Environmental consultancy report: Flood management evaluation and recommendations for the River Frome near Chipping Sodbury

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Chapter 1 - Introduction

This report aims to assess the flood risk of a 3km reach of the River Frome as it flows near Chipping Sodbury, north-east of Bristol (Figure 1&2), and to then provide a management plan based on this assessment. Alongside this 3km reach, the 78.5km^2 catchment before the Frome flows through the Frampton Cotterell gauging station will be evaluated (NRFA). Flooding presents a danger to human life, property and ecology (Fleming, 2002). Decreasing flood risk, the combination of flood event probability and event damage, is therefore incredibly important, especially considering the reaches proximity to Chipping Sodbury, a town with a population of 10,036 (South Gloucestershire Council, 2023).

Figure 3 shows the catchment bedrock is mostly dominated by limestone and siliciclastic argillaceous-rock. Land cover within the catchment is mostly grassland (>50%) with significant urban and agricultural areas (Figure 4). Flood probability, calculated by the Environment Agency, for Chipping Sodbury is shown below in Figure 5. The western side of the catchment has very low elevation, mostly below 25mAOD, however, the eastern part of the catchment is more elevated, with steeper slopes (Figures 6&7).

The remainder of this report will explain the applied river condition assessment method and then discuss the results from this method. The management objectives will then be outlined followed by a discussion of the available management techniques and then finally management recommendations based on the management objectives and available management techniques.

Figure 1 – *River Frome 3km reach*

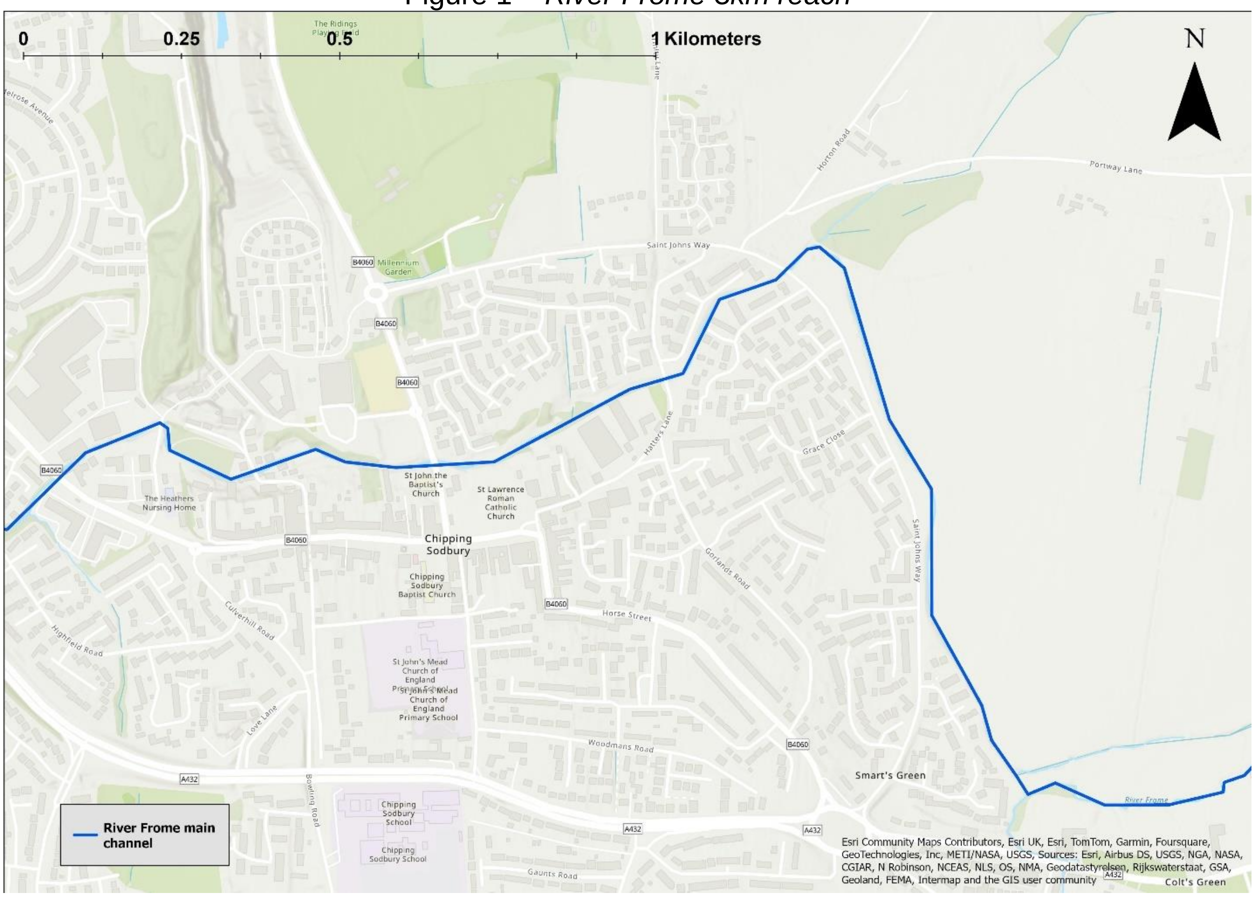


Figure 2 – *River Frome before Frampton Cotterell gauging station*

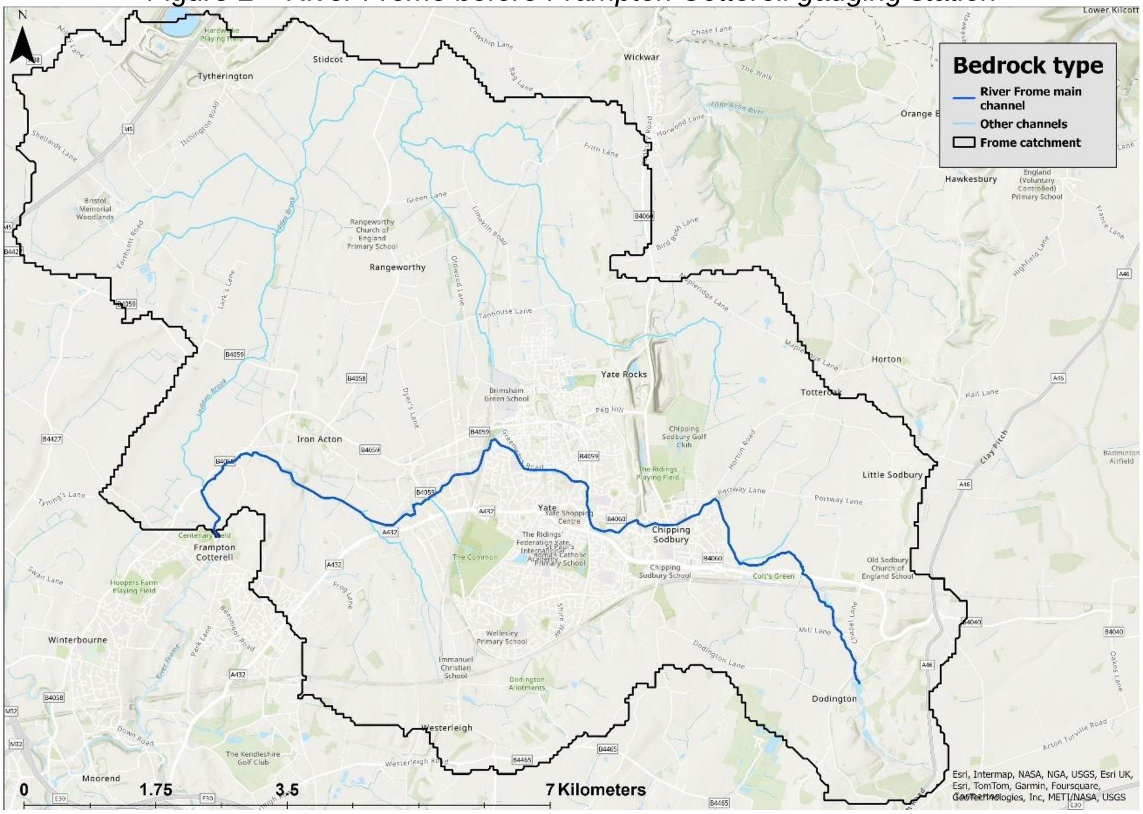


Figure 3 – *Geology of the River Frome*

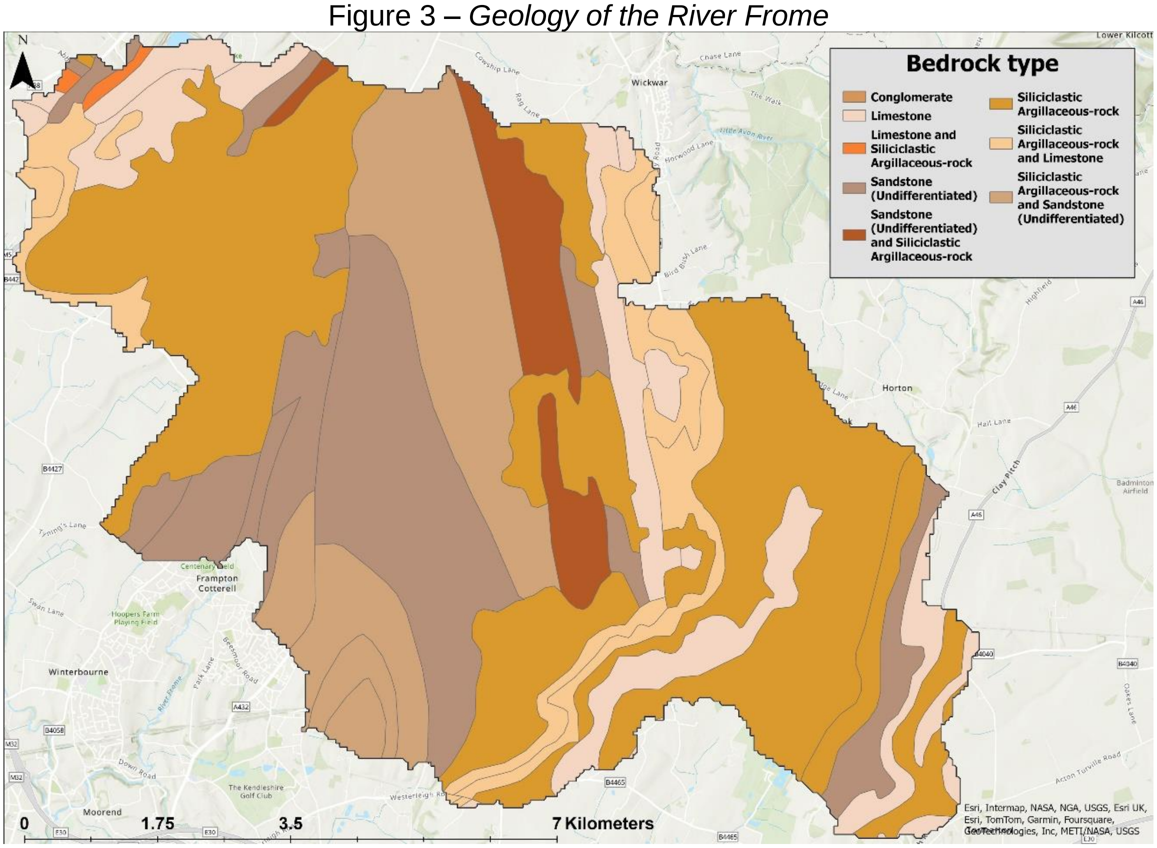


Figure 4 – *Land cover within the Frome catchment*

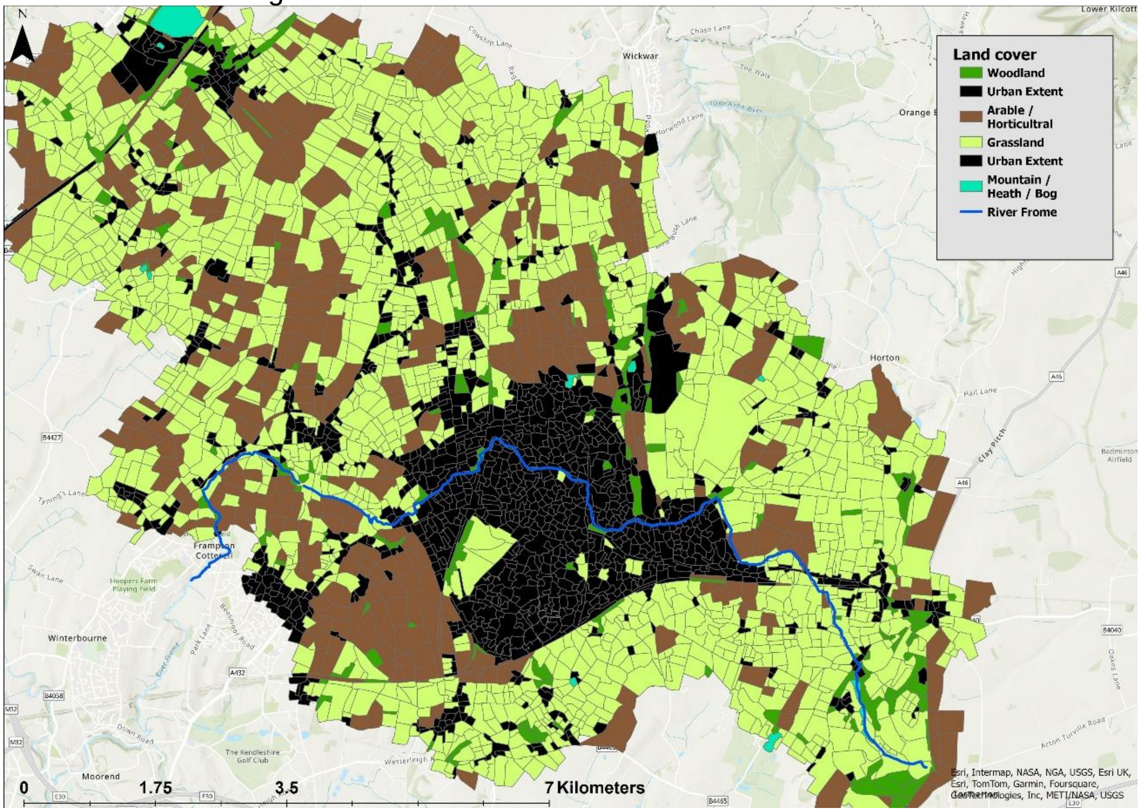


Figure 5 – *Environment Agency flood probability evaluation (Environment Agency, 2018a)*

