Investigating the Use of a High-Resolution 1D-2D Linked Hydrodynamic Model to Assess the Effects of River Restoration and Natural Flood Management Techniques on Flooding: A Case Study of the River Greet and Potwell Dyke, Southwell, Nottinghamshire, UK

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Abstract

A large number of residential properties within the UK are at risk of flooding from rivers and streams. In addition, increasing populations are resulting in growth within existing urban areas which are already at risk, putting a greater amount of the population at risk of flooding. Urbanisation results in greater amounts of impermeable surfaces and drainage systems resulting in increased levels of surface water runoff into watercourses and rapid rainfall-runoff response times. Additionally, the threat of climate change is resulting in greater amounts of precipitation, further exacerbating the the amount of runoff reaching local watercourses. Due to the increasing threats of urbanisation and climate change, the risk of flooding is expected to increase in both frequency and magnitude, presenting profound pressures and impacts upon urban services and infrastructure. As a result of these pressures, in recent decades there has been a move towards the use of more holistic river management techniques aimed at reducing the risk of flooding and returning river environments to a more natural state.

This study aims to test how effective a selection of river restoration and natural flood management techniques are at reducing flood risk to urbanised areas. Different techniques are used to limit flood risk in different ways, such as utilising additional floodplain attenuation to offer floodwater storage, methods that deflect floodwater away from high risk areas and methods that retain floodwater upstream to reduce flooding downstream.The study also aims to demonstrate that the techniques tested will work more effectively at reducing flood risk when combined, allowing the effects of each to compliment one another.

In order to test the effectiveness of the chosen river restoration and natural flood management techniques, a hydrodynamic model of Southwell, Nottinghamshire, was used. This study area comprises an urbanised area, the River Greet and Potwell Dyke and open space for accommodating the techniques. A linked 1D-2D hydrodynamic model of the River Greet and

Potwell Dyke and their surrounding floodplains has been built in order to assess baseline flood conditions for a range of events. The baseline model was then used in order to test a range of river restoration techniques individually to make an assessment of how effective they would be at reducing flood risk to an urban area. Due to some natural flood management techniques, such as individual pieces of woody debris, being relatively small a high-resolution 2D model grid cell size of $1m^2$ was utilised. In addition to more detailed definition when modelling restoration and natural flood management objects, the high-resolution grid drastically increases the level of detail for the results of a model, adding the benefit of reduced uncertainty which is common with natural, holistic flood management techniques.

The results of the study have found that the river restoration and natural flood management techniques tested individually were generally effective, particularly during low-order flood events. Woody debris showed some benefits in low-order events but the benefits were shown to increase exponentially with the magnitude of the flood event. Despite this, woody debris resulted in increased flooding issues elsewhere which were exacerbated as the magnitude of the flood event increased. Wetland ponds were able to offer reductions in peak flood depth downstream by offering storage for flood volumes throughout all events, with flooding prevented in places during low-order events. During larger flood events, the wetland ponds had generally less of a positive effect due to being fully inundated. Re-meandering the river channel and lowering the banks were shown to allow flooding into low-risk floodplain and deliver benefits to the opposite side of the channel throughout all events, though the deliberate increases in flooding were shown to outweigh the benefits during high-order events. Finally, by combining the tested techniques, the benefits of reduced flood risk were shown to improve, with the negative impacts of woody debris and re-meandering shown to be mitigated by the presence of wetland ponds.

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1 Introduction

1.1 Background

1.1.1 Flooding & Urbanisation

Urban flooding has been an increasing concern, with the effects of flooding on urban areas having significant impacts which can cause disruption to normal services, damage to infrastructure and danger to populations (Zhou et al., 2019). While there are numerous factors that contribute to the effects of increased flood risk, urbanisation and climate change are two of the most problematic (Arnone et al., 2018; Ceola et al., 2014; IPCC, 2013; Jongman et al., 2012; Kaspersen et al., 2017; Mahmood et al., 2017; Wu et al., 2017). As urban development continues to increase, waterbodies such as rivers and streams are placed under increasing pressure, with modifications that prevent their natural processes from taking place and increased impermeable areas with dramatically increase the rate of rainfall runoff (Rubinato et al., 2019). In the UK, over 80% of the population live within urbanised areas, with the rate of population set to continue increasing by 15% by 2039 (ONS, 2014). In 2013, approximately 2.7 million properties in England alone were shown to be in areas at risk of flooding (DEFRA, 2013), with this number having doubled by 2017 (Boyd, 2017). As such, there is increasing concern that the risk of flooding will continue to grow within urbanised areas (Huong and Pathirana, 2013; Jiang et al., 2018; Mahmood et al., 2017; Rosbjerg, 2017; Zhou et al., 2018).

Traditional building techniques have paid little to no concern for nearby watercourses or the effects that increased impermeable surfaces will have on the rainfall-runoff relationship and, ultimately, how this will impact the risk of flooding (Berndtsson et al., 2019). However, the issue is well-documented, with studies that have shown urbanisation can result in increased flood frequency and magnitude (Fletcher et al., 2013; Jacobson, 2011; Walsh et al., 2005). As urban centres have continued to grow due to demand, rivers and streams have been constrained, while drainage systems have been designed to remove water and discharge it to these watercourses as quickly and efficiently as possible (Egger and Maurer, 2015; Hlodversdottir et al., 2015; Kleidorfer et al., 2014; Wheater and Evans, 2009). As a result, greater volumes of surface water runoff are conveyed to these constrained watercourses within a shorter timeframe, leading to potential dramatic increases in flood peaks (Wheater and Evans, 2009). Within catchments where the natural rate of runoff is quite low due to naturally pervious soils, particularly during summer months where soils are less saturated, the effects of increased impermeable surfaces due to urbanisation will be much greater, potentially leading to more frequent flooding during intense, short summer rainfall events (Institute of Hydrology, 1999; Wheater and Evans, 2009).

In recent years, some urbanised areas have been developed with the intention of being more sustainable, utilising approaches that reduce the effects of increased rates of rainfall-runoff (Dawson et al., 2011), blue-green stormwater approaches being employed to reduce runoff volumes and nature-based flood mitigation being identified as efficient and sustainable measures at limiting flood risk within urban areas (Hammond et al., 2015; Haaland and van den Bosch, 2015; IUCN, 2009).

1.1.2 Flooding & Climate Change

There is an increasing acceptance that the global climate is changing due to anthropogenic emissions of greenhouse gasses (IPCC, 2014). In addition to this, there is increasing concern about how climate change will impact both our natural and built environments in the future (Kay et al., 2011). In the UK, this has resulted in the passing of the Climate Change Act 2008 and the publication of risk assessments, including the UK Climate Change Risk Assessment 2017 (DEFRA, 2017), outline the risks and requirements for the UK in relation to the current and future direct impacts of climate change. In terms of flood risk, data collection of river stage and flows using river gauges is relatively sufficient in the UK, though the data collected by these gauges, particularly observed changes in peak stage and flow, cannot be directly attributed to the impacts of climate change (Hannaford, 2015). This is because no single weather event can be attributed directly to climate change and only patterns and trends observed across multiple events can be attributed when compared to changes in global temperature (Allen, 2003; Stone and Allen, 2005). Due to natural variability in peak stage and flow, changes in the magnitude and frequency of floods as a result of anthropogenic activities directly associated to climate change results in a high degree of uncertainty (IPCC, 2014). However, climate change projections indicate that the UK will experience wetter and warmer winters with drier, hotter summers and greater variability in the future (Murphy et al., 2010). Therefore, the predicted future increase in rainfall during winter months as a result of climate change is expected to have a direct impact upon rainfall-runoff patterns and flood magnitude and frequency (Charlton and Arnell, 2014; Christierson et al., 2012; Miller and Hutchings, 2017).

Due to increased development density and greater amounts of impermeable areas, urbanised regions are understood to be more sensitive to changes in precipitation patterns as a result of climate change than in rural regions where rainfall runoff is greatly reduced (Scholz, 2013) However, future alterations in fluvial flooding within urban environments due to increased runoff will fundamentally be the result of interactions between both climate change and urbanisation as it very difficult to attribute any changes in fluvial characteristics to one of these impacts alone (Wheater and Evans, 2009). Due to the risks associated with climate change, combined with the expected increases in urbanisation as our towns and cities develop further, there is a demand for urban areas to become more resilient to extreme weather events by reducing their reliance upon traditional hard or “grey” infrastructure and to adopt more natural and sustainable blue-green infrastructure (Voskamp and van de Ven, 2015).

1.1.3 River Restoration & Natural Flood Management

In urbanised areas, watercourses such as rivers and streams have been subjected to hard engineering practices designed to prevent them from acting in their natural way and to allow for human exploitation. This has included activities such as channelisation and straightening, flow regulation, dredging, building hard and/or raised embankments and culverting in order to allow for construction of buildings and infrastructure within the floodplain and often immediately bordering the edge of watercourses (Brookes, 1988; Dodgshon and Butlin, 1990; Lange et al., 2015; Soar and Thorne, 2001). In addition, these watercourses have ended up being used as the receptors for pollutants and, as a result, these watercourses have lost their natural biodiversity and ecological states as well as having lost their ability to function in their natural configuration (Fletcher et al., 2013; Meyer et al., 2005, Soar and Thorne, 2001; Walsh et al., 2005).

Over the past few decades, attitudes towards environmental management and, in particular, river management have begun to shift in recognition of the need to incorporate and utilise natural characteristics rather than removing them entirely (Soar and Thorne, 2001). In addition, in recent years within the UK there has been a transition away from traditional flood defences that utilise hard engineering techniques towards a more sustainable and holistic management framework comprising the utilisation natural techniques (DEFRA, 2012; Miller and Hutchings, 2017). In England and Wales, changes in legislation have helped to encourage the shift in practices away from hard engineering and towards more natural techniques such as river restoration and natural flood management (Brookes and Gregory, 1988; Heaton, 1993; Holmes, 1993; Soar and Thorne, 2001; Ward et al, 1994), and throughout the EU the Water Framework Directive has directly legislated the aim of restoring all waterbodies to a good ecological state where possible (Berndardt and Hardt, 2006; Miller and Hutchings, 2017).

Despite the change in attitudes towards more natural methods for river and flood management, with numerous schemes having been completed in the UK, Europe and globally, judging whether a whole project utilising restoration and/or natural flood management or, indeed, individual components of such a scheme is effective is often treated subjectively. It has been argued that a restoration scheme can be considered successful provided that it has some form of recognition for achieving any of its intended objectives, from improvements to drainage and flood risk to public perception (Bannister et al., 2005). However, due to the risk involved in planning such a scheme that will only be judged after the fact, there remains a need for objective, numerical assessment which could ideally be completed during the planning stage.

1.1.4 Flood Modelling

In order to have a better understanding of water resources and wider water environments, forecasting tools and, in particular, computational hydrodynamic models have been developed as tools to be used during planning and assessment (Gourley et al., 2012; Braud et al., 2014). This has particularly been the case for predicting flood risk and flood hazard as hydrodynamic models can be applied to simulate characteristics such as flow, stage and velocity of a river to varying levels of detail and used to assess the amount and extent of flooding to a particular study area (Nguyen et al., 2016; Strayer and Dudgeon, 2010). This ultimately allows practitioners to form the basis to various schemes such as planning safe development within the floodplain and river restoration/rehabilitation projects (Wheaton et al., 2004; Pasternack et al., 2006; Brown and Pasternack, 2009; Gard, 2014).

As with the projects they are designed to predict and assess, hydrodynamic models involve levels of uncertainty relating to input data, calculations carried out during simulations and the resulting outputs. With many hydrodynamic models utilising a 2D cellular grid to represent the floodplain, the resolution of the model becomes a critical constraint as the grid size must be set to capture enough detail while maintaining reasonable simulation times (Nguyen et al., 2016). The resolution of such models is scalable and the cellar grid can be reduced in order to increase the level of detail simulated and output into the results or increased to reduced computational demand and time taken to simulate (Hardy et al., 1999; Crowder and Diplas, 2000; Legleiter et al., 2011; Conner and Tonina, 2014).

Due to the advancements made in remote sensing, particularly with LiDAR, which can accurately capture details below 1m in resolution, the level of detail input into a hydrodynamic is much greater and, therefore, the user is able to greatly increase the resolution of their model and greatly reduce the level of uncertainty (Fewtrell et al., 2008; Liu et al., 2015; Gallegos et al., 2009; Marks and Bates, 2000; Mason et al., 2007, 2014; Neal et al., 2009a; Ozdemir et al., 2013; Schubert et al., 2008). This presents one of the greatest advantages of 2D hydrodynamic models, as they can simulate flow routes through the floodplain based on details within the topography (Nguyen et al., 2016), with greater detail resulting in greater accuracy for individual flow routes. Modelling at a high-resolution does involve some disadvantages, largely due to be consuming significant amounts of time and expertise to build and the computational resources and time taken to run a simulation (Coulthard et al., 2007; Neal et al., 2010). In recent years, however, this issue has become less of a concern due to advancements in parallel computing methods including multi-core central processing units and graphics processing units which can greatly reduce simulation times by carrying out calculations simultaneously across multiple processing units (Noh et al., 2018). As a result, high-resolution modelling of watercourses becomes more practical and effective with regards to time and cost.

1.2 Aims & Objectives

The aim of this study is to demonstrate the effectiveness of river restoration and natural flood management techniques at reducing flood risk to an urbanised environment through the use of a computational hydrodynamic model of a river or stream. Therefore, the objectives of this study is to answer the following hypotheses:

a) River restoration and natural flood management techniques will be shown to be effective at reducing flood risk to an urbanised area.
b) By combining river restoration and natural flood management techniques together, the methods tested will be shown to be more effective at reducing flood risk to an urbanised area than when tested individually.

With the majority of 2D models comprising a grid cell resolution of 4m and above, and with many restoration and NFM techniques comprising features smaller than 4m, a high-resolution model representing the floodplain is will be utilised. It is also anticipated that the use of a high-resolution grid will increase the accuracy of results and reduce the uncertainty related to river restoration and natural flood management.

1.2.1 Flood Modeller

The subject watercourses will be modelled using Flood Modeller, which allows the user to represent the channel geomorphology using a series of sequential cross-sections running from the left bank to the right bank. Input hydrology is defined at the upstream of the model, with calculations for flow, stage and velocity carried out at each cross-section for each tilmestep of the simulation. Cross-sections are evenly spaced along the study reach, with interpolation used to solve equations between each.

As the focus will be to assess details of flooding outside of the channel, this relatively simplistic yet versatile method of modelling provides enough detail within the channel without making the model too complex and maintaining quick simulations and reliable results. While a free version of Flood Modeller is available, this is only suitable for smaller, less detailed watercourse models. Due to the size of the model being built for this study, the commercially available Flood Modeller Pro version is to be used.

1.2.2 TUFLOW

While the watercourses are to be modelled in 1D, greater detail utilising LiDAR data is required for the floodplain. Therefore, the floodplain will be modelled laterally in 2D using TUFLOW. TUFLOW is a script and command line based package which defines features using a mixture of LiDAR data and GIS layers to represent topographical features. A series of text files are used to link individual GIS layers together and to select specific simulation criteria. The 2D model is then linked to the 1D model within Flood Modeller and simulations run in tandem, with information relating to the transfer of flows between the channel and floodplain passed between Flood Modeller and TUFLOW as then run. Ahead of the simulation starting, TUFLOW generates a mesh of cells in a grid at the desired resolution, with calculations for flow, velocity, height and depth taking place for every tilmestep at each cell and with information transferred from one cell to the next as water flows through the floodplain.

In the case of this study, the cell resolution within TUFLOW will be set to 1m so that each cel represents a $1m^2$ area. As a result, the number of grid cells in the mesh that will be generated will be substantial and would take a significantly long period of time to simulate. In order to overcome this issue, the HPC add-on module will be used. In the past, TUFLOW was restricted to running on a single core of a CPU. In recent years, TUFLOW has developed so that simulations can be run on multiple CPU cores or by utilising a large number of small cores commonly found on graphics processing units if using the HPC add-on. By running simulations using HPC the time taken to complete a full simulation is reduced significantly.

1.3 Study Area

The town of Southwell, Nottinghamshire and the surrounding locality , shown below is Figure 1.1, was chosen as the study area as it is well-suited as an example of an urbanised area surrounded by open spaces that can accommodate river restoration and natural flood management alleviation methods. The town is located predominantly off the right bank of the River Greet, a tributary of the River Trent which, from Southwell to its confluence with the River Trent, is designated as an EA Main River. Potwell Dyke, which is designated as an Ordinary Watercourse, is a tightly constrained tributary of the River Greet which runs through parts of Southwell to the south.

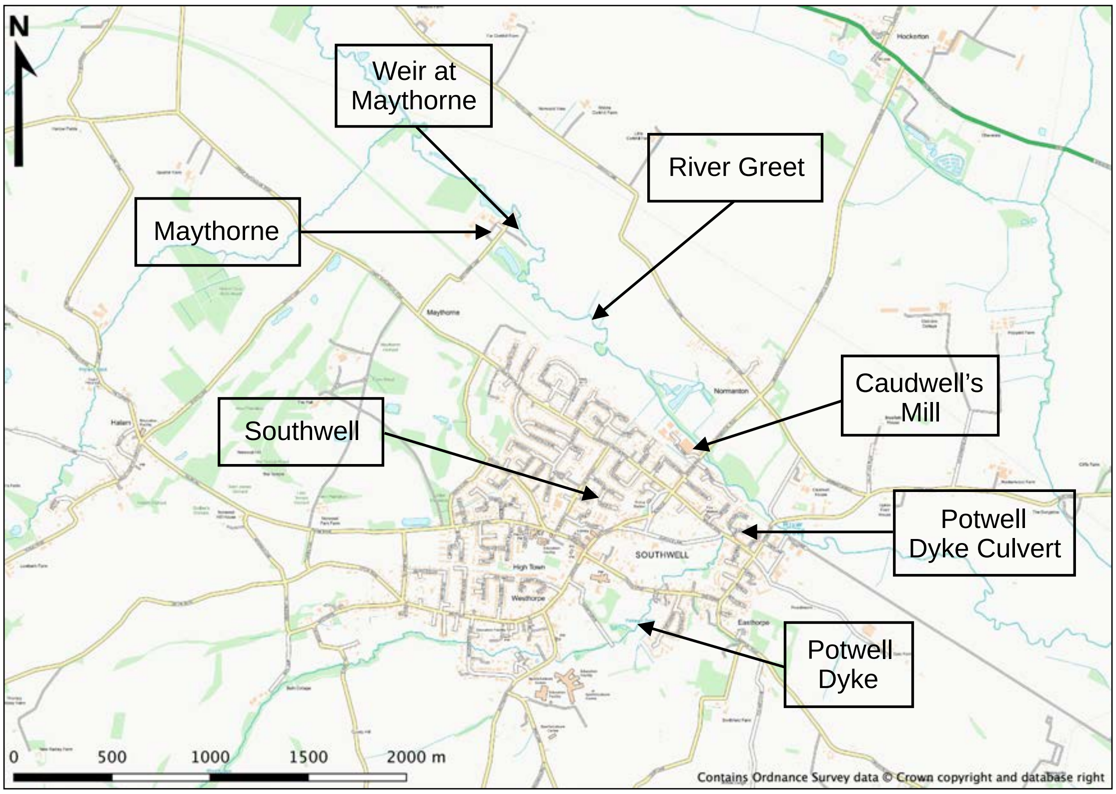


Figure 1.1: Study Location

In addition to its proximity to the River Greet and Potwell Dyke, Southwell is well suited as the study area due to being a reasonably sized urbanised location which results in the local watercourses being over-stressed with excessive runoff. Flooding within Southwell throughout the town's history has been prolific and has been well documented (Southwell Flood Forum, n.d.). The town is also surrounded by rural landscapes, allowing plenty of space to potentially accommodate river restoration and natural flood management schemes, particularly in the case of this study where land usage and ownership will not be considered when locating flood management techniques. For these reasons, Southwell is an ideal study location for testing the feasibility of river restoration and natural flood management techniques.

2 Literature Review

2.1 Anthropogenic Influences of Flooding

Human interaction with rivers and their catchments has had an increasing influence throughout history both directly and indirectly. In particular, direct modifications of river channels in the form of engineering works designed to curb the effects of flooding, erosion and deposition and indirect human activities within floodplains have had, and continue to have, a profound effect upon the characteristics of rivers, altering the stream response by impacting upon discharge of and/or sediment load (Knighton, 1998). A study analysing the methods for assessing flood risk in urban areas, completed by Hammond et al (2015), identifies that the effects of flooding can result in major disruptions within urbanised areas, leading to significant dangers and impacts to people, the economy and the environment, which can be intensified by the effects of climate change and socio-economic activities. However, the study does not account for future changes in land-use and socio-economic activities which may or may not adequately adjust to the effects of climate change. Miller and Hutchins (2017) identifies the need to assess and understand the combined impacts of urbanisation as a land-use, both present and future, and the distribution of population due to socio-economic activity upon flood risk in addition to the impacts of climate change. Throughout the Anthropocene, human activities have had a profound effect on the land on which we live. In particular, land use and the changing ways in which humans have managed the land have significantly affected the hydrology that determines flood hazard, water resources (for human and environmental needs) and the transport and dilution of pollutants (Wheater and Evans, 2009).

2.1.1 Climate Change Impacts on Flooding

In the United Kingdom there is a negative legacy of urbanisation and water management which has only begun to improve following improved technology, management techniques and a change in environmental management following changes in legislation towards the end of the 20th Century (Miller and Hutchings, 2017). The uncertainty regarding climate change has begun to have a defining influence on the way in which we manage water environments, controlling factors such as temperature, water quality and water flows (Acreman and Ferguson, 2010; Arnell et al., 2015).

Urban flooding has the potential to carry great socio-economic impacts, resulting in disruption to urban infrastructure and services, such as transportation, communication and utilities (Hlodversdottir et al., 2015; Karamouz et al., 2011; Wu et al., 2017; Yin et al., 2016). Flooding within urbanised areas has become one of the most significant environmental challenges within the UK, particularly due to the impacts it has upon human safety and economic growth, with general estimated annual damages from flooding of £1 billion (Hall et al., 2005) and costs of over £5 billion during recent major flooding events, such as during the winter of 2015-2016 (Miller and Hutchins, 2017). There is further concern that the risk of flooding is expected to increase throughout many regions of the world, with particular emphasis upon large urbanised areas where large populations are at risk (Huong and Pathirana, 2013; Jiang et al., 2018; Mahmood et al., 2017; Rosbjerg, 2017; Zhou et al., 2018).

Rainfall is a key driver for the current magnitude of flooding, and while future levels of precipitation as a direct result of climate change is undetermined, an increase in the frequency and magnitude of rainfall events is expected to occur. Alterations to the timing, duration and magnitude of rainfall events as a resulting effect of climate change are also expected to greatly impact upon the flooding experience within urban environments, raising concerns about how the resulting floods from various sources such as fluvial, pluvial and groundwater flooding will be managed. The effects of any increases in flooding are likely to have significant influence on infrastructure, the economy and the livelihoods of people (Ashley et al., 2005; Miller and Hutchins, 2017; Wheater and Evans, 2009).

There are a number of studies which have reviewed the impacts of climate change and water within urbanised environments at a global scale (eg.

Praskievicz and Chang, 2009; Hunt and Watkiss, 2011; Kundzewicz et al., 2013) which focus upon the challenges presented by increased urban development together with the threat of climate change. In addition, studies which have focused upon the direct impacts of climate change upon general water environments in the UK (eg. Watts et al., 2015; Arnell et al., 2015; Whitehead et al., 2013; Wilby et al., 2008; UK Met Office, 2011). However, these studies generally assess the impacts of climate change upon water environments without taking into account the effects of changing attitudes and policy changes regarding climate change. A study completed by Miller and Hutchins (2017) aims to analyse the combined impacts of urbanisation and climate change upon urban water environments within the UK while accounting for the underlying policy changes and responses to these issues.

In the United Kingdom 5.7% of the country's total land area is urbanised, putting in a group of just ten countries with over 5% urbanisation (Angel et al., 2011). Over 80% of the population in the UK, which has more than doubled over the last century and is set to increase by 15% by 2039, live within urbanised areas (ONS, 2014). As a result, in addition to the expected growth to existing urbanised areas, the UK government has, in recent years, been planning a number of garden towns and villages to cope with demand (Miller and Hutchins, 2017).

In the UK, The Department for Environment, Food and Rural Affairs (DEFRA) is the branch of government with the responsibility of administering flood management based policy, while the Environment Agency (EA), Natural Resources Wales (NRW) and the Scottish Environment Protection Agency (SEPA) are the authorities responsible for implementing such policies handed down from DEFRA (Miller and Hutchins, 2017). However, the subject of governance for water-based environments and the issue of managing flood risk is far more complex, with many more stakeholders such as private water companies, local authorities, internal drainage boards and land owners maintaining separate responsibilities for the likes of sewer systems, stormwater drainage systems, minor natural watercourses and manmade surface water drainage networks (Bubeck et al., 2013). Flood management is based on a risk analysis assessment where flooding is predicted on the basis of annual exceedance probability (AEP) and the consequences that such events occurring can have in terms of magnitude or extent and the hazards to human life and property, with the responsibility of managing the risks and consequences falling to some, or a combination of, the above stakeholders (Miller and Hutchins, 2017). Research carried out by the Environment Agency (2009), though already outdated, indicated that an estimated 2.4 million residential properties are at risk of flooding from either rivers or the sea in England and Wales.

In the UK, projections of climate change are provided as a result of the UKCP09, which is the Regional Climate Model built and run for a range of scenarios by the UK’s Met Office Hadley Centre. The projected scenarios completed under UKC09 indicate that climate change will bring about increasingly wetter and warmer winters and hotter, drier summers in general during the 21st Century with a degree of variability across different emissions scenarios (Murphy et al., 2010). As a relatively small island nation, the variability between seasons and across different emissions scenarios in the UK is not shown under global climate models, displaying an importance for climate change to be considered and assessed at more refined higher resolution regional climate models, particularly where hydrological processes within small catchments and urbanised areas are to be considered (IPCC, 2014; Miller and Hutchins, 2017).

2.1.2 Urbanisation Impacts on Flooding

Fluvial flooding is a natural process which is an essential part of a healthy river ecosystem and fully functional floodplain (Acreman et al., 2003). Studies have also been conducted on the positive effects that fluvial flooding can have, such as the forming of channels and floodplains and maintaining the equilibrium of the river environment (Knighton, 1998). However, studies have also shown that the magnitude and frequency of flooding can be increased due to urbanisation (Fletcher et al., 2013; Jacobson, 2011; Walsh et al., 2005), altering the natural equilibrium of river environments (Miller and Hutchins, 2017).

There is a prevailing change towards employing more natural and holistic flood management measures within the UK and other parts of the world as opposed to more traditional options, such as flood walls and raised embankments (DEFRA, 2012). Despite this change, the majority of flood risk in the UK is still mitigated through traditional defences, with £930 million spent on flood defences and an additional £180 million spent on maintenance of existing defences within England during 2014 (EA, 2014; Miller and Hutchins, 2017). While flood events since 2014, such as the winter 2015-2016 events, have raised the awareness of a need for more natural flood mitigation measures, traditional defences still play an important role in the mitigation of major flood events (Priestly, 2016).

Drainage systems are an essential part of infrastructure within urbanised areas as they are designed to convey excess and unwanted water away from urban areas in an attempt to limit flooding which may impact infrastructure, services and populations (Egger and Maurer, 2015; Hlodversdottir et al., 2015; Kleidorfer et al., 2014). It is commonly accepted that urbanisation results in the increased magnitude and frequency of flooding, with studies (eg. Hall, 1977; Hollis, 1975; Hollis, 1988; Hollis and Ovenden, 1988) in the UK completed relatively early on in the science of studying the impacts of flooding (Miller and Hutchins, 2017). However, there is also evidence that studies based upon the impacts of urbanisation on fluvial flooding within the UK are perhaps not as vigorous when compared to studies carried out in other regions internationally (eg. Braud et al., 2013; Burns et al., 2005; Sheeder et al., 2003; Sheng and Wilson, 2009). The data that results from these studies is important as it forms the starting point for the hydrological models which have quickly become the default method for analysing the impacts of urbanisation on surface water runoff and flooding (Praskievicz and Chang, 2009; Salvadore et al., 2015). Resulting studies using this data to assess the effects of urbanisation has provided evidence which suggests that, at the sub-catchment scale, the response times of flood events were reduced and the magnitude increased in the shift from rural to peri-urban environments, indicating that urbanisation results in larger floods that occur more quickly (Miller et al., 2014). A study conducted by Prosdocimi et el. (2015) also provides evidence that non-stationery statistical analysis of peak flow data from paired urban and rural catchments shows that urbanisation has an impact on the frequency and magnitude of extreme flood events. In addition, a regional analysis of the River Thames basin provides evidence that urbanisation throughout the 20th Century and early 21st Century has had an impact on the response time between rainfall and surface water runoff, showing an increase in the rainfall-runoff relationship and increased summer flows in the catchment (Crooks and Kay, 2015). However, Wheater (2006) has provided evidence that the relationship between an increase in flooding and increasing urbanisation becomes more complicated with scale, with the effects shown to be more obvious at the sub-catchment scale and less obvious when analysing larger catchments due to mitigation measures occurring at the sub-catchment scale.

While there is a significant number of river gauges throughout the UK, complete with a good history of recorded data, it is difficult to directly assign any observed changes in peak flows to climate change due to limited records relevant to the scale of time associated to climate change and the natural variability across river catchments which affect trends in the data (Hannaford, 2015). However, a study which assessed the late 2000 flood event has been conducted manages to attribute the impacts of climate change and highlights the likelihood that climate change has led to the increased probability of flooding (Kay et al., 2011). While it is accepted that climate change, caused by anthropogenic emissions of greenhouse gasses, has affected the frequency of flooding and the magnitude of individual flood events, the lack of long-term records has resulted in relatively low confidence in this conclusion (IPCC, 2014).

The Flood and Water Management Act (2010) sets out the legislative requirement to carry out detailed regionally and locally scaled analysis of flood risk and its impacts in the form of Strategic Flood Risk Assessments. However, there remains a lack of a nationally scaled assessment of the risk of flooding and the impacts that it may have to the UK as a whole. While research into the effects of flooding and the impacts that urbanisation has on flooding at a national scale in the UK is generally absent, the impacts of climate change directly upon river flows are more thoroughly studied and, as a result, are reflected more substantially in official guidance (Miller and Hutchins, 2017).

