M5 Junction 10 Improvements Scheme

Baseline Hydraulic Modelling Report

TR010063 - APP 9.18

Regulation 5(2)(e)

Planning Act 2008

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

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Infrastructure Planning

Planning Act 2008

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

M5 Junction 10 Improvements Scheme

Development Consent Order 202[x]

9.18 Baseline 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 by 2031.

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:

- An all-movements junction at M5 Junction 10;
- A new West Cheltenham Link Road from J10;
- 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 now been undertaken to understand the Baseline flood risk in the area. This report describes that Baseline flood modelling.

The model uses the Environment Agency's middle Chelt model from 2012, as was updated for the Boddington flood map challenge in 2019. New topographic survey has been added to the model, creating a fully linked 1D-2D model using the industry standard ESTRY-TUFLOW software.

A hydrology study was undertaken based on the FEH methods and following the 2012 Environment Agency flood estimation guidelines. 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 for to cover future climate change over the lifetime of the development.

The hydrological and hydraulic models were calibrated using the July 2007 flood event, considered to be in excess of the 1% annual exceedance probability event (1 in 100-year return period). The calibration was made against flows recorded at the now redundant Slate Mill gauge, and wrack marks recorded at the time by the Environment Agency. The calibration demonstrates the ability of the new model to predict flood levels accurately across the study area. Further confidence in the model prediction was developed through a series of sensitivity tests.

The flood model indicates that the design flood (1% annual exceedance probability event (1 in 100-year return period) with allowance for climate change) inundates a large swathe of land to the immediate east of the M5 motorway, joining up the flows of the River Chelt and Leigh Brook with floodwater moving north over the A4019 highway.

This report sets out the Baseline conditions against which the proposed scheme will be assessed. Subsequent reports will document:

- the development and testing of a with-scheme model (Scheme Hydraulic Modelling Report, Application document TR010063/APP/9.19);
- the Flood Risk Assessment (Application document TR010063/APP/6.15); and
- the Environmental Statement (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
AOD	Above ordinance datum
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
FRA	Flood Risk Assessment
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	National Policy Statement
NSIP	Nationally Significant Infrastructure Project
QH	Stage-discharge
RBD	River basin district
RofSW	Risk of Flooding from Surface Water
RP	Return period
SuDS	Sustainable Drainage System
TBC	Tewkesbury Borough Council

Contents

Tables

Figures

1. Introduction

1.1. Scheme background and the need for the Scheme

1.1.1. Gloucestershire faces significant challenges to achieve its vision for economic growth. A Joint Core Strategy (JCS) – a partnership between Gloucester City Council (GCC), Cheltenham Borough Council (CBC) and Tewkesbury Borough Council (TBC) has been formed to produce a co-ordinated strategic development plan to show how the region will develop during the period 2011 - 2031. This includes a shared spatial vision targeting 35,175 new homes and 39,500 new jobs by 2041. Major development of new housing (c.9,000 homes) and employment land (c.100ha) is proposed in strategic and safeguarded allocations in the West and North West of Cheltenham, much of which lies within TBC's boundary as the Local Planning Authority. This development, in turn, is linked to wider economic investment, including a government supported and nationally significant 45 ha Cyber Central UK adjacent to GCHQ in West Cheltenham, as part of the Golden Valley Development, which also comprises the Garden Community Development. The Cyber Central UK hub is predicted to support c.7,500 jobs.

1.1.2. National Highways (formerly Highways England) also identified that improvements to M5 Junction 10 are a critical requirement to maintain the safe and efficient operation of the M5 corridor in their Birmingham to Exeter Route Strategy, whilst enabling the planned development and economic growth around Cheltenham, Gloucester, and Tewkesbury.

1.1.3. The Scheme objectives are shown below.

Figure 1 – Scheme objectives

Objective 1:
Provide the transport connections and network capacity in west and north-west Cheltenham to facilitate the delivery of housing and economic development sites allocated or safeguarded in the JCS

Objective 2:
Provide a transport network in the west and north-west Cheltenham area with the levels of service, safety and accessibility to meet current and future needs

Objective 3:
Provide greater connectivity between the Strategic Road Network (SRN) and the transport network in west and north-west Cheltenham

Objective 4:
Provide a more integrated transport network by enabling opportunities to switch to more sustainable transport modes within and to west, north-west and central Cheltenham

Objective 5:
Deliver a package of measures which is in keeping with the local environment and minimises any adverse environmental impacts

1.1.4. A Business Case 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, which together make up the M5 Junction 10 Improvements Scheme. Funding was successfully awarded by Homes England in March 2020:

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

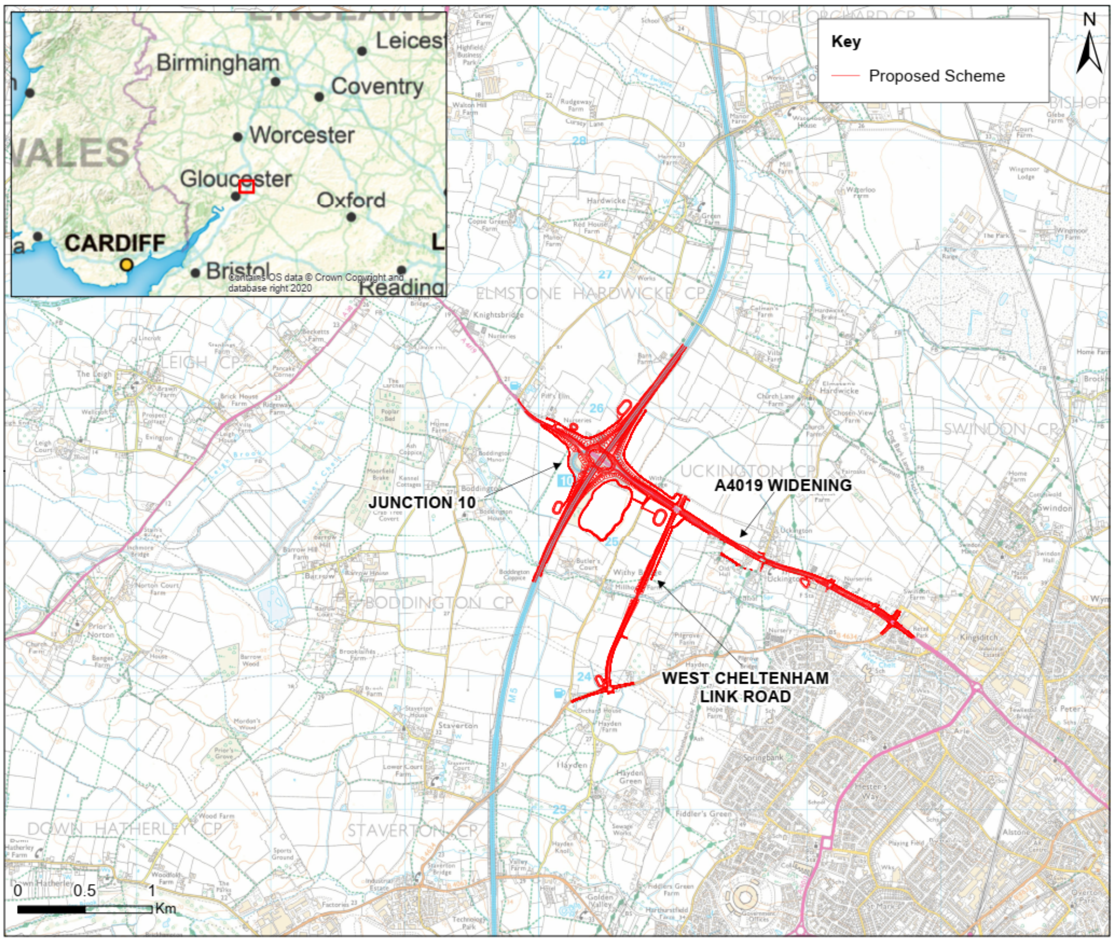
1.1.5. The upgrade to Arle Court Park and Ride (now known as the Arle Court Transport Hub) and the junction improvements at Coombe Hill were included as part of the package of improvements funded by Homes England. Gloucestershire County Council has decided to take these two elements forward as separate packages of work in order to accelerate the programme for these elements, and will deliver them through separate planning strategies.

1.2. Location of the Scheme

1.2.1. M5 Junction 10 is located 48 miles to the south of Birmingham, five miles to the south of Tewkesbury, four miles to the north-west of Cheltenham, and eight miles to the north-east of Gloucester. It is the northernmost of four junctions serving the Gloucester and Cheltenham urban areas. This places the junction 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.

1.2.2. The locations of the proposed infrastructure improvements that make up the M5 Junction 10 Improvements Scheme are illustrated in Figure 2 below.

Figure 2 – Location of the Scheme



1.3. Scope

Wider project scope

1.3.1. Atkins was appointed by Gloucestershire County Council (GCC) as the designer for the M5 Junction 10 Improvements Scheme (M5J10). This report documents the flood risk assessment of the following scheme elements:

- Scheme element 1: Improvements to Junction 10 on the M5 and a new road linking Junction 10 to west Cheltenham (West Cheltenham Link Road); and
- Scheme element 3: A4019 widening, east of Junction 10.

1.3.2. Several options for each of the elements involved in the M5 Junction 10 Improvements Scheme were considered. Each was subject to initial traffic, engineering and environmental surveys and assessments. GCC have worked closely with Tewkesbury Borough Council and Cheltenham Borough Council to understand local constraints and ensure that their aspirations for growth and development are accurately represented in our proposals.

1.3.3. For an option to have been taken forward to options consultation it was assessed to achieve the Scheme objectives, be affordable and offer value for money. Flood risk also formed a key part of the option selection process. More detail about the optioneering process for each scheme element can be found in the consultation brochure and supporting technical documents:

- Technical Appraisal Report - M5 Junction 10 Volume 1[1];
- Preliminary Environmental Assessment of Options Report Non-Technical Summary[2].

1.3.4. Following a non-statutory public consultation, a Staged Overview of Assessment Report[3] was produced taking into account the comments and views expressed during the consultation, and made a recommendation for a Preferred Option. The Preferred Option is the Scheme that GCC recommended be taken forward to an application for statutory powers to construct. This decision was guided by flood risk amongst other environmental, economic, and technical disciplines.

Flood risk scope and context

1.3.5. 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[4] (PEAOR).

1.3.6. Detailed hydraulic modelling was therefore undertaken to:

- understand the Baseline flood risk in the area;
- determine the impact of preferred (proposed) Scheme on flood risk; and
- determine the flood risk to the proposed Scheme.

1.3.7. This report documents the development of a flood model describing the Baseline risks associated with the River Chelt and Leigh Brook (locally pronounced “*Lie*”) in the vicinity of the Scheme.

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[1] Gloucestershire County Council (15 September 2020) M5 Junction 10 Improvement, volume 1 – report. Technical Appraisal Report. GCCM5J10-ATK-GEN-XX-RP-ZM-000001 revision C03

[2] Gloucestershire County Council (18 September 2020) M5 Junction 10 Improvement, Preliminary Environmental Assessment of Options Report – Non Technical Summary. GCCM5J10-ATK-EGN-ZZ-RP-LM-000001 revision C01

[3] Gloucestershire County Council (25 May 2021) M5 Junction 10 Improvement, Staged Overview of Assessment Report. GCCM5J10-ATK-GEN-XX-RP-CX-000002 revision C03

[4] 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

1.3.8. Subsequent reports will document:

- the development and testing of a with-scheme model, with the hydraulic modelling being used to advise the developing Scheme design of the preferred option;
- the Flood Risk Assessment; and
- the Environmental Impact Assessment.

Purpose of this report

1.3.9. The purposes of the Baseline modelling report are to:

- set out the current flood risk in the area surrounding the junction;
- document the development of a hydraulic model and its hydrology that will be used as the primary tool in evaluating impact to the Scheme from flood risk, and the impacts it might have on flood risk; and
- document how the hydraulic model and its hydrology has been calibrated and tested, and so generate confidence in its predictions for subsequent use in defining flood risk and impact of the design

Regulatory review

1.3.10. The Baseline model and its hydrology was initially reviewed by the Environment Agency and its external consultants in March 2021. Modifications were subsequently made to the model to address various comments and suggestions, and responses were made against each comment or query put forward. The Environment Agency reviews and our responses are contained in separate MS Excel spreadsheets from July 2021. Section 11 of this report describes a model handover for regulatory review, and references the responses made in Summer 2021 to the review.

1.3.11. The updated Baseline model will be reviewed by the Environment Agency 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 will eventually be used to prepare a Flood Risk Assessment and Environmental Statement in support of the planning process on this Scheme. Gloucestershire County Council, as Lead Local Flood Authority, will also be asked to review the work, as it includes the Ordinary Watercourse of the Leigh Brook.

1.3.12. The Environment Agency team shall note that the underlying River Chelt model originates from the Environment Agency itself and the most recent changes were approved in September 2020 by the Environment Agency for use in defining the flood zones in and around the village of Boddington, immediately west of the M5 motorway. A comparison of the modelling results from this M5J10 model and the approved Boddington model is provided in Section 8.6.

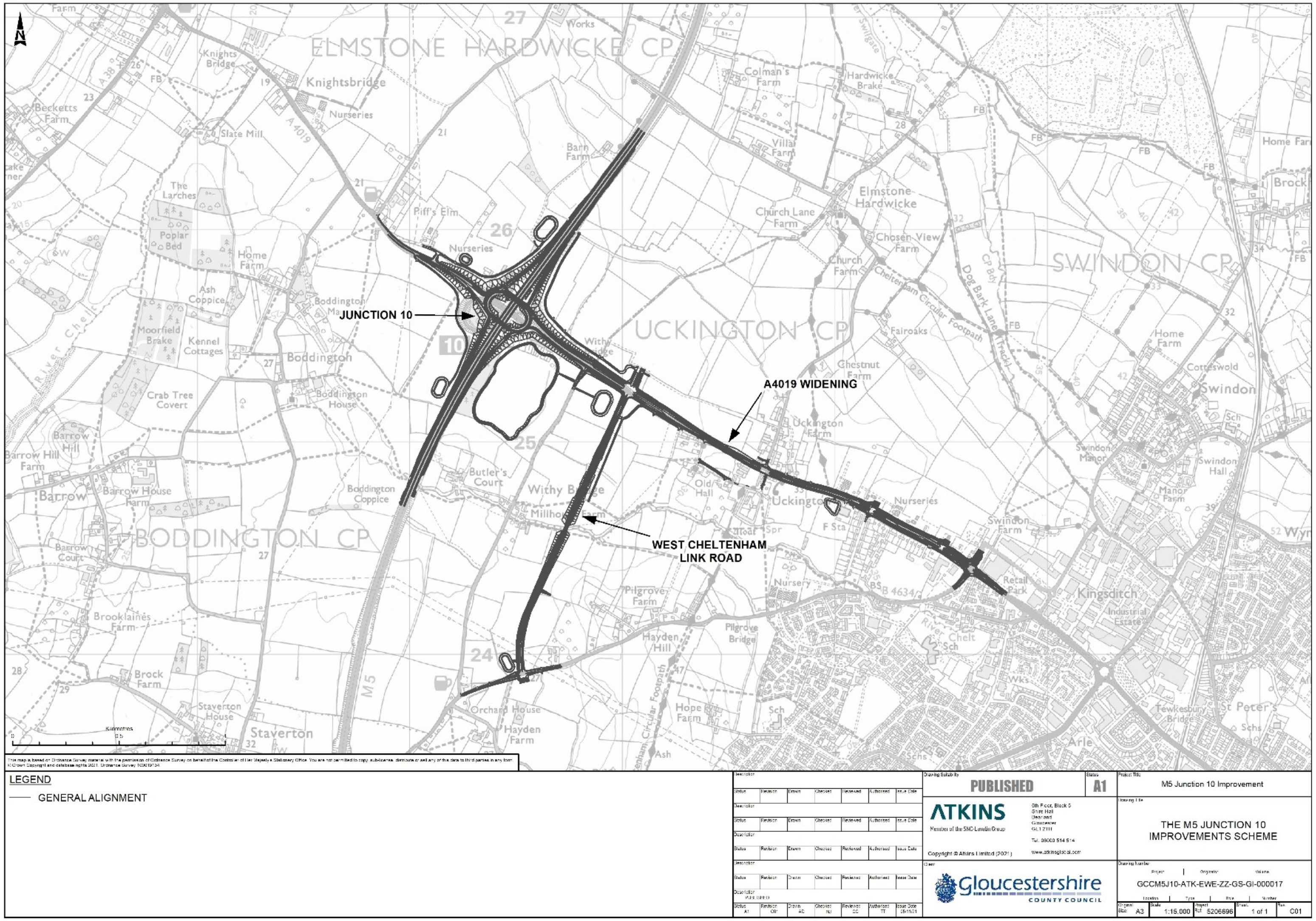
1.3.13. This report is only intended to describe the Baseline model, describing in general terms the build and performance of the model, specifically with respect to changes made from the approved Boddington model and the hydrology applied for a suite of events that advise the design, quantify impact and recommend any mitigation that might be required.

1.4. The River Chelt catchment

1.4.1. 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 5km^2. Its surface area is 0.1km^2.

1.4.2. 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.

Figure 3 – The M5 Junction 10 Improvements Scheme



1.4.3. 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.

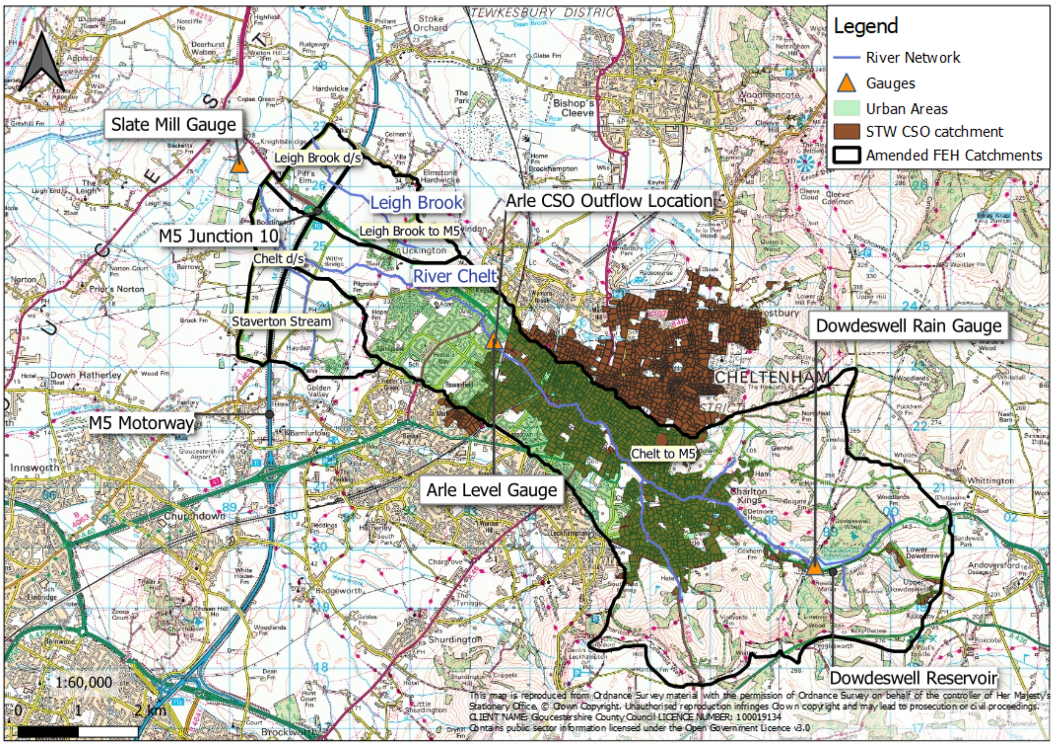
1.4.4. The catchment area of the River Chelt and its tributaries upstream of Boddington is approximately 32 km^2.

1.4.5. The Leigh Brook catchment has an area of 9.15 km^2 from its source, approximately 2 km upstream of the M5 motorway, to the confluence with the River Chelt. The watercourse 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 bedslope.

1.4.6. 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.

1.4.7. 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 4 – The Chelt catchment



2. Existing Flood Information

2.1. Existing Baseline

2.1.1. The published Environment Agency flood risk mapping provides a conflicting story in the vicinity of the M5 Junction 10.

- The Flood Map for Planning (see Figure 39) indicates a large Flood Zone 3 at the motorway, and south of the A4019 highway, with no flooding to the north. This is likely a result of the River Chelt to the south being Main River, and the Leigh Brook to the north being an Ordinary Watercourse: hence the Environment Agency is not mandated to provide flood risk mapping of the Leigh Brook.
- The Risk of flooding from Surface Water map (see Figure 40) indicates almost the opposite, with all the flooding being held against the motorway to the north of the A4019 highway, i.e. from the Leigh Brook, with far less flooding to the south associated with the River Chelt.
- The published reservoir inundation map, stemming from the Dowdeswell Reservoir, indicates significant flooding on both sides of the A4019, effectively a combination of the two other maps above, although clearly with greater flood extents and derived from a different source of flooding.

2.1.2. The Environment Agency has confirmed that its historic flood map, as used to describe Flood Zone 2, was a projection of surveyed wrack levels form the major event in July 2007. It is not known whether that was a 0.1% annual exceedance probability event (1 in 1000-year return period) or just the worst in living memory. However, anecdotal reports suggest that event was between a 0.8% annual exceedance probability event (1 in 125-year return period) and 0.25% annual exceedance probability event (1 in 400-year return period).

2.2. Existing hydraulic modelling

2.2.1. The Environment Agency previously provided the project with its three hydraulic models for the River Chelt. These comprised:

- “The Middle Chelt Hydraulic Model, August 2012” which was produced by Capita Symonds with URS as part of an Environment Agency commission under the SFRM2 framework to undertake flood risk modelling of the River Chelt.
- “The River Chelt Improvements Scheme, March 2010” hydraulic model produced by Black and Veatch.
- The “Lower Chelt” modelling study undertaken by JBA Consulting in 2011/12 extended up to the M5 motorway to support an Environment Agency biodiversity scheme directly downstream of the A38.

2.2.2. Further modelling was undertaken more recently by Edenvale Young (EVY) Associates on behalf of Robert Hitchens Ltd (RHL). This is described in the next section.

2.3. Boddington flood map challenge

2.3.1. Flood modelling was undertaken in 2018 and 2019 by Edenvale Young (EVY) Associates, on behalf of Robert Hitchens Ltd (RHL). EVY undertook hydraulic modelling and examined the flood risk local to the village of Boddington, to the west of the M5 motorway.

2.3.2. The EVY model, as was used for the Boddington flood map challenge, was supplied to the project by RHL in September 2020. That modelling is documented in the EVY Flood Map Challenge report[5].

[5] Edenvale Young (August 2019) Boddington Model Report – Flood Map Challenge. Reference EVY0630

2.3.3. The EVY modelling considered the hydrology and routing within the River Chelt, with a catchment area of approximately 39 km^2 at the model boundary, and the interaction with the Leigh Brook. The confluence of the two watercourses is close to their combined confluence with the River Severn, just north of the village of Boddington.

2.3.4. The model contained data from the existing Environment Agency models, such as dimensions of the existing culverts under the M5, critical structures along the River Chelt through Cheltenham, river channel sections and bed elevations for the River Chelt.

2.3.5. Figure 5, below, copied from EVY's model report, shows the geographical area of the catchments and the site outline for the RHL assessment.

Figure 5 – EVY River Chelt Model

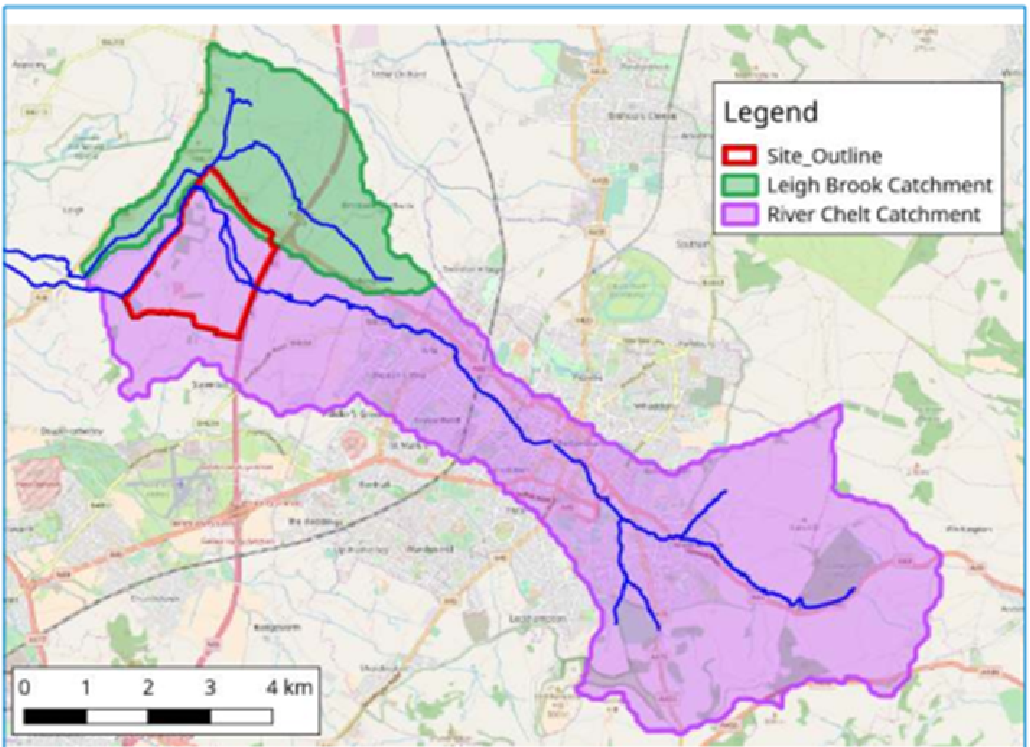


Figure 5.1: River Chelt and Leigh Brook catchments taken from confluence of the two watercourses (CEH-Web Server).

2.3.6. Due to the lack of gauged data, perched (embanked) channels, inter-catchment connectivity between the River Chelt and Leigh Brook, and floodplain attenuation at the M5 motorway, EVY concluded that the application of traditional Flood Estimation Handbook (FEH) hydrology and hydraulic modelling were not suitable for the area of interest at Boddington, and instead developed a direct rainfall (also known as rain-on-grid) model of the system. EVY describe this model in their reporting as a Distributed Hydrological Model (DHM), which should not be confused with the process of developing spatial hydrological resolution in a catchment instead of a lumped catchment approach.

2.3.7. The modelling applied standard rainfall hyetographs to a terrain model and allowed the software to evaluate the flow accumulation and routes. Runoff characteristics were included using a mix of surface roughness and soil infiltration parameters. Fundamentally these were calibrated with the July 2007 and December 2008 flood events, comparing model predicted flood extents and depths with site observation (photographic record), anecdotal evidence from witness reports, and recorded gauge records.

2.3.8. The work determined that the winter parameters applied to the December 2008 event produced a worse case flood extent. As such the winter parameters were applied to the design rainfall and used to derive Flood Zone 3 (1% annual exceedance probability event

(1 in 100-year return period)) and Flood Zone 2 (0.1% annual exceedance probability event (1 in 1,000-year return period)).

2.3.9. This model is herein described as the River Chelt model.

Boddington model

2.3.10. A truncated version of the River Chelt model was created by EVY to focus attention on the site of interest and speed up model run times with a smaller computational area. This is described as the Boddington model. Whilst this is a “more traditional model”, it uses the flow-time inputs derived from the direct rainfall River Chelt model and the same terrain grid. The approach EVY took to the modelling is summarised below:

- A model of the River Chelt catchment was developed and calibrated in ESTRY TUFLOW software. This is the “Distributed Hydrological Model” (the DHM) or the River Chelt model.
- Design storm hyetographs for the 1% annual exceedance probability event (1 in 100-year return period) and 0.1% annual exceedance probability event (1 in 1000-year return period) were applied uniformly across the catchment using a direct rainfall boundary. The hyetographs were generated in ReFH2 software using DDF2013 data. A storm duration relating to the critical storm for Boddington of 12 hours was applied (evaluated at the A38 downstream).
- As the direct rainfall (River Chelt) model does not generate baseflow, a baseflow component into the 1D river system was created using ReFH local catchment descriptors.
- Flow-time hydrographs were extracted at key locations from the River Chelt model using PO Lines in TUFLOW. These flow-time hydrographs were then used as the flow input to the 1D-2D ESTRY TUFLOW Boddington model.

2.3.11. The modelling was subsequently considered by the Environment Agency and the resulting flood map approved for use as the Environment Agency flood map, which was subsequently updated and published.

2.3.12. This truncated model is herein described as the Boddington model.

3. Model Approach and Justification

3.1.1. With the age of the Environment Agency models (~10 years old), and the omission of the Leigh Brook from them, it was considered that the exercise of updating them combining the three models and recalibrating them would be onerous and beyond the scope of the flood risk assessment and design development for the M5J10 Scheme. It was further considered that as the EVY model build was recent, had been calibrated to high order events, and approved by the Environment Agency in 2020, that it provided the best available Baseline flood model for the work.

3.1.2. The underlying approach for the M5J10 work was initially the same as that applied to Boddington and the flood map challenge: refinement of the River Chelt direct rainfall model to generate flows into a smaller, more workable, truncated model relevant to the M5 Junction 10 works as appropriate to the development site (the “M5J10” model).

3.1.3. This task was completed but lead to uncertainty on the hydrology and calibration. Consideration of the Environment Agency’s flood estimation guidelines[6] compounded those uncertainties, especially where the intelligence on the supplied River Chelt model was limited.

3.1.4. The approach was modified to a more traditional Flood Estimation Handbook (FEH) hydrology and 1D-2D modelling, which was considered appropriate for the M5J10 works, predominantly impacting the rivers and floodplains upstream (east) of the M5 motorway. A targeted hydraulic model was extracted from the wider River Chelt model, truncating the EVY model which in itself combined the original Environment Agency models. This truncated model is here described as the M5J10 model.

3.1.5. Refinement of the M5J10 model was undertaken to update the base data and improve the resolution in the area pertinent to the M5J10 project. This is described in the chapters below. The model was developed using the ESTRY TUFLOW software and is a 1D-2D dynamically linked hydrodynamic model.

3.1.6. The M5J10 model was then updated with new hydrology, being developed from the standard FEH techniques, applying flows into the model from calibrated ReFH units as flow-time inputs. No direct rainfall was applied.

3.1.7. The approach is justified by virtue of its compliance with Environment Agency guidelines and best practice. Further confidence has been obtained in the results with the different modelling approaches and revisions all generating similar flood extents. As described later in this report, the flood risk predictions for the study appear insensitive to changes in both hydraulic schematisation and hydrology with the M5 motorway acting as the significant hydraulic control within the reach.

3.2. Study area

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

- the extents of the material improvement 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 concentration/spread of the contributing watershed without affecting results.

[6] Environment Agency (06/07/2020) Flood Estimation guidelines. Reference LIT11832

3.2.2. The study area was defined as the 2D model domain, as indicated in Figure 7 overleaf. 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.

Upstream boundary

3.2.3. The upstream extent of both the 1D river channel and 2D domain for the River Chelt is set at its crossing of the B4634 Old Gloucester Road / Hayden Road.

3.2.4. A check was made on the likely influence of the Scheme with respect to the upstream boundary. Ground levels at the upstream boundary (~37 m AOD) are more than 13 m higher than beside the M5 motorway (~24 m AOD) and 12 m higher than the estimated 1% annual exceedance probability event (1 in 100-year return period) with allowance for climate change flood level (of approximately 25 m AOD). The boundary is located sufficiently far away from the Scheme for it not to have an impact on the relevant model results.

Figure 6 – Terrain section from the M5 motorway to upstream boundary

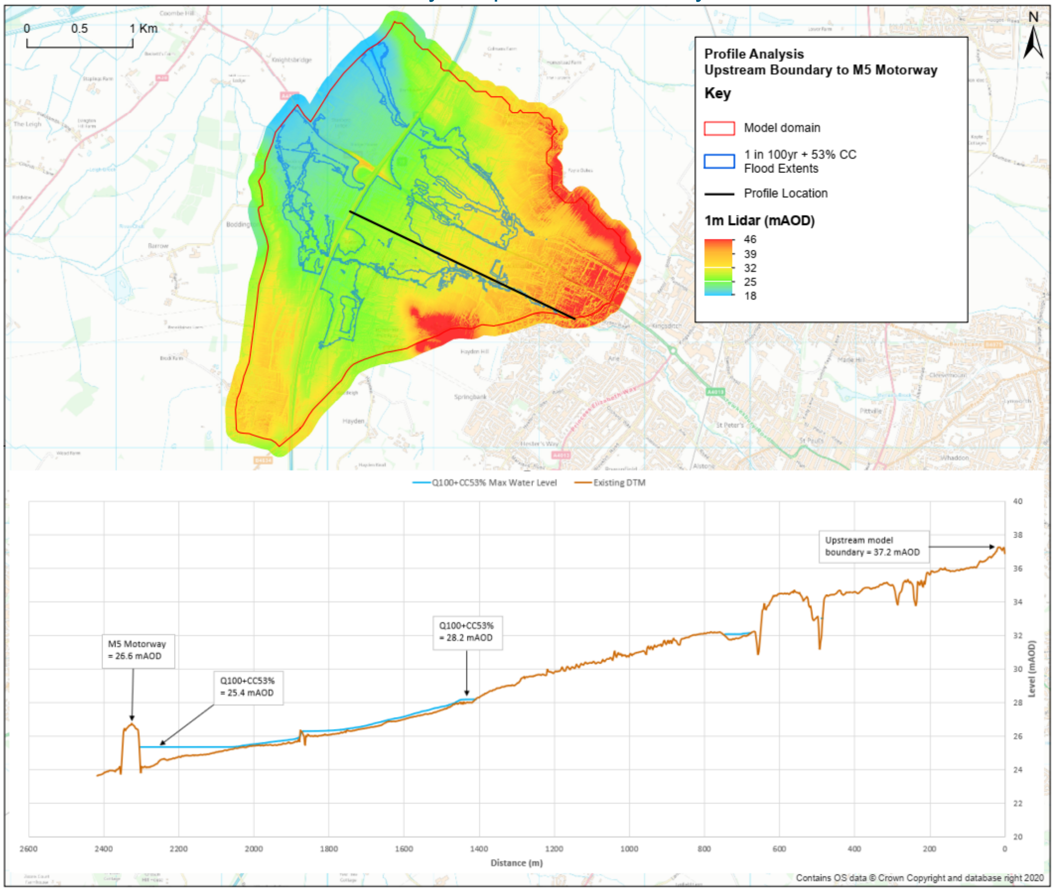
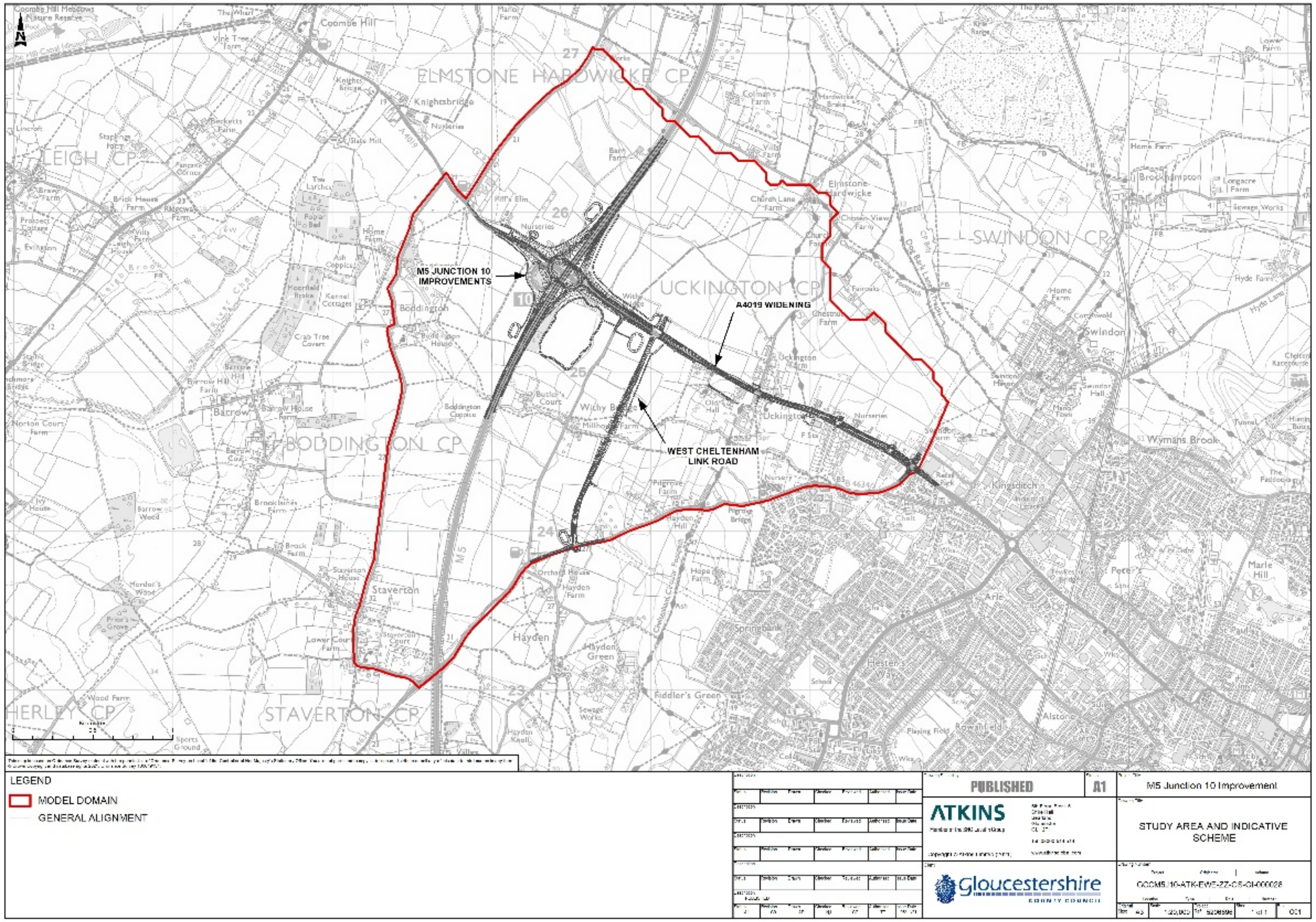


Figure 7 – Study area and indicative scheme

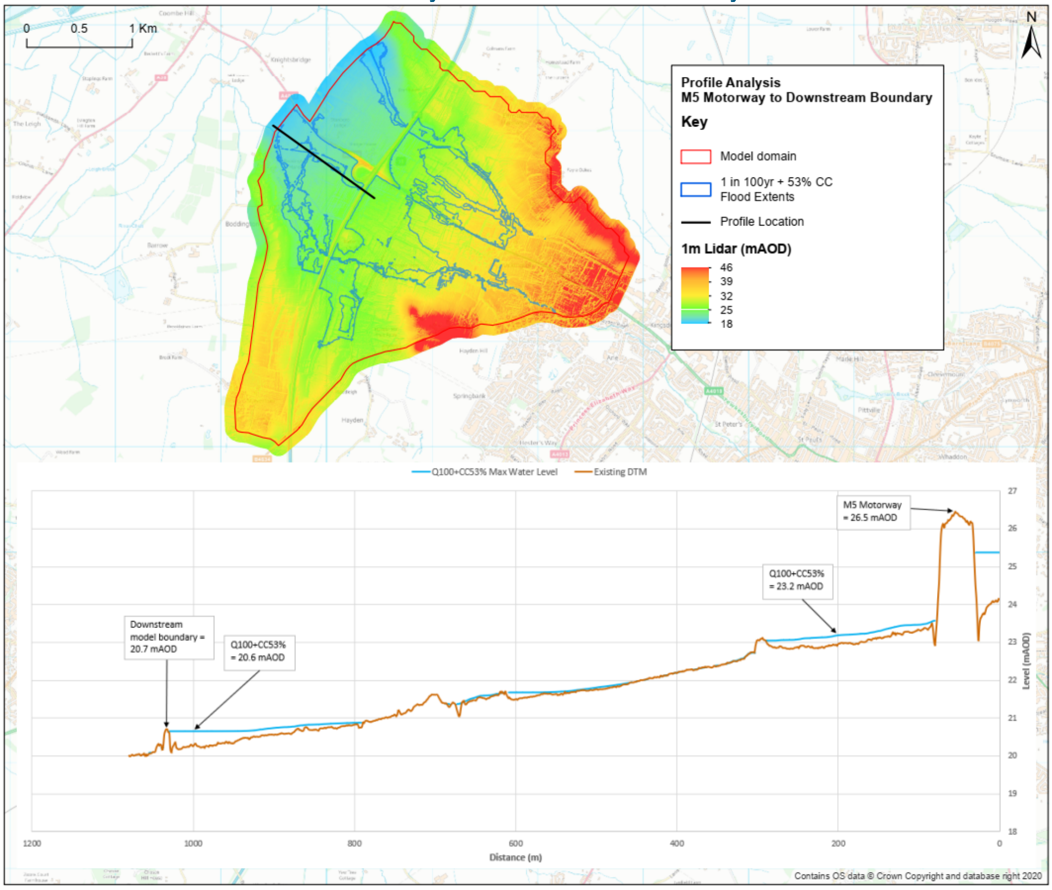


Downstream boundary

3.2.5. The location of the downstream boundary on the River Chelt is some 1.95 km west (downstream) of the M5 motorway at Church Road (Boddington) whilst the downstream boundary of the Leigh Brook is located 1.55 km downstream of the M5 motorway a the Elmstone Hardwicke road.

3.2.6. The terrain of the 2D area falls at a typical slope of 1 in 211 away from the motorway and, based on the Boddington model, has a floodplain depth of approximately 600 mm besides the local highway at the boundary. A nominal backwater distance (L = 0.7D/s) of 90 m was determined. Hence any variation in water levels at the 2D downstream boundary are unlikely to influence to model results for the Scheme. A sensitivity test on the downstream boundary is described in Section 7.3.

Figure 8 – Terrain section from the M5 motorway to downstream boundary



4. Input data

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

4.1. Hydrology

Data

4.1.1. The hydrology assessment used the following input data:

- 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 data base version 9, which includes data for water year 2019/2020 released on 24 September 2020 (current at the time of assessment)
- 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).

4.1.2. Use was made of the Slate Mill gauge (54026), on the River Chelt immediately downstream of the study area. This gauge was decommissioned in 2010 having had a record from 1969. It was a concrete trapezoidal flume that was prone to siltation. Its flows were not processed since 1984 due to a poor rating. The gauge was known to be bypassed during flood events and was more appropriate as a low flow gauge. However, the National River Flow Archive notes it being suitable for QMED estimation which is quoted as being 9.42 m^3/s. Although Slate Mill was never gauged to within 30% of QMED, the theoretical rating was expected to perform well to QMED.

4.1.3. Tests with the M5J10 hydraulic modelling show that the gauge is bypassed from approximately 19 m^3/s in the River Chelt.

4.1.4. Despite any issues with the flow rating, the gauge's measurement of stage remains valid.

4.1.5. The Cheltenham Combined Sewer Overflow (CSO) is managed by Severn Trent Water. This discharges to the River Chelt at Arle, some 1.5 km upstream of the study area. Severn Trent Water supplied flow-time discharge hydrographs for the CSO from their own hydraulic modelling. This covered a range of return periods from 20% annual exceedance probability event (1 in 5-year return period) to a 0.1% annual exceedance probability event (1 in 1,000-year return period), and included simulation results for the flood event in July 2007. The results provided by STW were for a similar storm duration (10¼hrs) to those applied in the FEH hydrology (10 ½ hours).

4.2. Hydraulic model

4.2.1. The updated flood M5J10 modelling for the Scheme was based on the approved Boddington model, which was itself developed from the available Environment Agency models.

4.2.2. The new M5J10 model uses the following input data in addition to that contained in the supplied model.

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

4.2.3. Much of the new M5J10 model remains unchanged from that applied by EVY for the Boddington work although the Leigh Brook is now explicitly modelled and new data applied throughout. The sections below draw out the key changes made in the development of a new Baseline model.

4.2.4. The M5J10 model was enhanced with new data, either obtained specifically for this project, or becoming publicly available since the Boddington work. The input data is tabulated in Table 4-1 below.

Table 4-1 – Hydraulic model input data

Data	Date	Origin	Comment
Environment Agency Middle Chelt Model (2012)	August 2012	Environment Agency (Capita Symonds/URS)	Historical model that was used to provide structure and cross sectional data
Boddington flood map model	September 2020	Robert Hitchens Ltd (Edenvale Young)	Based on Environment Agency models from 2012
LiDAR	2019	.Gov.UK Defra website[7]	Composite DTM, 1m resolution
River Chelt survey[8]	December 2017	Infomap surveys and Mapping	Cross sections and Structures
River Chelt survey[9]	November 2019	Infomap surveys and Mapping	Structures and check sections
Leigh Brook survey[9]	November 2019	Infomap surveys and Mapping	Cross sections and Structures
M5 structures	2013 to 2019	Highways England	Principal Inspection (PI) Reports and Highways England Drainage Data Management System (HEDDMS)
Aerial Survey	November 2020, with aerial survey from 2018	Atkins	M5J10 mobile scanning, infill, and aerial survey of critical areas

[7] https://environment.data.gov.uk/DefraDataDownload/?Mode=survey
[8] Infomap Surveys and Mapping (Dec 2017) Channel surveys Boddington, Cheltenham
[9] Infomap Surveys and Mapping (Nov 2019) Channel surveys M5J10 Cheltenham

5. Hydrological method and implementation

This section describes the methods used in the hydrological assessment, focusing on the key aspects of the approach and any non-standard aspects of calculations (rather than a detailed description of every stage of the process or a repeat of procedures that are well documented).

5.1. Hydrological assessment

5.1.1. The hydrological assessment comprised of FEH assessments (Statistical and ReFH2) for five sub catchments, as well as an additional inflow for the Cheltenham CSO.

Flood Estimation Handbook

5.1.2. The Flood Estimation Handbook methods were applied to the study in accordance with 2020 Environment Agency FEH guidelines[10].

5.1.3. A full FEH calculation record is included in Appendix B of this report. Hence this section only summarises the key facts and results of the work, and any non-standard aspects of hydrology.

Catchments

5.1.4. An assessment of the River Chelt and Leigh Brook catchments to the downstream boundary of the study area at Boddington was required for the M5J10 model. Five sub catchments were acquired from the FEH web service and assessed for use in this study.

- River Chelt catchment to the M5 motorway;
- Staverton Stream;
- Leigh Brook catchment to the M5 motorway;
- River Chelt catchment downstream of the M5 motorway; and
- Leigh Brook catchment downstream of the M5 motorway.

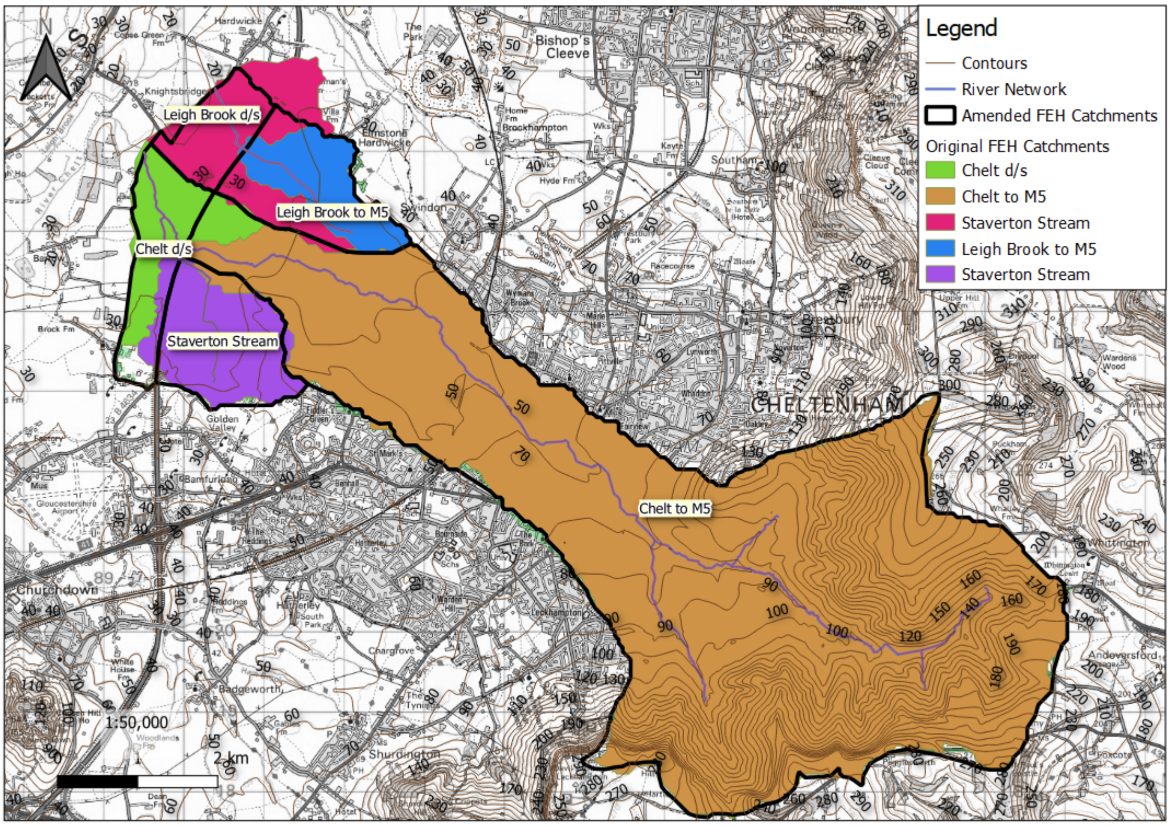
5.1.5. The catchments are shown in Figure 9 overleaf.

5.1.6. The boundaries of the catchments were downloaded from the FEH web service and amended based on 1 metre contours generated from the Environment Agency's 1 m composite LiDAR dataset (2019) and the OS Detailed River Network (DRN). Urbanisation was calculated using the latest OS mapping. The urban coverage of the catchment was increased by 3% from the FEH web catchments.

5.1.7. The catchment descriptors were updated based on the catchment boundary changes. The River Chelt and Leigh Brook catchments downstream of the M5 motorway were defined by removing the upstream catchment areas from the full FEH web catchments to generate the intervening catchments. For these two intervening catchments, the key catchment descriptors were area weighted such that the upstream catchment characteristics were not accounted for twice. For example, the influence of the Dowdeswell reservoir on the River Chelt (FARL) was removed from its catchment downstream of the M5 motorway.

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

Figure 9 – Flow estimation catchments.



5.1.8. The Dowdeswell reservoir is located in the upper Chelt catchment. The reservoir has a surface area of approximately 0.1 km^2 and drains a sub catchment area of 5 km^2. Its influence has been included in the hydrological assessment through the FARL catchment descriptor. FARL was manually calculated for the River Chelt catchment using the formula given in the FEH Volume 5, Chapter 4. The manually calculated value corroborated with the value given (to 2 decimal places) in the FEH catchment descriptors (FARL = 0.97). The reservoir drains a relatively small catchment of the River Chelt, compared to that draining to the M5 motorway. Its impact is minimal.

Cheltenham combined sewer overflow

5.1.9. The Cheltenham combined sewer overflow (CSO) managed by Severn Trent Water is known to have an effect on flows within the River Chelt catchment. Catchment boundaries and outputs of a CSO hydraulic model were provided by Severn Trent Water (June 2020). The CSO has a catchment area of 11.5 km^2 and discharges into the River Chelt at Arle. Severn Trent Water advised that 40% (4.6 km^2) of the CSO catchment falls outside of the watershed of the River Chelt catchment.

5.1.10. To account for the additional catchment area provided by the CSO, the flows of the CSO output at Arle were scaled by a factor of 0.4 (4.6 km^2 extra catchment as a proportion of a total catchment of 11.5 km^2). Scaling the CSO inputs by 0.4 ensures that only water from outside the Chelt watershed is being added to the model. This was to ensure that there was no double counting of inflows to the model. The CSO inflow was applied as a point inflow to the M5J10 model at the upstream boundary at the B4634 Old Gloucester Road. This boundary is some 1.5 km downstream of the actual CSO inflow. Hence the M5J10 model does not account for any attenuation of this CSO discharge in the reach between Arle and the B4634 Old Gloucester Road. The M5J10 model is thus precautionary in this aspect.

5.1.11. The FEH catchment has been retained for areas where the CSO catchment overlies the River Chelt catchment, as it was assumed that the drains and gullies associated with the

CSO would be over capacity during higher return period events and hence overland flows would continue as per the FEH determination.

5.1.12. An alternative approach would have been to exclude the full catchment area contributing to the CSO from the FEH calculations, and apply the total CSO discharge hydrograph supplied by Severn Trent Water. This approach was not applied given the above assumptions on sewer capacity during large order events.

5.1.13. The peak CSO inflows are from Severn Trent Water summarised in Table 5-1 below, being applied from the 10¼-hour storm duration series.

Table 5-1 – Peak CSO flows

Location	CSO flow m^3/s						
	2yr	5yr	10yr	25yr	50yr	100yr	1000yr
Total CSO discharge	-	5.3	6.0	7.5	8.5	9.8	13.6
CSO applied to model	No data	2.1	2.4	3.0	3.4	3.9	5.4

Statistical assessment

5.1.14. The statistical method was used to estimate peak flows for the FEH sub catchments. Two different pooling groups were generated for this study, reflecting the contrast between the River Chelt to M5 catchment (a large, urbanised catchment), and the catchments for the Leigh Brook, Staverton Stream and River Chelt west of the M5 motorway, which are smaller and predominantly rural. A suitable QMED donor was found for the River Chelt to the M5 motorway catchment. However, the rural catchments were too small in area to satisfy the suitable donor equation in the Environment Agency guidelines. Therefore, QMED was calculated from the descriptor equation only. A summary of the statistical method and the derivation of the pooling groups can be found in Appendix B.

5.1.15. A summary of the flow estimates at each location from the Statistical method is given below.

Table 5-2 – Flow estimates using the FEH statistical method

Location	Flow from statistical assessment (m^3/s)	
	2yr	100yr
River Chelt at M5	7.5	20.4
River Chelt downstream of M5	0.6	1.7
Leigh Brook at M5	0.6	1.8
Leigh Brook downstream of M5	0.4	1.0
Staverton stream	0.8	2.4

Revitalised flood hydrograph

5.1.16. The ReFH2 method was also applied in the ReFH2.3 software[11] to generate hydrograph shapes and peak flow estimates for all sub catchments.

5.1.17. Winter storms were applied based on the seasonality criteria from the ReFH2 guidance. The River Chelt catchment has an urban extent (URBEXT$_{2000}$) of 0.24 and baseflow index (BFIHOST19) of 0.459, and so satisfies the winter criteria. A summer storm was tested and generated a lower peak flow estimate.

5.1.18. The storm duration was tested in ReFH2.3 software to determine the worst case storm for flood risk at the M5 motorway. The critical storm for the River Chelt was determined to be 10.5 hours and applied to all sub catchments in the design events, including the Leigh Brook. The Leigh Brook has a smaller critical storm duration of 6.5 hours: during this shorter duration event the River Chelt does not contribute such high flows compared to

[11] Wallingford Hydrosolutions (December 2020) ReFH2 version V3.0.7270.30847

its own critical 10.5 hour event. As demonstrated by the various flood estimates, The River Chelt is the dominant catchment, contributing significantly more flow.

Table 5-3 – Flow estimates using the ReFH2 method

Location	Flow from ReFH2 assessment (m^3/s)	
	2yr	100yr
River Chelt at M5	8.9	24.5
River Chelt downstream M5	0.8	2.2
Leigh Brook at M5	0.9	2.5
Leigh Brook downstream M5	0.9	1.3
Staverton stream	1.5	4.1

5.2. Calibration of hydrology

5.2.1. It was intended to calibrate the hydrology independently of the hydraulic model. However, the presence of the M5 motorway as a raised feature across the floodplain with a series of fixed culverts controlling flows, and floodplain flow bypassing the only local river gauge, meant that this was not possible.

5.2.2. The hydraulic modelling demonstrates that the M5 motorway has a large influence on flows moving downstream and hence calibration at Slate Mill could not be undertaken in isolation.

5.2.3. The model calibration is described in Section 7. It describes how the observed July 2007 rainfall was applied in the ReFH2.3 software to produce inflows for the event. Those flows were then passed through the hydraulic model. A comparison of stage and flows at Slate Mill were then made, as well as with the Environment Agency wrack marks. This demonstrated that the ReFH hydrology was capable of estimating the appropriate flows for the event.

5.3. Final choice of method and flows

5.3.1. The ReFH2 method was used to provide the design events. The results of the ReFH2 assessment, shown in Table 5-3, demonstrated that the ReFH2 method provides higher, more precautionary flows for this study in comparison to the statistical method (Table 5-2). Moreover, the calibration of known events using the observed rainfall component of ReFH2 demonstrated that the default parameters suitably estimated appropriate flows for the given events in the catchment. Inflows for the 0.1% annual exceedance probability event (1 in 1,000-year return period) have been calculated using the ratio method, as per the Environment Agency guidelines[10].

5.3.2. In addition to the FEH assessment for the sub catchments, an inflow was applied to the model for the CSO that discharges at Arle. The CSO inflows for the design events, provided by STW, were scaled by 40% in order to account for the additional area drained by the CSO compared to the topographic catchment of the River Chelt. This was to ensure that there was no double counting of inflows to the model.

5.3.3. The final flow estimates for all design events are provided below.

Table 5-4 – Final 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

5.4. Climate change allowances

Environment Agency guidance

5.4.1. The Environment Agency climate change allowance (July 2021)[12] were applied to the Baseline model. As a river catchment, the allowances from Table 1 of the guidance were used.

5.4.2. The guidance describes climate change allowances as predictions of anticipated change for: peak river flow; peak rainfall intensity; sea level rise; offshore wind speed and extreme wave height. They are based on UK climate change projections. The guidance uses three basic measures to determine the climate change allowance to be applied to a given scheme:

- vulnerability classification;
- time horizon (development lifetime); and
- location.

Vulnerability

5.4.3. The proposed M5J10 improvements will be part of the transport infrastructure that are described as a key transport link with junctions to the existing road network. It is also designated as a Nationally Significant Infrastructure Project (NSIP). Furthermore, the Scheme was designated as a critical development to improve transport infrastructure at both a regional (Gloucestershire County Council) and national (Highways England) level.

5.4.4. It has here been assumed that under the NPPF guidance the development can be classified as Essential Infrastructure.

5.4.5. The same classification was applied to the link road and dualling of the A4019, these considered to be mass access and egress routes. However, it may be that these parts of the Scheme attract a lower vulnerability classification.

Time horizon

5.4.6. It would be usual to consider a 100-year life for the development, over which to apply climate change. For the proposed M5 Junction 10 project, with link road and dualling scheme, the new roads will serve a wider development of residential and commercial infrastructure. This further supports the application of a 100 year lifetime.