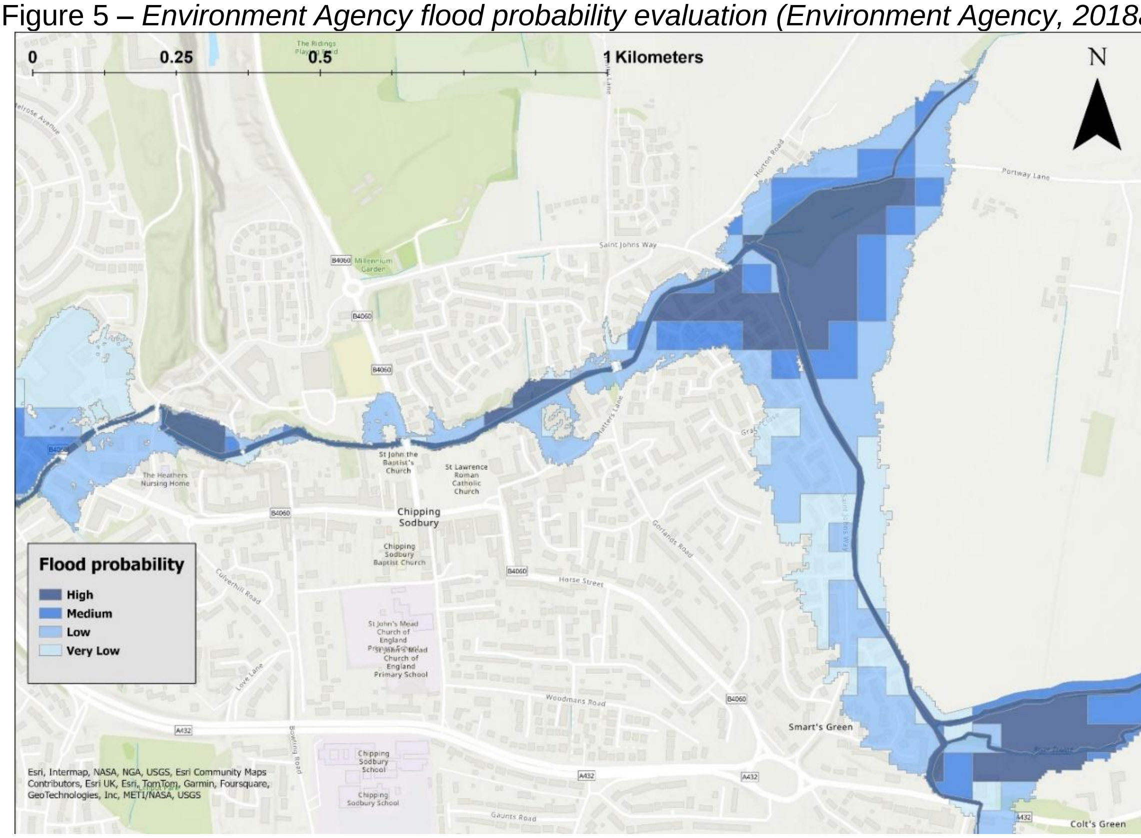


Figure 6 – *Elevation (mAOD) within the Frome catchment*

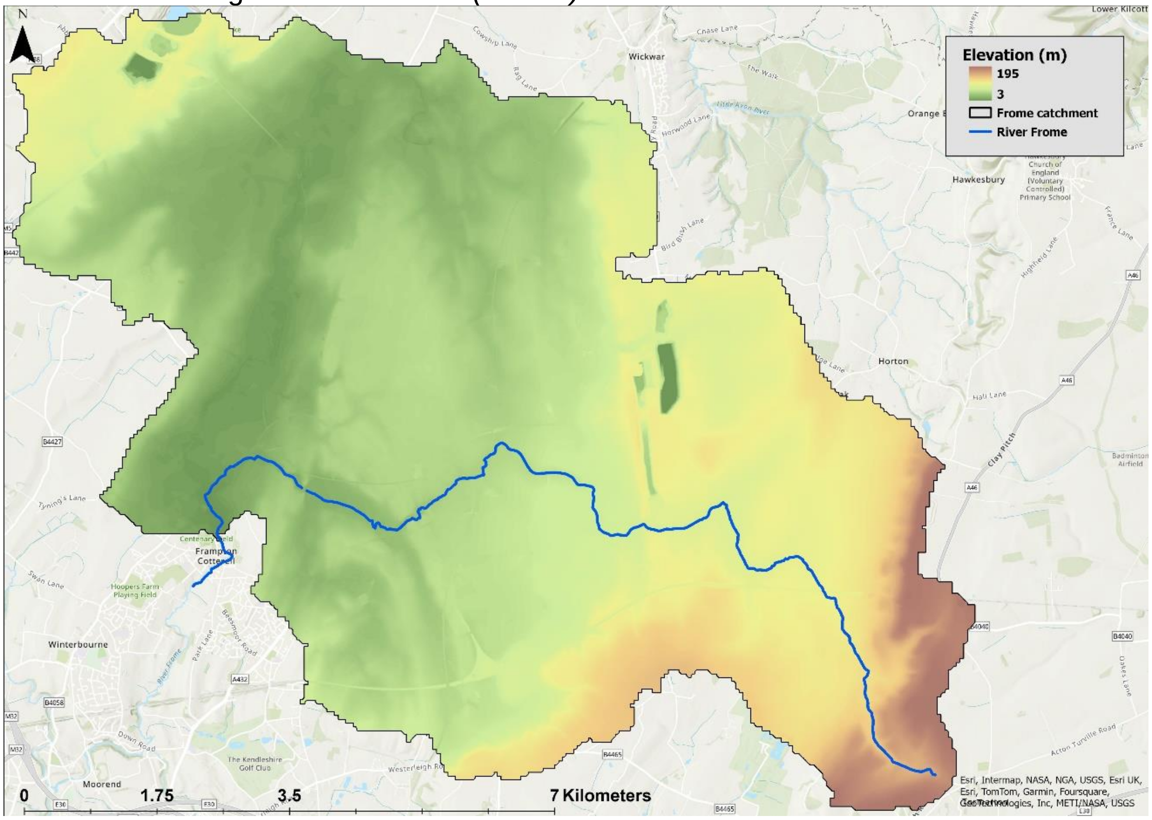
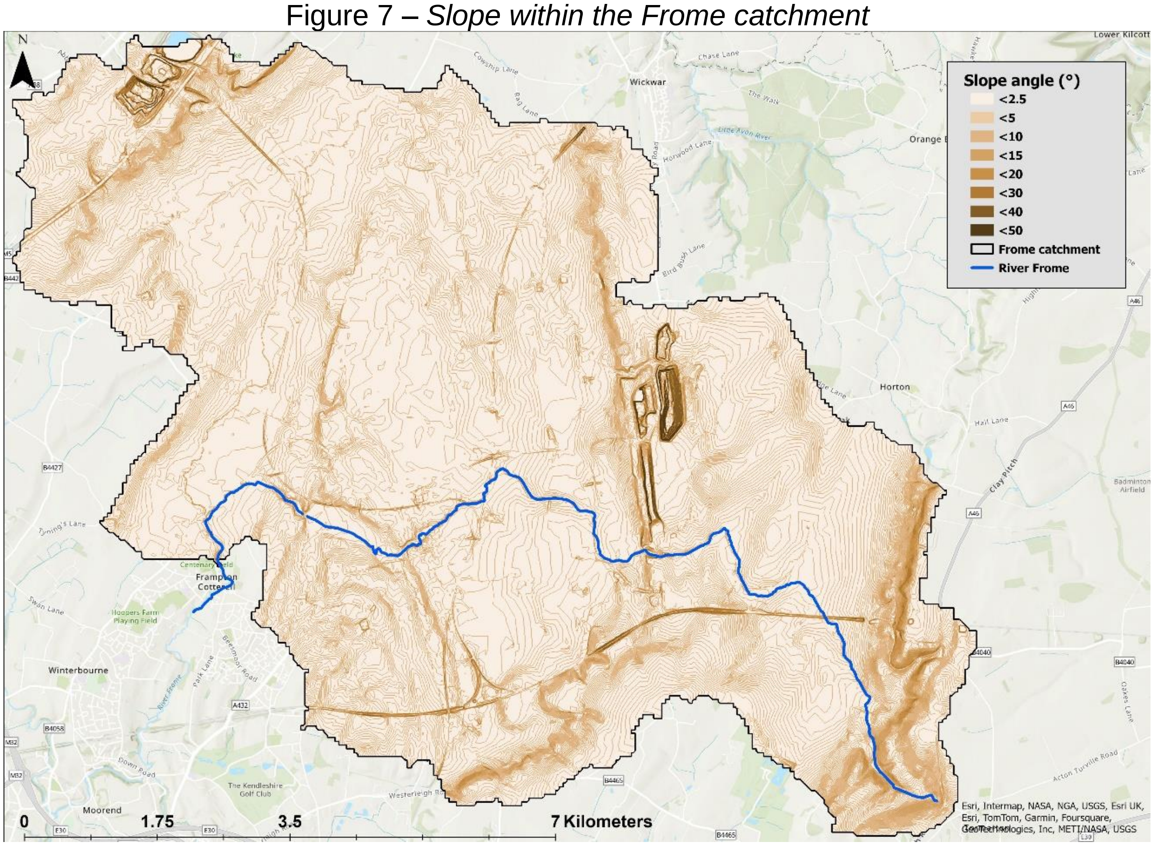


