCF	1D QT Polygon Inflowapplied from start of Leigh Brook to M5 to provide lateral inflows. Amended to suit scheme
24	2d_PO_FlowMeasurements_v13_L.shp	PO Lines																TCF	PO Lines extracting results from 2D - EVY Original File (Unchanged)
25	2d_PO_CalibrationPoints_v05_P.shp	PO Points																TCF	PO Points extracting results from 2D - EVY Original File (Unchanged)
26	2d_po_Q_Chelt_Atkins_001.shp	PO Lines																TCF	PO lines extracting flow results from 2D at key locations in M5 J10 study area
27	2d_po_H_Chelt_Atkins_001.shp	PO Points																TCF	PO points extracting water level results from 2D at key locations in M5 J10 study area
28	2d_po_M5J10_NRD_001.shp	PO Points																TCF	PO points based on EA NRD Dataset (2014) extracting results from 2D domain
29	2d_po_Q_M5J10_Atkins_001.shp	PO Lines																TCF	Additional PO lines extracting flow results from 2D at key locations in M5 J10 study area
30	2d_po_H_Right2Flood_001.shp	PO Points																TCF	PO points to assess possible 'Right to Flood' locations
31	2d_bc_CHT-ESTRY_Trunc-A_L_005.shp	CN/HX Lines																TBC	HX and CN lines linking 1D (ESTRY) section of River Chelt to 2D (TUFLOW) domain
32	2d_bc_MCH_Cul_014_Scheme_L_009.shp	CN/SX Lines																TBC	SX and CN lines linking 1D (ESTRY) M5 structures to 2D (TUFLOW) domain. Amended to suit scheme
33	2d_bc_LB_Atkins_HxBanks_Trunc_Scheme_ln_005.shp	CN/HX Lines																TBC	HX and CN lines linking 1D (ESTRY) section of Leigh Brook to 2D (TUFLOW) domain. Amended to suit scheme
34	2d_bc_LinkRoad_Cul_Scheme_L_007.shp	CN/SX Lines																TBC	SX and CN lines linking 1D (ESTRY) proposed Link Road structures to 2D (TUFLOW) domain
35	2d_bc_Uck_Pipe_001.shp	CN/SX Lines																TBC	SX and CN lines linking 1D (ESTRY) proposed structure at Uckington to 2D (TUFLOW) domain
36	2d_bc_Inputs_HQ_002.shp	2D HQ DS Boundary																TBC	2D downstream boundary lines for River Chelt and Leigh Brook - Baseline slope 1 in 200 (0.005)
37	2d_inflows_Trunc_FEH.shp	2D QT Inflow Point																TBC	1 x 2D QT inflow to represent Staverton stream
38	2d_loc_CLB_v01-A_L.shp	2D Location Line																TGC	2D location line specifying grid origin and orientation
39	Lidar_Composite_dtm_1m.asc	DTM Surface																TGC	2019 1m composite Lidar from EA to provide 2d underlying topography
40	M5J10Topo.asc	Aerial Survey Surface																TGC	1m surface mobile scanning, infill, and aerial survey of critical areas
41	LR_Reprovision_All_v7.asc	Scheme Surface																TGC	1m compensatory floodplain surface immediately upstream of Link Road
42	Wetland_v8_1.asc	Scheme Surface																TGC	1m wetland flood storage surface
43	Ponds.asc	Scheme Surface																TGC	1m drainage ponds surface
44	DF3_4_NoComp.asc	Scheme Surface																TGC	1m proposed scheme surface, not including flood compensation
45	DF3_4_NoComp_V2.asc	Scheme Surface																TGC	1m proposed scheme surface, not including flood compensation or access track around wetland
46	2d_code_Truncated_R_002.shp	2D Code Polygon																TGC	Polygon defining 2D Domain boundary
47	2d_code_CHT_Trunc_A_R_004.shp	2D Code Polygon																TGC	Polygon de-activating 1D Channel River Chelt from 2D Domain
48	2d_code_LB_Atkins_Trunc_Scheme_ply_004.shp	2D Code Polygon																TGC	Polygon de-activating 1D Channel Leigh Brook from 2D Domain. Amended to suit scheme
49	2d_zln_CHT-Banks_v01-Trunc_A_L_002.shp	Z Shape																TGC	Z line setting elevation of River Chelt Banks
50	2d_zln_CHT-Banks_v01-Trunc_A_P_002.shp	Z Shape																TGC	Z point setting elevation of River Chelt Banks
51	2d_zsh_Bridgedecks_v01-Trunc_A_R.shp	Z Shape																TGC	Z shape polygon representing bridge/culvert overlays