5.4.7. The assessment period thus extends to the year 2122. Whilst beyond the furthest epoch (2070 to 2115) the guidance directs use of this time horizon without any extrapolation.

Location

5.4.8. In addition to vulnerability and time horizon, the climate change allowances for river flow vary by location. The published peak river flow allowances also show the anticipated changes to peak flow that vary specifically by River Basin District and Management Catchment.

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

5.4.9. The proposed M5J10 Scheme lies in the Severn river basin district (RBD) and therein the Severn Vale management catchment.

Resulting climate change allowance

5.4.10. With a flood risk vulnerability classification of 'Essential Infrastructure' it is required by the Environment Agency guidance to use the Higher Central allowance for climate change.

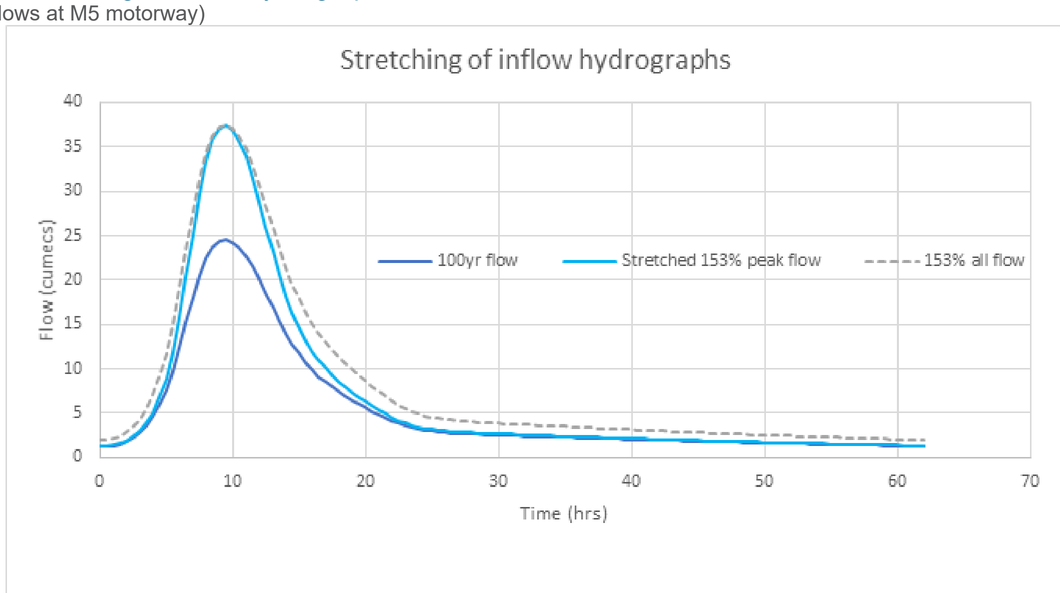
5.4.11. The Environment Agency updated its climate change guidance in July 2021, in line with the UKCP18 data. This has given rise to a downgrade of the climate risk profile and a change in the resulting peak river flow allowances: the guidance recommends using a Higher Central climate change allowance (+53% increase in flow). The flood modelling has been updated to include the application of this July 2021 climate change allowance.

5.4.12. In accordance with the guidance, **an uplift of 53% on peak flow was thus applied to account for the potential effects of climate change over the scheme life** (the next 100 years). This uplift was applied in the model testing to the 1% annual exceedance probability event (1 in 100-year return period) hydrographs.

5.4.13. The Environment Agency guidance is not specific how an increase in peak flow should be applied in hydraulic modelling, and whilst the common approach is to apply the scaling to all ordinates of the hydrograph, this approach is not in line with the intent of guidance, which concerns the peak flow. Scaling the full hydrograph also increases the volume of flow by 53% and not just the peak flow, and furthermore raises the baseflow at the start and end of the hydrograph being applied to the model.

5.4.14. A pragmatic approach was applied to stretch the inflow hydrograph such that the peak flow was uplifted by the full amount whilst the shoulders were scaled proportionately, with no uplift applied at the start and end of the time series. This avoids over-estimation of flood volumes and thence the Scheme requiring more land for mitigation that it might require. For the River Chelt at the M5 motorway, this increases the peak flow for the 1% annual exceedance probability event (1 in 100-year return period) from 24.5 m^3/s to 37.5 m^3/s (+53%). The corresponding increase in the hydrograph volume is 20%. Figure 10 presents the resulting hydrograph.

Figure 10 – Stretching of inflow hydrographs
(River Chelt flows at M5 motorway)



Compensatory floodplain

5.4.15. In July 2021, the Environment Agency advice was updated to include new climate change requirements for the sizing of compensatory floodplain. The guidance requires use of the Higher Central allowance (+53% on peak flow) to calculate floodplain storage compensation when the affected area:

- is particularly sensitive to small changes in volume, which could cause significant increases in flood depth or hazard; or
- contains essential infrastructure or vulnerable uses, such as primary schools, caravans, bungalows, or basement dwellings.

5.4.16. The guidance requires use of the Central Allowance for floodplain storage compensation where it can demonstrate that the affected area contains only low vulnerability uses.

5.4.17. Whilst there are no vulnerable receptors that might be impacted by the M5J10 Scheme, consideration of the likely future land uses has been made. The strategic growth being promoted in this area may well see development of this land with commercial or residential property in the future. As such, the Higher Central allowance (+53% on peak flow) for determining compensatory floodplain requirements will be used.

Upper End Scenario (Credible Maximum)

5.4.18. NSIPs are major infrastructure projects such as new harbours, roads, power stations and power lines. NSIPs need to assess the flood risk from a credible maximum climate change scenario, which is described in the National Networks Policy (see below).

5.4.19. In other cases, such as new settlements or significant urban extensions, the flood risk from a high impact climate change scenario needs to be assessed. In these circumstances the Upper End climate change allowances should be used. These are treated as a 'sensitivity test' to assess how sensitive the proposal is to changes in the climate for different future scenarios. This will ensure that the development can be adapted to large-scale climate change over its lifetime.

5.4.20. The Environment Agency advice for the Upper End scenario at this location is a +94% increase in peak flows.

National Policy Statement for National Networks

5.4.21. The December 2014 National Policy Statement for National Networks[13] 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.

5.4.22. Paragraph 4.41 of the NPS says that, "Where transport infrastructure has safety-critical elements and the design life of the asset is 60 years or greater, the applicant should apply the UK Climate Projections 2009 (UKCP09) high emissions scenario (high impact, low likelihood) against the 2080 projections at the 50% probability level." This reflects the Environment Agency's Central allowance (50th percentile) and hence a +37% increase in peak flow.

- Central allowance is based on the 50th percentile;
- Higher Central allowance is based on the 70th percentile; and
- Upper End allowance is based on the 90th percentile.

5.4.23. This conflicts with the Environment Agency guidance which directs a 70th percentile probability level and thus the Higher Central allowance as a +53% uplift in peak flow.

5.4.24. However, this NPS is out of date (e.g. relying on UKCP09). Instead, the modelling undertaken for the Baseline has applied the **+53% increase in peak flow for 100-years in the future**, in accordance with the Environment Agency guidance. This is a more precautionary approach than the National Policy Statement for National Networks.

5.4.25. The National Policy Statement for National Networks 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,

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

the policy requires demonstration that there are no critical features in 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 projections. Any potential critical features should be assessed taking account of the latest credible scientific evidence (e.g. by referring to additional maximum credible 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 credible maximum (Upper End) climate change allowance.

Design Manual for Roads and Bridges

5.4.26. It should be noted that the Scheme, as a component of the Highway England road network, is being designed to the Design Manual for Roads and Bridges (DMRB) standard.

5.4.27. CD356 on the Design of Highway Structures for Hydraulic Action[14] contains requirements for design of structures over rivers, estuaries, and floodplains. This guidance note (Clause 3.5) states that structures crossing watercourses shall be designed for the 0.5% annual exceedance probability event (1 in 200-year return period). A check on the hydraulics shall be made for the greater of the 0.1% annual exceedance probability event (1 in 1,000-year return period) or the 0.5% annual exceedance probability event (1 in 200-year return period) including climate change.

5.4.28. Clause 4.2 refers to climate changes and requires the 90th percentile estimate to be applied. This relates back to the former UKCP09 projections. Thus, DMRB CD356 promotes use of the UKCP09 Upper End climate change projection for new crossings over rivers. In the Severn RBD, this meant a +70% increase in peak flows for the years 2070 to 2115, and would now be +94%. However, CD356 has not been updated in line with UKCP18.

Tewkesbury Borough Supplementary Planning Document

5.4.29. The Flood and Water Management Supplementary Planning Document (SPD) (Tewkesbury Borough Council, 2018) details guidance on the approach that should be taken to manage flood risk and the water environment as part of new development proposals. It refers to the Environment Agency guidance on the .Gov website.

5.4.30. The document requires an assessment of the 1% annual exceedance probability event (1 in 100-year return period), with 53% allowance added to 'peak river flows' to account for climate change. The approach applied in the modelling conforms with this SPD.

Gloucestershire standing advice

5.4.31. The Standing Advice and Development Guidance by Gloucestershire County Council Lead Local Flood Authority[15] advises that, "*the National Planning Policy Framework (NPPF) and accompanying Technical Guidance (TG) provides guidance on the consideration of flood risk. It includes information on climate change (Section 10 of NPPF and para. 11 of TG*)." Note that the references here are out of date and do not reflect the right paragraphs in the current published material.

Climate change allowances applied to M5 J10

5.4.32. In summary, the modelling undertaken for this Baseline has applied the +53% increase in peak flow for 100-years in the future, in accordance with the Environment Agency guidance.

> A 53% increase in peak river flow was applied to account for future climate change

[14] Highways England et al (March 2020 Revision 1) Design of Highway Structures for Hydraulic Action , CG356 formerly BA 59/99

[15] Gloucestershire County Council Lead Local Flood Authority (2017) Standing Advice and Development Guidance, available online at https://www.gloucestershire.gov.uk/media/16743/standing-advice-march-2015.pdf

5.4.33. A sensitivity test has been undertaken using the credible maximum (Upper End allowance) of 94% and is described in Section 7.3

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

Table 5-5 – Design flows with climate change allowance

Location	Flow m^3/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

6. Hydraulic method and implementation

This section describes the methods used in the 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).

6.1. Hydraulic model build

6.1.1. The M5J10 model is a 1D-2D linked model truncated from the 2020 River Chelt model. It includes 1D models of the River Chelt and Leigh Brook, based on topographic survey (see Table 4-1).

Channels

6.1.2. 1D cross sections are represented in ESTRY. The 2D gulley lines applied in the EVY model from Old Gloucester Road (B4634) to Uckington (around 700 m downstream) to represent the River Chelt were replaced with cross sections taken from the Environment Agency Middle Chelt model (2012).

6.1.3. The 1D representation of the Leigh Brook (ESTRY) was extended using surveyed sections collected in November 2019.

6.1.4. The River Chelt has a slowly meandering channel which is typically around 8m wide, it has steep banks and is generally around 2m deep. The Leigh Brook has a straighter channel which is typically around 3m wide, it has shallower banks and is generally around 1m deep. Both watercourses have fairly flat bottoms.

6.1.5. A z-line was included in the model geometry to define the perched nature of the River Chelt through the study area. No such feature was deemed necessary on the Leigh Brook inside the study area, due to the topographic survey confirming that the watercourse is not particularly perched through the extent of the modelled domain.

6.1.6. Z-lines were included in the 2D model geometry to represent the following additional watercourses:

- the Staverton stream; beginning at the mapped upstream point of the tributary, east of the M5, and finishing at the confluence of the Staverton stream and River Chelt
- the River Chelt mill stream/leat at Millhouse Farm, which re-joins the River Chelt just downstream of Withybridge Lane.

Channel roughness

6.1.7. 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.

6.1.8. The channel roughness applied in the Boddington model was reviewed, being represented by a Manning’s roughness coefficient of between 0.035 and 0.048 for the River Chelt. These were considered representative, although low, for the River Chelt, which appears as a relatively uniform and clean channel at the time of the autumn photographs (Figure 11 below).

6.1.9. With the hydrology dictating a winter storm as being the critical event, a precautionary approach was taken by applying a Spring/Autumn roughness for the River Chelt. A value of 0.048 was applied to the full length of the River Chelt. The Leigh Brook is a much smaller, capricious channel being heavily vegetated with dense bramble along most of its length (Figure 12).

6.1.10. The channel roughness applied to the Leigh Brook in the Boddington model was reviewed, being represented by a Manning's roughness coefficient of between 0.035 and 0.040: these were considered too low. A Manning's roughness value of 0.060 was instead applied for the full length of the Leigh Brook. This is an above-normal (below maximum) value for an unmaintained channel, with uncut weeds and brush, being somewhat clean on the bottom.

Figure 11 – Photographs of the River Chelt channel
Source – Infomap surveys and Mapping, Autumn 2019

River Chelt CS 1-45US

River Chelt CS 1-52US

River Chelt CS 1-55US

River Chelt CS 1-56ds

River Chelt at Withybridge Lane

River Chelt at Old Gloucester Road

No images take

See B4634 - Google Maps

Figure 12 – Photographs of the Leigh Brook channel
Source – Infomap surveys and Mapping, November 2019

Leigh Brook CS2-57uus

Leigh Brook CS2-65dds

Leigh Brook CS2-72dds

Leigh Brook CS2-79d

6.1.11. The Staverton channel was similarly overgrown and small with woody debris and thick undergrowth influencing flow. This channel was not included in the M5J10 model as a 1D channel, and instead modelled as part of the 2D domain. A Manning's roughness value of 0.040 was applied to the water elements of the terrain. This is an average value for an unmaintained channel, with uncut weeds and brush, being somewhat clean on the bottom.

Figure 13 – Photographs of the watercourse channels
Source – Infomap surveys and Mapping, November 2019

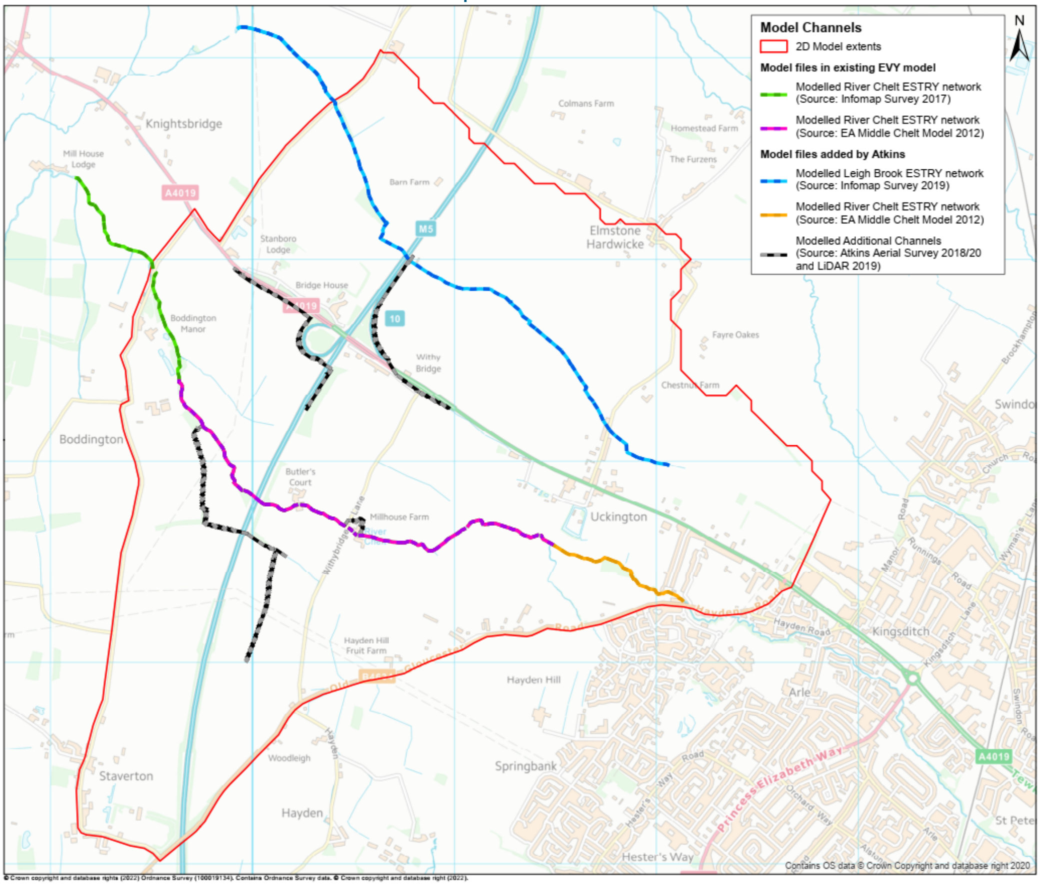
Staverton stream CS19-04u

Staverton stream CS19-03

6.1.12. Calibration of the model requires application of event specific conditions, including channel roughness. This is described in Section 7 on model proving. It is not known whether the channel was cleaned after the major flooding incident in July 2007 but higher summer roughness values are entirely possible. The model sensitivity to channel roughness has been tested on the basis of likely seasonal variations. This is also described in Section 7.

6.1.13. A schematic of the watercourse channels included in the M5J10 model is shown in Figure 14.

Figure 14 – Schematic of model channels and components



Floodplain representation

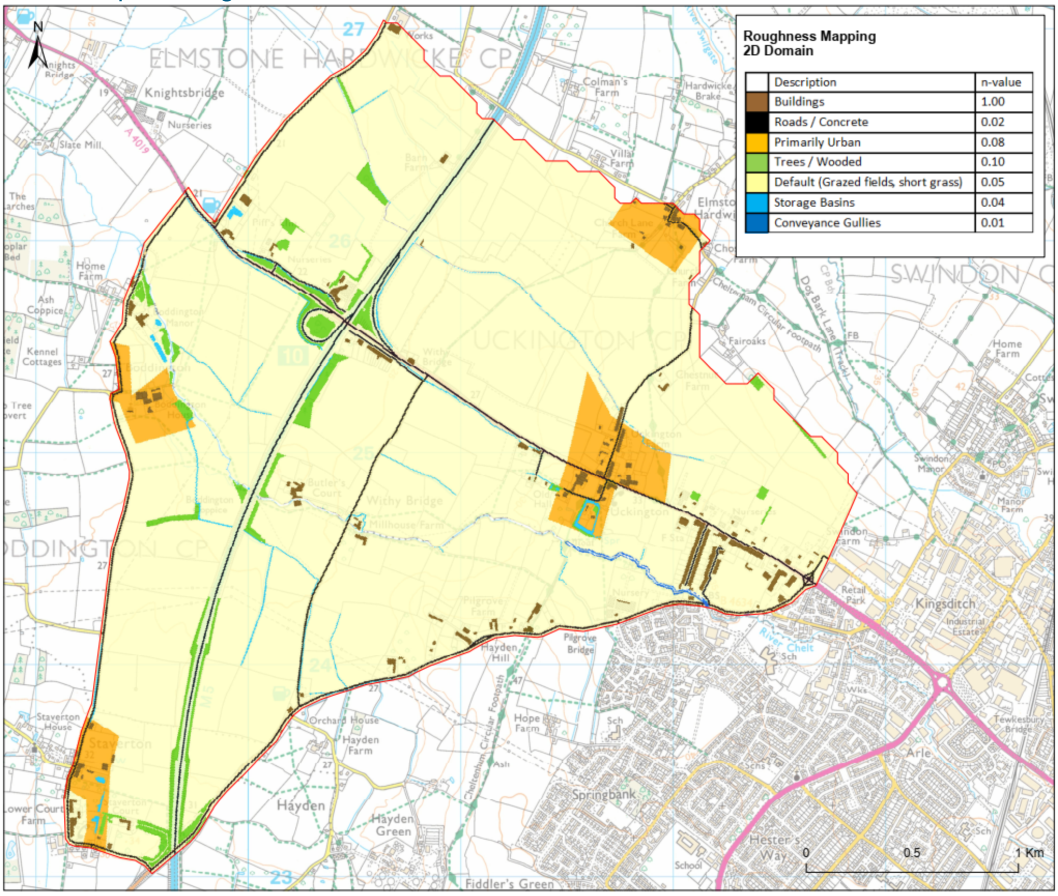
6.1.14. The floodplain was applied as a 2D domain within TUFLOW. The underlying ground model was replaced with the current 2019 1m LiDAR Composite DTM. This was obtained from the open source .Gov website. A LiDAR resolution of 1m was used, replacing the older 2m resolution LiDAR used in some areas of the Boddington model.

6.1.15. The DTM was enhanced with aerial survey of critical areas near M5J10.

6.1.16. A TUFLOW grid size of 4 m was adopted consistent with that used in the Boddington model. The grid was aligned along the main direction of flow through the M5J10 study site. This is in line with typical modelling guidance.

6.1.17. Hydraulic roughness was applied to the floodplain area using Manning's roughness coefficients. Those applied to the Boddington model were reviewed and deemed to be acceptable and has been adopted in the updated models. The values range from 0.010 for conveyance gullies, to 0.080 for urban areas. Buildings in the 2D domain have been identified using MasterMap land classes and assigned a roughness of 1.000. The roughness values applied are shown on Figure 15 below.

Figure 15 – Floodplain roughness



Key structures

6.1.18. All structures in Boddington model were cross checked against survey obtained for the M5J10 project in November 2019 and the Highways England Principal Inspection Reports (dates ranging from 2013 to 2019).

6.1.19. The Boddington model was based on the Environment Agency models from 2012 with unknown survey origins. Where differences were found the 2019 survey was applied. Several changes were made to the modelled Baseline structures. These are tabulated below.

Table 6-1 – Changes made to structures in the River Chelt model

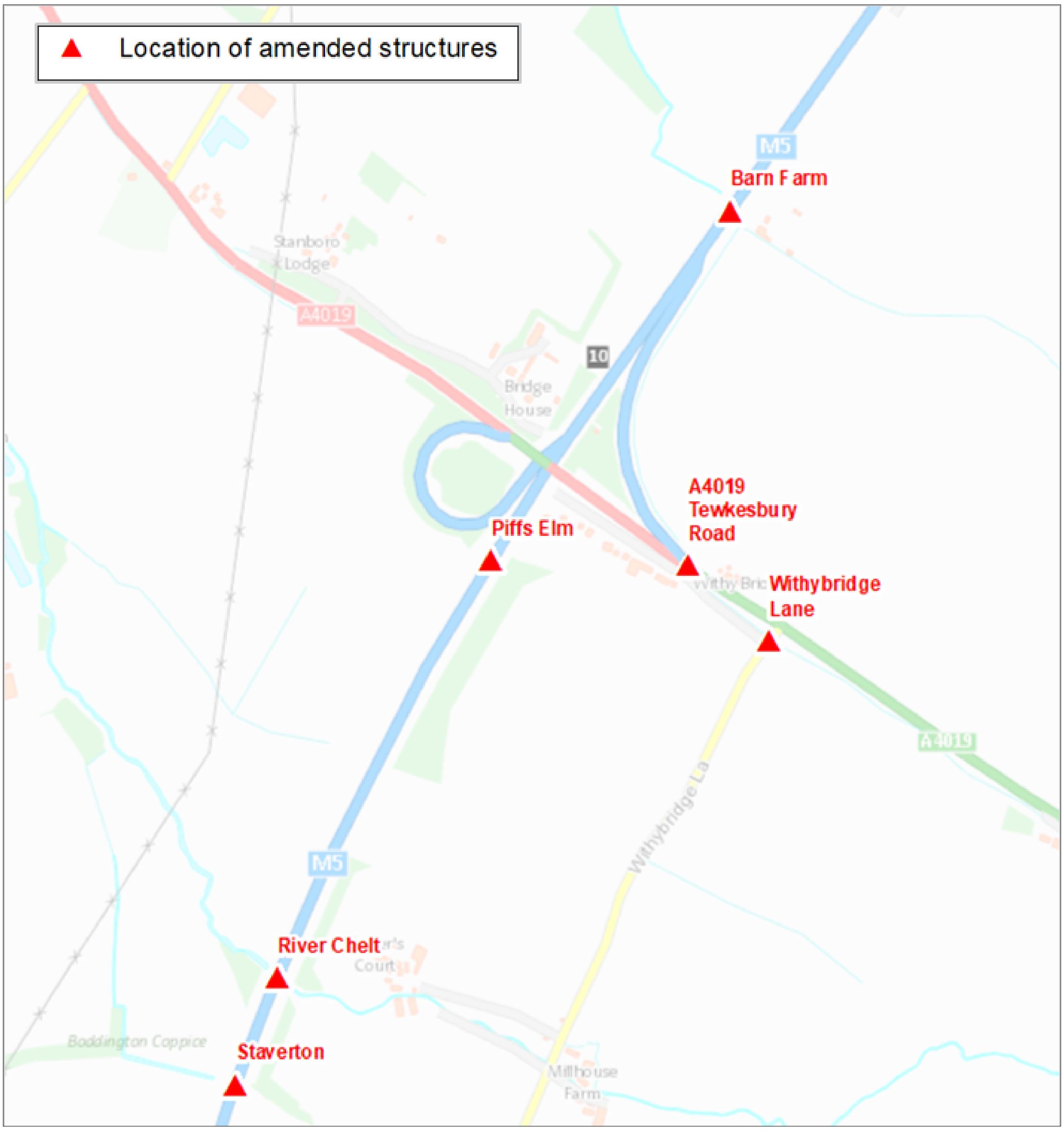
Structure	Description	Attribute(s) changed	Boddington / EA model	Amended model	Source of changes
Staverton Network ID's M5South_1 (left) and M5South_2 (right)	2x1000mm concrete pipes under M5	Upstream invert level (m AOD)	23.11 (for both)	Left - 22.65, Right - 22.69	Survey by InfoMap 2019
		Downstream invert level (m AOD)	23.02 (for both)	Left - 22.57, Right - 22.55	Highways England PI Report 2016
		Length (m)	60	50	
		Diameter (m)	1.2	1.0	

Structure	Description	Attribute(s) changed	Boddington / EA model	Amended model	Source of changes
River Chelt Network ID M5 Culvert	River Chelt concrete culvert under M5	Upstream invert level (m AOD)	21.93	22.24	Survey by InfoMap 2019 Highways England PI Report 2019
		Downstream invert level (m AOD)	22.16	22.17	
		Culvert type	Rectangular culvert	Irregular culvert	
		Width (m) Height (m)	6.27 3.68	Defined by Height-width csv but based around a 6.08 wide (3.48 high)	
Piffs Elm Network ID JUNC10	1200mm corrugated metal pipe under M5	Upstream invert level (m AOD)	23.8083	22.37	Survey by InfoMap 2019 No Highways England PI Report 2016 given site hazards.
		Downstream invert level (m AOD)	22.9979	22.03	
		Length (m)	50	47	
Barn Farm Network ID's LB_CH18a (left) and LB_CH18b (right)	Leigh Brook 2x 1250mm concrete pipes under M5	Upstream invert level (m AOD)	22.2 (for both)	Left - 21.64, Right - 21.62	Survey by InfoMap 2019 Highways England PI Report 2016
		Downstream invert level (m AOD)	22.1727 (for both)	Left - 21.27, Right - 21.29	
		Length	60	53.7	
		Diameter (m)	1.2	1.25	Survey by Atkins 2020
Withybridge Lane Network ID's Wbridge_1 (left) and Wbridge_2 (right)	2x 800mm concrete pipes	Upstream invert level (m AOD)	25.3795	Left - 24.49, Right - 24.48	Survey by InfoMap 2019
		Downstream invert level (m AOD)	24.426	Left - 24.37, Right - 24.29	
		Length (m)	13	10	
		Diameter (m)	0.6	0.8	
		No. of structures	1	2	
A4019 Tewkesbury Road Network ID's TEWK (twin pipes) and TEWK_2 (inverted triangle chamber)	Inverted triangle chamber leading to twin 750dia pipes	Upstream invert level (m AOD)	23.568 (for both twin pipes)	23.61 (twin pipes and chamber)	Survey by InfoMap 2019. DrainJet 2020-21.
		Downstream invert level (m AOD)	23.049 (for both twin pipes)	23.049 (twin pipes) 23.61 (chamber)	
		Culvert type	Circular culverts	Irregular culvert leading	

Structure	Description	Attribute(s) changed	Boddington / EA model	Amended model	Source of changes
				to 2 circular culverts	
		Diameter (m) / Size	0.6	0.75 (twin pipes) Irregular culvert opening defined by height-width csv. 0.7m wide at invert, 2.4m wide at soffit	
		No. of structures	2	2	

6.1.20. The location of these structures are shown in Figure 16 below.

Figure 16 – Plan showing location of amended structures



6.1.21. The geometry of the River Chelt mill stream at Millhouse Farm is modelled in 2D with the related culvert under Withybridge Lane included in 1D. This culvert was added to the model as a 1120 mm diameter pipe, based on a survey obtained for this project in October 2021. No other crossings along the mill stream were surveyed or included in the model as were observed to be larger than the culvert under the road: the mill leat was added purely to consider the threshold of flooding which appears regulated by the Withybridge Lane culvert. The mill stream is not included in any previous hydraulic modelling of the River Chelt likely because of its negligible impact on flood flows. The small weir in the River Chelt channel at the head of the leat is included, and was in the previous modelling. The impact of the mill stream on flooding is described further in Section 8.2.

6.1.22. The invert levels recorded by the new surveys are significantly different from the original model. However, the dimensions surveyed in 2019 compare well with the Highways England principal inspection reports and were thus taken forward for modelling.

Figure 17 – photographs of the key structures

Source – Infomap surveys and Mapping, Autumn 2017, and November 2019

River Chelt M5 culvert

Leigh Brook M5 culverts

Staverton stream M5 culvert

Piffs Elm M5 culvert

A4019 Tewkesbury Road

Withybridge Lane

6.2. Inflow boundaries

Upstream boundaries

6.2.1. The inflow points applied to the hydraulic modelling are summarised in Table 6-2, below. The principle was to estimate flows for a given point and apply them to a river reach upstream of that point. Hence the flows applied into the model are precautionary in those upper reaches and reflect the total contributing flow at the downstream end of a river reach. The exception to this was for the Leigh Brook: as the model includes the head of the Leigh Brook, applying a flow reflective of a downstream point into the minor ditch at its source was not representative of the catchment behaviour. For this watercourse the inflow was applied as a lateral inflow between the upstream boundary and the M5 motorway.

Table 6-2 – Hydrological catchments

Location	Catchment area(km^2)	Catchment description	Where inflow is applied in the model
River Chelt at M5	30.59	River Chelt catchment draining to the M5 motorway	Applied as a flow time boundary at the upstream boundary of the hydraulic model at the B4634 Old Gloucester Road
River Chelt downstream M5	1.71	Sub catchment of the River Chelt downstream of the M5 to the downstream boundary of the hydraulic model (River Chelt catchment upstream of the M5 motorway removed)	Applied as a flow time boundary on the downstream side of the M5 motorway, at the outlet of the motorway culvert
Leigh Brook at M5	2.29	Leigh Brook catchment draining to the M5 motorway	Applied a flow time boundary along the upstream reach of the Leigh Brook between its headwater and the M5 motorway as a lateral inflow
Leigh Brook downstream M5	1.13	Sub-catchment of the Leigh Brook downstream of the M5 motorway (Leigh Brook catchment upstream of M5 motorway removed)	Applied as a flow time boundary on the downstream side of the M5 motorway, at the outlet of the motorway culvert
Staverton stream	2.35	Tributary of the River Chelt which flows to the M5 motorway. The catchment of the Staverton stream downstream of the M5 is accounted for in the 'River Chelt downstream M5' catchment	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
Arle CSO	11.50	CSO catchment, which	As a flow-time point discharge

Location	Catchment area(km²)	Catchment description	Where inflow is applied in the model
		discharges at Arle. The inflows, provided by STW, have been scaled by 40% to account for the additional catchment area outside of the topographic catchment of the River Chelt	at the upstream boundary of the hydraulic model at the B4634 Old Gloucester Road

Internal Boundary

6.2.2. No direct rainfall component was modelled in the Baseline model. All flows arising from the land contained inside the M5J10 model domain (the floodplains of the River Chelt and Leigh Brook) are accounted for in the FEH hydrology.

6.2.3. 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 is applies higher flows to the upper lengths of a flow reach.

6.3. Downstream Boundary

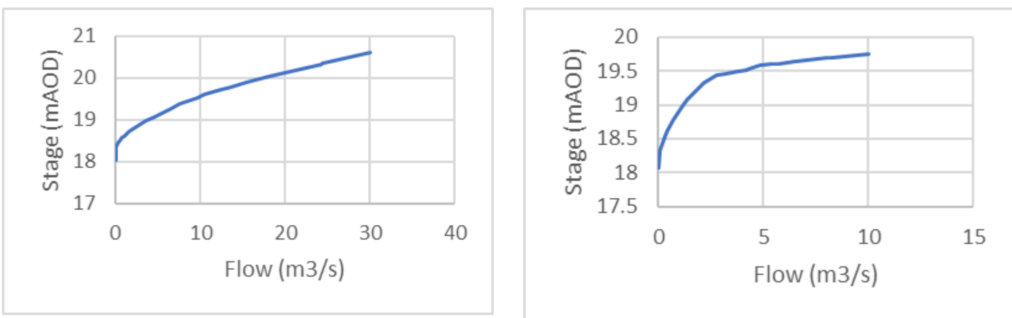
6.3.1. Stage-discharge data were developed for the 1D downstream boundaries on both the River Chelt and Leigh Brook. They were developed from the results of the River Chelt catchment (direct rainfall) model, as applied to the Boddington flood map challenge.

6.3.2. Early results from the enhanced River Chelt direct rainfall model (see Section 2.3 and Section 3), applied with a 40% increase in rainfall for climate change (early tests were undertaken to establish the impact of rainfall on flow when using the direct rainfall model) were used to provide the stage-discharge boundary. The stage discharge curves were further extrapolated to ensure that they are sufficient to deal with all extreme scenarios being tested (i.e. credible maximum).

6.3.3. It is recognised that the River Chelt direct rainfall model may, or may not, be fully reliable and thus there could be uncertainty on the downstream boundary as derived by it. However, as the stage-discharge relationship is based on flow in the 1D channel, being a function of channel roughness and hydraulic gradient, any error in the underlying model/hydrology can be forgiven. Furthermore, the downstream boundary for the M5J10 model was intentionally located remote from the proposed improvement works such that any uncertainty in the downstream boundary would not affect the model performance in and immediately around the scheme. This is also explained in Section 3 showing the likely backwater impacts at the downstream boundary.

Figure 18 – Stage discharge curves applied at the downstream boundaries

River Chelt   Leigh Brook



6.3.4. The downstream boundary for the 2D domains were based on normal flow depths. A gradient from the terrain at the boundary was derived from the LiDAR data. For both River Chelt and Leigh Brook, a 1 in 200 slope was applied. As described above, the

AtkinsRéalis

downstream boundary for the 2D domains are set sufficiently remote from the Scheme to not cause an impact on flood levels: the controlling M5 motorway culverts are well beyond the backwater reach of the downstream boundaries.

6.3.5. Sensitivity on the downstream boundaries is described in Section 7.3 below.

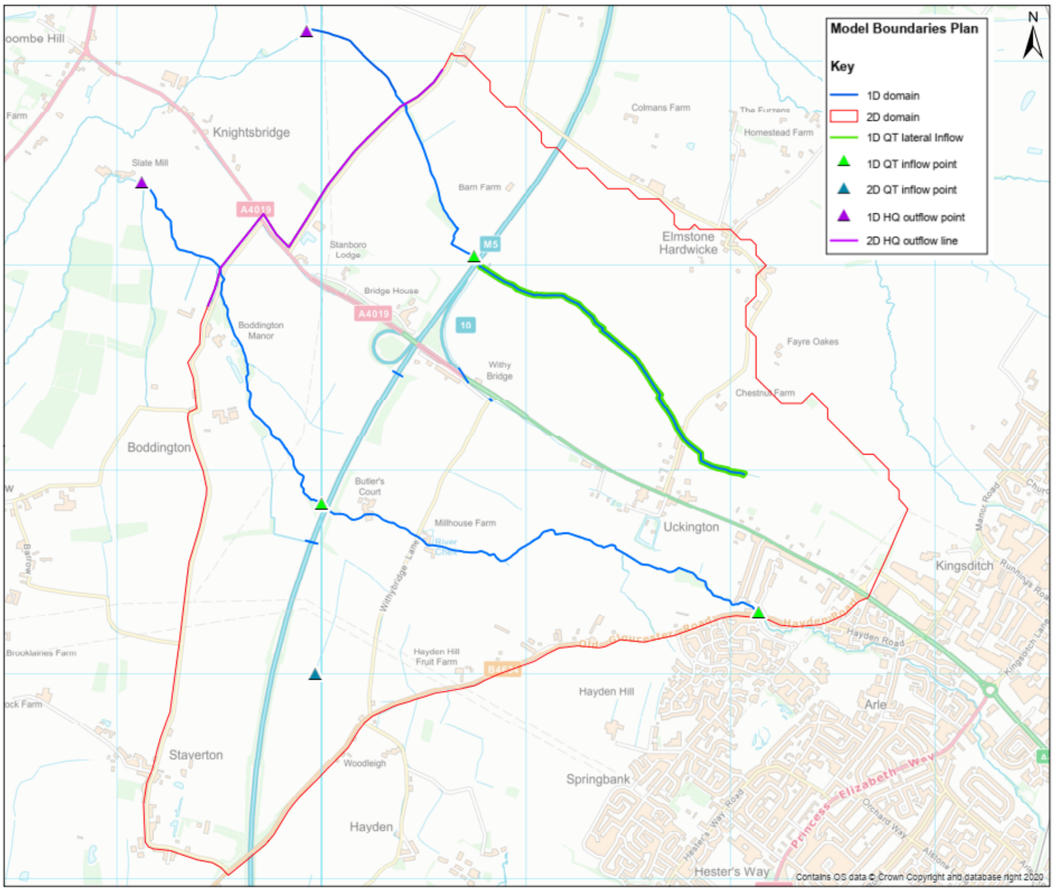
6.3.6. Figure 19 overleaf shows the location of the model boundaries.

6.4. Modelling assumptions made

6.4.1. No critical modelling assumptions were made. All relevant data has been obtained and used. Those modelling assumptions not deemed critical to the project 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.
- The additional crossings over the mill leat at Millhouse Farm are not critical to hydraulic performance, with the Withybridge Road crossing included and the smallest on that reach.

Figure 19 – Model boundaries



7. Baseline model proving

This section discusses run performance, calibration and verification, sensitivity analysis and comparison with other models and the implications of this in the context of this project. This section is particularly important for models reflecting high flood risk, to provide confidence in the model results generated.

7.1. Calibration and validation

7.1.1. The M5J10 model relies on the same calibration work undertaken for the Boddington model in 2019. Discussions between the Environment Agency and EVY focussed on the **20 July 2007** and **13 December 2008** flood events, having data by which to calibrate.

7.1.2. There were no flow or stage gauges inside the M5J10 study area.

7.1.3. Use was made of the now closed, and removed (2010), trapezoidal flume gauging station at Slate Mill. The Slate Mill gauge lies at the 1D downstream boundary. Comparison of the flows leaving the M5J10 1D domain and those recorded by the Slate Mill gauge was used for calibration.

7.1.4. The M5J10 model's 2D boundary at the Boddington road lies some 600 m upstream of the Slate Mill gauge. There are no watercourses joining the River Chelt between this boundary and Slate Mill, and only a small intervening catchment. The 2D domain was used to quantify the flow bypassing the Slate Mill gauge – although there are no records of these flows with which to calibrate the model.

7.1.5. The National River Flow Archive suggests that all flows were contained within the structure but that the gauge performance at high flow was uncertain and that there had been no metering since 1995. Furthermore, it is advised by the Environment Agency that the gauge was bypassed at high flows.

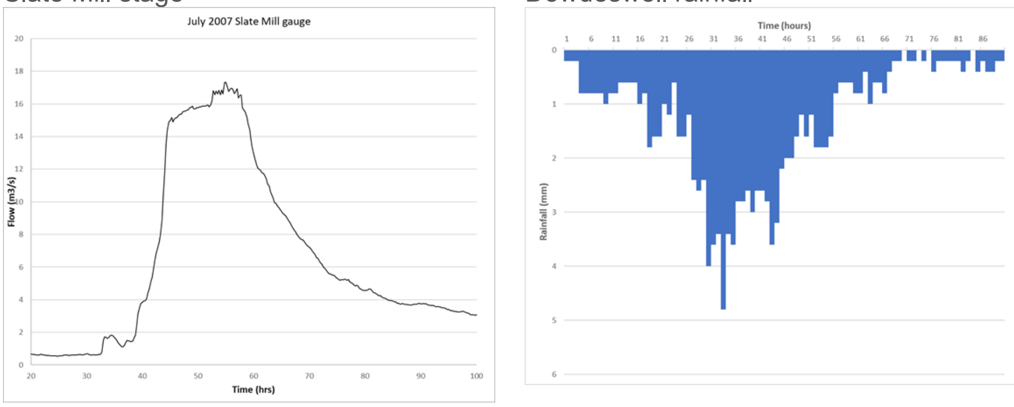
7.1.6. There is a flood warning gauge on the River Chelt, 1.3 km upstream of the model at Arle. This gauge records stage only and there is no rating available by which to ascertain flows. However, its data indicates recent peaks in 2020. These were used for validation.

20 July 2007

7.1.7. The flow gauge at Slate Mill recorded its largest flow, since the record began in 1969, on 20 July 2007 event. A peak flow of 17.3m^3/s was recorded with a peak stage of 2.227 m above gauge datum. Rainfall data from the Environment Agency's Dowdeswell rainfall gauge was applied to the ReFH2.3 software to define flows for the various inputs to the hydraulic model: 111.4mm of rain was recorded over 22 hours. The observed rainfall and flow are indicated below. The return period of this event has not been confirmed, although all sources describe it as more extreme that the 1% annual exceedance probability event (1 in 100-year return period), possible as much as 0.25% annual exceedance probability event (1 in 400-year return period).

Figure 20 – 20 July 2007 observed rainfall and gauges flow/stage

Slate Mill stage Dowdeswell rainfall



7.1.8. Given the attenuating effects of the M5 motorway, and the flow control presented by the various M5 culverts, the hydrology could not be calibrated in isolation from the hydraulic model. Initial tests demonstrated that the various hydrological parameters would need to be modified beyond their plausible limits in order to match the gauged record at Slate Mill: for example, inappropriate T_p, and C_{ini} would have been required. Instead, the flows predicted by the ReFH2.3 software were applied directly to the hydraulic model.

7.1.9. Severn Trent Water supplied the predicted CSO discharge hydrograph for July 2007, which was scaled by 40% (as per the hydrology approach). A flow of 2.9m^3/s was applied to the model.

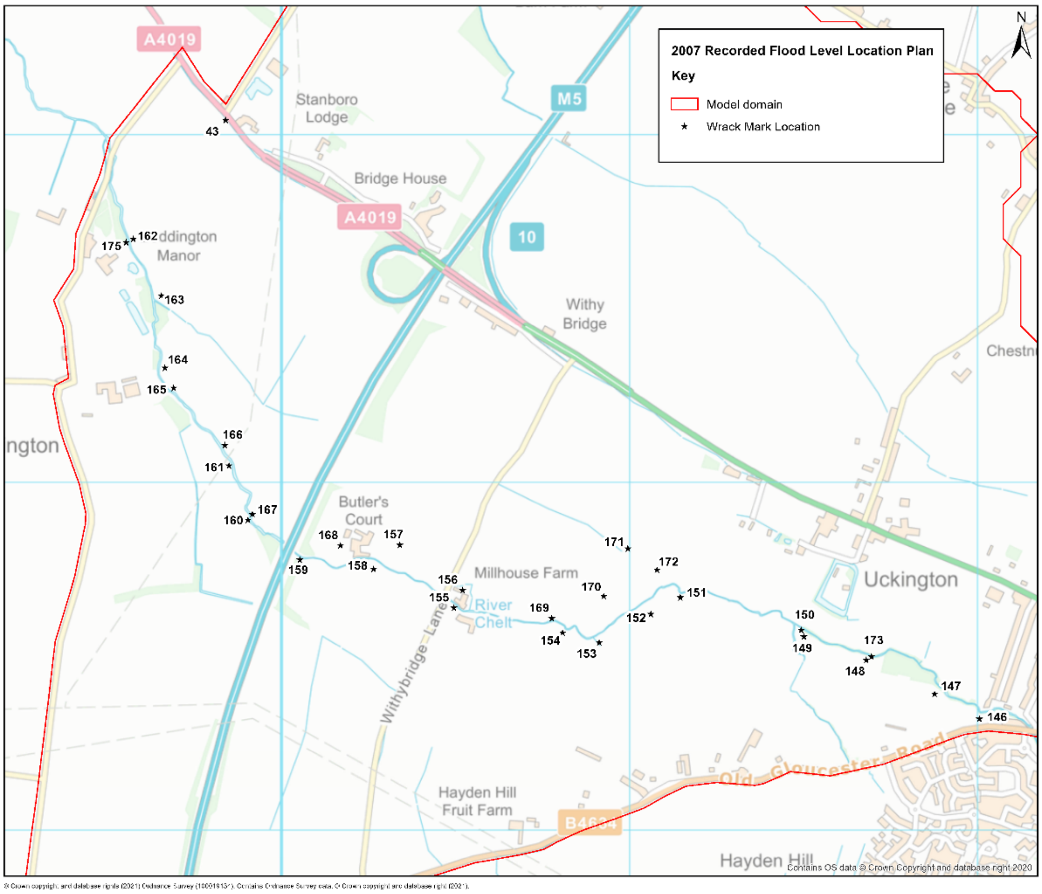
7.1.10. A process of calibration was then undertaken, comparing model predictions of flow and stage at the downstream boundary (almost at Slate Mill) and wrack mark observations for the River Chelt as supplied by the Environment Agency (Figure 21). The Environment Agency confirmed that its historic flood map, also used to describe Flood Zone 2, was a projection of surveyed wrack levels from the major event in July 2007.

7.1.11. The initial results demonstrated a good calibration east of the M5 motorway, but a poor match to the west, where peak flood levels were predicted some 600 mm lower than the recorded wrack mark data. However, flow passing the downstream boundary showed a good similarity with those recorded by the Slate Mill Gauge.

7.1.12. A sensitivity test was undertaken to consider the impact of sedimentation in the culverts over the period since 2007, applying the larger units (assumed being cleaner, having had 10 year less sediment accumulation) described in the original 2012 Environment Agency modelling. This was found to have little impact on flood levels downstream, although reduced flood levels to the east of the M5 motorway.

7.1.13. Discussions with the Environment Agency improved confidence in the recorded wrack mark data. However, it could not be confirmed whether the marks were generated by fluvial flows or rainfall and surface water flows on the land.

Figure 21 – Environment Agency wrack mark locations



7.1.14. Recourse was made to increases in channel roughness to reflect what could have been present in July 2007, being the height of the summer with likely dense vegetation growth on the channel banks. A Manning's roughness of 0.060 was found to provide good calibration comparison of flood levels with the wrack marks, and in the peak flow and discharge hydrograph passing the Slate Mill gauge as a 1D element of the model.

The predicted levels from the M5J10 model, and recorded wrack marks levels, are tabulated below in

7.1.15. Table 7-1. These show that the modelled flood levels at the vast majority of the wrack mark locations are within 250mm of the recorded levels, indicate a good calibration of the model to the July 2007 event. The location of the wrack marks are shown above in Figure 21.

Table 7-1 – Predicted flood level compared to recorded wrack marks for July 2007

Wrack Mark ID	Recorded flood level (Rec)	Predicted level		Difference		Additional Comments
		2D	1D	2D - Rec	1D - Rec	
Upstream of M5 Motorway Note the wrack mark numbers list in approximate order, upstream to downstream						
146	34.24	34.00	33.85	-0.24	-0.39	d/s of B4634
147	34.14	33.09	33.18	-1.05	-0.96	By allotments
173	31.71	32.17	32.17	0.46	0.46	
148	32.06	32.12	32.12	0.06	0.06	
149	31.21	31.17	31.24	-0.04	0.03	River Chelt opposite Moat at Uckington
150	31.1	31.23	31.24	0.13	0.14	River Chelt ~ at the abandoned gauging channel
151	29.4	29.48	29.56	0.08	0.16	u/s of low point in River Chelt right bank
172	28.53	28.74	N/A	0.21	N/A	In farmland. No 1D comparison as wrack mark over 50m away
171	27.9	28.22	N/A	0.32	N/A	In farmland. No 1D comparison as wrack mark over 150m away
152	28.9	29.05	28.61	0.15	-0.29	Low point in River Chelt right bank
170	27.71	27.97	N/A	0.26	N/A	In farmland. No 1D comparison as wrack mark over 80m away
153	28.15	28.17	27.95	0.02	-0.20	
154	27.71	27.56	27.58	-0.15	-0.13	
169	27.54	27.42	27.42	-0.12	-0.12	
155	26.67	26.51	26.68	-0.16	0.01	River Chelt at Withybridge Lane
156	26.59	26.51	N/A	-0.08	N/A	Withybridge Lane. No 1D comparison as wrack mark 50m away
157	25.43	25.92	N/A	0.49	N/A	Farmland at Butlers Court. No 1D comparison as wrack mark over 75m away
158	25.32	25.61	25.96	0.29	0.64	Butlers Court
168	25.32	25.45	N/A	0.13	N/A	Butlers Court. No 1D comparison as wrack mark over 65m away
159	24.98	24.88	24.88	-0.10	-0.10	~20m u/s M5 motorway

Wrack Mark ID	Recorded flood level (Rec)	Predicted level		Difference		Additional Comments
		2D	1D	2D - Rec	1D - Rec	
Downstream of M5 Motorway Note the wrack mark numbers quoted are those supplied by the Environment Agency and are not the same as those used in the Boddington flood map challenge.						
160	24.26	24.28	24.26	0.02	0.00	~140m d/s M5 motorway
167	24.33	24.27	24.20	-0.06	-0.13	~130m d/s M5 motorway
161	23.66	23.67	23.62	0.01	-0.04	
166	23.5	23.48	23.46	-0.02	-0.04	
165	22.88	22.68	22.91	-0.20	0.03	Boddington House
164	22.39	22.57	22.70	0.18	0.31	Boddington House
163	21.85	22.05	22.20	0.20	0.35	
175	21.69	21.68	21.69	-0.01	0.00	Boddington Manor
162	21.7	21.66	21.69	-0.04	-0.01	Boddington Manor
43	20.84	21.14	N/A	0.30	N/A	A4019. No EA wrack mark provided, but one was described in EVY report. Wrack mark over 390m from river.

7.1.16. The model appears to underestimate at its upstream boundary. The wrack mark at the B4634 and just downstream at the allotments indicate bank full flow. The hydraulic model is underestimating flood levels in this reach, by 1 m at the allotments, which may have been caused be localised channel blockage during the event. However, some 250 m downstream the model appears to overpredict the flood level. There is no evidence that flooding arose across the allotments from an overland flow path.

The comparison of flows passing Slate Mill confirm that the ReFH2 flows for the 2007 event are appropriately attenuated by the M5 motorway culverts, reducing a River Chelt flow of 31.0 m^3/s at the M5 motorway down to 18.6 m^3/s at the gauge. This compares well with the recorded 17.3 m^3/s for that event. See

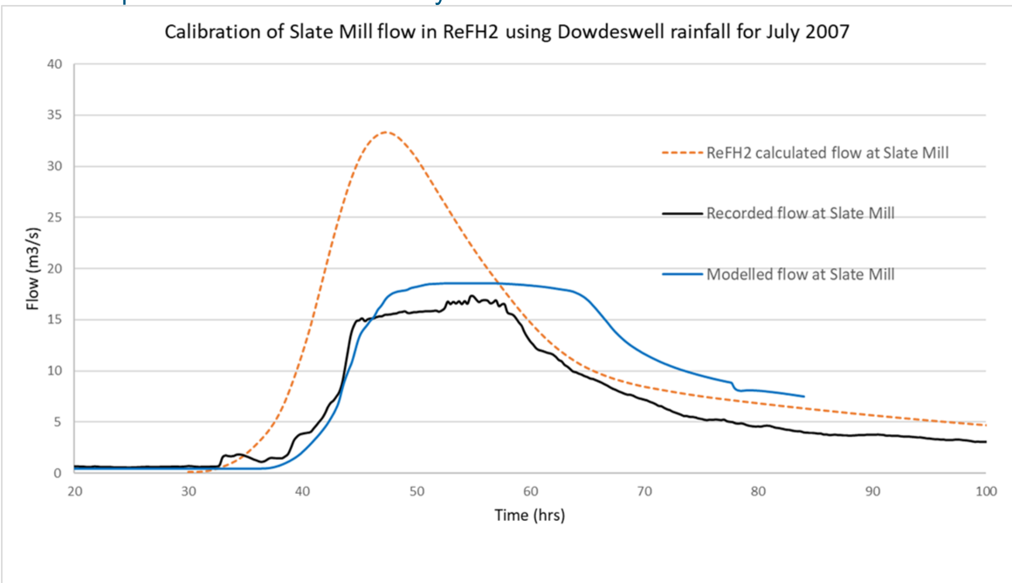
7.1.17. Figure 22.

7.1.18. The hydraulic model also predicted that up to 5.5 m^3/s was bypassing the Slate Mill gauge in this event, in addition to a peak of 8.3 m^3/s flow passing over the A4019 into the Leigh Brook. This is reflected in the flood mapping for the event.

7.1.19. Whilst the model predicts a peak flow comparable with that recorded at the gauge, the total volume passing the gauge during the event (volume under the recorded hydrograph) is much lower than the model describes. This relates to the falling limb of the event, where the observed data falls quickly, yet the model predicts a slower recession. No sensitivity tests were undertaken on the input hydrograph, for example such as reducing the time-to-peak: whilst this might improve the falling limb calibration, it would also increase the peak flow. Alternative explanations might be in the amount of floodwater bypassing the gauge, either passing under the M5 motorway through Piffs Elm culvert and alongside the A4019, or passing over the A4019 at Withy Bridge and flowing along the Leigh Brook.

7.1.20. The model in its current form appears robust and precautionary, matching peak flows at the downstream boundary (Slate Mill), having a good calibration at the Environment Agency wrack marks, and slightly over-predicting the volume held on the floodplain upstream.

Figure 22 – Flow comparison at Slate Mill for July 2007 event



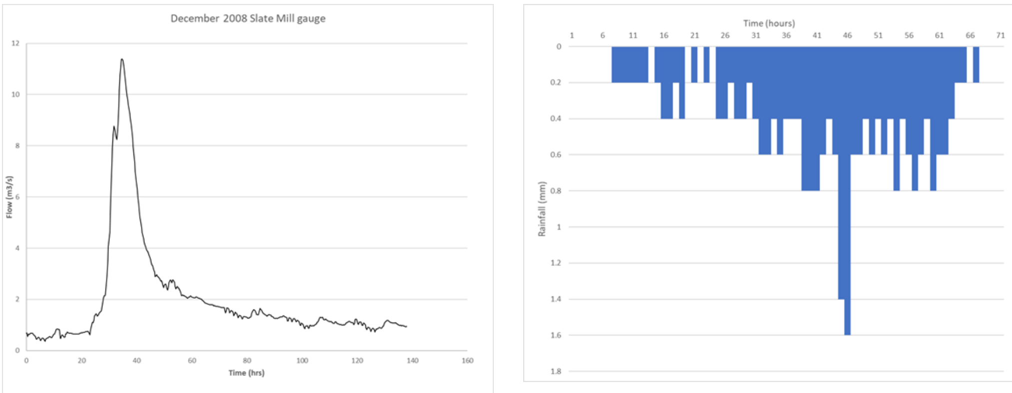
13 December 2008

7.1.21. The River Chelt flow gauge at Slate Mill recorded its 12th largest flow, on 13 December 2008 event. A peak flow of 11.39 m³/s was recorded with a peak stage of 1.873 m above gauge datum. Dowdeswell rainfall gauge recorded 26.2 mm of rainfall over 16 hours.

7.1.22. This event was selected for calibration by the Environment Agency for the 2019 Boddington work, based on its antecedent conditions. However, there are no local observations from this time, except at Slate Mill, despite it being the most recent 'large' event.

Figure 23 – 12 December 2008 observed rainfall and gauges flow/stage

Slate Mill stage | Dowdeswell rainfall

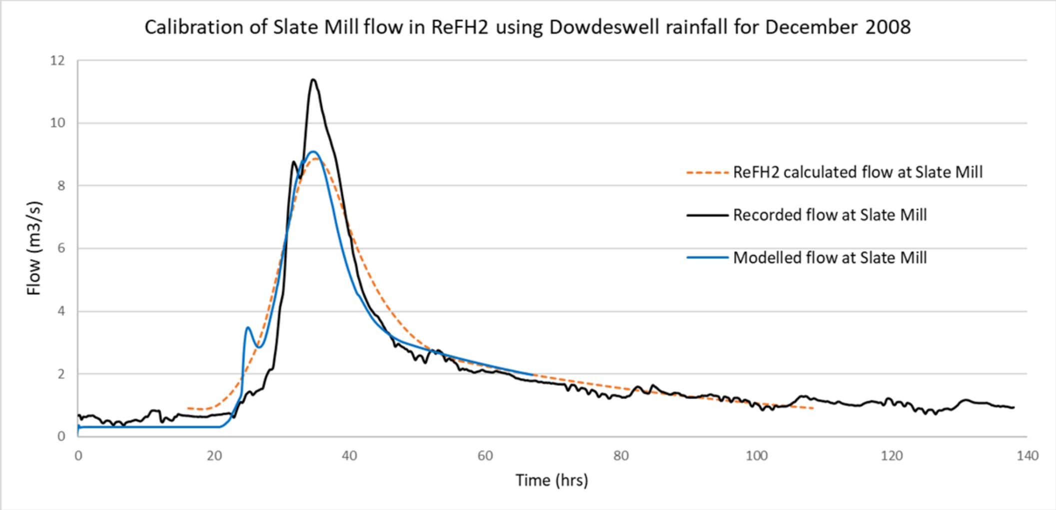


7.1.23. The hydrology derived a flow of 8.7 m³/s at the M5 motorway which was input to the upstream boundary of the hydraulic model. A flow for the Arle CSO reflecting a long duration 20% annual exceedance probability event (1 in 5-year return period) was added, as there was no event data from STW. This was a flow of 1.77m³/s. Additional inflows were applied downstream of the M5 reflecting the downstream catchment.

7.1.24. Comparison of recorded and predicted flows passing Slate Mill imply that there was less attenuation of flows by the M5 motorway embankment – presumably because of the smaller nature of the event. A flow of 9.1 m³/s was predicted at the gauge, which compares with the recorded 11.4 m³/s for the event.

7.1.25. The hydraulic model predicted that no flow was bypassing the Slate Mill gauge (alongside the A4019 through Piffs Elm culvert) in this event. Furthermore, no flow was predicted to be passing over the A4019 into the Leigh Brook.