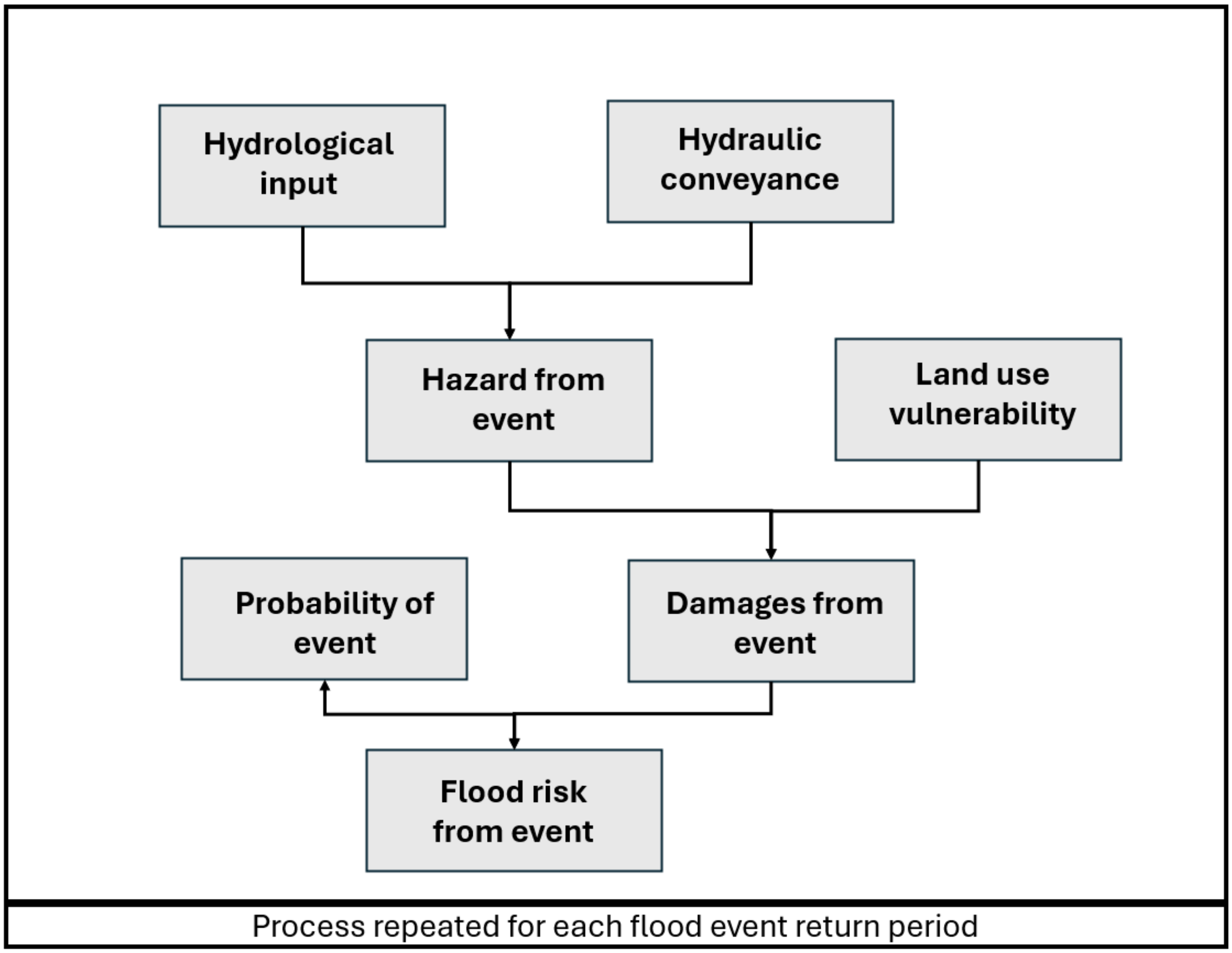
Figure 7 – *Slope within the Frome catchment*



Chapter 2 - River Condition Assessment Method

The following chapter will outline the river condition assessment method used to determine flood risk. This overall process is displayed below in Figure 8. This chapter will examine each of these components in greater detail and present the specific method used for calculating flood risk for the River Frome near Chipping Sodbury. The results of the discussed method are displayed in Chapter 3.

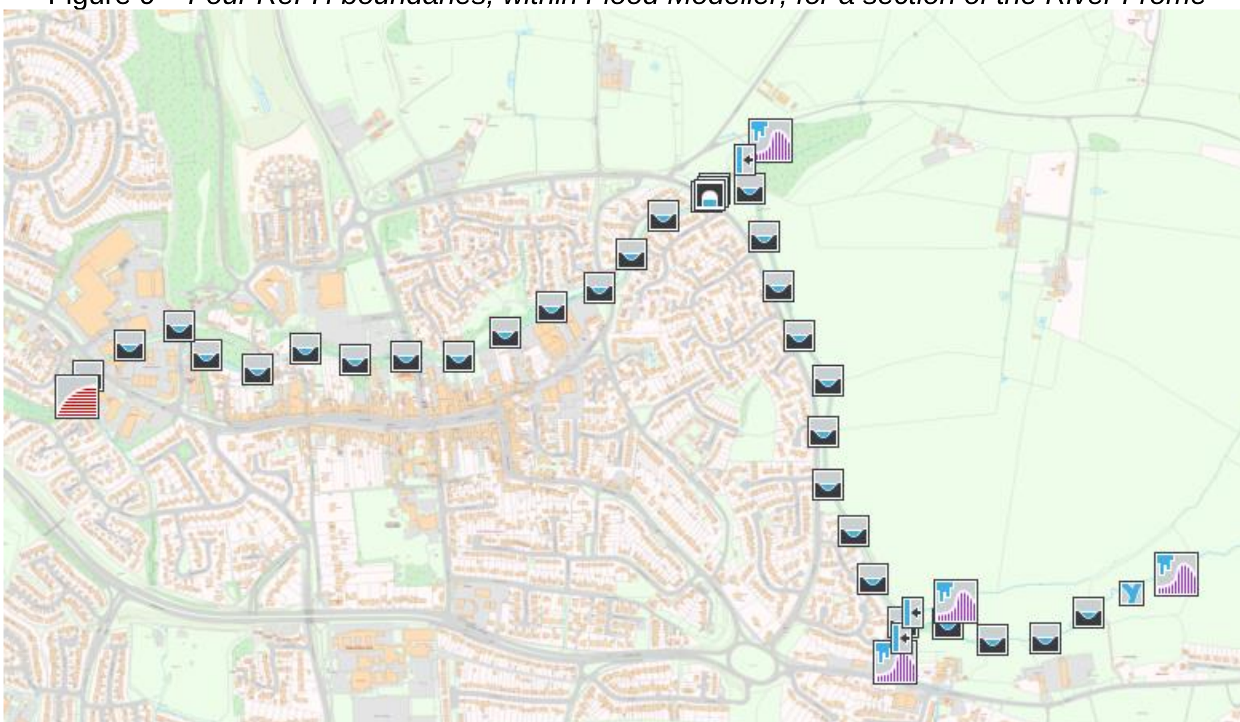
Figure 8 – *General flood risk assessment method*



2.1 - Hydrological Input

A core component of measuring flood risk is the hydrological input, simply put, the flow discharge which is delivered into the river channel from the upstream area. Precipitation rate is the primary factor which determines the amount and rate of flow discharge delivered, however, there are many other influential factors (Sheng *et al.*, 2022). For example, depending on local bedrock geology and soil composition, infiltration rates will change, with high infiltration rates leading to decreased surface runoff, lower peak flows and a longer lag time, and low infiltration rates leading to increased surface runoff, greater peak flows and a shorter lag time. The presence of vegetation can also cause interception, which decreases surface runoff and decreases peak flow rate (Sheng *et al.*, 2022). All these factors influence the hydrological input to the river catchment. In this report, hydrological input is represented by four revitalised flood hydrograph (ReFH) boundaries within the Flood Modeller software. These ReFH boundaries, shown in Figure 9, are the main river stem and three tributaries.

Figure 9 – *Four ReFH boundaries, within Flood Modeller, for a section of the River Frome*



2.2 - Hydraulic Conveyance

Hydraulic conveyance is the amount of water that can be effectively convey downstream without flooding (Peruzzi *et al.,* 2018). Channel hydraulic conveyance is calculated through Manning's equation, shown below (Andersson *et al.*, 2019).

$$Q = \frac{1.49}{n} A(R^{\frac{2}{3}})S^{\frac{1}{2}} \tag{1}$$

Where Q is discharge (m^3/s), n is Manning's roughness coefficient, A is the cross-sectional area of flow (m^2), R is hydraulic radius and S is channel bed slope.

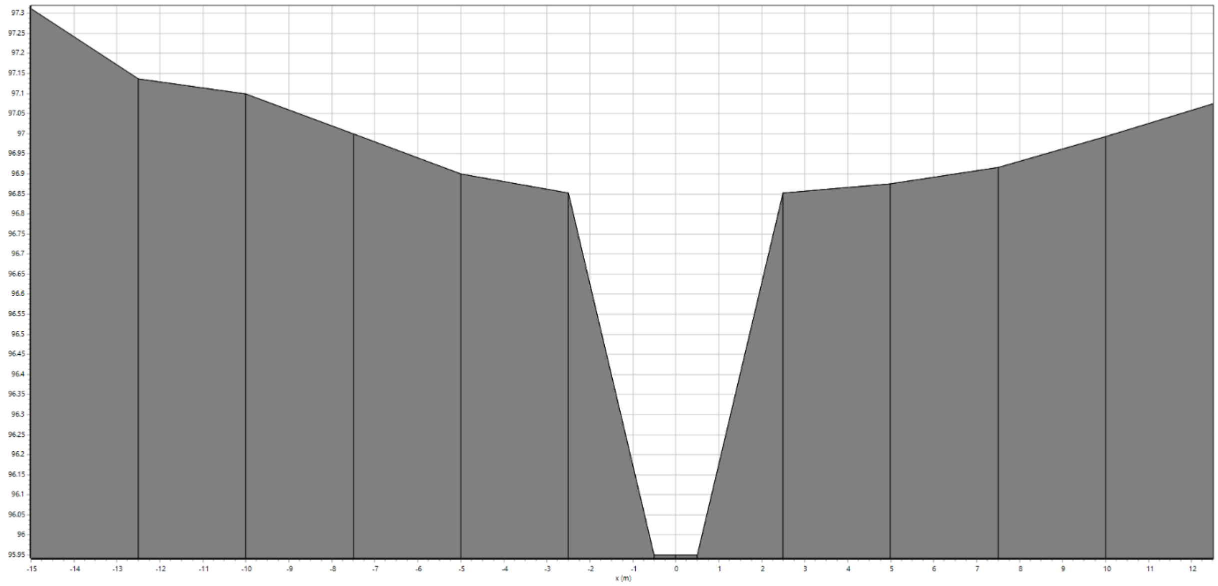
In studied section of the Frome the river channel has been subjected to channelisation, aimed at increasing conveyance capacity by making the channel straighter and deeper (Environment Agency, 2010). Hydraulic conveyance in this report is represented through 29 cross-sections within Flood Modeller. These include values for elevation (m AD) (used to show channel depth), width (m) and Manning's roughness coefficient (*n*). These values have been informed by observations based on a site visit for the studied section of the River Frome as well as remotely sensed LiDAR DTM data for elevation values. Channel width and depth values are based on visual approximations. Manning's roughness coefficient is calculated from Equation 2, with each of the variables used in the equation taken from in field observations, derived from the information in Appendix I (Arcement and Schnider 1989).

$$n = (n_b + n_1 + n_2 + n_3 + n_4)m \tag{2}$$

Where n is Manning's roughness coefficient, n_b is bed material, n_1 is degree of irregularity, n_2 is variation of channel cross section, n_3 is effect of obstruction, n_4 is amount of vegetation and m is degree of meandering.

The location of each of the cross-sections is displayed above in Figure 6, whilst an example of how each cross-section is represented within Flood Modeller once it has been updated with the data collected in the field is displayed below in Figure 10.

Figure 10 – *The first cross-section (FR-000) plot displaying elevation and channel width*



2.3 - Hazard from Event

As shown in Figure 5, hazard, the potential for a flood event to cause harm, is determined by a combination of hydraulic input and conveyance. Hazard is then used, alongside land use vulnerability to determine damage. To calculate the hazard from a flood event, the Flood Modeller values for conveyance and input are used to create a 1D model which predicts the velocity and depth of flow moving downstream and a 2D model to predict where water will flow once its depth exceeds the riverbank and enters the floodplain. This is an industry standard technique (Pasquier *et al*., 2019; Leandro *et al*., 2011). Using a 1D Network a 1D-Steady simulation is generated, this simulation uses Q_{10} event data to create a 'steady-stage' 1D model. From this, a 1D-Unsteady model was created with a timestep of 2.5 seconds and a finish time of 24 hours. This was done for three different return periods, Q_{20}, Q_{50} and Q_{100}. The reasoning behind these return values is discussed in Section 2.6. A 2D-Steady model was then created, this uses the 1D-Steady model for flow depth and velocity values, a DTM layer to represent topography, the active area shapefile and is set to a finish time of 24 hours. The 1D-Unsteady event files are then added with a link line shapefile. The outcome of this 2D-Steady model simulation is 10x10m cells, known as wet cells, over a map of Chipping Sodbury. These represent the area that is predicted to be flooded from a given flood return period and is the representation of the total hazard used in this report.

2.4 - Land Use Vulnerability

The land use vulnerability of an area is determined by population density and demographics as well as building density and type (Alvarez, Gomez-Rua and Vidal-Puga, 2019). Within this project, a Mastermap representation of the area surrounding Chipping Sodbury is used to provide information about building and urban development type and amount. This information can then be used alongside the 10x10m wet cell representation (event hazard) to calculate event damage.

2.5 - Damages from Event

Event damage is calculated from event hazard and land use vulnerability. The damage an event causes is the cost of replacing any damaged or destroyed buildings or infrastructure such as roads (Environment Agency 2018b). This report uses damage values (£) from the Environment Agencies estimated economic cost of the 2015/2016 winter floods (Appendix II&III) (Environment Agency, 2018b). These values have then been adjusted for inflation using the Bank of England inflation calculator (2016 to January 2024).

2.6 - Probability of Event

Event probability consists of a combination of event magnitude and frequency. Larger events have greater magnitude but occur less frequently. For example, an event with a 10-year return period (Q_{10}) would be expected to occur once every 10 years and would have a relatively low magnitude. Based on previous river flood risk studies, this report uses event return periods of Q_{20}, Q_{50} and Q_{100} when modelling flood hazard (Pinos and Timbe, 2019; Zhu *et al*., 2022; Slater *et al*., 2021).