A national allowance for climate change of 20% for river flows was derived through modelling work based upon the River Thames and River Severn catchments (Reynard et al., 1999). This 20% allowance has been seen to be well implemented across all river and floodplain modelling used to assess the risk of flooding to development but has since been replaced in 2016 by climate change allowances which vary between regions and climate change epochs, presenting practical challenges to the way in which local planners interpret such figures without carrying out detailed modelling (Reynard et al., 2017).

However, while there is still a degree of uncertainty regarding the level of climate change increase, the regionally varying allowances of climate change for river flows better represent the varying characteristics of different catchments within the UK and the disparity in the way in which they will respond to the same climate change scenario (Arnell et al., 2015). When looking at the evidence related to UK urban drainage systems, research using the UKCP09 projections indicate that small increases in flows during winter could be expected in the future as a result of climate change and increased precipitation during the winter months (Charlton and Arnell, 2014; Christierson et al., 2012).

Using the high resolution 1.5km RCM, developed by Kendon et al. (2014), more in-depth analysis can be carried out, such as showing the projected changes to seasonal peak flows in the future using the CLASSIC-GB hydrological model (Kay et al., 2015). Kay et al. (2015) have shown, through the use of the CLASSIC-GB model, the seasonal differences in percentage change for annual and seasonal peak flows between the UKCP09 12km RCM and the 1.5km RCM across a range of return periods, with the smallest percentage difference observed for peak summer flows, and the least percentage difference occurring during high return periods in the summer.

This observation contrasts the findings of Kendon et al. (2014), where it has been observed that the largest difference in percentage change for annual and seasonal peak flows is predicted to occur during the summer months, though with a greater percentage difference across the lower return periods. The likely cause for these opposing observations is due to the minimum catchment scale in the UK of 50km2, which is larger than many urban catchments where the effects of changes in frequent, shorter duration rainfall events are likely to have greater impacts (Kay et al., 2015). This provides emphasis that, despite more refined precipitation projections in the UK, there is further demand for high-resolution modelling which can encompass the smaller scale urban catchments of less than 50km2 within the country (Miller and Hutchins, 2017).

The interactions between the drivers of climate change and urbanisation and how our management of the environment and control measures for fluvial flooding will ultimately define the future changes that we experience in urban fluvial flooding and the extent of the impacts that it has (Wheater and Evans, 2009). Due to a dependency upon economics and a requirement for cost-benefit analyses ahead of the implementation of flood management and defence mechanisms, investigating the relative and cumulative impacts upon flooding can be complex, particularly given that national flood risk analyses show predictions that economic risks in the future will increase due to climate change and changes in socio-economic behaviour and activity (Hall, 2003;

Evans et al., 2004; Sayers et al., 2015). However, Miller and Hutchins (2017) states that there remains a lack of hydrological research which focuses on the combined impacts of climate change and urbanisation on a national scale, from which a national understanding of flooding within urban areas in the UK can be formulated.

2.2 River Restoration & Natural Flood Management

With climatic characteristics, such as temperature and precipitation, together with declining vegetation cover, as key defining factors of the flow regime of rivers and streams, the current concerns with climate change and global warming can be regarded as one basis for the regeneration of fluvial environments to their natural state (Knighton, 1998).

The EU Water Framework Directive (WFD) governs the maintenance of the water quality within watercourses in the UK and wider EU, defining targets in terms of ecological status for governing bodies in individual states of the EU to achieve (Miller and Hutchins, 2017). In the UK, approximately 75% of watercourses were identified to be failing to meet good ecological status under the implementation of the WFD, highlighting a need to improve the situation (Priestly, 2015). Influences and effects resulting from urbanisation, such as the output of effluent from wastewater treatment processes, are likely dominant in controlling the ecological status of watercourses, particularly in smaller receiving brooks and streams (McGrane et al., 2016). As such, the control of the hazardous content within wastewater effluent has prompted improvements to be made to the wastewater treatment processes and the infrastructure used for such processes (Miller and Hutchins, 2017).

In recent years there has been a rise in the momentum that sustainable catchment management carries which has, to some extent, been driven by the requirements of the EU WFD, resulting in steps to improve, protect and enhance watercourses and their wider environments (Chave, 2001). Despite this surge of activity which includes the restoration of rivers, the definition of such activity is still disputed. For example, Stockwell (2000) defines river restoration as the process of restoring a degraded stream as involving return to that stream's previously undisturbed condition by reinstating the structure and function of the ecosystem pre-disturbance. However, applying this definition at the catchment scale rather than at the reach scale insinuates that, for a river to be successfully restored, the whole river and its catchment must be returned to its pre-disturbed state, which is something that is wholly impractical for most river catchments due to both historic and ongoing anthropogenic influences (Bannister et al., 2005). Alternatively, Brookes (1999) argues that the restoration of rivers is an encompassing term referring to river management activities that include the enhancement, restoration or rehabilitation of a riverine environment, which is ultimately a more practical definition.

To the river management professional the aim should be to achieve a fluvial environment that is more natural and sustainable while taking into account the previous and current human activity which has resulted in the need for restoration (Bannister et al., 2005). However, due to the current status of the majority of rivers in the UK it is rarely practicable to restore rivers fully. Despite this, projects have been completed which have enhanced river environments in places in the UK, restoring certain aspects of their pre-disturbed state (e.g. Harper et al., 1998; Gore et al., 1998; Lehane et al., 2002; Hendry et al., 2003; Pretty et al., 2003). River restoration schemes such as these can generally be assessed as successful but often in a purely subjective manner. However, restoration schemes could be judged as being successful provided that they display recognition for improving secondary issues such as drainage, public perception, agricultural practices and flooding while still improving the primary objective of improved ecological status (Bannister et al., 2005). The key issue with this approach is that judgement can only be made after the scheme is in-place, following significant time and cost planning and implementing a scheme without guarantee of the end result.

River restoration has become a suitable management solution for rivers, streams and their environments which have become degraded in terms of their natural hydraulic, ecological and geomorphological states but still retain the potential to be returned to a state that resembles their natural conditions (Sersawy and El Barbary, 2016). Comprehending the morphological adjustments and changes in alluvial channels requires detailed consideration of the interactions of the full range of variables involved in fluvial processes (Richards, 1982). These variables reflect the extensive controls which supply the input discharge and sediment loads into a river or stream and the internal interactions between processes such as flow velocity, sediment entrainment and flow stage and the ever evolving morphology within the fluvial system as a result (Schumm, 1973).

2.3 Flood Modelling

The ever increasing human demand for freshwater as a resource and the manipulation of river channels and their floodplain environments for human gain are exacerbating the pressures faced by environmental practitioners as they aim to preserve riverine environments (Strayer and Dudgeon, 2010). On a global scale freshwater is in very high demand, with approximately 80% of the human population experiencing a lack of water security (Vörösmarty et al., 2010), with attempts to address this water scarcity by undertaking drastic modifications to water environments which affect natural flow regimes (Bunn and Arthington, 2002). Significant efforts have been made towards better understanding of water environments, including flooding and the processes involved, including the development of computational hydrodynamic models and forecasting tools (Gourley et al., 2012; Braud et al., 2014). Hydrodynamic models for the prediction of flooding have been designed for various applications with varying levels of complexity and detail (Nguyen et al., 2016), and has transpired as one of the most suitable tools in informing the management and mitigation of human activities which have put stress upon river environments, enabling insight to environmental practitioners that enables the preservation and restoration of these environments (Strayer and Dudgeon, 2010).

Hydrodynamic models have become a useful tool because of their capability for simulating hydraulic variables such as velocity, depth, flow and bed shear stress across a variety of discharges, supporting investigation of the impacts that flow regimes can have on environmental factors (Strayer and Dudgeon, 2010), forming the basis to schemes and projects involving restoration and rehabilitation or planning for development (Wheaton et al., 2004; Pasternack et al., 2006; Brown and Pasternack, 2009; Gard, 2014).

The resolution of a hydrodynamic model will define the level of detail available to the end-user and can therefore pose as a substantial limiting factor. The model resolution, however, is scalable and can be reduced to increase the level of detail available in the model results or it can be increased to reduced the computational demand and time taken to run a simulation, resulting in a customisable resolution and model to suit the required application (Hardy et al., 1999; Crowder and Diplas, 2000; Legleiter et al., 2011; Conner and Tonina, 2014).

It is necessary to make comparisons between actual recorded data and predictions made by a model, though these comparisons are often difficult to make due to the uncertainty raised by the spatial variability between observations in the real world and those predictions made based upon a fixed computational mesh (Wright et al., 2017). Studies (eg. Pasternack et al., 2006; Gard, 2009; Waddle, 2010) have shown that comparisons are often made between the results of a model and recorded data as part of the calibration and analysis of a model and its accuracy. However, Wright et al. (2017) argues that there is a lack of an accepted framework for making these comparisons and, because the comparisons are uncommon, this deters reliable analyses of model performance.

2.4 High Resolution Modelling

There are a number of hydrological models that have been developed in order to simulate different factors within catchments, such as runoff amounts, flood extents, flow routing and water quality (Elliot and Trowsdale, 2007). However, the vast majority of these hydrological models are based upon the relationship between precipitation and runoff which is usually derived using simplified methods and equations (Hailegeorgis and Alfredsen, 2018).

For example, the semi-distributed Storm Water Management Model (SWMM) is often applied for the simulation of rainfall event-based and/or continuous runoff within urbanised regions and effectively used to assess the hydraulic performance of sewers (eg. Denault et al., 2006; Krebs et al., 2014; Guan et al., 2015). The SWMM modelling package, however, is based upon semi-distributed rainfall-runoff by defining smaller sub-catchments within the wider sub-catchment, and then applying a percentage value of each sub-catchment which represents impermeable surfaces, which is a vague generalisation of the spatial distribution of areas that contribute to runoff as it fails to account for the precise locations and amounts of runoff generating surfaces (Easton et al., 2007; Hailegeorgis and Alfredsen, 2018).

Similarly, 1D-2D hydrodynamic models are capable of carrying out detailed hydraulic calculations and are capable of simulating the routing of flow in both rural and urban areas (eg. Paz et al., 2011). However, they utilise a lumped rainfall-runoff model which generalises the amounts of rainfall and the subsequent runoff that occurs on a full catchment scale, failing to capture the spatial distribution and variability of runoff from different contributing areas within the catchment (Hailegeorgis and Alfredsen, 2018).

Commercially available modelling packages, such as TUFLOW and Flood Modeller, offer wide functionalities which take advantage of 1D-2D coupled hydrodynamic methods, 1D methods for modelling pipe and channel flow (some of which have developed upon SWMM) and 2D grid meshes for modelling overland flow routing and floodplain inundation (eg. Phillips et al., 2005; Syme, 2008). However, these modelling software packages still lack the ability to fully account for all contributing factors, such as subsurface through flow of groundwater and, therefore, fail to fulfil the need for a modelling package which is capable of simulating the full rainfall-runoff process across different land cover types with absolute accuracy (Hailegeorgis and Alfredsen, 2018).

It has been suggested that future hydrodynamic models should reduce the level of uncertainty by accounting for all process interactions and spatial-temporal variability across the catchment, with the suggestion that only approximately 36% of the modelling approaches assessed were found to be adequately spatially distributed, with a resolution that ranges widely from 3m up to 10km (Elga et al., 2015). However, by accounting for all hydrodynamic processes, including the rainfall-runoff relationship, and ensuring that they are spatially distributed across a catchment has the potential for a more complex model which over-accommodates and includes factors which are not required for the specific model purpose (Grayson et al., 1992; Brooks et al., 2007).

Due to the nature of urbanised areas within wider catchments, the land use often differs at a very fine scale from impermeable to semi-permeable and permeable surfaces which demands the application of a spatially distributed model capable of representing such a fine scale so that the distribution of rainfall-runoff occurring across these surfaces can be captured accurately (Easton et al., 2007). 2D models that are spatially distributed by representing land cover types using a mesh of grid cells allow for more accurate representation of real world land usage as opposed to a semi-distributed model where land cover is represented as a percentage value of contributing area applied to a sub-catchment (Hailegeorgis and Alfredsen, 2018). Therefore, spatially distributed 2D models are able to more accurately respond to changes within a catchment and are more substantially suited for the study of factors such as the impacts of climate change and urbanisation on runoff and flooding (Hailegeorgis and Alfredsen, 2018; Harnett and Nash, 2017).

The hydrological response time of a catchment to varying rainfall events is affected dramatically by the routing of runoff within both urbanised and rural areas (Lhomme et al., 2004; Rodriguez et al., 2003; Miller et al., 2014). There are a number of flow routing modelling packages available which also take advantage of 1D, 2D and couple 1D-2D methods and studies which have assessed these methods (eg. Barnard et al., 2007; Gironas et al., 2009; Paz et al., 2011; Rodriguez et al., 2003; Rodiriguez et al., 2008; Xiong and Melching, 2005;). However, where flows and flow routing within the floodplain are represented within a 2D spatially distributed grid mesh, the resolution of the grid mesh needs to be detailed enough to capture the complexities of the flow routes being represented (Hailegeorgis and Alfredsen, 2018). While existing hydraulic models have been used to simulate and predict flooding and other hydrological processes, many of these models are inadequate due to the need for high spatial resolution which is required to simulate flows within some floodplains (Harnett and Nash, 2017).

Remote sensing technology, such as LiDAR, has greatly improved the level of detail that can be included in hydrodynamic modelling (Fewtrell et al., 2008; Liu et al., 2015). LiDAR is capable of recording topography in fine detail, often with a spatial resolution which is accurate below 1m while also maintaining high precision both vertically and horizontally, making it ideal for producing DEMs that can be used for accurate flood modelling (Gallegos et al., 2009; Marks and Bates, 2000; Mason et al., 2007, 2014; Neal et al., 2009a; Ozdemir et al., 2013; Schubert et al., 2008). As the routing of surface water runoff throughout the floodplain is largely governed by the topography of the catchment, the use of a DEM at a suitable spatial resolution, providing the level of detail required to represent the topographical features, is essential to accurately modelling the floodplain and producing realistic results (Abily et al., 2016; Bierkens et al., 2015; Bates et al., 2003; Leitão et al., 2009).

In addition, highly detailed spatial and geomorphological data, such as high-precision mapping, is also essential for accurate floodplain modelling where man-made structures need to be represented as a DEM will largely exclude these features (Mark et al., 2004). However, too much reliance can be made on high-resolution data as greater accuracy is not necessarily a direct result of increased resolution, particularly where uncertainty in the data is an issue

(Dottori et al., 2013). For example, while LiDAR data may be a highly accurate tool in the creation of DEMs, the technology works essentially by measuring the distance that light has to travel from a sensor to an object, including unwanted surfaces such as trees and buildings which must be filtered out of the data later, thus adding uncertainty (Noh et al., 2018). The use of high-resolution data also introduces further disadvantages, predominantly as a result of greatly increased level of detail which ultimately increases the model complexity, size and the computational power required to run simulations (Abily et al., 2016; Bates et al., 2003; Fewtrell et al., 2008; Mignot et al., 2006; Neal et al., 2012). Despite this, the benefits of developing and using high-resolution models has resulted in a greater range of useful applications, such as assisting in planning and development, hazard analysis and environmental management, particularly due to the improved accuracy of the results that they can produce (Bevan, 2007; Dottori et al., 2013). However, high-resolution 2D modelling of floodplain inundation is expensive in terms of computational resources and professional labour required to build and simulate the model and analyse the outputs, making it relatively impractical for many real-world applications (Coulthard et al., 2007; Neal et al., 2010). This is largely due to the vast number of individual cells within the computational grid that are required to cover large areas, with calculations occurring at each cell. Additionally, smaller time steps are required in order to maintain model convergence, increasing the frequency of calculations completed at each grid cell (Noh et al., 2018). Parallel computing methods, such as utilising multi-core graphics processing units (eg. Ament et al., 2011) can greatly reduce the time taken to simulate high-resolution models, making them more practical, though in some cases parallelisation is entirely necessary to bring computational processing times back down to a practical timeframe for real-world use (Noh et al., 2018).

3 Research Methodology

3.1 Model Build Summary

Two existing models, used to assess the level of flood risk risk to Southwell, have been created previously on behalf of the Environment Agency. However, these models do not cover enough of the rivers to satisfy the aim of this study and, due to the level of detail required for modelling both watercourses and the effects of river restoration and natural flood management techniques at a high resolution, a new model is required to be built in its entirety. The approach taken to model the River Greet and Potwell Dyke and the flood management methods to be assessed was to build a linked 1D and 2D, which comprises building a model of the river channel on a cross-sectional plane (1D) and a separate model of the floodplain on a lateral plane (2D), with the two linked together through a series of text-based commands that allow both to be simulated together. The model build process for a linked 1D-2D Flood Modeller-TUFLOW model is detailed below and summarised by the flow diagram in Figure 3.1 below.

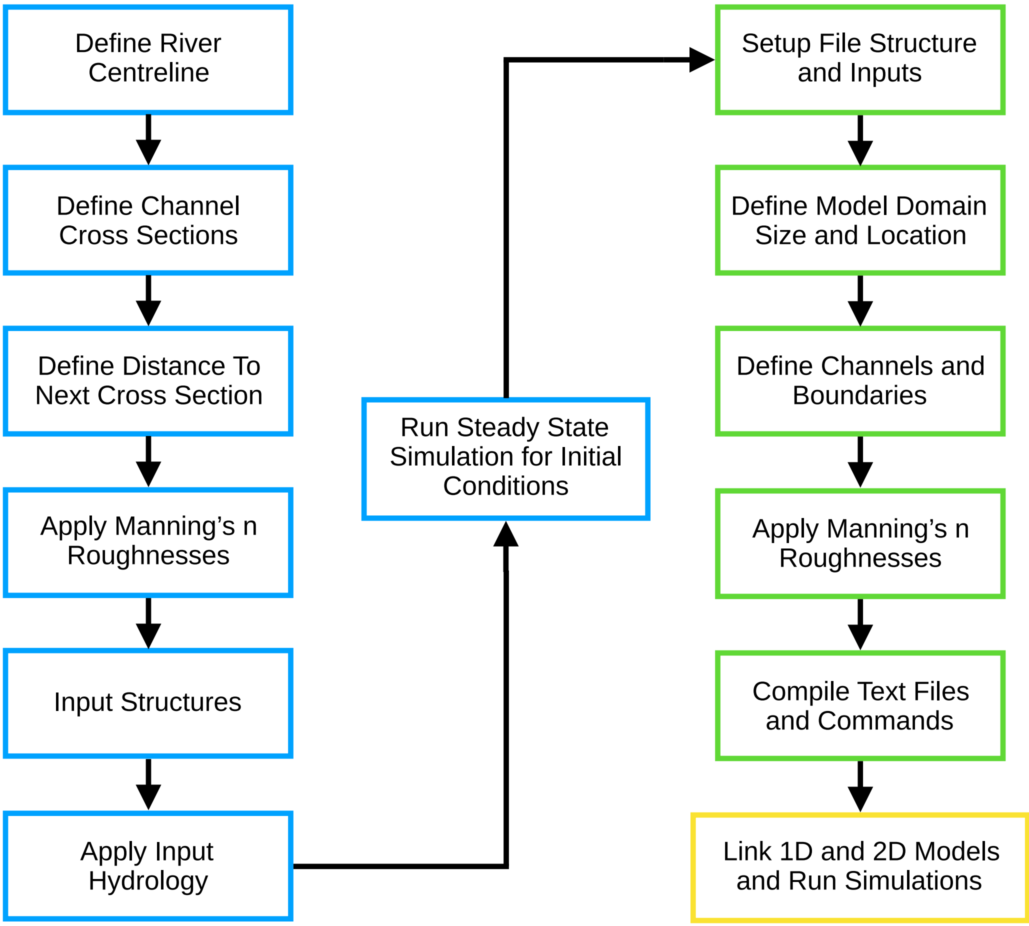


Figure 3.1: Summary of the model build process with 1D steps in blue, 2D steps in green and final linking and simulation step in yellow

3.2 LiDAR Preparation

Both the 1D and 2D components of the model require a ground model to define river channel cross-sections and topographical features. This has been achieved by using LiDAR Digital Terrain Model (DTM) data available directly from the Department for Environment, Food & Rural Affairs (DEFRA) under the Open Government Licence. Composite DTM LiDAR data with a spatial resolution of 1m and a vertical accuracy of +/-15cm Root Mean Square Error is available for download in ASCII format as 5km grids. While multiple DTM files can be used within Flood Modeller and TUFLOW, it is simpler to utilise a single DTM file that can be loaded easily and defined once. Therefore, all relevant 5km ASCII grids were combined using the raster merging tool in QGIS. Visual checks with and without hill-shading applied to the DTM were carried out to ensure the process has been completed successfully.

3.3 1D Model Build

3.3.1 Defining Channels

With a single DTM created, the ASCII file is imported into Flood Modeller and the projection is set to British National Grid to begin the 1D model build process. Again, using hill-shading on the DTM, the River Greet and Potwell Dyke can be easily defined visually. However, a river centreline drawn as a correctly projected Shapefile polyline layer is required so that Flood Modeller can define the location of the channels that are required, which is demonstrated by Figure 3.2 below.

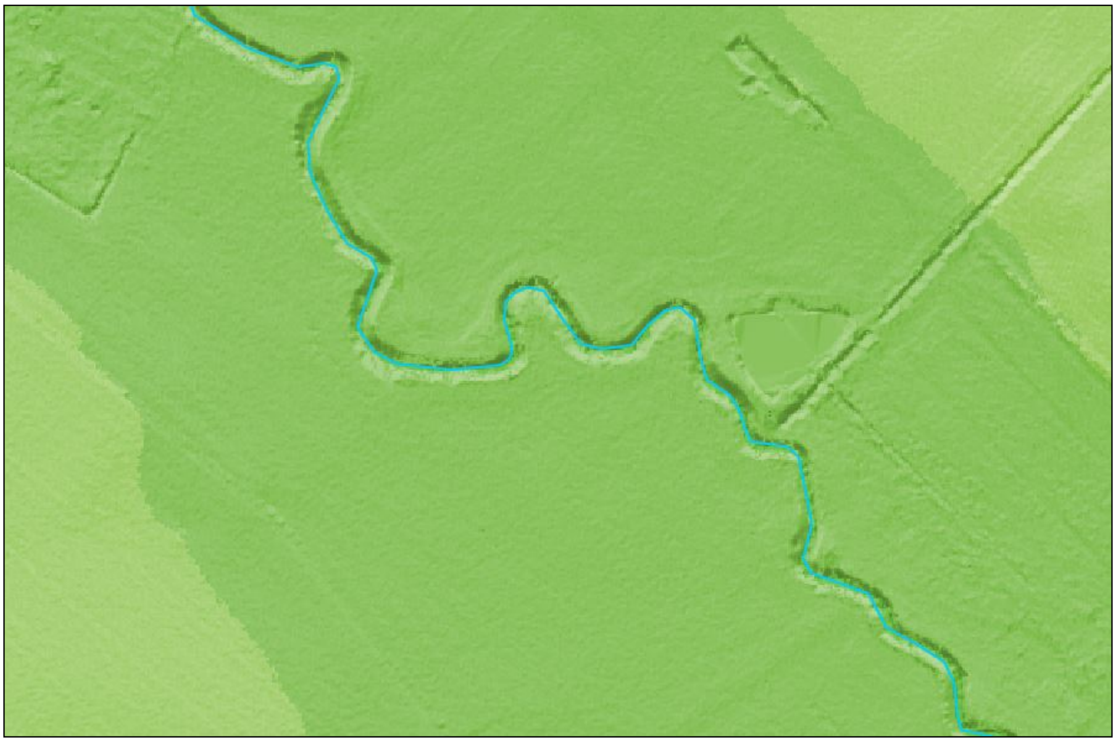


Figure 3.2: Model DTM with hill-shading applied and river centreline drawn

The centreline is drawn using the built-in GIS capabilities within Flood Modeller, starting at the upstream end of the channel within the study area. The centreline does not need to be precise but should follow the centre of the required channel so that cross-sections placed on the centreline are able to span the full channel correctly and so that Flood Modeller can calculate the distances between all cross-sections accurately. Once two separate polylines had been drawn, one for the River Greet and one for Potwell Dyke, cross-sections of the river channels can be created which will snap to the relevant centreline.

3.3.2 Generating Channel Cross-Sections

River channels within Flood Modeller are defined by a series of cross-sections which contain the channel profile using level data, coordinates and Manning's n roughness values, with the information stored within a River Unit. Cross-sections can be created by drawing a Shapefile line from the left bank, crossing the river centreline to the right bank, starting at the upstream end of the centreline and working along sequentially to the downstream end, as demonstrated by Figure 3.3 below.

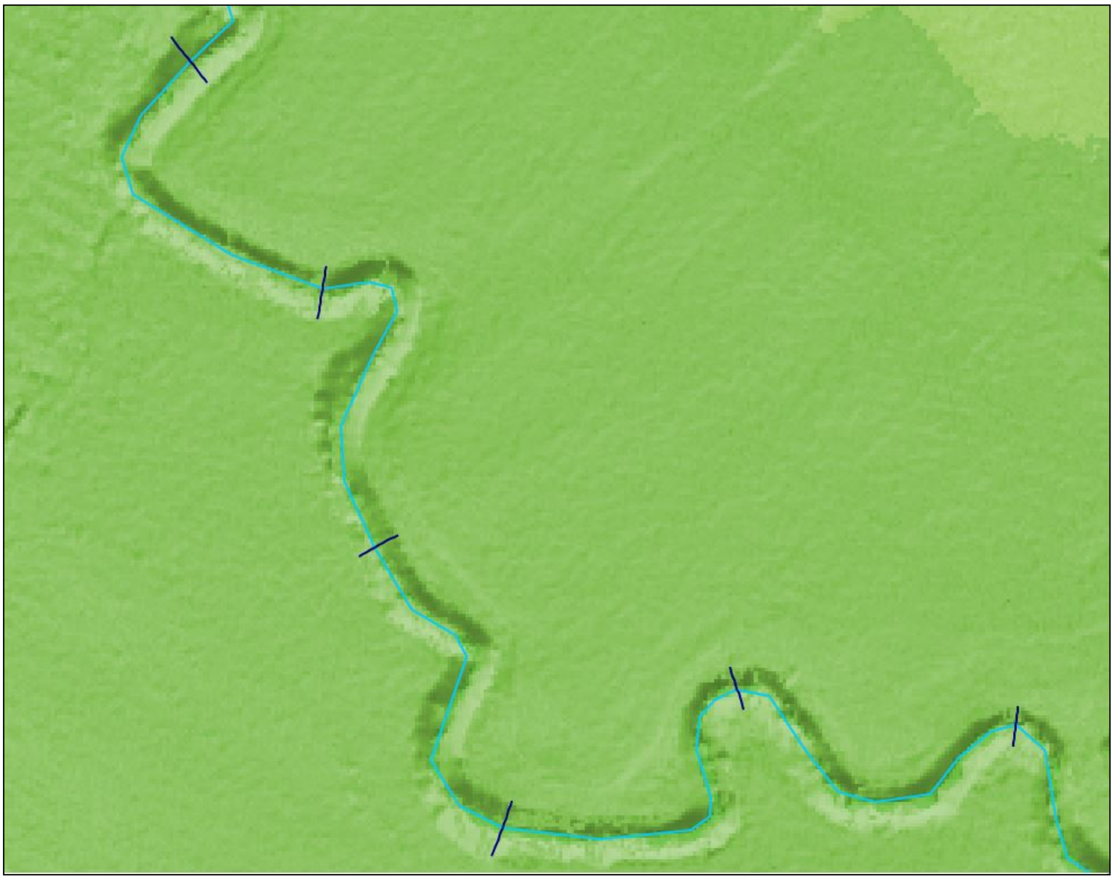


Figure 3.3: GIS polylines representing cross-sections through the river channel

This is a tedious and time-consuming process, so Flood Modeller includes a built-in tool for automatically generating cross-sections. The tool was used to quickly generate cross-sections with a width of 10m from the centreline in order to account for the full channel and banks. The relevant river centreline drawn previously for the River Greet is selected when starting the tool. The

Distance To Next (DTN), which defines the distance from one cross-section to the next cross-section downstream, was set to 100m, creating equally spaced cross-sections with an even coverage along the river reach. There is no set DTN to use, though model instabilities can often be encountered where greater distances are used as the 1D solver encounters situations where there is a lack of detail to carry out calculations. The 1D unsteady flow solver used within Flood Modeller simulations use the Preissmann implicit scheme to solve the equations for free surface flow which are based on the Saint-Venant equations for flow in open channels. These equations are used in conjunction with equations for hydraulic structures in order to calculate flow characteristics at each cross-section, with interpolation taking place between cross-sections. Therefore, cross-sections should be positioned based on changes in channel geometry. The general DTN used in the tool is, therefore, based on judgement for a particular river channel, with additional cross-sections added where required. The tool works by automatically drawing straight Shapefile lines to the specified width with nodes at regular intervals across the channel. When starting the tool, the DTM is specified, which the tool will use to apply ground levels at each node along the cross-section. Due to to the spatial resolution of the DTM of 1m, the nodes along the cross-section were set to be spaced 1m apart. With the process completed and cross-sections generated along the River Greet the process is then repeated for Potwell Dyke.

After visual checks are completed to check if enough cross-sections are added and other they are in the correct places, additional cross-sections were added. There are two options for adding single cross-sections The first, which is detailed above, involves drawing the cross-sections where they are required. The empty data within the attribute table of the cross-section is then completed using manual processes or by using individual tools built-into Flood Modeller. In particular, level data is assigned at individual nodes which are manually placed along the drawn Shapefile line using a dedicated tool which uses the loaded DTM. The second option, which maintains consistency between the new cross-sections and those that have been generated, is to copy the nearest generated cross-section and then paste it into the desired location. This was completed in a number of locations where geometry changes in the channel occurred, as shown in the DTM. The new cross-section then had its level and geolocation references nulled as these represent the copied cross-section. The nulled information is then reassigned using Flood Modeller's respective built-in tools, picking up the level data from the DTM at the new cross-section's current location.