Figure 24 – Flow comparison at Slate Mill for December 2008 event



7.2. Verification

7.2.1. The Arle flood warning gauge recorded its highest stage for seven years, twice in 2020. Whilst those events were not reported by the Environment Agency or local landowners to have caused significant flooding, it was intended to use them to validate the calibrated M5J10 model.

2020 Flood Events

7.2.2. An event on the 17 June 2020 was also recorded at Arle, with a peak level at 2.51 m ACD, although the average for the data was much lower at 0.92 m ACD. This event was not known to have caused significant flooding but was a response to a sudden intense rainfall of 9.6mm in 45 minutes. Discussions with a local landowner confirmed that floodwater overtopped the River Chelt in two places on its right bank near the existing footbridge (some 650 m upstream of Withybridge Lane) and flooded some 30 m into the adjacent arable fields with a maximum depth of 250 mm.

7.2.3. The June 2020 rainfall data was processed through the ReFH2 model to derive a peak flow of 2.5m^3/s. No STW CSO data was available for this event. However, a discharge value of 4m^3/s was extrapolated from the STW design data for a 5-year 0.75hr storm. Hence a total peak flow in the order of 6.5m^3/s was estimate for this event. Consideration with a 10-year 0.75hr storm CSO outflow indicated a total peak flow of 7m^3/s.

7.2.4. The channel geometry for the overtopping river reach was considered, so establishing that a River Chelt stage of over 29 m AOD would be required to overtop the right bank. Using the stage-discharge data from the hydraulic model, such a water level would be generated with a flow of 17.9m^3/s. Hence the estimated flow for the event is less than half that required to cause flooding, and brings no surprise that the hydraulic model was not able to recreate the observations of the time. It is here suggested that the event was caused by blockage in the channel, it occurring during the summer when more debris may have been present to block the channel.

7.2.5. A second event in 2020, on 23 December 2020, saw the Arle gauge record an average daily stage of 1.77 m above chart datum (ACD), with a peak at 2.14 m ACD. This event was reported by the same landowners as above to similarly overtop the River Chelt in the same two places, although the extent of flooding was far less No validation work was undertaken with this event.

7.3. Sensitivity analysis

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

7.3.2. Informal tests 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.

7.3.3. Formal tests were undertaken 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
- Sensitivity to TUFLOW software version.

7.3.4. The tests were only applied at the present day 1% annual exceedance probability event (1 in 100-year return period).

Results reporting

The results have been documented in this report at key locations to reflect maximum flooded depths (being more tangible than absolute flood levels) and peak flows at key locations. These key locations are described below in Table 7-2 and

7.3.5. Table 7-3, and shown on Figure 25.

7.3.6. The full results are contained in the hydraulic model files. Flood extent mapping for each sensitivity test is included in Appendix C.

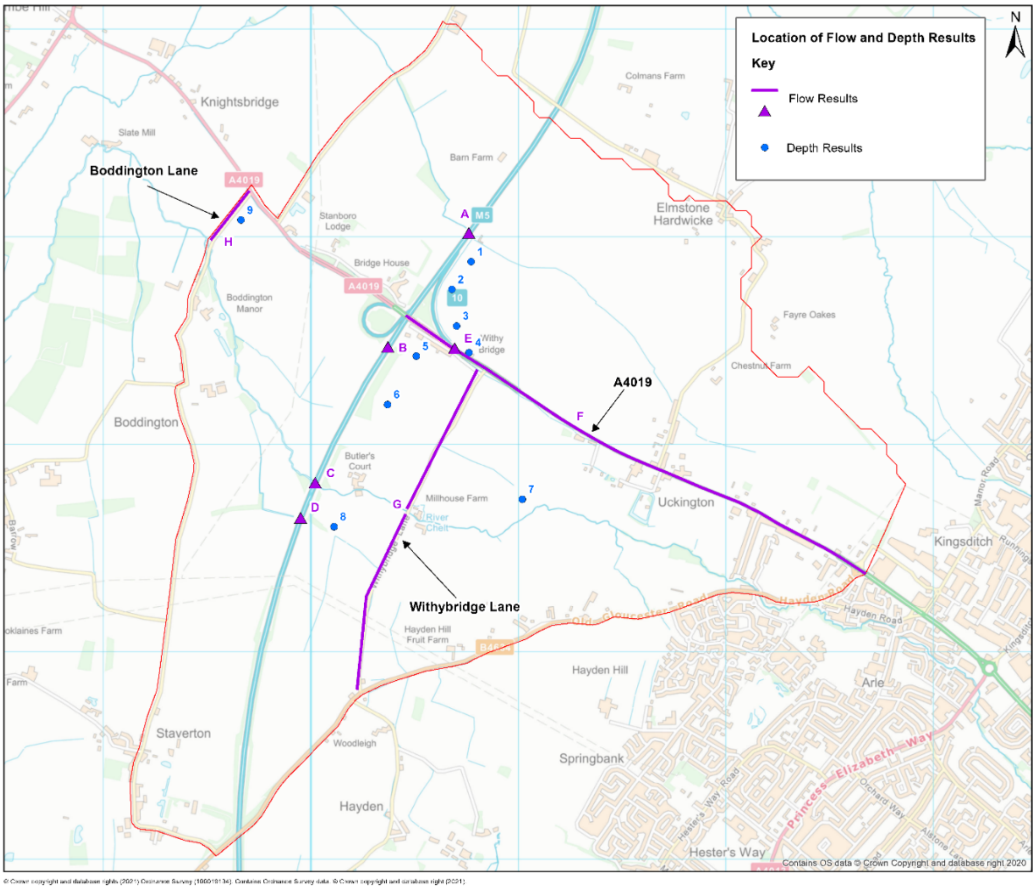
Table 7-2 – Key locations for reporting flood depth

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 7-3 – 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 25 – Location of points for result reporting



Sensitivity to channel and floodplain roughness

7.3.7. A sensitivity test was undertaken on the channel and floodplain roughness. Tests were made by applying a model wide modification to reflect the maximum envisaged seasonal variation from what was considered to be a reasonable spring/autumn Baseline. These are tabulated below.

Table 7-4 – Variation in Manning's roughness

	Summer	Baseline	Winter
River Chelt (1D)	0.070	0.048	0.035 – 0.045
Leigh Brook (1D)	0.080	0.060	0.055
River Channel (2D)	0.070	0.048	0.035
Open land/agricultural land (2D)	0.070	0.050	0.020
Scrub (2D)	0.080	0.055	0.040

7.3.8. The results indicate that the model is reasonably insensitive to changes in roughness values in some locations. Higher roughness values associated with the Summer simulation generally results in more water exiting channels onto the floodplain and therefore larger flood extents, compared to applying Baseline roughness values. However, reducing roughness values for the Winter simulation causes less of a difference to the Baseline.

7.3.9. Summer roughness results show water overtopping the banks of the River Chelt much more frequently from the upstream boundary at Old Gloucester Road to Withybridge Lane, compared to the Baseline and Winter results.

7.3.10. Where roughness values have been increased, there appears to be more water at the eastern end of the River Chelt floodplain. There is around 3 – 4 m^3/s more water passing over Withybridge Lane in the 2D model in the Summer simulation, compared to the Baseline and Winter simulations. Similarly, whereas the Baseline and Winter simulations show no flow through the A4019 culvert, the results of the Summer simulation show 1.1 m^3/s passing through this structure. This results in some flooding extending between the A4019 and the Leigh Brook, east of the motorway, which is not present in the Baseline or Winter results.

7.3.11. The Winter roughness results are generally very similar to the Baseline extents. However, flood extents are less extensive in certain areas; particularly along the Leigh Brook between the motorway and the downstream boundary of the model where there is less out of bank flooding in the Winter simulation. In this area, the Summer roughness flood extents are much wider and show more out of bank flooding along the Leigh Brook.

7.3.12. Downstream of the motorway along the River Chelt, the results follow a similar pattern. Increasing roughness in the Summer simulation has resulted in increased flooding in the floodplain between the River Chelt and the A4019. At Boddington Manor, the Winter roughness results show very little out of bank flooding whereas both the Baseline and Summer roughness results show flooding in the fields at this location. There is significantly more flood water passing over Boddington Lane at the downstream boundary in the Summer simulation; 6.5 m^3/s compared to 3.0 m^3/s in the Baseline and 2.9 m^3/s in the Winter simulation.

7.3.13. Selected point results are tabulated below 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 25 above.

Table 7-5 – Sensitivity of flood depth to Manning's roughness

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

Location	Summer depth (m)	Baseline depth (m)	Winter depth (m)
1 Leigh Brook nr Barn Farm culvert	0	0	0
2 Leigh Brook existing slip road	0	0	0
3 Leigh Brook nr A4019	0	0	0
4 A4019	0	0	0
5 Withybridge Gardens	1.100	0.811	0.748
6 north of Butlers court	0.393	0.140	0.135
7 Eastern end of River Chelt floodplain	0.215	0.184	0.176
8 nr Staverton culvert	0.312	0.308	0.314
9 Boddington Lane	0.474	0.433	0.432

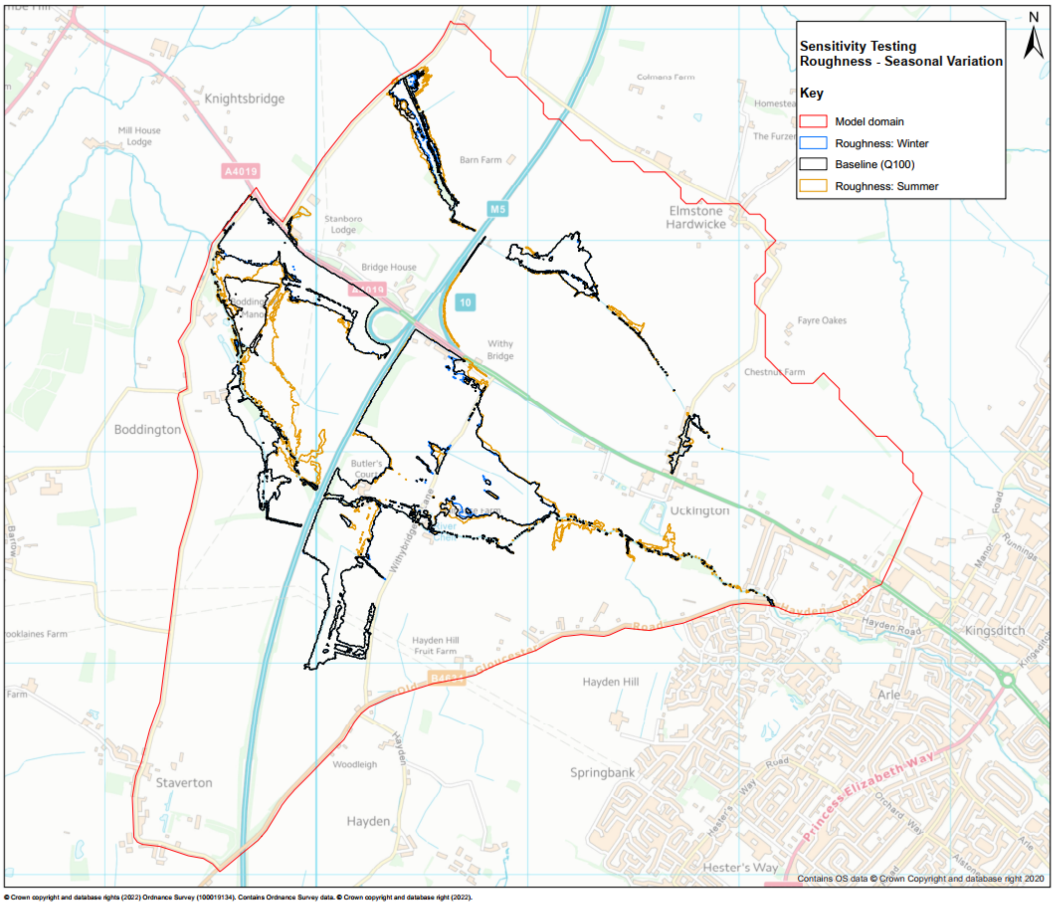
Table 7-6 – Sensitivity of flood flows to Manning's roughness

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

Location	Summer flow (m^3/s)	Baseline flow (m^3/s)	Winter flow (m^3/s)
A Barn farm culvert	2.5	2.2	2.2
B Piffs elm culvert	3.3	3.0	2.9
C River Chelt culvert	16.1	18.3	18.7
D Staverton culvert	2.7	2.7	2.7
E A4019 culvert	1.1	0.0	0.0
F A4019 over the top	0.0	0.0	0.0
G Withybridge Lane	11.4	8.2	7.5
H Boddington Lane (nr downstream boundary)	6.5	3.0	2.9

7.3.14. Whilst it may be precautionary to promote the summer roughness values for use in the design events, and the calibration of the model used such values, the condition of the channel at the time of survey suggests that for at least 9 months of the year it would be unreasonable to apply such high Manning's values. Furthermore, as the hydrology specified a winter storm for the critical event, the approach of using the Baseline values has been retained.

Figure 26 – Sensitivity of flood extent to channel and floodplain roughness



Sensitivity to structure coefficients including structure blockage

Coefficients

7.3.15. A sensitivity test was undertaken on the hydraulic performance of the key structures – being those under the M5 motorway: River Chelt culvert, Staverton culvert, Piffs Elm culvert and Barn Fam culvert. The A4019 culvert at Withybridge Gardens was also tested as being directly relevant to flood levels in the study area.

7.3.16. Tests were made on the losses applied to each culvert, comprising the inlet loss and outlet loss. A ± 10% variation to each was applied.

Table 7-7 – Variation in structure coefficients

ex = exit loss coefficient. **en** = entry loss coefficient

Structure	Reduced losses	Baseline	Increased losses
River Chelt culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
Staverton culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
Piffs Elm culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
Barn Fam culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
A4019	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex

7.3.17. The results indicate that varying structure coefficients has little impact on the results and that the model is generally insensitive to changes in entry and exit losses to these structures. Flood extents, depth and flow results are very similar across the reduced structure losses, increased structure losses and Baseline simulations. All noticeable differences in flood extents occur downstream of the motorway in both the Chelt and Leigh Brook floodplains.

7.3.18. There is slightly more flooding downstream of Piffs Elm Culvert where structure losses have been reduced, and similarly, slightly less flooding here where structure losses have been increased. This is also reflected in the flows passing through Piffs Elm Culvert; 3.3 m^3/s where reduced structure losses are applied, compared to 3.0 m^3/s and 2.9 m^3/s where Baseline and increased structure losses are applied respectively. Further downstream, water passes from south to north over the A4019 in all three simulations. However, where structure losses have been reduced, flood waters extend further north to the pond west of Stanboro Lodge. This does not occur in the Baseline and increased structure losses simulations.

7.3.19. There is also more flooding immediately downstream of the Staverton Culvert where structure losses have been reduced, and slightly less flooding downstream of this structure where structure losses have been increased. This is reflected in the flows passing through the Staverton Culvert; 2.8 m^3/s where reduced structure losses are applied, compared to 2.7 m^3/s where Baseline and increased structure losses are applied.

Selected point results are tabulated below 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 25 above.

Table 7-8 – Sensitivity of flood depths to structure coefficients

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

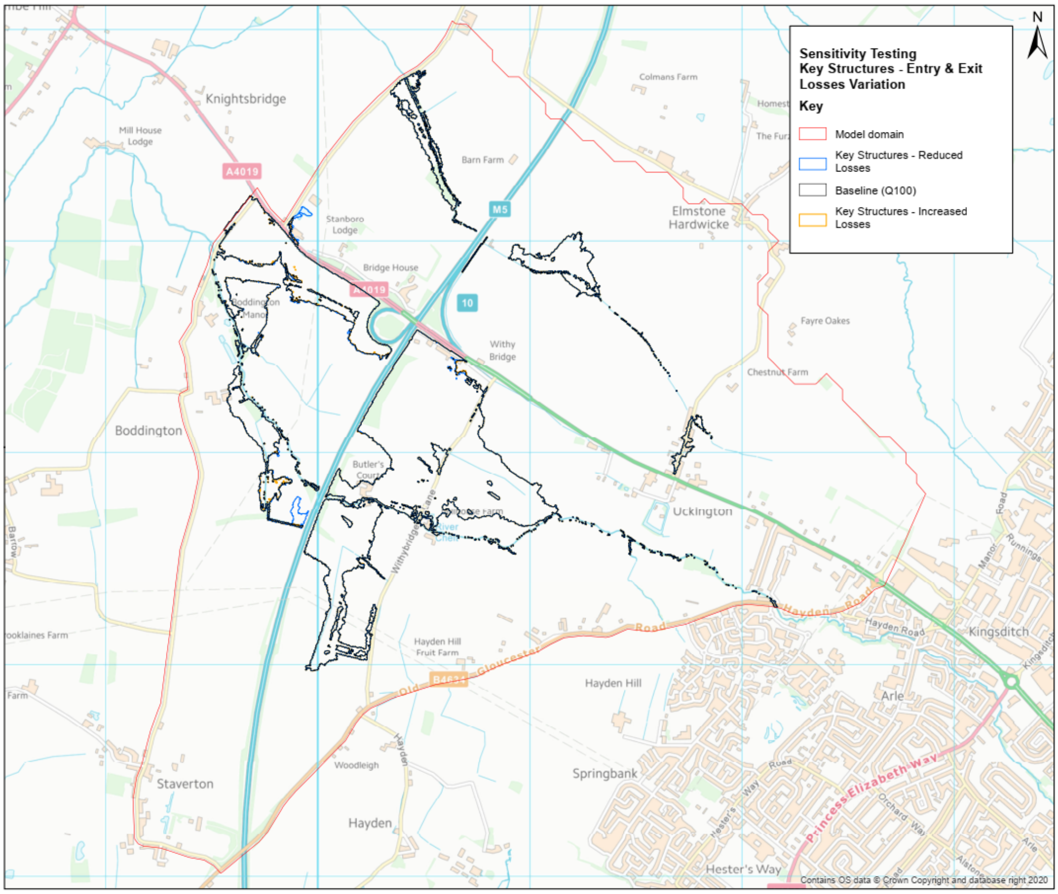
Location	Reduced losses depth (m)	Baseline depth (m)	Increased losses depth (m)
1 Leigh Brook nr Barn Farm culvert	0.000	0.000	0.000
2 Leigh Brook existing slip road	0.000	0.000	0.000
3 Leigh Brook nr A4019	0.000	0.000	0.000
4 A4019	0.000	0.000	0.000
5 Withybridge Gardens	0.773	0.811	0.820
6 north of Butlers court	0.140	0.140	0.140
7 Eastern end of River Chelt floodplain	0.184	0.184	0.184
8 nr Staverton culvert	0.306	0.308	0.311
9 Boddington Lane	0.438	0.433	0.432

Table 7-9 – Sensitivity of flood flows to structure coefficients

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

Location	Reduced losses flow (m^3/s)	Baseline flow (m^3/s)	Increased losses flow (m^3/s)
A Barn farm culvert	2.2	2.2	2.2
B Piffs elm culvert	3.3	3.0	2.9
C River Chelt culvert	18.2	18.3	18.3
D Staverton culvert	2.8	2.7	2.7
E A4019 culvert	0.0	0.0	0.0
F A4019 over the top	0.0	0.0	0.0
G Withybridge Lane	8.1	8.2	8.2
H Boddington Lane (nr downstream boundary)	3.2	3.0	2.9

Figure 27 – Sensitivity of flood extent to structure coefficients



Blockage

7.3.20. A further test was undertaken to consider blockage of the key structures. As the main River Chelt culvert under the M5 motorway is large, a 10% blockage of this was applied. The other structures (Staverton culvert, Piffs Elm culvert, Barn Fam culvert and A4019) were all tested as being 90% blocked – reflective of the vegetation present in each catchment and likelihood of each culvert to block. Given the small and overgrown nature of the minor culverts, all culverts were blocked with the same model run, not independently.

7.3.21. The results indicate that blockage of key structures significantly increases flooding upstream of the motorway. The most significant increase in flooding occurs on the Leigh Brook floodplain, north of the A4019. No water overtops the A4019 at this location in the Baseline results, whereas the blockage results indicate that 0.6 m^3/s would overtop this road and result in widespread flooding between the A4019 and Leigh Brook watercourse, that is not present in the Baseline scenario. The depth results show that flood water in the Leigh Brook floodplain, near the existing slip road and Barn Farm Culvert, would be almost 0.8 m deep in the blockage simulation whereas there is no flooding present in the Baseline simulation.

7.3.22. Adding to this, the blockage of Barn Farm Culvert allows less of this water to pass through the structure; 0.7 m^3/s compared to 2.2 m^3/s in the Baseline results. This results in less extensive flooding downstream of the motorway along the Leigh Brook.

7.3.23. A similar pattern of results are seen at Piffs Elm and Staverton Culverts; the flood extents in the Baseline are far wider downstream of these points as less flow is able to pass through the culverts in the blockage scenario. This is also reflected in the depths in both sets of results, whereby all depth results immediately upstream of the M5 are higher in the blockage simulation than in the Baseline. However, the impacts do not propagate far upstream with the effects being diminished at Withybridge Lane and negligible impact upstream of it.

7.3.24. Even though a 10% blockage is applied to the Chelt Culvert under the M5, more flow passes through this structure in the blockage scenario (20.9 m^3/s) compared to in the Baseline (18.3 m^3/s). This is likely due to the 90% blockage applied to other key culverts (Staverton, Piffs Elm and A4019), allowing less flows through and therefore more water is built up in the Chelt floodplain and forced through the Chelt culvert. The increased depths at Withybridge Gardens and north of Butlers court confirm that water is ponding to a higher level upstream of the M5 motorway in the blockage simulation (1.1 m and 0.4 m respectively, compared to 0.8 m and 0.1 m in the Baseline results).

7.3.25. Applying blockages to key structures also results in less water reaching the downstream boundary at Boddington Lane, since more water is held east of the motorway than in the Baseline where flow is less obstructed. The results show that only 0.3 m^3/s of water passes over Boddington Lane in the blockage simulation compared to 3.0 m^3/s in the Baseline.

7.3.26. Selected point results are tabulated below 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 25 above.

Table 7-10 – Sensitivity of flood depths to structure blockage

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

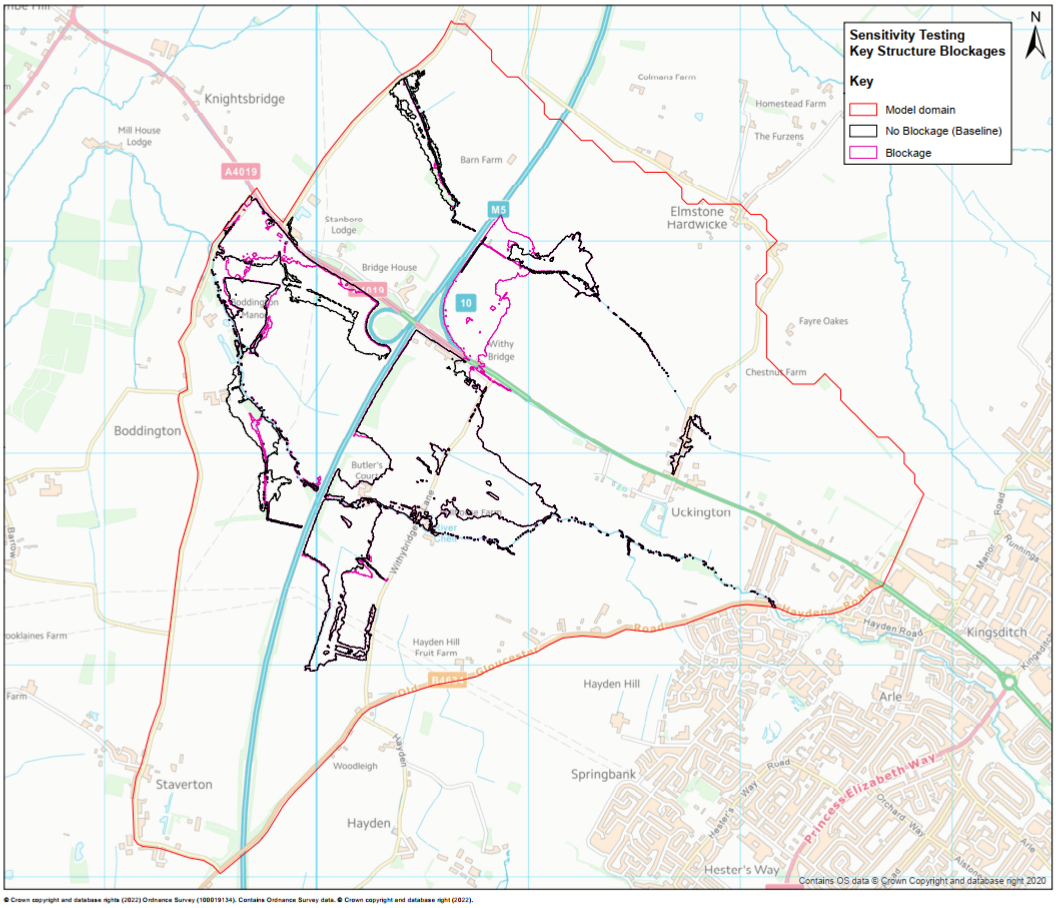
Location	With blockage depth (m)	Without blockage (Baseline) depth (m)
1 Leigh Brook nr Barn Farm culvert	0.752	0.000
2 Leigh Brook existing slip road	0.789	0.000
3 Leigh Brook nr A4019	0.139	0.000
4 A4019	0.042	0.000
5 Withybridge Gardens	1.147	0.811
6 north of Butlers court	0.439	0.140
7 Eastern end of River Chelt floodplain	0.184	0.184
8 nr Staverton culvert	0.388	0.308
9 Boddington Lane	0.366	0.433

Table 7-11 – Sensitivity of flood flows to structure blockage

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

Location	With blockage flow (m^3/s)	Without blockage (Baseline) flow (m^3/s)
A Barn farm culvert	0.7	2.2
B Piffs elm culvert	0.2	3.0
C River Chelt culvert	20.9	18.3
D Staverton culvert	0.3	2.7
E A4019 culvert	0.1	0.0
F A4019 over the top	0.6	0.0
G Withybridge Lane	8.2	8.2
H Boddington Lane (nr downstream boundary)	0.3	3.0

Figure 28 – Sensitivity of flood extent to structure blockage



Sensitivity to downstream boundary

7.3.27. A sensitivity test was undertaken on the downstream boundaries. Tests were made by applying a modification to all downstream boundaries to evaluate the impact of change in the stage-discharge relationships and normal depth conditions used.

7.3.28. Changes were made to reflect extreme boundary conditions from what was considered to be a reasonable Baseline. The variations applied are tabulated below.

Table 7-12 – Variation in downstream boundary

Downstream boundary	Reduced level	Baseline	Increased level
River Chelt 1D	All stage -1 m	QH	All stage + 1 m
River Chelt 2D normal-depth slope	1 in 100	1 in 200	1 in 1,000
Leigh Brook 1D	All stage - ½m	QH	All stage + 1 m
Leigh Brook 2D normal-depth slope	1 in 100	1 in 200	1 in 1,000

7.3.29. The results indicate that generally the model is insensitive to variations in the downstream boundary. Flood extents, depth and flow results are very similar whether the downstream boundary levels are reduced, increased, or set at Baseline conditions.

7.3.30. There are minor differences in flood extents at the downstream boundaries of both the Leigh Brook and Chelt, but these do not propagate upstream to the M5 motorway in either the increased or reduced downstream level simulations.

7.3.31. Increasing the downstream boundary levels results in slightly more flooding at the downstream boundaries, compared to the Baseline results. Similarly, reducing the downstream boundary levels results in slightly less flooding at these locations, compared to the Baseline results.

7.3.32. The sensitivity of the model to changes in water level at the downstream boundaries confirms the initial backwater calculation used in setting the boundary location.

Selected point results are tabulated below to give an indication of the scale of change in the study area, 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 25 above.

Table 7-13 – Sensitivity of flood depths to downstream boundary

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

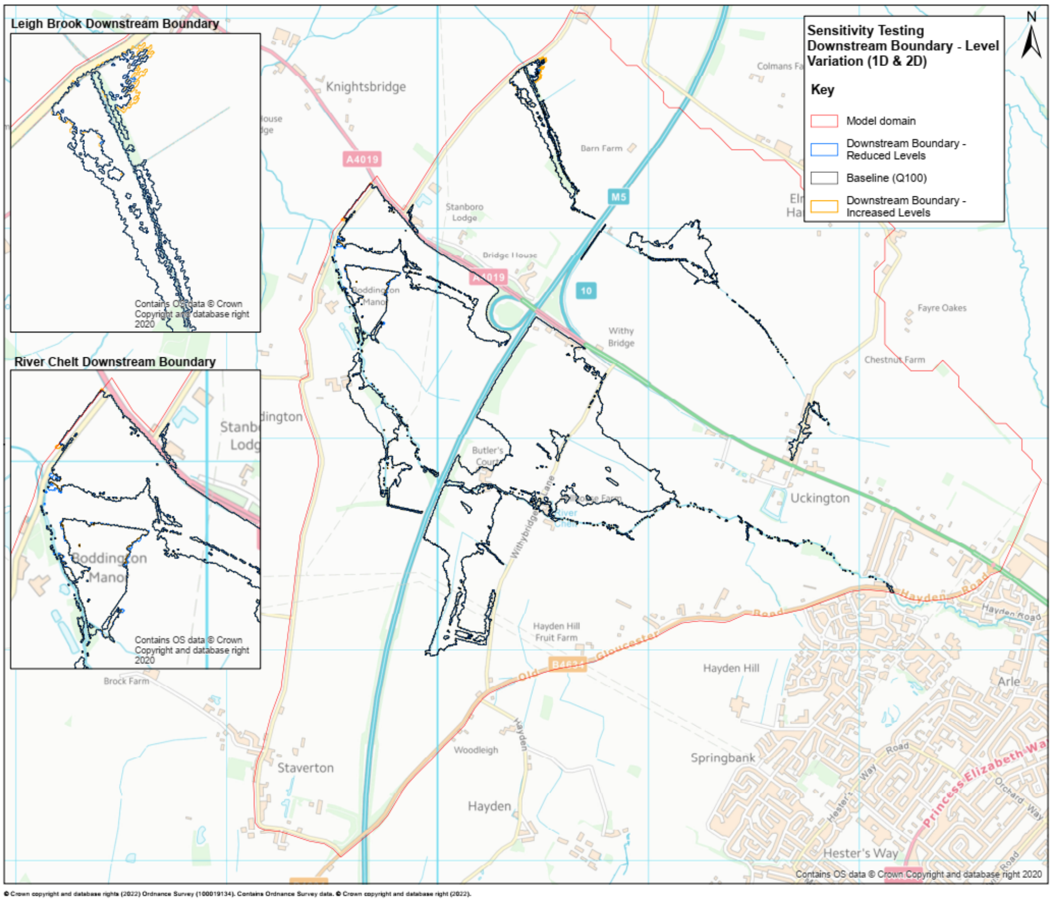
Location	Reduced boundary depth (m)	Baseline depth (m)	Raised boundary depth (m)
1 Leigh Brook nr Barn Farm culvert	0.000	0.000	0.000
2 Leigh Brook existing slip road	0.000	0.000	0.000
3 Leigh Brook nr A4019	0.000	0.000	0.000
4 A4019	0.000	0.000	0.000
5 Withybridge Gardens	0.811	0.811	0.811
6 north of Butlers court	0.140	0.140	0.140
7 Eastern end of River Chelt floodplain	0.184	0.184	0.184
8 nr Staverton culvert	0.308	0.308	0.308
9 Boddington Lane	n/a - at the downstream boundary		

Table 7-14 – Sensitivity of flood flows to downstream boundary

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

Location	Reduced level flow (m^3/s)	Baseline flow (m^3/s)	Increased level flow (m^3/s)
A Barn farm culvert	2.2	2.2	2.2
B Piffs elm culvert	3.0	3.0	3.0
C River Chelt culvert	18.3	18.3	18.3
D Staverton culvert	2.7	2.7	2.7
E A4019 culvert	0.0	0.0	0.0
F A4019 over the top	0.0	0.0	0.0
G Withybridge Lane	8.2	8.2	8.1
H Boddington Lane (nr downstream boundary)	3.0	3.0	3.0

Figure 29 – Sensitivity of flood extent to downstream boundary



Sensitivity to upstream boundary

7.3.33. A sensitivity test was undertaken on the upstream boundaries. Tests were made by varying the inflow applied to all upstream boundaries, applying the flow hydrographs scaled to the lower FEH Statistical flow estimates, and adding a 20% increase. These are tabulated below.

Table 7-15 – Variation in flow

	FEH Stat flow	Baseline (ReFH2)	ReFH2 + 20%
River Chelt at M5	20.4	24.5	29.4
River Chelt downstream M5	1.7	2.2	2.7
Leigh Brook at M5	1.8	2.5	3.0
Leigh Brook downstream M5	1.0	1.3	1.6
Staverton stream	2.4	4.1	4.9
Arle CSO*	3.9	3.9	4.7

*Flows provided by Severn Trent Water

7.3.34. The results indicate that generally the model is sensitive to flows at the upstream boundary. As expected, increasing flows (ReFH2+20%) has increased flood extents, depth and flow results compared to the Baseline, whereas decreasing flows (flows scaled to FEH statistical peak) has reduced these compared to the Baseline results. The most significant increase in flood extents occurs upstream of the motorway on the Leigh Brook floodplain, where the River Chelt overtops the A4019 and contributes to the Leigh Brook floodplain with a 20% higher inflow, yet does not using the Baseline inflows.

7.3.35. In particular, where flows have been increased at the upstream boundary, there is more water coming out of bank from the River Chelt channel onto the eastern end of the Chelt floodplain. This is reflected in the increase in flows passing over Withybridge lane in the ReFH2+20% simulation, being 12.9 m^3/s compared to 8.2 m^3/s in the Baseline and 4.0 m^3/s in the lower FEH statistical flow simulation.

7.3.36. The increase in River Chelt flood water at this location results in overtopping of the A4019 and larger flood extents north of the A4019 where flooding extends into the Leigh Brook. The results show 1.1 m^3/s overtopping the A4019 in the ReFH2+20% simulation. In comparison, the lower FEH statistical flow and Baseline results show no overtopping of the A4019 in this event, and there is very little flooding between the Leigh Brook and A4019. Furthermore, the ReFH2+20% (increased flow) simulation was predicted to increase flooding to the properties near Uckington Farm, just west of the start of the Leigh Brook watercourse.

7.3.37. There are increased flows through all motorway culverts in the higher flow ReFH2+20% simulation, resulting in larger flood extents downstream of the motorway compared to the Baseline. Similarly, there is considerably less water passing through the motorway culverts in the lower statistical flow simulation, resulting in smaller flood extents downstream of the motorway compared to the Baseline.

7.3.38. There is more flooding downstream of Piffs Elm Culvert where flows have been increased at the upstream boundary, resulting in water overtopping the A4019 further downstream and entering the pond west of Stanboro Lodge. Whilst floodwater overtops the A4019 in the Baseline simulation, it does not extend as far north as the pond. In the reduced flows simulation, water does not overtop this road.

7.3.39. The depth results follow the same pattern as the flow results. All depth results, both upstream and downstream of the motorway, are higher in the ReFH2+20% simulation due to the increase in model inflows compared to the Baseline. Whereas all depth results are lower in the statistical flow simulation due to a decrease in inflows.

7.3.40. Consideration was made to how the preferred flows entered each watercourse, specifically how a flow might be spread across a 2D boundary. However, as each inflow hydrograph was applied from a baseflow such that all water was contained within the 1D cross section, no out of bank flows were required at the start of each model run.

7.3.41. The risk of flows entering the River Chelt via overland flow paths, bypassing the upstream boundary was considered. The LiDAR data indicates that any overland flow would be directed towards the River Chelt bridge, although with a low risk of water being able to outflank the river on the northern (right) bank of the river into the forecourt of the Bristol Street Motors car dealership. However, given the relatively high ground along Appleyard Close (off the A4019), any overland flow would be directed back to the river as it passed across the sports ground of the Cheltenham Civil Service club.

7.3.42. Selected point results are tabulated below 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 25 above.

Table 7-16 – Sensitivity of flood depths to upstream boundary

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

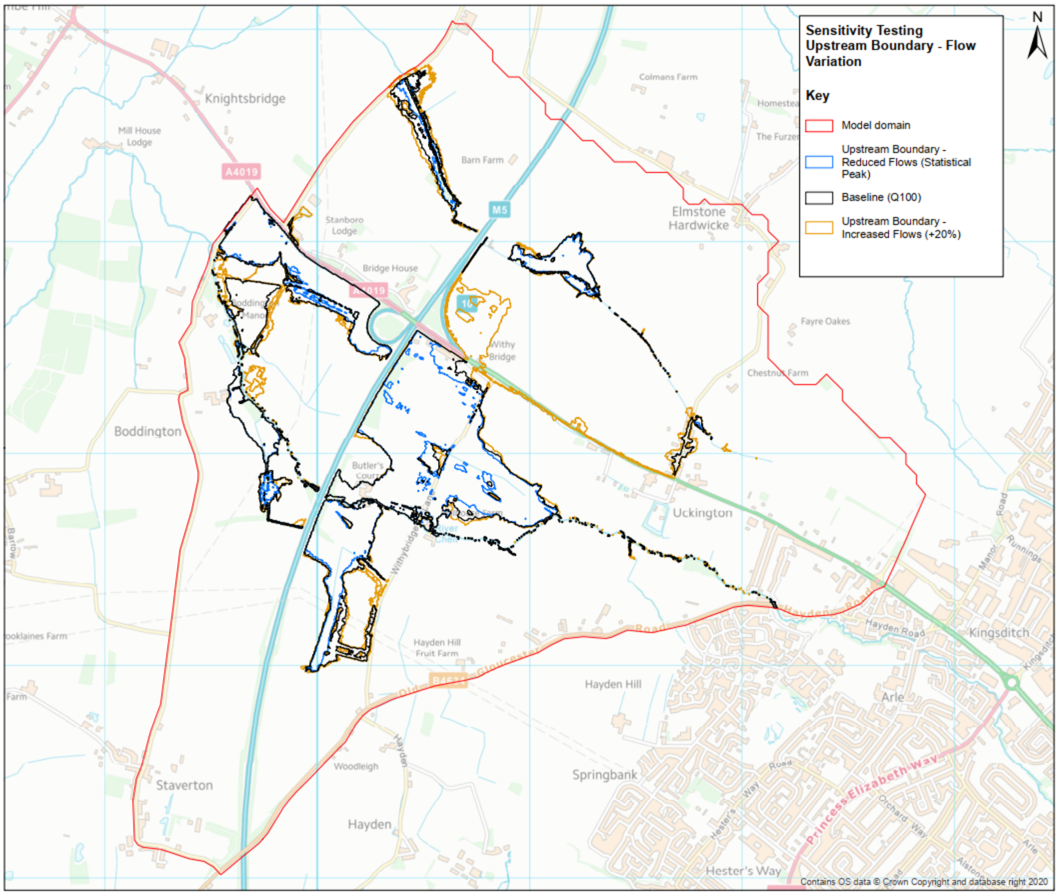
Location	FEH Stat flow depth (m)	Baseline (ReFH2) depth (m)	ReFH2 + 20% depth (m)
1 Leigh Brook nr Barn Farm culvert	0.000	0.000	0.000
2 Leigh Brook existing slip road	0.000	0.000	0.006
3 Leigh Brook nr A4019	0.000	0.000	0.152
4 A4019	0.000	0.000	0.074
5 Withybridge Gardens	0.210	0.811	1.212
6 north of Butlers court	0.116	0.140	0.504
7 Eastern end of River Chelt floodplain	0.109	0.184	0.217
8 nr Staverton culvert	0.119	0.308	0.350
9 Boddington Lane	0.415	0.433	0.446

Table 7-17 – Sensitivity of flood flows to upstream boundary

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

Location	FEH Stat flow (m^3/s)	Baseline (ReFH2) flow (m^3/s)	ReFH2 + 20% flow (m^3/s)
A Barn farm culvert	1.5	2.2	4.2
B Piffs elm culvert	2.3	3.0	3.5
C River Chelt culvert	17.2	18.3	19.9
D Staverton culvert	2.5	2.7	2.8
E A4019 culvert	0.0	0.0	3.1
F A4019 over the top	0.0	0.0	1.1
G Withybridge Lane	4.0	8.2	12.9
H Boddington Lane (nr downstream boundary)	1.8	3.0	3.9

Figure 30 – Sensitivity of flood extent to upstream boundary



Sensitivity to climate change

7.3.43. A sensitivity test was undertaken by applying alternative climate change allowances, including the Upper End (credible maximum) uplifts, on the flows. For the River Chelt and its tributaries, the Upper End scenario requires a +94% increase in peak flow. See Section 5.4.

7.3.44. Changes were made to reflect these scenarios by stretching the peak flows as with the Higher Central allowance used in the design flood.

Table 7-18 – Peak flow with different climate change allowances

	Peak 100yr flow m³/s			
	Present day (+0%)	Central (+37%)	Higher (+53%)	Upper End (+94%)
River Chelt at M5	24.5	33.5	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	4.8
Leigh Brook downstream M5	1.3	1.8	2.0	2.5
Staverton stream	4.1	5.5	6.2	7.9
Arle CSO	4.0	5.4	6.0	7.7

7.3.45. The results indicate that the model is 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.

7.3.46. In the present day event, there is no overtopping of the A4019 upstream of the M5 whereas all climate change events lead to overtopping of this road. In the highest climate change allowance event (Upper End), flows overtopping the A4019 reach 19.9 m^3/s. This significantly increases the flood extents north of this road. There is very little flooding in the present day between the A4019 and Leigh Brook watercourse, but flood extents in the climate change simulations extend from the A4019 to north of the watercourse and extend east as far as The Green road. This will result in further flooding to the properties around Uckington Farm, just west of the source of the Leigh Brook.

7.3.47. Adding climate change allowances to the model also results in further out of bank flooding along the River Chelt, both upstream and downstream of the M5 motorway. In the Higher Central (+53%) and Upper End (+94%) climate change simulations flooding reaches the properties around Moat Lane, which does not occur in the Baseline or Central allowance (37%) simulations. There is also a significant increase in flooding in the Higher Central allowance (+53%) and Upper End (94%) climate change simulations west of the M5 motorway, just upstream of Boddington Manor. This appear due to the increase in flows through the Chelt Culvert under the M5: Baseline 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.

7.3.48. Selected point results are tabulated below 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 25 above.

7.3.49. A key finding of this sensitivity test, and from the sensitivity to upstream boundary, is that any increase in peak flow, or flow estimate, by only 4.9 m^3/s, will lead to overtopping of the A4019 in its current geometry, and an increase in flooding in the Leigh Brook catchment. In effect, this scenario would play out if applying the Central climate change estimate (+19%) for the 2050s epoch (the years 2040 to 2069). Furthermore, it may well occur in the 2020s epoch (the years 2015 to 2039) should the Higher Central (+20%) scenario come to bear.

Table 7-19 – Sensitivity of flood depths to climate change

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

Location	Present day depth (m)	Central +37% depth (m)	Higher Central +53% depth (m)	Upper End +94% depth (m)
1 Leigh Brook nr Barn Farm culvert	0.000	0.202	0.708	1.500
2 Leigh Brook existing slip road	0.000	0.303	0.750	1.538
3 Leigh Brook nr A4019	0.000	0.203	0.234	0.879
4 A4019	0.000	0.196	0.254	0.347
5 Withybridge Gardens	0.811	1.340	1.427	1.563
6 north of Butlers court	0.140	0.633	0.721	0.857
7 Eastern end of River Chelt floodplain	0.184	0.238	0.257	0.289
8 nr Staverton culvert	0.308	0.389	0.431	0.535
9 Boddington Lane	0.433	0.460	0.469	0.485

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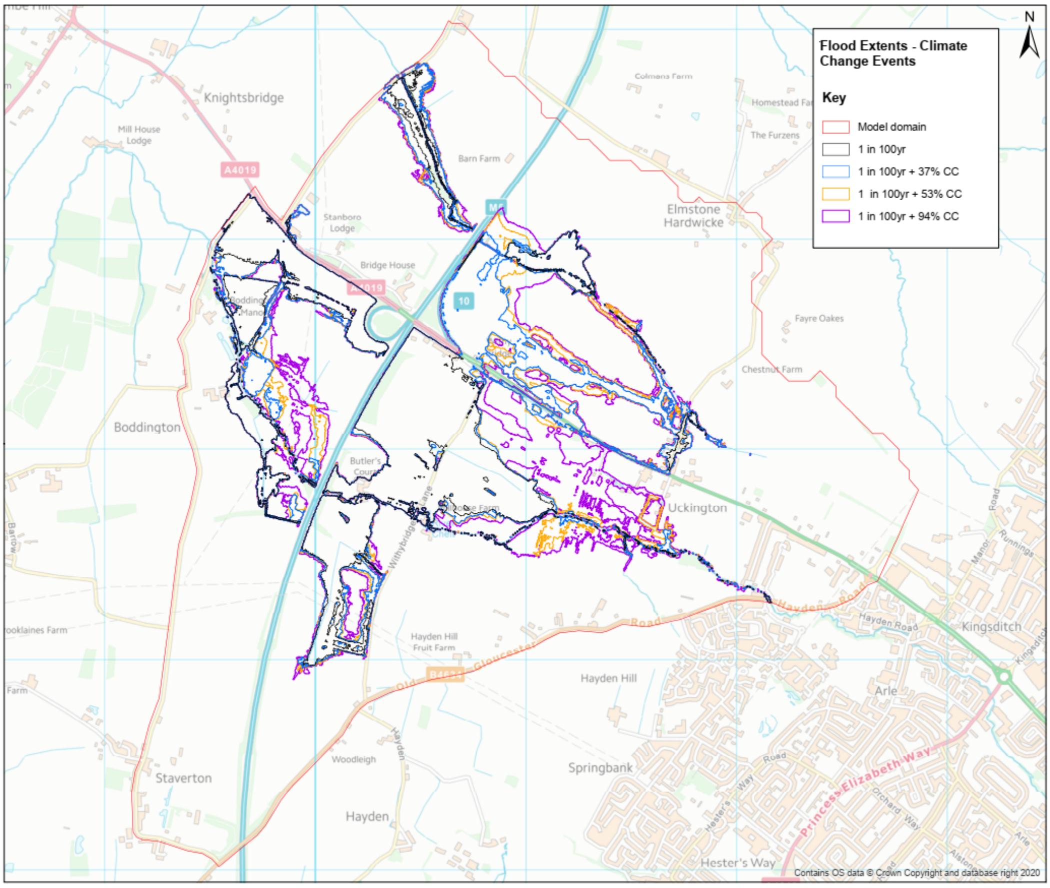
Table 7-20 – Sensitivity of flood flows to climate change

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

Location	Present day flow (m^3/s)	Central +37% flow (m^3/s)	Higher Central +53% flow (m^3/s)	Upper End +94% flow (m^3/s)
A Barn farm culvert	2.2	8.0	9.4	11.2
B Piffs elm culvert	3.0	3.6	3.7	3.8
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	1.6	1.6	1.7
F A4019 over the top	0.0	5.9	10.3	19.9
G Withybridge Lane	8.2	16.9	20.6	28.7
H Boddington Lane (nr downstream boundary)	3.0	5.1	5.9	7.7

Figure 31 – Sensitivity of flood extent to climate change



7.4. Run parameters

TUFLOW version

7.4.1. The 2020-01-AB-iSP-w64 version of TUFLOW (and ESTRY) was applied for the calibration and Baseline runs. A Sensitivity test was undertaken using the latest version of TUFLOW (2020-10-AC).

7.4.2. The results indicate that the model is generally insensitive to the version of TUFLOW which is applied to the model. There are little to no differences in flood extents, depth and flow results whether the model is run with TUFLOW 2020-01-AB or the latest version, TUFLOW 2020-10-AC.

7.4.3. The only minor difference in depth results is at Withybridge gardens; whereby using TUFLOW 2020-01-AB generates a depth of 0.811 m, compared to using TUFLOW 2020-10-AC which generates a slightly smaller depth of 0.809 m at this location. Similarly, the only minor difference in flow results is over Withybridge Lane; whereby using TUFLOW 2020-10-AC results in a slightly lower flow of 8.1 m^3/s than that generated using TUFLOW 2020-10-AB (8.2 m^3/s).

7.4.4. There are no noticeable differences in flood extents across the TUFLOW 2020-10-AC and TUFLOW-01-AB simulations.

7.4.5. Selected point results are tabulated below to give an indication of the scale of change, comparing the present day 1% annual exceedance probability event (1 in 100-year return period) run using both TUFLOW 2020-01-AB and TUFLOW 2020-10-AC. The location of these points are shown in Figure 25 above.

Table 7-21 – Sensitivity of flood depths to TUFLOW version

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

Location	2020-10-AB-iSP-w64	2020-10-AC-iSP-w64
1 Leigh Brook nr Barn Farm culvert	0.000	0.000
2 Leigh Brook existing slip road	0.000	0.000
3 Leigh Brook nr A4019	0.000	0.000
4 A4019	0.000	0.000
5 Withybridge Gardens	0.811	0.809
6 north of Butlers court	0.140	0.140
7 Eastern end of River Chelt floodplain	0.184	0.184
8 nr Staverton culvert	0.308	0.308
9 Boddington Lane	0.433	0.433

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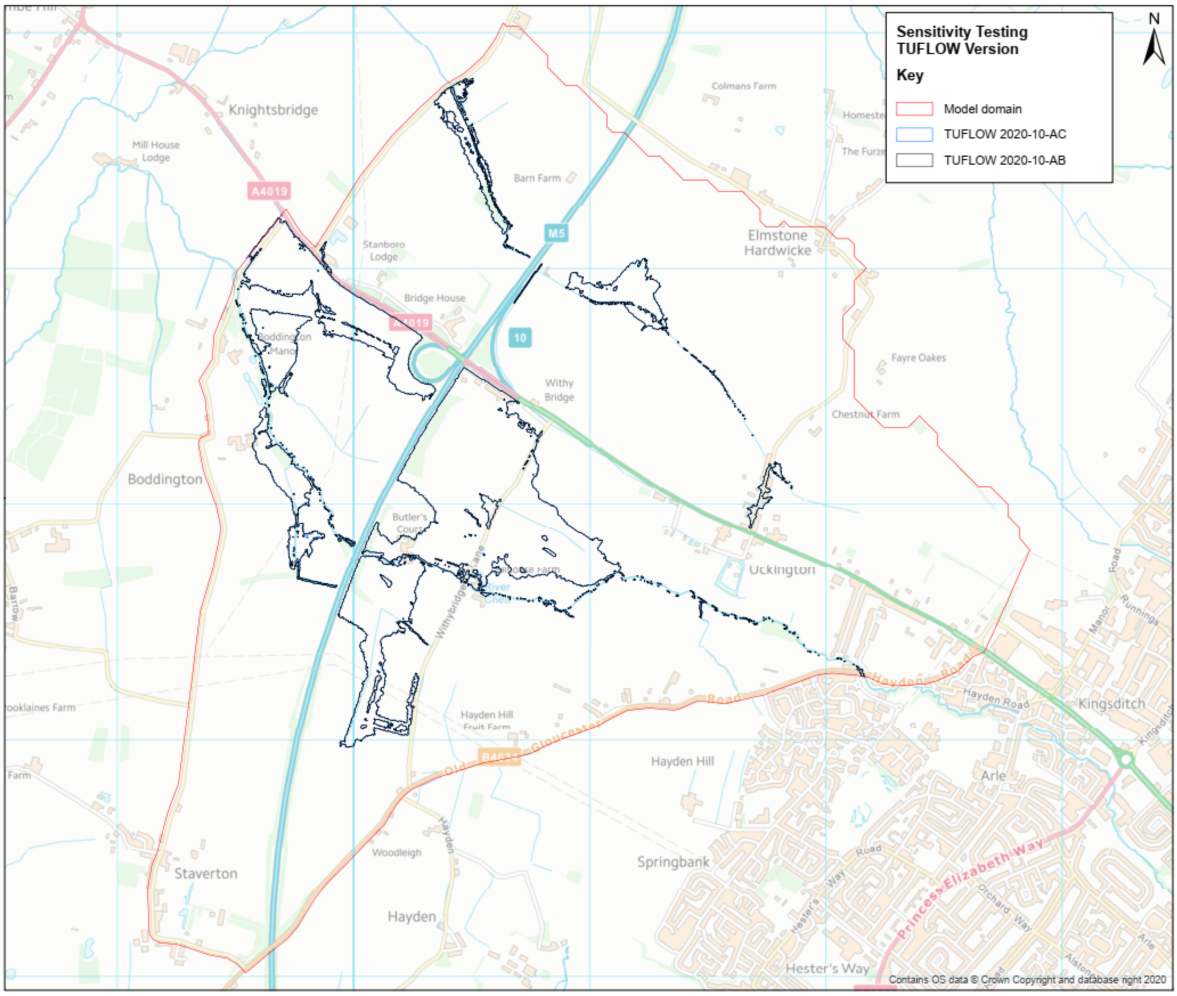
Table 7-22 – Sensitivity of flood flows to TUFLOW version

1% annual exceedance probability event (1 in 100-year return period) flow in m³/s

Location	2020-10-AB-iSP-w64	2020-10-AC-iSP-w64
A Barn farm culvert	2.2	2.2
B Piffs elm culvert	3.0	3.0
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	8.1
H Boddington Lane (nr downstream boundary)	3.0	3.0

Figure 32 – Sensitivity of flood extent to TUFLOW version



TUFLOW Hardware Configuration

7.4.6. The TUFLOW model was applied using the highly parallelised compute option (HPC) to speed up run times in combination with GPU hardware. A sensitivity test was undertaken on the model's sensitivity to TUFLOW hardware configuration, comparing results using TUFLOW GPU and TUFLOW Classic.

7.4.7. The results indicate that the model is generally insensitive to variations in the TUFLOW hardware configuration. Flood extents, depth and flow results are very similar whether the model is run with TUFLOW GPU or TUFLOW Classic.

7.4.8. There are minor differences in flood extents both upstream and downstream of the motorway; with the most obvious differences occurring downstream of the motorway. Downstream of the Staverton Culvert, TUFLOW GPU generates larger flood extents than TUFLOW Classic. Also, west of Stanboro Lodge, flows overtop the A4019 from south to north in both simulations. However, where TUFLOW Classic has been utilised, flood waters extend further north to the pond west of Stanboro Lodge. This does not occur where TUFLOW GPU is used.

7.4.9. TUFLOW GPU produces greater depths upstream of the motorway but lesser depths downstream of the motorway, compared to TUFLOW Classic.

7.4.10. The greatest difference in flow is at Withybridge Lane whereby the TUFLOW GPU simulation generates a peak flow of 8.2 m^3/s, compared to a smaller peak flow of 7.3 m^3/s generated by TUFLOW Classic.

Selected point results are tabulated below to give an indication of the scale of change, comparing the present day 1% annual exceedance probability event (1 in 100-year return period) run using both TUFLOW GPU and TUFLOW Classic. The location of these points are shown in Figure 25 above.

Table 7-23 – Sensitivity of flood depths to TUFLOW version

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

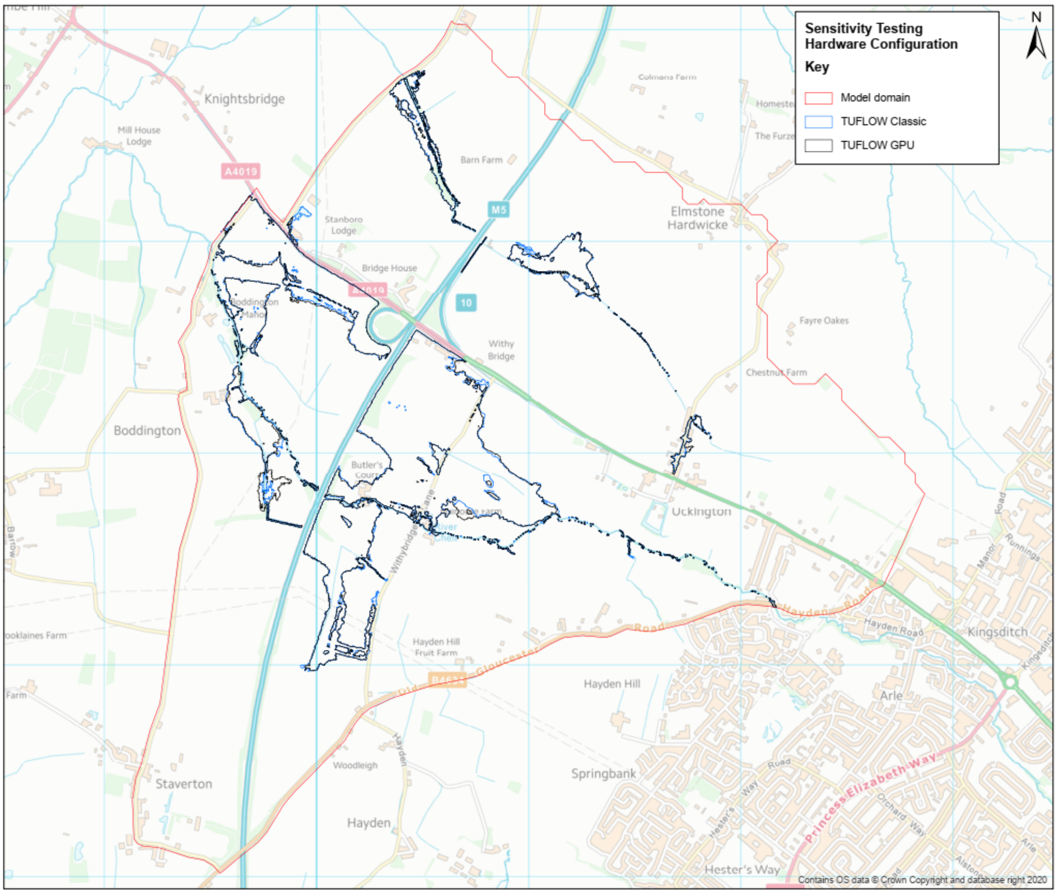
Location	TUFLOW GPU (m)	TUFLOW Classic (m)
1 Leigh Brook nr Barn Farm culvert	0.000	0.000
2 Leigh Brook existing slip road	0.000	0.000
3 Leigh Brook nr A4019	0.000	0.000
4 A4019	0.000	0.000
5 Withybridge Gardens	0.811	0.696
6 north of Butlers court	0.140	0.124
7 Eastern end of River Chelt floodplain	0.184	0.175
8 nr Staverton culvert	0.308	0.325
9 Boddington Lane	0.433	0.438

Table 7-24 – Sensitivity of flood flows to TUFLOW version

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

Location	TUFLOW GPU (m^3/s)	TUFLOW Classic (m^3/s)
A Barn farm culvert	2.2	2.2
B Piffs elm culvert	3.0	2.9
C River Chelt culvert	18.3	18.1
D Staverton culvert	2.7	3.2
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	2.9

Figure 33 – Sensitivity of flood extent to TUFLOW solver



Other run parameters

7.4.11. Standard run parameters have been adopted within the model run with sensitivity analysis undertaken on key factors.