2.7 - Flood Risk from Event

The overall flood risk from an event is calculated by multiplying the probability and damages, as displayed in Figure 5. The steps listed previously in this chapter are repeated for all of the flood event return periods (Q_{20}, Q_{50}, Q_{100}).

Chapter 3 – River Condition Assessment Results

The following chapter will display and discuss the individual results from the previously discussed method before presenting the overall key findings and a strengths, weaknesses, opportunities and threats (SWOT) analysis presented in Figure 18. Figures 11, 12 and 13 display the flood hydrograph results for the three modelled return periods, whilst Figures 14, 15 and 16 present the maximum modelled flood depth. Field based observations of depth, width and roughness are shown in Appendix IV.

3.1 – Method Outputs

Figure 11 – *Q_{20} Hydrograph*

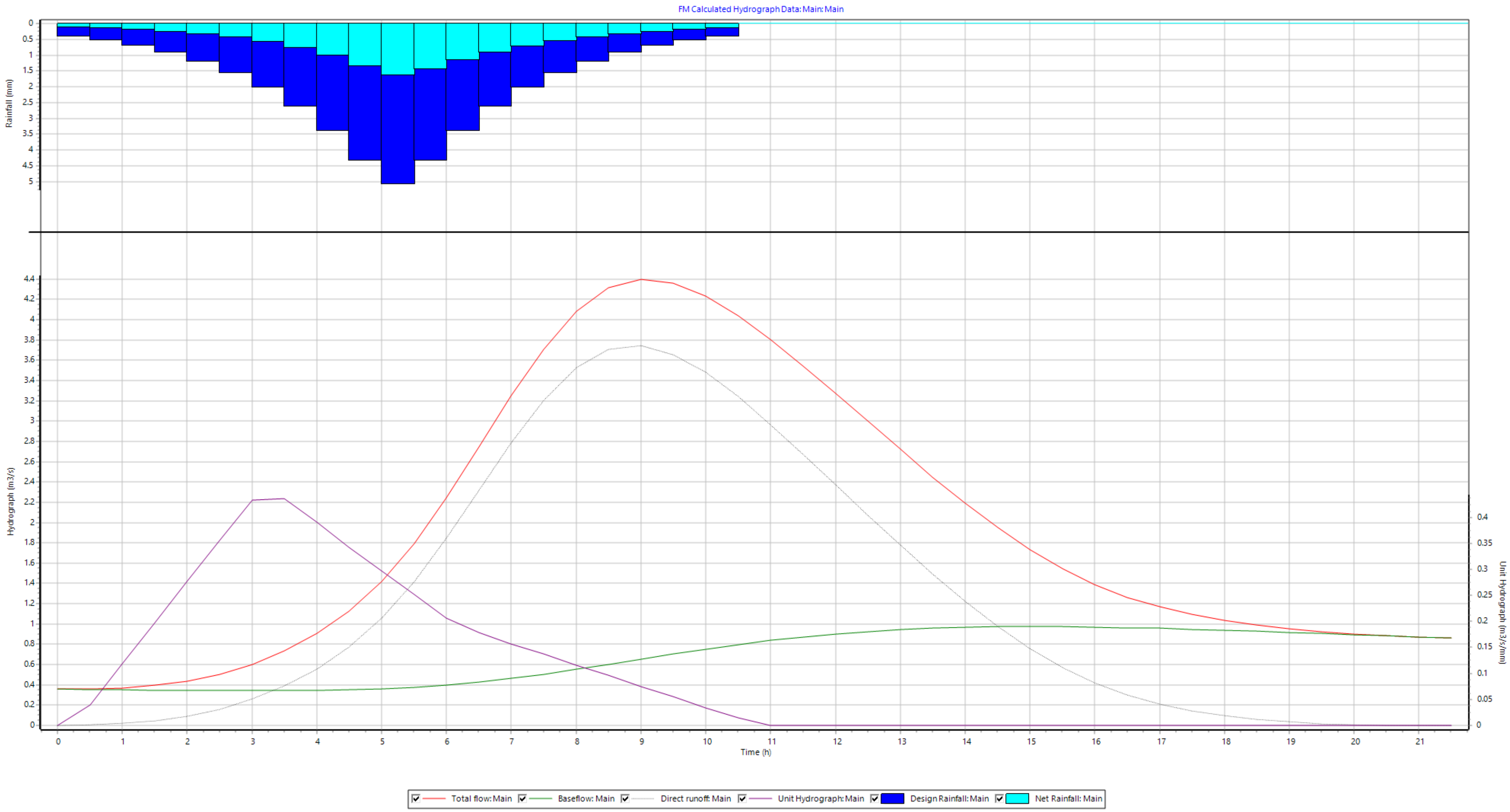


Figure 12 – *Q_{50} Hydrograph*

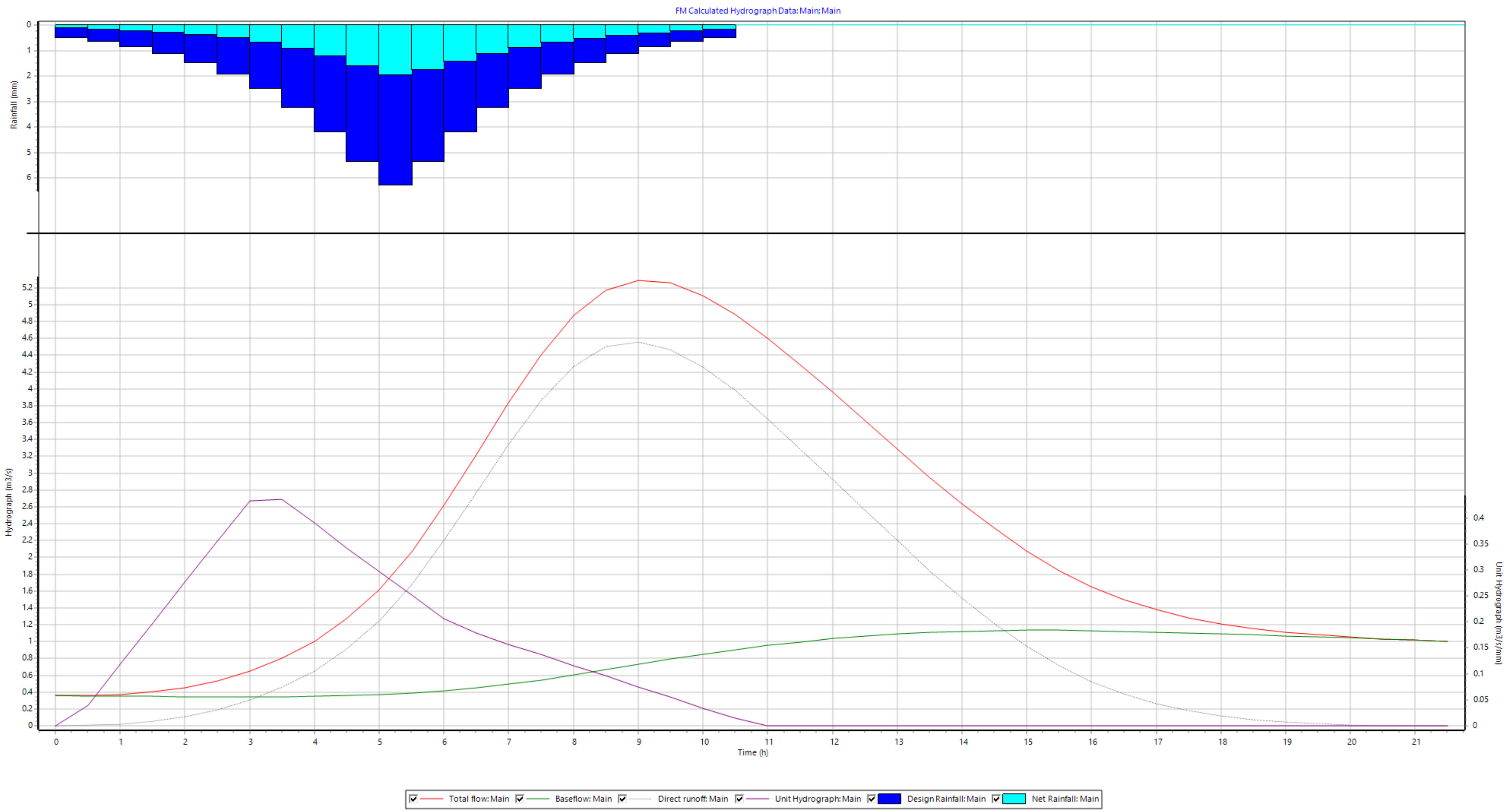


Figure 13 – *Q_{100} Hydrograph*

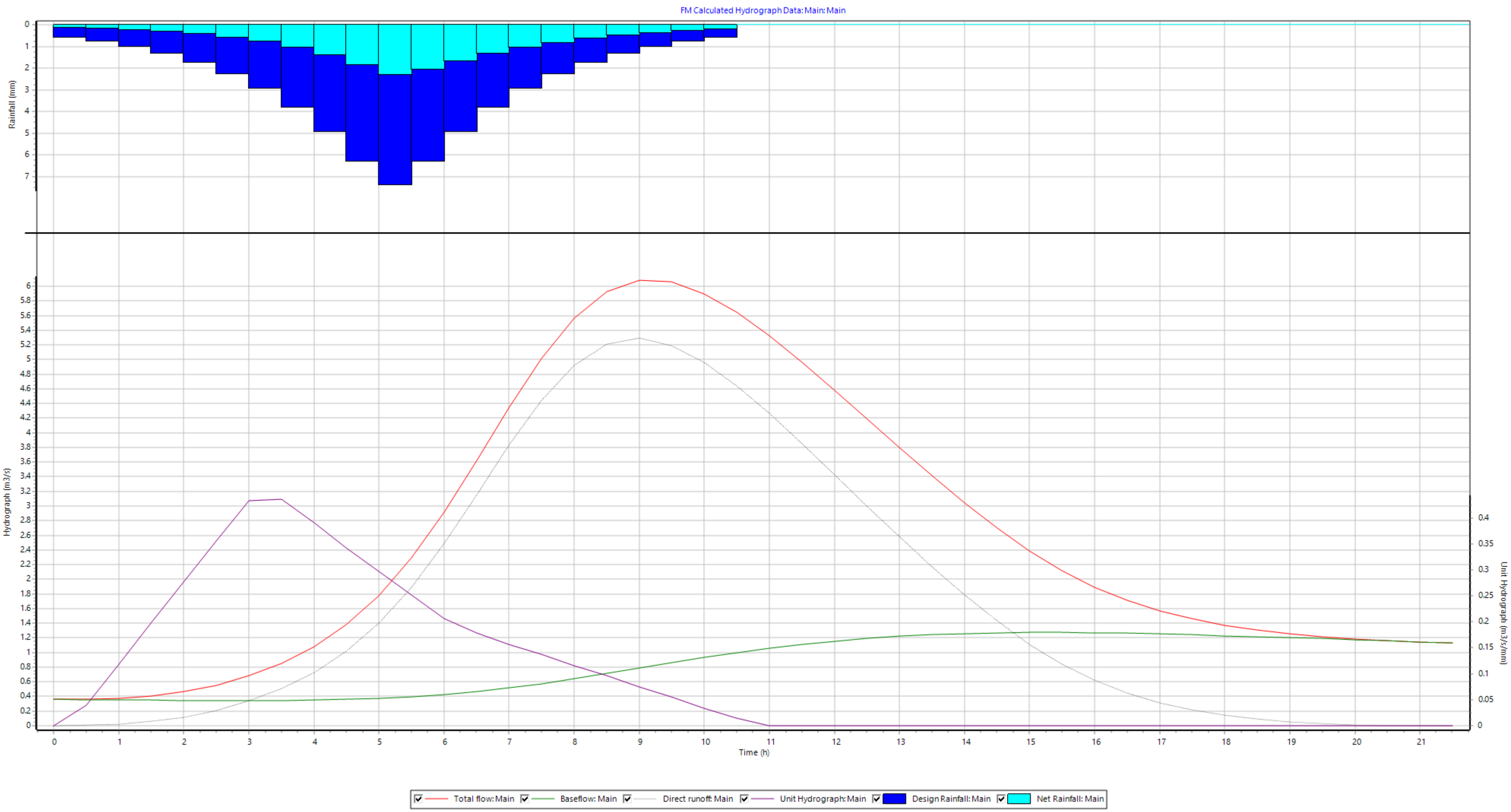


Figure 14 – *Q_{20} Flood max depth*

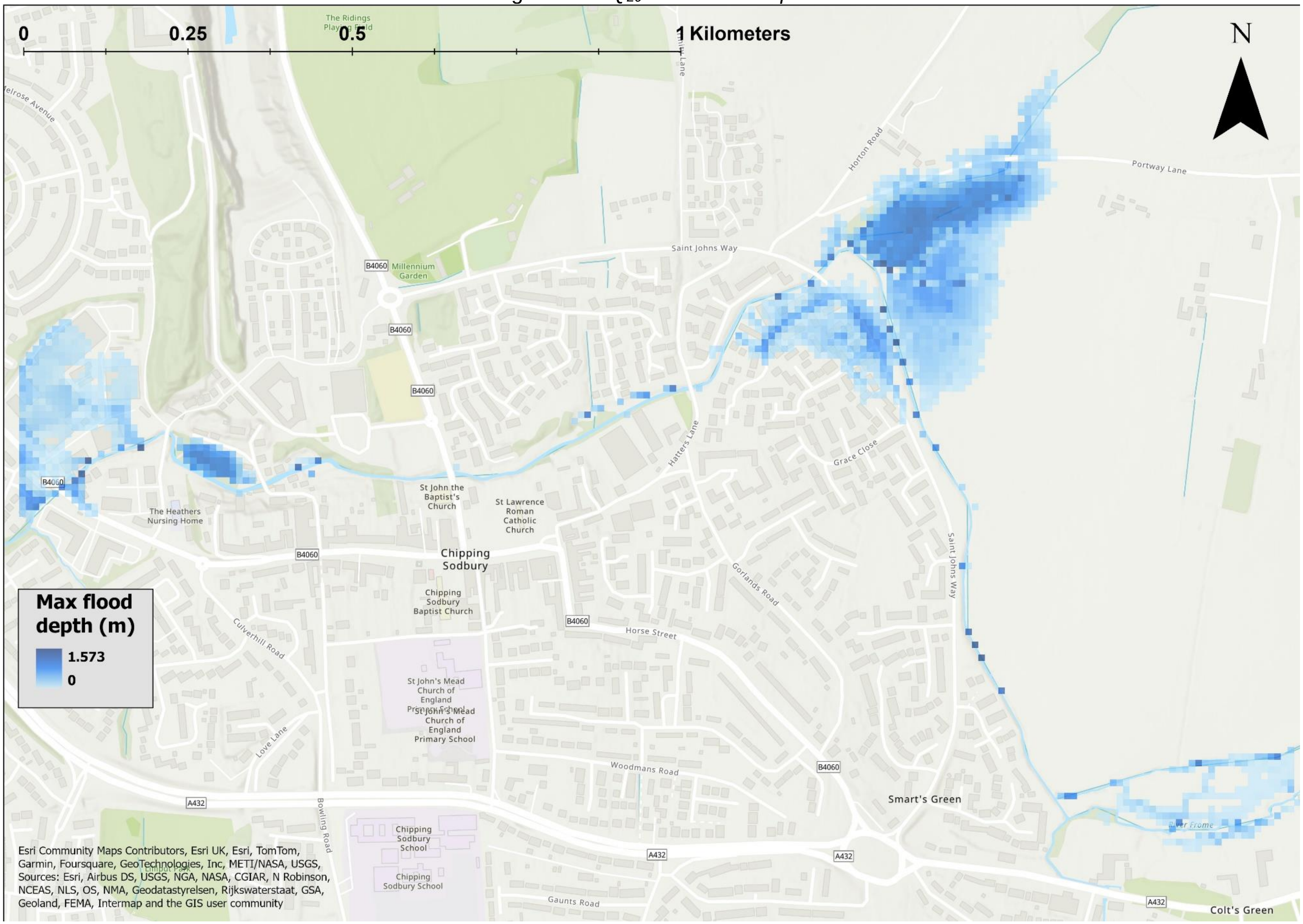


Figure 15 – *Q_{50} Flood max depth*

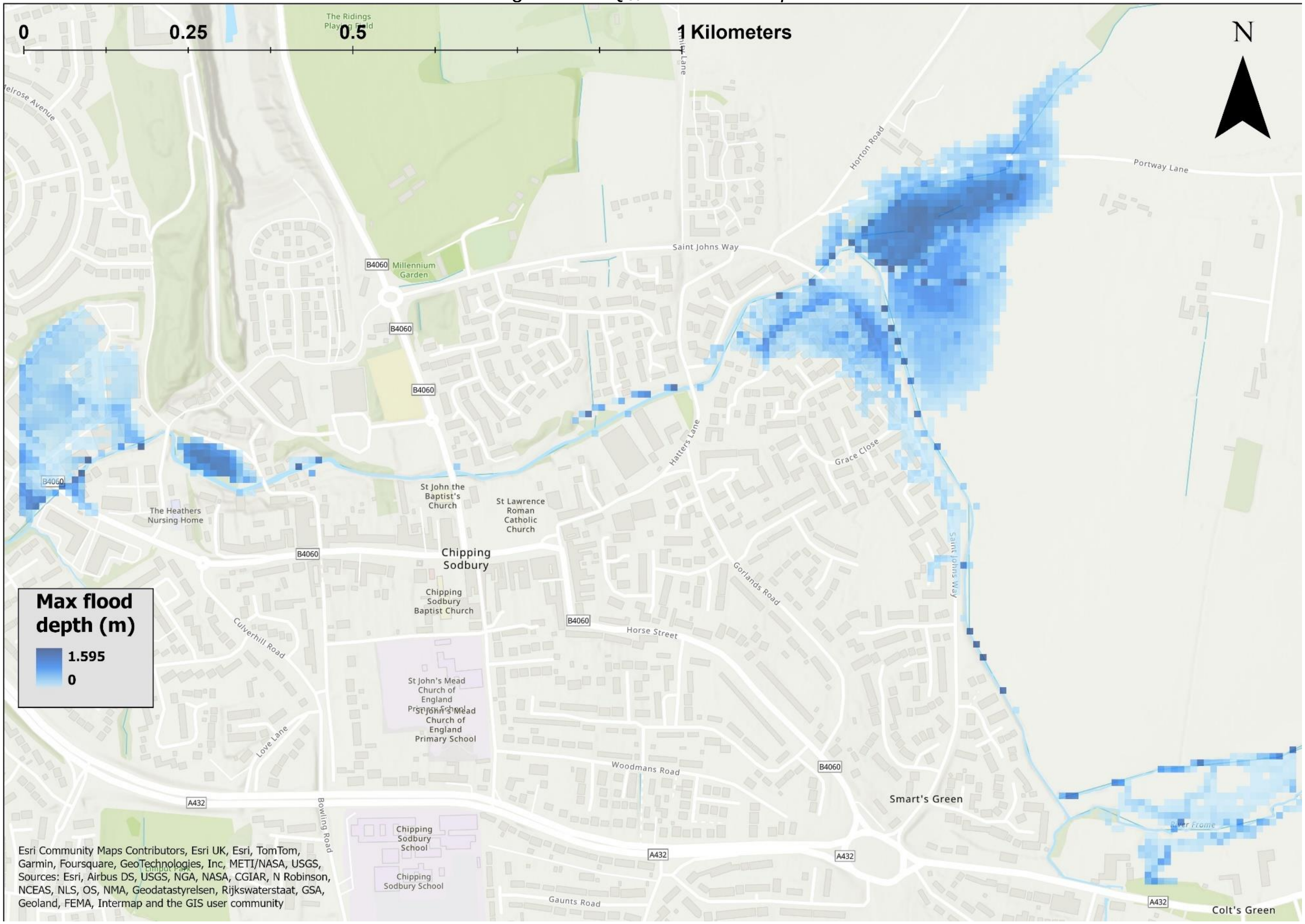


Figure 16 – Q_{100} *Flood max depth*

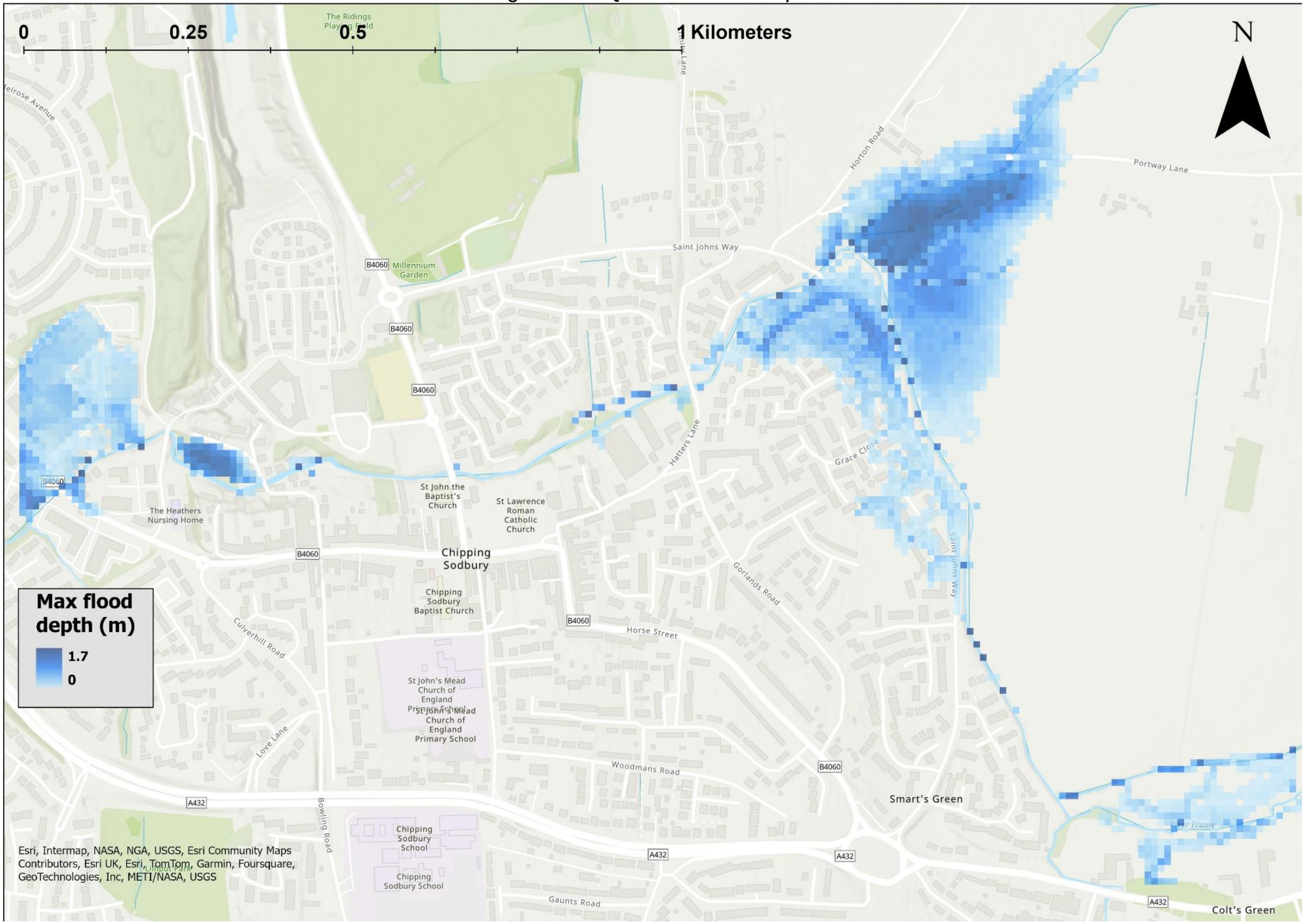


Table 1 – *Damage value (£) calculations*

Flood Event Return Period	Averaged cost estimate (£)	Flood event probability	Annual flood risk (£)
Q_{20}	2,769,874	0.05	83,096
Q_{50}	3,679,920	0.02	36,799
Q_{100}	4,720,110	0.01	47,201
Total Annual Flood Risk (£)	**167,096**		