3.3.3 Refining Channel Cross-Sections

With all cross-sections that are likely to be required have been created, the next step is to carry out stringent checks for each one to ensure that any discrepancies are corrected. It is crucial that the DTN is correct as instabilities and model failures will occur where the total DTN does not match the total length of the river reach. As stated earlier, where cross-sections are generated, the DTN is based on the correctly project river centreline. Where the centreline does not accurately follow the river channel the DTN will be incorrect. This was corrected by manually measuring the distance between cross-sections using the measurement tool built-into Flood Modeller where required. An additional check that was carried out involved checking the geolocation of each cross-section. Flood Modeller represents cross-sections in a linked, linear schematic and does not account for the georeferenced location of cross-sections. However, placing cross-sections in there correct location is important when visualising the model, ensuring that cross-sections can be seen and not easily overlooked, and will aid the build of the 2D model later on. A check of geolocations was carried out by running a tool within Flood Modeller which assigns coordinates to the Shapefile line nodes for all selected cross-sections. All cross-sections were selected, the tool was run and then a visual check is completed to make sure all cross-sections are correctly located. Any incorrectly located cross-sections are relocated manually by moving the Shapefile line for the relevant cross-section to the correct location and position, nulling any coordinate information within that cross-section's attribute table, selecting only that cross-section and then re-running the georeferencing tool to fill in the correct coordinates. Finally, with cross-sectional profile based on LiDAR, inaccuracies such as repeated levels in the chainage of the cross-section can occur. Each cross-section is checked, with any inaccuracies corrected manually, either by removing duplicated levels or by changing erroneous levels by interpolating them between the previous and next values. Inaccuracies in bed levels throughout the river reach were also checked by creating a long-section of both channels separately to show any erroneous changes in bed levels, as demonstrated by Figure 3.4 below.

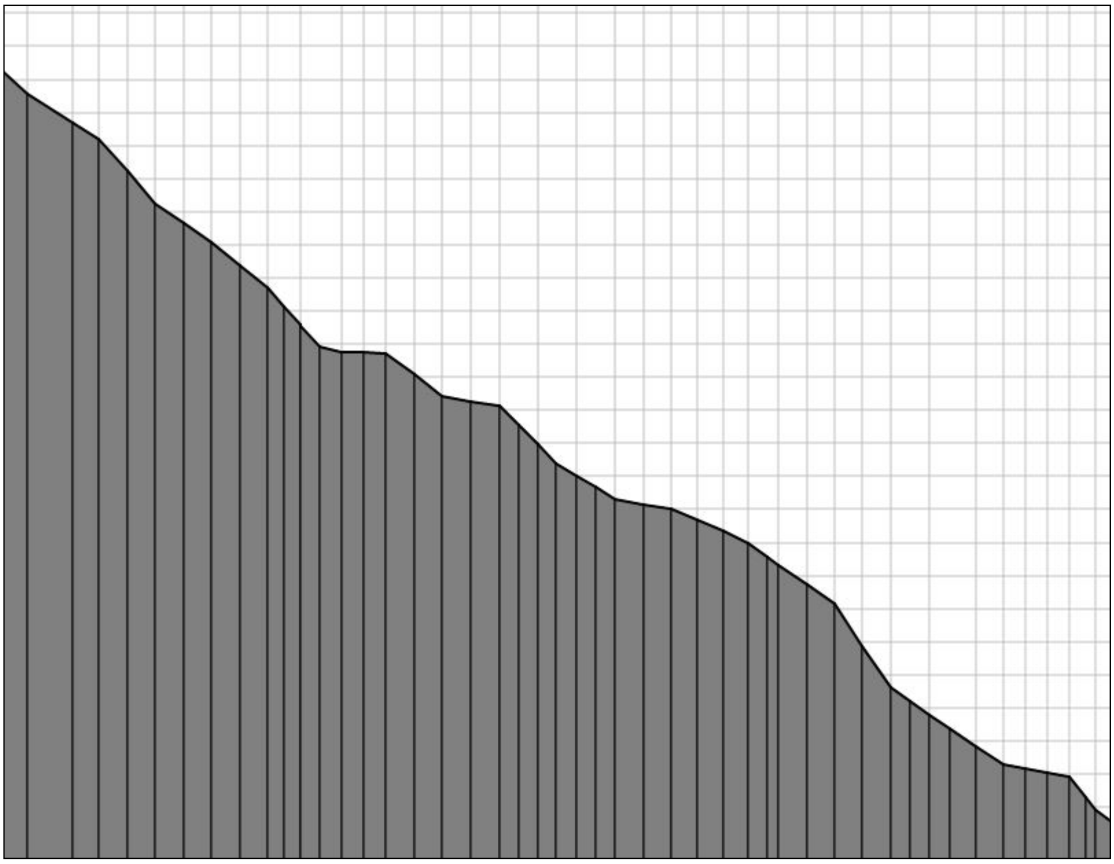


Figure 3.4: Channel long section of Potwell Dyke used to identify irregularities in bed profile

While it would be incorrect to assume that the bed profile would be a smooth decline from upstream to the downstream end, any sudden dips and crests can result in a dramatic change in flow and stage, which can result in an unstable model run. Any obvious errors in bed levels in both channels are removed manually by interpolating the bed levels from the upstream and downstream cross-sections. Based on the characteristics of Potwell Dyke, one particular sudden drop has been identified as being genuine and not the result of an error in the DTM. In order to avoid the possibility of model instabilities, the cross-section before the drop was replaced by a spill unit with the same cross-sectional data used. A spill unit is used because it allows for the calculation of flow over irregular weir-like objects and is better suited for allowing sudden drops.

3.3.4 Defining Channel Roughness

In order for the model to simulate realistic flow velocities within the channel, roughness values representing the channel surfaces are defined within each cross-section. This is done by by applying a Manning's n value at relevant points in the cross-section change that accurately represents the surface roughness. Chow (1959) has defined a suite of Manning's n values which are commonly used for applying roughness values to open channels in the assessment of hydraulic flow dynamics. As with all values within the cross-sections, the Manning's n values are interpolated from one cross-section to the next cross-section downstream, though most cross-sections within a model are generalised and sudden changes are uncommon.

3.3.5 Defining Structures

A number of structures, including bridges, culverts and a weir are present on the River Greet and Potwell Dyke. These structures need to be included in the model due to the hydraulic effects that they have upon flow, velocity and stage. The various structures present can be included directly within the 1D model by representing them with different types of units available within Flood Modeller. Bridges are generally represented by Arch Bridge Units or US BPR Bridge Units, which calculate the flow of water through one or more openings in conjunction with the channel profile represented as a cross-section. However, bridges with small or narrow openings which are liable to surcharge can result in instabilities. In this instance, bridge units have the option to switch automatically to calculating flows as if passing through an orifice, which do not account losses due to roughness. Alternatively, bridges with small, short openings can be modelled as an Orifice Unit where roughness losses are less important. All of the bridges present within the study area have been modelled as Arch Bridge Units.

Potwell Dyke joins the River Greet via an approximately 46m long culvert (See Fig. 1.1) which will result in profound effects on hydraulic flows. Flood

Modeller includes tools for the modelling of long culverts, where the culvert opening, headwall, culvert diameter and length and the outfall are defined. In addition, a mill situated on the River Greet (see Fig. 1.1) which concentrates river flows and comprises of a steep steep is also modelled as a culvert as this is the most representative method to do so. Where shorter culverts are present, these can be modelled as orifice Units in a similar fashion to short bridge openings as discussed above.

A single historic weir is located on the River Greet, downstream of the mill at Maythorne (see Fig. 1.1). Although Flood Modeller includes specific weir units for calculating water flow over different types of weirs, these weir units can only represent uniform, level and regular weir crests. However, many weirs in the UK, particularly historic weirs which are in a state of disrepair, have become heavily silted or have become weathered will have an irregular crest. As such, and as previously used for the drop found on Potwell Dyke, a spill unit is used which is able to calculate the drop of water over a crest while providing the ability to define the profile of the weir as a cross-section. Cross-sectional data from a nearby river unit is added to a spill unit and is edited to include the height of the weir crest and the length between the banks, allowing the weir and the adjacent banks to be accounted for.

3.3.6 Shortening Cross-Sections & Checking Channel Conveyance

A 1D model can be used to represent the floodplain as well as the river channel, enabling a simplified method for predicting and assessing flooding out of a channel. There are a number of ways to represent the floodplain, primarily though, this is done by extending cross-sections into the floodplain. However, because a separate 2D model will be created to add much greater detail to represent the floodplain than is possible with a 1D model, the cross-sections need to only represent the channel up to the bank. Each cross-section is checked and shortened. Rather than deleting what parts of the cross-sectional data that extends beyond the bank, Flood Modeller enables the top of the bank to be selected, deactivating any data beyond the point selected. This was completed for all cross-sections, preparing them for linking to the 2D model later. At the same time, the conveyance of each cross-section is checked. The cross-sectional area's ability to convey flow is represented as a plot overlaying the cross-sectional profile, as shown in Figure 3.5 below. Any erratic changes or drops in the plot indicates a drop in conveyance caused by there being changes in the wetted perimeter of the cross-section increasing significantly without a corresponding large increase in area, leading to an unrealistic reduction in channel conveyance. In order to overcome this issue, panel markers are placed which improve the calculation of conveyance within that particular cross-section.

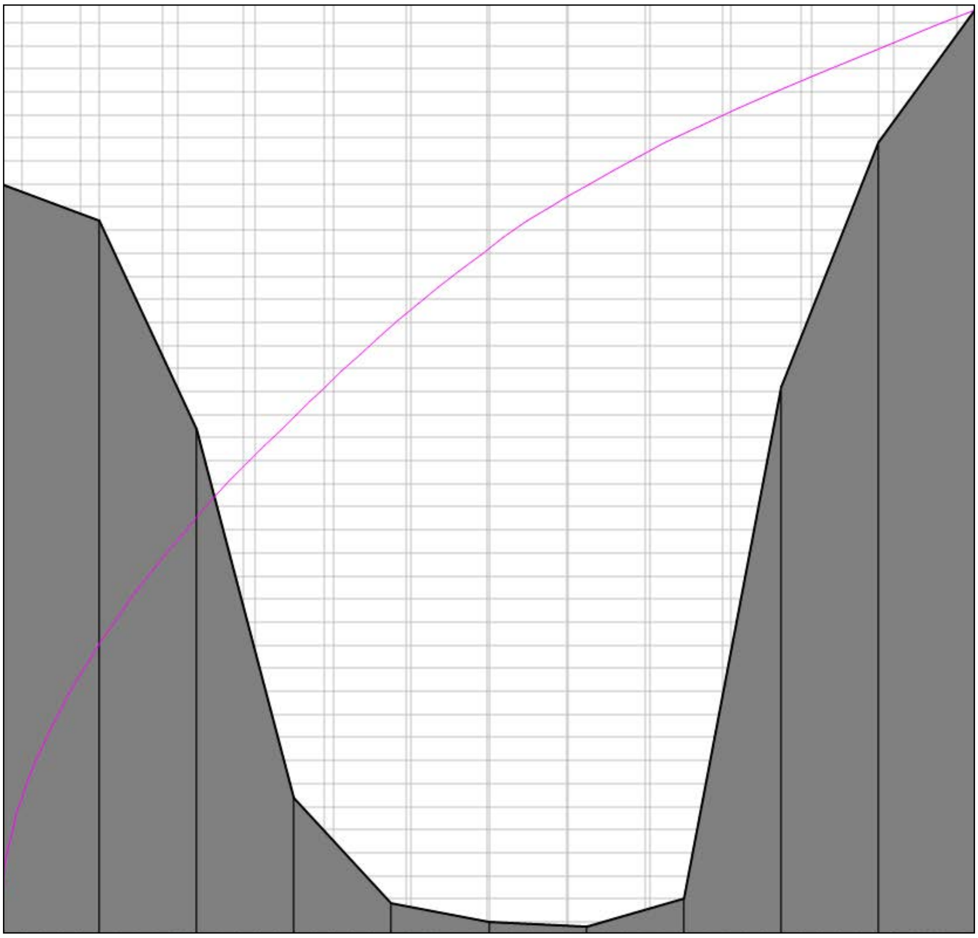


Figure 3.5: Channel cross-section with a desired smooth flow conveyance profile highlighted in pink

3.4 Catchment Hydrology

3.4.1 Defining Catchment Hydrology

In order to simulate river flows for a range of storm events hydrological input boundaries, containing the desired flows for each open channel being modelled, are added at the upstream ends of each channel or input. There are a number of methods for defining the hydrological inputs for each storm event, such as defining a single stage flow which is constant through the model run to a full unit hydrograph. Due to the size of the catchments of the River Greet and Potwell Dyke, unit hydrographs were defined which would provide gradual increases in flow based on a suitable time-to-peak before flows decrease gradually back to the channel baseflow as floodwater subsides. The primary unit hydrograph methods in the UK are based upon the Flood Studies Report (FSR) (Institute of Hydrology, 1975) and the Flood Estimation Handbook (FEH) (Institute of Hydrology, 1999) and use derived catchment descriptors based on soil types, runoff percentages, standard average annual rainfall (SAAR), urbanisation and catchment size. Both are generally only suitable for catchments over 50ha in size. However, adjustments can be made to both to scale results down for smaller catchments. The unit hydrographs for each event, obtained for the River Greet, Potwell Dyke and Halam Beck, another tributary of the River Greet which is not modelled but needs to be hydrologically accounted for, were obtained using the FSR IH124 unit hydrograph method (Marshall and Bayliss, 1994) within Micro Drainage. Based on the required catchment characteristics, which can be obtained easily using Micro Drainage, the software generates flows at regularly defined intervals for each event. The results were exported to CSV files and reviewed in Microsoft Excel so that the data shortened to just include the full rising limb, peak and falling limb. The data was also exported from Micro Drainage in imperial units and were converted to SI metric in order to copy the data over to Flood Modeller. Checks were also carried out to validate the inflow data by comparing the obtained results against the generated FSR QBAR and FEH QMED Greenfield runoff rates, included in Appendix A, which are generated using the UKSuDS website (HR Wallingford, n.d.).

Due to the differences between FSR and FEH flow rates, and based on sense checks and initial model simulations, FSR flows were deemed excessive in the River Greet. It was, therefore, decided to apportion the generated hydrographs to FEH flow rates. This was done by reducing rates for the River Greet by 40.45%, Halam Beck (a major inflow to the River Greet upstream of Southwell) by 41.56% and Potwell Dyke by 44.14%. However, with FEH flow rates it was discovered that Potwell Dyke would run dry and the simulation would fail. To overcome this issue, the FEH flow rates for Potwell Dyke were increased by 77.4%, bringing them back to just below the original FSR flow rates. Doing so prevented Potwell Dyke from running dry any further.

The hydrographs generated as part of this study have been included in Appendix A.

The hydrograph data can then be simply copied and pasted from Excel into a flow-time input hydrology boundary within Flood Modeller, defining the incoming flows for the 1D model. In order to allow water to leave the 1D model at the downstream end, a normal depth boundary is added at the downstream end of the River Greet. This boundary allows in-channel water to exit the 1D model at a flow rate which is calculated based upon the general slope of the channel. Only the one downstream boundary is required, with all incoming water from the River Greet, Potwell Dyke and Halam Beck exiting the 1D model by either converging at the downstream end of the River Greet or by exiting the channels laterally and remaining in the floodplain.

Further adjustments are made to the hydrology after running the baseline model and making comparisons to the extents of the Environment Agency's Risk of Flooding from Rivers and Sea flood zone mapping.

3.4.2 Steady State Simulations

Finally, a simulation is completed in order to obtain initial conditions that define characteristics such as stage, flow and velocity to be applied to the model and used at the start of every future full simulation. The steady state simulation uses the input hydrology to calculate event maximums for the channel, outputting results that can then be used to define the initial states of both watercourses.

3.5 2D Model Build

3.5.1 2D Model Preparation

TUFLOW is an MS-DOS based software package and operates through the use of text-based commands and scripts which define a combination of largely GIS-based inputs. As such, a folder structure to contain numerous different types of files for model inputs and outputs, is required before starting. With a folder structure created, the model can start to be populated by placing the LiDAR DTM into a relevant folder. The primary text files that would be used for this model were then created: the TCF, which contains commands for controlling model simulations; the TGC, which contains commands to define the floodplain geometry files; and, the TBC, which contains commands to define the floodplain boundary files. With a basic TCF file, TUFLOW can be run to generate empty GIS files to be used to represent features such as river banks, surface roughnesses and links to the 1D model.

3.5.2 Defining Domain Location, Dimensions & Grid Size

The study area to be covered by the 2D model is defined by providing geolocation information to TUFLOW. The DTM is loaded into MapInfo so that a line can be drawn to represent the width and orientation of the 2D domain, with coordinates from the leftmost and rightmost points on the line taken and input into the TGC. Further details, such as the projection, length and width of the domain are input into the TGC allowing TUFLOW to create a domain. The domain is created by TUFLOW is rectangular, covering the full extents of the study area. As a result, there are regions within the domain, such as hills and other areas outside of the floodplain, which are not required. Therefore, a polygon, referred to as the 2D code, is drawn which covers the extent of the floodplain using the extents of the Environment Agency's Flood Zone 2, representing areas with an annual probability of flooding from rivers or the sea of between 1 in 100 and 1 in 1,000, which the largest event to be simulated (1% AEP plus 30% climate change) falls within. The code polygon is used to define the actual area that will be simulated, with any parts of the domain falling outside of the polygon being ignored, as demonstrated in Figure 3.6 below. Keeping the code polygon as small as possible ensures that hardware requirements and simulation times are minimised. The grid resolution (1m in this instance) is also defined within the TGC, informing TUFLOW to draw a grid comprising of 1m^2 cells covering the full active code area covering the floodplain.

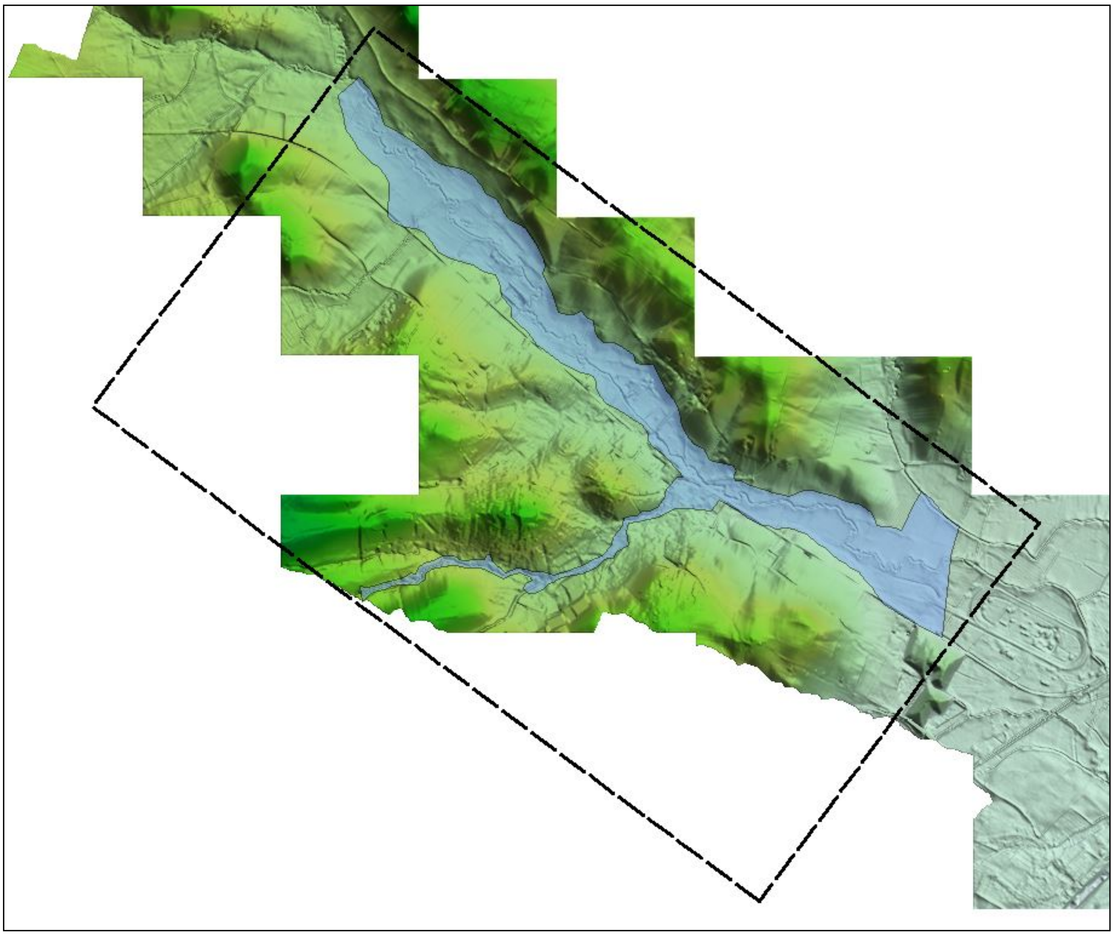


Figure 3.6: Domain polygon (dashed black line) defining full study area and active code polygon (blue) used to define the active floodplain area to be simulated

3.5.3 Defining 1D Channel Locations & Bank Heights

While the 1D elements of the River Greet and Potwell Dyke have been modelled within Flood Modeller, the channels need to be defined using a number of GIS layers so that TUFLOW can determine where the channels are and so that 1D and 2D models can be linked properly, allowing the transfer of water between the two. First, the locations of each cross-section are exported as a Shapefile point layer from Flood Modeller. The Shapefile is then imported into MapInfo before copying the points and the cross-section IDs into an empty TUFLOW GIS. The actual cross-sections, represented as polylines, are also exported as a Shapefile layer from Flood Modeller and imported into

MapInfo. These are then copied to another empty TUFLOW GIS layer which represents channel boundary conditions. The cross-section polylines are copied to the new layer and split at the points created earlier. The result is a point representing the cross-section and a linking polyline from the point to the peak of the bank. This process can be completed simply by drawing both the cross-section points and the linking cross-section lines. However, the above process, while requiring extra steps, ensures absolute accuracy between Flood Modeller and TUFLOW. Points are also added to the boundary conditions layer at the end of each cross-section polylines. These points are then populated with the heights of each bank-top, which can be taken from the DTM using a point inspection tool. Checks are then completed on the points to ensure that the levels taken from the DTM correspond precisely to the bank-top heights in Flood Modeller. Still within the same boundary conditions layer, a polyline is drawn along the banks of each channel, linking the bank-top points. The 1D model only carries out calculations at each cross-section. Therefore, interpolation must take place between cross-sections. The polyline representing the channel banks allows the results of the interpolation to interact with the 2D model, such as allowing spill out of the channel and into the 2D domain between cross-sections. Although the 1D channels have been defined within the 2D model, TUFLOW will still represent the channels within the topography of the floodplain. As the channel is already being modelled within Flood Modeller, to ensure that water is passed between the channels and floodplain correctly without misrepresented, a polygon is drawn over the channels, between the banklines only, and a code is applied to the layer. Figure 3.7 below demonstrates how the discussed GIS layers are arranged to define the channel so that it can be excluded from the 2D simulation.

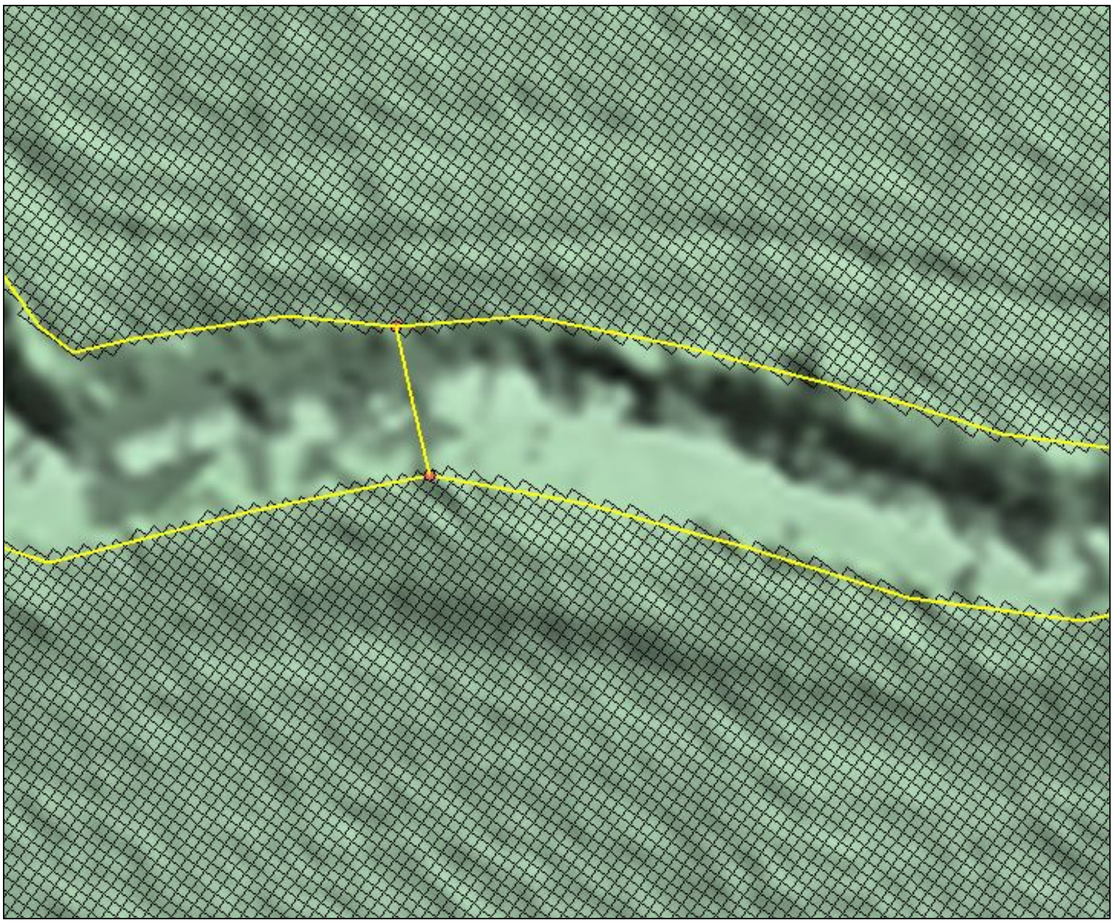


Figure 3.7: Channel bank lines and cross-sections (yellow) and bank heights (red points) used by TUFLOW to define 1D elements to be excluded from the 2D grid and model

When linked to the TGC, the layer that has been created in this process will exclude the channels from the grid, domain and topography of the model, allowing TUFLOW to know where the channels are without allowing it to calculate anything within the channels. The final step to defining the 2D model boundary conditions is to allow water contained in the floodplain to leave the 2D domain. A polyline is drawn across the floodplain from the bank of the channel to the outer extent of any expected flooding, perpendicular to the direction of the flow of floodwater in the floodplain. This is generally done either side of the channel at the downstream end of the model domain but should also be completed along any domain edges where flooding is likely to occur. With a general floodplain slope applied to the polyline attributes, water present in the floodplain is able to flow across the polyline and exit the model domain. Without completing this step, water will hit the edge of the model domain and become trapped, resulting in unrealistic flow characteristics, increased flood height and increased flood extents. Boundary lines were added to the downstream end of the River Greet on either side of the river channel, with one boundary line added off the right bank at the upstream extent after an early model run identified minimal floodwater flowing upstream in the floodplain.

3.5.4 Defining Floodplain Roughnesses

The flow of water across different surfaces and around various objects contained within the floodplain is calculated by using Manning's n roughness values. The roughness values are assigned to the different objects and surfaces using highly accurate OS MasterMap mapping to enable TUFLOW to calculate the flow and velocity of water as it comes into contact with them. Where more smooth surfaces such as concrete or tarmac are present, flow and velocity will be increased, while more rough surfaces such as long grasses and woodland will result flow and velocity being decreased. In order to apply Manning's n values to different surface types, a copy of the OS MasterMap GIS layer covering the study area is made. The OS MasterMap contains attribute data do different surfaces and objects, including including a land use type for every object represented within the layer. TUFLOW will not read these land use designations, which are represented as plain text. Therefore, each land use type is assigned a numeric ID by updating the attribute data within MapInfo, ensuring that every occurrence of a particular land use type now has a single code. All other attribute data is removed, leaving a single column with material IDs for each object which TUFLOW is able to read when it opens the layer. In order for TUFLOW to apply a Manning's n roughness value to a particular material ID, a text file called a TMF is created. This text file contains each material ID listed along with the relevant Manning's n roughness value representative of that surface material type. The corresponding MasterMap land use type can also be listed for reference only. The TMF file is linked to within the TGC text file along with the materials GIS layer that has also been created, pointing TUFLOW to the information it requires to apply roughness values across the floodplain.

3.6 Linking Models & Running the Baseline

With all the required components for the 2D model completed, such as boundaries, channel definition files and floodplain roughnesses, the 1D and 2D models need to be linked together before a simulation can be started. A good portion of the linking is completed during the 2D model build process by including the various GIS layers that define the 1D channel and subsequently using command lines in the TBC, TGC and TCF files. The final steps involved in linking the two models together involves creating an IEF model which is used for running a model simulation within Flood Modeller as was the case for running the 1D model alone. The final link is made by specifying the 2D TCF simulation file within the IEF, along with the 2D model time-steps, which is generally half of the 2D model grid cell size. With the correct corresponding 2D TCF file specified, when a simulation is now started from the IEF file Flood Modeller will automatically start TUFLOW which will simulate the 2D part of the linked model. Throughout the simulation, Flood Modeller and TUFLOW will run in tandem while transferring information regarding flows between the 1D channel and the 2D floodplain, particularly where bank-full flow and subsequent spill into the floodplain occurs.

Provided there are no technical issues with running Flood Modeller and TUFLOW together, the baseline model can be run. It is normal to expect the simulation to fail before completing for the baseline model run as instabilities arise and/or errors from the model build become apparent. Where this occurs, errors and instabilities are fixed iteratively by investigating errors messages that indicate potential causes and making corrections and changes in anything from TUFLOW commands to adding more data to the GIS layers. In the case of this model, representing the River Greet and Potwell Dyke, only a couple of minor errors were found based on the correct linking of files within the TGC and TCF. Fortunately, there were no instabilities found within the 2D model and after a few attempts the baseline model completed successfully for the full range of events in Table 3.1 below. Table 3.1 also shows the approximate simulation times taken for each Baseline model run, showing that for the larger events the time taken to simulate the flood event was effectively equal to real-time.