7.4.12. A timestep of 1 second has been applied to both the 1D and 2D models. TUFLOW recommends that the timestep is typically between $^1/_5$ to $^1/_2$ of the cell size. Therefore, a 4m cell size would typically have a timestep between 0.8 and 2 seconds. Whilst the previous Baseline was run with a 0.5 second timestep, no sensitivity on computation timestep has been undertaken.

7.5. Run performance

7.5.1. The TUFLOW models were simulated using GPU hardware in addition to the HPC software. This is the same approach as applied by EVY in 2019.

7.5.2. The mass balance for the revised model is comfortably within recommended bounds (1%) as indicated in Table 7-25.

Table 7-25 – River Chelt model numerical errors

	Q100	Q1000	Q100+CC53
Volume Error	-0.00%	-0.00%	-0.00%
Final Cumulative ME	-0.02%	-0.02%	-0.02%

7.5.3. 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.

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

8. Baseline model results

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

8.1. Production of flood extents

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

- 1% annual exceedance probability event (1 in 100-year return period) – a River Chelt flow of 24.5 m^3/s estimated at the M5 motorway. See Section 8.2 below and in Appendix D of this report.
- 0.1% annual exceedance probability event (1 in 1,000-year return period) – a River Chelt flow of 38.5 m^3/s estimated at the M5 motorway. See Section 8.4 below and in Appendix D of this report.
- 1% annual exceedance probability event (1 in 100-year return period) with allowance for climate change giving 37.5 m^3/s estimated at the M5 motorway. See Section 8.5 below and in the Appendix D 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).

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

8.2. Threshold event

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

8.2.2. The river banks are predicted to overtop at the 5% annual exceedance probability event (1 in 20-year return period) with the resulting discharge flooding as far inland as Withybridge Lane. Floodwater in this event was not predicted to reach the M5 motorway.

8.2.3. The hydraulic modelling indicates that the River Chelt will spill from its right bank upstream approximately 650 m of Withybridge Lane and flow across the fields and arrives at the M5 motorway in a 4% annual exceedance probability event (1 in 25-year return period).

8.2.4. Prior to this, some out of bank flow is predicted near Withybridge Lane and Butlers Court, at a low spot in the northern bank opposite Millhouse Farm. This is predicted at the 10% annual exceedance probability event (1 in 10-year return period). At this location the historic mapping indicates a former mill stream around the property with several private crossings before being culverted under Withybridge Lane. This culvert was added to the model as a 1120 mm diameter pipe, based on survey.

8.2.5. The M5J10 model currently passes floodwater into the former mill stream in its 2D domain and overtops its right (north) bank around the property. No evidence has been received to support the predicted frequency of flooding here, although the low spot in the bank and fields is visible on site

8.2.6. The results show that there is limited flooding on the Leigh Brook floodplain during the 4% annual exceedance probability event (1 in 25-year return period). Along this watercourse, floodwater exits the channel just upstream of Barn Farm culvert and there is some out of bank flooding downstream of the M5 motorway which continues west along the watercourse to the downstream model boundary.

8.2.7. The flooding upstream of the Staverton culvert extends south to the upstream point of the Staverton tributary. Downstream of the Staverton culvert there is further flooding which extends to the confluence between the River Chelt and the Staverton tributary and continues west up to Boddington Manor.

8.2.8. Flooding downstream of Piffs Elm culvert is generally contained within a roadside ditch until it overtops its left bank near the cricket ground and then extends west to Boddington Lane, which it does not overtop. Flooding does not reach the model downstream boundary, located west of this road.

8.2.9. Selected point results are tabulated below to give an indication of the flooding. The location of these points are shown in Figure 25 above.

Table 8-1 – 4% AEP event (1 in 25-year return period) Baseline depths

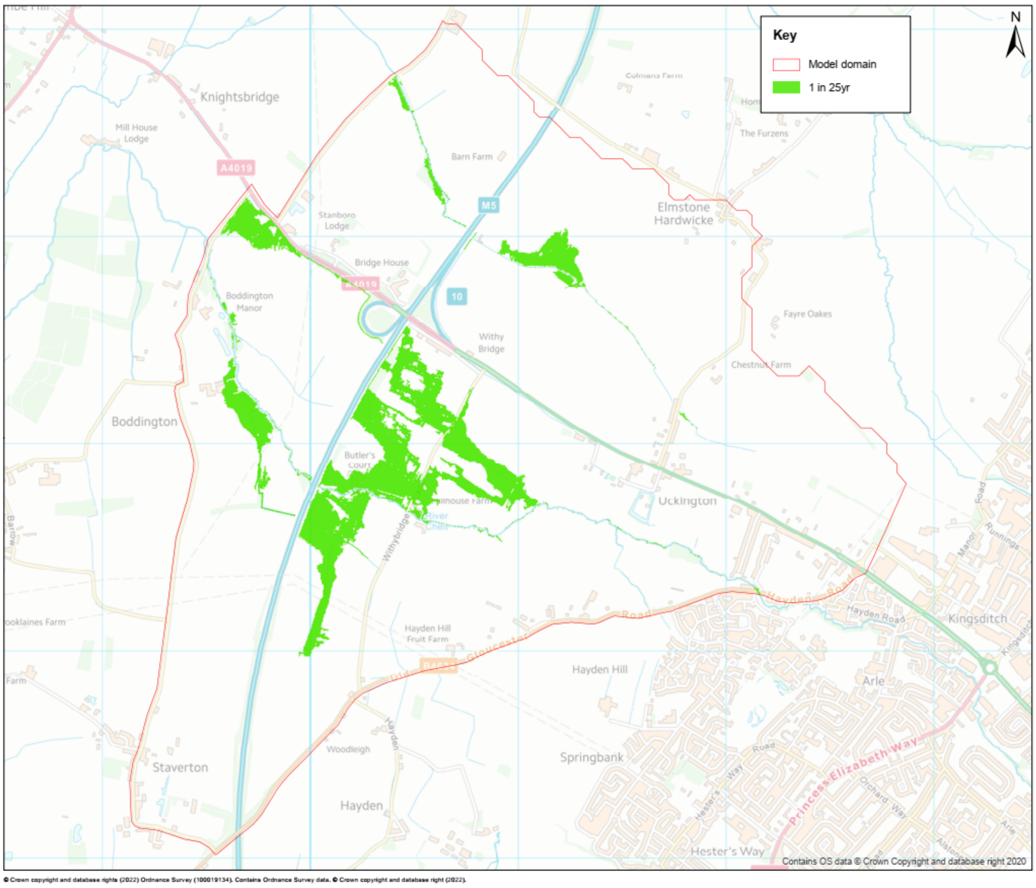
Location	Depth (m)
1 Leigh Brook nr Barn Farm culvert	0.000
2 Leigh Brook existing slip road	0.000
3 Leigh Brook nr A4019	0.000
4 A4019	0.000
5 Withybridge Gardens	0.030
6 north of Butlers court	0.000
7 Eastern end of River Chelt floodplain	0.010
8 nr Staverton culvert	0.026
9 Boddington Lane	0.086

Table 8-2 – 4% AEP event (1 in 25-year return period) Baseline flows

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

8.2.10. Flooding is predicted upstream of the Piffs Elm, River Chelt and Staverton culverts under the M5 motorway. A peak flows of 17.1 m^3/s passes through the River Chelt culvert under the M5 during this event. No water overtops the A4019 and there is also no flow passing under the road through the A4019 culvert.

Figure 34 – Flood extents for the 4% AEP event (1 in 25-year return period)



8.3. 1% AEP event (1 in 100-year return period)

8.3.1. The results show that extensive 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.

8.3.2. 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.

8.3.3. 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 during this event (1.2 m^3/s more than that in the 4% annual exceedance probability event (1 in 25-year return period)).

8.3.4. 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.

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

8.3.6. Selected point results are tabulated below to give an indication of the flooding. The location of these points are shown in Figure 25 above.

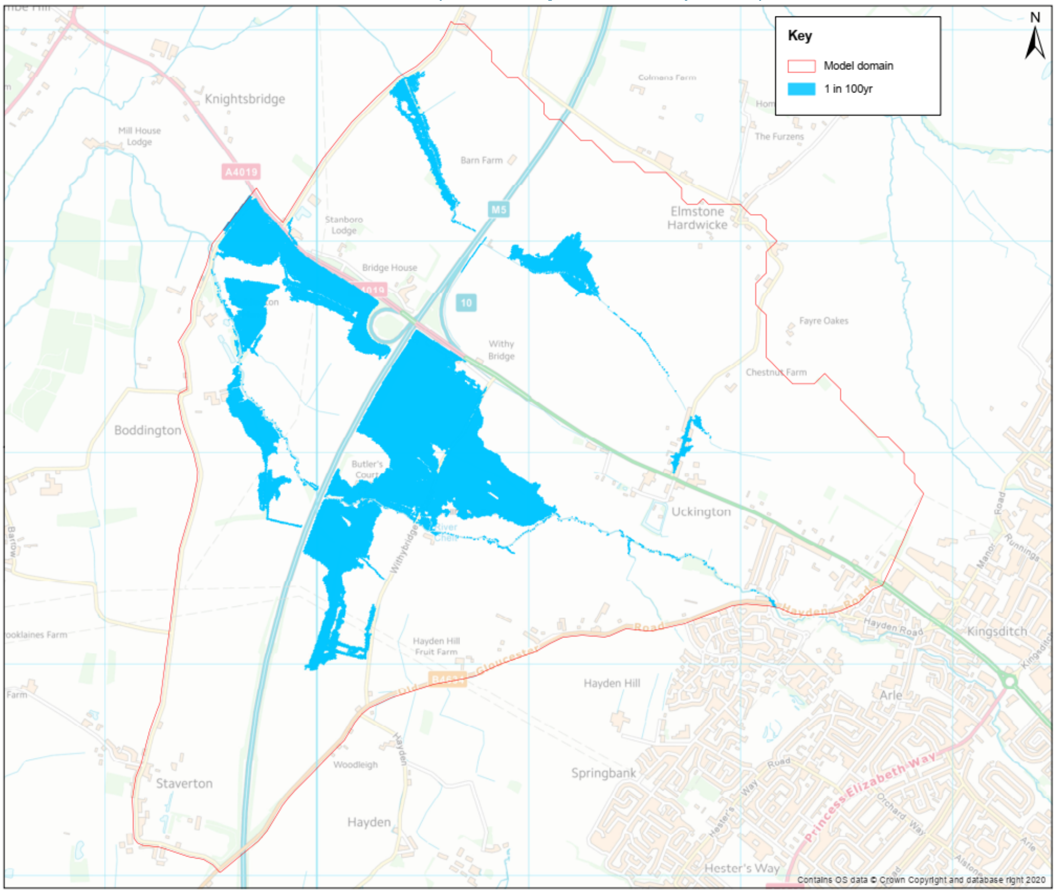
Table 8-3 – 1% AEP event (1 in 100-year return period) Baseline depths

Location	Depth (m)
1 Leigh Brook nr Barn Farm culvert	0.000
2 Leigh Brook existing slip road	0.000
3 Leigh Brook nr A4019	0.000
4 A4019	0.000
5 Withybridge Gardens	0.811
6 north of Butlers court	0.140
7 Eastern end of River Chelt floodplain	0.184
8 nr Staverton culvert	0.308
9 Boddington Lane	0.433

Table 8-4 – 1% AEP event (1 in 100-year return period) Baseline flows

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

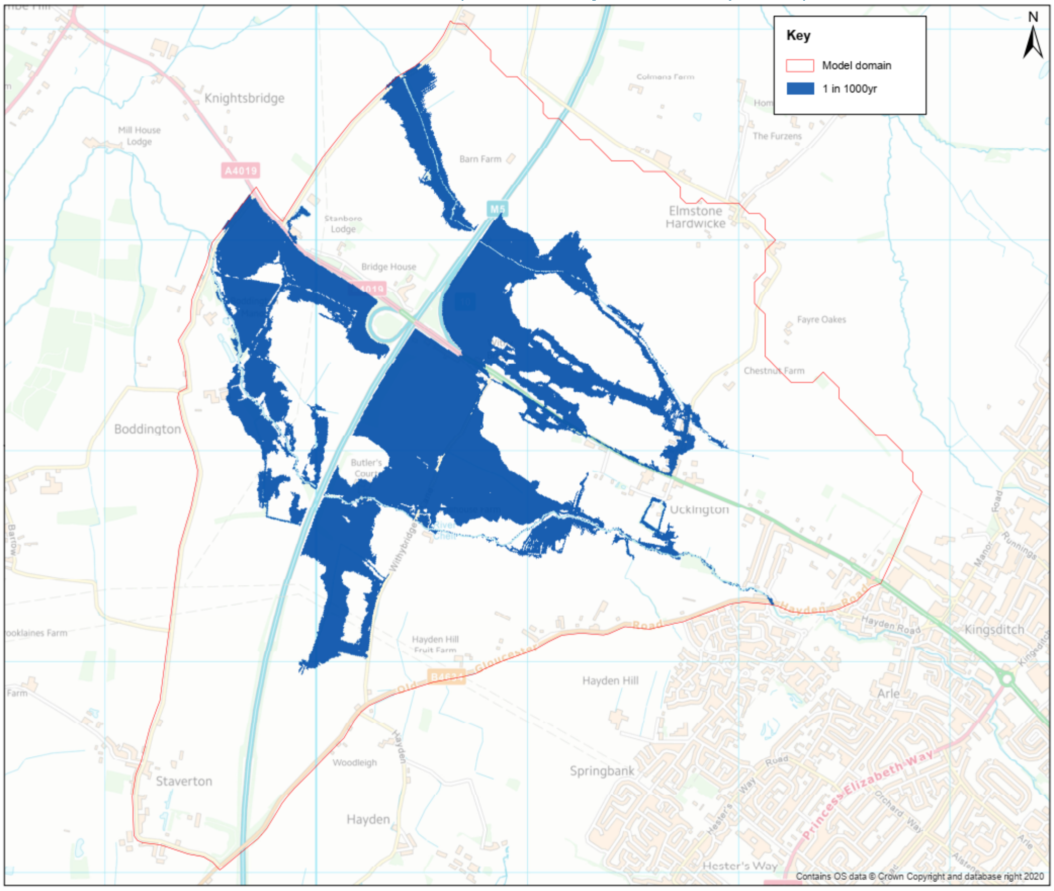
Figure 35 – Flood extents for the 1% AEP event (1 in 100-year return period)



8.4. 0.1% AEP event (1 in 1,000-year return period)

8.4.1. The 0.1% annual exceedance probability event (1 in 1,000-year return period) is predicted to cause greater extents of flooding than the 1% annual exceedance probability event (1 in 100-year return period) and the design event (includes climate change). The results are show below in Figure 36.

Figure 36 – Flood extents for the 0.1% AEP event (1 in 1,000-year return period)



8.4.2. The results again show that extensive flooding occurs on the Leigh Brook floodplain during the 0.1% annual exceedance probability event (1 in 1,000-year return period), even compared to that in the 1% annual exceedance probability event (1 in 100-year return period). In the latter there is no overtopping of the A4019, whereas the 0.1% annual exceedance probability event (1 in 1,000-year return period) results show significant overtopping of this road (13.3 m^3/s) as well as increased flows through the A4019 culverts (1.6 m^3/s). This results in widespread flooding in the Leigh Brook floodplain east of the motorway, which was not present in the 1% annual exceedance probability event (1 in 100-year return period). This flooding extends from the A4019 to the fields north of the Leigh Brook, upstream of Barn Farm culvert.

8.4.3. There is also extensive flooding just west of the headwaters of the Leigh Brook watercourse, which extends south along the Green road and causes further flooding to the properties around Uckington Farm. This flooding reaches the A4019 and flows west along this road, before overtopping it and joining the Chelt floodplain to the south.

8.4.4. More extensive flooding is also seen on the Chelt floodplain, compared to the 1% annual exceedance probability event (1 in 100-year return period). Further flood water exits the River Chelt channel at the eastern end of the Chelt floodplain, resulting in 22.4 m^3/s passing over Withybridge Lane into the fields east of the motorway.

8.4.5. There is significant flooding held east of the motorway and upstream of the Piffs Elm, River Chelt and Staverton culverts under the M5 motorway. Flows of 21.7 m^3/s pass through the River Chelt culvert under the M5 during this event (3.5 m^3/s more than that in the 1% annual exceedance probability event (1 in 100-year return period)).

8.4.6. There is more extensive flooding upstream of the Staverton culvert which extends south to the upstream point of the Staverton tributary and spreads east to Withybridge lane, compared to the 1% annual exceedance probability event (1 in 100-year return period). Downstream of the Staverton culvert there is further out of bank flooding which extends to the confluence between the River Chelt and the Staverton tributary and west up to Boddington Manor. There is also further out of bank flooding into the fields east of Boddington Manor, which joins the flood extent downstream of Piffs Elm culvert.

8.4.7. Flooding downstream of Piffs Elm culvert extends west to the downstream boundary at Boddington Lane; where 6.4 m^3/s overtops this road (3.5 m^3/s more than that in the 1% annual exceedance probability event (1 in 100-year return period)).

8.4.8. Selected point results are tabulated below to give an indication of the scale of change. The location of these points are shown in Figure 25 above.

Table 8-5 – 0.1% AEP event (1 in 1,000-year return period) Baseline depths

Location	Depth (m)
1 Leigh Brook nr Barn Farm culvert	1.046
2 Leigh Brook existing slip road	1.084
3 Leigh Brook nr A4019	0.429
4 A4019	0.287
5 Withybridge Gardens	1.474
6 north of Butlers court	0.768
7 Eastern end of River Chelt floodplain	0.265
8 nr Staverton culvert	0.448
9 Boddington Lane	0.473

Table 8-6 – 0.1% AEP event (1 in 1,000-year return period) Baseline flows

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

8.5. Climate change impacts

8.5.1. Climate change was applied by stretching the inflow hydrographs such that the peak flow was increased by 53%. The flood extents are indicated in Figure 37.

8.5.2. As described above, and indicated in the figure overleaf, 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).

8.5.3. Figure 36 presents this design event alongside those for the present day 1% annual exceedance probability event (1 in 100-year return period) and 0.1% annual exceedance probability event (1 in 1000-year return period).

8.5.4. The results show that in general:

- the 1% annual exceedance probability event (1 in 100-year return period) with 53% allowance for 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.
- All three events are typically following the same floodway and floodplain, and the flooded extents are similar on the River Chelt floodplain. There is a less flooded extent on the Leigh Brook floodplain during the 1% annual exceedance probability event (1 in 100-year return period), however the flood extents of the present day 0.1% annual exceedance probability event (1 in 1,000-year return period) as well as the 1% annual exceedance probability event (1 in 100-year return period) with 53% allowance for climate change are almost undistinguishable north of the A4019.

8.5.5. Selected point results are tabulated below to give an indication of the scale of change. The location of these points are shown in Figure 25 above.

8.5.6. 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 impact 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 phenomenon. 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.

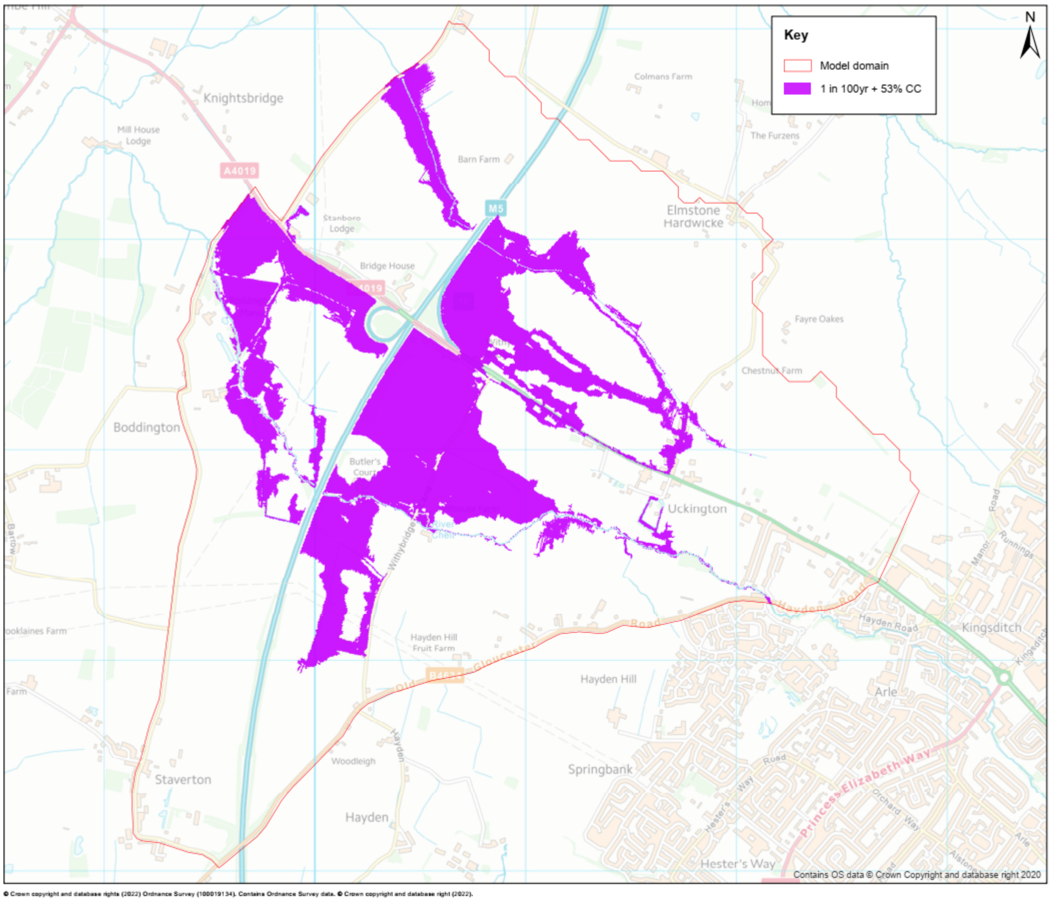
Table 8-7 – 1% AEP event (1 in 100-year return period) with climate change Baseline depths

Location	Present day depth (m)	Depth in the Year 2121 (m)	Difference from present day (m)
1 Leigh Brook nr Barn Farm culvert	0	0.708	+0.803
2 Leigh Brook existing slip road	0	0.750	+0.843
3 Leigh Brook nr A4019	0	0.234	+0.240
4 A4019	0	0.254	+0.264
5 Withybridge Gardens	0.811	1.427	+0.631
6 north of Butlers court	0.14	0.721	+0.595
7 Eastern end of River Chelt floodplain	0.184	0.257	+0.074
8 nr Staverton culvert	0.308	0.431	+0.127
9 Boddington Lane	0.433	0.469	+0.037

Table 8-8 – 1% AEP event (1 in 100-year return period) with climate change Baseline flows

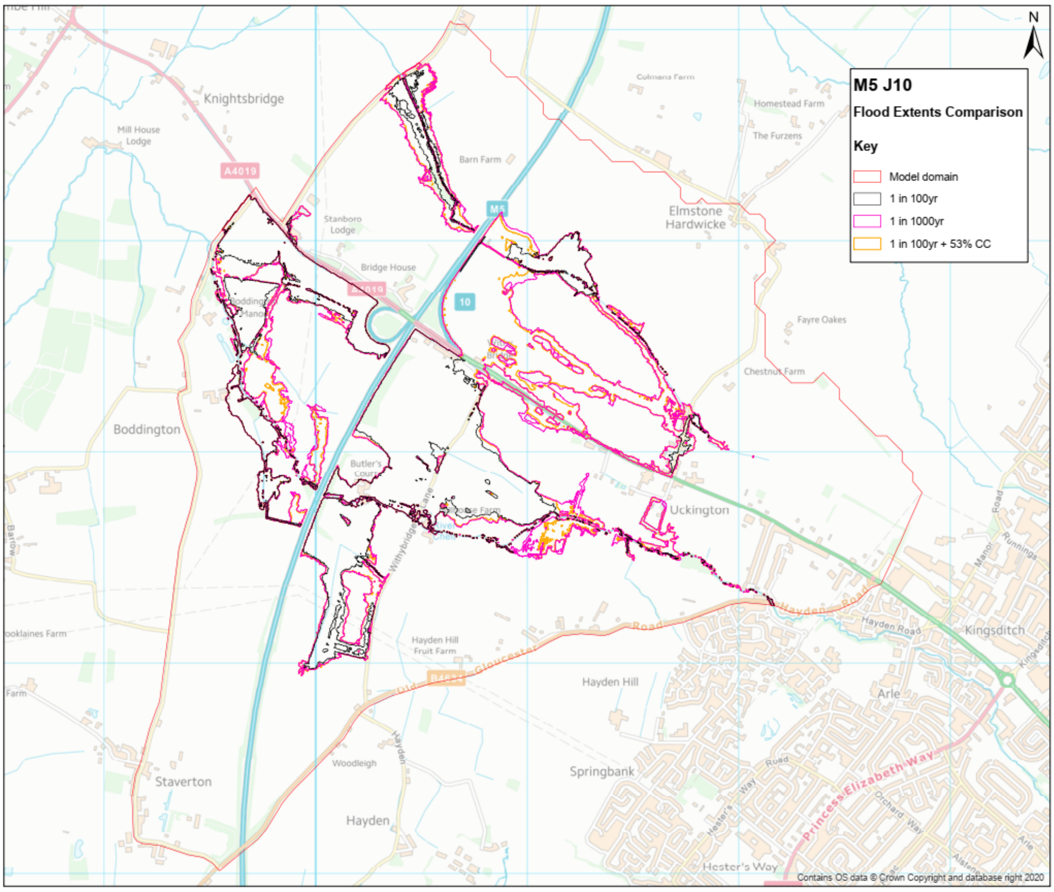
Location	Present day flow (m^3/s)	Flow in the Year 2121 (m^3/s)	Difference from present day (m^3/s)
A Barn farm culvert	2.2	9.4	+7.2
B Piffs elm culvert	3.0	3.7	+0.7
C River Chelt culvert	18.3	21.5	+3.2
D Staverton culvert	2.7	2.8	+0.1
E A4019 culvert	0.0	1.6	+1.6
F A4019 over the top	0.0	10.3	+10.3
G Withybridge Lane	8.2	20.6	+12.4
H Boddington Lane (nr downstream boundary)	3.0	5.9	+2.9

Figure 37 – Flood extents for the 1% AEP event (1 in 100-year return period) with climate change



8.5.7. As described above, and indicated in the figure overleaf, 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).

Figure 38 –Future impact of climate change on 1% AEP event (1 in 100-year return period)



8.6. Comparison with previous flood mapping

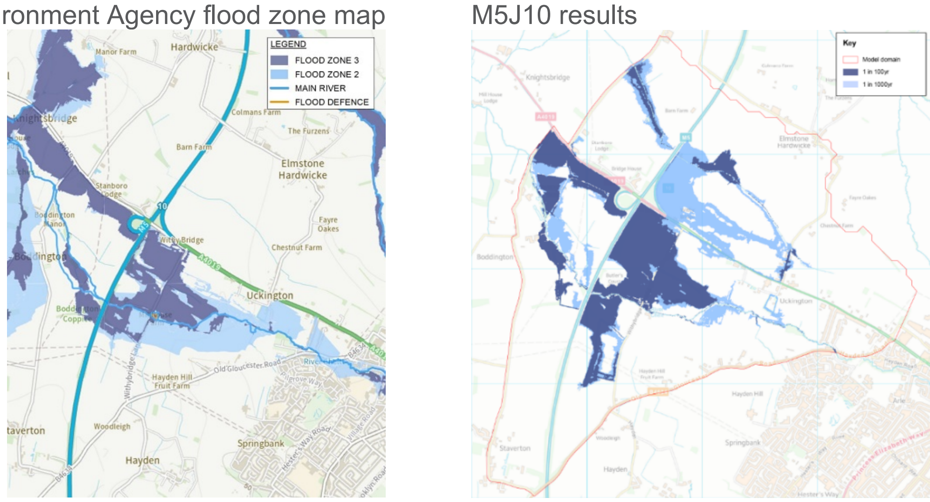
Environment Agency published flood map

8.6.1. The M5J10 model was compared to the published Environment Agency flood zone map (Flood map for planning as accessed online in February 2022). It appears that the flood zone map no longer reflects the Boddington work, although has been updated since commencement of this project. Flood Zone 2 remains based on the historic outline from 2007, although that, in itself, is based on projected wrack marks information and not the observed extents of flooding.

8.6.2. The New M5J10 modelling shows differences from the published Flood Map, notably picking up the Leigh Brook, but also flooding along the Staverton Stream. The flood map downstream of the M5 motorway appears similar to the M5J10 modelling, although there is more flooding predicted by the model than shown by the Environment Agency.

Figure 39 – Comparison of Environment Agency flood zones and M5J10 modelling

Environment Agency flood zone map M5J10 results

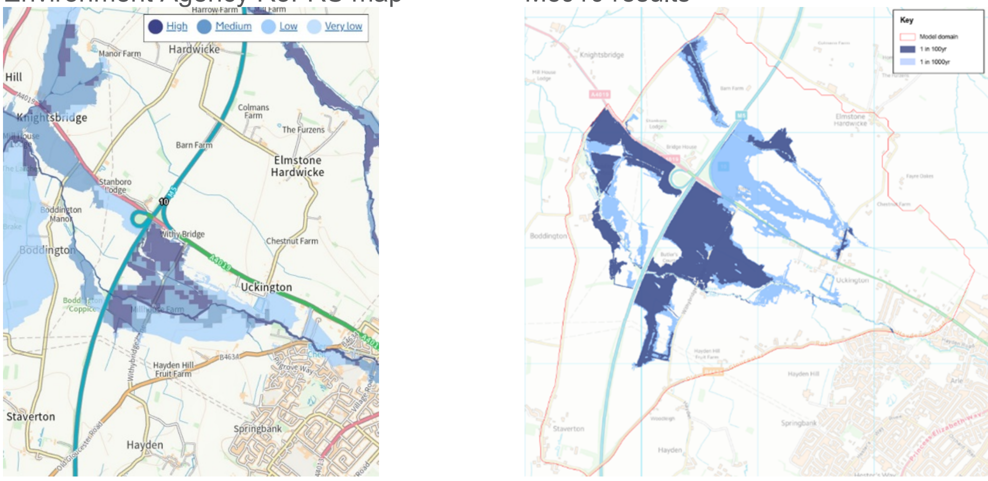


Environment Agency published flood risk from rivers or sea

8.6.3. This Environment Agency mapping (flood risk from rivers and sea) as accessed online in February 2022 does not reflect the recent work undertaken for Boddington. The New M5J10 modelling shows a bit more flooding downstream of the M5 motorway especially for the 'Low Risk' (0.1% annual exceedance probability event (1 in 1,000-year return period) extent. As above, the M5J10 modelling reflects the Leigh Brook in the area at risk of flooding, not shown on the Environment Agency flood map.

Figure 40 – Comparison of Environment Agency RoFRS and M5J10 modelling

Environment Agency RoFRS map | M5J10 results



Boddington flood map challenge

8.6.4. The M5J10 model was compared to that defined by the now approved Boddington flood map challenge. Whilst that 2019 work was used for the Environment Agency's November 2020 flood map update, it did also provide flood extents for the land to the east of the M5 motorway.

8.6.5. The New M5J10 modelling shows a similar extent of flooding. It must be remembered that the Boddington work used a direct rainfall approach and hence the flood mapping from that work reflects surface water ponding, as well as fluvial flooding.

8.6.6. The primary difference is on the Leigh Brook. The Boddington work indicates a 1% annual exceedance probability event (1 in 100-year return period) floodplain immediately upstream of the M5 motorway, with overtopping of the A4019 highway. In contrast, the M5J10 modelling does not predict either at that event.

8.6.7. In addition to the use of direct rainfall, a comparison of the flow hydrographs in the River Chelt for the 1% annual exceedance probability event (1 in 100-year return period) highlights differences in peak flow: the Boddington work simulated a higher peak flow of 30.2 m^3/s at the B4634 Old Gloucester Road, whereas the M5J10 model, with its calibrated FEH hydrology, applies 24.5m^3/s.

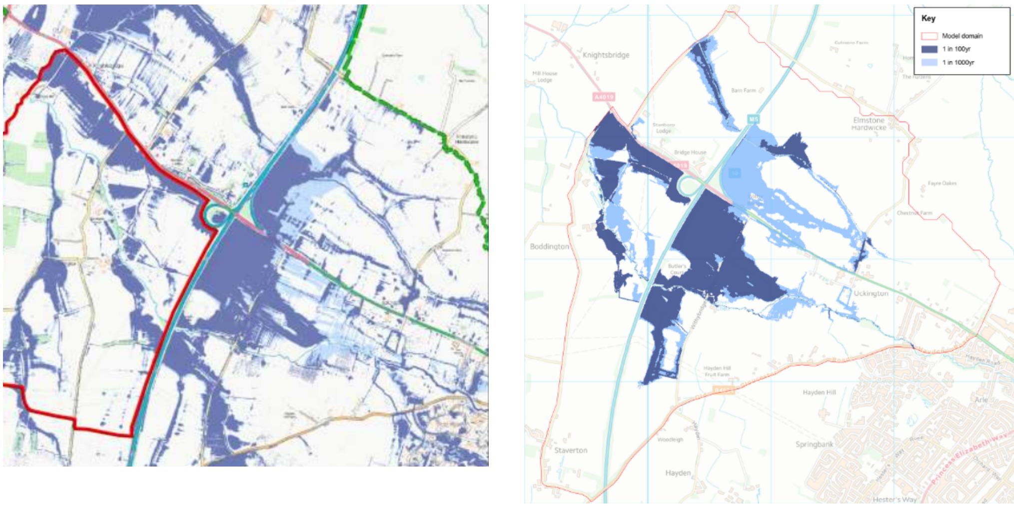
8.6.8. This is also reflected in the comparison the of July 2007 flood flows at Slate Mill, where the Boddington model predicted a higher 26.3 m^3/s at the gauge, compared to the M5J10 model of 18.6m^3/s and the recorded gauged data of 17.3 m^3/s.

8.6.9. Based on this data, if would appear that the new M5J10 model is better reflecting floods at and more extreme than the 1% annual exceedance probability event (1 in 100-year return period) and hence the prediction of little flooding upstream of Barn Farm culvert (Leigh Brook) in the present day 1% annual exceedance probability event (1 in 100-year return period).

Figure 41 – Comparison of Boddington flood zones and M5J10 modelling

Boddington map sourced from Edenvale Young (August 2019) Boddington Model Report – Flood Map Challenge. Reference EVY0630, as extract from Figure 10.2

Boddington flood map | M5J10 results



9. Assumptions and limitations

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

9.2. Assumptions

9.2.1. The application of climate change factors to the truncated M5J10 model assume a 53% uplift to the peak flow passing into the M5J10 model domain, with the runoff 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).

9.2.2. The model assumes channel, floodplain and structure conditions as observed at the time of survey and site visits. Subsequent degradation or changes taking place following this report in 2022 are not captured in the modelling.

9.3. Limitations

9.3.1. 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.

9.3.2. The model is a fluvial model and does not reflect surface water flooding caused by direct rainfall.

9.4. Future improvements

9.4.1. Atkins has applied its previous recommendations for this model since the first issued in early 2021. That included additional survey, testing software version, solution timestep, and minor improvements.

9.4.2. No further recommendations are made for the model.

10. Summary and recommendations

10.1.1. A new 1D-2D linked hydraulic model of the River Chelt and Leigh Brook has been developed using ESTRY-TUFLOW from the Environment Agency middle Chelt model (2012) upstream of the M5 motorway and the EVY Boddington model (2019) downstream of the M5 motorway. The model includes the 2019 LiDAR, topographic survey of the Leigh Brook from 2019, and enhanced throughout with new survey data at the M5 motorway and other critical structures.

10.1.2. New hydrology has been applied to the model based on ReFH2.3 assessments. A 1% annual exceedance probability event (1 in 100-year return period) flow for the River Chelt at the M5 motorway of 24.5 m^3/s was estimated, and 2.5 m^3/s for the Leigh Brook.

10.1.3. Climate change allowances have been applied to define the Baseline and hence enable scheme design evaluation. Based on an essential infrastructure classification, the new roads will need to be considered against the Higher Central allowance, being +53% on peak flow, which results in a 37.5 m^3/s design flow. The credible maximum (Upper End) scenario of +94% on peak flow will also be used as a sensitivity test in the design.

10.1.4. The model has been calibrated to the July 2007 flood and its predictions compare well with recorded flow at Slate Mill and Environment Agency wrack marks both upstream and downstream of the M5 motorway. Eight sensitivity tests were undertaken. The model is sensitive to Manning's roughness with summer vegetation increasing the river of out of bank flooding. A Spring/Autumn condition has been taken forward to the design events, being a precautionary approach for the winter storm conditions being directed by the hydrology.

10.1.5. Flooding of the farmland to the east of the M5 motorway (upstream) is underway in the 4% annual exceedance probability event (1 in 25-year return period). This may be considered to be the threshold of flooding (onset of flooding).

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

- The flooding upstream of the M5 motorway embankment, south of the A4019, reaches just under 1 km east, but not as far as Uckington
- The flooded depth by the M5 motorway is approximately 1000 mm at Withybridge Gardens (from the River Chelt)
- The flooded depth by the M5 motorway, north of Butlers Court is approximately 140 mm
- the area flooded sees the floodplain of the River Chelt separate from that of the Leigh Brook in the lands to the immediate east of the M5 motorway
- The A4019 highway is not overtopped and inundated.

10.1.7. The impacts of climate change on the 1% annual exceedance probability event (1 in 100-year return period) are for greater depths and extents of flooding on the east of the M5 motorway, notably with the River Chelt spilling over the A4019 into the catchment of the Leigh Brook. Flood depths in the Leigh Brook, at Barn Farm culvert, increase by over 700 mm with a 53% uplift on inflow. Elsewhere the impacts are typically less than 375mm with minor changes in flooded extent.

10.1.8. The 0.1% annual exceedance probability event (1 in 1,000-year return period) was predicted as causing slightly more inundation and flooded depths than the 1% annual exceedance probability event (1 in 100-year return period) with 53% increase in rainfall for climate change. The A4019 would again overtop and the depth of flooding dangerously high, being 1.43 m at Withybridge Gardens and 0.72 m just north of Butlers Court.

10.2. Recommendations

10.2.1. It is recommended that the proposed M5 Junction 10 improvements are applied to the Baseline model, such that the flood risk to and from the M5J10 Scheme can be quantified and duly mitigated.

11. Model handover

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

11.1.2. It is envisaged that the new Baseline model will be reviewed by the Environment Agency 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.

11.1.3. The model handover comprises the ESTRY TUFLOW model files akin to an Environment Agency Product 7 delivery. A model handover spreadsheet is supplied with the model files, listing the required files or model run names for each design event.

11.1.4. The review team shall note that the underlying model (geometry) originates from the Environment Agency itself and its use was approved in September 2020 by the Environment Agency for defining the flood zones in and around the village of Boddington, west of the M5 motorway. A comparison the modelling results from this M5J10 model and the approved Boddington model is provided in Section 8.6 above.

11.1.5. The baseline model and its hydrology was initially reviewed by the Environment Agency and its external consultants in March 2021. Modifications were subsequently made to the model to address various comments and suggestions, and responses were made against each comment or query put forward. The Environment Agency reviews and our responses are contained in separate MS Excel spreadsheets from July 2021[16] [17].

11.1.6. The study area for the M5J10 Scheme 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.

11.1.7. This report is intended only as an update on the Baseline model, describing in general terms the build and performance of the model, specifically with respect to changes made from the Environment Agency middle Chelt model and the approved Boddington model.

[16] Gloucestershire County Council (7 July 2021) Jacobs_HYDROLOGY_AUDIT_M5_Junction, GCCM5J10-ATK-EWE-ZZ-CA-LW-000001 revision C01
[17] Gloucestershire County Council (8 July 2021) Non-Real Time Hydraulic Model Review and response, GCCM5J10-ATK-EWE-ZZ-CA-LW-000002 revision C01

Appendices

Appendix A. Topographic survey

A.1. Survey of Leigh Brook and hydraulic structures

STRUCTURE LIST: Channel-1 (River Chelt)
(1) CS 1.04u Access Bridge 1 Concrete Bridge
(2) CS 1.07d & 1.08u A38 Inchmore Bridge Concrete Culvert - varying type
(3) CS 1.11u Access Bridge 2 Concrete Bridge
(4) CS 1.22u Access Bridge 3 Concrete Bridge
(5) CS 1.35u Footbridge 1 Timber Footbridge
(6) CS 1.42u Footbridge 2 Concrete footbridge
(7) CS 1.48d & 1.49u Boddington Bridge Brick & concrete road bridge
(8) CS 1.52u Footbridge 3 Steel arch footbridge

STRUCTURE LIST: Channel-2 (Leigh Brook)
(1) CS 2.01u Field Access 1 Brick arch culvert
(2) CS 2.06u Field Access 2 1200mm Concrete Pipe
(3) CS 2.07d & 2.08u A38 Stain's Bridge 1700mm Concrete pipe - (varying)
(4) CS 2.10u Field Access 3 Concrete bridge
(5) CS 2.14d Field Access 4 Brick arch culvert
(6) CS 2.16d Field Access 5 Steel & concrete bridge
(7) CS 2.21d & 2.22u Field Access 6 Steel & concrete bridge
(8) CS 2.30u Field Access 7 Brick arch culvert
(9) CS 2.34d Field Access 8 1100mm Steel pipe
(10) CS 2.41u Field Access 9 1100mm Steel pipe

STRUCTURE LIST: Channel-2 (Continued)
(11) CS 2.43u A4019 Knights Bridge Brick/masonry arch culvert & 1050mm concrete pipe

STRUCTURE LIST: Channel-3
(4) CS 3.01u Field Access 1 500mm Concrete pipe

STRUCTURE LIST: Channel-4 No Structures

STRUCTURE LIST: Channel-5
(1) CS 5.01u Timber Footbridge Timber footbridge
(2) CS 5.02u Field Access 900mm Concrete pipe

STRUCTURE LIST: Channel-6
(1) CS 6.02u Track Culvert 900mm Concrete pipe
(2) CS 6.03u Field Access 1 750mm Concrete pipe
(2) CS 6.05d Field Access 1 300mm Plastic pipe
(3) CS 6.07u Field Access 2 520mm Concrete pipe

STRUCTURE LIST: Channel-7 No Structures

STRUCTURE LIST: Channel-8
(1) CS 8.01u Field Access 1 500mm Concrete pipe

STRUCTURE LIST: Channel-9
(1) CS 9.01u Field Access 1 500mm Concrete pipe

STRUCTURE LIST: Channel-10
(1) CS 10.03u Field Access 300mm Plastic pipe

STRUCTURE LIST: Channel-11 No Structures

STRUCTURE LIST: Channel-12
(1) CS 12.03u Field Access 1 Brick arch culvert
(2) CS 12.04u Field Access 2 600mm Concrete pipe
(3) CS 12.05u Access Track 1 600mm Concrete pipe
(4) CS 12.07d & 2.08u Boddington Lane Culvert 1100mm Steel pipe - varying type
(5) CS 12.09u Field Access 3 Brick arch culvert

STRUCTURE LIST: Channel-13
(1) CS 13.01u Field Access 1 300mm Concrete pipe

STRUCTURE LIST: Channel-14 No Structures

STRUCTURE LIST: Channel-15
(1) CS 15.01u Boddington Lane Culvert 1 600mm Concrete pipe
(2) CS 15.02u Boddington Lane Culvert 2 600mm Plastic pipe
(3) CS 15.03d Field Access 1 600mm Plastic pipe
(4) CS 15.04u Field Access 2 450mm Concrete pipe
(5) CS 15.09u Barrow Lane Culvert 310mm Circular brick pipe

STRUCTURE LIST: Channel-16
(1) CS 16.01u Field Access 1 Collapsed culvert (construction unknown)
(2) CS 16.03u Barrow Lane Culvert Brick arch culvert
(3) CS 16.04u Field Access 2 500mm Concrete pipe

STRUCTURE LIST: Channel-17
(1) CS 17.02d Pipe Outfall 700mm Concrete pipe

STRUCTURE LIST: Channel-18
(1) CS 18.02u Field Access 1 670mm Concrete pipe
(2) CS 18.03u Field Access 2 Brick arch culvert
(3) CS 18.05u Field Access 3 520mm Concrete pipe

STRUCTURE LIST: Channel-19
(1) CS 19.01u Field Access 1 600mm Concrete pipe
(2) CS 19.04u Field Access 2 & M5 Culvert Concrete bridge & 2x 1000mm Concrete pipes

STRUCTURE LIST: Channel 1 (River Chelt)
(9) CS 1.56d & 1.57u River Chelt M5 Culvert Concrete culvert

STRUCTURE LIST: Channel 2 (Leigh Brook)
(12) CS 2.48u Footbridge 1 Timber plank with rail
(13) CS 2.51d & 2.52u Field Access 10 1530mm Concrete pipe culvert
(14) CS 2.53u Footbridge 2 Timber footbridge
(15) CS 2.57u Field Access 11 1350mm Concrete pipe culvert
(16) CS 2.58u Field Access 12 1350mm Concrete pipe culvert
(17) CS 2.59d & 2.60u Road Culvert 2x Concrete pipes

STRUCTURE LIST: Channel 2 (Leigh Brook)
(18) CS 2.64d & 2.65u Field Access 13 Brick arch culvert
(19) CS 2.67d & 2.68u M5 Culvert 2x 1250mm concrete pipes
(20) CS 2.72d & 2.73u Field Access 14 600mm Plastic pipe
(21) CS 2.79d & 2.80u Green Lane Culvert 600mm Concrete pipe
(22) CS2.81d & 2.82u Field Access 15 450mm Brick arch
(23) CS 2.84d Field Access 16 450mm Brick arch

2019 Structures Added

SHEET INDEX

1 2 3 4 5 6

LEGEND

STRUCTURE No. S1

CROSS SECTION LOCATION SYMBOL 2017

CROSS SECTION LOCATION SYMBOL 2019

RIVER CENTRELINE

100 0 100 200 300 400 500m

Scale: 1/2500 at A1; 1/5000 at A3

Client	Project
Atkins Woodcote Grove, Ashley Road Epsom KT18 5BW	Channel survey for M5 Junction 10
Surveyed: D.J. & M.B.	Apprd: R.J.FLEW
Date: Dec 2017 / Updated Nov 2019	File Ref:
Scale: 1/2500 at A1; 1/5000 at A3	Datum: OSTN15 / OSGM15

INFOMAP
SURVEYS AND MAPPING
CHARTERED SURVEYORS
Seymours House
Sunnyside Road North
Weston-super-Mare
North Somerset BS23 3PZ
Tel: 01934 644060 /fax 01934 644060
E-mail: mail@infomapsurveys.co.uk
Website: www.infomapsurveys.co.uk
RICS
ISO 9001 REGISTERED FIRM

DRAWING REFERENCE

CHANNEL SURVEYS - M5 J10 CHELTENHAM

M5-J10 ISM KEY-PLAN-SHEET 4 of 6

STRUCTURE LIST: Channel-1 (River Chelt)
1 CS 1.04u Access Bridge 1 Concrete Bridge
2 CS 1.07d & 1.08u A38 Inchmore Bridge Concrete Culvert - varying type
3 CS 1.11u Access Bridge 2 Concrete Bridge
4 CS 1.22u Access Bridge 3 Concrete Bridge
5 CS 1.35u Footbridge 1 Timber Footbridge
6 CS 1.42u Footbridge 2 Concrete footbridge
7 CS 1.48d & 1.49u Boddington Bridge Brick & concrete road bridge
8 CS 1.52u Footbridge 3 Steel arch footbridge

STRUCTURE LIST: Channel-2 (Leigh Brook)
1 CS 2.01u Field Access 1 Brick arch culvert
2 CS 2.06u Field Access 2 1200mm Concrete Pipe
3 CS 2.07d & 2.08u A38 Stain's Bridge 1700mm Concrete pipe - (varying)
4 CS 2.10u Field Access 3 Concrete bridge
5 CS 2.14d Field Access 4 Brick arch culvert
6 CS 2.16d Field Access 5 Steel & concrete bridge
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8 CS 2.30u Field Access 7 Brick arch culvert
9 CS 2.34d Field Access 8 1100mm Steel pipe
10 CS 2.41u Field Access 9 1100mm Steel pipe

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STRUCTURE LIST: Channel-4 No Structures

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1 CS 6.02u Track Culvert 900mm Concrete pipe
2 CS 6.03u Field Access 1 750mm Concrete pipe
2 CS 6.05d Field Access 1 300mm Plastic pipe
3 CS 6.07u Field Access 2 520mm Concrete pipe

STRUCTURE LIST: Channel-7 No Structures

STRUCTURE LIST: Channel-8
1 CS 8.01u Field Access 1 500mm Concrete pipe

STRUCTURE LIST: Channel-9
1 CS 9.01u Field Access 1 500mm Concrete pipe

STRUCTURE LIST: Channel-10
1 CS 10.03u Field Access 300mm Plastic pipe

STRUCTURE LIST: Channel-11 No Structures

STRUCTURE LIST: Channel-12
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3 CS 12.05u Access Track 1 600mm Concrete pipe
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STRUCTURE LIST: Channel-14 No Structures

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15 CS 2.57u Field Access 11 1350mm Concrete pipe culvert
16 CS 2.58u Field Access 12 1350mm Concrete pipe culvert
17 CS 2.59d & 2.60u Road Culvert 2x Concrete pipes

STRUCTURE LIST: Channel 2 (Leigh Brook)
18 CS 2.64d & 2.65u Field Access 13 Brick arch culvert
19 CS 2.67d & 2.68u M5 Culvert 2x 1250mm concrete pipes
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2019 Structures Added

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LEGEND

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CROSS SECTION LOCATION SYMBOL 2019

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100 0 100 200 300 400 500m

Scale: 1/2500 at A1; 1/5000 at A3

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INFOMAP SURVEYS AND MAPPING
CHARTERED SURVEYORS
Seymours House
Sunnyside Road North
Weston-super-Mare
North Somerset BS23 3PZ
Tel: 01934 644060 /fax 01934 644060
E-mail: mail@infomapsurveys.co.uk
Website: www.infomapsurveys.co.uk
RICS
ISO 9001 REGISTERED FIRM

Surveyed: D.J. & M.B.	Apprd:	R.J.FLEW	
Date: Dec 2017 / Updated Nov 2019	File Ref:		
Scale: 1/2500 at A1; 1/5000 at A3	Datum:	OSTN15 / OSGM15	

DRAWING REFERENCE

CHANNEL SURVEYS - M5 J10 CHELTENHAM

M5-J10 ISM KEY-PLAN-SHEET 5 of 6

STRUCTURE LIST: Channel-1 (River Chelt)

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3. CS 1.11u – Access Bridge 2 – Concrete Bridge
4. CS 1.22u – Access Bridge 3 – Concrete Bridge
5. CS 1.35u – Footbridge 1 – Timber Footbridge
6. CS 1.42u – Footbridge 2 – Concrete footbridge
7. CS 1.48d & 1.49u – Boddington Bridge – Brick & concrete road bridge
8. CS 1.52u – Footbridge 3 – Steel arch footbridge

STRUCTURE LIST: Channel-2 (Leigh Brook)

1. CS 2.01u – Field Access 1 – Brick arch culvert
2. CS 2.06u – Field Access 2 – 1200mm Concrete Pipe
3. CS 2.07d & 2.08u – A38 Stain's Bridge – 1700mm Concrete pipe - (varying)
4. CS 2.10u – Field Access 3 – Concrete bridge
5. CS 2.14d – Field Access 4 – Brick arch culvert
6. CS 2.16d – Field Access 5 – Steel & concrete bridge
7. CS 2.21d & 2.22u – Field Access 6 – Steel & concrete bridge
8. CS 2.30u – Field Access 7 – Brick arch culvert
9. CS 2.34d – Field Access 8 – 1100mm Steel pipe
10. CS 2.41u – Field Access 9 – 1100mm Steel pipe

STRUCTURE LIST: Channel-2 (Continued)

11. CS 2.43u – A4019 Knights Bridge – Brick/masonry arch culvert & 1050mm concrete pipe

STRUCTURE LIST: Channel-3

4. CS 3.01u – Field Access 1 – 500mm Concrete pipe

STRUCTURE LIST: Channel-4
No Structures

STRUCTURE LIST: Channel-5

1. CS 5.01u – Timber Footbridge – Timber footbridge
2. CS 5.02u – Field Access – 900mm Concrete pipe

STRUCTURE LIST: Channel-6

1. CS 6.02u – Track Culvert – 900mm Concrete pipe
2. CS 6.03u – Field Access 1 – 750mm Concrete pipe
2. CS 6.05d – Field Access 1 – 300mm Plastic pipe
3. CS 6.07u – Field Access 2 – 520mm Concrete pipe

STRUCTURE LIST: Channel-7
No Structures

STRUCTURE LIST: Channel-8

1. CS 8.01u – Field Access 1 – 500mm Concrete pipe

STRUCTURE LIST: Channel-9

1. CS 9.01u – Field Access 1 – 500mm Concrete pipe

STRUCTURE LIST: Channel-10

1. CS 10.03u – Field Access – 300mm Plastic pipe

STRUCTURE LIST: Channel-11
No Structures

STRUCTURE LIST: Channel-12

1. CS 12.03u – Field Access 1 – Brick arch culvert
2. CS 12.04u – Field Access 2 – 600mm Concrete pipe
3. CS 12.05u – Access Track 1 – 600mm Concrete pipe
4. CS 12.07d & 2.08u – Boddington Lane Culvert – 1100mm Steel pipe - varying type
5. CS 12.09u – Field Access 3 – Brick arch culvert

STRUCTURE LIST: Channel-13

1. CS 13.01u – Field Access 1 – 300mm Concrete pipe

STRUCTURE LIST: Channel-14
No Structures

STRUCTURE LIST: Channel-15

1. CS 15.01u – Boddington Lane Culvert 1 – 600mm Concrete pipe
2. CS 15.02u – Boddington Lane Culvert 2 – 600mm Plastic pipe
3. CS 15.03d – Field Access 1 – 600mm Plastic pipe
4. CS 15.04u – Field Access 2 – 450mm Concrete pipe
5. CS 15.09u – Barrow Lane Culvert – 310mm Circular brick pipe

STRUCTURE LIST: Channel-16

1. CS 16.01u – Field Access 1 – Collapsed culvert (construction unknown)
2. CS 16.03u – Barrow Lane Culvert – Brick arch culvert
3. CS 16.04u – Field Access 2 – 500mm Concrete pipe

STRUCTURE LIST: Channel-17

1. CS 17.02d – Pipe Outfall – 700mm Concrete pipe

STRUCTURE LIST: Channel-18

1. CS 18.02u – Field Access 1 – 670mm Concrete pipe
2. CS 18.03u – Field Access 2 – Brick arch culvert
3. CS 18.05u – Field Access 3 – 520mm Concrete pipe

STRUCTURE LIST: Channel-19

1. CS 19.01u – Field Access 1 – 600mm Concrete pipe
2. CS 19.04u – Field Access 2 & M5 Culvert – Concrete bridge & 2x 1000mm Concrete pipes

STRUCTURE LIST: Channel 1 (River Chelt)

9. CS 1.56d & 1.57u – River Chelt M5 Culvert – Concrete culvert

STRUCTURE LIST: Channel 2 (Leigh Brook)

12. CS 2.48u – Footbridge 1 – Timber plank with rail
13. CS 2.51d & 2.52u – Field Access 10 – 1530mm Concrete pipe culvert
14. CS 2.53u – Footbridge 2 – Timber footbridge
15. CS 2.57u – Field Access 11 – 1350mm Concrete pipe culvert
16. CS 2.58u – Field Access 12 – 1350mm Concrete pipe culvert
17. CS 2.59d & 2.60u – Road Culvert – 2x Concrete pipes

STRUCTURE LIST: Channel 2 (Leigh Brook)

18. CS 2.64d & 2.65u – Field Access 13 – Brick arch culvert
19. CS 2.67d & 2.68u – M5 Culvert – 2x 1250mm concrete pipes
20. CS 2.72d & 2.73u – Field Access 14 – 600mm Plastic pipe
21. CS 2.79d & 2.80u – Green Lane Culvert – 600mm Concrete pipe
22. CS2.81d & 2.82u – Field Access 15 – 450mm Brick arch
23. CS 2.84d – Field Access 16 – 450mm Brick arch

2019 Structures Added

SHEET INDEX

1, 2, 3, 4, 5, 6

LEGEND

STRUCTURE No. S1

CROSS SECTION LOCATION SYMBOL 2017

CROSS SECTION LOCATION SYMBOL 2019

RIVER CENTRELINE

100 0 100 200 300 400 500m

Scale: 1/2500 at A1; 1/5000 at A3

Client	Project
Atkins Woodcote Grove, Ashley Road Epsom KT18 5BW	Channel survey for M5 Junction 10
Surveyed: D.J. & M.B.	Apprd: R.J.FLEW
Date: Dec 2017 / Updated Nov 2019	File Ref:
Scale: 1/2500 at A1; 1/5000 at A3	Datum: OSTN15 / OSGM15

INFOMAP
SURVEYS AND MAPPING
CHARTERED SURVEYORS
Seymours House
Sunnyside Road North
Weston-super-Mare
North Somerset BS23 3PZ
Tel: 01934 644060 /fax 01934 644060
E-mail: mail@infomapsurveys.co.uk
Website: www.infomapsurveys.co.uk
RICS
ISO 9001 REGISTERED FIRM

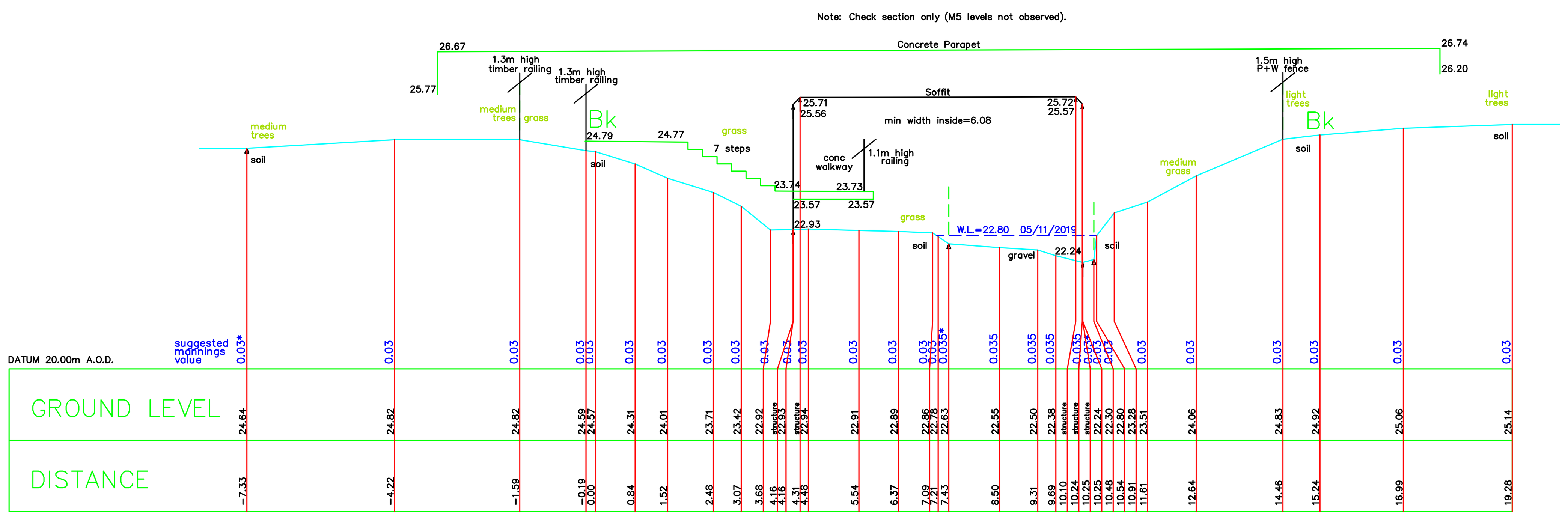
DRAWING REFERENCE

CHANNEL SURVEYS - M5 J10 CHELTENHAM

M5-J10 ISM KEY-PLAN-SHEET 6 of 6

Structure no. 1. River Chelt M5 Culvert
Description: Concrete culvert
(upstream face of structure)

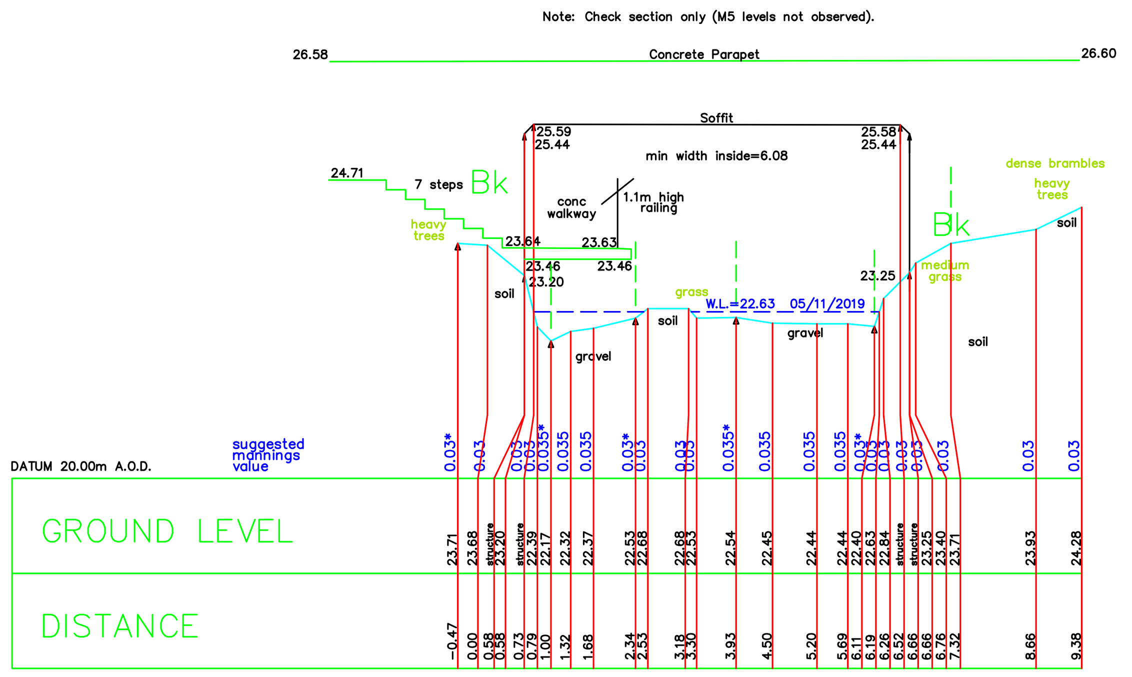
Note: Check section only (M5 levels not observed).