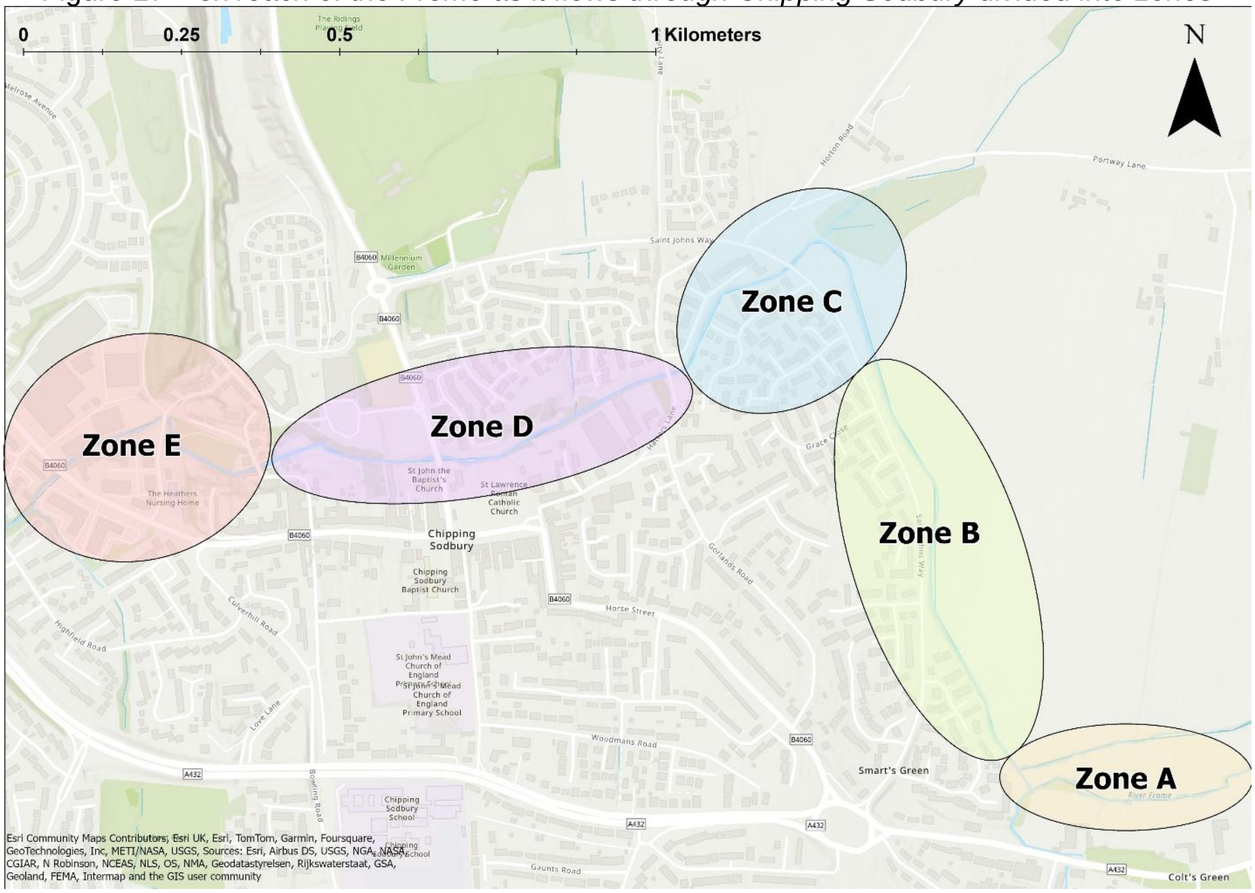
3.1.1 Results Description

The above results display the outputs of the applied method, with Table 1 displaying the total annual flood risk (the combination of return period and damages). Based on this data, the 3km studied reach of the Frome has been divided into five ‘zones’ for the purposes of flood management. Figure 17 displays the location of each of these zones, and Table 2 details the total annual flood risk within each zone. Annual flood risk is highest in Zones C and E. This is due to their urbanised nature (land use) as well as insufficient conveyance in these zones. On higher return period events, Zone B also has significant annual flood risk, suggesting that the conveyance in this zone is insufficient for a large event.

Table 2 – *Averaged damage value (£) calculations for the 3km reach zones*

Flood Event Return Period	Zone A Cost (£)	Zone B Cost (£)	Zone C Cost (£)	Zone D Cost (£)	Zone E Cost (£)
Q_{20}	31,348	130,122	1,183,526	98,774	1,326,104
Q_{50}	31,348	587,914	1,246,222	130,122	1,684,314
Q_{100}	31,348	1,337,298	1,277,570	130,122	1,881,054
Total Annual Flood Risk (£)	1,566	23,156	60,744	5,565	75,436

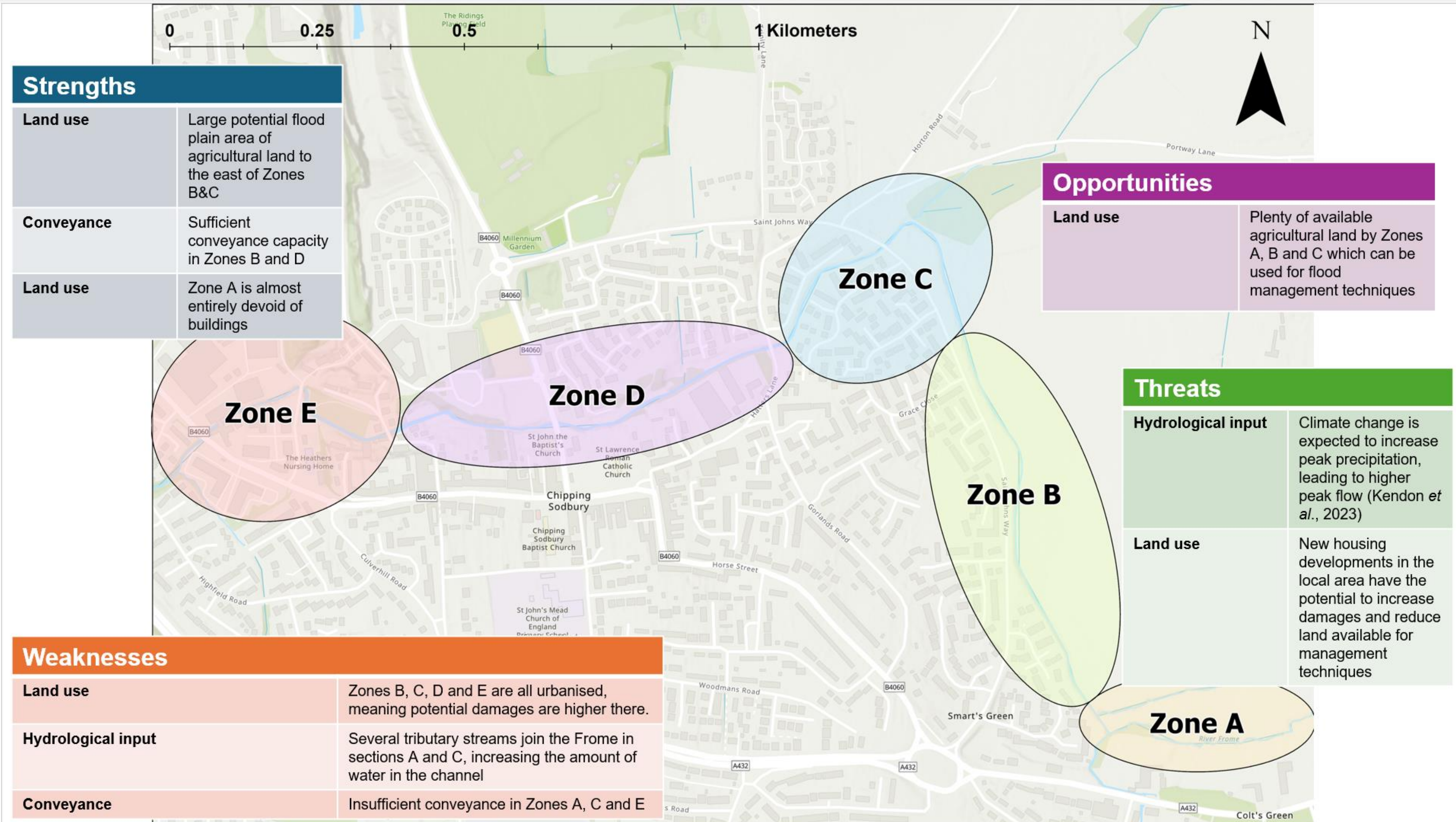
Figure 17 – *3k reach of the Frome as it flows through Chipping Sodbury divided into zones*



3.2 – SWOT Analysis

Figure 18 below displays a strengths, weaknesses, opportunities and threats (SWOT) analysis of the studied 3km reach of the Frome. This makes use of the zones outlined in Figure 17 to highlight key areas of concern or key areas for improvement and will be used to determine the management objectives outlined in the next chapter. Each management objective is aimed at nullifying a weakness/threat or amplifying an opportunity or strength.

Figure 18 – *SWOT Analysis of the 3km reach*



Chapter 4 – Management Objectives

This chapter will outline this report's core management objects, based on the results displayed in Chapter 3. Table 2 outlines Zones C and E as having the greatest overall flood risk. However, flooding hazard is high in Zone A and Zone B has high land use vulnerability due to its urban nature. The following management objectives aim to take a holistic approach, considering all the variables that contribute to flood risk, ultimately with the goal of reducing this risk along the 3km reach and the Frome catchment more generally.

4.1– Hydraulic Regime

Objective I – Decrease peak flows to account for increase in precipitation caused by climate change by 2050.

4.2 – Conveyance

Objective II – Increase conveyance capacity in Zones C&E to reduce flood hazard by 2028.

Objective III – Maintain or increase conveyance in Zones B&D by 2030.

4.2- Damages

Objective IV - Reduce damages from the Q20 event to below £600,000 in Zone C and Below £650,000 in Zone E by 2030.

Chapter 5 – Available Management Techniques

This chapter will describe and discuss available management techniques for the Frome catchment. Table 3 displays a list of possible management techniques, showing which component of flood risk they aim at addressing, alongside examples of locations that specific techniques have been used effectively as well as references explaining the specifics of how each technique works. The following section explains the structuring of the table and provides a brief overview of how each sub-category lowers overall flood risk.

5.1 – Hydrological regime

Categories related to hydrology generally aim to delay or reduce hydrological input into the river channel to reduce flood hazard. Changing the hillslope response refers to management techniques that aim to decrease peak surface runoff and thus lower peak flows. This category is then subdivided into sustainable urban drainage systems (SUDS), targeted at urban areas, and catchment sensitive farming (CSF), targeted at rural and agricultural areas. Modelling can be used to determine the most effective location for these techniques to be applied, so that peak surface runoff can be lowered as much as possible. The other possible way to adjust hydrology is via channel routing. Within this category, impoundments hold back water within the river channel, whereas flood plain storage involves storing water outside of the river channel during peak flows.

5.2 - Conveyance capacity

Categories related to conveyance generally aim to increase conveyance capacity, allowing greater flow levels before the river floods. Equation 1 in Chapter 2 displays the equation to calculate conveyance capacity. Conveyance sub-categories listed below all change the value for one aspect of this equation. Firstly, constructing embankments/walls increases cross-sectional area outside the existing channel whereas re-sectioning/dredging removes material from the channel to increase its cross-sectional area. Greater cross-sectional area leads to greater conveyance capacity. Secondly, straightening the river channel and increasing the slope leads to greater flow velocity, also allowing for greater conveyance capacity. Finally, roughness can be reduced within the river channel, again leading to greater flow velocity.

5.3 - Land use vulnerability

Categories related to land use vulnerability generally aim to decrease the vulnerability of areas prone to flooding, typically lowering the tangible damage a flood causes. There are several ways this is done, firstly, categories related to making space for water aim to avoid building on areas that have high flood hazard. This lowers the flood hazard, leading to less risk. Secondly, there are management techniques that involve ‘living with water’. This is sub-divided into two categories; dry-proofing, where efforts are focused on preventing any water from entering buildings while acknowledging the area around the building will flood, and wet-proofing, where flooding is planned for and allowed to occur in sections of properties, with the idea that most of the damage can be avoided by this planning. Finally, flood warning systems can be employed to allow for people to prepare for flooding, reducing property damage.