Table 3.1: Simulated flood events and simulation durations

Baseline Model Event	Real-world Time to Complete (approx. hours)
1 in 10-year	16
1 in 20-year	17
1 in 30-year	18
1 in 50-year	19
1 in 75-year	19
1 in 100-year	21
1 in 100-year + 30% Climate Change	22

3.7 Study Scenarios

In order to test the effectiveness of modelling river restoration and natural flood management techniques at a high resolution a number of techniques from the use of woody debris and improvements to the riparian environment to re-establishing riparian wetlands and remaindering the river channel were modelled as examples. These techniques would be tested individually to assess how effective they are alone at reducing flood risk in the downstream catchment, with a final scenario combining all the previously tested techniques together to assess whether a combination of restoration methods would be more or less effective in reducing flood risk.

3.7.1 Scenario 1 - Woody Debris & Riparian Woodland

The first scenario to be tested is the inclusion of woody debris within the floodplain and within the river channel itself, together with increased areas of woodland along the riparian corridor. In order to represent woody debris within the model, a new GIS layer is created which will represent items spatially while being assigned with a category ID for a set Manning's n value. This layer essentially achieves the same function as the previously created layer containing the OS MasterMap, whereby a Manning's n value is applied to different surface types contained within the mapping through the use of a TUFLOW TMF file. Within the new layer, woody debris is drawn in the desired location, aided by the use of the baseline results so that items can be placed in an attempt to block and interrupt flow paths within the floodplain and reduce the flow rate and velocity of floodwaters. A key reason for building a model with a high resolution is that finer details can be included more accurately. As some woody debris will generally be very small it is necessary to represent them at an appropriate scale. Due to the 1m cell resolution of the model, it is possible to size the woody debris to a minimum of $1m^2$, which is generally representative of individual pieces of woody debris such as tree trunks and small clusters of branches. The most effective way of adding woody debris to the new GIS layer is to use the grid created by TUFLOW based on specification input into the TCF for a simulation. This GIS layer simply displays all of the 1m cells arranged as a grid for the full model domain and allows for single cells for the desired location of woody debris to be copied into the new layer. The result is a scatter of single $1m^2$ squares throughout the floodplain, as shown in Figure 3.8 below. Where woody debris larger than $1m^2$ was required, multiple grid adjacent cells in the desired shapes were copied into the new layer. Finally, a Manning's n value of 0.05 was applied for the woody debris within the TMF.

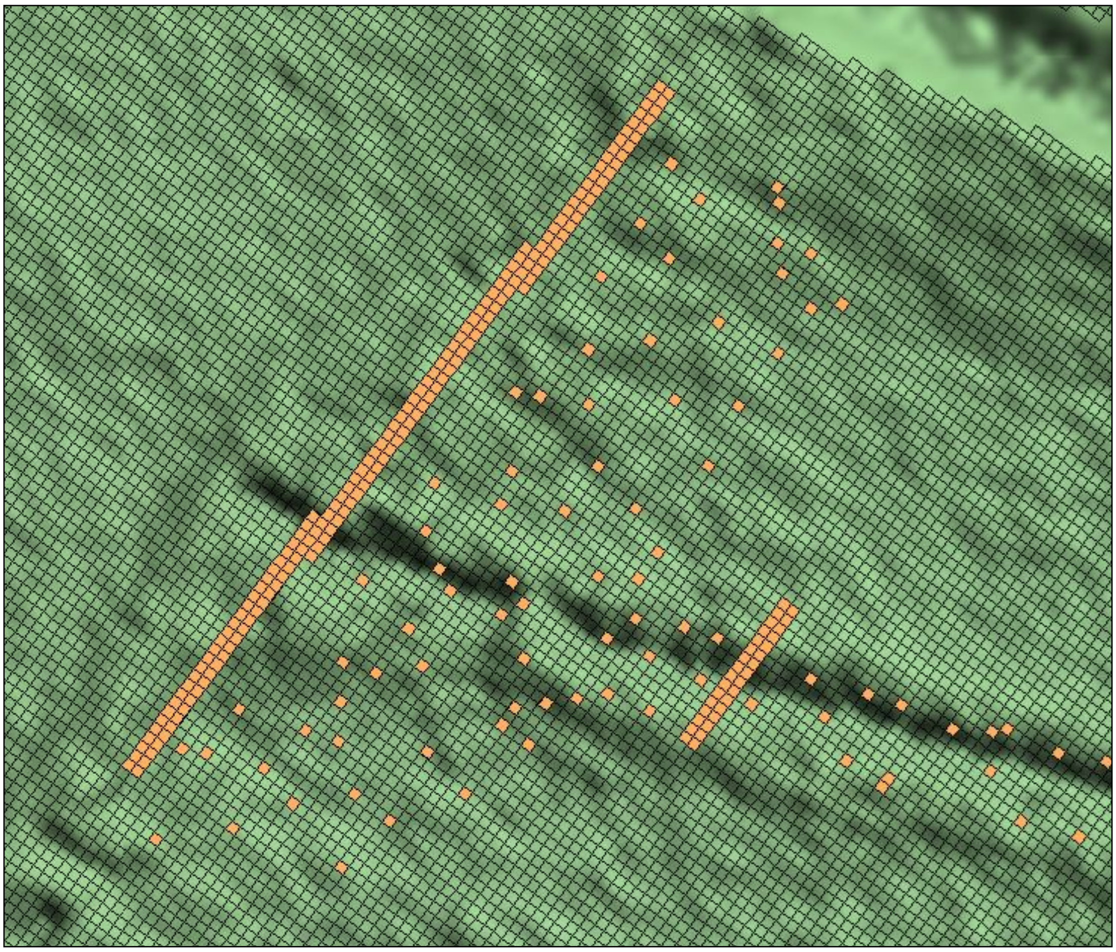


Figure 3.8: Individual pieces of woody debris scattered within the floodplain and a woody debris barrier modelled by copying and arranging 1m² grid cells

In a number of locations along the river banks where rapid spill over the banks was shown to occur in the baseline results, additional polygons were added to the same new layer as the woody debris. This was done in order to represent the addition of woodland introduced to the river banks in an attempt to still allow water to escape onto the floodplain but at reduced flow rates and velocities. These new woodland areas were applied the same Manning's n value of 0.07 as existing woodland within the model as the higher value better represents more substantial undergrowth.

Finally, woody debris was represented within the river channels at a number of locations where reductions in flow and velocity would likely be beneficial. As the river channels are represented by cross-sections with level and roughness data at varying intervals along the section chainage, representing woody debris is much more challenging. The most appropriate option, which was completed for this model scenario, is to alter the Manning's n values at different points in the chainage. Ground levels within the channel were left unchanged in order to avoid impeding flow too drastically and overcompensating the effects of minor blockages such as woody debris.

3.7.2 Scenario 2 - Wetland Attenuation Ponds

The second scenario to be added to the model and then simulated comprises the addition of riparian wetland ponds, with an aim to allow flooding in a controlled manner and to increase floodplain attenuation. When adding ponds within TUFLOW, there are a few different approaches that modify the ground levels within the DEM that TUFLOW uses. These generally involve the use of GIS layers that alter levels by a specified amount to a specific defined level at the location of a spatial object in the layer. Some of these methods would result in a straight drop rather than resulting in a drop with graded banks. Therefore, for the purpose of this study, the ponds were added to the model using the TUFLOW ZTIN layer method. This method essentially creates a TIN layer which will better represent the morphology of the existing topography while still creating a pond that would also comprise sloped banks. The ZTIN layer is created and comprises a spatially located polygon drawn to the desired size and shape and points which are contained within the polygon. The points are used as the reference point of level data for the TIN to triangulate between and these are placed throughout the desired base of the pond, as demonstrated by Figure 3.9 below, which shows the polygon and points being used to set new ground levels which result in the modified DTM also shown in Fig. 3.9.

Figure 3.9: Creation of wetland ponds using polygons and points to create a TIN, modifying the DTM (shown)

The ponds were to comprise a depth of 1m, ensuring that the base of the pond would not be smooth and flat but would instead be based on the existing topography. Due to the large number of points in the layer, current ground levels were applied using a point inspection tool based upon the unmodified DEM delivered from LiDAR. The data is then exported to Excel so that 1m can be easily removed from each level before the results are imported back into a GIS layer. The border of the polygon within the ZTIN layer represents the point at which the modified ground levels will merge back into the existing DEM. Therefore, the point are placed within the polygon with a gap maintained between the edge of the polygon. The triangulation that occurs when TUFLOW is run will result in smooth interpolation between points and from the points to the edge of the polygon, resulting in smooth and even bank slope. Due to the size of the ponds being larger than, a high-resolution grid is not essential. However, having a high-resolution of 1m means that the shape of the ponds could be highly defined. A final addition to the ZTIN layer is to add small channels to link some of the ponds. These drainage channels would allow ponds to fill sequentially and ensure that floodwater is retained within the ponds rather than spilling out of a pond once the peak capacity is reached. As these drainage channel are relatively small (approx. 1m within the channel and 2m between bank-tops), a high resolution grid allows for these to be well-defined and kept within the 2D domain rather than being modelled as a 1D culvert or open channel. A new materials layer is also created with polygons representing the ponds and channels so that an appropriate Manning's n of 0.035 could be applied to them via the TMF.

3.7.3 Scenario 3 - Re-meandering & Reconnecting to Floodplain

The third scenario to be modelled and subsequently simulated involves the re-meandering of the channel and reconnection of the river channel to the floodplain, with the aim of slowing flows and velocities and deliberately allowing flooding in open areas of floodplain where the impacts are less likely to be an issue. To achieve this, three locations on the River Greet upstream of Southwell were chosen. One of these locations comprises a significant meander already and would be used simply to test the lowering of the banks and adjacent floodplain to reconnect the channel to the floodplain. The remaining two locations were re-meandered and bank levels dropped at both locations, with one having the adjacent floodplain lowered and the other having its bank dropped to the existing floodplain level.

In order to re-meander the channel within TUFLOW, all of the layers that define the river channel's location were copied and amended. This involves moving any relevant points that represent 1D nodes that link back to the 1D model and adding a meander to the layer containing the river centreline and banks. As the bank heights in TUFLOW are defined by points within the channel boundary layer, these points were moved where the channel is re-meandered and edited for all three locations to drop the banks. The levels were dropped by a different amount at each location to suit the surrounding topography, but the amount varies between 200mm and 600mm. With the new meanders added to the relevant TUFLOW layers, a new ZTIN layer was created which was used to defined the floodplain lowering in two locations. As with Scenario 2, a polygon is added which defines the full area to be lowered, with points added to the base area to define the levels to be lowered to and a gap between the group of points to the edge of the polygon to define a slope. However, the difference to the ZTIN layer in Scenario 3 would be that the edge closest to the river channel would need to match the defined bank level rather than the existing levels in the DEM, while the edge of the polygon on the opposite side would need to match the existing ground levels in the DEM and the other edges would need to be graded between the two, essentially creating a basin or pond with an open, flat bank on one side. In order to achieve this, points are snapped to the edge of the polygon where levels need to be defined. The points along the river bank were set to that of the new lowered river bank level, with the points on the opposite side of the polygon edge set to existing ground levels. This process is demonstrated by Figure 3.10 below, which shows the use of a polygon with points containing elevation data in order to set new ground levels, resulting in the DTM also shown in Fig. 3.10.

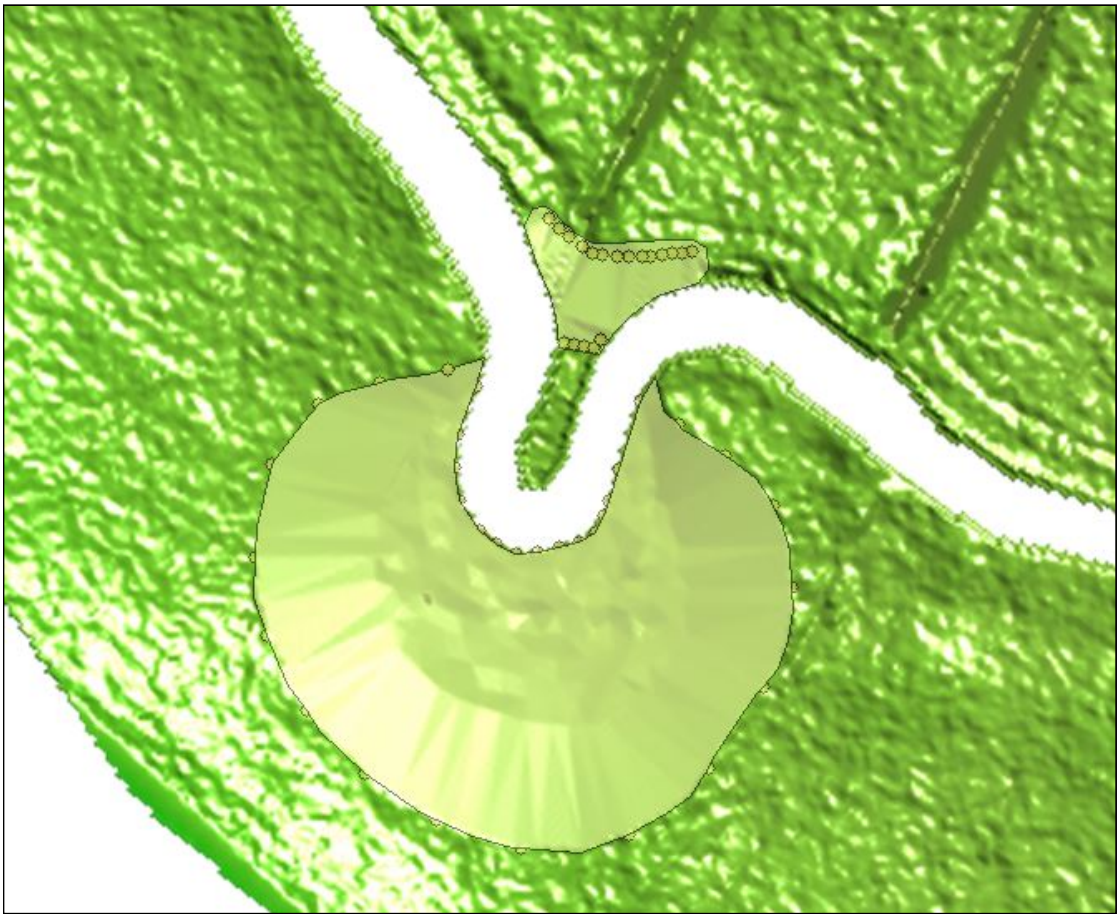


Figure 3.10: Creation of new channel meanders using polygons and points to create a TIN, modifying the DTM (shown). The old channel course is removed using the same method

While the channel boundary layers have been moved, the DEM still reflects the original course of the river channel and needs to be removed. This is done using additional polygons and points within the ZTIN to cover the old channel area and raise levels to the floodplain level. A materials layer is also created and the former channel areas that are no longer desired are patched by a polygon, with a new Manning’s n value which matches the surrounding floodplain.

As the channel geometry has been altered within the 2D model, it also requires modifying within the 1D model. Within Flood Modeller, the relevant cross-sections are edited, with the bank heights amended to match those set in the TUFLOW bank points layer. As the meanders have also lengthened the river channel, the Distance To Next values also need to be recalculated and changed.

3.7.4 Scenario 4 - Combined Methods

The final model scenario consists of all methods adopted under Scenario 1, 2 and 3 combined. In order to achieve this the model files generated under the previous scenarios are used. The Flood Modeller network for Scenario 4 will remain unchanged from Scenario 3, so the files used within Flood Modeller for Scenario 3 are simply used again. While the GIS layers from all previous scenarios can be used for TUFLOW, alterations are required due to conflicts. In the case of Scenario 4, the channel boundary and definition layers from Scenario 3 are used. However, the ZTIN and materials layers for all three previous scenarios are combined together into a new layer and conflicts where woody debris, ponds and the re-meandered channels overlap are edited, first by removing the woody debris and then ponds where required. Some minor changes were also made to the positioning of riparian woodland, with woodland removed at the new channel meanders and then new woodland placed to the edge of the lowered floodplain.

4 Results, Findings & Analysis

This section discusses and analyses the results of three modelled hydrological flood events: the 1 in 10-year (10% AEP); the 1 in 50-year (2% AEP); and, the 1 in 100-year (1% AEP) plus 30% climate change. While seven hydrological flood events were modelled for each scenario, the three chosen event provide an acceptable spread, representing a low order, a medium order and a high order event.

4.1 Baseline

Figures 4.1, 4.2 and 4.3 below show the Baseline maximum depth and flood extent results for the 1 in 10-year (10% AEP), 1 in 50-year (2% AEP) and 1 in 100-year (1% AEP) plus 30% climate change events respectively. These results are used in comparison with the results of Scenarios 1, 2, 3 and 4 in turn later in this section. However, some observations are made regarding the flooding that occurs under Baseline conditions. Flooding during the 1 in 10-year (10% AEP) event is shown to occur in three distinguishable areas: upstream on the River Greet; the middle of the reach on the River Greet; and, the downstream end of the River Greet. There are clear breaks in the extent of flooding between these three areas, as shown by Figure 4.1 below. It is also noted that no flooding occurs on Potwell Dyke during the 1 in 10-year (10% AEP) event.

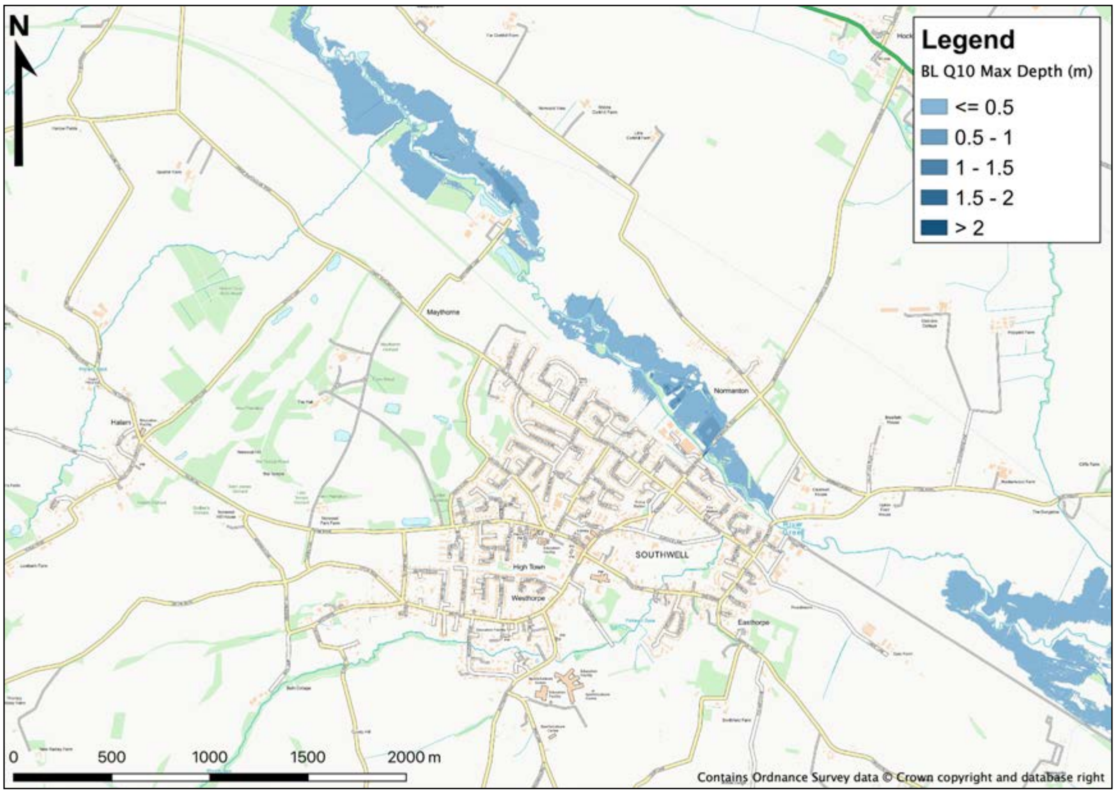


Figure 4.1: Baseline - 1 in 10-year (10% AEP) Max Depth (m)

During the 1 in 50-year (2% AEP) event, shown in Figure 4.2 below, flooding is seen to start at the upstream end of the River Greet and continue downstream to the confluence with Potwell Dyke. The flooding at the downstream end of the River Greet is still completely separated from the rest of the flooding observed, though the overall extents and maximum depths of the flooding are greater than observed during the 1 in 10-year (10% AEP) event, as is to be expected. The first properties are also shown to be affected by flooding, in the village of Maythorne within the upstream reach of the River Greet. Flooding is also observed on Potwell Dyke, though relatively minor as it affects open floodplain in the downstream end of the watercourse and is constrained to Nottingham Road in the middle of the reach.

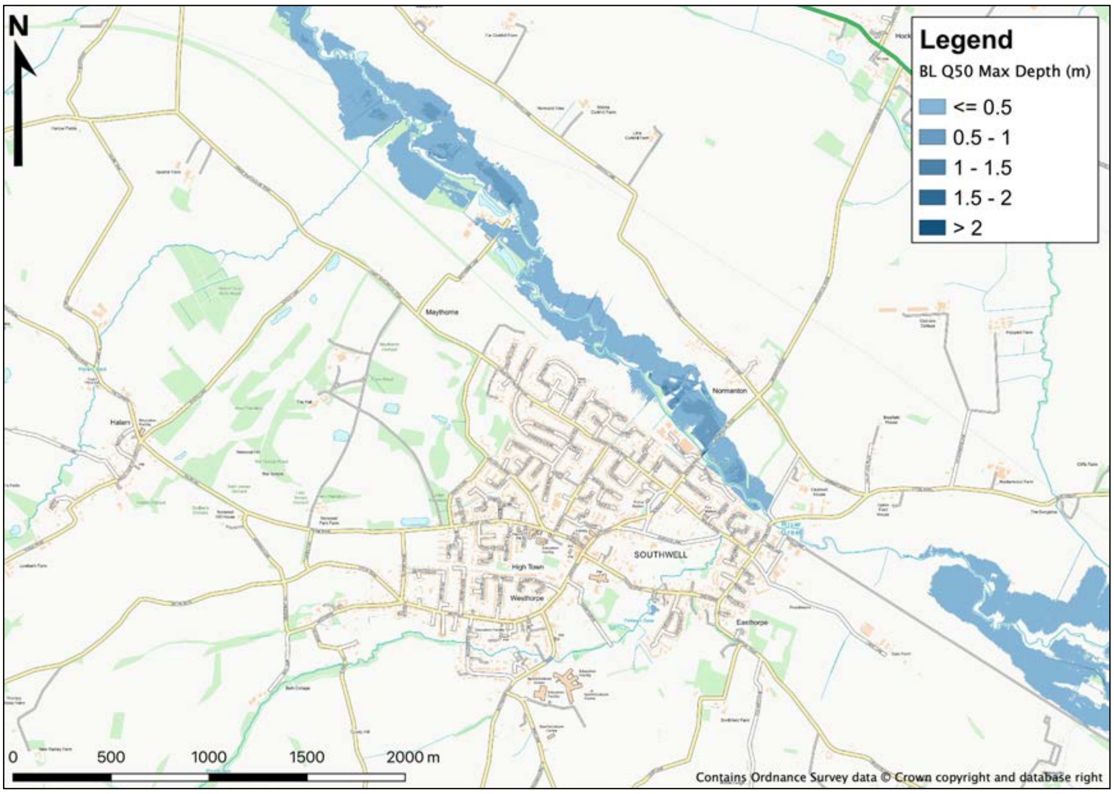


Figure 4.2: Baseline - 1 in 50-year (2% AEP) Max Depth (m)

During the 1 in 100-year (1% AEP) plus 30% climate change event, flooding on the River Greet is observed throughout the full reach, with no distinguishable breaks in flooding. The extents and maximum depths of flooding, shown below in Figure 4.3, throughout the model domain are much greater than has been observed in the previous two events which, again, is to be expected. Flooding within the village of Maythorne has increased and properties that back onto the right bank of the River Greet, immediately downstream of Normanton Road in Southwell are shown to be affected. The flooding on Potwell Dyke, while still not severe, now impacts properties upstream of Church Street and the flooding that occurs on Nottingham Road has also increased.

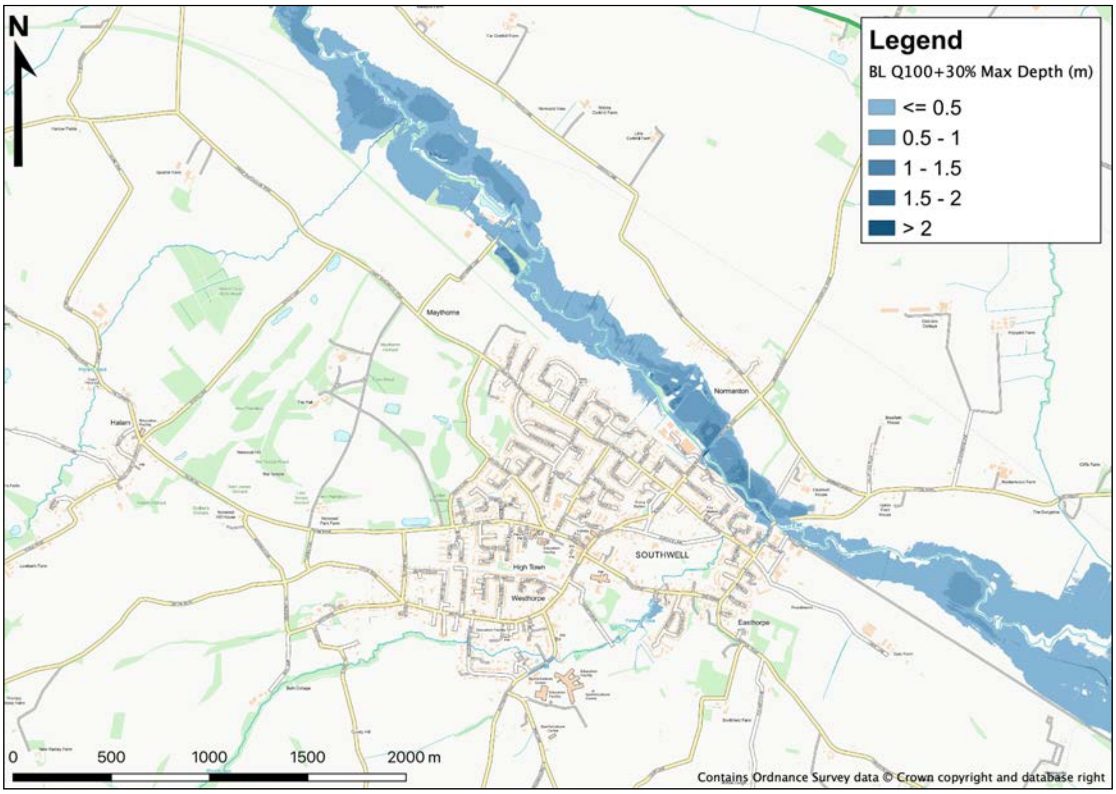


Figure 4.3: Baseline - 1 in 100-year (1% AEP) plus 30% Climate Change Max Depth (m)

4.2 Scenario 1 - Woody Debris & Woodland

Figure 4.4 below shows the maximum predicted flood depth of the 1 in 10-year (10% AEP) event for Scenario 1, which comprises the addition of individual woody debris and woodland within the floodplain and woody debris within the river channel. In general, there are increases in the extents and depths of floodwater can be seen in the upstream floodplain of the River Greet where woody debris and woodland have been modelled, with decreases further downstream where the model has been left unchanged from the Baseline. Potwell Dyke is shown to remain free of flooding during the 1 in 10-year (10% AEP) event.

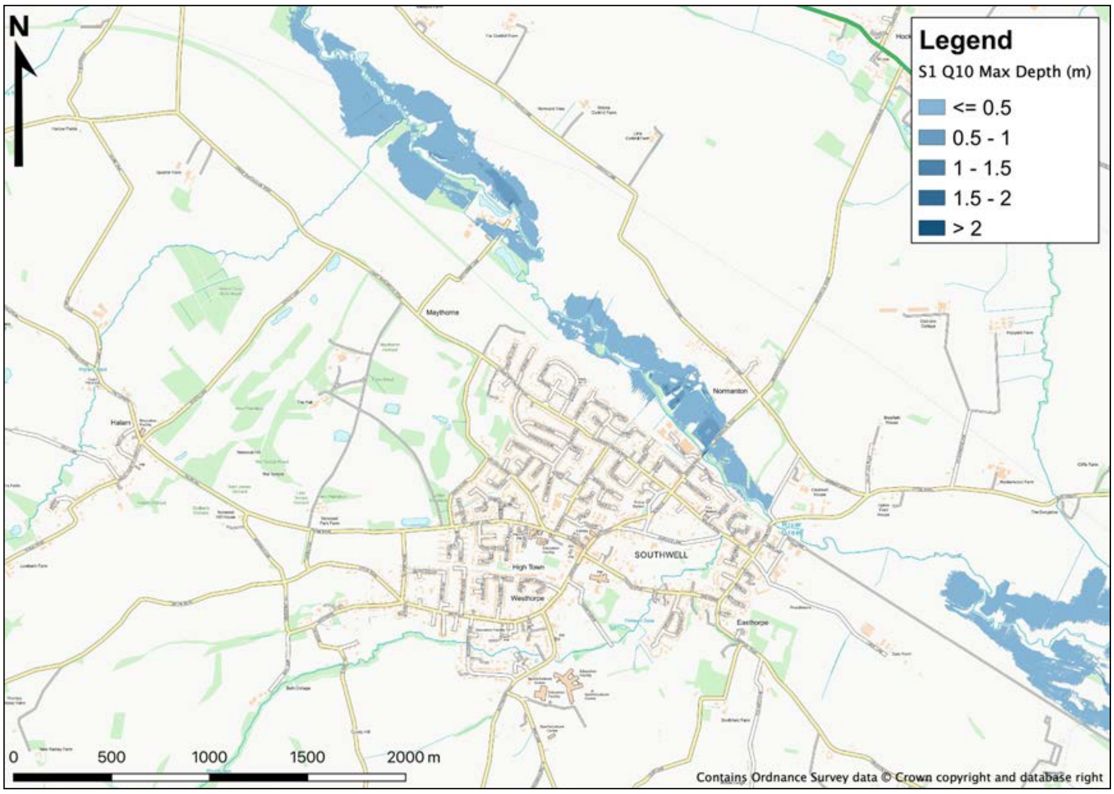


Figure 4.4: Scenario 1 - 1 in 10-year (10% AEP) Max Depth (m)

Figure 4.5 below shows the difference between the 1 in 10-year (10% AEP) maximum flood depth for Scenario 1 and the results of the same event for the Baseline model, providing a more comparable representation of the results. The difference grid generated shows a large area of increased flood depth within the floodplain adjacent to the right bank of the River Greet in the upstream extents of the reach, with increases of >0 <=0.15m during Scenario 1, with smaller areas, including adjacent to the left bank of the River Greet, showing increases of >0.15 <=0.3m. Increases in flood depth within these areas are expected due to the presence of woody debris and woodland blocking flow paths and reducing velocities within the floodplain, retaining floodwater within that particular part of the floodplain for longer and increasing the storage capacity of the floodplain. A general decrease of maximum flood depth of upstream on the River Greet and adjacent to the left bank of >-0.15 <=-0.001m is observed, though increases of >0 <=0.15m can be seen in places due to localised depressions. This general decrease suggests that the presence of woody debris adjacent to the left bank has less of an effect on flood depths and that the presence of woodland along the bank makes it more difficult for water to leave the channel over the left bank, encouraging water to spill over the right bank instead. Similar decreases with minor, localised increases due to depressions within the topography are shown to occur on the mid and downstream extents of the River Greet. Finally, a small, localised area of flood depth increase of >0.3m is shown to occur adjacent to Maythorne Lane.