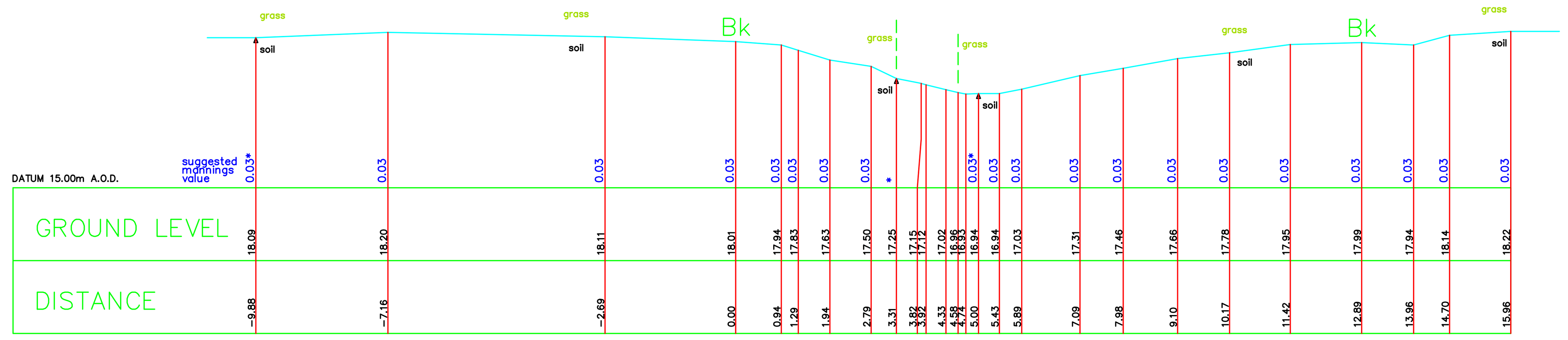
River Chelt CS 1.57u Ch. 6219.5 N.B. Structure 13 deg angle from Perpendicular.
Centre OSNG Coordinates E.390039.48 N.224797.61

Structure no. 1. River Chelt M5 Culvert
Description: Concrete culvert
(downstream face of structure)

Note: Check section only (M5 levels not observed).

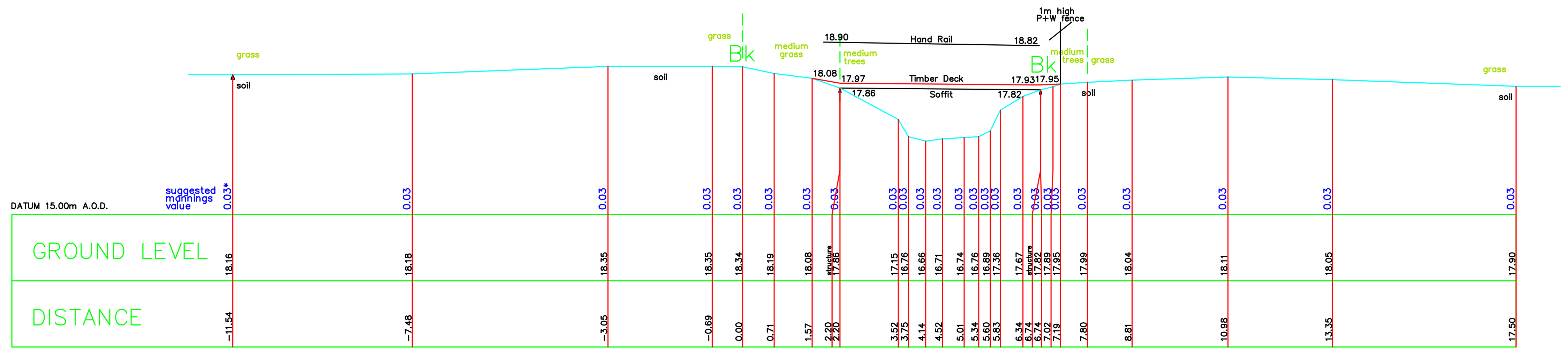


Channel 1 (River Chelt) CS 1.56d Ch. 6172.3 N.B. Structure 13 deg angle from Perpendicular.
Centre OSNG Coordinates E.390002.81 N.224827.34

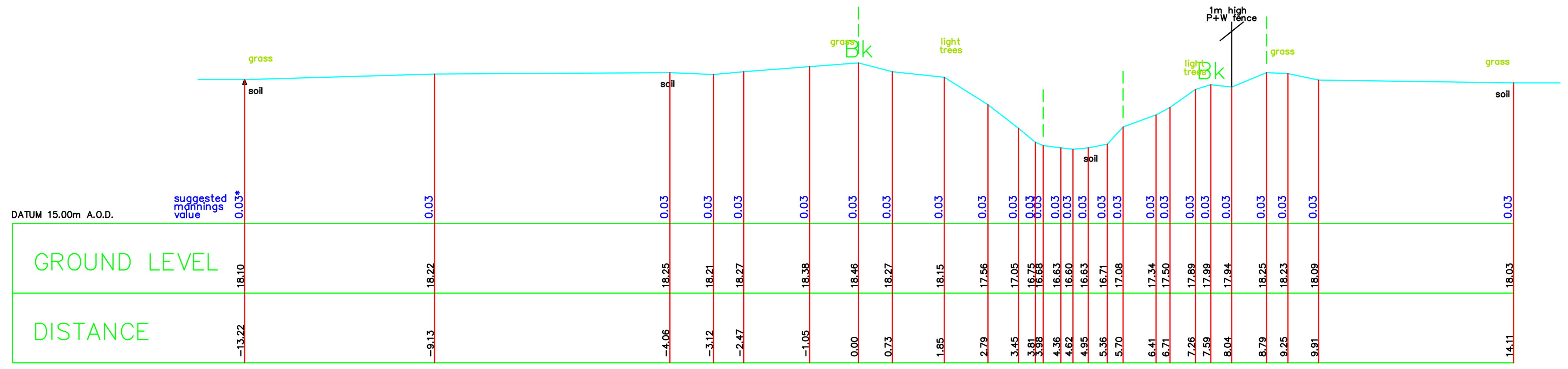


Channel 2 (Leigh Brook) CS 2.49 Ch. 4471.3
Centre OSNG Coordinates E.389732.39 N.227020.59

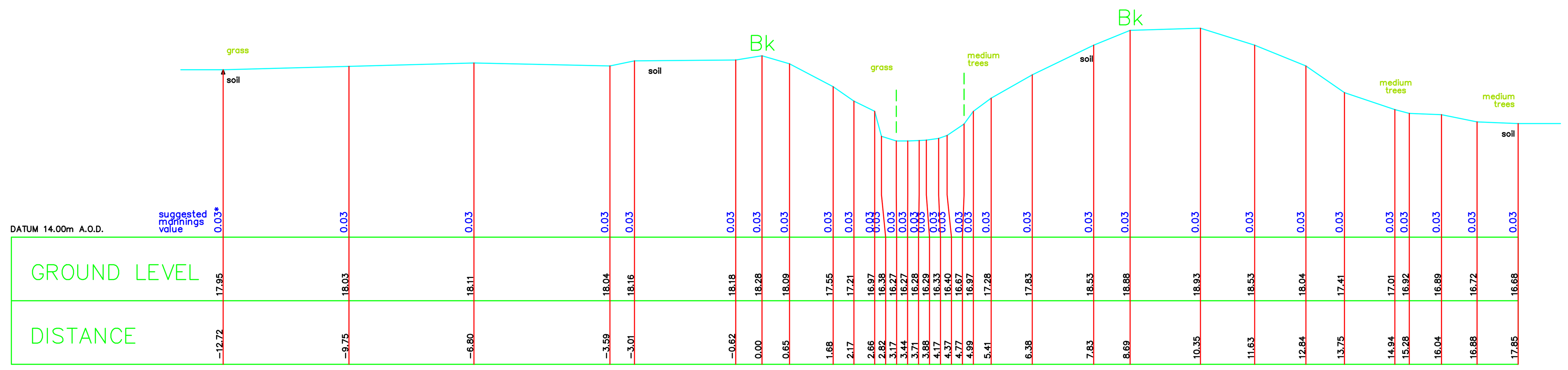
Structure no. 12. Footbridge 1
Description: Timber plank with rail
(upstream face of structure)



Channel 2 (Leigh Brook) CS 2.48u Ch. 4360.3
Centre OSNG Coordinates E.389632.76 N.226979.50



Channel 2 (Leigh Brook) CS 2.47 Ch. 4223.0
Centre OSNG Coordinates E.389521.01 N.226911.16



Channel 2 (Leigh Brook) CS 2.46 Ch. 4106.2
Centre OSNG Coordinates E.389406.70 N.226919.39

Scale: 1/100 at A1; 1/200 at A3

SURVEYED BY GPS TO OSNG. LEVEL DATUM OSGM15.
ALL SECTIONS SHOWN PERPENDICULAR TO WATERCOURSE UNLESS STATED ON DRAWING

Client: Atkins, Woodcote Grove, Ashley Road, Epsom, KT18 5BW

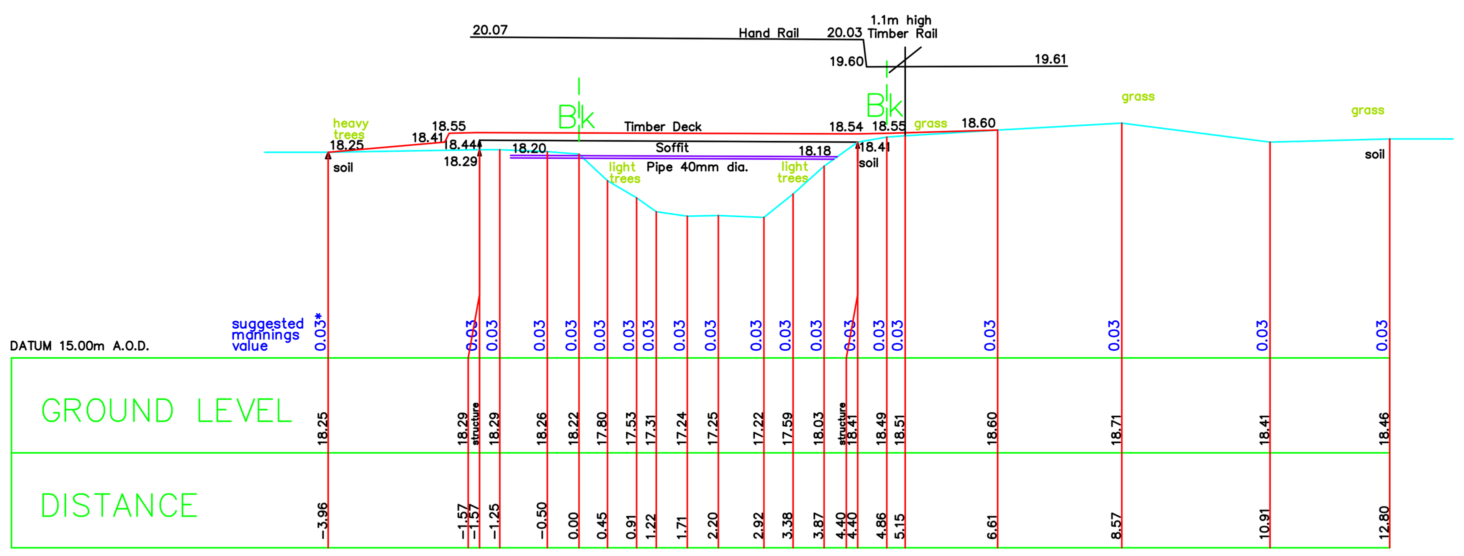
Project: Channel survey for M5 Junction 10

INFOMAP SURVEYS AND MAPPING
CHARTERED SURVEYORS
Seymours House
Sunnyside Road North
Weston-super-Mare
North Somerset BS23 3PZ
Tel: 01934 644060 /fax 01934 644060
E-mail: mail@infomapsurveys.co.uk
Website: www.infomapsurveys.co.uk

Surveyed: M.B. & D.J. | Apprd: R.J.FLEW
Date: Nov 2019 | File Ref:
Scale: 1/100 at A1; 1/200 at A3

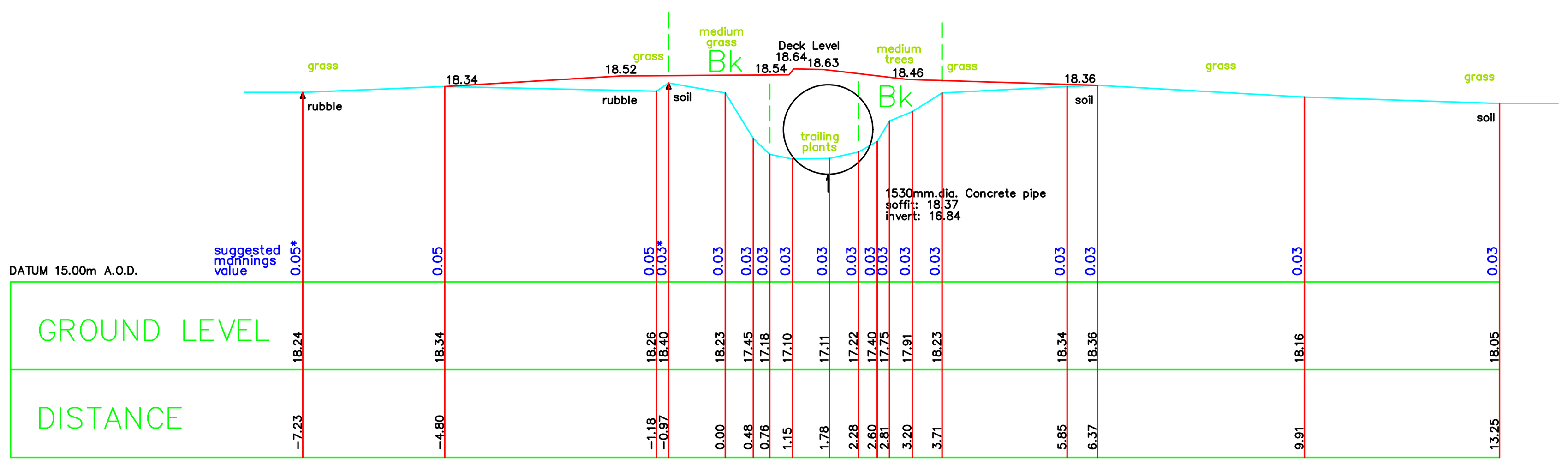
DRAWING REFERENCE
CHANNEL SURVEYS - M5 J10 CHELTENHAM
M5-J10 ISM X-SECTIONS-SHEET 1 of 6

Structure no. 14. Footbridge 2
Description: Timber footbridge
(upstream face of structure)



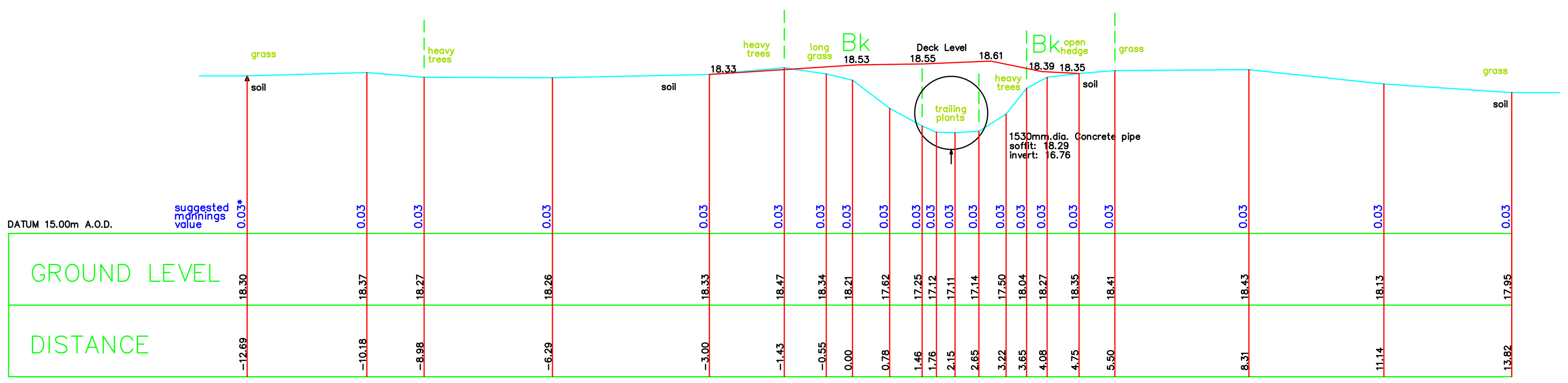
Channel 2 (Leigh Brook) CS 2.53u Ch. 4679.6
Centre OSNG Coordinates E.389911.27 N.227123.75

Structure no. 13. Field Access 10
Description: 1530mm Concrete pipe culvert
(upstream face of structure)

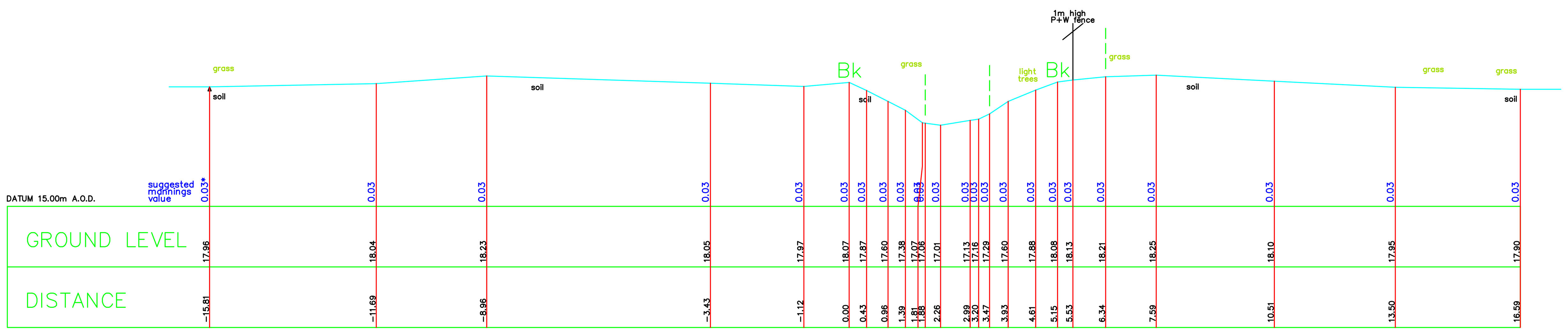


Channel 2 (Leigh Brook) CS 2.52u Ch. 4654.1
Centre OSNG Coordinates E.389888.89 N.227113.54

Structure no. 13. Field Access 10
Description: 1530mm Concrete pipe culvert
(downstream face of structure)

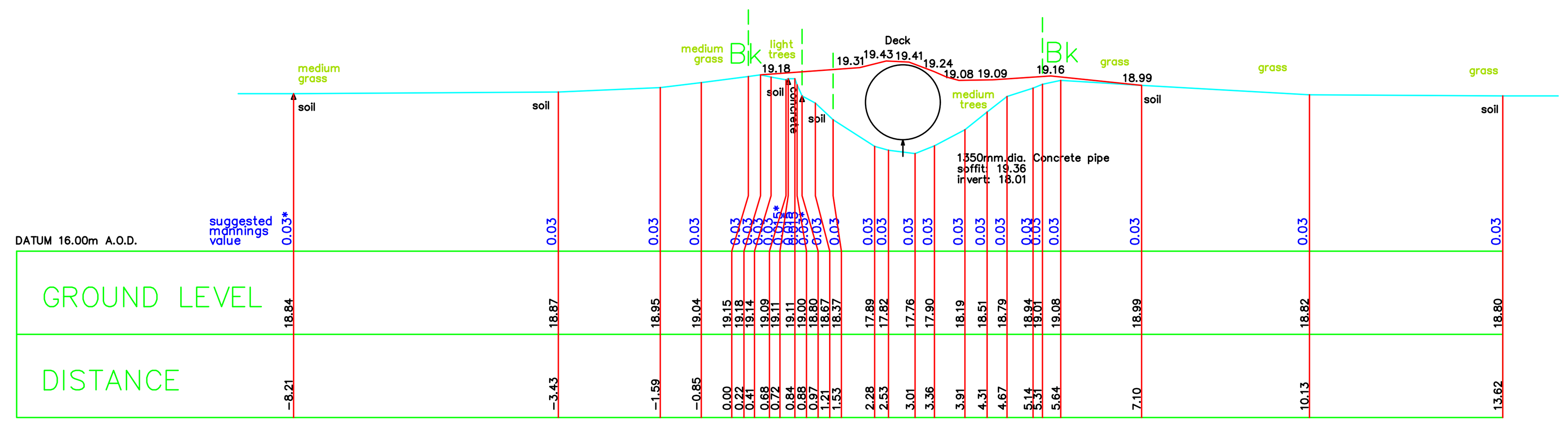


Channel 2 (Leigh Brook) CS 2.51d Ch. 4649.2
Centre OSNG Coordinates E.389884.86 N.227110.70

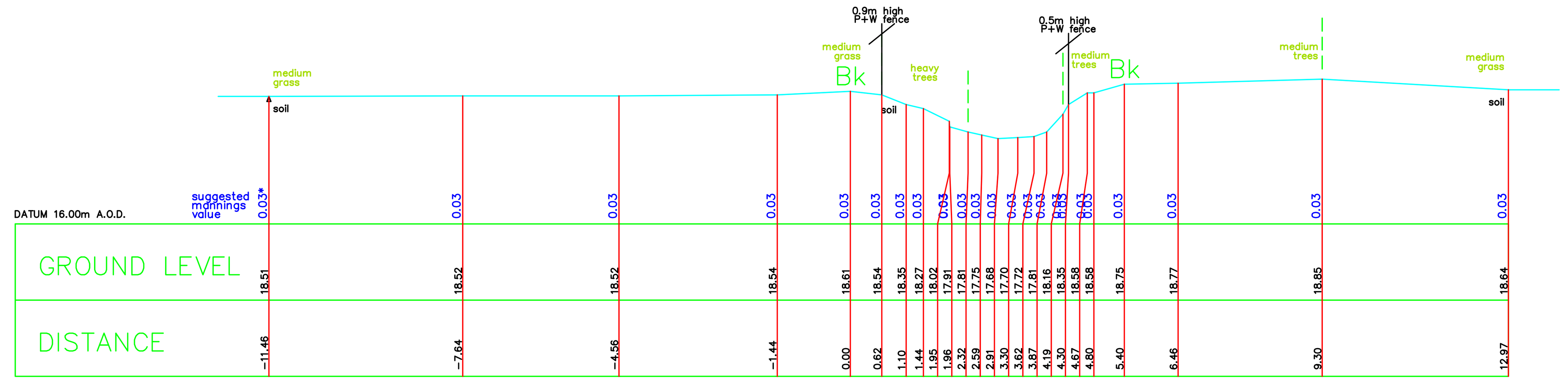


Channel 2 (Leigh Brook) CS 2.50 Ch. 4565.6
Centre OSNG Coordinates E.389816.46 N.227063.05

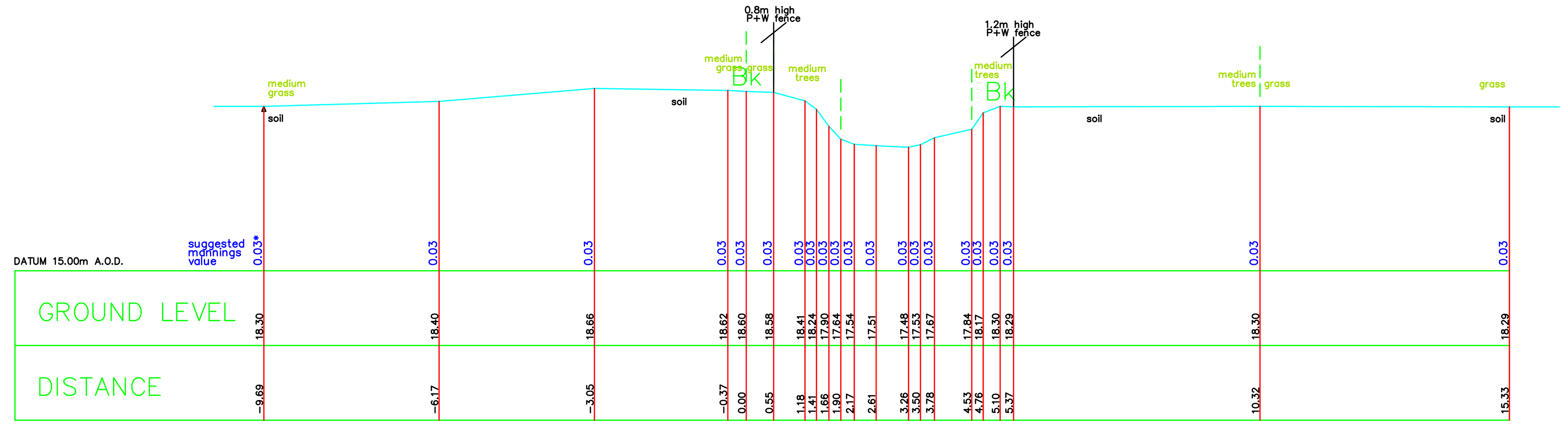
Structure no. 15. Field Access 11
Description: 1350mm Concrete pipe culvert
(upstream face of structure)



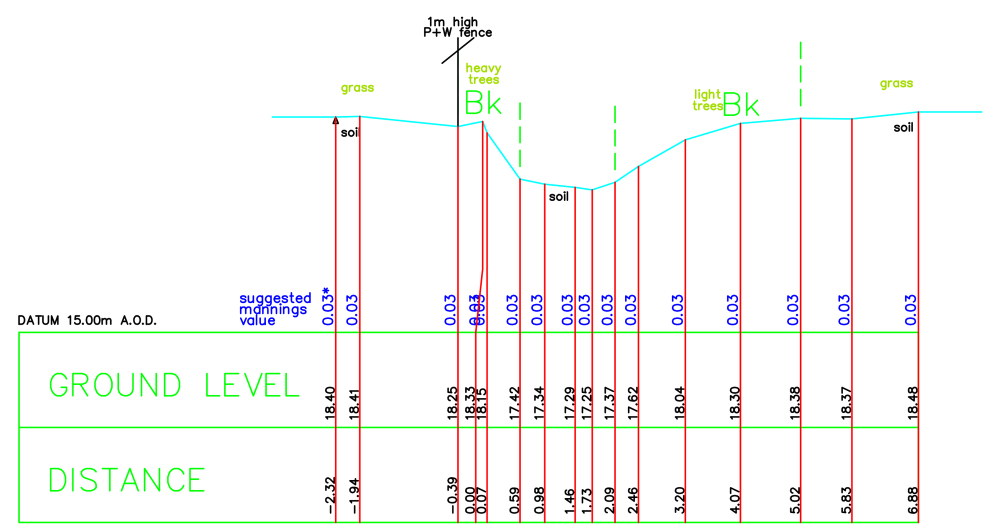
Channel 2 (Leigh Brook) CS 2.57u Ch. 5128.0
Centre OSNG Coordinates E.390279.16 N.226958.00



Channel 2 (Leigh Brook) CS 2.56 Ch. 5012.2
Centre OSNG Coordinates E.390195.41 N.227037.89



Channel 2 (Leigh Brook) CS 2.55 Ch. 4891.4
Centre OSNG Coordinates E.390103.45 N.227112.30

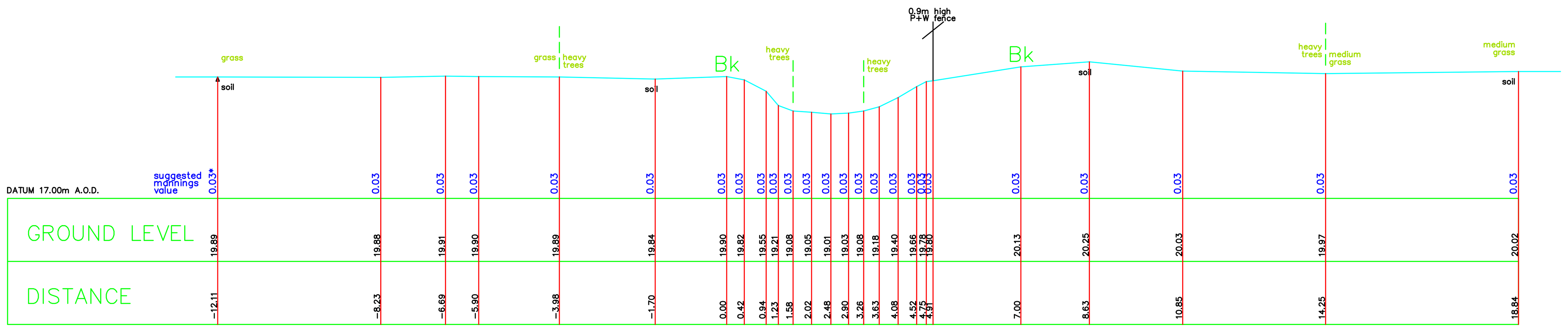


Channel 2 (Leigh Brook) CS 2.54 Ch. 4706.2
Centre OSNG Coordinates E.389926.57 N.227143.46

5 0 5 10 15 20 25m
Scale: 1/100 at A1; 1/200 at A3

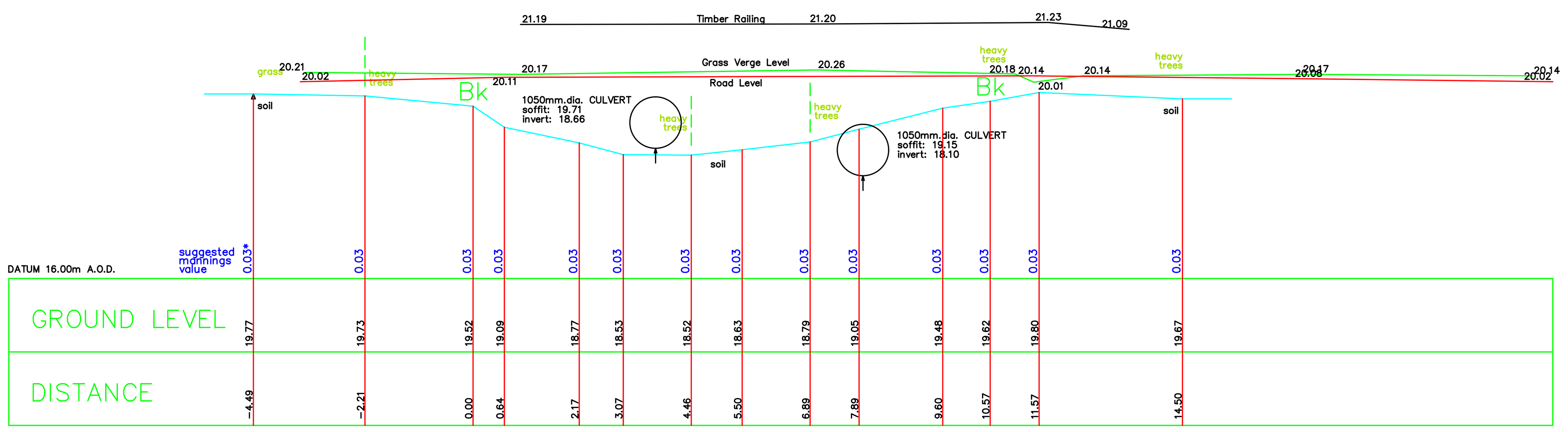
SURVEYED BY GPS TO OSNG. LEVEL DATUM OSGM15.
ALL SECTIONS SHOWN PERPENDICULAR TO WATERCOURSE UNLESS STATED ON DRAWING

Client	Project	
Atkins Woodcote Grove, Ashley Road Epsom KT18 5BW	Channel survey for M5 Junction 10	INFOMAP SURVEYS AND MAPPING CHARTERED SURVEYORS Seymours House Sunnyside Road North Weston-super-Mare North Somerset BS23 3PZ Tel: 01934 644060 /fax 01934 644060 E-mail: mail@infomapsurveys.co.uk Website: www.infomapsurveys.co.uk
Surveyed: M.B. & D.J.	Apprd: R.J.FLEW	DRAWING REFERENCE
Date: Nov 2019	File Ref:	CHANNEL SURVEYS - M5 J10 CHELTENHAM
Scale: 1/100 at A1; 1/200 at A3		M5-J10 ISM X-SECTIONS-SHEET 2 of 6



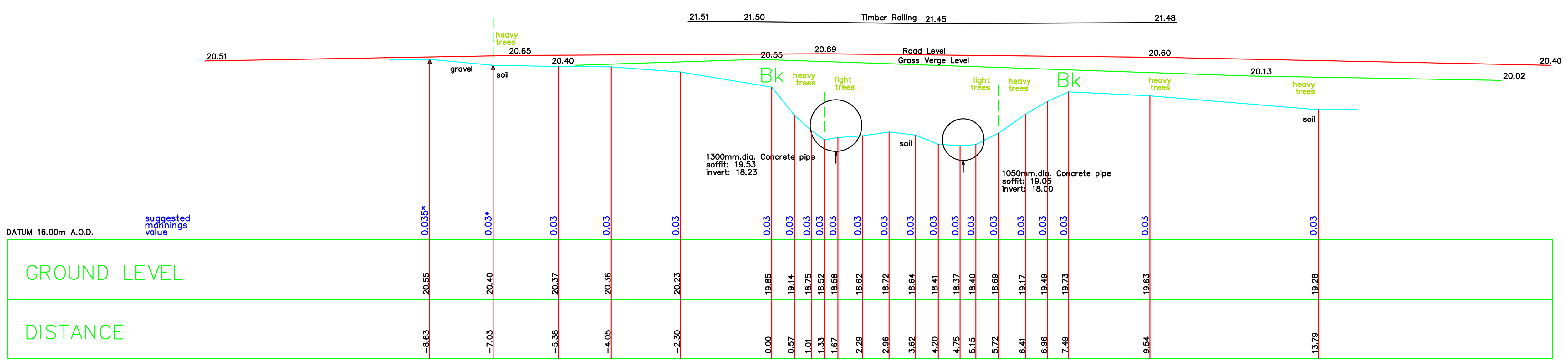
Channel 2 (Leigh Brook) CS 2.61 Ch. 5562.7
Centre OSNG Coordinates E.390490.30 N.226587.76

Structure no. 17. Road Culvert
Description: 2x Concrete pipes
(upstream face of structure)



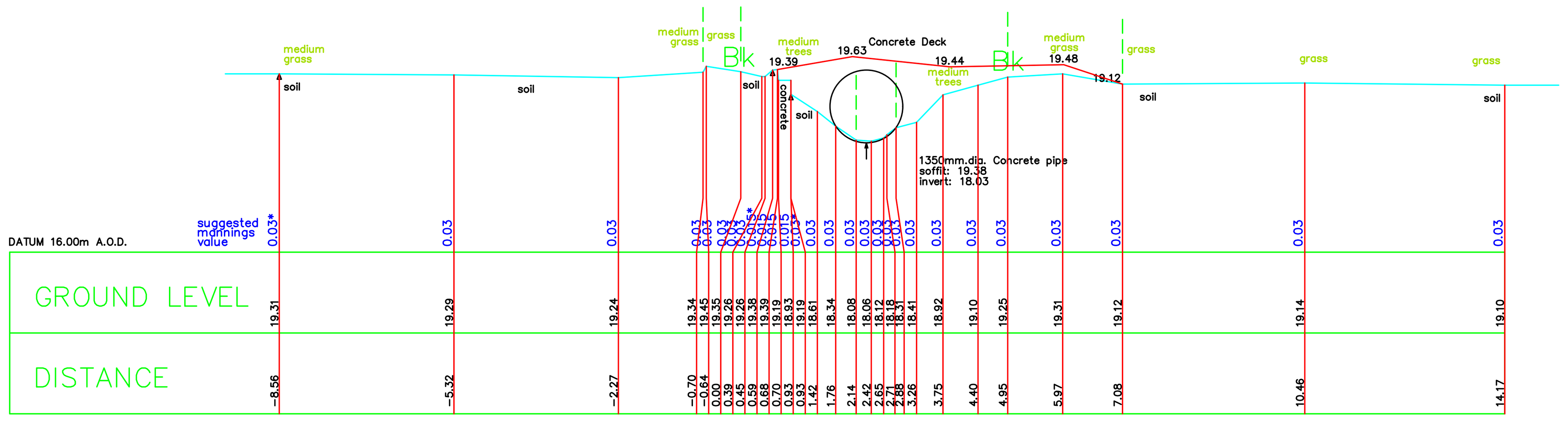
Channel 2 (Leigh Brook) CS 2.60u Ch. 5370.2
Centre OSNG Coordinates E.390412.97 N.226763.86

Structure no. 17. Road Culvert
Description: 2x Concrete pipes
(downstream face of structure)



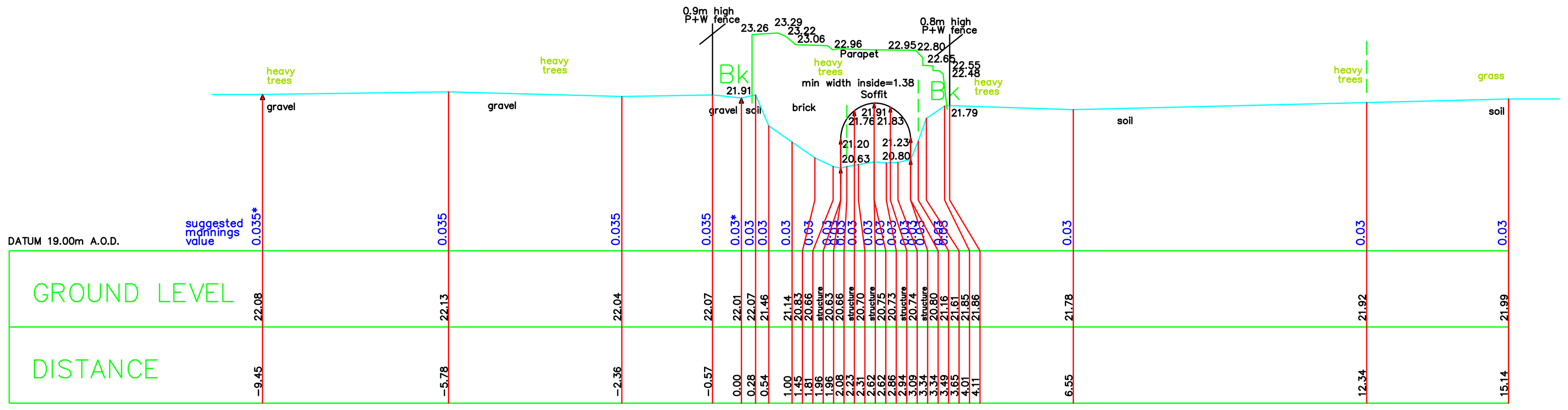
Channel 2 (Leigh Brook) CS 2.59d Ch. 5354.3
Centre OSNG Coordinates E.390411.42 N.226779.61

Structure no. 16. Field Access 12
Description: 1350mm Concrete pipe culvert
(upstream face of structure)



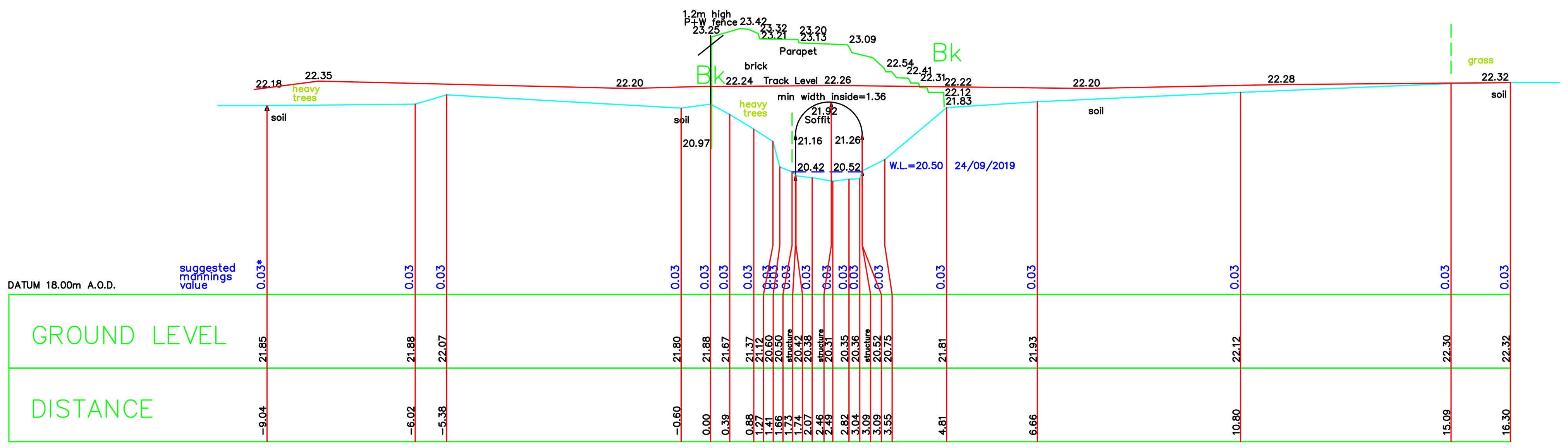
Channel 2 (Leigh Brook) CS 2.58u Ch. 5266.9
Centre OSNG Coordinates E.390360.05 N.226847.95

Structure no. 18. Field Access 13
Description: Brick arch culvert
(upstream face of structure)

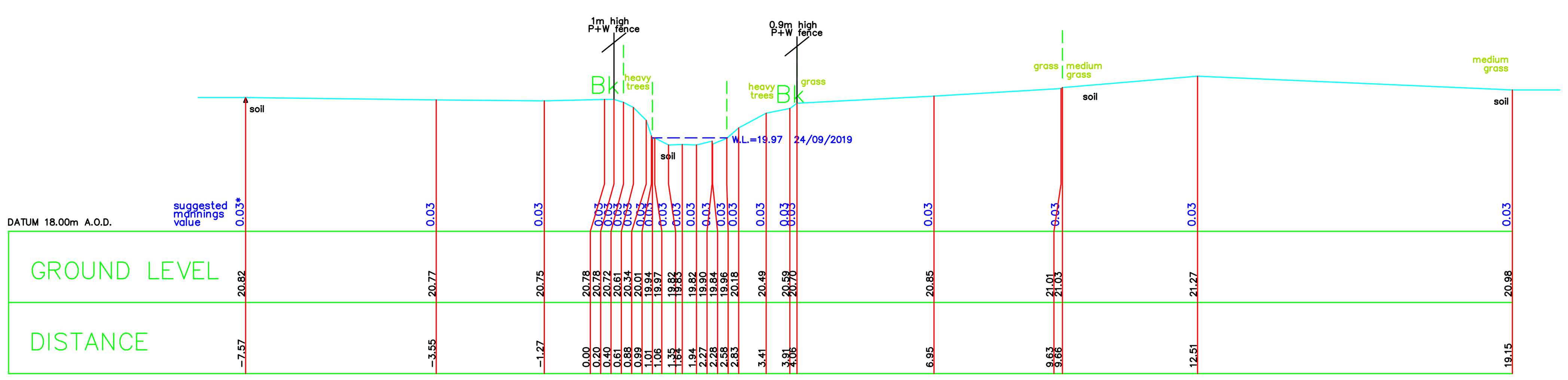


Channel 2 (Leigh Brook) CS 2.65u Ch. 6012.9
Centre OSNG Coordinates E.390665.19 N.226179.70

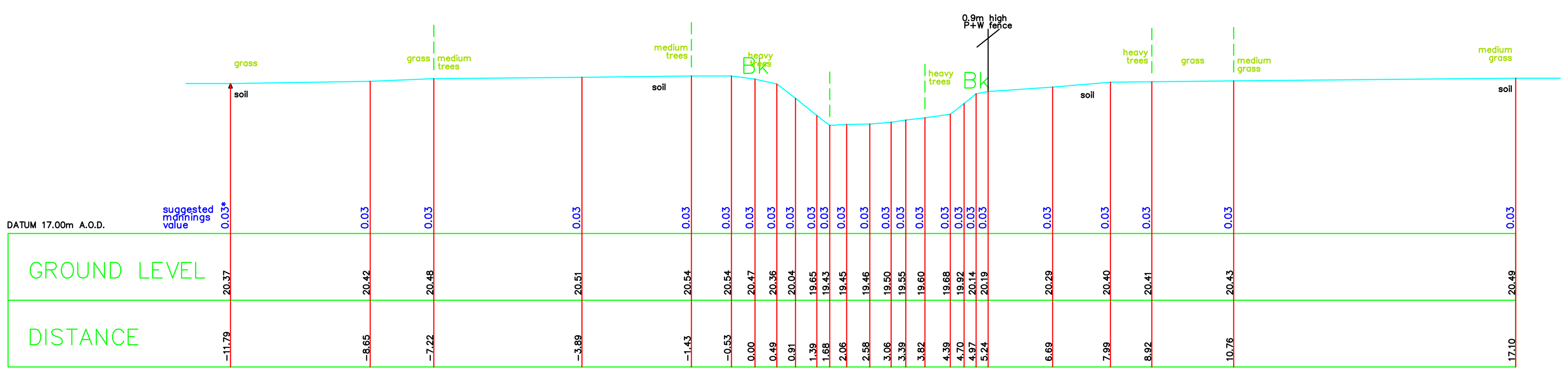
Structure no. 18. Field Access 13
Description: Brick arch culvert
(downstream face of structure)



Channel 2 (Leigh Brook) CS 2.64d Ch. 6008.3
Centre OSNG Coordinates E.390661.87 N.226182.92



Channel 2 (Leigh Brook) CS 2.63 Ch. 5850.7
Centre OSNG Coordinates E.390579.79 N.226315.66



Channel 2 (Leigh Brook) CS 2.62 Ch. 5697.9
Centre OSNG Coordinates E.390533.69 N.226460.09

5 0 5 10 15 20 25m

Scale: 1/100 at A1; 1/200 at A3

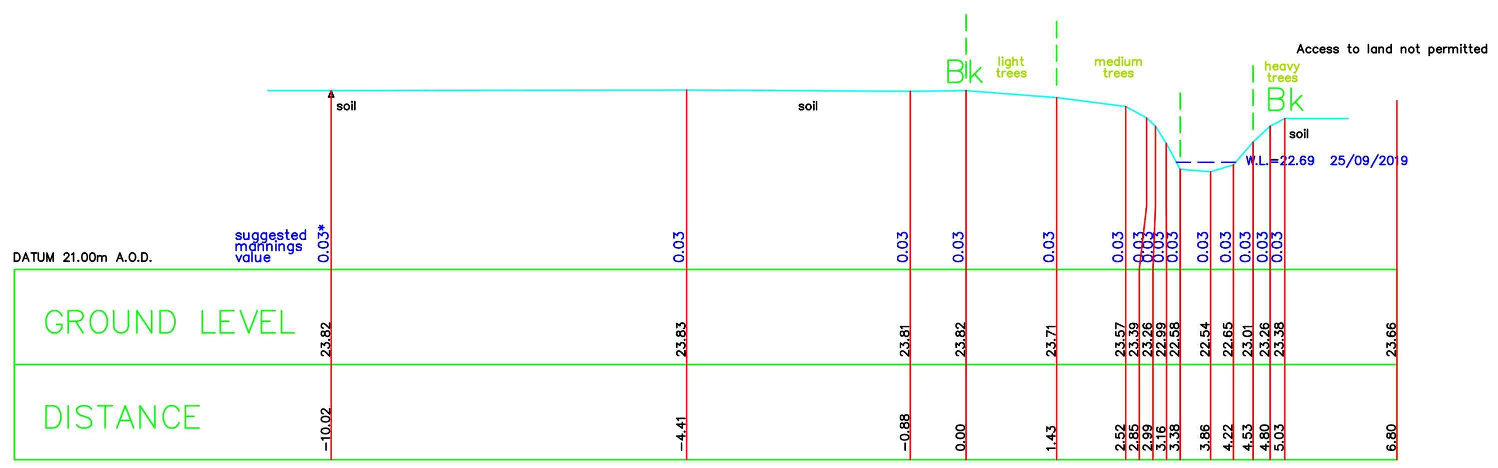
SURVEYED BY GPS TO OSNG. LEVEL DATUM OSGM15.
ALL SECTIONS SHOWN PERPENDICULAR TO WATERCOURSE UNLESS STATED ON DRAWING

Client	Project
Atkins Woodcote Grove, Ashley Road Epsom KT18 5BW	Channel survey for M5 Junction 10

INFOMAP
SURVEYS AND MAPPING
CHARTERED SURVEYORS
Seymours House
Sunnyside Road North
Weston-super-Mare
North Somerset BS23 3PZ
Tel: 01934 644060 /fax 01934 644060
E-mail: mail@infomapsurveys.co.uk
Website: www.infomapsurveys.co.uk

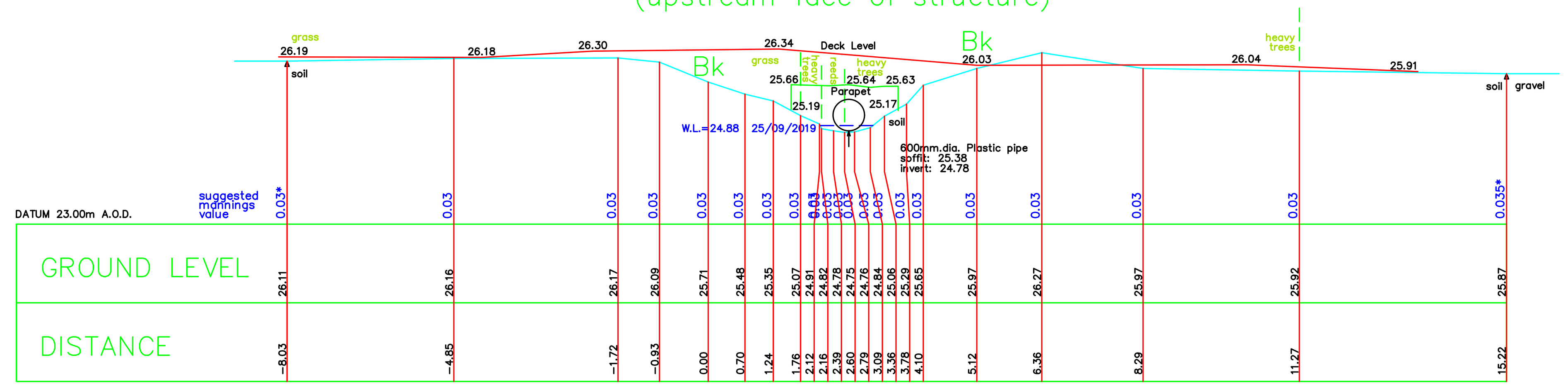
Surveyed: M.B. & D.J.		Apprd:	R.J.FLEW
Date: Nov 2019		File Ref:	
Scale: 1/100 at A1; 1/200 at A3			

DRAWING REFERENCE
CHANNEL SURVEYS - M5 J10
CHELTENHAM
M5-J10 ISM X-SECTIONS-SHEET 3 of 6



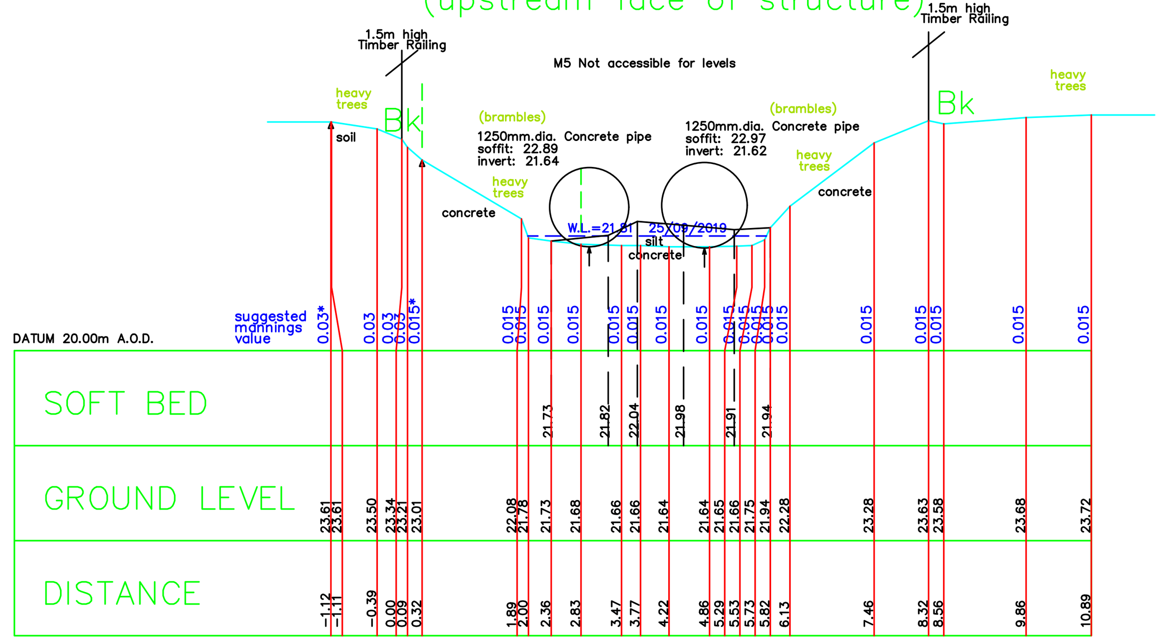
Channel 2 (Leigh Brook) CS 2.69 Ch. 6420.8
Centre OSNG Coordinates E.390894.67 N.225919.22

Structure no. 20. Field Access 14
Description: 600mm Plastic pipe
(upstream face of structure)



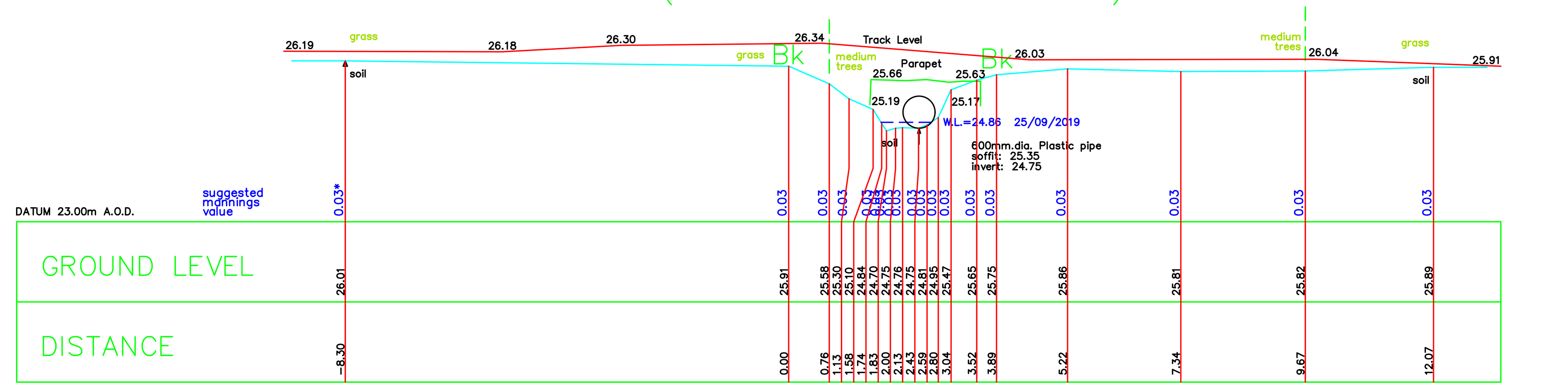
Channel 2 (Leigh Brook) CS 2.73u Ch. 6847.2
Centre OSNG Coordinates E.391283.91 N.225783.30