52	2d_zsh_Bridgedecks_v01-A_P.shp	Z Shape																TGC	Z shape polygon representing bridge/culvert overlays
53	2d_zsh_MCH_DrainageLine_014_Scheme_002-L.shp	Z Shape																TGC	Z shape representing drainage features in 2d model domain. Amended to suit scheme
54	2d_zsh_MCH_DrainageLine_014_Scheme_002-P.shp	Z Shape																TGC	Z shape representing drainage features in 2d model domain.Amended to suit scheme
55	2d_zsh_MCH_MHFarm_Wall_001-L.shp	Z Shape																TGC	Z shape representing defence wall around Mill house farm
56	2d_zsh_MCH_MHFarm_Wall_001-P.shp	Z Shape																TGC	Z shape representing defence wall around Mill house farm
57	2d_zsh_MCH_MHFarm_Channel_002-L.shp	Z Shape																TGC	Z shape representing channel around Mill house farm
58	2d_zsh_MCH_MHFarm_Channel_001-P.shp	Z Shape																TGC	Z shape representing channel around Mill house farm
59	2d_zsh_MCH_MHFarm_BBParapet_001-L.shp	Z Shape																TGC	Z shape representing parapet on bridge over Chelt near Mill house farm
60	2d_zsh_MCH_MHFarm_BBParapet_001-P.shp	Z Shape																TGC	Z shape representing parapet on bridge over Chelt near Mill house farm
61	2d_zsh_LR_Comp_North_Wall_Scheme_001-L.shp	Z Shape																TGC	Z shape preventing water extending north outside of Link Road compensatory floodplain
62	2d_zsh_Wetland_Pond_Scheme_001-L.shp	Z Shape																TGC	Z shape creating raised perimeter around drainage pond east of Wetland
63	2d_zsh_Wetland_Join_Scheme_001-L.shp	Z Shape																TGC	Z shape lowering area of high ground between wetland and Piffs Elm culvert
64	2d_mat_Urban_v02-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for urban areas in 2D domain
65	2d_mat_Woodland_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for woodland areas in 2D domain. Amended to suit scheme
66	2d_mat_Buildings_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for buildings in 2D domain
67	2d_mat_Roads_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
68	2d_mat_RGrassland_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
69	2d_mat_Woodland_Scheme_v02-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
70	2d_mat_Scrub_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
71	2d_mat_Scrub_Scheme_v02-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme sensitivity test.
72	2d_mat_WGrassland_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme

Model Simulations																			
	GIS Filename	Model File Type	1 in 2yr	1 in 5yr	1 in 10yr	1 in 20yr	1 in 25yr	1 in 50yr	1 in 100yr	1 in 1000yr	1 in 100yr+37%CC (Central)	1 in 100yr+53%CC (Higher Central)	1 in 100yr+94%CC (Upper End)	ST01 Scheme without embedded mitigation	ST02 Scheme with part embedded mitigation	ST03 Link Road culverts with part blockage	ST04 Piffs Elm culvert with part blockage	TUFLOW File	Description
73	2d_mat_WGrassland_Scheme_v02-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme sensitivity test.
74	2d_mat_Water_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
75	2d_mat_CarPark_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
76	2d_mat_Ditches_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for roads in 2D domain. Amended to suit scheme
77	2d_mat_SurfaceWater_Scheme_v01-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for surface water areas in 2D domain. Amended to suit scheme
78	2d_mat_SurfaceWater_v13-A_R.shp	Mat Polygon File																TGC	Materials polygon setting roughness value for surface water areas in 2D domain
79	2d_zsh_A4019West_GlassWall_006-L.shp	Z Shape																TGC	Z shape creating raised ground along the A4019 downstream of Piffs Elm to prevent flooding of the A4019.

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