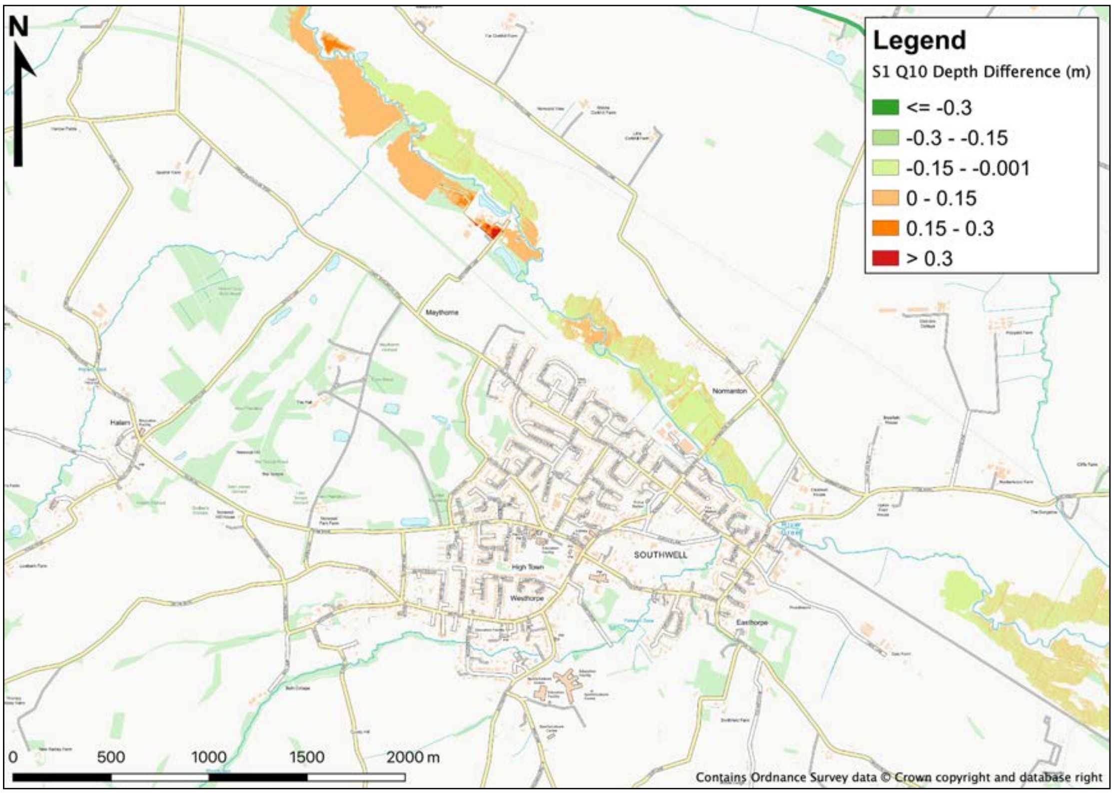


Figure 4.5: Scenario 1 - 1 in 10-year (10% AEP) Depth Difference (m)

During the 1 in 50-year (2% AEP) flood event, the effects that woody debris and increased woodland have become less proficient. Figure 4.6 below shows the maximum depth during the event is very similar to that of the Baseline, with some relatively minor changes to the extents and depths that occur.

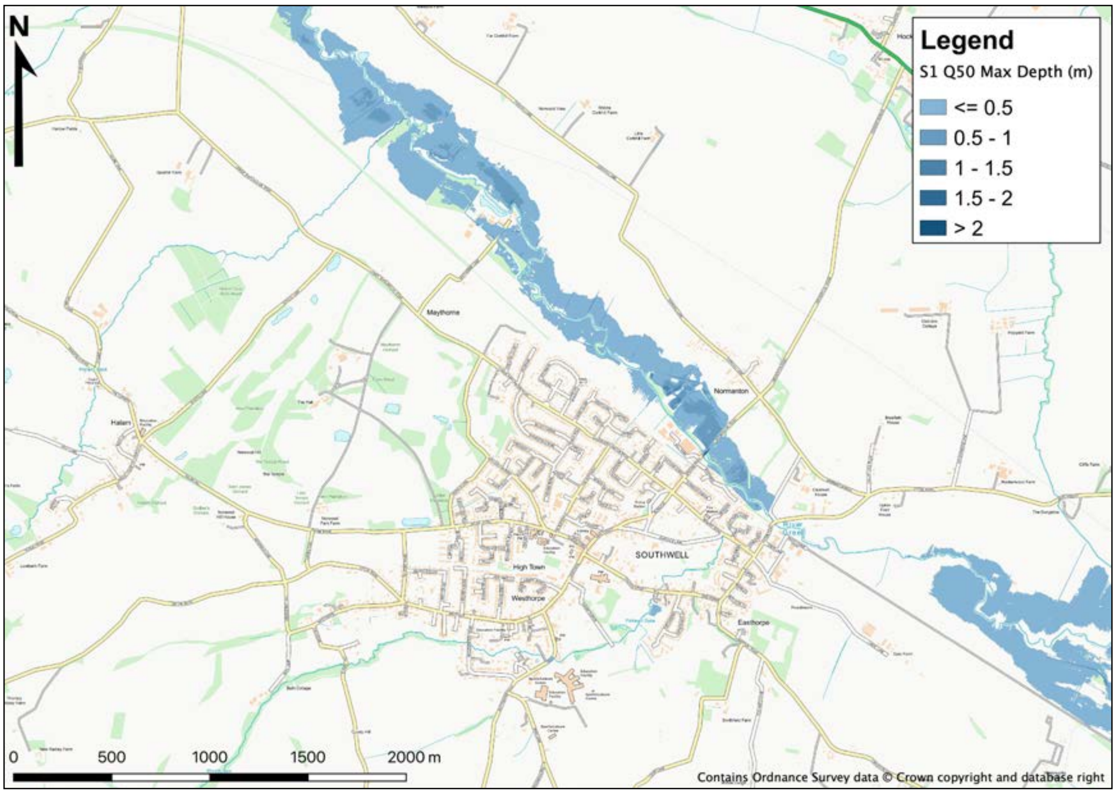


Figure 4.6: Scenario 1 - 1 in 50-year (2% AEP) Max Depth (m)

Figure 4.7 below shows that the difference in maximum depth between Scenario 1 and the Baseline during the 1 in 50-year (2% AEP) event shows a similar relationship to that of the 1 in 10-year (10% AEP) event. However, the extent of the increases at the upstream end of the reach adjacent to the right bank, showing an increase of >0.15 <=0.3m, cover a much larger area, which is to be expected for a larger flood event. However, the areas showing a positive reduction in flood depth of >-0.15 <=-0.001m adjacent to the left bank and downstream in the mid and lower extents of the reach downstream have reduced in extent. Where minor increases of >0.15 <=0.3m and minor decreases of >-0.15 <=-0.001m are shown to be mixed, particularly in the middle and downstream of the reach, suggests that depth differences between the Baseline and Scenario 1 are very marginal around 0m and are displayed differently due to the categorisation used to represent depth increase and decrease.

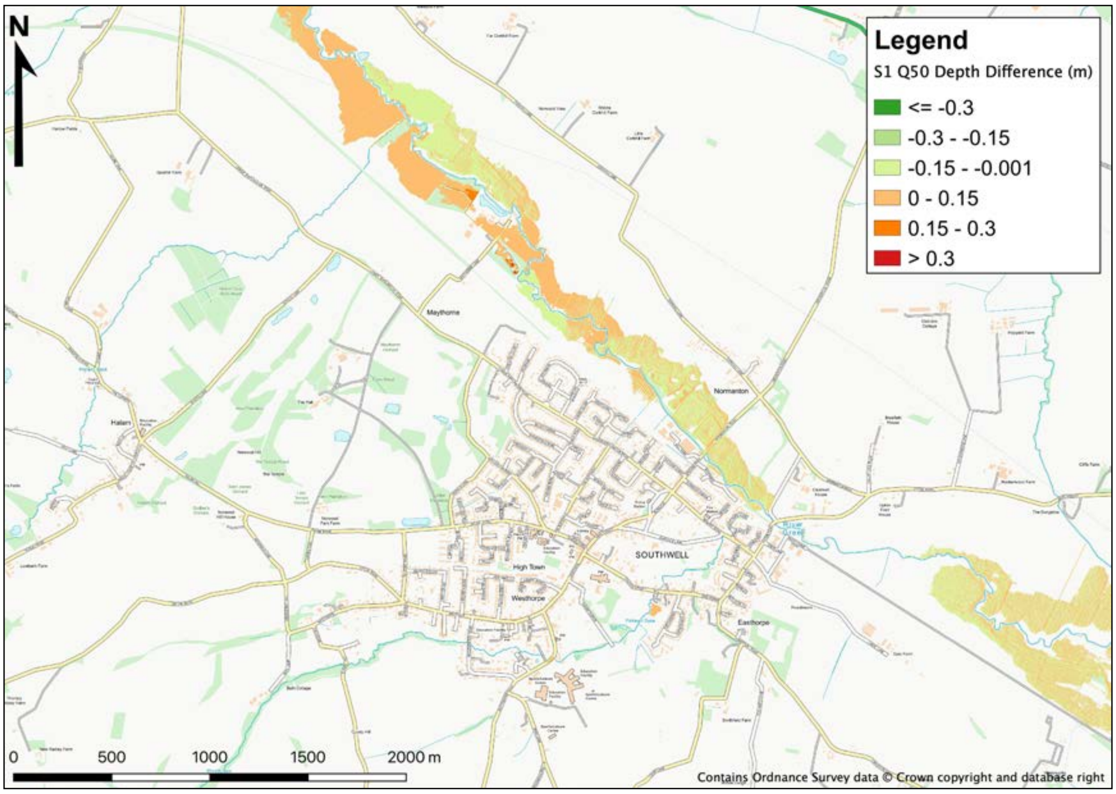


Figure 4.7: Scenario 1 - 1 in 50-year (2% AEP) Depth Difference (m)

Figure 4.8 below shows the maximum depth during the 1 in 100-year (1% AEP) plus 30% climate change flood event for Scenario 1 which, when compared to the Baseline results for the same event, appear to be very similar. The extents and depths during this substantial flood event appear to be relatively unaffected by the addition of woody debris and woodland, with results appearing relatively indifferent to those of the same event for the Baseline shown in Fig. 4.3.

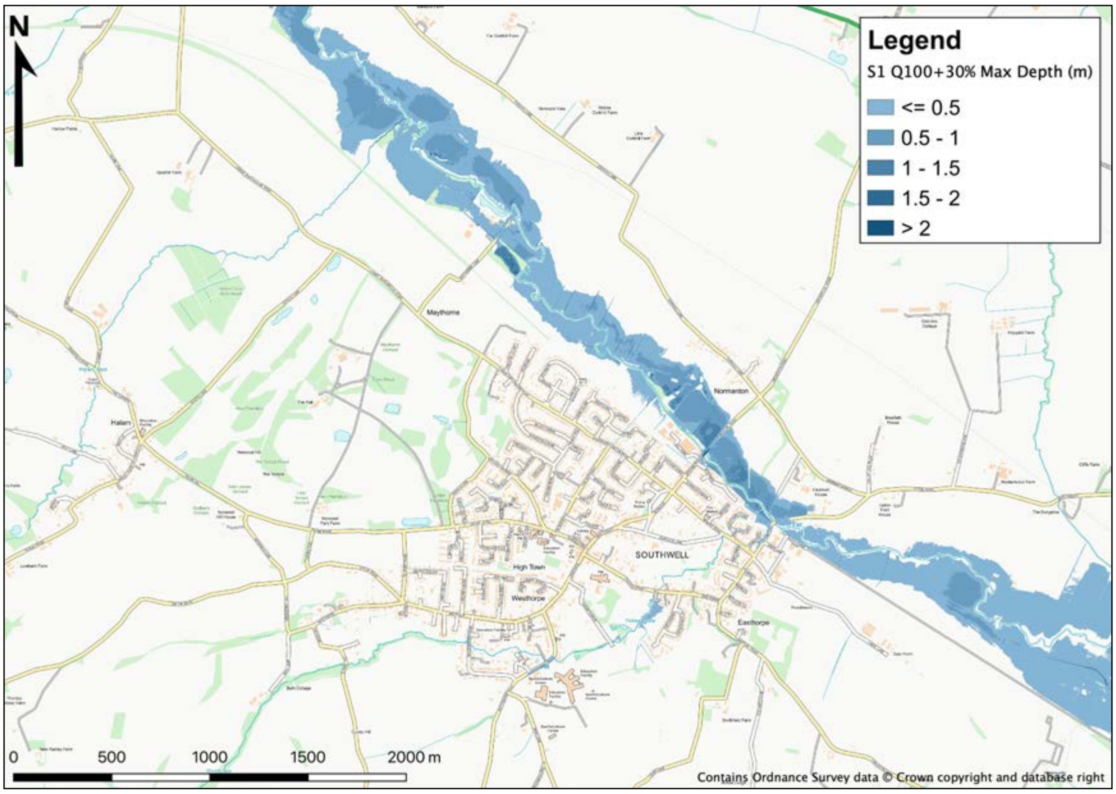


Figure 4.8: Scenario 1 - 1 in 100-year (1% AEP) plus 30% Climate Change Max Depth (m)

Figure 4.9 below however, shows the changes in maximum depth occurring during the 1 in 100-year plus 30% climate change event between Scenario 1 and the Baseline simulations. While the extents of flooding appears to be relatively similar between the scenarios, flood depths are generally greater upstream where woody debris and woodland are present. This is particularly the case at the upstream adjacent to the right bank. As has been observed with the less onerous flood events, a large area adjacent to the left bank in the upstream end of the reach shows a decrease in depth of >-0.15 <=-0.001m. The mixed marginal depth differences observed for the smaller events are no longer present, with increases and decrease being more segregated.

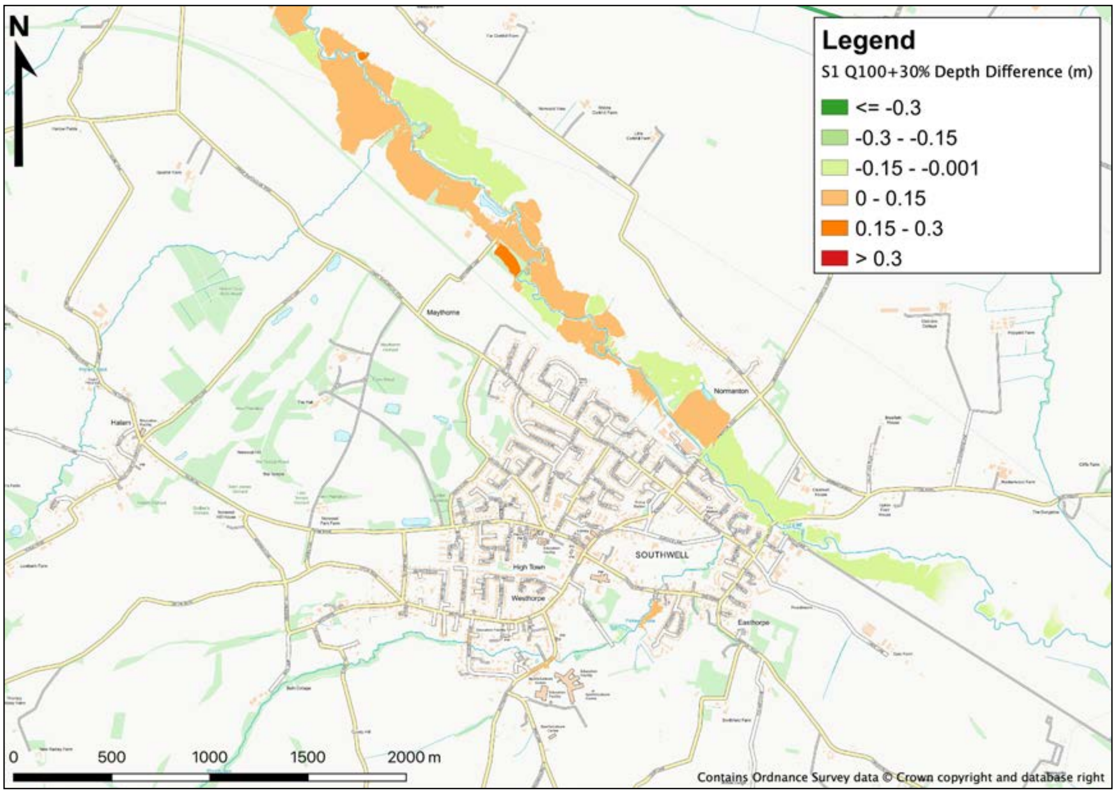


Figure 4.9: Scenario 1 - 1 in 100-year (1% AEP) plus 30% Climate Change Depth Difference (m)

Figure 4.10 below shows the Baseline maximum velocity for the 1 in 100-year (1% AEP) plus 30% climate change at the same location upstream, referred to as 'Location A'. During this event, water is shown to spill out of bank at a rate in excess of 1.2m/s. Due to the rural nature of this location, flooding should be encouraged as ample flood storage is available without presenting a severe risk to people or property. However, with the relatively high velocity that the bank spill into the floodplain occurs during this event, rapid inundation will occur and the capacity of the adjacent floodplain will be reached much sooner during the event.

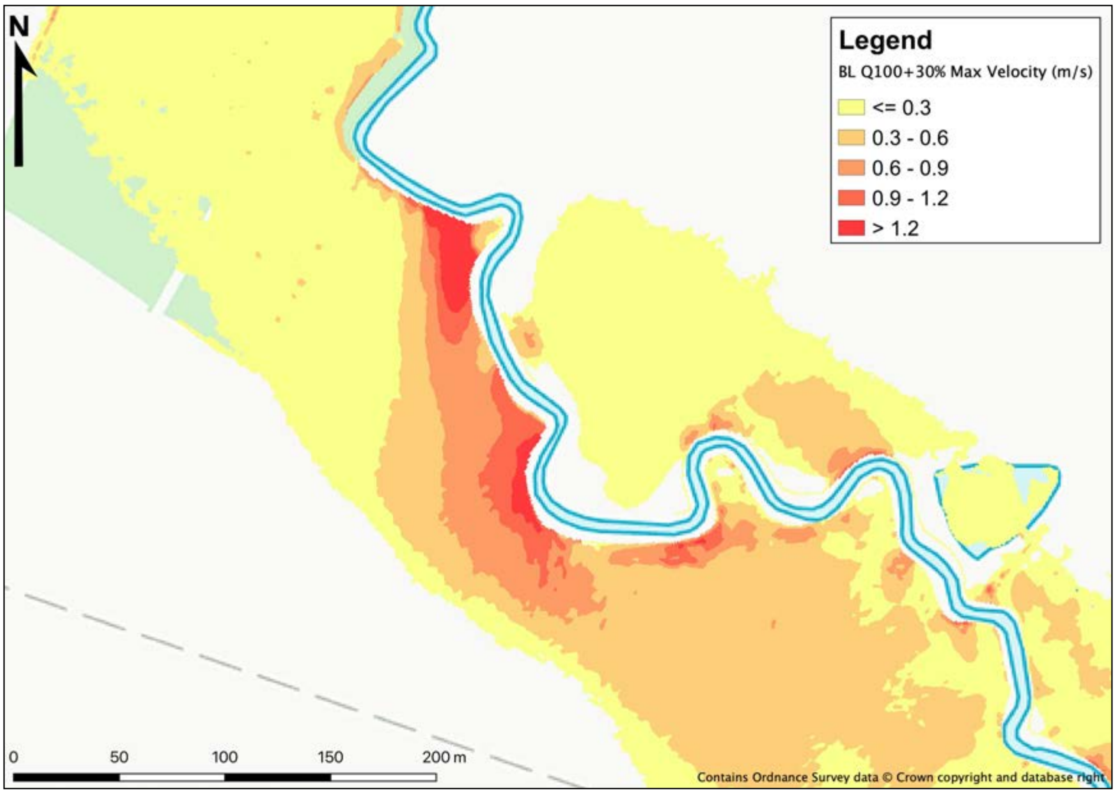


Figure 4.10: Baseline - 1 in 100-year (1% AEP) plus 30% Climate Change River Greet 'Location A' Velocity (m/s)

Figure 4.11 below shows that, while the placement of individual woody debris within the floodplain appears to have a marginal effect by slightly reducing velocities in places by >-0.15 <=-0.001, the placement of woodland along the banks has a significant effect, particularly in Location A. With in excess of 1.2m/s of flow occurring during the Baseline, the presence of woodland along the banks results in a reduction of over 0.3m/s, bringing the velocity to below 0.9m/s. While the velocity has been significantly reduced, water is still able to spill into the floodplain and utilise the storage volume of the floodplain.

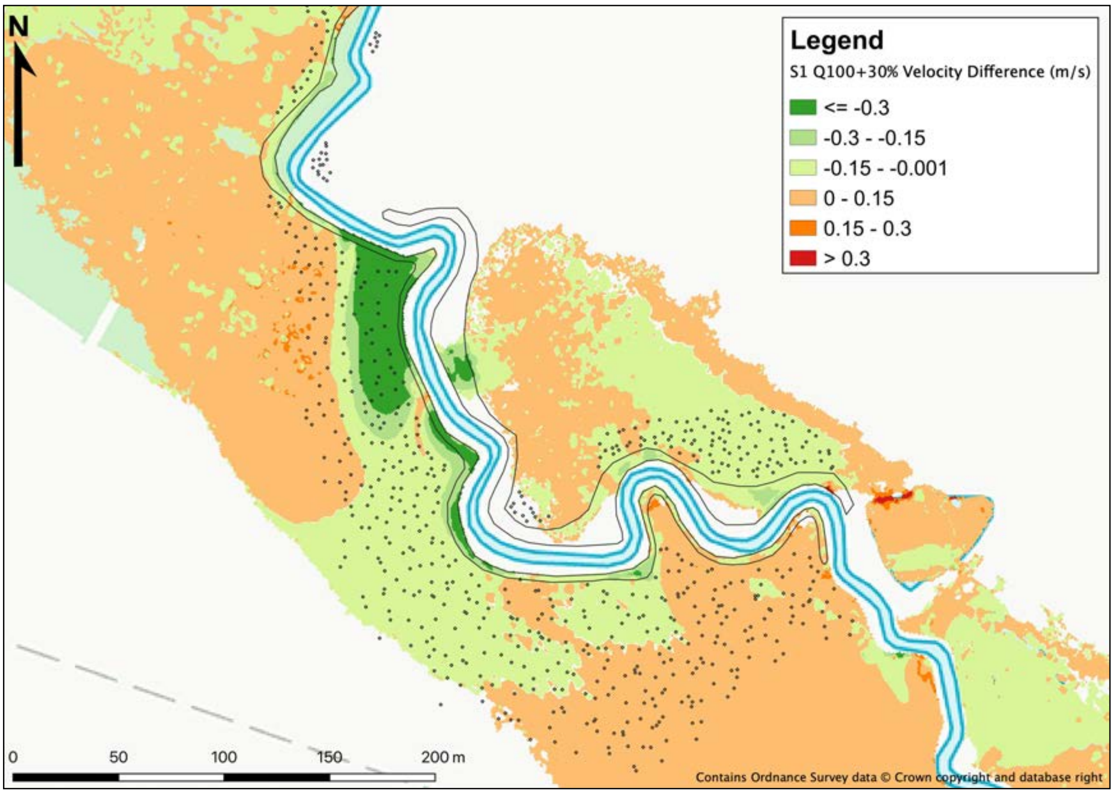


Figure 4.11: Scenario 1 - 1 in 100-year (1% AEP) plus 30% Climate Change River Greet 'Location A' Velocity Difference (m/s)

Figures 4.12 and 4.13 show the difference between the Baseline and Scenario 1 in 10-year (10% AEP) flood event maximum depth and maximum velocity respectively in the village of Maythorne adjacent to the River Greet, referred to as 'Location B'. The results show a narrow flow path through woodland upstream which continues through Maythorne to Maythorne Lane. As part of Scenario 1, in an attempt to reduce the flow velocities observed in the Baseline, woody debris was arranged to form several barriers. Figures 4.12 and 4.13 below show that maximum flood depth and maximum flood velocity in Location B, particularly along the narrow flow path, have increased significantly, suggesting that the woody debris barriers have been ineffective and have potentially worsened flooding conditions in the village. As the velocity of floodwater along the flow path is shown to greatly increase, water becomes trapped in a low-spot adjacent to Maythorne Lane and, as a result, peak flood depths are increased significantly. A potential cause of the increases in velocity in Fig. 4.13 and subsequent increases in maximum depth observed would appear to be an increase in water being stored within the floodplain upstream of Location B, which is shown in Fig. 4.12.

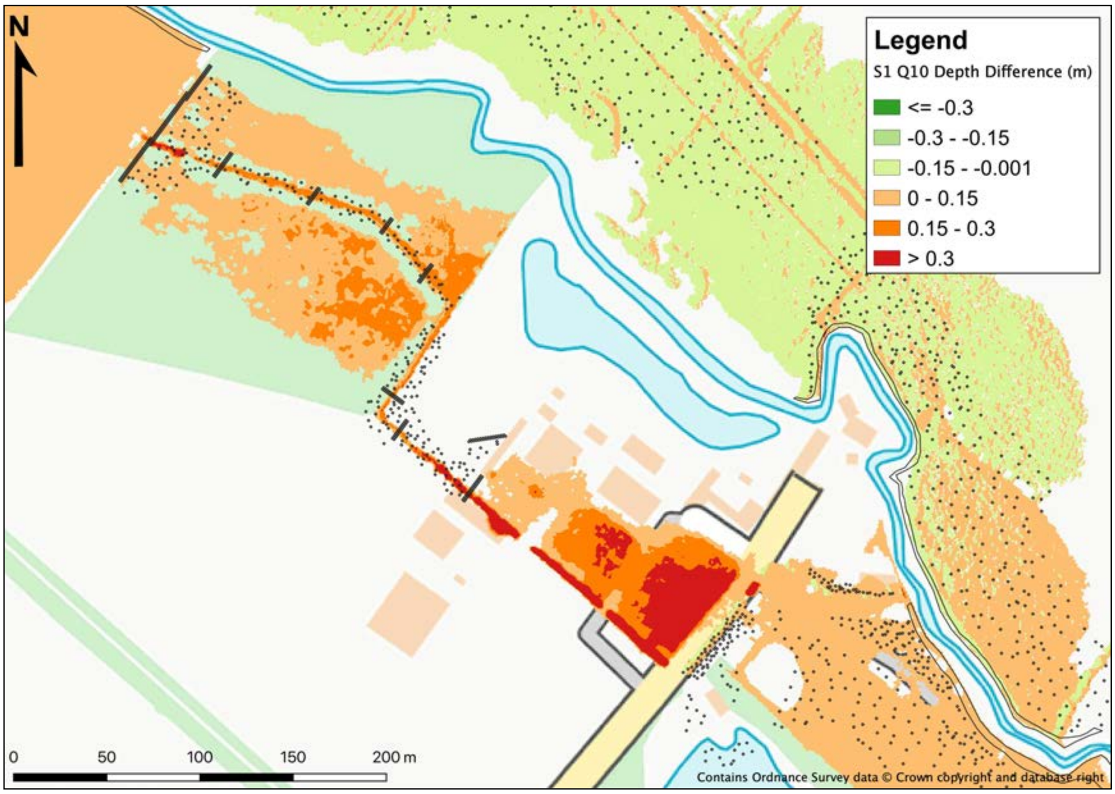


Figure 4.12: Scenario 1 - 1 in 10-year (10% AEP) Maythorne Flooding ‘Location B’ Depth Difference (m)

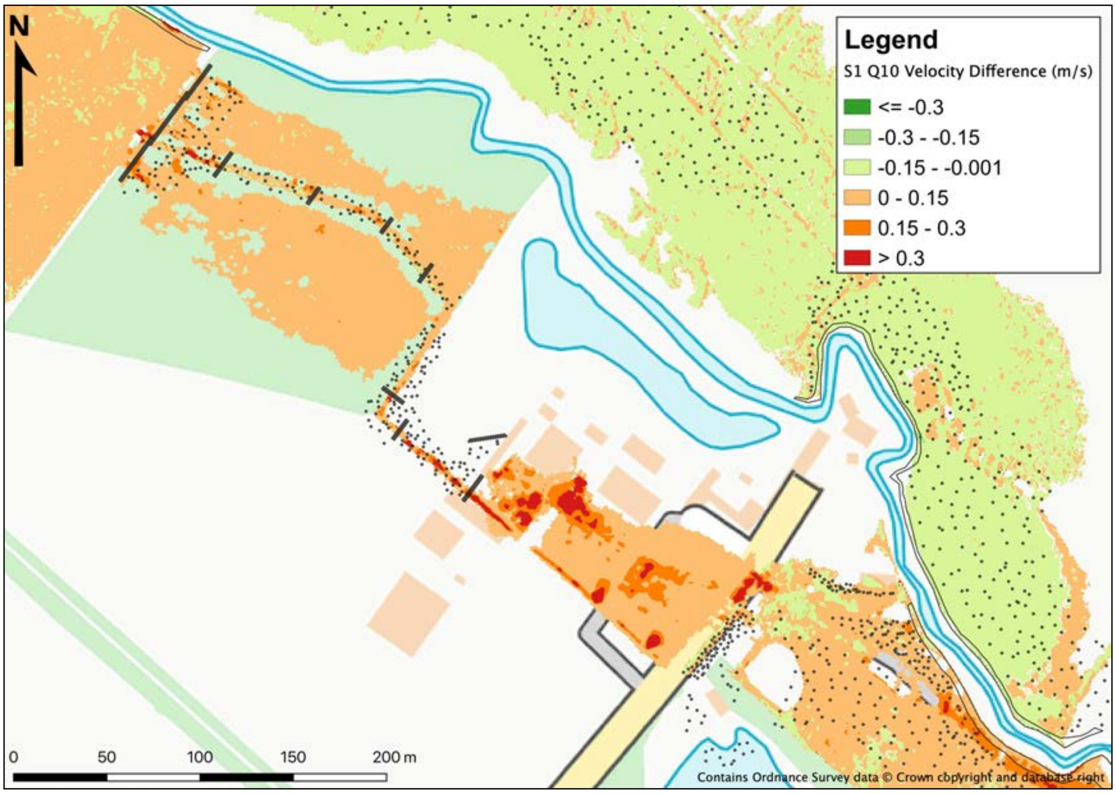


Figure 4.13: Scenario 1 - 1 in 10-year (10% AEP) Maythorne Flooding ‘Location B’ Velocity Difference (m/s)

Although it is to a smaller extent, similar effects to those shown at Location A are observed with flooding from Potwell Dyke, focusing on an area referred to as ‘Location C’. Figure 4.14 below shows that the combined use of woodland along the right bank and scattered woody debris within the floodplain has resulted in a decrease in velocity of >-0.15 <=-0.001 in the flow of water spilling into the floodplain during the 1 in 100-year (1% AEP) plus 30% climate change event. However, as water reaches beyond the woodland and woody debris velocities are shown to increase slightly by >0 <=0.15.