Structure no. 19. M5 Culvert
Description: 2x 1250mm concrete pipes
(upstream face of structure)



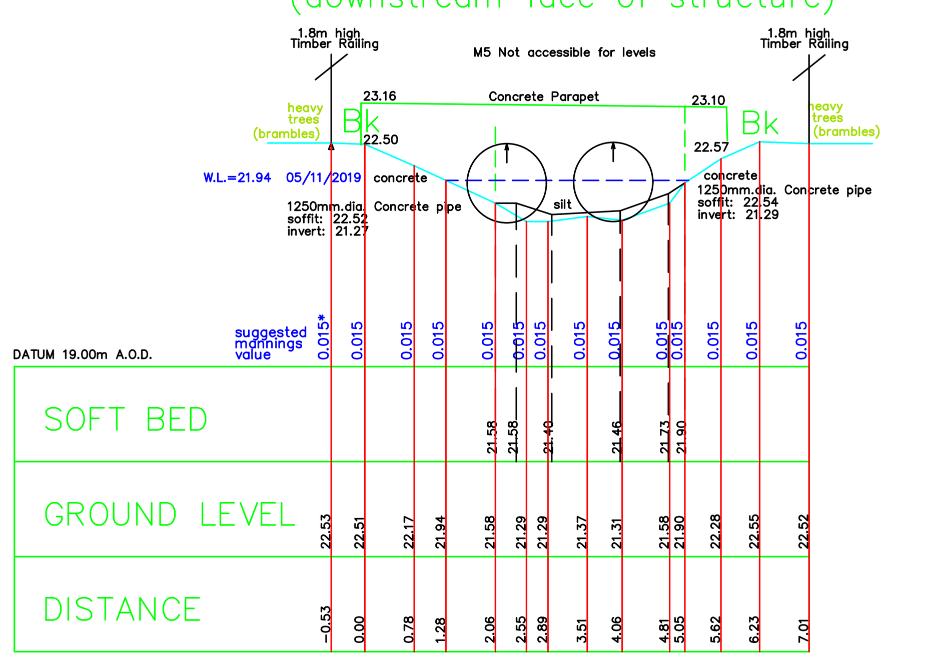
Channel 2 (Leigh Brook) CS 2.68u Ch. 6281.5
Centre OSNG Coordinates E.390778.01 N.225995.02

Structure no. 20. Field Access 14
Description: 600mm Plastic pipe
(downstream face of structure)

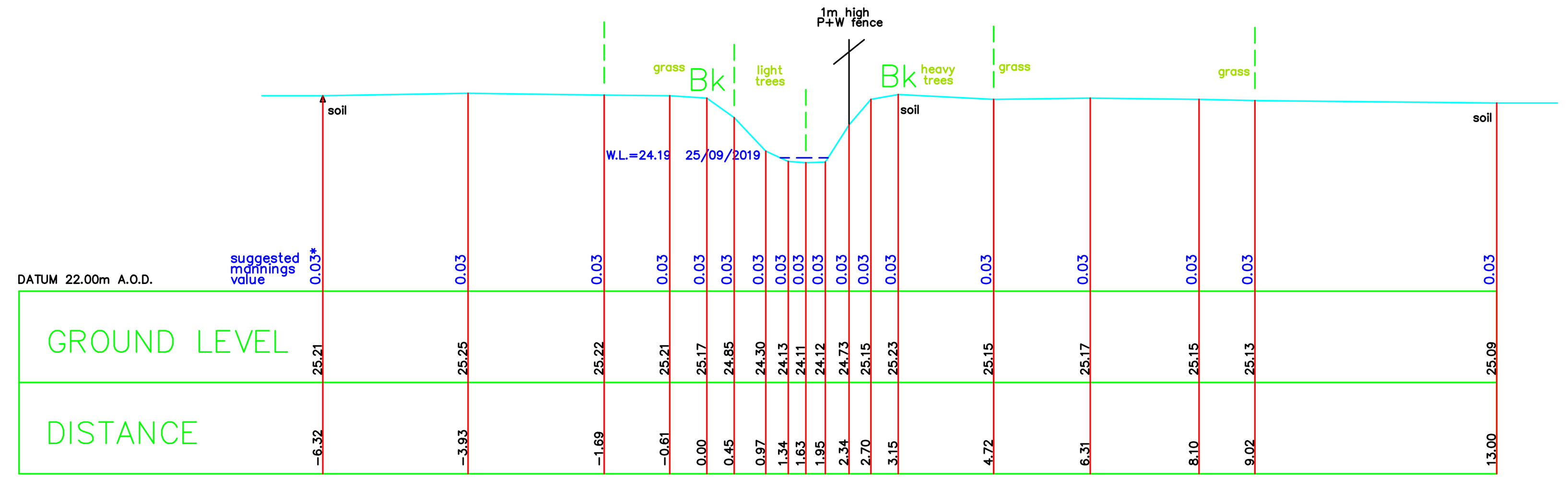


Channel 2 (Leigh Brook) CS 2.72d Ch. 6840.3
Centre OSNG Coordinates E.391278.75 N.225787.89

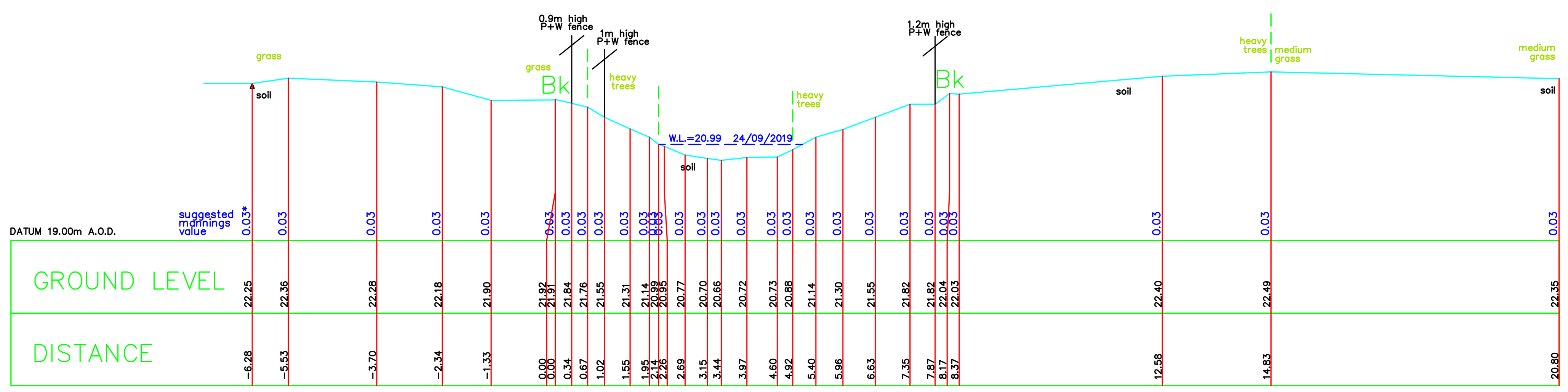
Structure no. 19. M5 Culvert
Description: 2x 1250mm concrete pipes
(downstream face of structure)



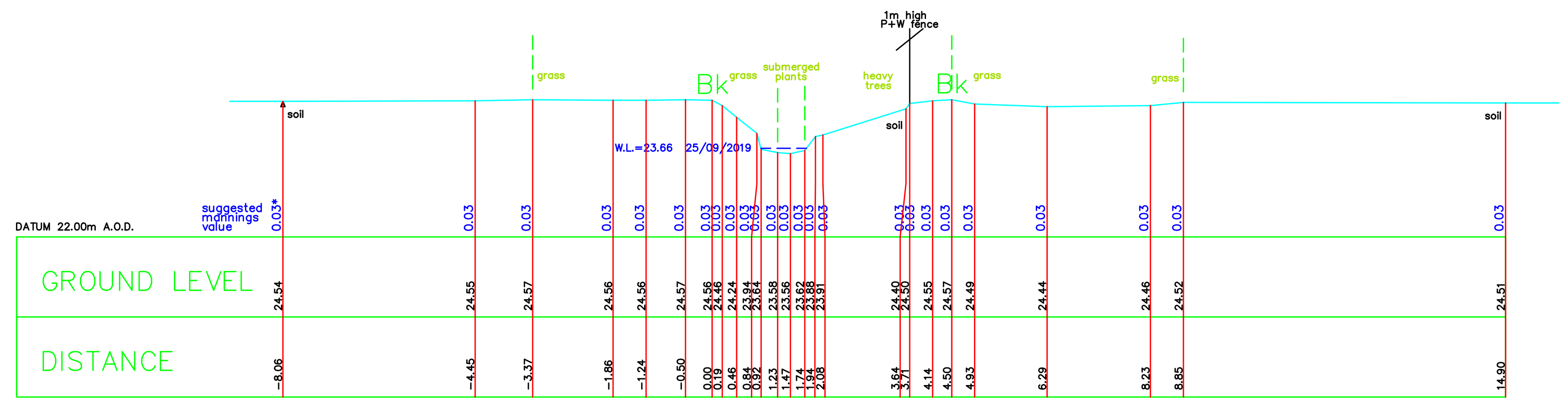
Channel 2 (Leigh Brook) CS 2.67d Ch. 6225.0
Centre OSNG Coordinates E.390747.08 N.226041.96



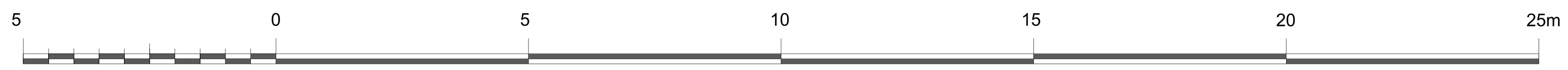
Channel 2 (Leigh Brook) CS 2.71 Ch. 6719.7
Centre OSNG Coordinates E.391177.44 N.225851.21



Channel 2 (Leigh Brook) CS 2.66 Ch. 6099.1
Centre OSNG Coordinates E.390638.09 N.226102.92



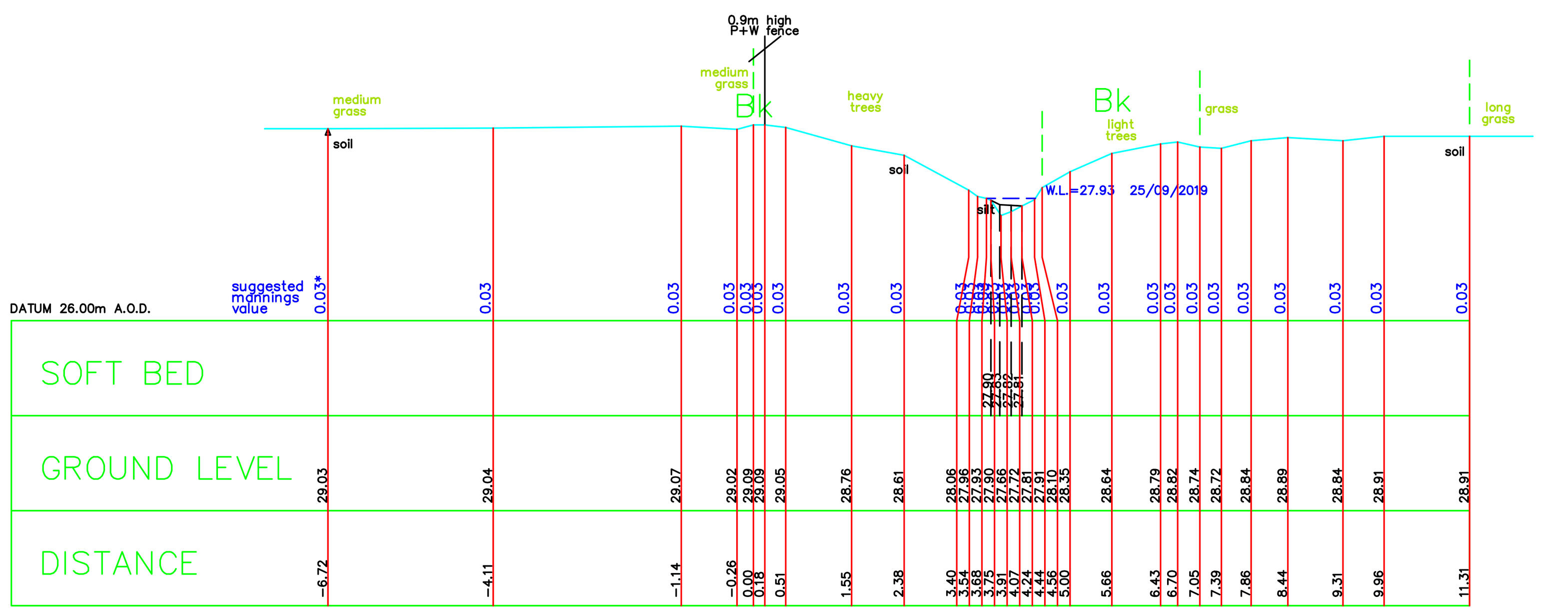
Channel 2 (Leigh Brook) CS 2.70 Ch. 6581.5
Centre OSNG Coordinates E.391039.76 N.225853.57



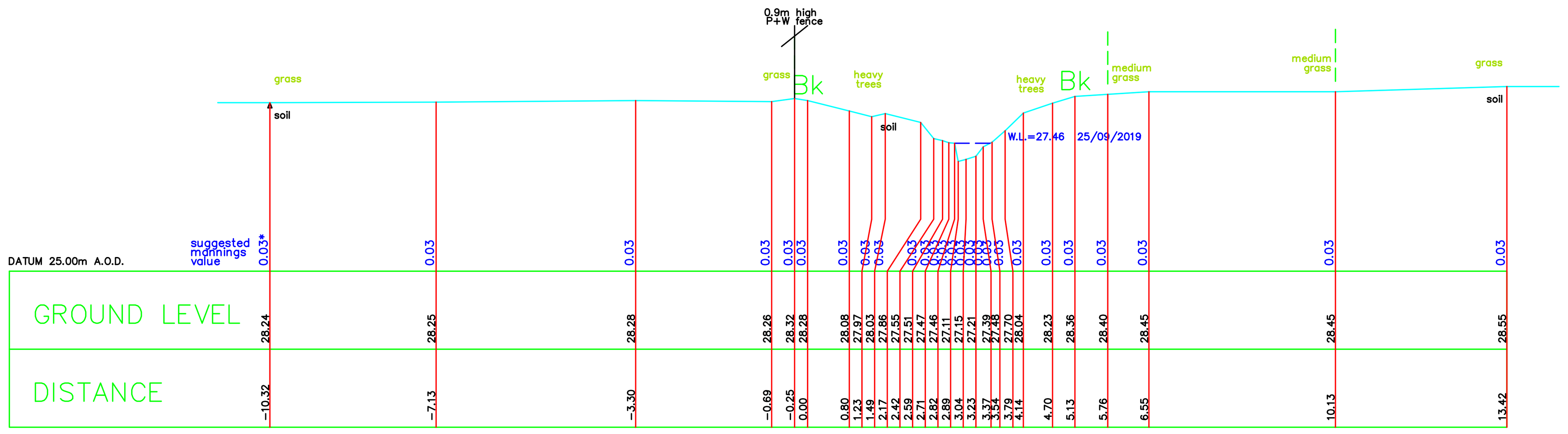
Scale: 1/100 at A1; 1/200 at A3

SURVEYED BY GPS TO OSNG. LEVEL DATUM OSGM15.
ALL SECTIONS SHOWN PERPENDICULAR TO WATERCOURSE UNLESS STATED ON DRAWING

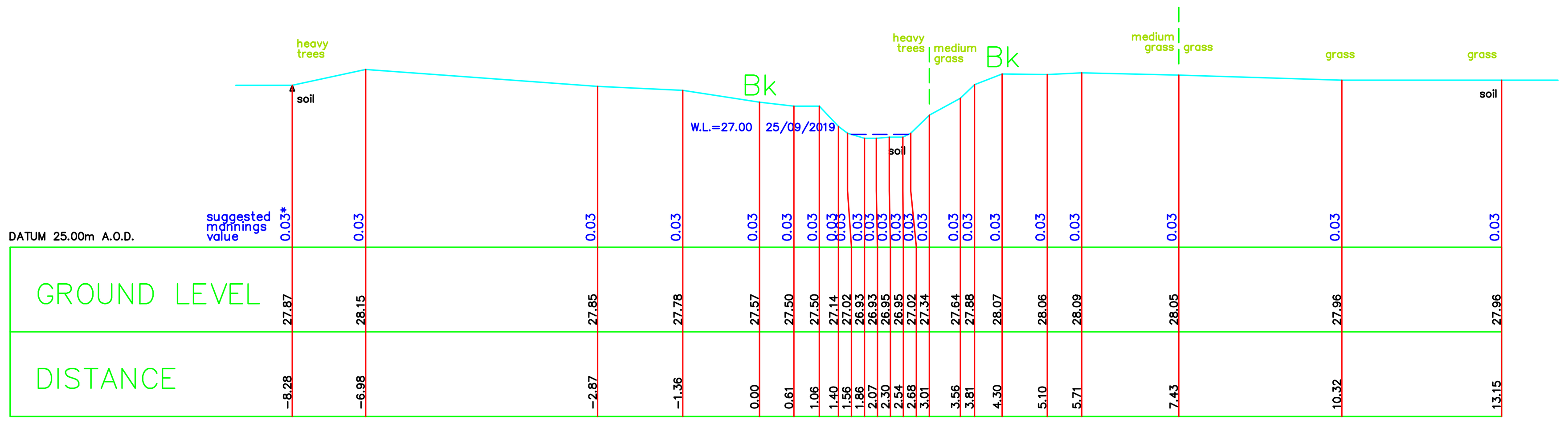
Client	Project	
Atkins Woodcote Grove, Ashley Road Epsom KT18 5BW	Channel survey for M5 Junction 10	INFOMAP SURVEYS AND MAPPING CHARTERED SURVEYORS Seymours House Sunnyside Road North Weston-super-Mare North Somerset BS23 3PZ Tel: 01934 644060 /fax 01934 644060 E-mail: mail@infomapsurveys.co.uk Website: www.infomapsurveys.co.uk
Surveyed: M.B. & D.J.	Apprd: R.J.FLEW	DRAWING REFERENCE
Date: Nov 2019	File Ref:	CHANNEL SURVEYS - M5 J10 CHELTENHAM
Scale: 1/100 at A1; 1/200 at A3		M5-J10 ISM X-SECTIONS-SHEET 4 of 6



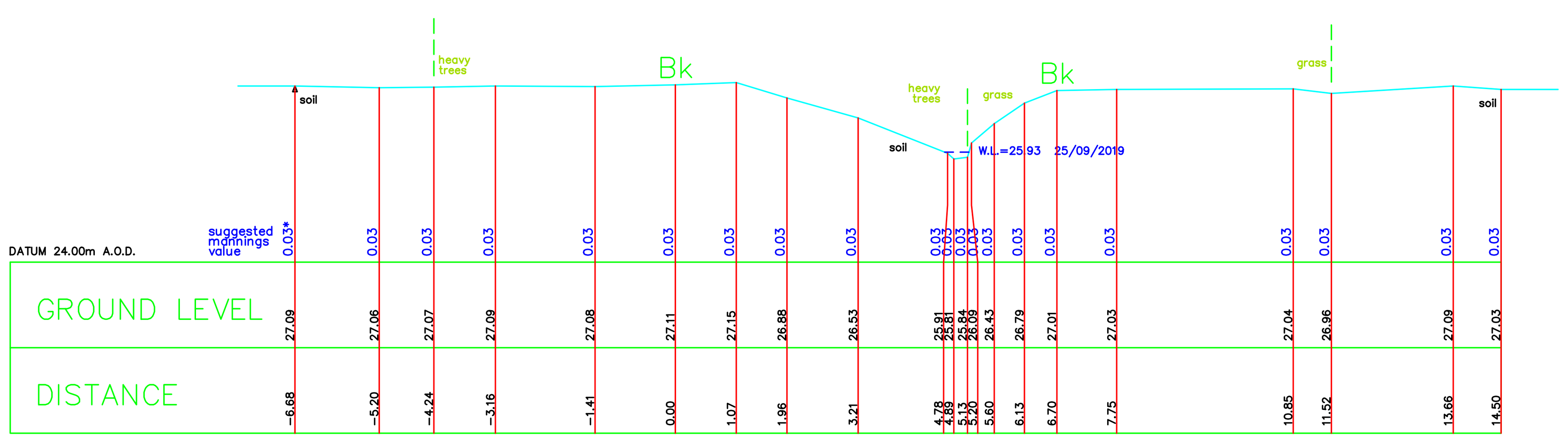
Channel 2 (Leigh Brook) CS 2.77 Ch. 7380.7
Centre OSNG Coordinates E.391637.13 N.225393.55



Channel 2 (Leigh Brook) CS 2.76 Ch. 7282.1
Centre OSNG Coordinates E.391583.11 N.225475.85

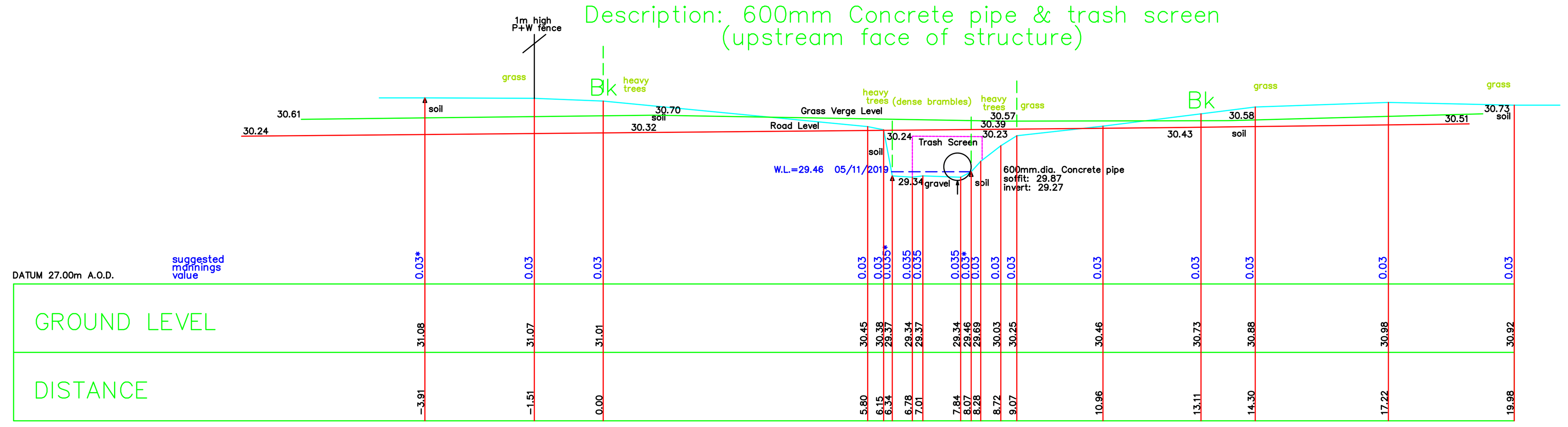


Channel 2 (Leigh Brook) CS 2.75 Ch. 7194.6
Centre OSNG Coordinates E.391532.97 N.225547.18



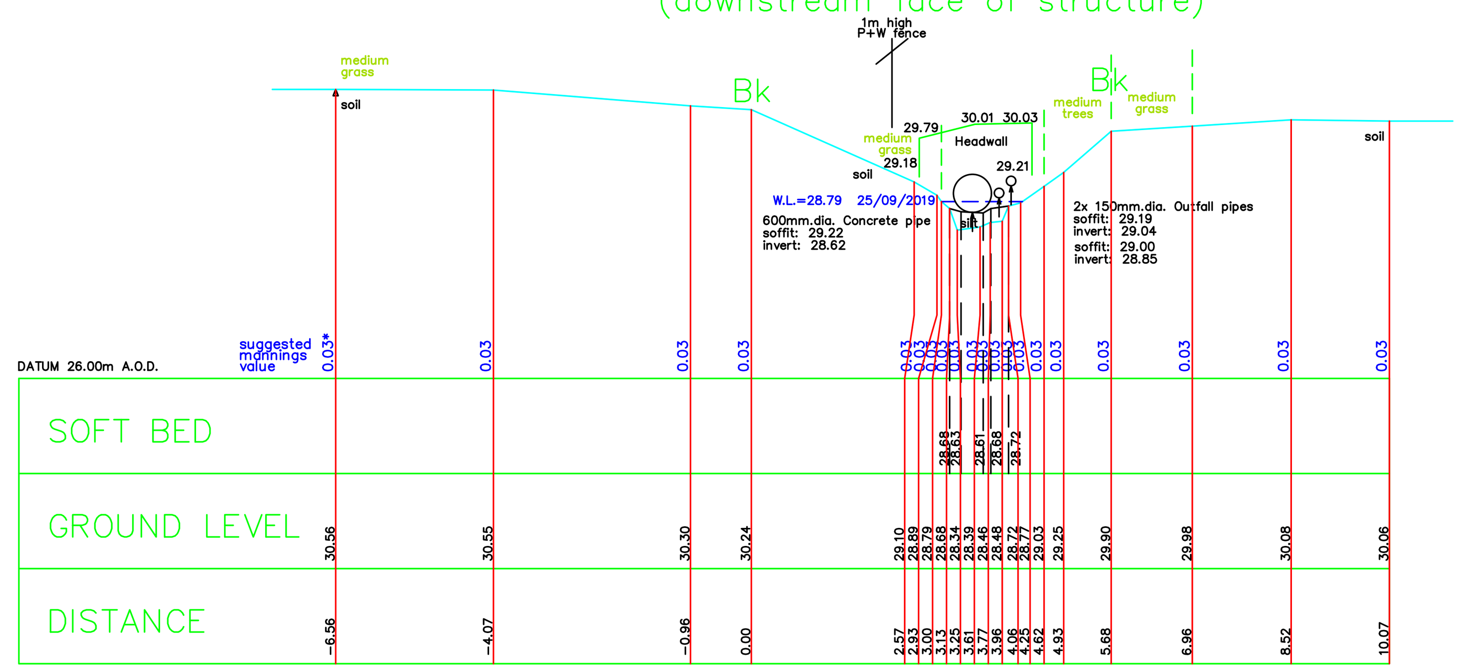
Channel 2 (Leigh Brook) CS 2.74 Ch. 7023.2
Centre OSNG Coordinates E.391402.56 N.225658.28

Structure no. 21. Green Lane Culvert
Description: 600mm Concrete pipe & trash screen
(upstream face of structure)

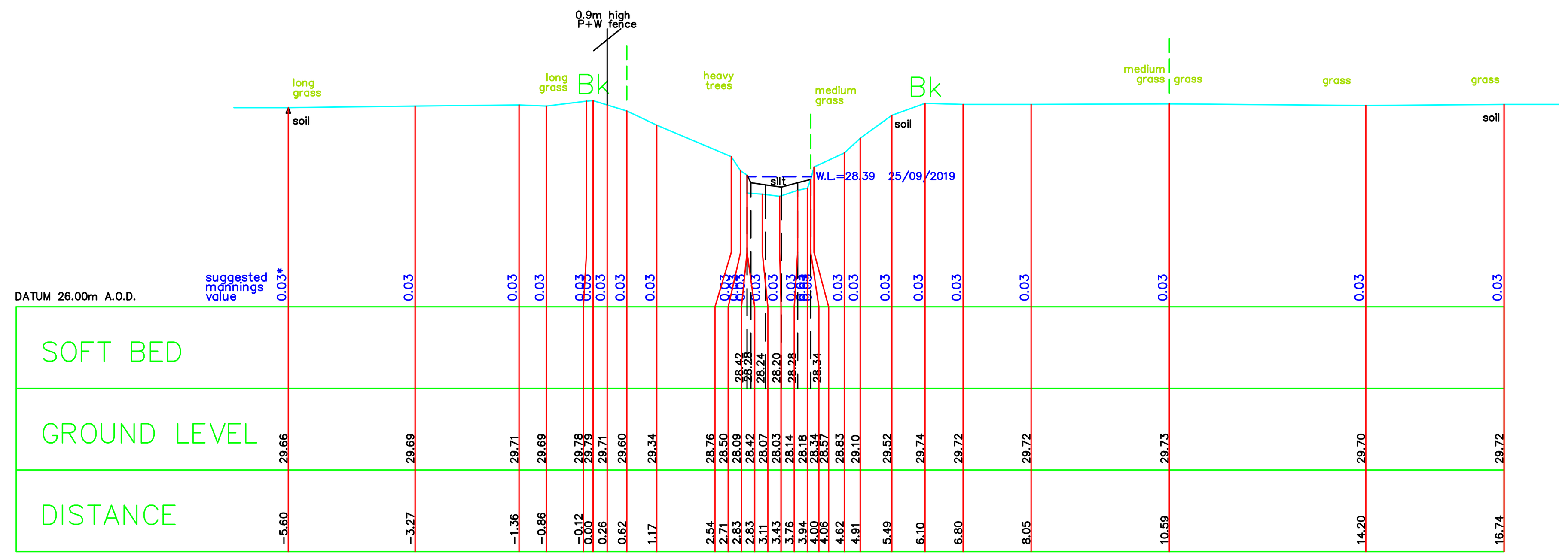


Channel 2 (Leigh Brook) CS 2.80u Ch. 7661.3
Centre OSNG Coordinates E.391771.22 N.225155.69

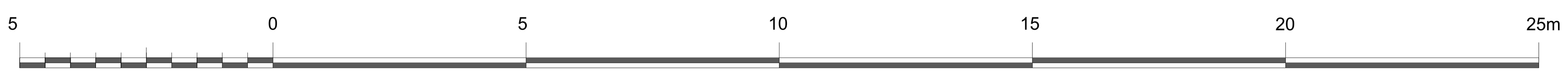
Structure no. 21. Green Lane Culvert
Description: 600mm Concrete pipe
(downstream face of structure)



Channel 2 (Leigh Brook) CS 2.79d Ch. 7607.1
Centre OSNG Coordinates E.391741.02 N.225200.67



Channel 2 (Leigh Brook) CS 2.78 Ch. 7499.9
Centre OSNG Coordinates E.391689.98 N.225294.52



Scale: 1/100 at A1; 1/200 at A3

SURVEYED BY GPS TO OSNG. LEVEL DATUM OSGM15.
ALL SECTIONS SHOWN PERPENDICULAR TO WATERCOURSE UNLESS STATED ON DRAWING

Client	Project	
Atkins Woodcote Grove, Ashley Road Epsom KT18 5BW	Channel survey for M5 Junction 10	INFOMAP SURVEYS AND MAPPING CHARTERED SURVEYORS Seymours House Sunnyside Road North Weston-super-Mare North Somerset BS23 3PZ Tel: 01934 644060 /fax 01934 644060 E-mail: mail@infomapsurveys.co.uk Website: www.infomapsurveys.co.uk
Surveyed: M.B. & D.J.	Apprd: R.J.FLEW	DRAWING REFERENCE
Date: Nov 2019	File Ref:	CHANNEL SURVEYS - M5 J10 CHELTENHAM
Scale: 1/100 at A1; 1/200 at A3		M5-J10 ISM X-SECTIONS-SHEET 5 of 6

Structure no. 23. Field Access 16
Description: 450mm Brick arch
(downstream face of structure)
No access to upstream face
Brick Headwall
GROUND LEVEL
DISTANCE
Channel 2 (Leigh Brook) CS 2.84d Ch. 7874.1
Centre OSNG Coordinates E.391909.38 N.225017.96
Leigh Brook
Channel 20 CS 20.02 Ch. 27.8
Centre OSNG Coordinates E.389919.81 N.227148.02
Channel 2 (Leigh Brook) CS 2.83 Ch. 7811.7
Centre OSNG Coordinates E.391855.55 N.225048.19
Channel 20 CS 20.01 Ch. 6.0
Centre OSNG Coordinates E.389908.73 N.227129.31
Structure no. 22. Field Access 15
Description: Brick arch culvert
(upstream face of structure)
section taken 2m upstream from culvert opening due to vegetation
River Chelt CS 2.82u Ch. 7693.3
Centre OSNG Coordinates E.391792.77 N.225132.08
SOFT BED
Channel 2 (Leigh Brook) CS 2.85 Ch. 8037.8
Centre OSNG Coordinates E.392067.00 N.224976.20
Structure no. 22. Field Access 15
Description: Brick arch culvert
(downstream face of structure)
channel in bramble & hawthorn hedge
River Chelt CS 2.81d Ch. 7685.2
Centre OSNG Coordinates E.391787.12 N.225137.88
5 0 5 10 15 20 25m
Scale: 1/100 at A1; 1/200 at A3
SURVEYED BY GPS TO OSNG. LEVEL DATUM OSGM15.
ALL SECTIONS SHOWN PERPENDICULAR TO WATERCOURSE UNLESS STATED ON DRAWING
Client
Atkins
Woodcote Grove,
Ashley Road
Epsom
KT18 5BW
Project
Channel survey for
M5 Junction 10
INFOMAP
SURVEYS AND MAPPING
CHARTERED SURVEYORS
Seymours House
Sunnyside Road North
Weston-super-Mare
North Somerset BS23 3PZ
Tel: 01934 644060 /fax 01934 644060
E-mail: mail@infomapsurveys.co.uk
Website: www.infomapsurveys.co.uk
RICS
Surveyed: M.B. & D.J.
Apprd: R.J.FLEW
Date: Nov 2019
File Ref:
Scale: 1/100 at A1; 1/200 at A3
Revision 1
Sections 2.81d & 2.82u updated
DRAWING REFERENCE
CHANNEL SURVEYS - M5 J10
CHELTENHAM
M5-J10 ISM X-SECTIONS-SHEET 6 of 6

Appendix B. FEH calculation record

Flood estimation report: M5 Junction 10 improvements scheme

Introduction

This report template is a supporting document to the Environment Agency's Flood Estimation Guidelines. It provides a record of the hydrological context, the method statement, the calculations and decisions made during flood estimation and the results. This document can be used for one site or multiple sites. If only one site is being assessed, analysts should remove superfluous rows from tables.

Guidance notes (in red text) are included throughout this document in column titles or above tables. These should be deleted before finalising the document. Where relevant, references to specific sections of the Flood Estimation Guidelines document are included to indicate where further useful information can be found.

Note: Column size / page layout can be adapted, where necessary, to best present relevant information, for example, maps do not need to be within the tables if they would be better as a separate page.

Contents

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Abbreviations

AEP................................ annual exceedance probability
AM.................................. Annual Maximum
AREA .... Catchment area (km^2)
BFI .... Base Flow Index
BFIHOST .... Base Flow Index derived using the HOST soil classification
CPRE.............................. Council for the Protection of Rural England
FARL............................... FEH index of flood attenuation due to reservoirs and lakes
FEH................................. Flood Estimation Handbook
FSR................................. Flood Studies Report
HOST.............................. Hydrology of Soil Types
NRFA .... National River Flow Archive
OS.................................. Ordnance Survey
POT................................ Peaks Over a Threshold
QMED .... Median Annual Flood (with return period 2 years)
ReFH .... Revitalised Flood Hydrograph method
ReFH2 .... Revitalised Flood Hydrograph 2 method
SAAR .... Standard Average Annual Rainfall (mm)
SPR................................ Standard percentage runoff
SPRHOST .... Standard percentage runoff derived using the HOST soil classification
Tp(0) .... Time to peak of the instantaneous unit hydrograph
URBAN .... Flood Studies Report index of fractional urban extent
URBEXT1990 .... FEH index of fractional urban extent
URBEXT2000 .... Revised index of urban extent, measured differently from URBEXT1990
WINFAP-FEH .... Windows Frequency Analysis Package – used for FEH statistical method

1 SUMMARY OF ASSESSMENT

1.1 Summary

This table provides a summary of the key information contained within the detailed assessment in the following sections. The aim of the table is to enable quick and easy identification of the type of assessment undertaken. This should assist in identifying an appropriate reviewer and the ability to compare different studies more easily.

The aim of this table is to provide a summary so keep the text to one or two sentences for each point.

Catchment location	The River Chelt and Leigh Brook catchments, Cheltenham, Gloucestershire. The approximate grid reference is SO908244.
Purpose of study and scope e.g. for scope just include whether it is simple, routine, moderate, difficult, very difficult	The M5 Junction 10 project is proposed to enhance transport links in the Cheltenham area. The proposed location of the scheme, which is to the west of Cheltenham, is prone to flooding. Atkins has developed hydraulic modelling to understand the risk of flooding in the area and to assess the potential impacts of the scheme.
Key catchment features e.g. permeable, urban, pumped, mined, reservoired	Two river catchments are studied; the River Chelt (30km^2) and the Leigh Brook (9km^2). The River Chelt catchment is steep and has high contrast between its densely urban areas through Cheltenham and its contrasting rural areas upstream and downstream of the town. Dowdeswell reservoir (surface area: 0.1km^2) is located in the upper catchment. The Leigh Brook catchment is low lying and rural in nature. The Cheltenham CSO, managed by STW, contributes to flows on the River Chelt (outfall at Arle). The CSO's catchment area is 11.5km^2 (derived from STW model).
Flooding mechanisms e.g. fluvial, surface water, groundwater	The main mechanisms for flooding in the area are fluvial flooding and intense rainfall. Flows are also attenuated by the M5's road embankment.
Gauged / ungauged State if there are flow or level gauges and a very brief indication of quality if there are	The catchment is gauged. A tipping bucket rainfall (TBR) gauge is located at Dowdewell reservoir in the upper catchment. The Arle level gauge is located in the west of Cheltenham on the River Chelt. The Slate Mill flow gauge is located to the west of the M5, although it was removed in 2010 due to bypassing and siltation.
Final choice of method	The ReFH2 method has been used for the sub catchment inflows, as it provided higher, more precautionary flows compared to the FEH statistical method. The default parameters of ReFH2 also calibrated well with observed rainfall events in the catchment. A weighted-by-area (40%) CSO inflow has also been used to account for the additional flows provided by the CSO outside of the topographic boundary of the River Chelt catchment.
Key limitations / uncertainties in results	It has not been possible to calibrate the hydrological inflows independently of the hydraulic model due to the attenuation caused by the M5 motorway embankment.

1.2 Note on flood frequencies

The frequency of a flood can be quoted in terms of a return period, which is defined as the average time between years with at least one larger flood, or as an annual exceedance probability (AEP), which is the inverse of the return period.

Return periods are are output by the Flood Estimation Handbook (FEH) software and can be expressed more succinctly than AEP. However, AEP can be helpful when presenting results to members of the public who may associate the concept of return period with a regular occurrence rather than an average recurrence interval. Results tables in this document contain both return period and AEP titles; both rows can be retained or the relevant row can be retained and the other removed, depending on the requirement of the study.

The table below is provided to enable quick conversion between return periods and annual exceedance probabilities.

Annual exceedance probability (AEP) and related return period reference table

AEP (%)	50	20	10	5	3.33	2	1.33	1	0.5	0.1
AEP	0.5	0.2	0.1	0.05	0.033	0.02	0.0133	0.01	0.005	0.001
Return period (yrs)	2	5	10	20	30	50	75	100	200	1,000

2 METHOD STATEMENT

For all but simple or routine projects, establish a break-point in which the method statement is reviewed before work continues. This creates a valuable opportunity to agree on the intended approach and address any difficulties with availability of data or information from previous work.

2.1 Requirements for flood estimates

<table>
<tr><td>Overview
The content and level of detail provided in this section will depend on the scope of the study. The following should be included as a minimum:
• Purpose of study
• Peak flows or hydrographs?
• Design events for which flow estimates are to be made given as AEP (%)
• Climate change allowances with reference to relevant guidance
• Potential number of locations for flow estimation
• The purpose of the document</td><td>The M5 Junction 10 Improvement project (hereafter referred to as ‘the scheme’) is being proposed by Gloucestershire County Council (GCC) to support major redevelopment of Cheltenham and the surrounding area.

The junction and its surrounding geographical areas are prone to flooding, as shown on the Environment Agency’s (EA) flood maps. The two predominant watercourses flowing under the M5 at this location are the River Chelt and the Leigh Brook. There are also numerous culverts draining smaller watercourses under the M5 in the area. Blockage of these structures could exacerbate the effects of flooding.

Added to this, the scheme is located some 1.8km downstream of the town of Cheltenham, which has suffered significant flood damage in the past. Notable flooding occurred in the summer of 2007, where two separate heavy rainfall events in June and July led to severe flood damage in the town.

Understanding of the mechanisms and the potential consequences of flooding in the area are crucial to the Scheme’s success. Detailed hydraulic modelling is therefore required to firstly understand the baseline flood risk in the area, and to then test the different scheme options and their effects on flood risk. For this, peak flows and hydrographs are required for the River Chelt and Leigh Brook to inform a new 1D-2D hydraulic model, known as the ‘M5J10 model’.

The key areas of interest for this hydrological assessment are where the River Chelt and the Leigh Brook flow under the existing M5, as well as the upstream land where the scheme is proposed to be located.

Flows are required for a range of events, including: 50% Annual Exceedance Probability (AEP), 20% AEP, 10% AEP, 4% AEP, 2%AEP, 1.33% AEP, 1% AEP, 0.5% AEP and 0.1% AEP. The scheme is defined as critical infrastructure; thus, assessment is required for the 1% (1 in 100) Annual Exceedance Probability (AEP) event, plus 70% climate change. Climate change allowances are described in further detail in 7.2.</td></tr>
<tr><td>Project scope
What is the complexity of the study – simple, routine, moderate, difficult, very difficult?
What analyses need to be included within the study, for example:
• Review of existing studies?
• Rating reviews / updates?
• Simple / detailed flood history review?
• ReFH model parameter</td><td>Peak flows and hydrographs using the FEH statistical and ReFH2 methods are required to inform the 1D-2D hydraulic model. Hydrological calibration will also be attempted for major flood events; which are the July 2007 and December 2008 events.
Calibration will be achieved by applying historical rainfall data recorded at Dowdeswell rain gauge in the upper Chelt catchment to the observed rainfall component of ReFH2.3 software. Flows will be produced for the catchment draining to Slate Mill gauge in the lower catchment. ReFH2.3 rainfall calibration is described further in 2.8.

In addition to calculating flows the River Chelt and Leigh Brook, this study must also include an allowance for the Cheltenham Combined Sewer Overflow (CSO) system, which is managed by Severn Trent Water. The CSO is known to have an effect on the flows in the River Chelt downstream of Arle, where it discharges to the River</td></tr>
</table>

estimation? • Joint probability?	Chelt. Its catchment is 11.5km^2. The method adopted to account for the CSO inflow is described in 2.9.

2.2 The catchment

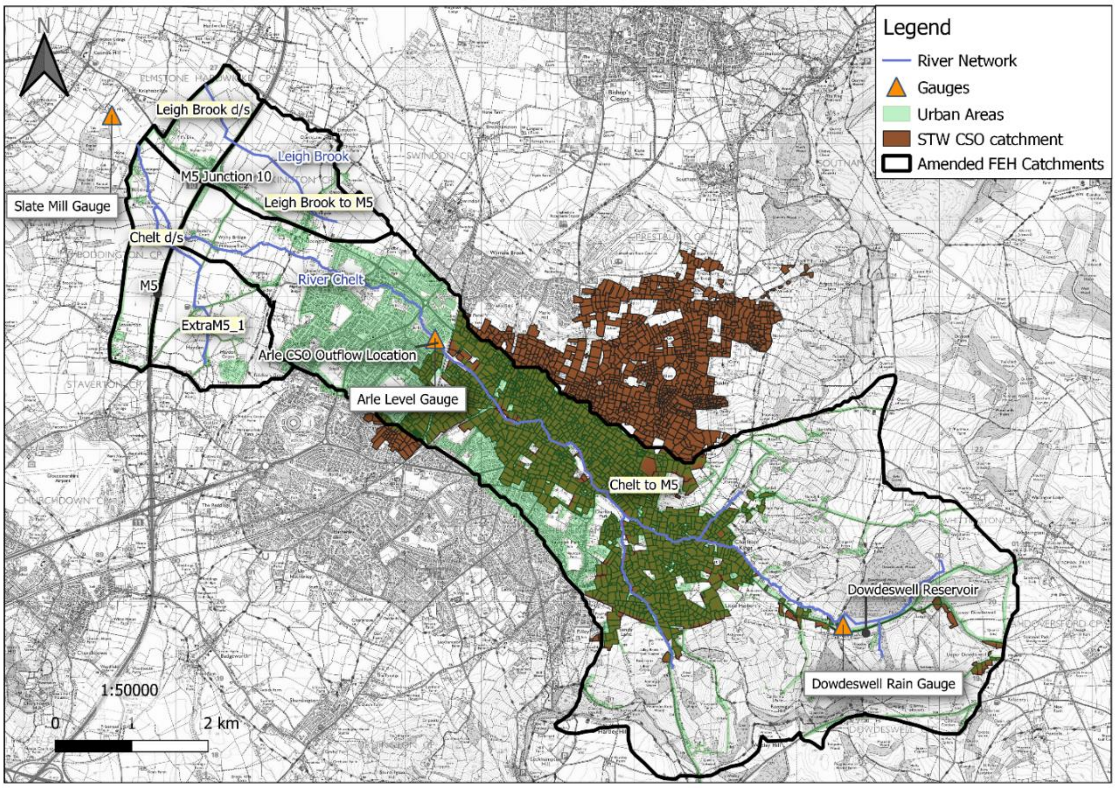


Figure 1: Overview of the River Chelt and Leigh Brook catchments

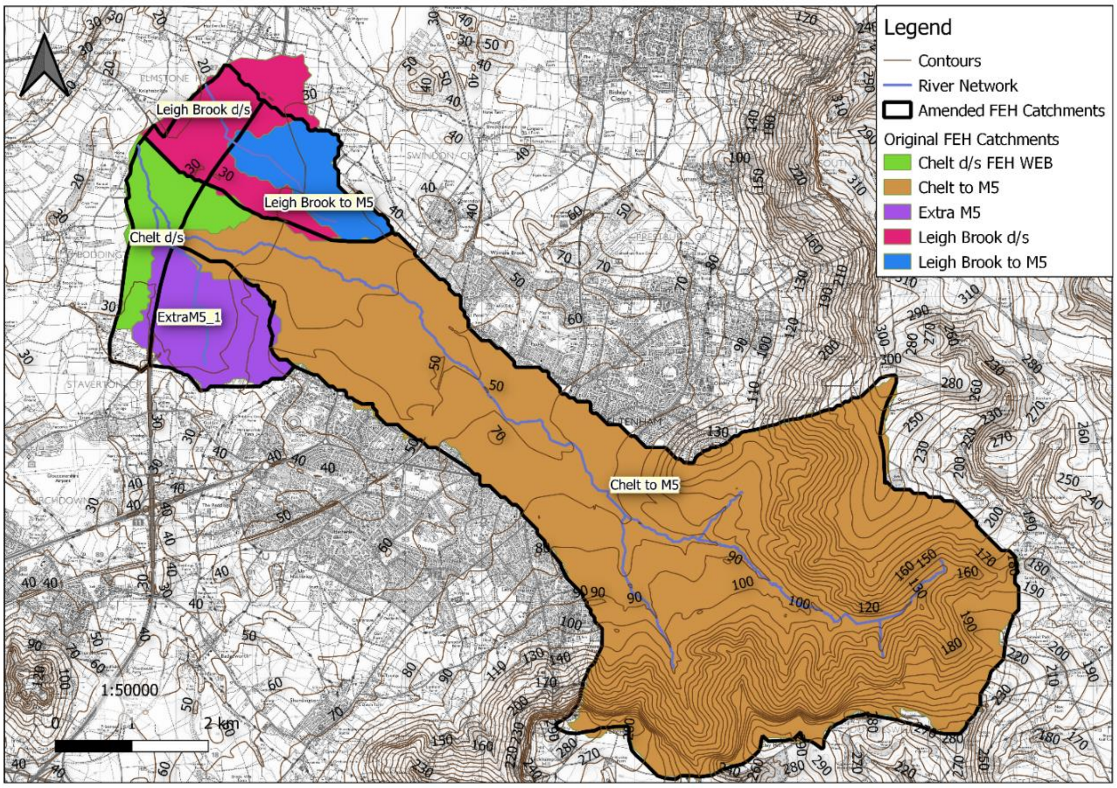


Figure 2: FEH catchment amendemnts

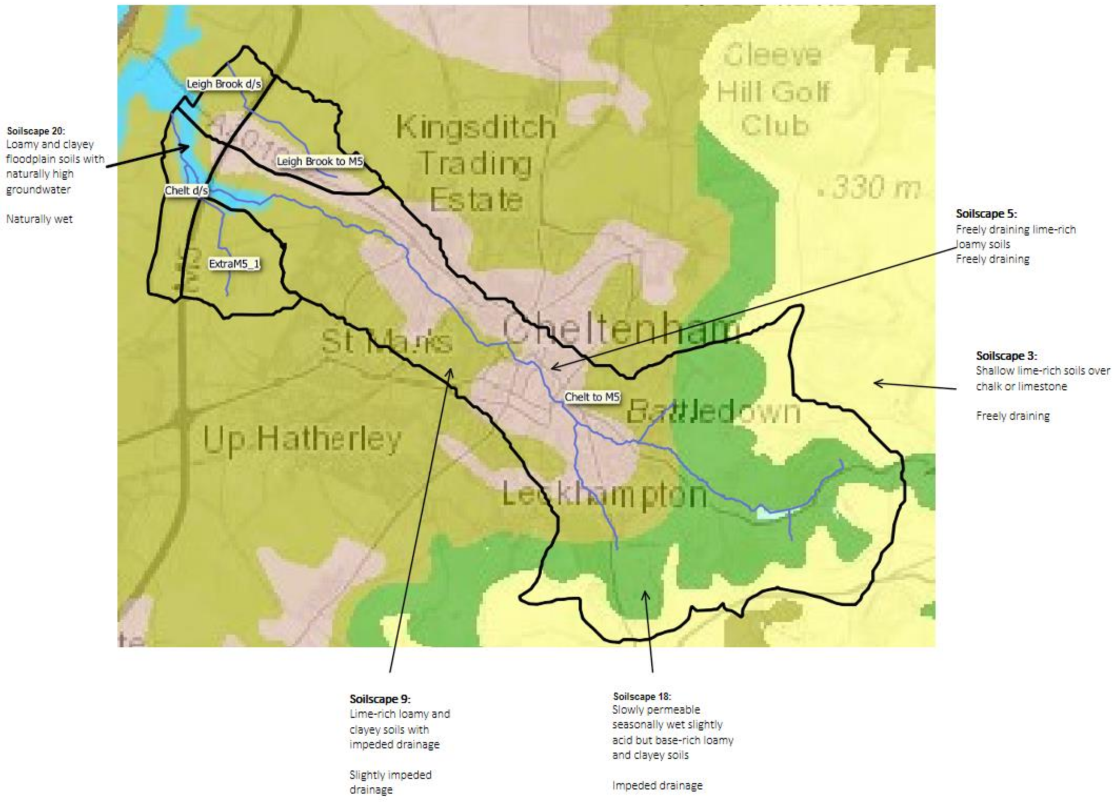
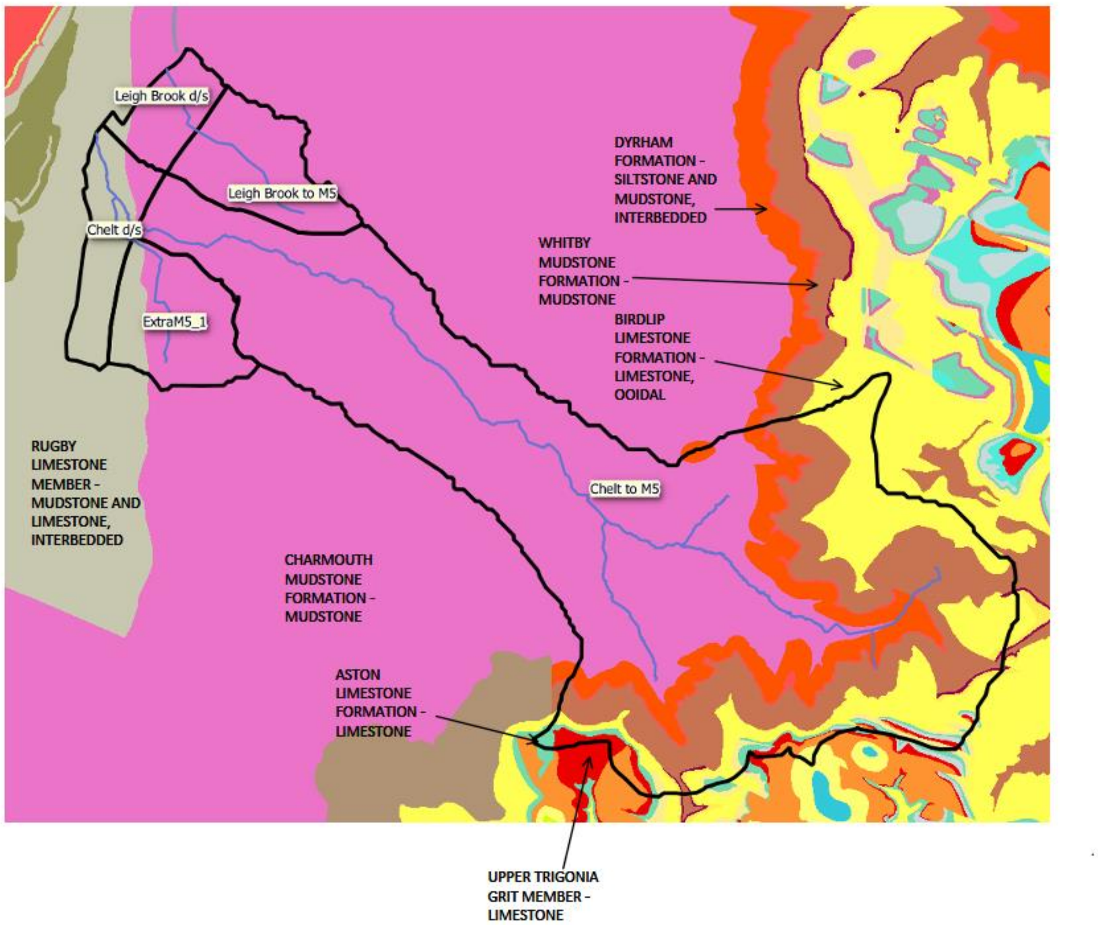


Figure 3: Catchment soilscapes[1]



[1] Soilscapes soil types viewer - National Soil Resources Institute. Cranfield University (landis.org.uk)

<table>
<tr><th colspan="2">Figure 4: Catchment geology[2]</th></tr>
<tr><td>Description
Include topography, climate, geology, soils, land use and any unusual features (e.g. reservoirs, historic mining) that may affect the flood hydrology. In some cases, it may be useful to include reference to things such as amount of modelled reach that is culverted but remember that this is not a hydraulic modelling report and detail on hydraulic features, such as weir and culvert sizes, is not required. Think about what features are going to affect runoff from the contributing catchment reaching the watercourse.</td><td>The two watercourses that require assessment in this study are the River Chelt and one of its tributaries: the Leigh Brook. The confluence of these rivers is located approximately 5km downstream of the M5. The River Chelt then flows into the River Severn a further 3km downstream. This study assesses the catchment of the Chelt (including the Leigh Brook catchment) from its source to the downstream boundary of the hydraulic model at Boddington, approximately 1km west of the M5.

The Chelt catchment

This catchment area of the River Chelt and its tributaries upstream from Boddington is approximately 32km^2. The catchment is predominantly urban, as a large proportion of the catchment flows through the town of Cheltenham. In contrast, its headwaters upstream of Cheltenham comprise of steep woodlands; and its land cover downstream of the town is characterised by low-lying farmland. The catchment is steep, ranging from a maximum elevation of 260mAOD in the upper catchment to 30mAOD in the lower catchment at the M5.

There are also a number of tributaries that flow into the River Chelt throughout the catchment, such as the Ham Brook, Lilley Brook and Leigh Brook.

Dowdeswell reservoir is located in the upper catchment, which drains a sub-catchment area of 5km^2. Its surface area is 0.1km^2.

The urban area of Cheltenham is served by many hydraulic structures and a Combined Sewer Overflow (CSO). Both the reservoir and CSO are managed by Severn Trent Water (STW).
STW provided a range of hydrographs from their model of the CSO, which has been incorporated into this study. The CSO drains a catchment area of 11.5km^2. GIS analysis conducted by Atkins demonstrated the 40% of the CSO's catchment area falls outside of the topographic catchment/watershed of the River Chelt.

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. Flows are also attenuated upstream of the M5 Motorway embankment, as demonstrated on the EA's flood maps.

The underlying geology of the catchment is largely Lower Lias clays with Middle and Upper Lias formations in the headwaters with river terrace sands and gravels along the main valley (Figure 4). The soils are a mixture of impeded or freely draining Soilscapes[3] in both the headwaters and lower reaches (Figure 3):
• The headwaters comprise of a mixture of freely draining 'Soilscape 3: Shallow lime-rich soils over chalk or limestone' and 'Soilscape 18: Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils', which has impeded drainage.
• The lower reaches are a mixture of 'Soilscape 9: Lime-rich loamy and clayey soils with impeded drainage' and 'Soilscape 5: Freely draining lime-rich loamy soils'.
These soil characteristics correlate with the BFIHOST and SPRHOST values for</td></tr>
</table>

[2] Geology of Britain viewer | British Geological Survey (BGS)

[3] http://www.landis.org.uk/soilscapes/

	the catchment, based on the FEH catchment descriptors . ***The Leigh Brook Catchment*** The Leigh Brook catchment has an area of 9.15km2 from its source to the confluence with the River Chelt. The confluence of these rivers is located immediately upstream of the A38 road, which is approximately 5km downstream of the Scheme and approximately 3km upstream of the River Severn. The source of the Leigh Brook watercourse is approximately 2km upstream of the M5. The river is culverted under the M5 and flows westwards, before heading south towards the River Chelt. The Leigh Brook catchment is predominantly rural, although it does contain many roads and villages in its realtively small area. It is situated in the lower reaches of the Chelt and thus has a shallow gradient. The catchment is a mixture of naturally wet 'Soilscape 20: Loamy and clayey floodplain soils with naturally high groundwater' and Soilscape 9: Lime-rich loamy and clayey soils with impeded drainage (Figure 3)

2.3 Source of flood peak data

This should be updated to the latest version of the dataset at the time of the assessment.