Table 3 – *List of possible management techniques divided by category*

Category				Example of management technique
Hydrology	Hillslope response	SUDS	Detention Ponds	Auckland, New Zealand (Semadeni-Davies, 2012).
			Soakaways	Copenhagen, Denmark (Roldin *et al*., 2012).
			Green Rooves	Wroclaw, Poland (Burszta-Adamiak and Mrowiec, 2013). Sheffield, UK (Stovin, 2010).
			Pervious pavements	Madrid and Barcelona, Spain (Castro-Fresno *et al*., 2013).
			Urban wetland areas	Stockholm, Sweden (Cettner, 2012).
		CSF	Tree belts	River Thames, United Kingdom (Collins *et al.,* 2023). Warwickshire, United Kingdom (Revell *et al.,* 2022).
			Retention ponds	Barabai River, Indonesia (Mufarida and Rizal, 2022).
			Debris jams	Carmel River, USA (East *et al.,* 2023)
		Modelling of where best to apply techniques	SCIMAP-FLOOD	River Eden, England (Reaney, 2022)
	Channel routing	Impoundment	Nature based (leaky dams)	River Cover, England (Leeuwen *et al.,* 2024)
			Engineering based	Odra River, Poland (Banasiak, 2024)
		Floodplain storage		River Hauihe, China (Hu *et al*., 2024)

Conveyance	Increasing cross-sectional area	Embankments/walls	Embankment	River Elba, Germany (Thieken *et al.,* 2016)
			Temporary flood walls	Torksey Lock, Lincolnshire (Cartwright *et al.,* 2019)
			Set-back embankment	Da-Han Creek, Taiwan (Cheng *et al.,* 2017)
		Re-sectioning/dredging	Dredging	River Waal, the Netherlands (Bardoel, 2010). River Parrett, Somerset (Somerset Rivers Authority, 2021).
			Two-stage ditch design	Sipoo, Finland (Västilä *et al*., 2021)
	Straightening/Increasing slope			Sainte-Marguerite River, Canada (Talbot and Lapointe, 2002)
	Reducing roughness	Vegetation removal		Tamshui River, Taiwan (Shih and Chen, 2021)
		Obstruction		Diyala River, Iraq (Ghali and Azzubaidi, 2021)
		Cross-section		Diyala River, Iraq (Ghali and Azzubaidi, 2021)
		Decrease Irregularity		Indus River, Pakistan (Zamir, 2011)
		Reducing degree of meandering		Moncho-Esteve *et al.* (2018)
Land use vulnerability	Making space for water			River Suldalslågen, Norway (Saltviet, Brabrand and Brittain, (2019)
	Living with water	Dry proofing		River Mela, Italy (Ventimiglia, Candela and Aronica, 2020)
		Wet proofing		Meuse River, The Netherlands (Poussin *et al.,* 2012)
	Flood warning	Real time		Vu Gia-Thu Bon River basin (Nguyen *et al.,* 2020)
		Public warning systems		Hong Kong and Pearl River Delta, China (Chan *et al.,* 2013)

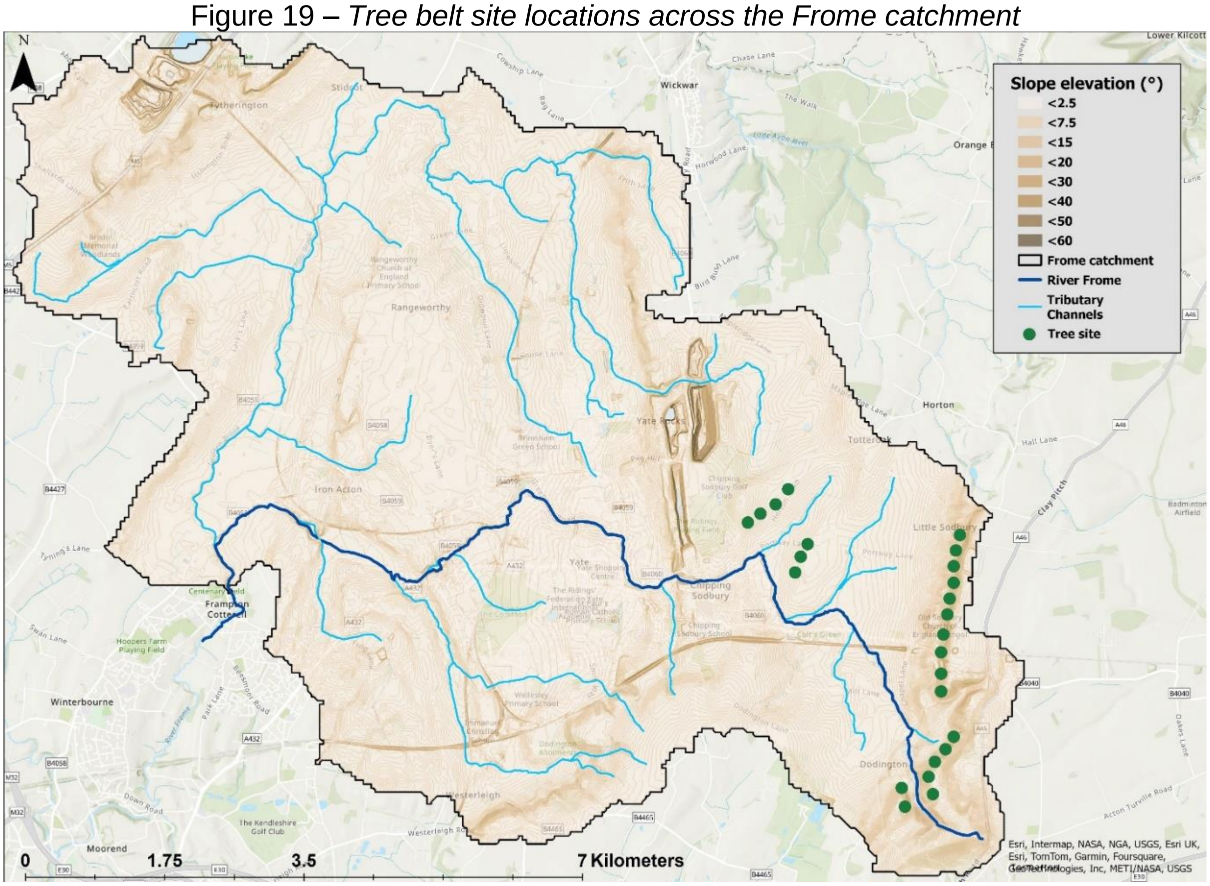
Chapter 6 – Management Recommendations

This chapter outlines various recommended management techniques that aim to help achieve the objectives set out in Chapter 4. These management techniques will be applied to both the 3km reach as well as the Frome catchment more generally.

6.1 - Objective I

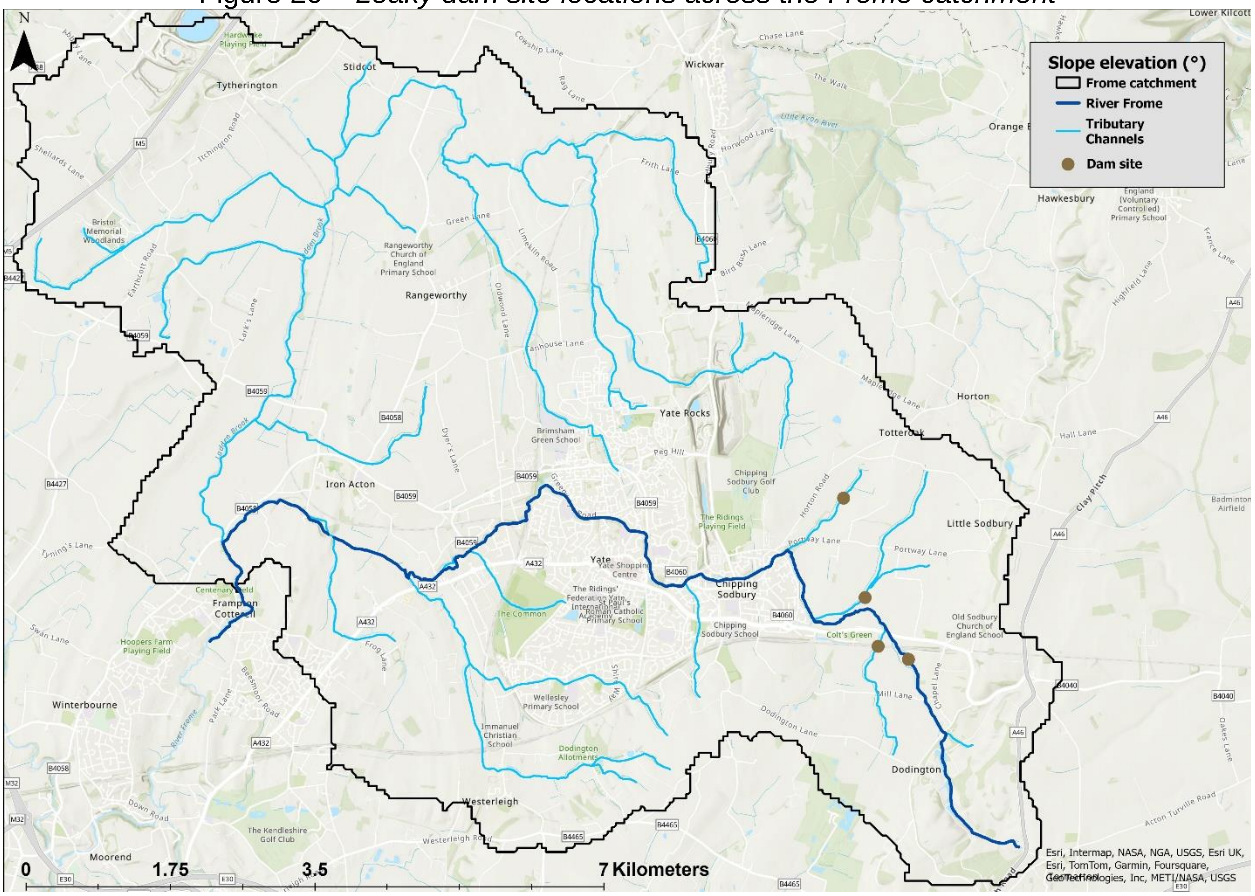
The purpose of Objective I is to decrease peak flows within the Frome catchment in anticipation of the increase in precipitation that is predicted to occur as a result of climate change. It is recommended that this is achieved through an increase in interception via the planting of tree belts across the catchment as well as through the construction of leaky dams upstream of the 3km reach. Tree belts can effectively increase interception, decreasing peak runoff and therefore peak flows (Carrick *et al.,* 2017). Tree belts are also ecology beneficial and relatively cheap (Woodland Trust). Tree belts are best planted on agricultural/non-urban land, where the slope is steep. This is because areas of steep slope have the highest runoff velocity, meaning reducing runoff here has the greatest effect on reducing peak flow, as well as these areas not being able to be utilised for other types of land use due to their steep slope (Mueller, Wainwright and Parsons, 2007). Sycamore trees (*Acer pseudoplatanus*) have been chosen as the main planted species due to their thick canopy, quick growth rate and stable root systems which allow them to grow on slopes (Lemoine, Peltier and Marigo 2001; Woodland trust 2024). Tree planting typically costs between £900-2000 per hectare (Woodland Trust). Tree belt site locations are displayed below in Figure 19, each site represents a 1ha area.

Figure 19 – *Tree belt site locations across the Frome catchment*



Leaky dams are a small-scale type of impoundment typically made of wood. They hold back water during periods of high flow but are generally permeable, having less of an effect on river hydrology than other impoundment types. Several leaky dams will be installed upstream of the 3km reach, along the main channel of the Frome and various tributary streams. The purpose of this is to reduce the peak flow within the 3km reach. It is recommended that leaky dams are installed in a sequence of three, with the distance between each dam being seven times the channel width (Yorkshire Dales Rivers Trust). The cost of leaky dams is low, at around £81 per dam (Herefordshire Council). The location of these dams is shown in Figure 20, each site on the map represents a series of three dams spaced apart as specified.

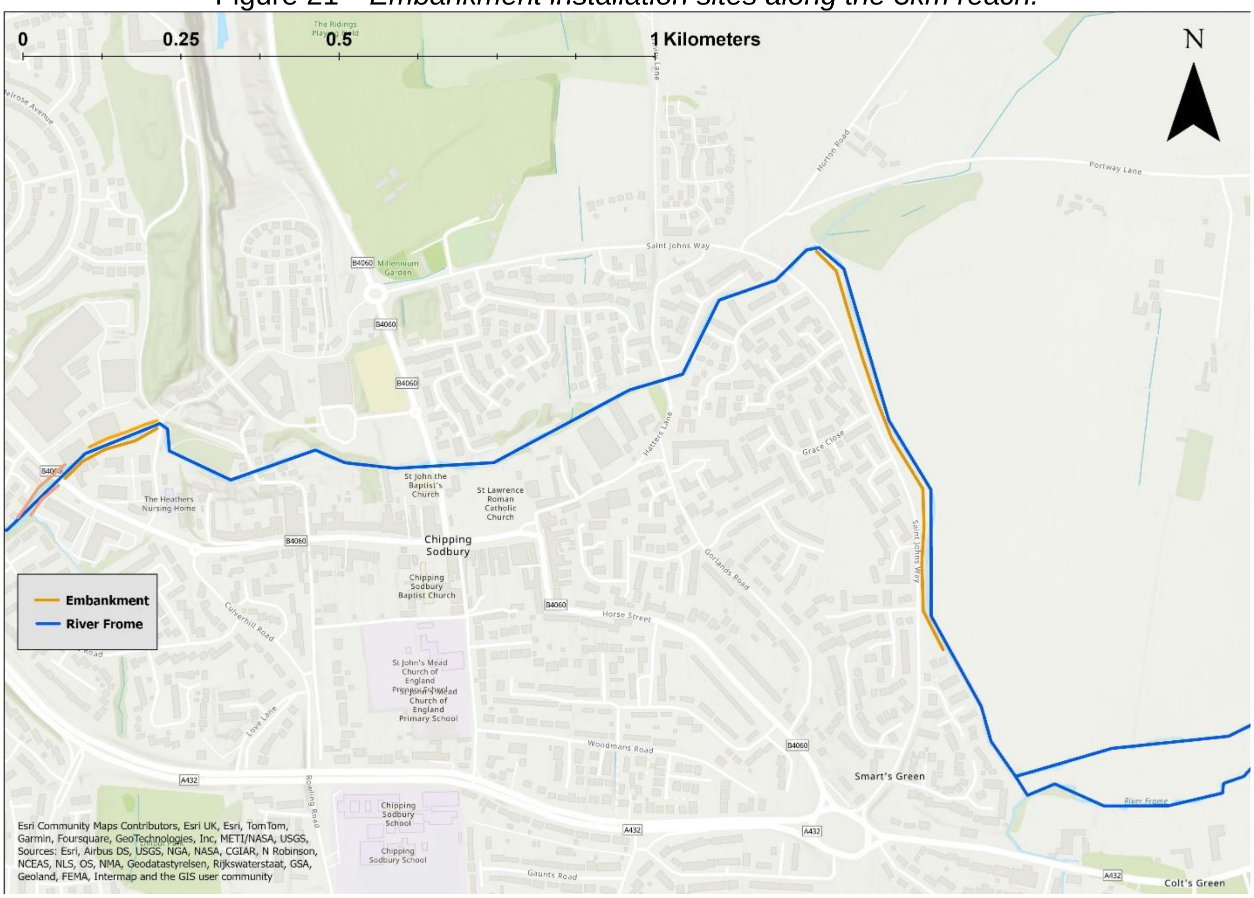
Figure 20 – *Leaky dam site locations across the Frome catchment*