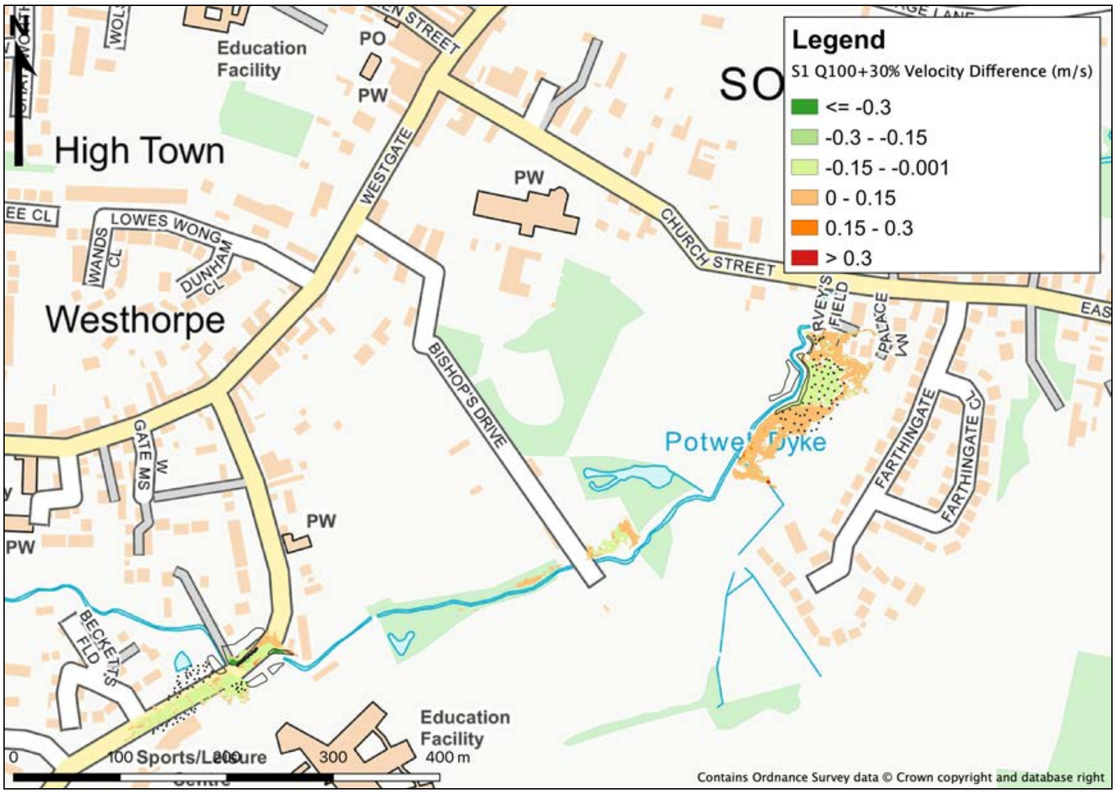


Figure 4.14: Scenario 1 - 1 in 100-year (1% AEP) plus 30% Climate Change Potwell Dyke ‘Location C’ Velocity Difference (m/s)

4.3 Scenario 2 - Wetland Floodplain Storage

Figure 4.15 below shows the maximum predicted flood depth of the 1 in 10-year (10% AEP) event for Scenario 2 which comprises the addition of wetland attenuation ponds within the floodplain. When compared visually to the baseline results for the same event in Figure 4.1, shows flooding to a much lesser extent. This is particularly the case around the village of Maythorne, where flooding no longer occurs, upstream of Southwell and Hockerton Road, where the extent of flooding has noticeably decreased and at the downstream extent of the reach where flooding has dramatically decreased. The maximum flood depths also appear to have improved, with depths of >2m only occurring within the newly added wetland ponds. Outside of the ponds, flood depths are generally >0.5 <=1m to the upstream end of the reach and <=0.5m to the middle and downstream end of the reach.

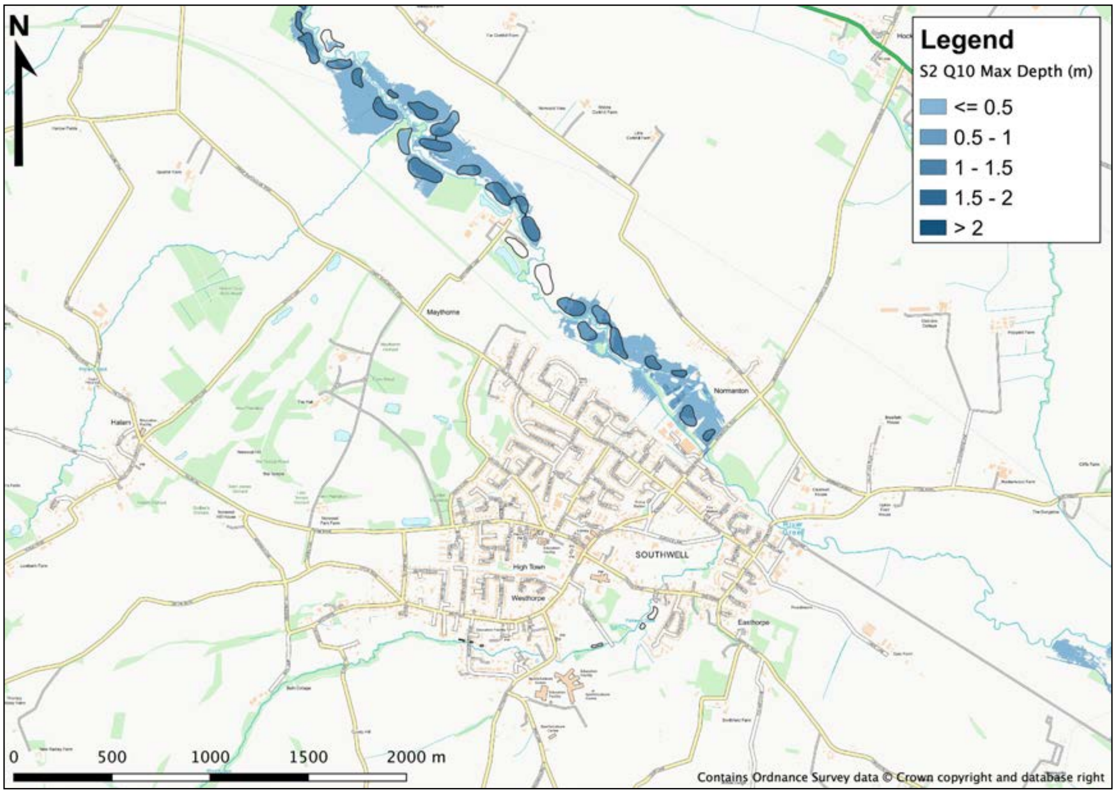


Figure 4.15: Scenario 2 - 1 in 10-year (10% AEP) Max Depth (m)

Figure 4.16 below displays the difference between the 1 in 10-year (10% AEP) maximum flood depth for Scenario 2 and the results of the same event for the Baseline model and shows that flood depths have decreased >-0.001 <=-0.3m and in excess of -0.3m in places, particularly downstream of Normanton Road. In places, flooding has been completely prevented, leaving areas dry. The only increases in flood depth seen during this model simulation have occurred within the wetland storage ponds, indicating that they are working effectively at retaining floodwater volumes to reduce and even prevent flooding downstream.

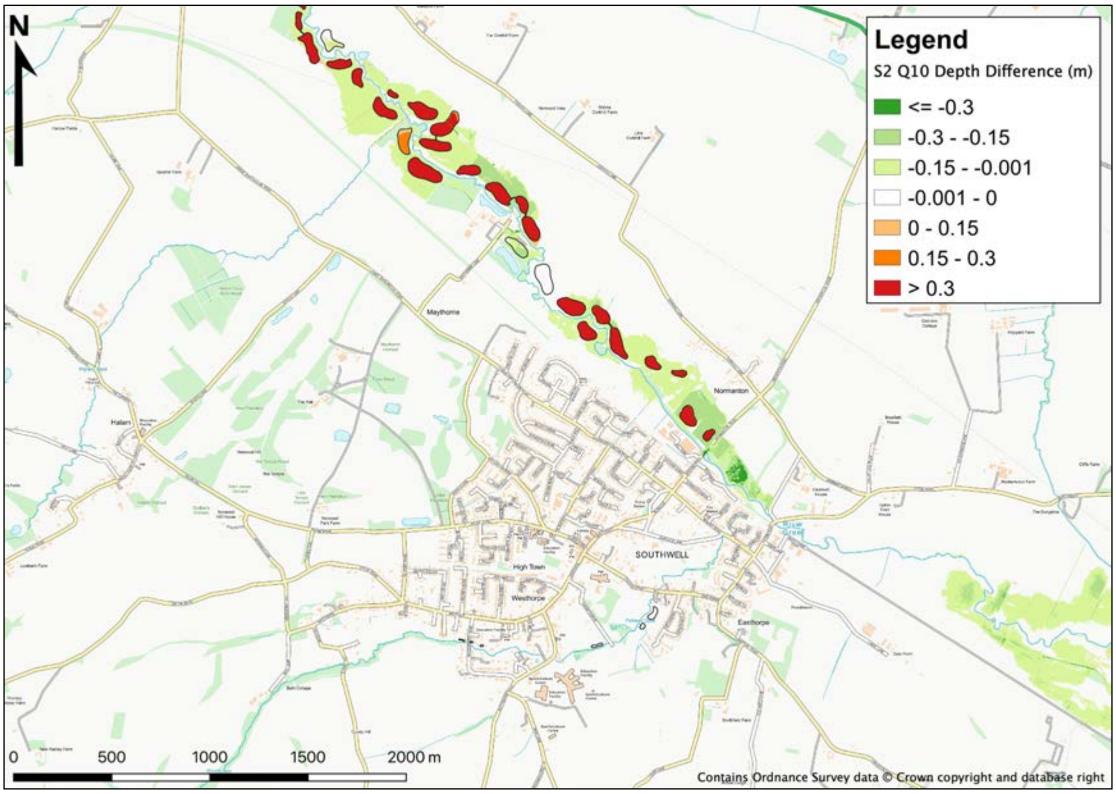


Figure 4.16: Scenario 2 - 1 in 10-year (10% AEP) Depth Difference (m)

Figure 4.17 below shows that, during the 1 in 50-year (2% AEP) event, the extents and depths of flooding appear relatively unchanged during Scenario 2 when compared directly to the results of the same event during the Baseline. However, in places, the extents of flooding are shown to be smaller, though to a much lesser degree than can be seen with the 1 in 10-year (10% AEP) event. This is particularly noticeable in and around the village of Maythorne where flooding is shown to occur to the centre of the village and to the northwest during the Baseline 1 in 50-year (2% AEP) event, as shown in Figure 4.2. As Figure 4.17 shows, there is no flooding to the village of Maythorne itself, with the extent of flooding immediately to the northwest reduced due to the storage provided by the wetland ponds.

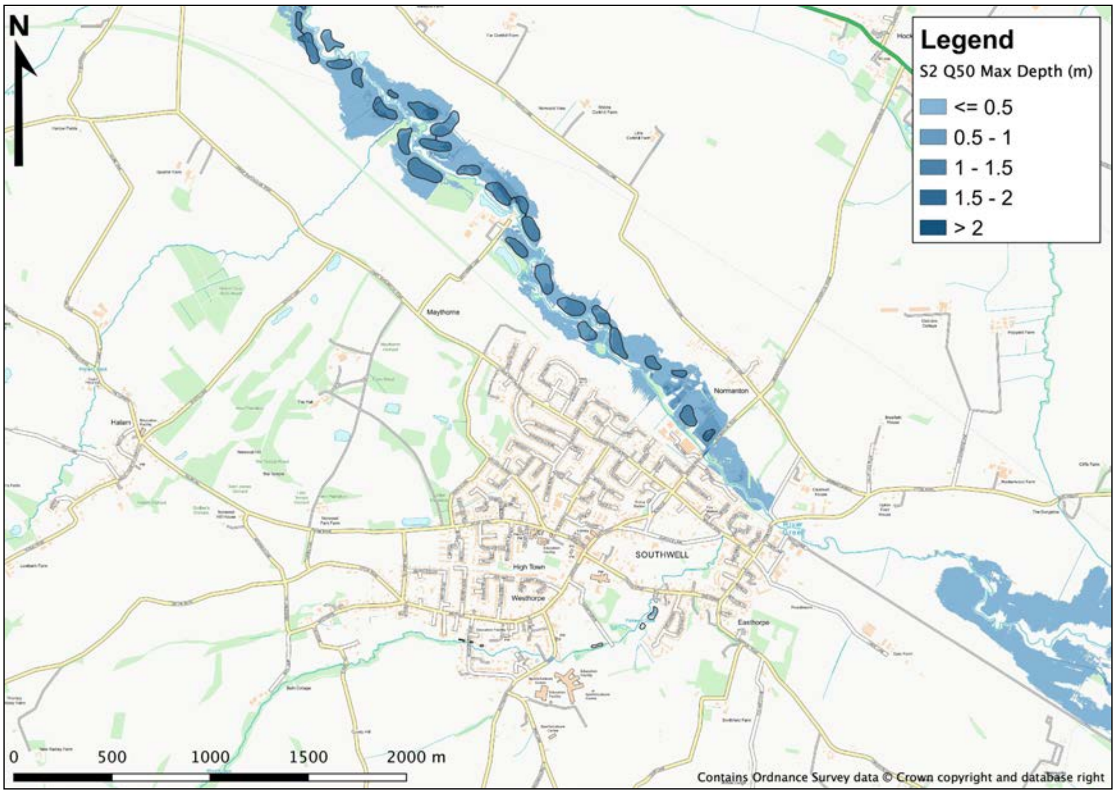


Figure 4.17: Scenario 2 - 1 in 50-year (2% AEP) Max Depth (m)

While the extents of flooding between the Baseline and Scenario 2 appear broadly similar across the majority of the model domain, Figure 4.18 below shows that a general decrease in the depth of flooding that does occur of >-0.15 <=-0.001m across much of the model domain, with greater decreases of <=-0.3 in Maythorne. The addition of ponds along the banks of Potwell Dyke has also seen flooding decrease. However, the flooding that occurs on Nottingham Road as it crosses Potwell Dyke has remained unchanged due to it being the first point shown to flood, which cannot be mitigated by adding additional floodplain storage upstream where flooding does not occur. In places, an increase in flood depth of >0 <=0.3m can be seen to occur, particularly adjacent to the right bank between Maythorne and Southwell and adjacent to the right bank at the downstream end of the River Greet. These increases are shown to occur on Greenfield land and do not appear to affect any properties.

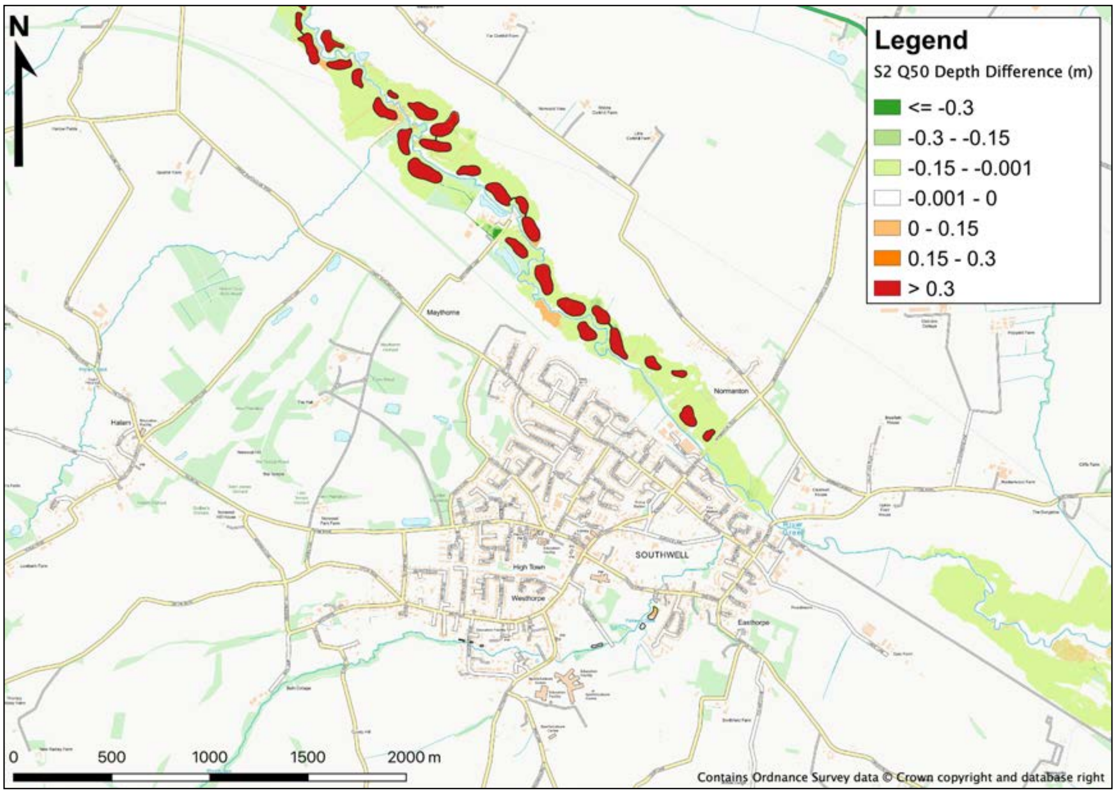


Figure 4.18: Scenario 2 - 1 in 50-year (2% AEP) Depth Difference (m)

Figure 4.19 below shows that, during the 1 in 100-year (1% AEP) plus 30% climate change event, the addition of the wetland ponds appears to have made little difference to the extent of flooding shown when compared directly to the results of the Baseline, shown in Figure 4.3. The areas that were previously shown to benefit from the ponds during lesser events, particularly Maythorne, are shown to flood during Scenario 2, suggesting that the volumetric capacity of the ponds has been exceeded and they have become fully inundated.

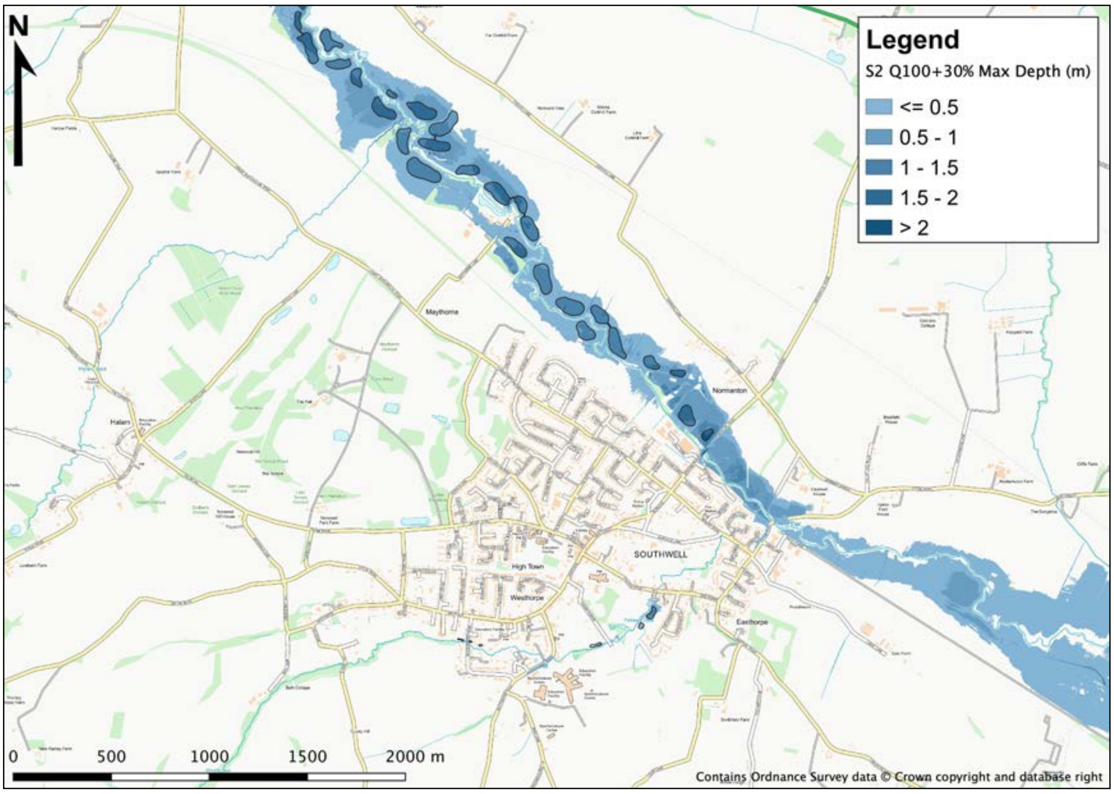


Figure 4.19: Scenario 2 - 1 in 100-year (1% AEP) plus 30% Climate Change Max Depth (m)

As has been observed with the results of the 1 in 50-year (2% AEP) event for Scenario 2, the ponds are incapable of dramatically reducing the extent of flooding but have resulted in a reduction in the depth of floodwater. Figure 4.20 indicates that, in general, the difference in depth between the Baseline and Scenario 2 is >-0.15 <=0.001m throughout much of the floodplain, with a difference of >-0.3 <=-0.15m in a couple of isolated places. However, increases of >0 <=0.15m are shown to occur to a greater extent during the 1 in 100-year (1% AEP) plus 30% climate change event when compared to the same results for the 1 in 50-year (2% AEP) event. This increase is generally seen immediately downstream of several ponds, suggesting the increase occurs as a result of water spilling out of the pond as it pushes downstream.

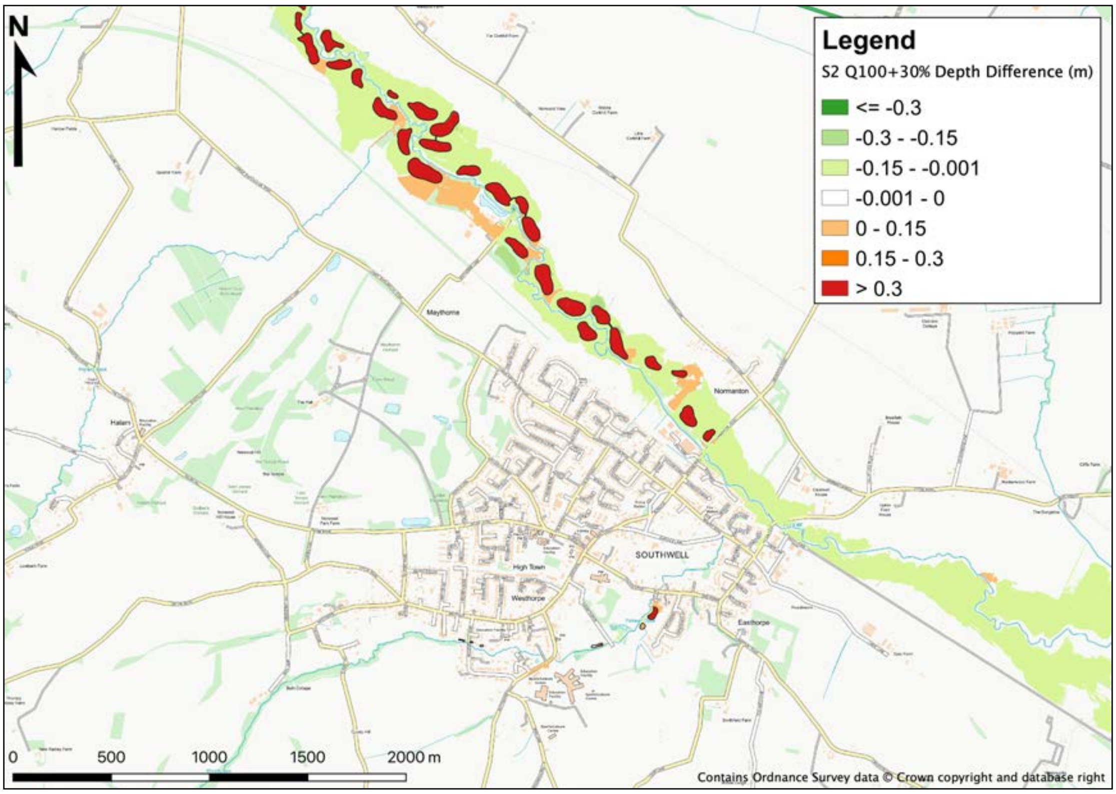


Figure 4.20: Scenario 2 - 1 in 100-year (1% AEP) plus 30% Climate Change Depth Difference (m)

By building a model with a high resolution, small, refined features within the floodplain can be represented and coarse results can be avoided. Figure 4.21 below shows the maximum velocity during the 1 in 50-year (2% AEP) flood event for Scenario 2, focusing on three wetland ponds which have been linked by swales within the floodplain to the opposite side of the River Greet to the village of Maythorne. While the swales are more than 1m wide (approx. 2.5m for the swale to the north and approx. 3.5m for the swale to the south), Fig 4.21 shows that, by using a grid of 1m, the swale shape can be more highly refined than if a larger grid size had been used. Fig 4.21 also shows that the changes in maximum flow velocity can be more accurately modelled and represented when a high resolution of 1m is used, with maximum velocities of >1.2m/s within the swale channels, branching out from the outlets into the next pond downstream, before gradually reducing to <=0.3m/s to the centre of the ponds.

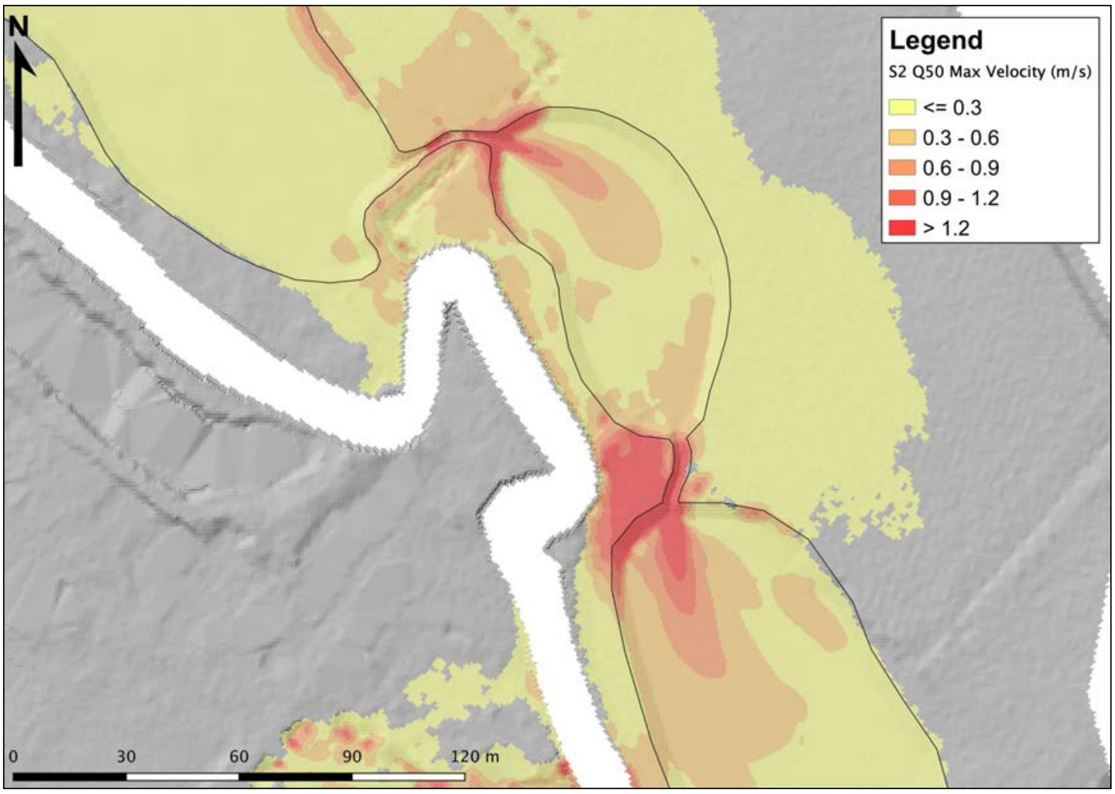


Figure 4.21: Scenario 2 - 1 in 50-year (2% AEP) Max Velocity (m/s) River Greet Swale-Linked Wetland Ponds

4.4 Scenario 3 - Re-meandering and Reconnecting

Scenario 3 comprises re-meandering the river channel and reconnecting the channel to the floodplain by lowering the bank and floodplain profile. Figure 4.22 below shows the maximum depth and flood extents for the 1 in 10-year (10% AEP) event for Scenario 3 which, when compared visually to the results of the same event for the Baseline model (Figure 4.1), appear to be very similar. However, when focusing on the reach of the River Greet where the channel has been re-meandered the flood flood extents have increased slightly, largely due to the lowering of the bank heights and surrounding floodplain to deliberately increase flooding in the area.