Source	NRFA peak flows dataset, Version 9, released October 2020. This contains data up to water year 2018-2019.

2.4 Gauging stations (flow or level)

Only need to include gauges at or very near to the sites of flood estimates unless there is an exceptional reason to include other gauges.

Note: If you have data extracted from WISKI the datafile may only provide the digital data period of record, and the actual operating period of the gauge may be longer. It is useful to check this.

Water-course	Station name	Gauging authority number	NRFA number	Catchment area (km^2)	Type (rated / ultrasonic / level…)	Start of record and end if station closed
River Chelt	Slate Mill	Environment Agency - West Midlands (2026)	54026	34.5km^2	Concrete trapezoidal flume	01/1969 - 09/2010
River Chelt	Arle	Environment Agency – West Midlands (2174)	N/A, level only gauge	23.66	Level	Dec 2006 - present

2.5 Data available at each flow gauging station in Table 2.4

This table can be deleted if the study catchment is ungauged.

A quality check of the data is not required if the gauge is in the NRFA, unless specifically called for in the project brief.

There is no need to repeat everything in the NRFA station description, for example, weir length, wingwall height. Just add the key factors which will affect the quality of flood flow measurement and hence confidence in the data. For more detailed studies consider looking for other sources of information, for example, gauging authority rating review reports, station files held at CEH Wallingford, or reports on earlier flood studies.

Station name	Start and end of NRFA flood peak record	Update for this study?	OK for QMED?	OK for pooling ?	Data quality check needed?	Other comments on station and flow data quality
Slate Mill	01/1969 - 09/2010	No	Yes	No	No	NRFA describes Slate Mill as a poor station. It is known to bypass during high flows and prone to silt build-up at the lowe end of the flume. Flows were not processed after 1984 due to poor rating and station closed in 2010 and structure removed. Its predominant purpose was a low-flow gauge. This station is not considered to be reliable to inform this study due to the high level of uncertainty in flows. There is significant concern over the use of flows from the Slate Mills site at high flows, due to silt and vegetation build up affecting the rating at high flows. Through discussion with the Environment Agency, it was agreed that the gauge data at Slate Mill was not appropriate to use to directly derive flow estimates through the FEH Statistical Method. Previous flood studies also did not use the gauge to inform the hydrological estiamtes due to its uncertainty at high flows.
Arle	Dec 2006 - present	No	N/A – level gauge	N/A – level gauge	No	A level gauge, which is located at Arle, upstream of the model boundary. It has been used to identify flood events.

2.6 Rating equations

This table can be deleted if the catchment is ungauged or if all gauges are in the NRFA and a rating review is not requested in the project brief.

-More information on rating reviews is provided in Section 2.1 of the Flood Estimation Guidelines.

Station name	Type of rating e.g. theoretical, empirical; degree of extrapolation	Rating review needed?	Comments and link to any rating reviews
Slate Mill	Empirical	No	Used to convert level data at Slate Mill to flow for calibration of known flood events. Rating obtained from NRFA website and applied to record[4].

2.7 Other data available and how it has been obtained

Type of data	Data relevant to this study?	Data available?	Source of data	Details
Check flow gaugings (if planned to review ratings)	N/A			No rating review required.
Historical flood data Include chronology and interpretation of flood history in Annex or separate report. The detail included will depend on requirements in the project scope. If there is a flow gauge within the study reach (or close by), consider if the historical flood data could be used to extend the systematic gauge record (see FEH Local guidance for more information)	Yes	Yes	Environemnt Agency NRFA	Historical flood outlines, photographs and wrack marks have been provided by the EA for the July 2007 event. EA rainfall and flow (Dowdeswell and Slate Mill) data have been obtained for the July 2007 and December 2008 events. Level data has also been obtained at Arle.
Flow or river level data for events	Yes	Yes	EA	Yes, for July 2007 and December 2008 events. Antecedent rainfall and event rainfall have been extracted from Dowdeswell rain gauge. Rated flow data has been calculated at Slate Mill.
Rainfall data for events	Yes	Yes	EA	15 minute rainfall data from Dowdeswell gauge.
Potential evaporation data This may be required if the ReFH2 Calibration Utility is being used	No			ReFH2 calibration utility not used in this study. Observed rainfall component of ReFH2.3 has been used.
Results from previous studies	Yes, used to compare final estimates	Yes	Black and Veatch model report (2010), used to develop EA 1D-2D hydraulic model of Cheltenham	Document Reference: River Chelt Improvements Scheme Modelling reportv4
			Capita (2012), as part of an update to the EA model package	Document reference: Middle_Chelt_SFRM_Report_Final_v2
			Eden Vale	Document Reference:

[4] NRFA Station Peak Flow Data for 54026 - Chelt at Slate Mill (ceh.ac.uk)

			Young Associates, prepared on behalf of Robert Hitchins Limited as part of an EA flood map challenge at Boddinton (2018)	Boddington_Model_Report_RevE_Final_compressed
Other data or information (e.g. groundwater, tides, channel widths, low flow statistics, sewer network data)	Yes		Severn Trent Water (STW)	Catchment areas (GIS shapefile) and model outputs (spreadsheet) of the Arle CSO have been supplied by STW (January 2020).

2.8 Hydrological understanding of catchment

This table can be deleted if the catchment is ungauged. The second table (conceptual model and unusual features) should not be deleted as this information is relevant for all catchments / studies.

The table below is an opportunity to assess any catchment river gauge data to provide an understanding of the hydrological behaviour of a watercourse. Examples of information which could be here are:

- Plots of flow data, for example, annual flow hydrographs or example flood events. This should be followed by an interpretation of the plots, for example, discussion of catchment processes, response time, propagation of a flood, and contributions from tributaries. If there is more than one gauge in the study area it can be useful to plot the data for all gauges on the same graph as this can aid understanding of the relationship between flow at different locations. These plots can be useful for checking the quality of the data and it is often helpful to plot flow and rainfall together as this may identify problems.
- Plots of stage data. Many catchments do not have flow gauges, but stage / level data may be available. This data can provide valuable information on the catchment response in the absence of flow data.

More information is provided in Section 2 of the Flood Estimation Guidelines.

Add rows to the table if required and change titles in the left column if necessary.

Plots of flow data and interpretation	The flow record at Slate Mill has not been plotted here as it is a poor station, which is known to silt up and is bypassed at higher flows. Therefore, it is not deemed an accurate representation of the flow regime of the River Chelt catchment. This has been demonstrated in the analysis of the observed rainfall and flow during the July 2007 event. Calibration of the default ReFH2.3 parameters (Cmax and Tp) for the July 2007 event were unrealistic (green line in the graph below). Tp was extended to 10 hours to match the peak timing of the event, which is acceptable. However, Cmax, the maximum soil moisture capacity of the catchment, required amending from a default value of 367 to 900 (considered unrealistic). Cini, the initial soil moisture, is determined from the antecedent rainfall to the event, which has been applied to ReFH2.3. The graph below also demonstrates the default ReFH2.3 parameters applied to the 2007 rainfall (orange line). At first obsrevations, this hydrograph is greatly different to the recorded flow at Slate Mill (blue line), with the ReFH2.3 peak flow double that at Slate Mill. However, as mentioned previously, flow on the River Chelt is attenuated by the embankment of the M5. As a test, the observed rainfall of the July 2007 event with default ReFH2.3 parameters was applied to the hydraulic model and produced the dashed line in the graph below. This provides a good fit to flows recorded at the Slate Mill gauge. As this has been applied to the 1D-2D hydraulic model, the bypassing of the gauge is represented in the model. Overall, this demonstrates that the ReFH2.3 method provides a good fit to the 2007 event and the testing of the flows within the hydraulic model demonstrates that the M5 embankment attenuates flows in the River Chelt and that the Slate Mill gauge is bypassed.

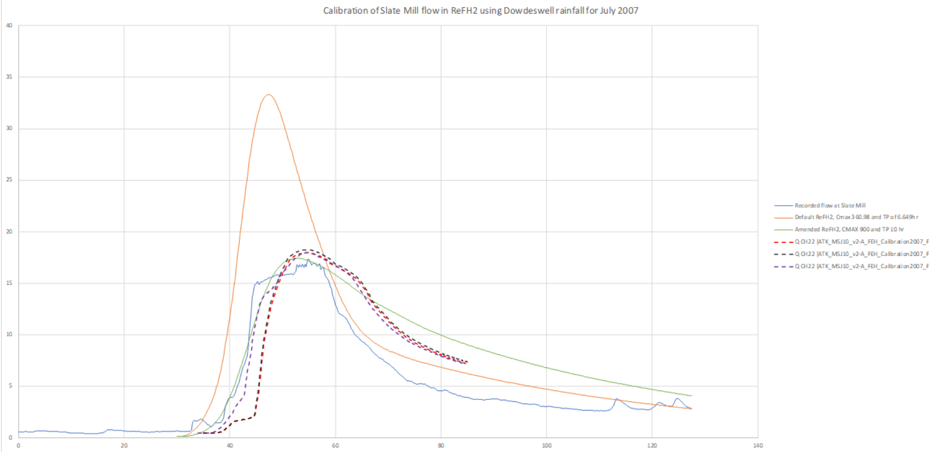


Figure 5: Calibration of July 2007 event

Plots of flood peak data and interpretation

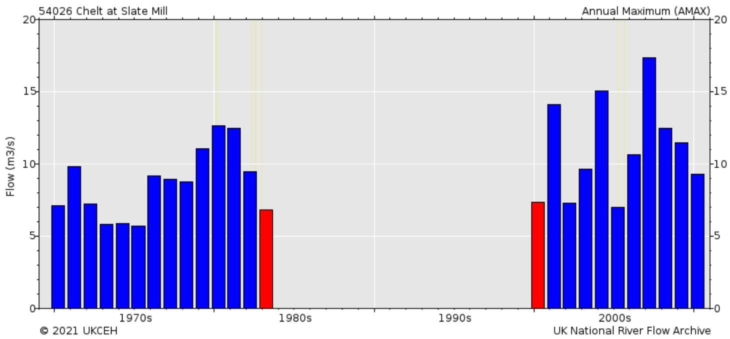


Figure 6: AMAX record at Slate Mill gauge (NRFA)

The AMAX record has been obtained from the NRFA. This demonstrates that the July 2007 event was the highest event on record.

Conceptual model

Include information on factors such as:

- Where are the main sites of interest?
- What is likely to cause flooding at those locations? (peak flows, flood volumes, combinations of peaks, groundwater, snowmelt, tides…)
- Might those locations flood from runoff generated on part of the catchment only, e.g. downstream of a reservoir?
- Is there a need to consider temporary debris dams that could collapse?

The aim of this hydrological assessment is to inform the ‘M5J10’ model. Peak flows and hydrographs are required for the 1D-2D hydrodynamic ESTRY TUFLOW model.

The River Chelt and Leigh Brook catchments have been divided into sub catchments for use in the hydraulic model. Catchment boundaries from the FEH web have been amended based on the contours and OS river network.

Traditional FEH methods (statistical estimate for peak flows and ReFH2.3 hydrographs) will be estimated for each sub catchment. The results of both estimates will be compared to determine the most suitable methodology to carry forward to the design events.

The critical storm duration will be calculated in ReFH2.3 software for the River Chelt catchment draining to the M5, as this is the main site of interest for the scheme. The aim of this is to replicate the worst-case storm for the scheme.

A hydrological calibration will also be conducted for the July 2007 and December 2008 events. This will be completed in ReFH2.3 software using the observed rainfall component.

As mentioned, it is important that the CSO input to the River Chelt at Arle is represented in this study, as it is known to have an effect on flows in the River Chelt downstream of Arle. Atkins has received model output data and GIS shapefiles of the CSO sub catchments from STW. Analysis

	of the CSO catchments in comparison to the topographic catchment of the River Chelt demonstrated that 40% of the CSO catchment drains an area outside of the topographic catchment of the River Chelt. As a result, the CSO model outputs provided by STW will be scaled by 0.4 to account for the additional flow from outside the topographic catchment boundary. The FEH topographic catchment has been maintained, as it is assumed that the pipes associated with the CSO will be overcapacitated during rarer, higher magnitude events.
Unusual catchment features Include information on factors such as: • highly permeable • heavily urbanised • pumped watercourse • major reservoir influence (FARL<0.90) • flood storage areas, particularly those which are normally dry • historical mining or operational mining activities Guidance on methods for unusual catchments is contained in Section 7 of the Flood Estimation Guidelines	The River Chelt catchment draining to the M5 is urban (URBEXT=0.24) Dowdeswell reservoir is located in the upper Chelt catchment. GIS analysis has determined its surface area as 0.1km^2 and drains a catchment area of approximately 5km^2 (17% of the total River Chelt catchment area draining to the M5). FARL has been manually calculated in GIS and verifies the catchment descriptor value of 0.97. The catchment is therefore not highly attenuated by the reservoir. The EA flood maps and calibration of the July 2007 event has demonstrated that flows are attenuated by the M5 embankment. There is a CSO (catchment area 11.5km^2) that discharges to the River Chelt at Arle.

2.9 Initial choice of approach

Is FEH appropriate? (it may not be for extremely heavily urbanised or complex catchments). If not, describe other methods to be used.	Yes. This study will apply FEH methods to estimate flows for the topographic catchments. A scaled by area (40%) inflow of the CSO will be applied to the model to account for the area outside of the topographic catchment.
Initial choice of method(s) and reasons Think about: (i) the type of problem, (ii) the type of catchment, and (ii) the type of data available. Which methods are appropriate? If more than one method is appropriate will all be applied, and the results compared before a final decision is made? How will hydrograph shapes be derived if needed? e.g. ReFH1 / ReFH2 shapes, average hydrograph shape from gauge data Will the catchment be split into sub-catchments? If so, how? If the hydrological assessment is being undertaken to supply inflows to a hydraulic model, it is likely that a distributed approach will be taken, with the catchment split into sub-catchments and design flows routed from each sub-catchment. Think about what the split into sub-catchments will be based on, e.g. tributary confluences, changes in geology / urbanisation, key areas of interest, sewer outfalls. Will intervening area hydrographs be required and how will these be derived? If the catchment area changes significantly over the study reach, or tributaries are also being modelled, will different storm durations need to be considered / tested?	FEH statistical and ReFH2 will be applied to the topographic catchments and the CSO inflows will be scaled by area to account for the catchment area outside of the topographic catchment. Although 60% of the CSO catchment is within the topographic catchment of the River Chelt, it is assumed that the capacity of the CSO pipes will be exceeded for higher return period events. ReFH2 will be used to calculate the hydrograph shape and timing. Catchments will be divided into sub catchments for use in the hydraulic model. The two downstream sub catchments have been amended to match the model extent.
Software to be used (with version numbers) Delete entries in the column on the right as appropriate	FEH Web Service[5] / WINFAP 4[6] / ReFH2.3

[5] CEH 2015. The Flood Estimation Handbook (FEH) Online Service, Centre for Ecology & Hydrology, Wallingford, UK.

[6] WINFAP 4 © Wallingford HydroSolutions Limited 2016.

3 LOCATIONS WHERE FLOOD ESTIMATES REQUIRED

Simple catchments map

The table below lists the locations of subject sites. The site codes listed below are used in all subsequent tables to save space.

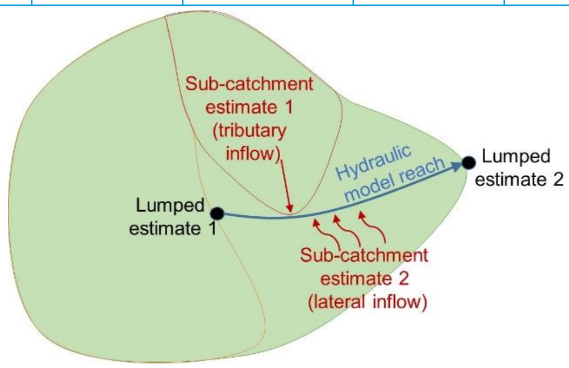
3.1 Summary of subject sites

Site code	Type of estimate L: lumped catchment S: Sub-catchment	Watercourse	Name or description of site	Easting	Northing	AREA on FEH CD-ROM (km^2)	Revised AREA if altered
River Chelt to M5	L	River Chelt	River Chelt catchment draining to the M5, applied at the upstream boundary of the model	390050,	224800	30.05	30.59
Extra M5	L	Un named tributary to River Chelt	Un named tributary to the River Chelt which flows to the Staverton culvert at the M5	389750	224800	2.50	2.35
Chelt d/s	SC	River Chelt	Sub-catchment of the River Chelt, downstream of the M5 (catchment upstream of M5 removed from area)	387250	225000	38.66	1.71
Leigh Brook to M5	L	Leigh Brook	Leigh Brook catchment draining to the M5	390750	226050	1.53	2.29
Leigh Brook d/s	SC	Leigh Brook	Sub-catchment of the Leigh Brook, downstream of the M5 (catchment upstream of M5 removed from area)	387250	225050	2.21	1.13
CSO	L	Arle CSO	CSO catchment, managed by STW. 40% of the CSO's catchment is outside of the River Chelt's topographic catchment/watershed	393200	223900	N/A	11.5 (provided by STW)

Note: Lumped catchments (L) are complete catchments draining to points at which design flows are required.

Sub-catchments (S) are catchments or intervening areas that are being used as inputs to a semi-distributed model of the river system. There is no need to report any design flows for sub-catchments, as they are not relevant: the relevant result is the hydrograph that the sub-catchment is expected to contribute to a design flood event at a point further downstream in the river system. This will be recorded within the hydraulic model output files. However, catchment descriptors and ReFH model parameters should be recorded for sub-catchments so that the results can be reproduced.

The schematic diagram illustrates the distinction between lumped and sub-catchment estimates.



3.2 Important catchment descriptors at each subject site (incorporating any changes made)

Consider using a different colour text / highlighting to identify catchment descriptors which have been changed from the FEH values.

Include any intervening areas required for a distributed approach in here as these are necessary to reproduce results.

Site code	FARL	PROPWET	BFIHOST	BFIHOST2019	DPLBAR (km)	DPSBAR (m/km)	SAAR (mm)	URBEXT 2000**	FPEXT
River Chelt to M5	0.973*	0.33	0.44	0.46	6.51	82.8	730	0.24	0.09
Extra M5	1	0.33	0.23	0.27	1.89	16.4	637	0.08	0.27
Chelt d/s	1 (influence of upstream catchment has been removed)	0.33	0.41	0.43	1.34	67.4	708	0.09	0.13
Leight Brook to M5	1	0.33	0.36	0.45	1.57	12.2	632	0.07	0.11
Leigh Brook d/s	1	0.33	0.34	0.39	1.07	12.6	623	0.13	0.21

* FARL for the Chelt catchment to the M5 was manually calculated using GIS, using the equations in FEH volume 5, Chapter 4 'Indexing the attenuation effect attributable to reservoirs and lakes'. The same
** URBEXT for each sub catchment has been updated based on recent OS map data

3.3 Checking catchment descriptors

Record how catchment boundary was checked and describe any changes Add maps if needed to aid explanation of any changes If changes are made to the catchment boundary (and hence AREA), identify if any other descriptors will be updated and how	Catchments were downloaded from the FEH web service[7]. Topogrpahic catchment boundaries were assessed in GIS software, based on the EA's 1m LiDAR (2019) and 1m contours. Checks were also made against the OS River Network layer to ensure that no watercourses crossed catchment and inter catchment boundaries. Minor amendments were made to the catchment boundaries (Figure 2). The key catchment descriptors for the two catchments downstream of the M5 (River Chelt d/s and Leigh Brook d/s) were area weighted such that the upstream catchment areas were not accounted for twice. DPLBAR updated if area changed significantly, ased on the folmula DPLBAR = AREA^0.548
Record how other catchment descriptors were checked and describe any changes. Include before/after table if necessary.	Soils and geology were compared to the respective GIS layers, as shown in Figure 3 and Figure 4, respectively. No changes were made.
Source of URBEXT Delete as needed. URBEXT1990 is only used for ReFH1 An alternative is the URBAN50k method if URBEXT values need to be substantially revised due to discrepancies between the FEH urban extent layers and current mapping	URBEXT2000 – used in FEH statistical and ReFH2 software Urban areas were digitised using the latest Ordnance Survey 1:50,000 raster mapping, as shown in Figure 1. The urban areas of each catchment were calculated.

[7] Home Page - FEH Web Service (ceh.ac.uk)

Method for updating of URBEXT Delete as needed (CPRE formula from FEH Volume 4 is for URBEXT1990) An update to the current year is not required when the URBAN50k method is used as it will be implicitly accounted for in the latest mapping	URBEXT 2000 for each sub catchment was calculated using the formula: URBEXT2000 = Urban proportion of catchment x 0.629

4 STATISTICAL METHOD

4.1 Application of Statistical method

What is the purpose of applying this method? Brief summary of the reasons, specific to this study, for applying the method. For example, lumped estimates at key locations for the purpose of checking modelled peak flow estimates.	FEH statistical is the preferred method in EA guidelines for calculating QMED and growth curves for higher return period events. Initial investigation of the FEH statistical method included one pooling group calculation for the one urban catchment (Chelt to M5) and one pooling group for rural catchments, based on the Leigh Brook to M5 cathcment.

4.2 Overview of estimation of QMED at each subject site

If more than one donor is used, use multiple rows for the site and give the weights used in the averaging. Record the weighted average adjustment factor in the penultimate column.

The final estimate of QMED should include any relevant donor and urban adjustment. If QMED is derived directly from AMAX or POT data, an urban adjustment factor should not be applied as this is implicitly included in the estimate and would be double-counted.

Site code	QMED (rural) from CDs (m^3/s)	Final method	Data transfer					Urban adjust-ment factor UAF	Final estimate of QMED (m^3/s)
			NRFA numbers for donor sites used (see 4.3)	Distance between centroids d_{ij} (km)	Moderated QMED adjustment factor, (A/B)[a]	If more than one donor: Weight	If more than one donor: Weighted ave. adjustment		
River Chelt to M5	5.86	DT	54036 (Isbourne @ Hinton on the Green)	13.22	0.98	0.354		1.27	7.49
Extra M5	0.77	CD	N/A	N/A	N/A	N/A	N/A	1.07	0.82
Chelt d/s	0.55	CD	N/A	N/A	N/A	N/A	N/A	1.07	0.60
Leight Brook to M5	0.58	CD	N/A	N/A	N/A	N/A	N/A	1.07	
Leigh Brook d/s	0.32	CD	N/A	N/A	N/A	N/A	N/A	1.07	0.36

Are the values of QMED spatially consistent?		Yes
Method used for urban adjustment for subject and donor sites (delete method in the column to the right as needed)		Kjeldsen (2010)[8] / WINFAP v4[9]
Parameters used for WINFAP v4 urban adjustment if applicable (these are 'standard' values and should be revised if alternative values have been applied)		
Impervious fraction for built-up areas, IF	Percentage runoff for impervious surfaces, PR_{imp}	Method for calculating fractional urban cover, URBAN
0.3	70%	From updated URBEXT2000

[8] Kjeldsen, T. R. (2010). Modelling the impact of urbanization on flood frequency relationships in the UK. Hydrol. Res. **41**. 391-405.

[9] Wallingford HydroSolutions (2016). WINFAP 4 Urban adjustment procedures.

Notes

Methods: AM – Annual maxima; POT – Peaks over threshold; DT – Data transfer (with urban adjustment); CD – Catchment descriptors alone (with urban adjustment); BCW – Catchment descriptors and bankfull channel width (add details); LF – Low flow statistics (add details).

The QMED adjustment factor A/B for each donor site is moderated using the power term, a, which is a function of the distance between the centroids of the subject catchment and the donor catchment. The final estimate of QMED is $(A/B)^a$ times the initial (rural) estimate from catchment descriptors.

Important note on urban adjustment

The method used to adjust QMED for urbanisation published in Kjeldsen (2010)[8] in which PRUAF is calculated from BFIHOST is not correctly applied in WINFAP-FEH v3.0.003. Significant differences occur only on urban catchments that are highly permeable. This is discussed in Wallingford HydroSolutions (2016)[9].

4.3 Search for donor sites for QMED (if applicable)

Comment on potential donor sites Provide details regarding how potential donors were selected and the reasons why they were chosen / rejected. Include a map if necessary, which shows the location of the study catchment and donor stations under consideration. Section 4 of the Flood Estimation Guidelines provides guidance on selecting a donor(s) for data transfer.	WINFAP selects 10 donors, which were assessed for each catchment based on the following criteria: • Area of donor not more than 5x the area of the catchment • SAAR not more than 25% greater • BFIHOST not beyond +/-0.18 • FARL not less than -0.05 of the catchment's FARL • URBEXT not more than 25% greater. No suitable catchments were found for the rural catchments, as their area was too small. One suitable donor was found for the River Chelt catchment draining to the M5.

4.4 Donor sites chosen and QMED adjustment factors

NRFA no.	Method (AM or POT)	Adjustment for climatic variation?	QMED from flow data (A)	QMED from catchment descriptors (B)	Adjustment ratio (A/B)
54036 (Isbourne @ Hinton on the Green	AM	No	13.225	13.924	0.95

4.5 Derivation of pooling groups

Try to use as few groups as possible, this avoids step changes in flow estimates between flow estimation points for catchment-wide studies. If all catchments being assessed have AREA <25km^2 and similar SAAR, FARL and FPEXT values, normally use one group.

Section 4.3 of the Flood Estimation Guidelines provides further details on reviewing pooling groups.

Name of group	Site code from whose descriptors group was derived	Subject site treated as gauged? (enhanced single site analysis)	Changes made to default pooling group, with reasons (if there are no changes just say "None", although it is helpful to provide details of stations which were investigated even if they were ultimately retained)	Weighted average L-moments L-CV and L-skew, (before urban adjustment)
River Chelt to M5 (urban)	River Chelt to M5	No	Stations removed 7011 (Black Burn @ Pluscarden Abbey) – Less than 8 years of data 33054 (Babingley @ Castle Rising) – removed due to high permeability (SPRHOST < 20) 26013 (Driffield Trout Stream @ Driffield) – Small record of data and removed due to high permeability 26014 (Water Forlornes @ Driffield) – Chalk catchment with SPRHOST of 6.5, remove due to high permeability 9006 (Deskford Burn @ Cullen) – abstractions influence the flows, remove 33032 (Heacham @ Heacham) – Remove due to permeability (SPRHOST < 20) 26003 (Foston Beck @ Foston Mill) - Remove due to permeability (SPRHOST < 20) Stations investigated but retained 36010 (Bumpstead Brook @ Broad Green) – permeable station but removed 11 non-flood years from record (where AMAX < 0.5xQMED) 36003 (Box @ Polstead) – removed 11 non flood years (where AMAX < 0.5xQMED)	0.248 0.182
Rural catchments	Leigh Brook to M5	No	Stations removed 76011 (Coal Burn @ Coalburn) – Underestimates peak flows by up to 10%, removed due to underestimation 27073 (Brompton Beck @ Snainton Ings) – Remove due to high permeability (SPRHOST < 20) 26016 (Gypsey Race @ Kirby Grindalythe) - Remove due to high permeability (SPRHOST < 20) 49005 (Bolingey Stream @ Bolingey Cocks Bridge) – Removed due to short record 47022 (Tory Brook @ Newnham Park) – China clay works alters hydrology 44008 (South Winterbourne @ Winterbourne Steepleton) - Remove due to high permeability (SPRHOST < 20) Stations investigated but retained 36010 (Bumpstead Brook @ Broad Green) – permeable station but removed 11 non-flood years from record (where AMAX < 0.5xQMED)	0.237 0.245

Note: Pooling groups were derived using the procedures from Science Report SC050050 (2008).

4.6 Derivation of flood growth curves at subject sites

Any relevant frequency plots from WINFAP, particularly showing any comparisons between single-site, enhanced single-site and pooled growth curves (including flood peak data on the plot), should be shown here.

An individual urban adjustment should be applied even if the same pooling group (including enhanced single-site analysis) has been applied to several sites, as each site is likely to have a different URBEXT2000 value and hence a different urban adjustment.

For single-site analysis on a permeable catchment, or a pooled analysis for a group consisting largely of permeable catchments, a permeable adjustment should be applied to the growth curve using the technique described in the FEH Volume 3, Chapter 19 for removing flood-free years by adjusting the L-moments.

Site code	Method (SS, P, ESS, J)	If P, ESS or J, name of pooling group	Distribution used and reason for choice	Note any urban adjustment or permeable adjustment	Parameters of distribution (location, scale and shape after adjustments)	Growth factor for 100-year return period / 1% AEP (delete as needed)
River Chelt to M5	P	River Chelt to M5	Generalised Logistic	UAF of 1.27 applied	Location: 1 Scale: 0.214 Shape: -0.223	2.717
Leigh Brook to M5	P	Rural catchments	Generalised Logistic	UAF of 1.07 applied	Location: 1 Scale: 0.203 Shape: -0.275	2.873

Notes
Methods: SS – Single site; P – Pooled; ESS – Enhanced single site; J – Joint analysis
Urban adjustments are all carried out using the method of Kjeldsen (2010).
Growth curves were derived using the procedures from Science Report SC050050 (2008).

4.7 Flood estimates from the statistical method

Site code	Flood peak (m³/s) for the following return periods (in years)									
	2	5	10	25	50	100	200	1000		
	Flood peak (m³/s) for the following AEP (%) events									
	50	20	10	4	2	1	0.5	0.1		
River Chelt to M5	7.49	10.10	12.05	14.92	17.45	20.36	23.74	33.89		
Extra M5	0.82	1.11	1.33	1.67	1.99	2.37	2.82	4.28		
Chelt d/s	0.60	0.81	0.97	1.22	1.45	1.73	2.06	3.13		
Leight Brook to M5	0.62	0.83	1.00	1.26	1.50	1.79	2.13	3.23		
Leigh Brook d/s	0.36	0.48	0.58	0.73	0.87	1.03	1.23	1.87		

5 REVITALISED FLOOD HYDROGRAPH (REFH) METHOD

5.1 Application of ReFH method

What is the purpose of applying this method? Brief summary of the reasons, specific to this study, for applying the method. For example, lumped estimates at key locations for the purpose of checking modelled peak flow estimates, distributed approach to apply inflows to a hydraulic model, deriving hydrograph shapes only, extending the flood frequency curve out to extreme events (long return periods).	The ReFH method has not been used in this study. ReFH2 has been used and is described in Section 6.

5.2 Catchment sub-divisions for urban ReFH model

This section can be deleted if the catchment is essentially rural.

If the catchment is urban…

Did you calculate paved areas using a method other than from URBEXT using the standard equations?

Did you allow for transfer of water via sewers across the topographic catchment boundary?

If yes to either of these questions provide details which give sufficient information to understand the process applied and any assumptions made. It may be useful to include a map of sub-catchments here, if not provided earlier in the report.

5.3 Parameters for ReFH model (rural catchments)

Lumped and sub-catchment / intervening areas should be included in this table.

Site code	Method	Tp (hours) Time to peak	C_{max} (mm) Maximum storage capacity	BL (hours) Baseflow lag	BR Baseflow recharge
Brief description of any flood event analysis carried out (further details should be given in the annex)					
Methods: OPT: Optimisation, BR: Baseflow recession fitting, CD: Catchment descriptors, DT: Data transfer (give details)					

5.4 Parameters for ReFH model (urban or mixed urban & rural catchments)

Lumped and sub-catchment / intervening areas should be included in this table.

If applying the method in Flood Modeller Pro, Tp_{urban} values are not directly specified by the user; the model works them out from the supplied URBEXT, DPLBAR, etc. It is simpler just to report Tp rather than separate URBEXT, etc, values for rural and urban portions.

Note: ReFH is also implemented in InfoWorks ICM which does not include the urban component.

Site code	Method	Tp_{rural} (hours)	Tp_{urban} (hours)	C_{max} (mm)	PR_{imp} % runoff for impermeable surfaces	BL (hours)	BR

5.5 Design events for ReFH method: Lumped catchments

This table can be deleted if ReFH is not being applied for lumped catchments. Note: ReFH may be applied for both lumped catchments and sub-catchments in a study; if this is the case both this table and the next should be completed.

Storm durations detailed here should be the values for the individual catchments. Lumped flows should be generated using the storm duration relevant to each lumped catchment for comparison with Statistical estimates.

Site code	Urban or rural	Season of design event (summer or winter)	Storm duration (hours)

5.6 Design events for ReFH method: Sub-catchments and intervening areas

This table can be deleted if ReFH is not being applied for sub-catchments.

This table is included to identify the storm which will be applied to all inflows to a distributed model (see Section 6.1 of the Flood Estimation Guidelines) and avoid the scenario of using a different storm for each inflow to the model.

If there are multiple flood risk areas throughout the model it may be necessary to allow for different storms in different parts of the model by carrying out multiple model runs. Each model run should use the same storm applied to all inflows. Use one row for each storm to be applied. If only one storm is to be applied, delete the additional rows.

If storm duration testing using the hydraulic model is being undertaken ensure that the results are included in the last row of this table when the testing is complete, for example, which duration(s) has been selected and why, what the process will be in terms of presenting model results if more than one duration is selected.

Site code	Season of design event	Storm duration (hours)	Storm area for ARF (if not catchment area)	Reason for selecting storm
All				
All				
All				
Results of storm duration testing. This row can be deleted if storm duration testing is not being undertaken.				

5.7 Flood estimates from the ReFH method: lumped catchments

Note: This table is for recording results for lumped catchments. There is no need to record peak flows from sub-catchments or intervening areas that are being used as inputs to a semi-distributed model of the river system.

Site code	Flood peak (m³/s) for the following return periods (in years)									
	Flood peak (m³/s) for the following AEP (%) events									

6 REVITALISED FLOOD HYDROGRAPH 2 (REFH2) METHOD

6.1 Application of ReFH2 method

What is the purpose of applying this method? Brief summary of the reasons, specific to this study, for applying the method. For example, lumped estimates at key locations for the purpose of checking modelled peak flow estimates, distributed approach to apply inflows to a hydraulic model, deriving hydrograph shapes only, extending the flood frequency curve out to extreme events (long return periods).	ReFH2 has been used to estimate hydrograph shape and peak flows for all sub catchments (to compare to statistical estimate). The observed rainfall component of ReFH2 has also been used in an attempt to calibrate historical flood events in July 2007 and December 2008 , respectively.

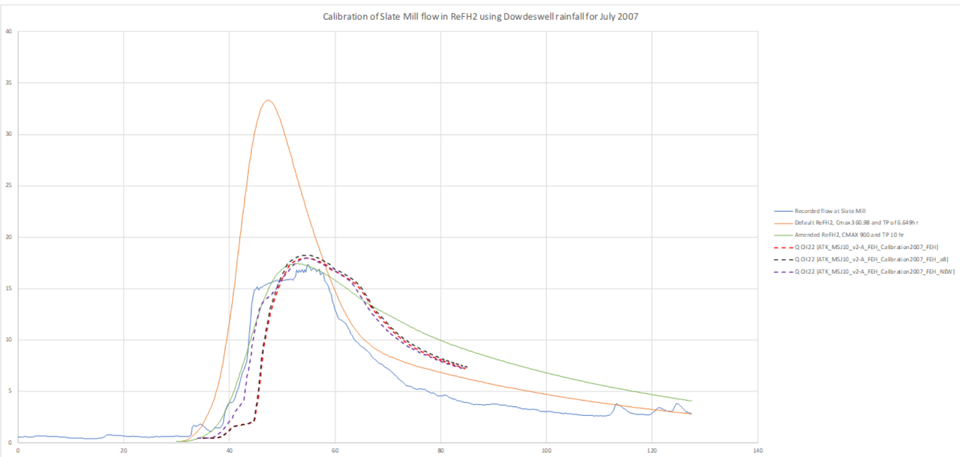
6.2 Parameters for ReFH2 model

Lumped and sub-catchment / intervening areas should be included in this table.

Note: The lower limit of Tp_{rural} is 1.0hr; Tp_{urban} can drop below this.

Note: ReFH2 is also implemented in InfoWorks ICM which does not include the urban component.

Site code	Method	Tp_{rural} (hours)	Tp_{urban} (factor)	C_{max} (mm)	PR_{imp} % runoff for impermeable surfaces	BL (hours)	BR
River Chelt to M5	CD	4.87	0.5	352.64		47.15	1.05
Extra M5	CD	4.01	0.5	201.74		24.00	0.79
Chelt d/s	CD	2.11	0.5	327.05		32.05	0.97
Leight Brook to M5	CD	3.97	0.5	284.25		30.48	0.83
Leigh Brook d/s	CD	3.15	0.5	301.75		29.10	0.89

Brief description of any flood event analysis carried out (further details should be given in the annex)	 The Slate Mill gauge is a poor station to calibrate hydrological inflows, as it is known to silt up and is bypassed at higher flows. This has been demonstrated in

Site code	Method	Tp_{rural} (hours)	Tp_{urban} (factor)	C_{max} (mm)	PR_{imp} % runoff for impermeable surfaces	BL (hours)	BR
			the analysis of the observed rainfall and flow during the July 2007 event. Calibration of the default ReFH2.3 parameters (Cmax and Tp) to match the observed flow at Slate Mill during the July 2007 event were unrealistic (green line in the graph above). Tp was extended to 10 hours to match the peak timing of the event, which is acceptable. However, Cmax, the maximum soil moisture capacity of the catchment, required amending from a default value of 367 to 900. This is an unrealistic change, as the WHS guidance on ReFH2 states that Cmax should typically be determined from catchment descriptors[10]. Cini, the initial soil moisture, is determined from the antecedent rainfall to the event, which has been applied to ReFH2.3. The graph above also demonstrates the default ReFH2.3 parameters applied to the 2007 rainfall (orange line). At first observations, this hydrograph is greatly different to the recorded flow at Slate Mill (blue line), with the ReFH2.3 peak flow double that at Slate Mill. However, as mentioned previously, flow on the River Chelt is attenuated by the embankment of the M5. As a test, the observed rainfall of the July 2007 event with default ReFH2.3 parameters was applied to the hydraulic model and produced the dashed line in the graph below. This provides a good fit to flows recorded at the Slate Mill gauge. As this has been applied to the 1D-2D hydraulic model, the bypassing of the gauge is represented in the model. Overall, this demonstrates that the ReFH2.3 method provides a good fit to the 2007 event and the testing of the flows within the hydraulic model demonstrates that the M5 embankment attenuates flows in the River Chelt and that the Slate Mill gauge is bypassed.				
Methods: OPT: Optimisation, BR: Baseflow recession fitting, CD: Catchment descriptors, DT: Data transfer (give details)							

6.3 Design events for ReFH2 method: Lumped catchments

This table can be deleted if ReFH2 is not being applied for lumped catchments. Note: ReFH2 may be applied for both lumped catchments and sub-catchments in a study; if this is the case both this table and the next should be completed.

Storm durations detailed here should be the values for the individual catchments. Lumped flows should be generated using the storm duration relevant to each lumped catchment for comparison with Statistical estimates.

Site code	Urban or rural	Season of design event (summer or winter)	Storm duration (hours)
River Chelt to M5	Urban	Winter	10.5
Extra M5	Urban	Winter	7.5
Chelt d/s	Urban	Winter	6.5
Leight Brook to M5	Urban	Winter	8.5
Leigh Brook d/s	Urban	Winter	6.5
The final design inlows apply a 10.5 hour storm duration to all sub catchments. This is the critical storm duration for the River Chelt at the M5.			

[10] Introduction - ReFH Technical Guide (hydrosolutions.co.uk)

6.4 Design events for ReFH2 method: Sub-catchments and intervening areas

This table can be deleted if ReFH2 is not being applied for sub-catchments.

This table is included to identify the storm which will be applied to all inflows to a distributed model (see Section 6.1 of the Flood Estimation Guidelines) and avoid the scenario of using a different storm for each inflow to the model.

If there are multiple flood risk areas throughout the model it may be necessary to allow for different storms in different parts of the model by carrying out multiple model runs. Each model run should use the same storm applied to all inflows. Use one row for each storm to be applied. If only one storm is to be applied, delete the additional rows.

If storm duration testing using the hydraulic model is being undertaken ensure that the results are included in the last row of this table when the testing is complete, for example, which duration(s) has been selected and why, what the process will be in terms of presenting model results if more than one duration is selected.

Site code	Season of design event	Storm duration (hours)	Storm area for ARF (if not catchment area)	Reason for selecting storm
All	Winter	10.5	ReFH default	Critical storm at the M5
Results of storm duration testing. This row can be deleted if storm duration testing is not being undertaken.		Storm durations were tested in ReFH2 software to understand the worst case storm duration at the M5 (the site of interest for this study). This was calculated to be 10.5 hours and has been applied to all sub catchments.		

6.5 Flood estimates from the ReFH2 method

Note: This table is for recording results for lumped catchments. There is no need to record peak flows from sub-catchments or intervening areas that are being used as inputs to a semi-distributed model of the river system.

Site code	Flood peak (m^3/s) for the following return periods (in years)								
	2	5	10	25	50	100	1000		
	Flood peak (m^3/s) for the following AEP (%) events								
	50	20	10	4	2	1	0.1		
River Chelt to M5	8.91	11.88	14.22	17.77	20.93	24.49	38.53		
Extra M5	1.45	1.96	3.57	2.95	3.47	4.05	6.13		
Chelt d/s	0.77	1.04	1.26	1.59	1.89	2.22	3.58		
Leight Brook to M5	0.86	1.17	1.40	1.77	2.10	2.48	4.02		
Leigh Brook d/s	0.45	0.61	0.73	0.92	1.09	1.29	2.09		

7 DISCUSSION AND SUMMARY OF RESULTS

7.1 Comparison of results from different methods

This table compares peak flows from various methods with those from the FEH Statistical method at example sites for two key return periods / AEP events. Delete columns which are not required.

Site code	Ratio of peak flow to FEH Statistical peak					
	Return period 2 years / 50% AEP			Return period 100 years / 1% AEP		
	Statistical	ReFH2	Ratio	Statistical	ReFH2	Ratio
River Chelt to M5	7.49	8.91	0.84	20.36	24.49	0.53
Extra M5	0.82	1.45	0.57	2.37	4.16	0.39
Chelt d/s	0.60	0.82	0.78	1.73	2.44	0.48
Leight Brook to M5	0.62	0.87	0.72	1.79	2.52	0.45
Leigh Brook d/s	0.36	0.46	0.80	1.03	1.37	0.49
Comment	Comparisons have been made between the statistical peaks and the ReFH2 peaks for the critical storm duration of each sub catchment, rather than the 10.5 hours storm duration used in the design events. This is to ensure that a like for like peak is compared, rather than the peak inflows used in the design events. The ReFH method provides higher flows for all sub catchments and for all return periods. The gauged QMED at Slate Mill is 9.42m^3/s. This compares to a 50% AEP flow of 10.06 m^3/s, which is the result of the routed 50% AEP inflows in the hydraulic model. This further increases the validity in the use of the ReFH2 method to provide design event inflows, as it is slightly more precautionary than the gauged QMED value, which needs to be used with caution due to the uncertainty surrounding the Slate Mill gauge.					

7.2 Final choice of method

Choice of method and reasons Include reference to type of study, nature of catchment and type of data available.	The table in 7.1 demonstrates that the ReFH2 method provides higher, more precautionary flows than the statistical method for all catchments and all return periods. In addition, the default ReFH2 parameters, which were used to generate hydrographs based on the July 2007 and December 2008 rainfall events, provided a good calibration to flood extents and flows. As a result, there is additional confidence that the ReFH2 method, with no adjustments to Tp and CMAX, provides reasonable estimates for the River Chelt and Leigh Brook catchments. Additionally, flows for the 0.1% AEP event have been calculated using the ratio method: Q1000 = Q100statistical * (Q1000REFH / Q100REFH) As mentioned in the conceptual model, the inflow provided by STW for the CSO have been scaled by a factor of 0.4 and applied to the model at Arle in order to represent the additional catchment area that the CSO provides outside of the topographic catchment boundary. A comparison exercise has also been conducted, whereby an unscaled CSO flow would be used, and the CSO sub catchment areas removed from the FEH boundary (such that catchment areas are not accounted for twice). The results demonstrate that both methods provide similar flow estimates, and are shown below.

Approach	Sum of peak flow for 1% AEP event (FEH + CSO)
Full FEH catchment with scaled CSO inflow (factor of 0.4)	28.4
Full CSO inflow with CSO sub catchment areas removed from FEH catchment descriptors	28.5

The first approach, whereby the CSO inflows are scaled by 0.4 and the full FEH catchment has been retained, has been carried forward to the design events. This method is mainly preferred as it is assumed that the CSO system will be overwhelmed during higher return period events. Secondly, this approach means that the FEH catchment descriptors obtained from the FEH web are retained, rather than recalculated based on insufficient data (only a shapefile) about the CSO catchment.

The scheme has been classified as Critical Infrastructure. The EA climate change allowances (July 2020) [11] were applied to the peak flows for the design event (1% AEP). The scheme is proposed within the River Severn Basin District, and as such an uplift of 70% on peak flow has been applied to account for the potential effects of chlimate change over the scheme lifetime (the next 100 years). In addition, inflows have been provided for the H++ allowance, which requires a 90% uplift on peak flows.

How will the flows be applied to a hydraulic model? If relevant. Will model inflows be adjusted to achieve a match with lumped flow estimates, or will the model be allowed to route inflows?	The model will route the final inflows.

7.3 Assumptions, limitations and uncertainty

Careful thought should be put into identifying the specific assumptions and limitations applicable to the design peak flow estimates (and design hydrographs). Assessing and reporting on the uncertainty in the estimates is also very important. These sections should be completed for every study and never left blank.

List the main assumptions made (specific to this study)	The main assumptions in this study are: • The catchment boundaries are representative • The flow file for the CSO is representative for its catchment and area • The urban area on OS mapping can be used to estimate URBEXT2000 accurately • Data used to calibrate the 2007 event is accurate
Discuss any particular limitations, e.g. applying methods outside the range of catchment types or return periods for which they were developed.	Hydrological calibration was attempted for the catchment draining to the Slate Mill gauge. However, through comments on the NRFA website and consultation with the Local EA team, it has been determined that the gauge is not reliable to calibrate flow estiamtes. However, rainfall from observed events have been applied to ReFH2.3 and the resulting hydrographs have been applied to the hydraulic model. This has produced good calibration fit at Slate Mill, with the observed bypassing of the gauge by the EA replicated by the hydraulic model.

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

Provide information on the uncertainty in the design peak flow estimates and the methodology used Uncertainty in the peak flow estimates should always be provided. The default is the 95-percentile upper and lower bounds, but other estimates may need to be provided depending on the requirements of the study. Further information can be found in Section 5.4 of the Flood Estimation Guidelines.	Section 5.4 of the 2020 EA Hydrology guidelines outlines methods to assess uncertainty in flow estiamtes. This section of the guidelines mainly focusses on the statistical method. The guidelines state *'It is more difficult to quantify uncertainty in design flows estimated from the ReFH rainfall-runoff model'.* The only suggested method is to compare ReFH2 estimates with Enhanced Single Site analysis at gauging stations. This is not possible in this estimate due to the uncertainty and unreliability of the Slate Mill gauge data. Although it is not possible to quantify the uncertainty in the ReFH2 design estimates for this assessment, the uncertainty has been reduced through the calibration exercise. The default ReFH2.3 parameters, which were used in the design events, provided a good fit to the flood outline and observed flow at Slate Mill in the hydraulic model. This gives confidence that the ReFH2 method suitably represents flood events in the catchment. method with defau
Comment on the suitability of the results for future studies, e.g. at nearby locations or for different purposes, would a project for scheme design require additional detail, etc.	The design peak flow estimates and hydrographs were derived for the purposes of this modelling study. If peak flow estimates and hydrographs are required for a different purpose it is recommended that, at a minimum, a review of the results is carried out.
Give any other comments on the study, e.g. suggestions for additional work, such as flow monitoring, rating reviews, etc.	Flow monitoring within the catchment would be beneficial for future hydrological assessments.

7.4 Checks

These checks are important as a way of ensuring that everything has been considered and that the results are sensible. All relevant sections should be completed for every study. Where sections are not relevant (where there are no flow gauges or previous studies, for example) a comment should be added to this effect rather than leaving a blank space.

Are the results consistent, for example at confluences? This will not be relevant for a study where there is only a single flow estimation point.	Yes. Checks undertaken at confluences show flow increasing downstream. In addition, the ReFH2 calibration using the antecedent and observed rainfall for the 2007 event demonstrates that the model performs well in this catchment.
What do the results imply regarding the return periods / frequency of floods during the period of record? This will only be relevant where there is flow gauge data.	No review of the gauging records or flood history was undertaken as part of this study.
What is the range of 100-year / 1% AEP growth factors? Is this realistic?	The growth factors of 2.71 (Chelt to M5 pooling group) and 2.87 (rural pooling group) are within the expected range for the statistical method. However, the statistical method has not been used for the design events. The growth curves for each catchment using the ReFH2 method ranges from 2.75 to 2.88, which is within the expected range and is comparable to the growth curves of the statistical method.
If 1000-year / 0.1% AEP flows have been derived, what is the range of ratios for 1000-year / 0.1% AEP flow over 100-year / 1% AEP flow?	The 0.1% AEP flows have been derived using the Ratio method: Q1000 = Q100statistical * (Q1000REFH / Q100REFH) The ratios of the 0.1% AEP/1% AEP for each sub catchment for the ReFH2 method are given below: Catchment — Ratio to apply to 0.1% statistical estiamte River Chelt to M5 — 1.57 Extra M5 — 1.51 River Chelt d/s — 1.61

	Leigh Brook to M5 — 1.62 Leigh Brook d/s — 1.62
How do the results compare with those of other studies? Explain any differences and conclude which results should be preferred. This will not be relevant if there are no previous hydrological assessments.	Results of the initial flood investigations (2012 and 2015), which were used in the EA model of Cheltenham, are not comparable. The 2012 report explicitly states that hydrological estiamtes made downstream of Cheltenham should be treated with caution. The results obtained during the Boddington Flood Map challenge were produced using a different method, which is direct rainfall. The 1% AEP estimate at Arle, estimated from extracting PO lines from the direct rainfall model, was 30cumecs, whereas this study has estimated flows for the same event at this location to be approximately 24 cumecs. The direct rainfall model and method was not used for this study, as it was difficult to establish confidence in how key parameters, such as baseflow and infiltration, had been applied to the model.
Are the results compatible with the longer-term flood history? This will not be relevant if there is no flow gauge data or historical flooding information.	The flows produced by the ReFH2 default parameters with the antecedent and observed rainfall for the July 2007 event provided good calibration.
Describe any other checks on the results, e.g. sense-checking hydraulic model results	The flows generated from the July 2007 rainfall have been calibrated within the hyudralic model using wrack mark data, photographs and flood extents collected by the EA.

7.5 Final results

Show the final results here for all flow estimation points (unless using a distributed approach, with no lumped catchment flow estimation points, and allowing the hydraulic model to route the flows) and design events, and give any other data or results needed for the next stage of the study.

Site code	Flood peak (m^3/s) for the following return periods (in years)								
	2	5	10	25	50	100	100+70%	100+90%	1000
	Flood peak (m^3/s) for the following AEP (%) events								
	50	20	10	4	2	1	1+70%	1+90%	0.1
River Chelt to M5	8.91	11.88	14.22	17.77	20.93	24.49	41.63	46.53	37.35
Extra M5	1.45	1.96	2.57	2.95	3.47	4.05	6.89	7.70	4.27
Chelt d/s	0.77	1.04	1.26	1.59	1.89	2.22	3.78	4.22	3.32
Leight Brook to M5	0.86	1.17	1.40	1.77	2.10	2.48	4.22	4.71	3.45
Leigh Brook d/s	0.45	0.61	0.73	0.92	1.09	1.29	2.19	2.45	1.99
CSO	No data provided by STW	2.10	2.44	2.98	3.41	3.95	6.71	7.51	5.50

7.6 Uncertainty bounds

This table reports the flows derived from the uncertainty analysis detailed in Section 7.3. The 'true' value is more likely to be near the estimate reported in Section 7.5 than the bounds. However, it is possible that the 'true' value could still lie outside these bounds.

Complete this table with the flows from the uncertainty analysis. Some key design events have been added to the table, but these can be amended as required.

Site code	Flood peak (m^3/s) for the following return periods (in years)							
	2		25		100		1,000	
	Flood peak (m^3/s) for the following AEP (%) events							
	50		4		1		0.1	
	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
It is not possible to estimate uncertainty in the ReFH2 method, as per the 2020 EA guidelines								

If flood hydrographs are needed for the next stage of the study, where are they provided? (e.g. give filename of spreadsheet, hydraulic model, or reference to table below)	

8 ANNEX

Include any additional information which best sits here rather than in the section text, for example, flood peak series, details of historical flood events, rating reviews, pooling groups, or details of flood event analysis. Include important information in the section text, for example, comparison of growth curves, or results of flood event analysis.