6.2 - Objectives II and III

Objectives II&III are both concerned with either maintaining or increasing conveyance capacity. The purpose of this is to reduce flood hazard and therefore overall flood risk. Zones C&E suffer from significant flooding at even the Q_{20} event, so increasing conveyance capacity here is a priority. Zones B&D have sufficient conveyance and only suffer very minor flooding damage so the goal for these zones is to at least maintain this conveyance and prevent the deterioration of the channel condition. To this end, it is recommended that a serious of embankments are installed along various points of the 3km. The location of these embankments is shown in Figure 21. Embankments direct and constrain floodwater, helping to protect more vulnerable zones (Thieken *et al*., 2016). The average cost for an 18m^3, 1m embankment installation is £1,152 with a further maintenance cost of up to £5,430/km/year (Environment Agency, 2015a). It is recommended that around 1km of embankments are installed along the 3km reach, so the total installation cost would be approximately £1,152,000. However, this is justified by the annual flood risk cost of £164,900 along the affected zones. Embankments have been selected due to their relatively low maintenance costs, low environmental impact and ease of implementation (Marchand *et al.,* 2021). The Embankments placed in Zone E are to protect the industry/commercial sites located there, and to channel water further downstream towards a nearby area of urban woodland.

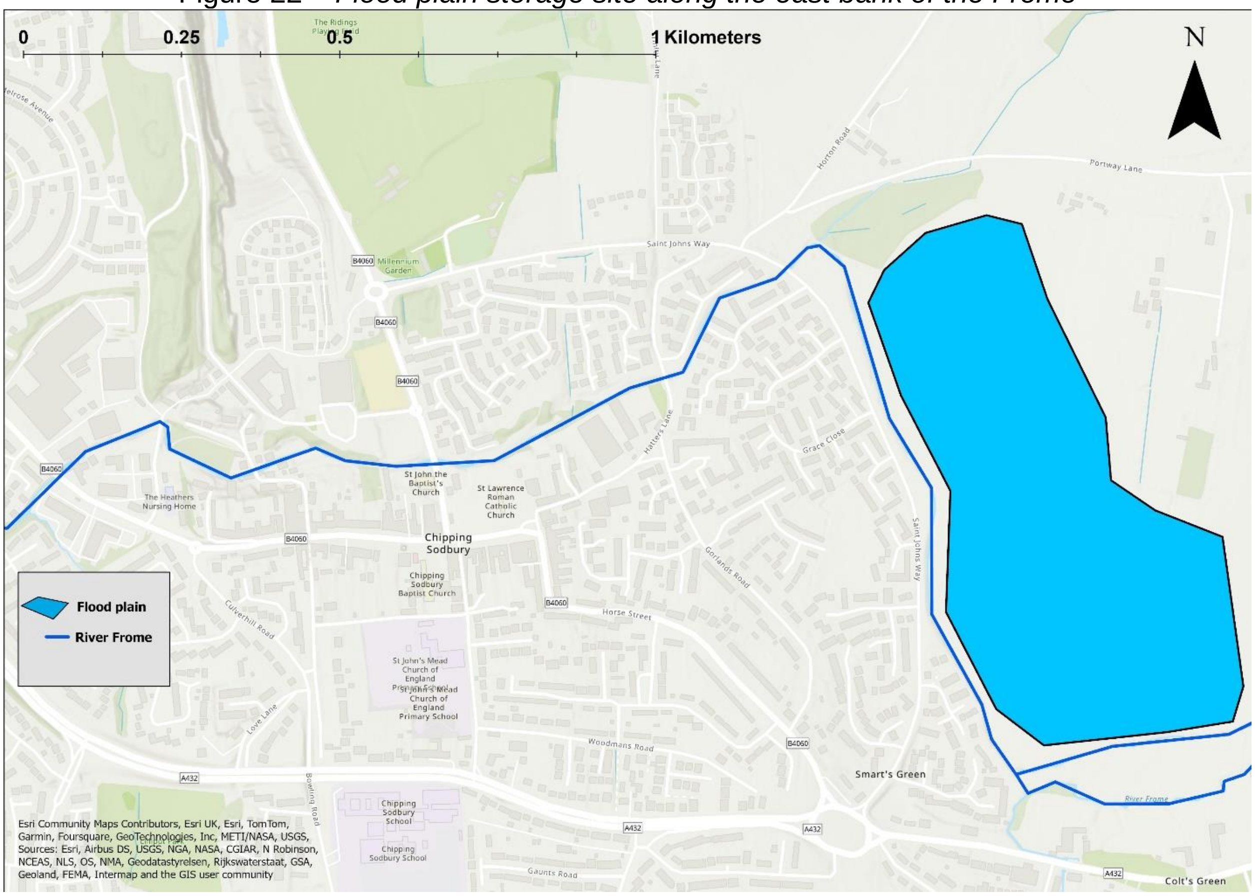
Figure 21 – *Embankment installation sites along the 3km reach.*



6.3 - Objective IV

Objective IV is to reduce damages from the Q_{20} by 50% in the two highest risk zones, C and E. Damages are determined by land use and flood hazard. It is suggested that management techniques aimed at these zones focus on flood hazard as the land use is set as urban at this point. To meet this objective, it is recommended that the large section of agricultural land to the east of Zones B&C is converted into a flood plain, this would decrease the peak flow and water velocity heading into Zones C, D and E, lowering the hazard and therefore potential damage. An outline of where the flood plain would be situated is shown below in Figure 22. The cost of flood plain storage creation varies greatly; however, it is generally between £1.5-6/m^3 (Environment Agency, 2015b). The reason flood plain storage is recommended is due to its cheap economic cost as well as utilising the less developed land on the east bank of the river being preferable to management techniques in the urban west side (Jung *et al.,* 2014).

Figure 22 – *Flood plain storage site along the east bank of the Frome*



6.4 – Management Recommendation Conclusions and Timeline

Table 4 details a proposed timeline (until 2028) for the completion of the various aspects of the management recommendations.

Table 4 – *Management recommendations timeline*

Year and month	Objective number	Action
2024 (Jul)	I	Tree site verification, survey and planning application
2024 (Jul)	I	Leaky dam site survey and planning application
2024 (Jul)	II&III	Embankment public consultation and application
2024 (Jul)	IV	Flood plain planning permission application
2024 (Aug)	I	Leaky dam construction
2024 (Sep)	IV	Flood plain creation begins
2024 (Nov)	II&III	End of embankment public consultation and beginning of construction
2025 (May)	I	Tree planting
2025 (Jul)	IV	End of flood plain creation
2025 (Sep)	II&III	End of embankment construction
2026 (May)	I	Survey of tree health
2027 (May)	I	Survey of tree health
2028 (May)	I	Survey of tree health

If the listed management recommendations are implemented and the timeline is kept, then overall flood risk within both the 3km reach and the Frome catchment will be reduced, and the goals of the management objectives will be achieved.

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Appendices

Appendix I - Adjustment values for factors that affect channel roughness (Arcement and Schnider 1989; Aldridge and Garrett, 1973)

Channel conditions		*n* value adjustment[1]	Example
Degree of irregularity (n_1)	Smooth	0.000	Compares to the smoothest channel attainable in a given bed material.
	Minor	0.001–0.005	Compares to carefully dredged channels in good condition but having slightly eroded or scoured side slopes.
	Moderate	0.006–0.010	Compares to dredged channels having moderate to considerable bed roughness and moderately sloughed or eroded side slopes.
	Severe	0.011–0.020	Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channels in rock.
Variation in channel cross section (n_2)	Gradual	0.000	Size and shape of channel cross sections change gradually.
	Alternating occasionally	0.001–0.005	Large and small cross sections alternate occasionally, or the main flow occasionally shifts from side to side owing to changes in cross-sectional shape.
	Alternating frequently	0.010–0.015	Large and small cross sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape.
Effect of obstruction (n_3)	Negligible	0.000–0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the cross-sectional area.
	Minor	0.005–0.015	Obstructions occupy less than 15 percent of the cross-sectional area, and the spacing between obstructions is such that the sphere of influence around one obstruction does not extend to the sphere of influence around another obstruction. Smaller adjustments are used for curved smooth-surfaced objects than are used for sharp-edged angular objects.
	Appreciable	0.020–0.030	Obstructions occupy from 15 to 50 percent of the cross-sectional area, or the space between obstructions is small enough to cause the effects of several obstructions to be additive, thereby blocking an equivalent part of a cross section.
	Severe	0.040–0.050	Obstructions occupy more than 50 percent of the cross-sectional area, or the space between obstructions is small enough to cause turbulence across most of the cross section.
Amount of vegetation (n_4)	Small	0.002–0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation.
	Medium	0.010–0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the average depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1- to 2-year-old willow trees in the dormant season, growing along the banks, and no significant vegetation is evident along the channel bottoms where the hydraulic radius exceeds 2 ft.
	Large	0.025–0.050	Turf grass growing where the average depth of flow is about equal to the height of the vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foliage) where the hydraulic radius exceeds 2 ft; bushy willows about 1 year old intergrown with some weeds along side slopes (all vegetation in full foliage), and no significant vegetation exists along channel bottoms where the hydraulic radius is greater than 2 ft.
	Very large	0.050–0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; bushy willow trees about 1 year old intergrown with weeds along side slopes (all vegetation in full foliage), or dense cattails growing along channel bottom; trees intergrown with weeds and brush (all vegetation in full foliage).
Degree of meandering[2] (m)	Minor	1.00	Ratio of the channel length to valley length is 1.0 to 1.2.
	Appreciable	1.15	Ratio of the channel length to valley length is 1.2 to 1.5.
	Severe	1.30	Ratio of the channel length to valley length is greater than 1.5.

[1] Adjustments for degree of irregularity, variations in cross section, effect of obstructions, and vegetation are added to the base *n* value (table 1) before multiplying by the adjustment for meander.

[2] Adjustment values apply to flow confined in the channel and do not apply where downvalley flow crosses meanders.

Appendix II – Environment Agency low and high cost estimations (Environment Agency, 2018b).

Best estimate of residential property damages (£350 million) = Low estimate (£308 million) + High estimate (£392 million)/2

Low estimate of residential property damages (£308 million) = ABI residential insurance costs – temporary accommodation costs + adjustment for underinsurance – economic adjustments

where:

- ABI value of residential property claims (£480 million) = ABI public data and personal correspondence
- adjustment for temporary accommodation costs (£443 million) = £480 million – £37 million (see Section 4.4)
- adjustment for underinsurance (£591 million) = £443 million/0.75
- adjustment for economic estimate (£308 million) = [(£591 million × 0.75 × 0.5) + (£591 million × 0.25)]/1.2
- economic adjustments = VAT 20%, inventory items75% of insured damages, remaining value 50%
- an average insurance penetration rate for domestic properties of 75% is assumed

High estimate of residential property damages (£392 million) = (DCLG estimated number of properties damaged by flooding × average economic cost property) – temporary accommodation costs

where:

- number of residential properties damaged by flooding (15,981) = DCLG reported numbers
- ABI financial cost per household (49,485) = from ABI data
- economic unit cost per residential property (£24,599) = [(ABI financial cost per household × 0.75 × 0.5) + (ABI financial cost per household × 0.25)]/1.2
- economic adjustments = VAT 20%, inventory items 75% of insured damages, remaining value 50%
- temporary accommodation costs = £37 million (see Section 4.4)

Key uncertainties

- Levels of underinsurance
- Average property claim per household (which may be skewed depending on the levels of underinsurance)
- Economic adjustments for VAT and betterment

Appendix III – *Table of costs (Environment Agency, 2018b).*

Asset	Estimated economic damage (£)
Residential Property	24,000
Business Property	99,000
Road	51,620

Appendix IV – Width and Depth