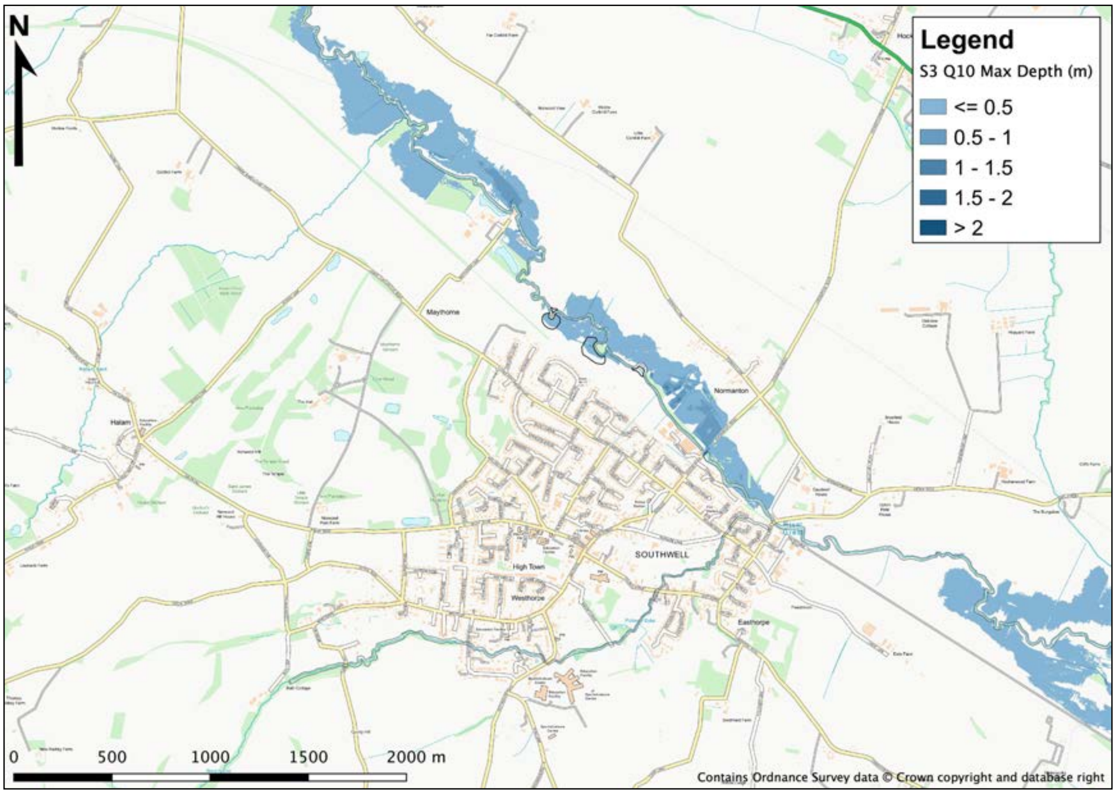


Figure 4.22: Scenario 3 - 1 in 10-year (10% AEP) Max Depth (m)

The results of the difference grid generated by subtracting the results of the Baseline maximum depth from the Scenario 3 maximum depth results for the 1 in 10-year (10% AEP) event, shown below in Figure 4.23, show a general increase of >0 <=0.15m which generally extends from the new meanders and downstream to the edge of the model domain. This suggests that, by simply lowering the bank height and profiling the surrounding floodplain as a reconnection method has allowed too much water into the floodplain, resulting in increases. This is most notable at the furthest downstream re-meander, with the majority of the maximum depth increases seen during this event as a direct result of this meander. As seen in previous results, where minor increases of >0.15 <=0.3m and minor decreases of >-0.15 <=-0.001m are shown to be mixed, this time to the upstream extent of the River Greet, suggests that depth differences between the Baseline and Scenario 3 are very marginal, with maximum depth change likely very close to 0m throughout this area. A decrease of >-0.15 <=-0.001 in maximum flood depths from the Baseline to Scenario 3 is shown to occur adjacent to the left bank of the River Greet opposite the first two meanders (upstream), with decreases of >-0.15 <=-0.001m in general and in excess of -0.15m occurring opposite the third meander (downstream) due to the lowered banks on the outside of the meander allowing additional water to spill into the floodplain instead.

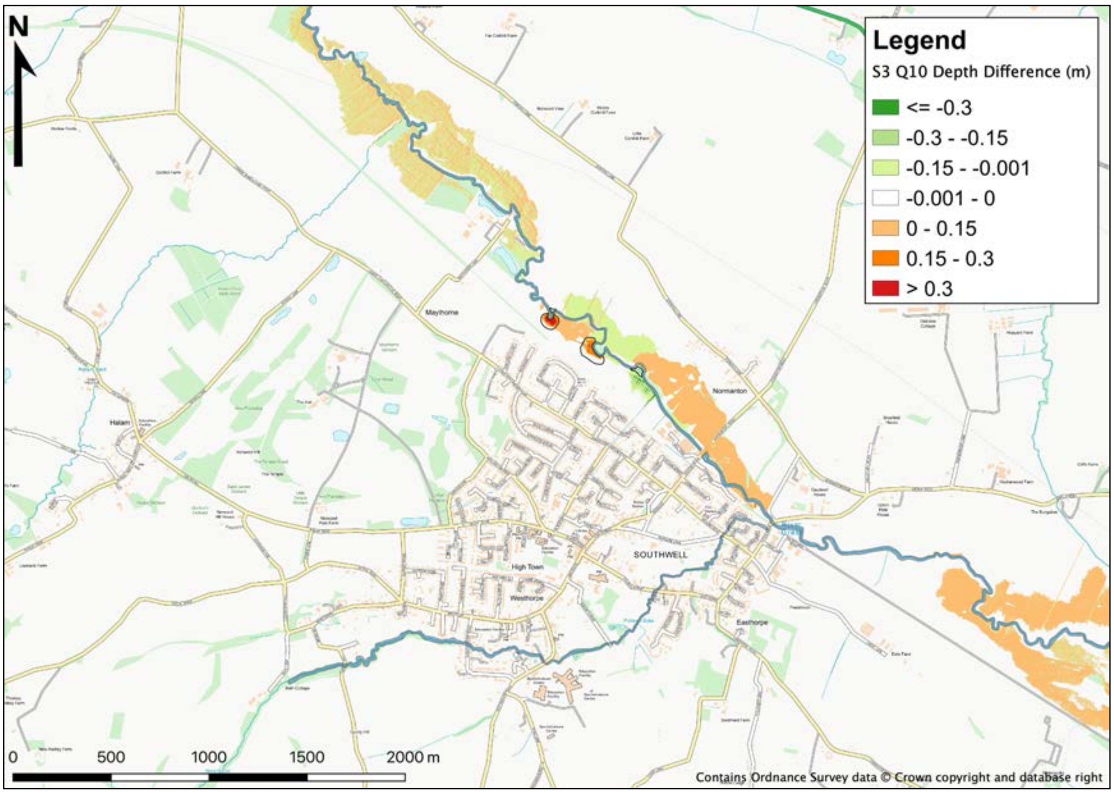


Figure 4.23: Scenario 3 - 1 in 10-year (10% AEP) Depth Difference (m)

As with the results of the 1 in 10-year (10% AEP) flood event, the results of the 1 in 50-year (2% AEP) flood event for Scenario 3 show minor decreases in flood extent from the Baseline simulation (Figure 4.2) of the same event. As shown in Figure 4.24 below, minor decreases in the extent of flooding are seen in the floodplain adjacent to the right bank of the River Greet in the area surrounding the re-meandered channel. However, minor increases in the extent of the flooding are now observed in the floodplain adjacent to the left bank, also in the same area.

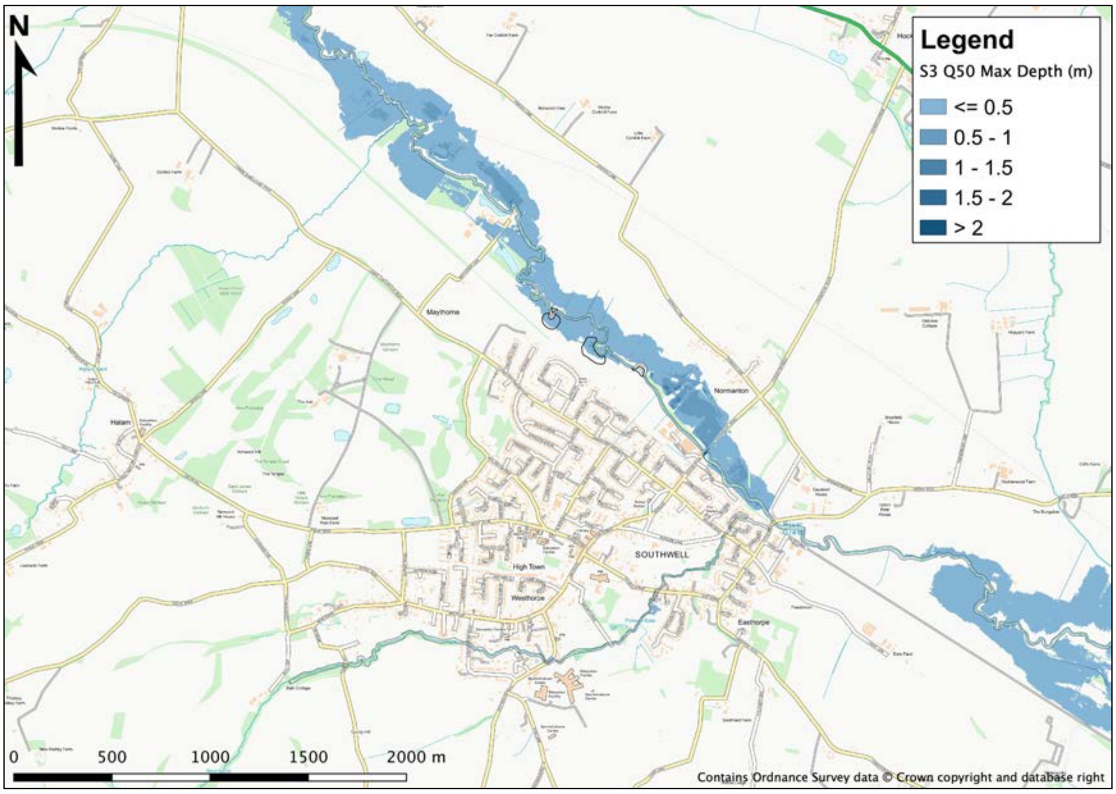


Figure 4.24: Scenario 3 - 1 in 50-year (2% AEP) Max Depth (m)

The difference grid generated from the results of the 1 in 50-year (2% AEP) event for the Baseline and Scenario 3, shown below in Figure 4.25, shows a similar relationship to that of the 1 in 10-year (10% AEP) event, with general increases in flood depth in Scenario 3 within and immediately downstream of the lowered and profiled floodplain of the outer banks of the new meanders. General decreases are also still seen within the floodplain adjacent to the inside of the new meanders.

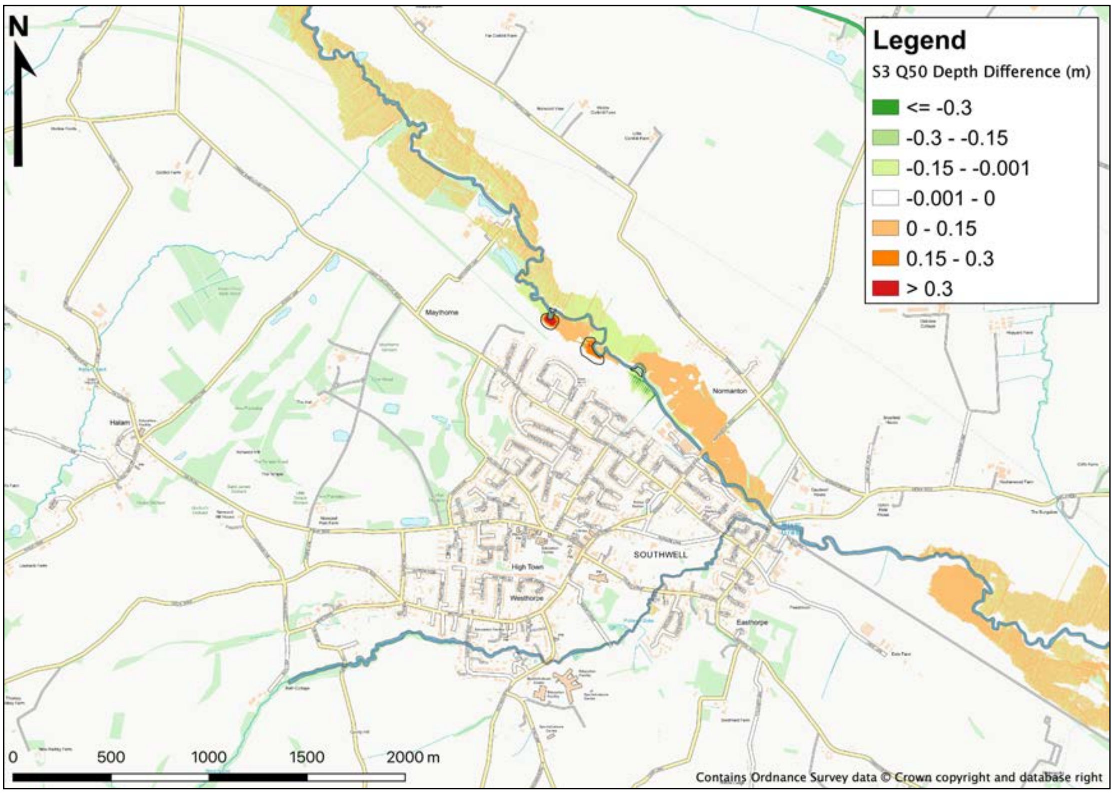


Figure 4.25: Scenario 3 - 1 in 50-year (5% AEP) Depth Difference (m)

Figure 4.26 below shows the maximum depth and flood extents observed during the 1 in 100-year (1% AEP) plus 30% climate change event for Scenario 3. As has been observed with the smaller events simulated for Scenario 3, a minor incremental decrease in the extent of flooding is shown in the floodplain adjacent to the right bank of the River Greet in there area around the new meanders, with an incremental increase in flood extent in the floodplain adjacent to the left bank in the same area. It is also noted that in all three events, and particularly during the more onerous 1 in 100-year (1% AEP) plus 30% climate change event, the floodplain profiling surround the central new meander is not fully inundated and shows that water is still unable to fully enter the floodplain at this location, with water instead partially finning the lowered area surrounding the meander and then spilling out to the left and right flanks.

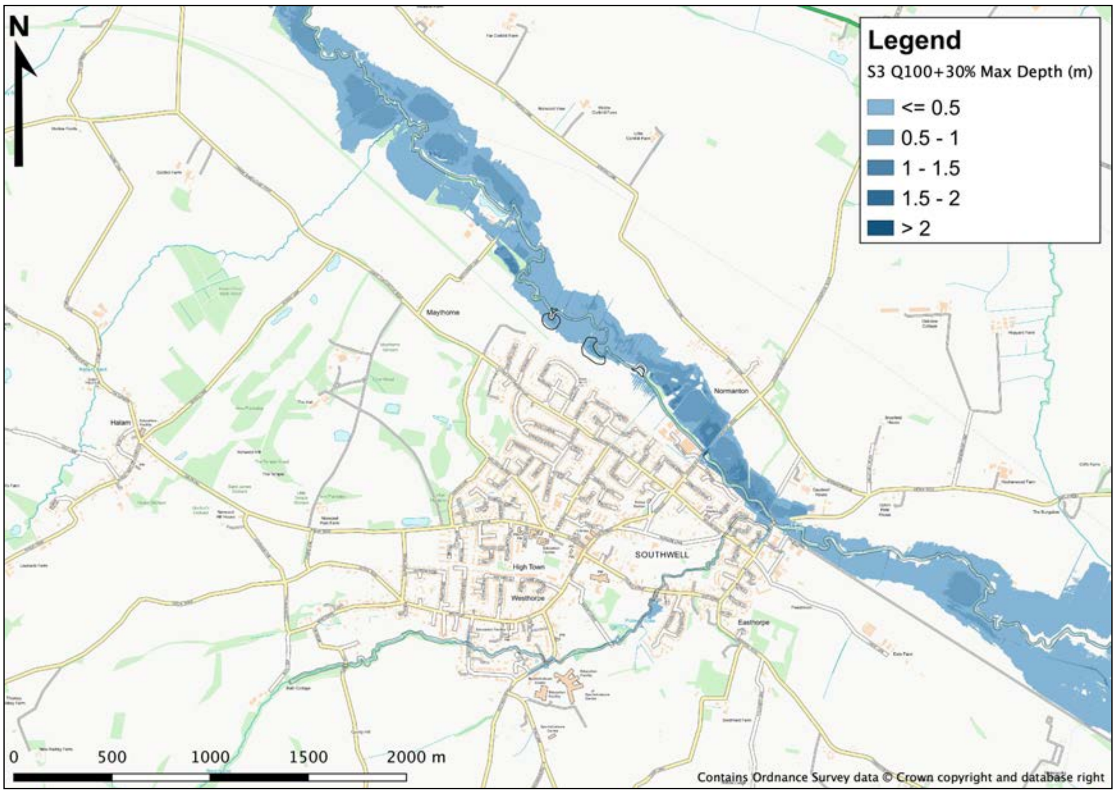


Figure 4.26: Scenario 3 - 1 in 100-year (1% AEP) plus 30% Climate Change Max Depth (m)

Figure 4.27 below shows the difference between the Baseline and Scenario 3 for the 1 in 100-year (1% AEP) plus 30% climate change event. Similarly to the previous two events for Scenario 3, incremental increases in maximum flood depth are shown immediately downstream of the outer banks of the new meanders where water has been allowed to enter the floodplain more easily and, as a result, incremental decreases in maximum flood depth are shown in the floodplain adjacent to the inside banks of the new meanders. Increases in flood depth of >0 <=0.15m are still shown to extend downstream past Normanton Road, where the increase affects less properties, with the vast majority of development in Southwell existing on the opposite side of the River Greet. However, Figure 4.27 also shows a change occurring from the previous results for the 1 in 10-year (10% AEP) and 1 in 50-year (2% AEP) flood events, as large areas of marginal increases and decreases fluctuating around 0m at the upstream end of the River Greet and increases of >0 <=0.15m at the downstream end of the River Greet are no longer observed. This suggests that, while flooding in these areas is still occurring, as shown by Figure 4.26 above, the re-meandering and reconnecting of the floodplain which has been implemented in Scenario 3 has no effect on the up and downstream extents and instead, the effects of the channel and floodplain modifications are only noticed in the surrounding areas.

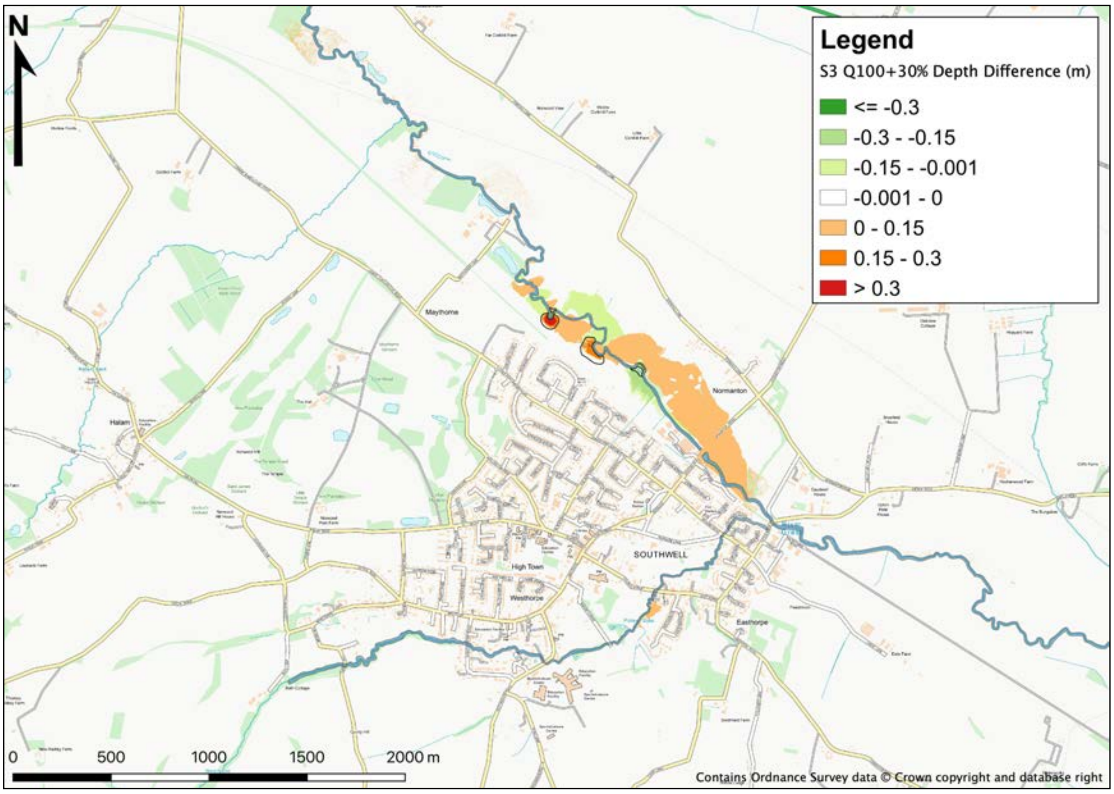


Figure 4.27: Scenario 3 - 1 in 100-year (1% AEP) plus 30% Climate Change Depth Difference (m)

Figure 4.28 below shows the maximum velocity during the 1 in 50-year (2% AEP) flood event for Scenario 3, and shows how velocities increase where water is able to spill over the banks and enter the floodplain quicker and utilise the storage capacity of the floodplain due to re-meandering and lowering of banks to reconnect the channel to the floodplain. Noticeable increases in maximum velocity of >0.3 <=1.2m/s are shown to originate from the outer banks of the meanders, extending into the floodplain. This is shown to be the case from existing meanders in the River Greet but is also shown to occur from the two new meanders, particularly the one furthest downstream.

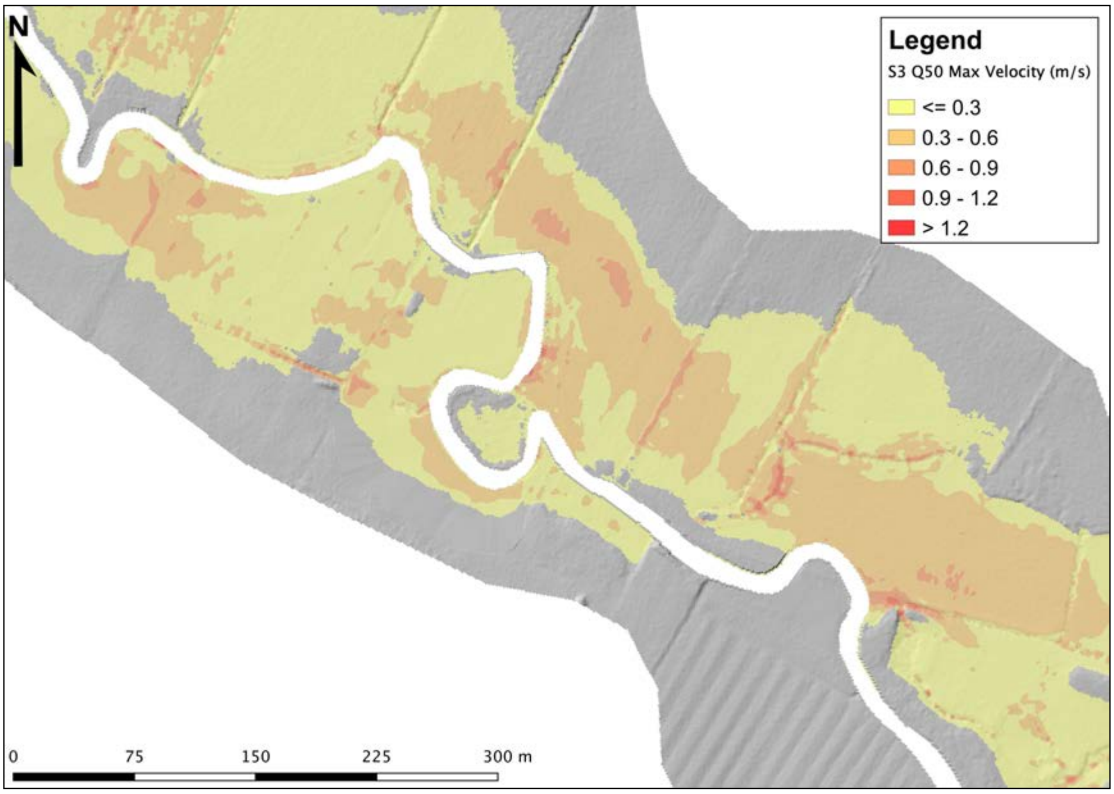


Figure 4.28: Scenario 3 - 1 in 50-year (2% AEP) Max Velocity (m/s) River Greet Re-Meandering and Floodplain Reconnection

Figure 4.29 below shows the difference between the maximum velocities for the Baseline and Scenario 3 during the 1 in 50-year (2% AEP) flood event. While Figure 4.28 above shows increased velocities from existing meanders in comparison to surrounding areas, Fig 4.29 indicates very little change on these same meanders, with increases of >0 <=0.15m/s in isolated places within the floodplain nearby but, in general, decreases of >-0.001 <=-015m/s are shown. In contrast, significant increases in velocity from the Baseline to Scenario 3 are shown to occur at the two new meanders and the existing leader with lowered banks. These increases range from >0 >0.3m/s, with greater increases shown to occur closer to the meander banks and the more modest increases occurring further out into the floodplain which, again, shows how water is able to escape the channel and utilise the natural floodplain storage at a quicker rate due to the remaindering and lowering of the banks.

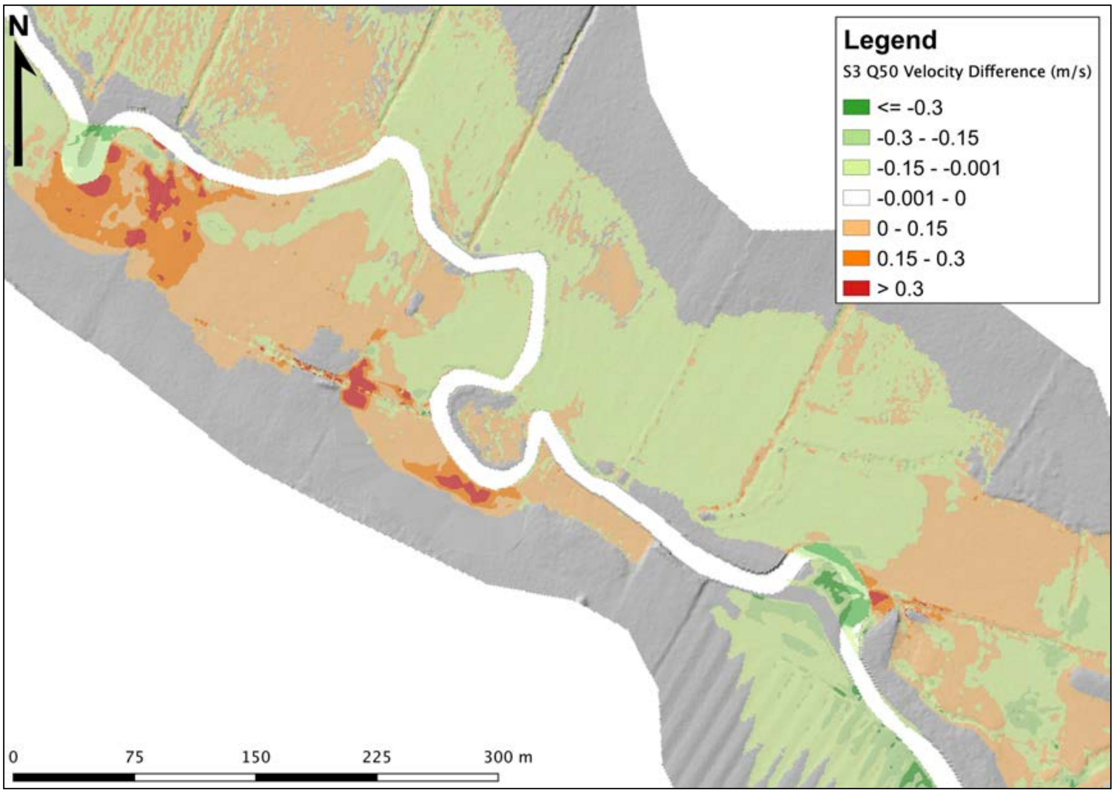


Figure 4.29: Scenario 3 - 1 in 50-year (2% AEP) Velocity Difference (m/s) River Greet Re-Meandering and Floodplain Reconnection

4.5 Scenario 4 - Combined Methods

Scenario 4 comprises a combination of Scenarios 1, 2 and 3 together with alterations made to ensure there were no clashes with each method (eg. Woody debris removed where wetland ponds were present in Scenario 2. Figure 4.30 below shows the maximum depth and extent of flooding during the 1 in 10-year (10% AEP) flood event which, when compared to the Baseline results for the same event (Figure 4.1), show a noticeable reduction in the extent of flooding in places. The reductions in flood extent are relatively minor in upstream areas. However, the extent of flooding at the downstream end of the River Greet is shown to have reduced dramatically. To the middle of the reach, the extent of flooding has also reduced within the floodplain adjacent to the right bank, reducing the risk of flooding to Southwell.