Final Statistical pooling groups

River Chelt to M5 catchment (urban)

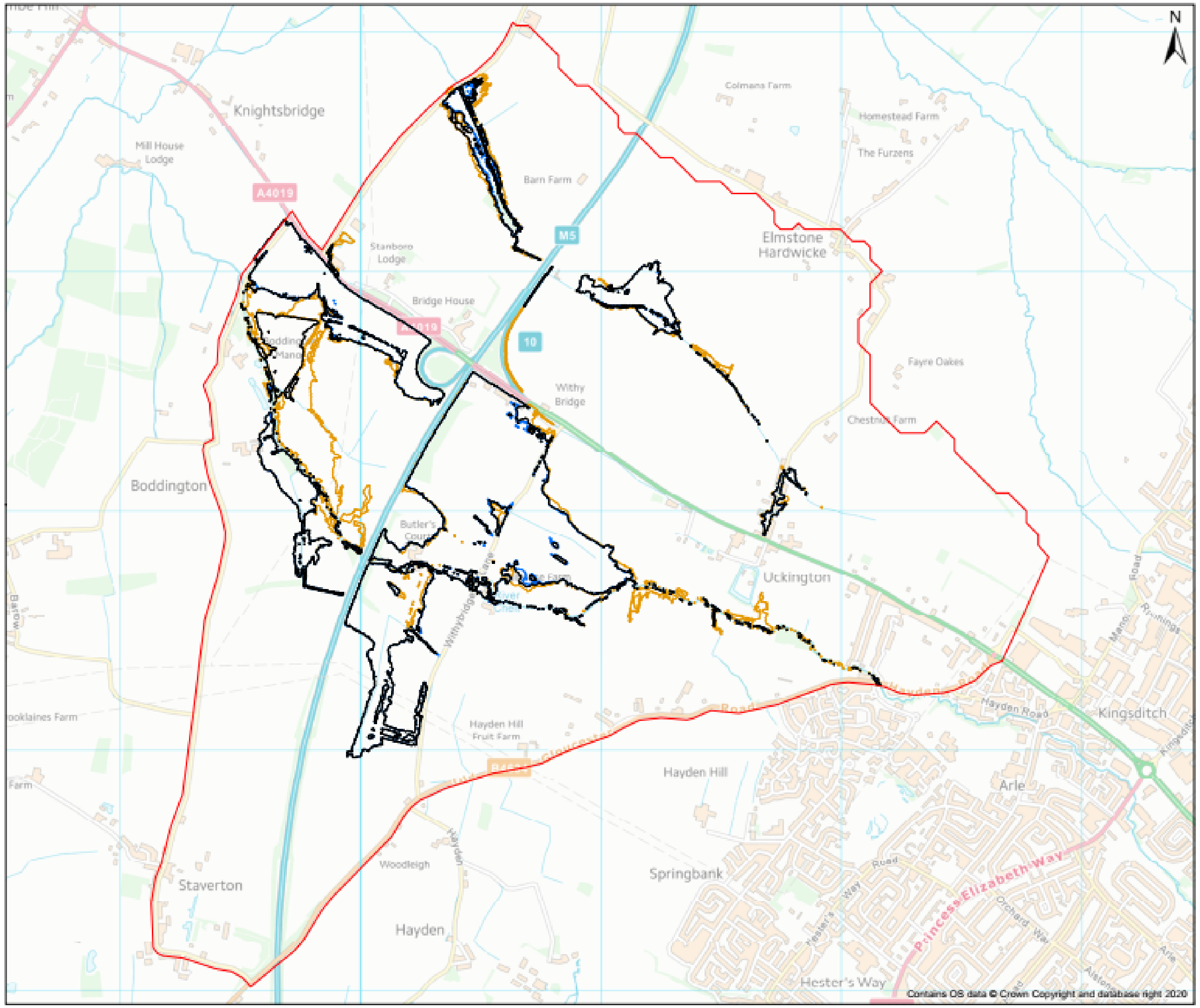
Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	AREA	SAAR	FPEXT	FARL	URBEXT 2000	SPRHOST
41020 (Bevern Stream @ Clappers Bridge)	0.462	50	13.575	0.207	0.182	1.093	35.48	886	0.076	0.993	0.013	43.25
36010 (Bumpstead Brook @ Broad Green)	0.669	40	7.395	0.382	0.181	0.98	27.58	588	0.045	0.999	0.007	44.57
53017 (Boyd @ Bitton)	0.786	46	13.845	0.246	0.092	0.106	47.58	807	0.05	0.998	0.016	37.6
28058 (Henmore Brook @ Ashbourne)	0.815	13	8.838	0.188	-0.109	1.316	38.52	895	0.03	0.977	0.021	31.03
39033 (Winterbourne Stream @ Bagnor)	0.844	57	0.397	0.345	0.395	1.948	45.31	717	0.033	1	0.001	22.35
36004 (Chad Brook @ Long Melford)	0.864	52	5.062	0.306	0.164	0.506	50.33	589	0.065	1	0.006	40.53
41022 (Lod @ Halfway Bridge)	0.877	49	15.9	0.294	0.182	0.135	52.44	857	0.061	0.951	0.009	38.72
73015 (Keer @ High Keer Weir)	0.894	28	12.375	0.204	0.26	1.622	30.04	1158	0.074	0.976	0.003	35.79
72014 (Conder @ Galgate)	0.928	51	16.646	0.231	0.16	0.252	28.99	1183	0.082	0.975	0.006	35.96
24007 (Browney @ Lanchester)	1	15	10.981	0.222	0.212	1.044	44.67	797	0.015	1	0.001	40.49
30004 (Lymn @ Partney Mill)	1	57	7.128	0.226	0.039	0.285	60.09	686	0.06	0.979	0.006	32.47
36003 (Box @ Polstead)	1.002	47	3.85	0.317	0.097	0.648	56.72	566	0.093	0.993	0.012	37.7
		505	Non-flood year removed									

Remaining sub catchments (rural)

Station	Distance	Years of data	QMED AM	L-CV	L-SKEW	Discordancy	AREA	SAAR	FPEXT	FARL	URBEXT 2000	SPRHOST
27051 (Crimple @ Burn Bridge)	2.186	47	4.524	0.218	0.156	0.264	8.17	855	0.013	1	0.006	40.77
45816 (Haddeo @ Upton)	2.279	26	3.456	0.3	0.406	0.861	6.81	1210	0.011	1	0.005	31.27
28033 (Dove @ Hollinsclough)	2.555	44	4.177	0.228	0.371	0.75	7.92	1346	0.007	1	0	42.5
25019 (Leven @ Easby)	2.889	41	5.09	0.342	0.386	0.992	15.09	830	0.019	1	0.004	38.58
25011 (Langdon Beck @ Langdon)	3.108	33	15.647	0.232	0.328	0.833	12.79	1463	0.012	1	0.001	58.21
25003 (Trout Beck @ Moor House)	3.187	46	15.142	0.168	0.29	0.512	11.4	1905	0.041	1	0	59.86
71003 (Croasdale Beck @ Croasdale Flume)	3.195	37	10.9	0.212	0.323	0.352	10.71	1882	0.016	1	0	54.51
27010 (Hodge Beck @ Bransdale Weir)	3.283	41	9.42	0.224	0.293	0.147	18.82	987	0.009	1	0.001	50.58
91802 (Allt Leachdach @ Intake)	3.291	34	6.35	0.153	0.257	0.585	6.54	2554	0.003	0.992	0	53.31
106002 (Laxdale @ Laxdale)	3.312	12	17.449	0.103	0.132	1.115	10.64	1993	0.024	0.888	0	
206006 (Annalong @ Recorder)	3.359	48	15.33	0.189	0.052	2.099	14.44	1704	0.023	0.981	0	51.72
54022 (Severn @ Plynlimon Flume)	3.423	38	14.988	0.156	0.171	0.901	8.75	2481	0.01	1	0	52.68
36010 (Bumpstead Brook @ Broad Green)	3.568	52	7.395	0.382	0.181	2.091	27.58	588	0.045	0.999	0.007	44.57
49003 (de Lank @ de Lank)	3.666	53	13.646	0.225	0.213	0.058	21.61	1628	0.064	0.998	0	47.75
	Total	522										

Appendix C. Sensitivity test results

C.1. Sensitivity to channel and floodplain roughness



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M5 J10

Sensitivity Testing
Roughness - Seasonal Variation

Key

- Model domain
- Roughness: Winter
- Baseline (Q100)
- Roughness: Summer

	Summer	Baseline	Winter
River Chelt 1D	0.07	0.048	0.035 – 0.040
Leigh Brook 1D	0.08	0.06	0.055
Default 2D (ID 1 in tmf)	0.070 - crop	0.050	0.030 - bare
Scrub 2D (ID 5 in tmf)	0.080	0.055	0.040

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Data sources: Ordnance Survey

0 0.25 0.5 Km

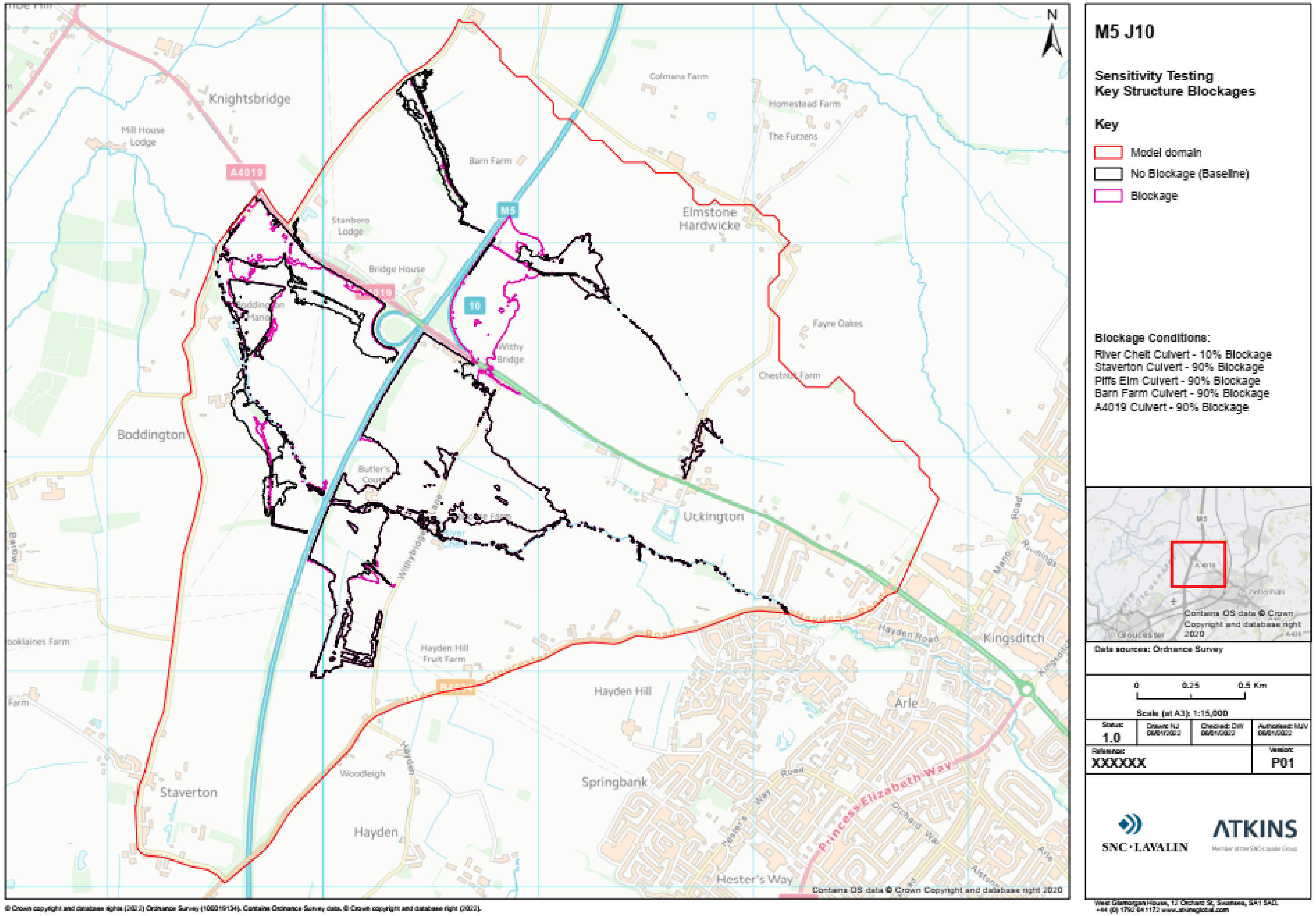
Scale (at A3): 1:15,000

Status: 1.0	Drawn: NJ 06/01/2023	Checked: DW 06/01/2023	Authorised: MJV 06/01/2023

Reference: XXXXXX	Version: P01

West Glamorgan House, 12 Orchard St, Swansea, SA1 5AD.
+44 (0) 1792 641172 www.atkinsglobal.com

C.2. Sensitivity to structure coefficients including structure blockage


N
Knightsbridge
Mill House Lodge
A4019
Barn Farm
Stanboro Lodge
Bridge House
M5
10
Withy Bridge
Colmans Farm
Homestead Farm
The Furzens
Elmstone Hardwicke
Fayre Oakes
Chestnut Farm
Boddington
Butler's Court
Uckington
Kingsditch
Hayden Hill Fruit Farm
Hayden Hill
Arle
Staverton
Woodleigh
Hayden
Springbank
Princess Elizabeth Way
Hester's Way
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M5 J10
Sensitivity Testing
Key Structure Blockages
Key
Model domain
No Blockage (Baseline)
Blockage
Blockage Conditions:
River Chelt Culvert - 10% Blockage
Staverton Culvert - 90% Blockage
Piffs Elm Culvert - 90% Blockage
Barn Farm Culvert - 90% Blockage
A4019 Culvert - 90% Blockage
Data sources: Ordnance Survey
0 0.25 0.5 Km
Scale (at A3): 1:15,000
Status: 1.0
Reference: XXXXXX
Version: P01
SNC·LAVALIN
ATKINS
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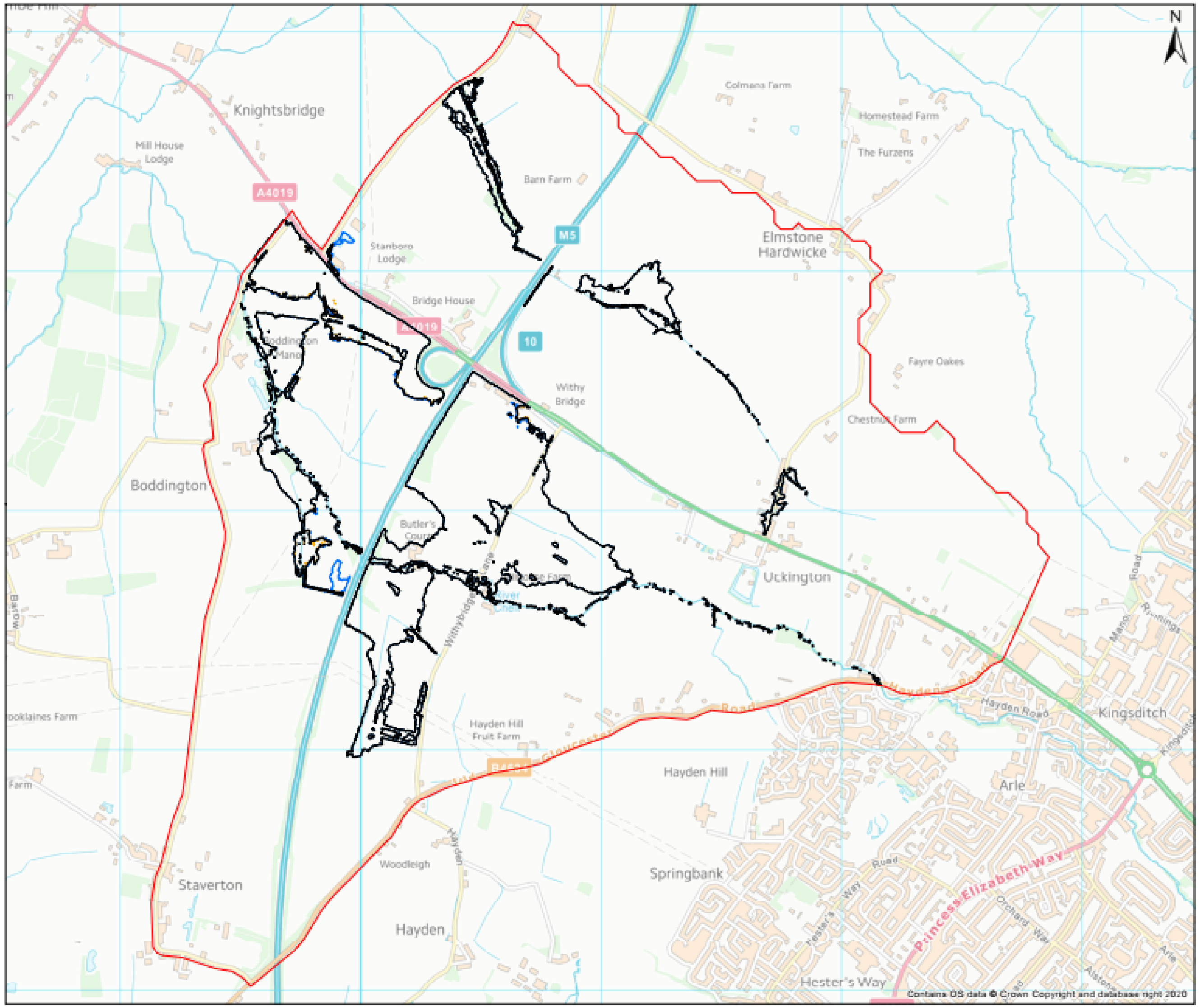

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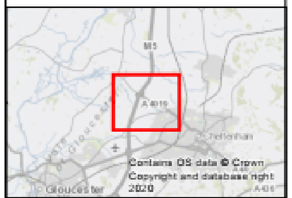
M5 J10

Sensitivity Testing
Key Structures - Entry & Exit Losses Variation

Key

- Model domain
- Key Structures - Reduced Losses
- Baseline (Q100)
- Key Structures - Increased Losses

Structure	Reduced losses	Baseline	Increased losses
River Chelt culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
Staverton culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
Piffs Elm culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
Barn Farm culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex
A4019 culvert	0.3en 0.5ex	0.5en 1.0ex	0.7en 1.0ex



Data sources: Ordnance Survey

0 0.25 0.5 Km

Scale (at A3): 1:15,000

Status: 1.0	Drawn: HJ [illegible]	Checked: DW [illegible]	Authorised: MJV [illegible]

Reference: XXXXXX	Version: P01

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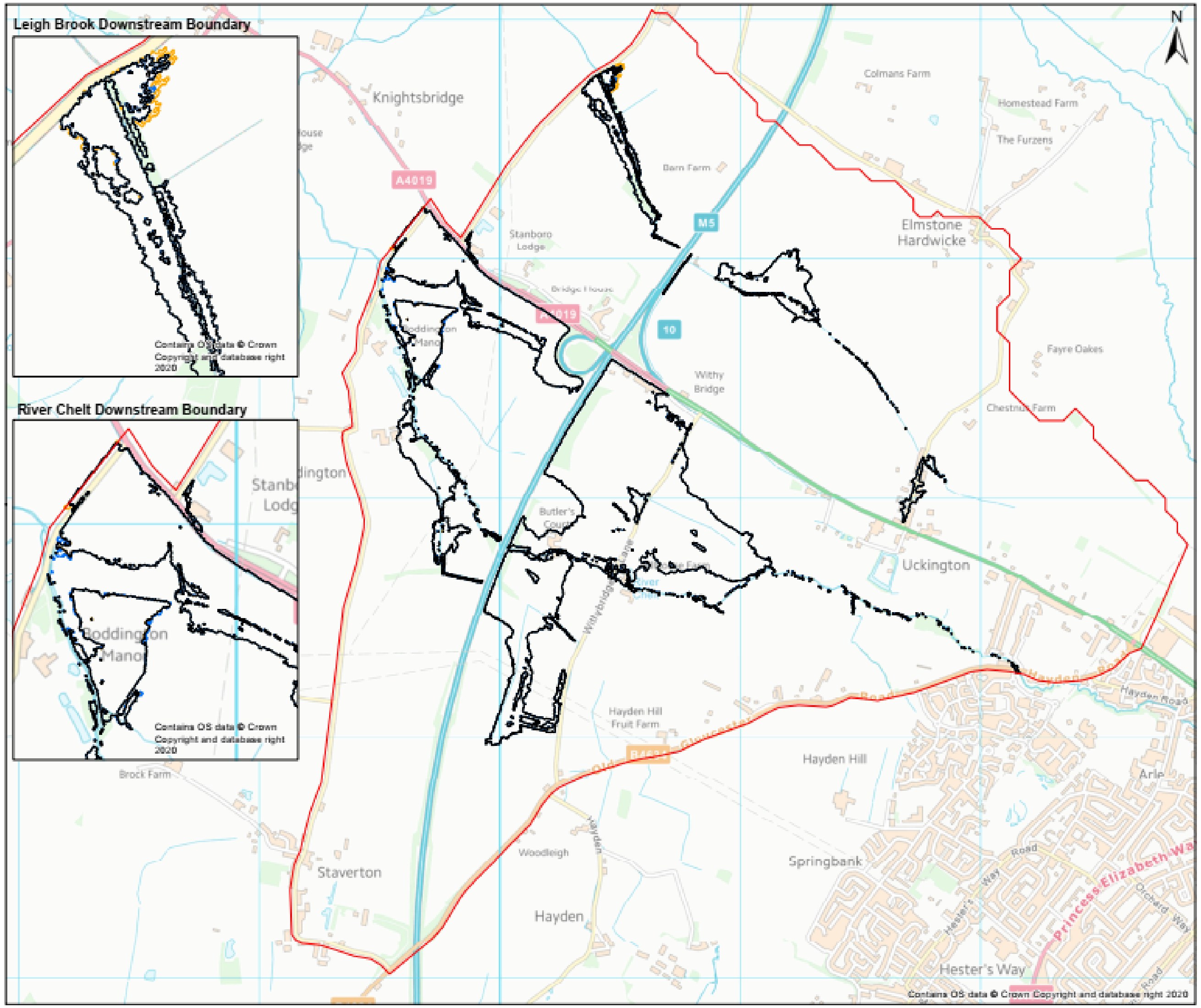
C.3. Sensitivity to downstream boundary

AtkinsRéalis

Gloucestershire County Council



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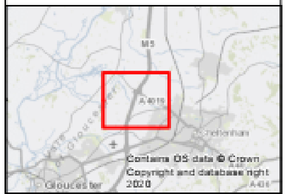
M5 J10

Sensitivity Testing Downstream Boundary - Level Variation (1D & 2D)

Key

- Model domain
- Downstream Boundary - Reduced Levels
- Baseline (Q100)
- Downstream Boundary - Increased Levels

	Reduced level	Baseline	Increased level
River Chelt 1D	All stage -1m	QH	All stage + 1m
River Chelt 2D normal depth	1 in 100	1 in 200	1 in 1000
Leigh Brook 1D	All stage -0.5m	QH	All stage + 1m
Leigh Brook 2D normal depth	1 in 100	1 in 200	1 in 1000



Data sources: Ordnance Survey

0 0.25 0.5 Km

Scale (at A3): 1:15,010

Status: 1.0	Drawn: NJ [illegible]	Checked: DW [illegible]	Authorised: MJV [illegible]
Reference: XXXXXX			Version: P01

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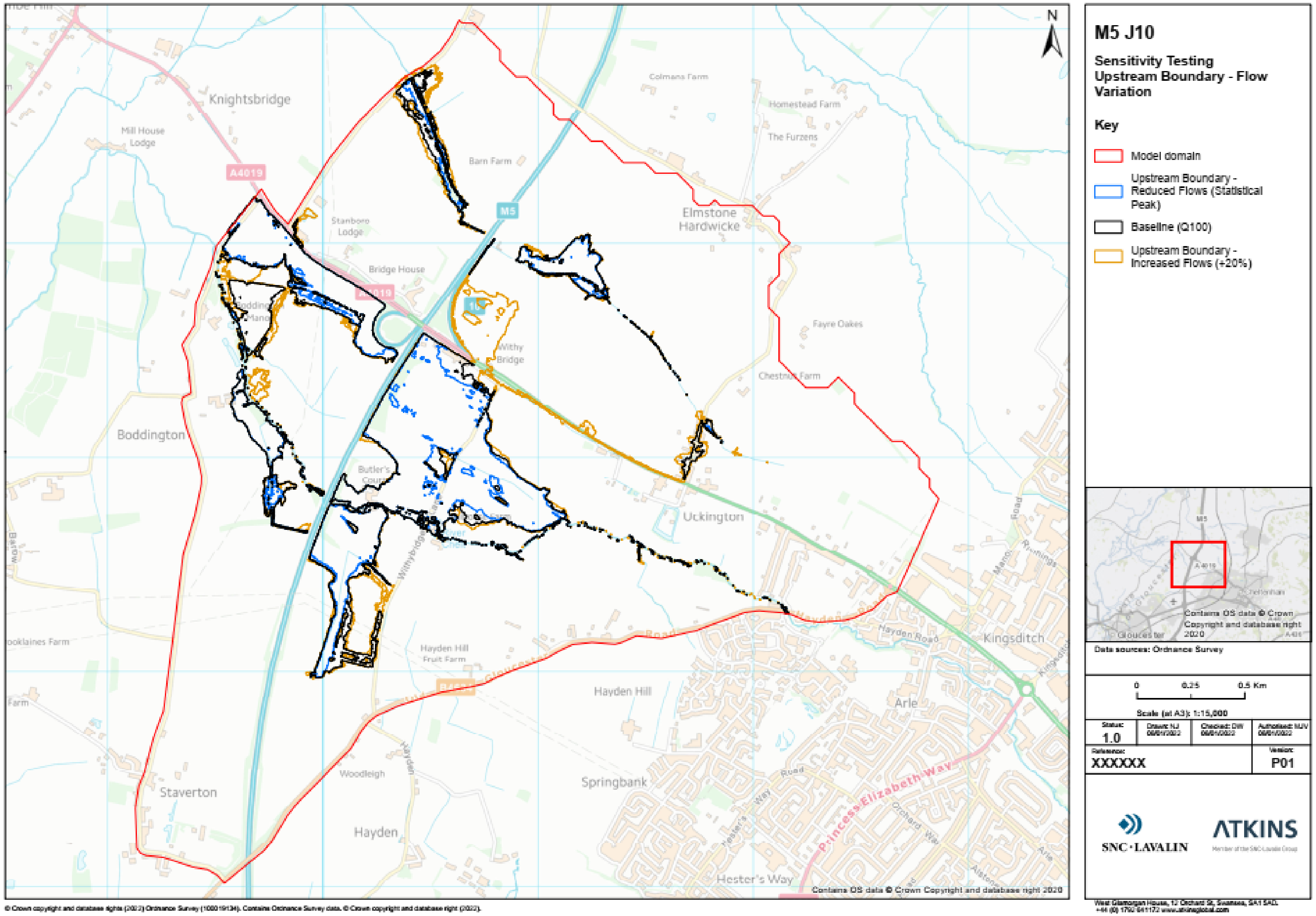
C.4. Sensitivity to upstream boundary


M5 J10
Sensitivity Testing Upstream Boundary - Flow Variation
Key
Model domain
Upstream Boundary - Reduced Flows (Statistical Peak)
Baseline (Q100)
Upstream Boundary - Increased Flows (+20%)
Data sources: Ordnance Survey
0
0.25
0.5 Km
Scale (at A3): 1:15,000
Status: 1.0
Reference: XXXXXX
Version: P01
SNC·LAVALIN
ATKINS
Knightsbridge
Boddington
Elmstone Hardwicke
Uckington
Staverton
Hayden
Springbank
Kingsditch
Arle
Hester's Way
Hayden Hill
M5
A4019
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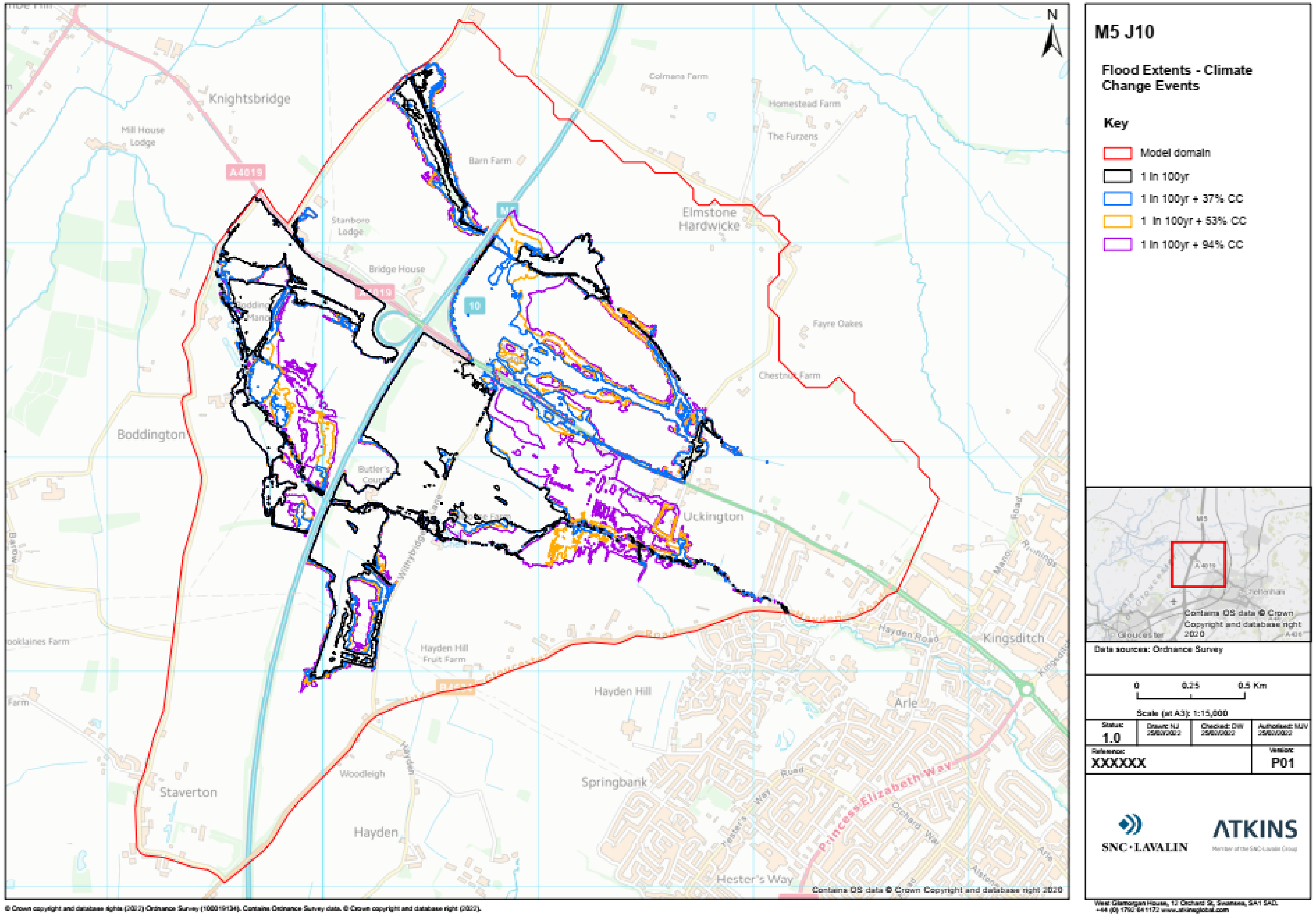
C.5. Sensitivity to flow using the H++ climate change allowance


M5 J10
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
Knightsbridge
Mill House Lodge
Barn Farm
Colmans Farm
Homestead Farm
The Furzens
Elmstone Hardwicke
Stanboro Lodge
Bridge House
Fayre Oakes
Chestnut Farm
Boddington
Uckington
Kingsditch
Hayden Hill Fruit Farm
Hayden Hill
Arle
Springbank
Staverton
Woodleigh
Hayden
Hester's Way
Princess Elizabeth Way
A4019
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Data sources: Ordnance Survey
0 0.25 0.5 Km
Scale (at A3): 1:15,000
Status: 1.0
Reference: XXXXXX
Version: P01
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ATKINS
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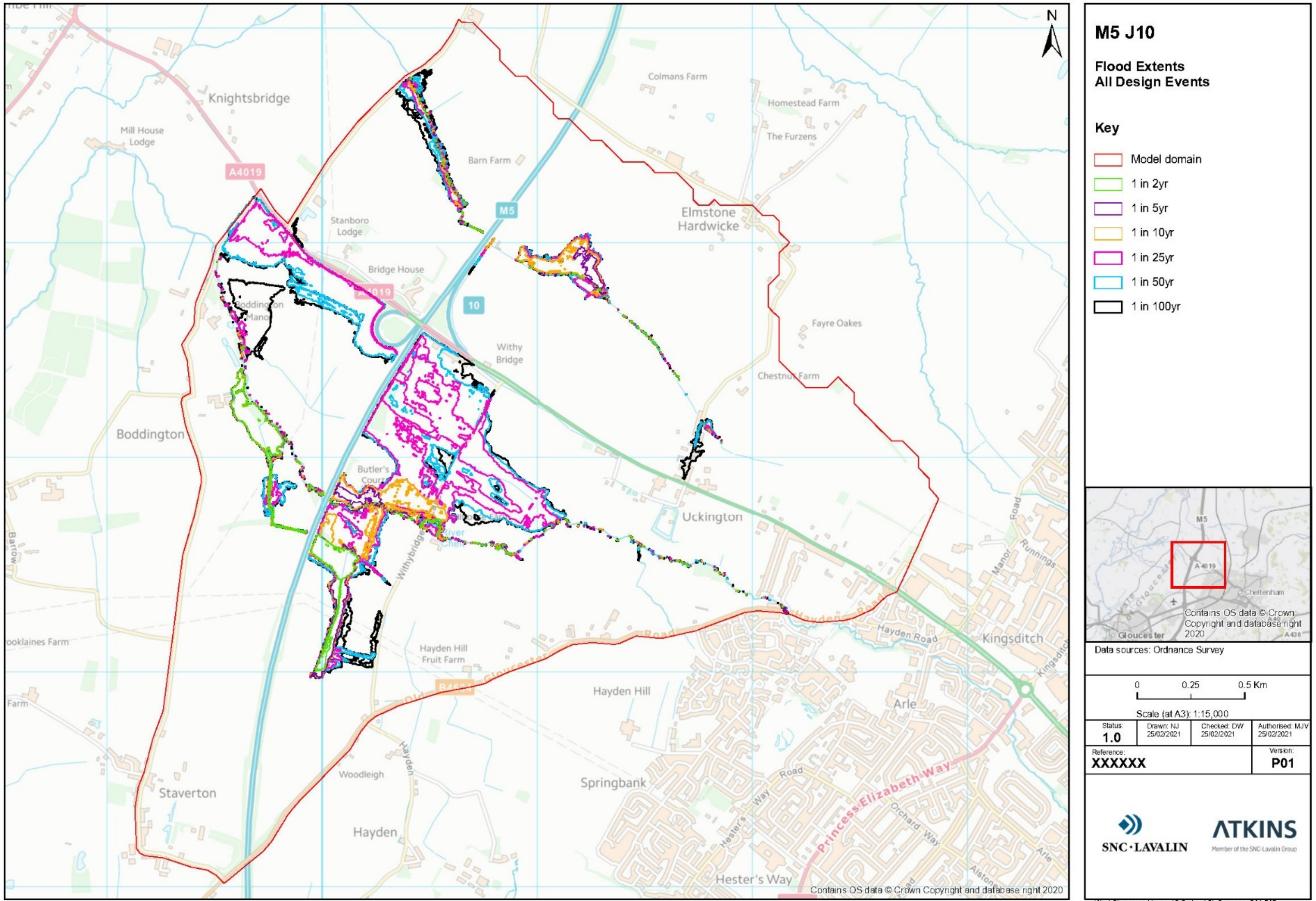
Appendix D. Baseline model results

Flood extent maps and depth grids for the Baseline design events.

D.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)



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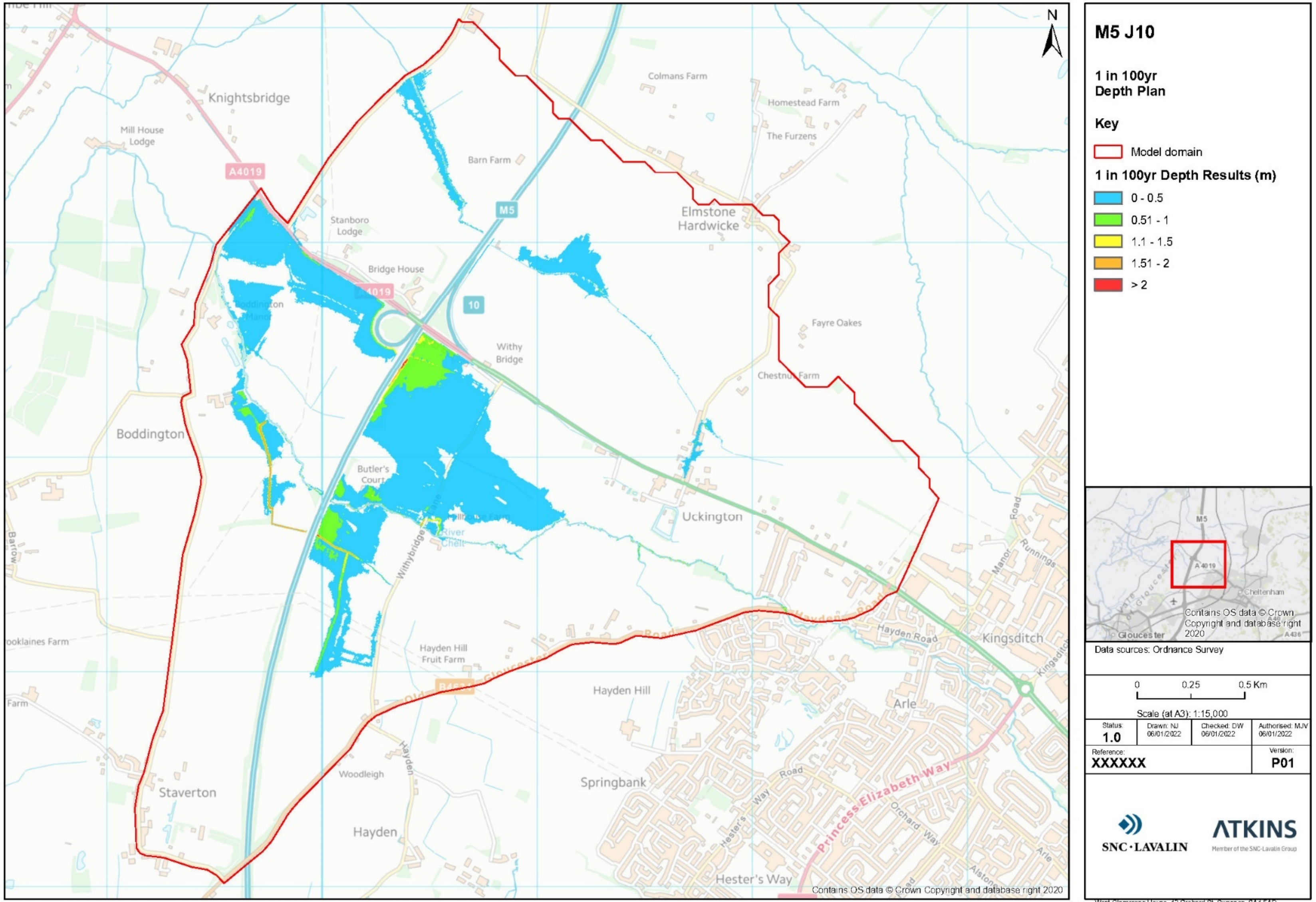
D.2. 1% AEP event (1 in 100-year return period)


M5 J10
1 in 100yr
Depth Plan
Key
Model domain
1 in 100yr Depth Results (m)
0 - 0.5
0.51 - 1
1.1 - 1.5
1.51 - 2
> 2
Data sources: Ordnance Survey
Scale (at A3): 1:15,000
Status: 1.0
Drawn: NJ 06/01/2022
Checked: DW 06/01/2022
Authorised: MJV 06/01/2022
Reference: XXXXXX
Version: P01
Knightsbridge
Boddington
Elmstone Hardwicke
Uckington
Staverton
Hayden
Springbank
Kingsditch
Arle
Hayden Hill
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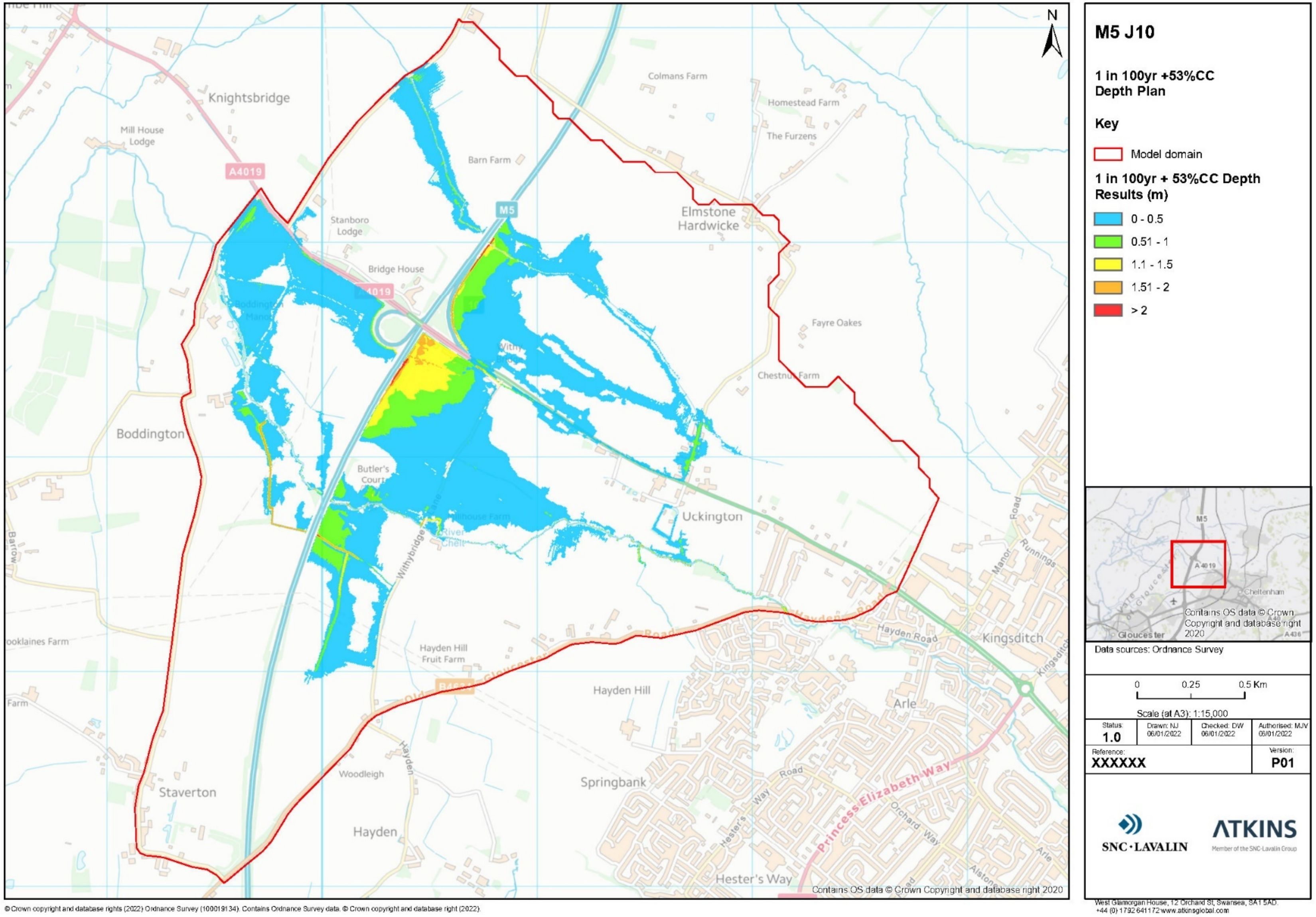
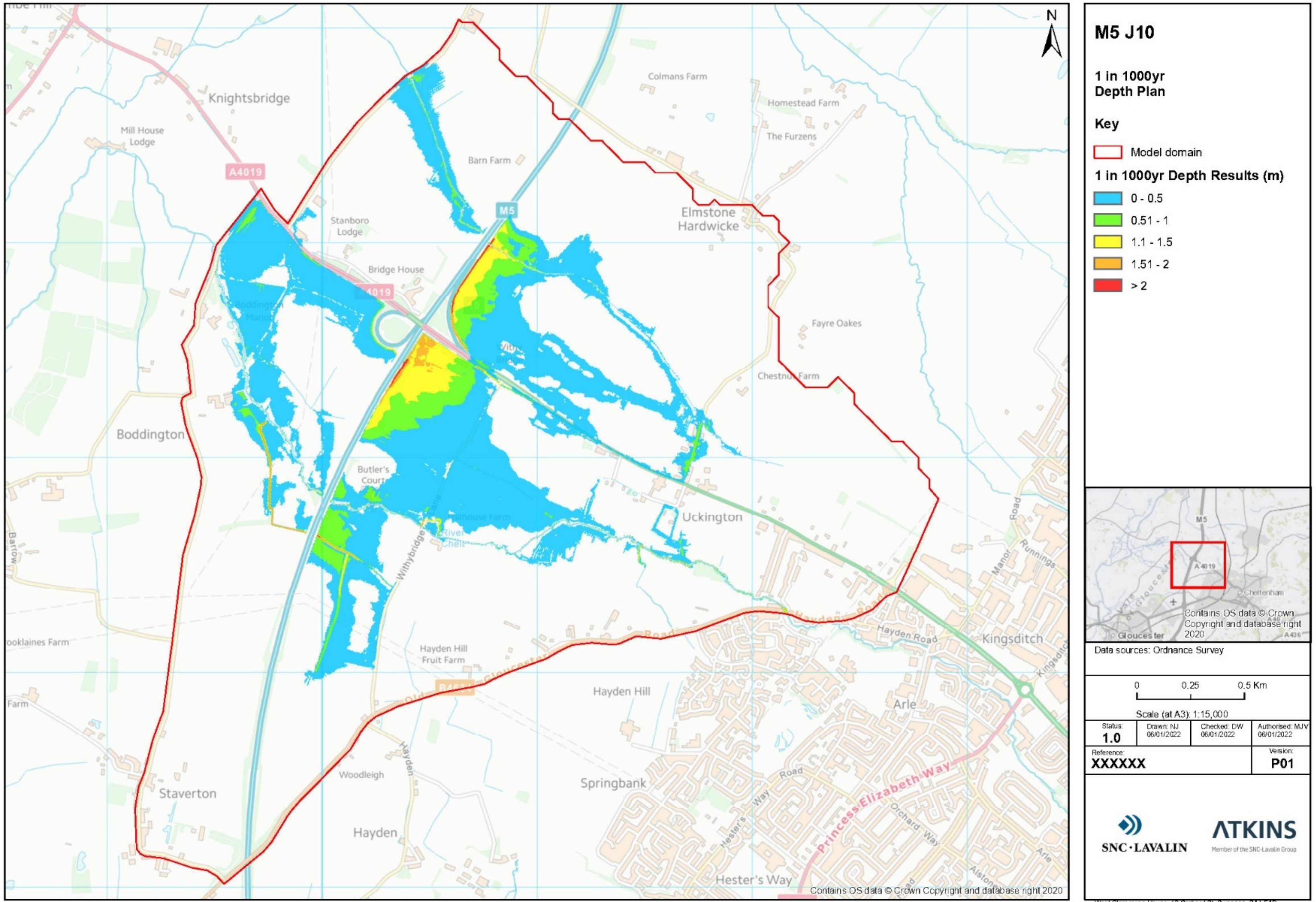
D.3. 1% AEP event (1 in 100-year return period) with climate change

AtkinsRéalis

Gloucestershire County Council



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



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Appendix E. Model log

E.1. Model log

	Model Simulation	Type	Description	Hydrology Applied	TUFLOW Control File (.tcf)	TUFLOW Materials File (.tmf)	TUFLOW Boundary Control File (.tbc)	TUFLOW Geometry Control File (.tgc)	TUFLOW Event File (.tef)	TUFLOW Boundary Condition Database (.csv)
1	2007 Calibration Event	Historic Event	Simulation of 2007 historical flood event through model to calibrate with EA recorded data	2007 Inflows	ATK_M5J10_v9-A_FEH_Baseline_Calib07_~e~.tcf	CLB_v13-A_Man_v3.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_Calibration_v02.csv
2	2008 Calibration Event	Historic Event	Simulation of 2008 historical flood event through model to calibrate with EA recorded data	2008 Inflows	ATK_M5J10_v9-A_FEH_Baseline_Calib08_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_Calibration_v02.csv
3	1 in 2yr	Design Event	1 in 2yr Design Event	REFH2 (1 in 2yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
4	1 in 5yr	Design Event	1 in 5yr Design Event	REFH2 (1 in 5yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
5	1 in 10yr	Design Event	1 in 10 year Design Event	REFH2 (1 in 10yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
6	1 in 20yr	Design Event	1 in 20 year Design Event	REFH2 (1 in 20yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
7	1 in 25yr	Design Event	1 in 25 year Design Event	REFH2 (1 in 25yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
8	1 in 50yr	Design Event	1 in 50 year Design Event	REFH2 (1 in 50yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
9	1 in 100yr (Baseline)	Design Event	1 in 100 year Design Event (Baseline)	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
10	1 in 1000yr	Design Event	1 in 1000 year Design Event	REFH2 (1 in 1000yr)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
11	1 in 100yr+37%CC (Central)	Design Event with Climate Change Allowance	1 in 100 year Design Event with 37% Climate Change allowance applied	REFH2 (1 in 100yr+37%)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
12	1 in 100yr+53%CC (Higher Central)	Design Event with Climate Change Allowance	1 in 100 year Design Event with 53% Climate Change allowance applied	REFH2 (1 in 100yr+53%)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
13	1 in 100yr+94%CC (Upper End)	Design Event with Climate Change Allowance	1 in 100 year Design Event with 94% Climate Change allowance applied	REFH2 (1 in 100yr+94%)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
14	Roughness variation: Summer	Model Sensitivity Test	Sensitivity test on channel and floodplain roughness simulating the summer variation	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_01_RV_S_~e~.tcf	CLB_v13-A_Summer.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
15	Roughness variation: Winter	Model Sensitivity Test	Sensitivity test on channel and floodplain roughness simulating the winter variation	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_02_RV_W_~e~.tcf	CLB_v13-A_Winter.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
16	Downstream boundaries: Reduced level	Model Sensitivity Test	Sensitivity test on downstream boundaries simulating reduced levels in stage-discharge relationships (1D) and normal depth conditions (2D)	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_03_DB_Red_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A_Reduced.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03_Reduced.csv
17	Downstream boundaries: Increased level	Model Sensitivity Test	Sensitivity test on downstream boundaries simulating increased levels in stage-discharge relationships (1D) and normal depth conditions (2D)	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_04_DB_Inc_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A_Increased.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03_Increased.csv
18	Upstream Boundaries: Reduced flow	Model Sensitivity Test	Sensitivity test on upstream boundaries simulating reduced flows (hydrographs scaled to lower FEH statistical flow estimates)	FEH Stat Flow (1 in 100yr scaled)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
19	Upstream Boundaries: Increased flow	Model Sensitivity Test	Sensitivity test on upstream boundaries simulating increased flows (hydrographs producing using REFH2+20%)	REFH2 (1 in 100yr+20%)	ATK_M5J10_v9-A_FEH_Baseline_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
20	Key Structures: Reduced losses	Model Sensitivity Test	Sensitivity test on coefficients of key structures simulating reduced entry and exit losses	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_05_Struc_Red_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
21	Key Structures: Increased losses	Model Sensitivity Test	Sensitivity test on coefficients of key structures simulating increased entry and exit losses	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_06_Struc_Inc_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
22	Key Structures: Blockages	Model Sensitivity Test	Sensitivity test considering blockage of key structures under M5 and A4019	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_ST_07_Struc_B_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
23	TUFLOW Hardware: Classic	Model Sensitivity Test	Sensitivity test on TUFLOW hardware configuration using TUFLOW Classic	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_Classic_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv
24	TUFLOW Version: 2020-10-AC	Model Sensitivity Test	Sensitivity test on TUFLOW version using TUFLOW 2020-10-AC	REFH2 (1 in 100yr)	ATK_M5J10_v9-A_FEH_Baseline_TUFLOWv20-10-AC_~e~.tcf	CLB_v13-A.tmf	ATK_M5J10_v06-A.tbc	ATK_M5J10_v05-A.tgc	ATK_CLB_v10_FEH.tef	ATK_CLB_bc_dbase_FEH_v03.csv

E.2. Model files description

			Model Simulations																								
	GIS Filename	Model File Type	Calibration 2007 Event	Calibration 2008 Event	1 in 2yr	1 in 5yr	1 in 10yr	1 in 25yr	1 in 50yr	1 in 100yr	1 in 1000yr	1 in 100yr+37%CC	1 in 100yr+53%CC	1 in 100yr+94%CC	Summer Roughness Values	Winter Roughness Values	Reduced Downstream Boundary	Increased Downstream Boundary	FEH Stat Flow	ReFH2+20%	Reduced Structure Losses	Increased Structure Losses	Key Structure Blockages	TUFLOW Classic	TUFLOW 2020-10-AC	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
4	1d_nwk_Chelt_EA_ln_003.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 filesm File updated to reflect roughnesses assumed with the 2007 flood event.
5	1d_nwk_Chelt_EA_ln_002_Summer.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. Roughness of 0.070 for summer test
6	1d_nwk_Chelt_EA_ln_002_Winter.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. Roughness of 0.035 for winter test
7	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
8	1d_nwk_CheltStructures_v14-Trunc_A_L_004_Red.shp	River Chelt 1d structures network																								TCF	River Chelt structures network line based on EVY's original file. River Chelt M5 culvert reduced losses sensitivity test (entry/exit parameters)
9	1d_nwk_CheltStructures_v14-Trunc_A_L_004_Inc.shp	River Chelt 1d structures network																								TCF	River Chelt structures network line based on EVY's original file. River Chelt M5 culvert increased losses sensitivity test (entry/exit parameters)
10	1d_nwk_CheltStructures_v14-Trunc_A_L_004_Block.shp	River Chelt 1d structures network																								TCF	River Chelt structures network line based on EVY's original file. River Chelt M5 culvert blockage test (10% blockage applied)
11	1d_nwk_LB_Atkins_Trunc_ln_003.shp	Leigh Brook 1d network																								TCF	Truncated Leigh Brook network line based on Infomap 2019 survey
12	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
13	1d_nwk_LB_Atkins_Trunc_ln_003_Summer.shp	Leigh Brook 1d network																								TCF	Truncated Leigh Brook network line based on Infomap 2019 survey. Roughness of 0.080 for summer test
14	1d_nwk_LB_Atkins_Trunc_ln_002_Extended_Summer.shp	Leigh Brook 1d network																								TCF	Leigh Brook network line based on Infomap 2019 survey - extended to reach updated downstream boundary location. Roughness of 0.080 for summer sensitivity test
15	1d_nwk_LB_Atkins_Trunc_ln_003_Winter.shp	Leigh Brook 1d network																								TCF	Truncated Leigh Brook network line based on Infomap 2019 survey. Roughness of 0.055 for winter sensitivity test
16	1d_nwk_LB_Atkins_Trunc_ln_002_Extended_Winter.shp	Leigh Brook 1d network																								TCF	Leigh Brook network line based on Infomap 2019 survey - extended to reach updated downstream boundary location. Roughness of 0.055 for winter sensitivity test
17	1d_nwk_LB_Atkins_Trunc_ln_003_Red.shp	Leigh Brook 1d network																								TCF	Truncated Leigh Brook network line based on Infomap 2019 survey. Barn Farm (M5) culvert reduced losses sensitivity test (entry/exit)
18	1d_nwk_LB_Atkins_Trunc_ln_003_Inc.shp	Leigh Brook 1d network																								TCF	Truncated Leigh Brook network line based on Infomap 2019 survey. Barn Farm (M5) culvert increaseed losses sensitivity test (entry/exit)
19	1d_nwk_LB_Atkins_Trunc_ln_003_Block.shp	Leigh Brook 1d network																								TCF	Barn Farm culvert blockage sensitivity test (90%)
20	1d_nwk_MCH_Cul_014_L_004.shp	M5 Structures 1d XS																								TCF	M5 Structures file updated using Infomap 2019 survey and Highways England PI reports where required
21	1d_nwk_MCH_Cul_014_L_004_Red.shp	M5 Structures 1d XS																								TCF	M5 Structures file updated using Infomap 2019 survey and Highways England PI reports where required. M5/A4019 structures reduced losses test (entry/exit parameters)
22	1d_nwk_MCH_Cul_014_L_004_Inc.shp	M5 Structures 1d XS																								TCF	M5 Structures file updated using Infomap 2019 survey and Highways England PI reports where required. M5/A4019 structures increased losses test (entry/exit parameters)
23	1d_nwk_MCH_Cul_014_L_004_Block.shp	M5 Structures 1d XS																								TCF	M5 Structures file updated using Infomap 2019 survey and Highways England PI reports where required. M5/A4019 structures blockage test (90% blockage applied)
24	1d_xs_Chelt_v10-Trunc_A_L_006.shp	River Chelt 1d XS																								TCF	River Chelt XS based on EVY's original file
25	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
26	1d_xs_Chelt_EA_L_001.shp	River Chelt 1d XS																								TCF	River Chelt XS's extracted from EA Middle Model (2012) files
27	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
28	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
29	1d_XS_LB_Atkins_Trunc_ln_002.shp	Leigh Brook 1d XS																								TCF	Leigh Brook XS's based on Infomap 2019 survey
30	1d_XS_LB_Atkins_ln_001_Extended.shp	Leigh Brook 1d XS																								TCF	Leigh Brook XS's based on Infomap 2019 survey
31	1d_XS_LBStructures_Atkins_Trunc_ln_001.shp	Leigh Brook Structures 1d XS																								TCF	Leigh Brook structures XS's based on Infomap 2019 survey
32	1d_XS_A4019Structure_Atkins_ln_002.shp	A4019 Structure 1d XS																								TCF	Structure under A4019 XS's based on Infomap 2019 survey
34	1d_bc_Trunc_bndy_001_Extended.shp	1D HQ Point Boundaries																								TCF	Downstream HQ boundaries for 1D sections of River Chelt and Leigh Brook
35	1d_bc_Trunc_FEH_002.shp	1D QT Point Inflow																								TCF	1D QT Point Inflows for River Chelt upstream, River Chelt downstream, Leigh Brook downstream and CSO catchments
36	1d_bc_Trunc_FEH_R_001.shp	1D QT Polygon Inflow																								TCF	1D QT Polygon Inflowapplied from start of Leigh Brook to M5 to provide lateral inflows.
37	2d_PO_FlowMeasurements_v13_L.shp	PO Lines																								TCF	PO Lines extracting results from 2D - EVY Original File (Unchanged)
38	2d_PO_CalibrationPoints_v05_P.shp	PO Points																								TCF	PO Points extracting results from 2D - EVY Original File (Unchanged)
39	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
40	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
41	2d_po_M5J10_NRD_001.shp	PO Points																								TCF	PO points based on EA NRD Dataset (2014) extracting results from 2D domain
42	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
43	2d_po_H_Right2Flood_001.shp	PO Points																								TCF	PO points to assess possible 'Right to Flood' locations
44	2d_bc_CHT-ESTRY_Trunc-A_L_005.shp	HX/CN Lines																								TBC	HX and CN lines linking 1D (ESTRY) section of River Chelt to 2D (TUFLOW) domain
45	2d_bc_MCH_Cul_014_L_002.shp	CN/SX Lines																								TBC	SX and CN lines linking 1D (ESTRY) structures to 2D (TUFLOW) domain
46	2d_bc_LB_Atkins_HxBanks_Trunc_ln_004.shp	HX/CN Lines																								TBC	HX and CN lines linking 1D (ESTRY) section of Leigh Brook to 2D (TUFLOW) domain
47	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)
48	2d_bc_Inputs_HQ_002_Reduced.shp	2D HQ DS Boundary																								TBC	2D downstream boundary lines for River Chelt and Leigh Brook - Slope reduced to 1 in 100 (0.01)
49	2d_bc_Inputs_HQ_002_Increased.shp	2D HQ DS Boundary																								TBC	2D downstream boundary lines for River Chelt and Leigh Brook - Slope increased to 1 in 1000 (0.001)
50	2d_inflows_Trunc_FEH.shp	2D QT Inflow Point																								TBC	1 x 2D QT inflow to represent Staverton stream
51	2d_loc_CLB_v01-A_L.shp	2D Location Line																								TGC	2D location line specifying grid origin and orientation
52	Lidar_Composite_dtm_1m.asc	DTM Surface																								TGC	2019 1m composite Lidar from EA to provide 2d underlying topography
53	2d_code_Truncated_R_002.shp	2D Code Polygon																								TGC	Polygon defining 2D Domain boundary
54	2d_code_CHT_Trunc_A_R_004.shp	2D Code Polygon																								TGC	Polygon de-activating 1D Channel River Chelt from 2D Domain
55	2d_code_inactive_LB_Atkins_Trunc_ply_003.shp	2D Code Polygon																								TGC	Polygon de-activating 1D Channel Leigh Brook from 2D Domain
56	2d_zsh_LiDARPatch_v01-A.shp	Z Shape																								TGC	Z polygon correcting LIDAR elevations
57	2d_zln_CHT-Banks_v01-Trunc_A_L_002.shp	Z Shape																								TGC	Z line setting elevation of River Chelt Banks
58	2d_zln_CHT-Banks_v01-Trunc_A_P_002.shp	Z Shape																								TGC	Z point setting elevation of River Chelt Banks
59	2d_zsh_Bridgedecks_v01-Trunc_A_R.shp	Z Shape																								TGC	Z shape polygon representing bridge/culvert overlays
60	2d_zsh_Bridgedecks_v01-A_P.shp	Z Shape																								TGC	Z shape polygon representing bridge/culvert overlays
61	2d_zsh_MCH_DrainageLine_014_Baseline_001-L.shp,	Z Shape																								TGC	Z shape representing drainage features in 2d model domain
62	2d_zsh_MCH_DrainageLine_014_Baseline_001-P.shp	Z Shape																								TGC	Z shape representing drainage features in 2d model domain
63	2d_zsh_MCH_MHFarm_Wall_001-L.shp	Z Shape																								TGC	Z shape representing defence wall around Mill house farm
64	2d_zsh_MCH_MHFarm_Wall_001-P.shp	Z Shape																								TGC	Z shape representing defence wall around Mill house farm
65	2d_zsh_MCH_MHFarm_Channel_002-L.shp	Z Shape																								TGC	Z shape representing channel around Mill house farm
66	2d_zsh_MCH_MHFarm_Channel_001-P.shp	Z Shape																								TGC	Z shape representing channel around Mill house farm
67	2d_zsh_MCH_MHFarm_BBParapet_001-L.shp	Z Shape																								TGC	Z shape representing parapet on bridge over Chelt near Mill house farm
68	2d_zsh_MCH_MHFarm_BBParapet_001-P.shp	Z Shape																								TGC	Z shape representing parapet on bridge over Chelt near Mill house farm
69	2d_mat_Urban_v02-A_R.shp	Mat Polygon File																								TGC	Materials polygon setting roughness value for urban areas in 2D domain
70	2d_mat_Woodland_v02-A_R.shp	Mat Polygon File																								TGC	Materials polygon setting roughness value for woodland areas in 2D domain
71	2d_mat_Buildings_v02-A_R.shp	Mat Polygon File																								TGC	Materials polygon setting roughness value for buildings in 2D domain

Model Simulations																											
	GIS Filename	**Model File Type**	Calibration 2007 Event	Calibration 2008 Event	1 in 2yr	1 in 5yr	1 in 10yr	1 in 25yr	1 in 50yr	1 in 100yr	1 in 1000yr	1 in 100yr+37%CC	1 in 100yr+53%CC	1 in 100yr+94%CC	Summer Roughness Values	Winter Roughness Values	Reduced Downstream Boundary	Increased Downstream Boundary	FEH Stat Flow	ReFH2+20%	Reduced Structure Losses	Increased Structure Losses	Key Structure Blockages	TUFLOW Classic	TUFLOW 2020-10-AC	**TUFLOW File**	**Description**
72	2d_mat_Roads_v02-A_R.shp	Mat Polygon File																								TGC	Materials polygon setting roughness value for roads in 2D domain
73	2d_mat_SurfaceWater_v03-A_R.shp	Mat Polygon File																								TGC	Materials polygon setting roughness value for surface water areas in 2D domain
74	2d_mat_SurfaceWater_v13-A_R.shp	Mat Polygon File																								TGC	Materials polygon setting roughness value for surface water areas in 2D domain

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