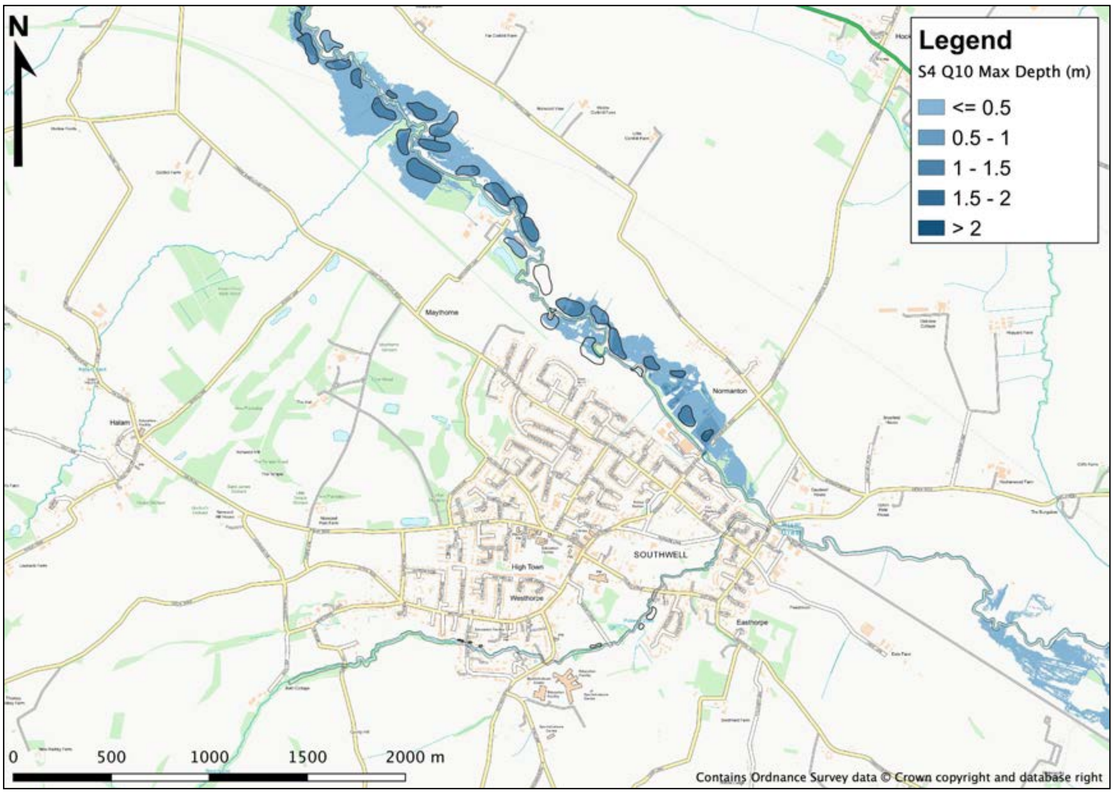


Figure 4.30: Scenario 4 - 1 in 10-year (10% AEP) Max Depth (m)

Figure 4.31 below shows the difference in maximum depths between Scenario 4 and the Baseline for the 1 in 10-year (10% AEP) flood event. This shows general decreases in flood depth during Scenario 4 downstream of Normanton Road of >-0.001 <=-0.15m, with decreases of >-0.15 <=-0.3 in places. Increases in flood depth of >0 <=0.15m are shown to occur where ponds have been placed with minimal woody debris, particularly in the upstream region of the River Greet in the floodplain adjacent to the right bank and in the middle of the reach adjacent to the left bank and upstream of Normanton Road. Where ponds have been placed with more significant amounts of woody debris and woodland in-between, flood depths are shown to generally decrease >-0.15 <=-0.001m, with decreases of >-0.3 <=-0.15m and by <=-0.3m in some isolated places. The decreases observed appear to generally take place in the floodplain adjacent to the left bank, excluding an area immediately upstream of Normanton Road.

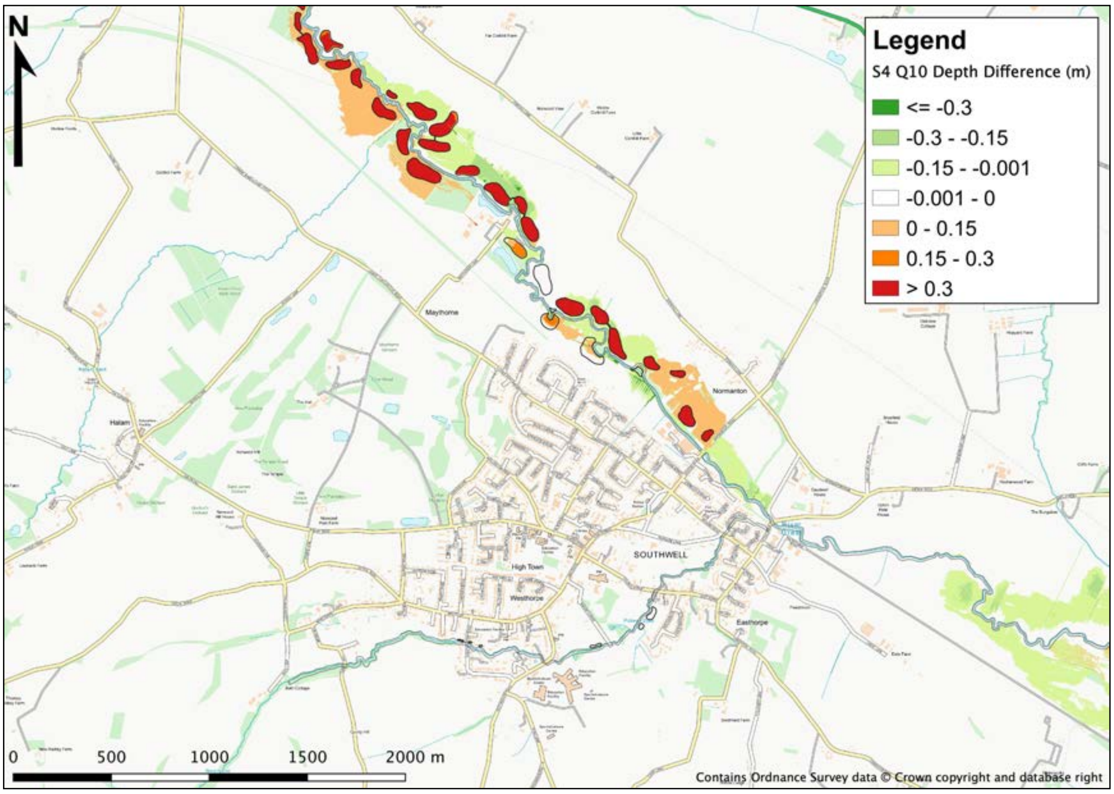


Figure 4.31: Scenario 4 - 1 in 10-year (10% AEP) Depth Difference (m)

Figure 4.32 below shows the maximum depth results and flood extents for Scenario 4 during the 1 in 50-year (2% AEP) event. As has been observed in the results of the 1 in 10-year (10% AEP), the extent of flooding has been reduced during Scenario 4 when compared to the results for the same event for the Baseline (Figure 4.2). However, the decrease in flood extents are less prevalent during the 1 in 50-year (2% AEP) than has been observed for the results of the 1 in 10-year (10% AEP). In particular, flooding is shown to have reduced to the middle of the reach on the River Greet. Most notably, however, the dramatic decrease in flooding at the downstream end of the River Greet during the 1 in 10-year (10% AEP) is shown to no longer occur during the 1 in 50-year (2% AEP).

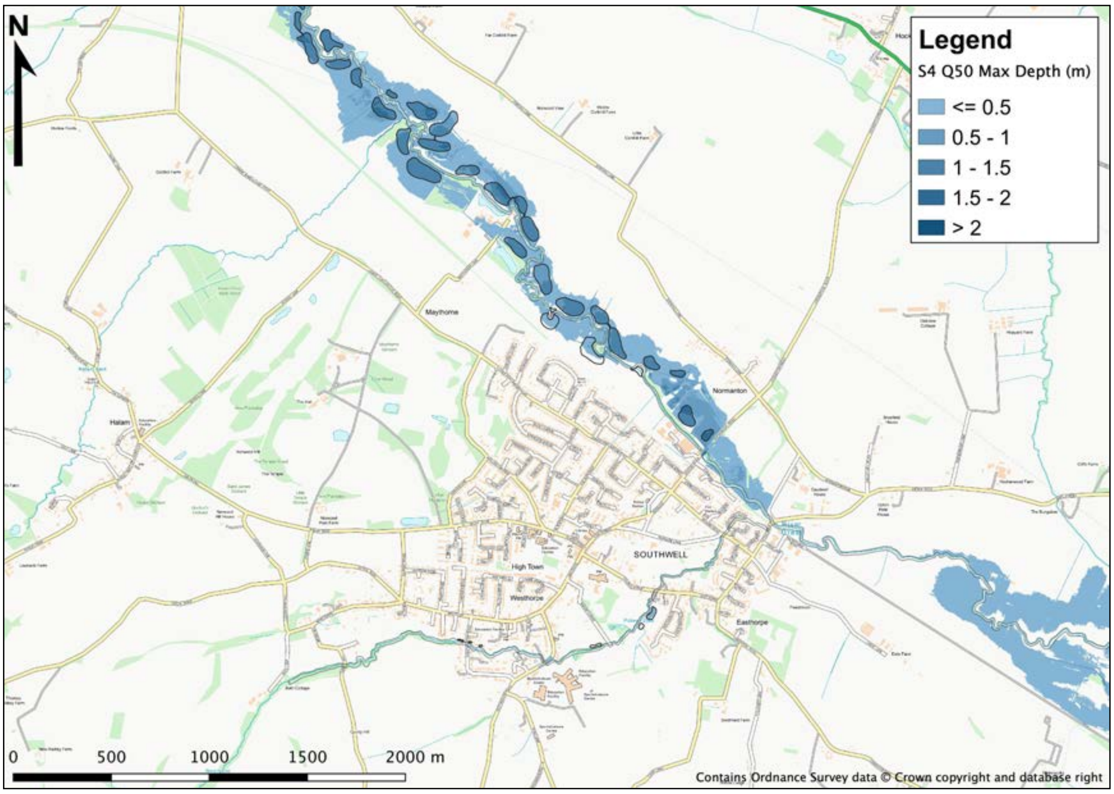


Figure 4.32: Scenario 4 - 1 in 50-year (2% AEP) Max Depth (m)

Figure 4.33 below shows the difference in maximum flood depths between Scenario 4 and the Baseline for the 1 in 50-year (2% AEP) event and, in general, shows a similar pattern in maximum depth differences that has been observed for the 1 in 10-year (10% AEP) event shown in Figure 4.31. The general decreases in flood depth during downstream of Normanton Road of >-0.15 <=-0.001m are still observed, though there are no longer any decreases of >-0.3 <=-0.15m. Instead, Figure 4.33 shows that at the downstream end of the reach on the River Greet there are some minor increases in flood depth of >0 <=0.15m, particularly adjacent to the right bank close to the edge of the 2D model domain. Increases in flood depth of >0 <=0.15m are again shown to occur where ponds have been placed with minimal woody debris, with decreases of >-0.15 <=-0.001m where ponds have been placed with more significant amounts of woody debris and woodland. While increases along Potwell Dyke are observed, this is predominantly within a wetland pond adjacent to the right bank. However, flooding on Nottingham Road is also shown to increase by >0 <=0.15m.

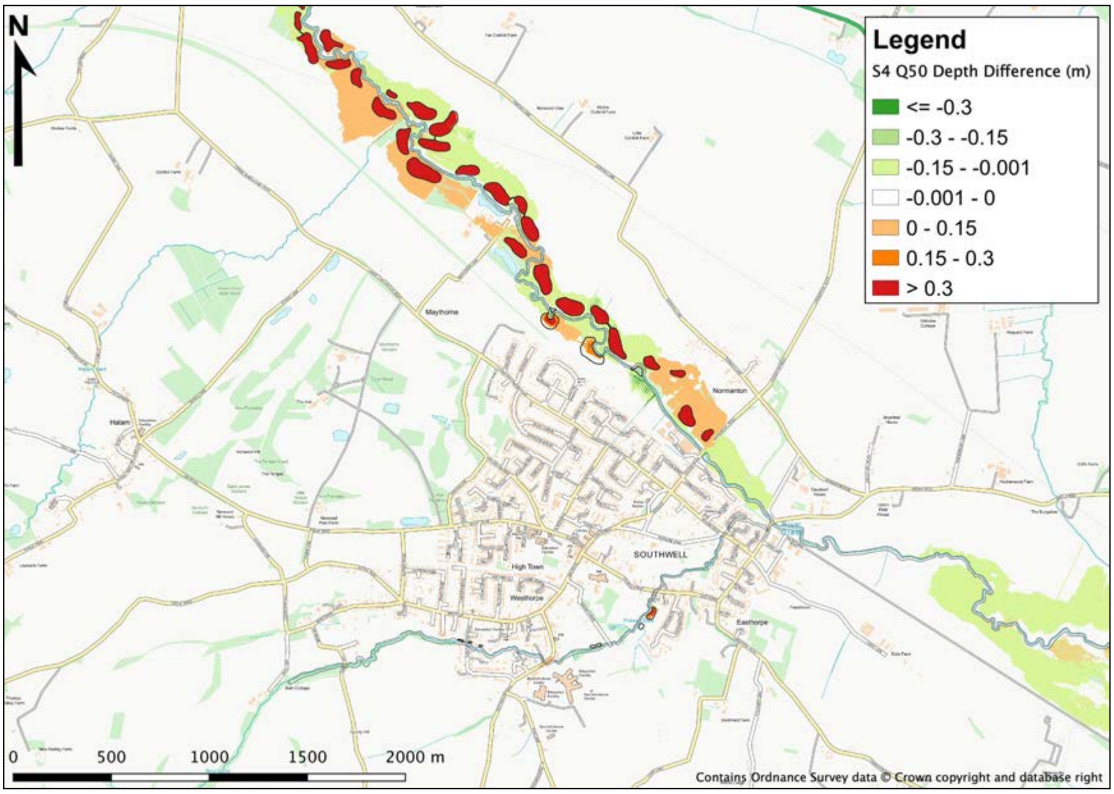


Figure 4.33: Scenario 4 - 1 in 50-year (2% AEP) Depth Difference (m)

Figure 4.34 below shows the maximum depth and flood extents observed during the 1 in 100-year (1% AEP) plus 30% climate change event for Scenario 4 and shows that, during the more onerous flood event, the restoration techniques used have a less noticeable effect in the overall extents and depths of flooding. When compared to the results of the Baseline model for the same event (Figure 4.3), there are no significant increases or decreases in the maximum extent of flooding. Where the river channel has been reconnected to the floodplain to the centre of the River Greet reach, floodwater should theoretically be able to spill into the floodplain to a greater extent. However, the extent of floodplain largely remains the same. Wetland ponds which offer additional floodplain storage appear to make little difference due to being fully inundated.

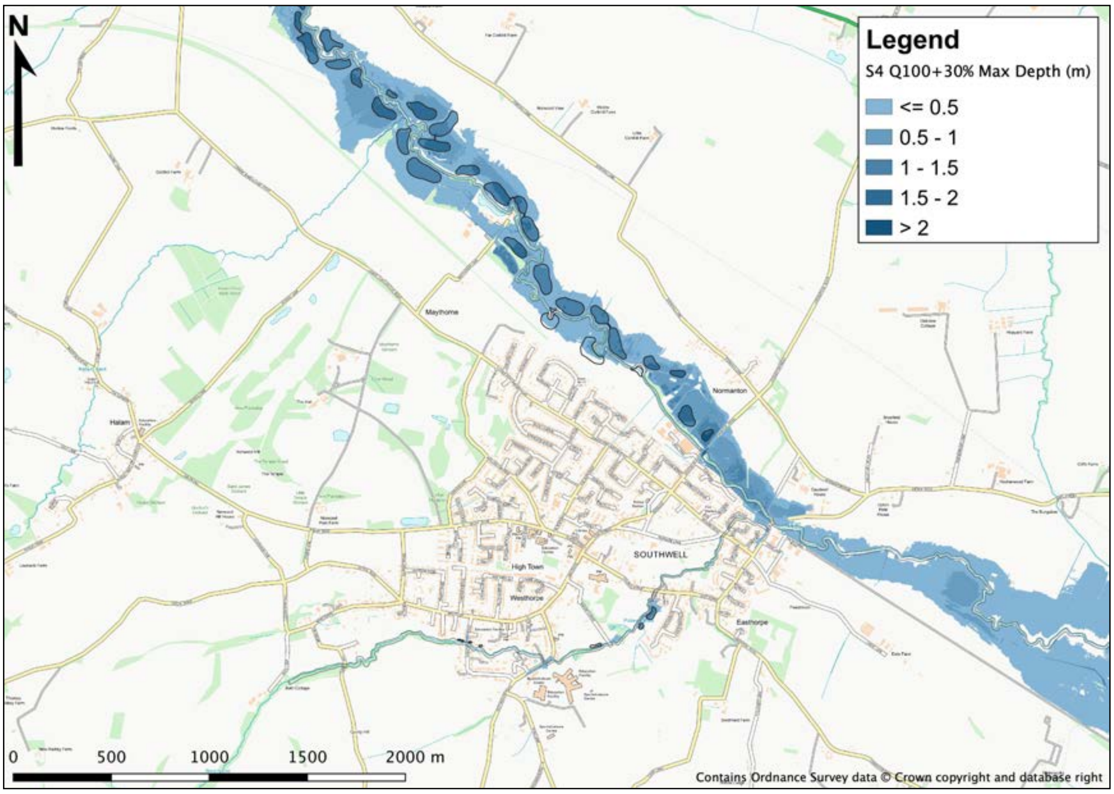


Figure 4.34: Scenario 4 - 1 in 100-year (1% AEP) plus 30% Climate Change Max Depth (m)

The differences in maximum depth between the Baseline and Scenario 4 for the 1 in 100-year (1% AEP) plus 30% climate change event, shown below in Figure 4.35, again shows a similar pattern to the results of the 1 in 10-year (10% AEP) and 1 in 50-year (2% AEP) events for Scenario 4, with general decreases in maximum flood depth of >-0.15 <=-0.001m adjacent to the left bank in the upstream reach of the River Greet, while a general increase of >0 <=0.15m is observed adjacent to the right bank in the upstream reach of the River Greet and immediately upstream of Normanton Road adjacent to the left bank. The decreases in maximum flood depth downstream of Normanton Road, however, have been replaced by minor increases of >0 <=0.15m and minor decreases of >-0.15 <=-0.001m, again suggesting that depth differences are very marginal around 0m. Flooding is shown to increase along Potwell Dyke as a result of the restoration measures used by >0 <=0.15m.

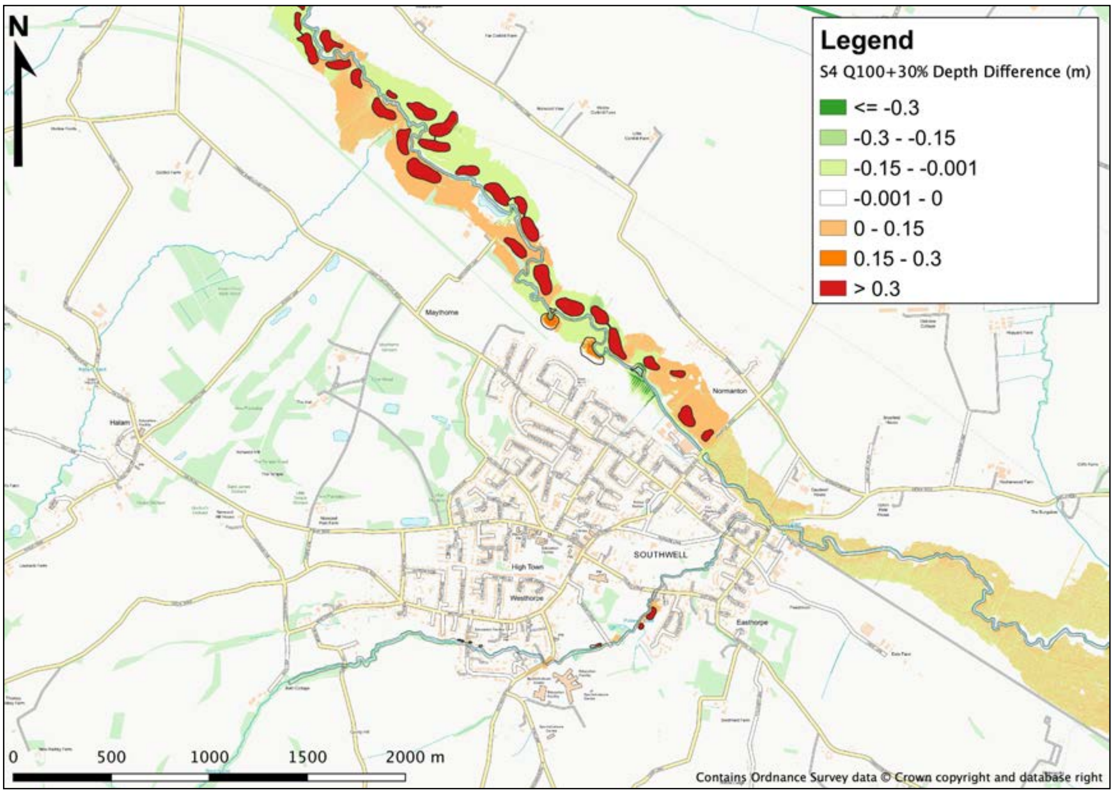


Figure 4.35: Scenario 4 - 1 in 100-year (1% AEP) plus 30% Climate Change Depth Difference (m)

Figures 4.36 and 4.37 below show the results of the 1 in 10-year (10% AEP) flood event maximum depth difference and maximum velocity difference from the Baseline for Scenario 4 respectively, focusing on Location B which has been previously assessed for Scenario 1. The differences for maximum depth and velocity from the Baseline for Scenario 1 (Figs. 4.12 and 4.13) suggest that the placement of woody debris barriers had limited success in mitigating increases in maximum depth and velocity, with the cause likely the result of increased pressure of additional water within the floodplain upstream of Location B. As part of Scenario 4 a wetland pond has been placed upstream of Location B, providing additional floodplain storage which is capable of retaining floodwater and minimising water flowing towards Location B through the floodplain. While increases increases are still observed along the flow path through Maythorne during, the addition of floodplain storage has dramatically reduced the flow path while allowing the use of woody debris upstream which otherwise resulted in the flow path.

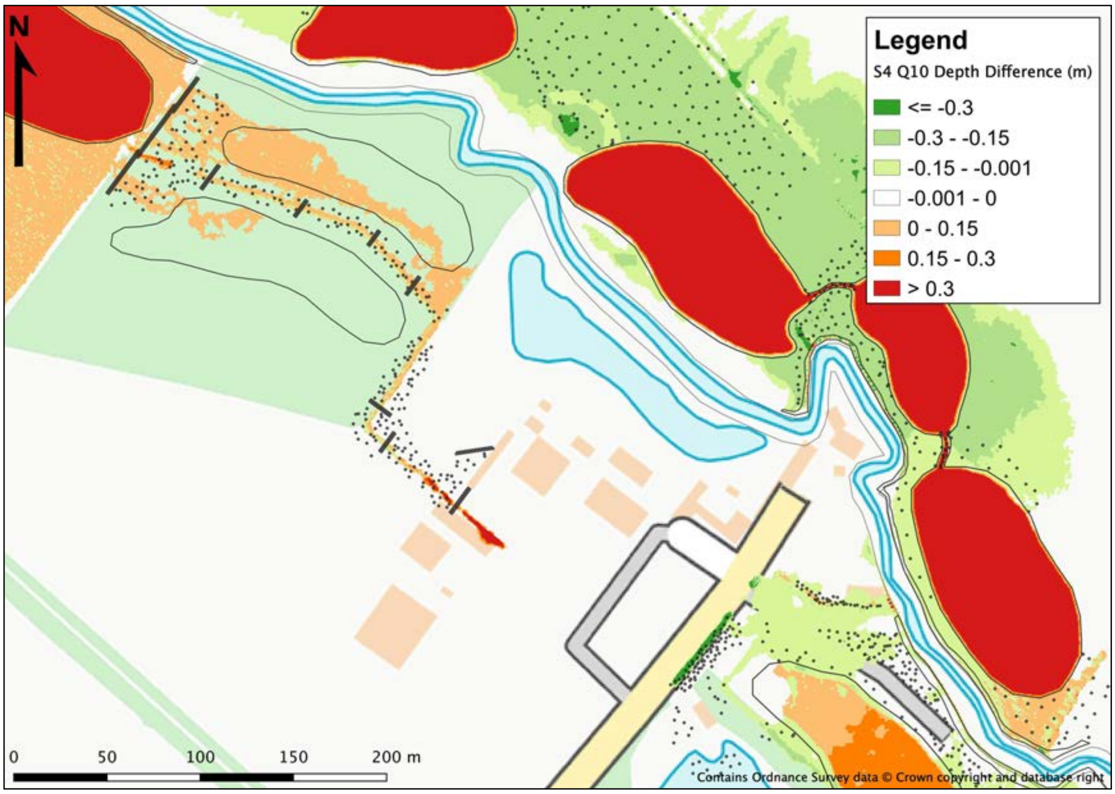


Figure 4.36: Scenario 4 - 1 in 10-year (10% AEP) Maythorne Flooding 'Location B' Depth Difference (m)

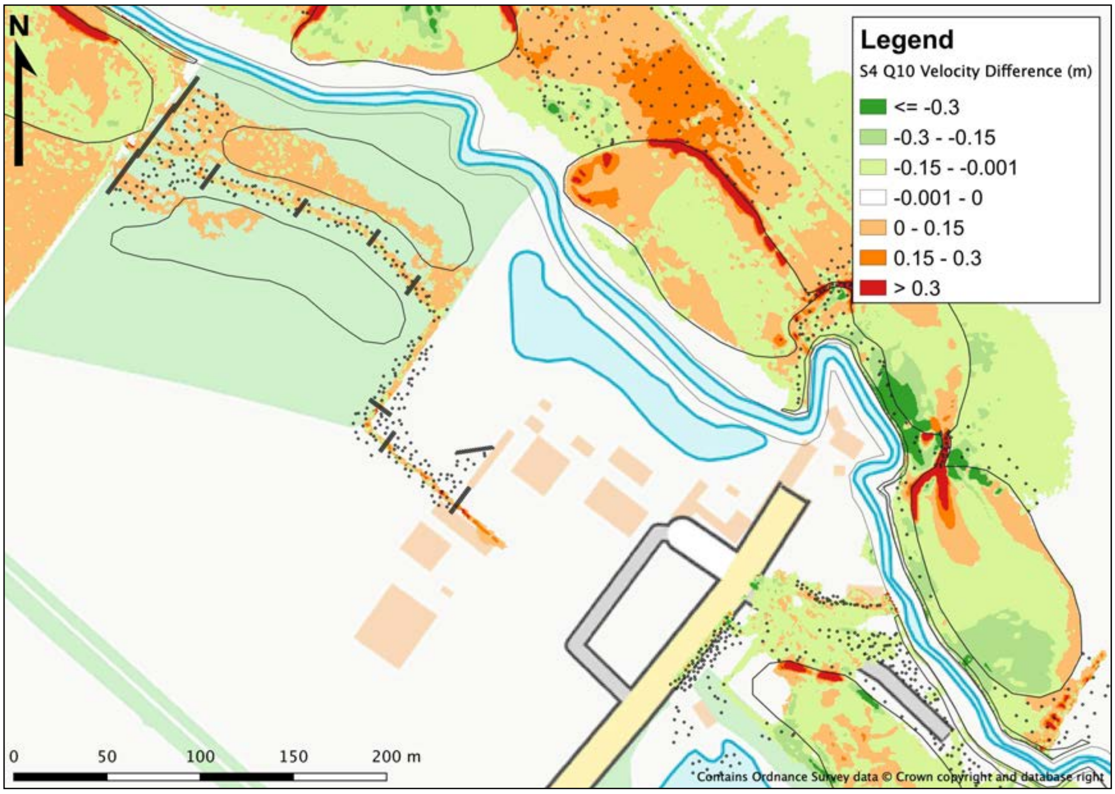


Figure 4.37: Scenario 4 - 1 in 10-year (10% AEP) Maythorne Flooding 'Location B' Velocity Difference (m)

4.6 1D Stage Analysis

Figures 4.38 and 4.39 below show the in-channel maximum stage (m) taken form the results of the 1D model for the River Greet (Fig. 4.38) and Potwell Dyke (Fig. 4.39) for each scenario during the 1 in 10-year (10% AEP) flood event. Figure 4.38 shows that, in the upstream end of the reach for the River Greet and at the very downstream end, the maximum stage appears to remain generally similar across the Baseline and all test scenarios. A sudden drop in maximum stage is shown to the centre of the reach, representing the drop at the Cauldwell's Mill on Normanton Road, Southwell. Upstream of the sudden drop, a minor difference (approx. 100mm) in maximum stage between the Baseline and Scenario 1 can be seen. With the addition of woody debris the maximum stage during Scenario 1 is seen to increase over the Baseline in the area of Maythorne and a small weir. Aside from this area, Scenario 1 remains relatively on par with the Baseline. In the same area, the maximum stage for Scenario 2 is shown to be around 100mm lower than the Baseline as floodwater is retained in wetland ponds. Downstream of the Cauldwell's Mill, however, a more dramatic decrease in maximum stage of approximately 300-350mm is shown to occur during Scenario 2. During Scenario 3 the maximum stage is relatively the same as in the Baseline for the majority of the reach, including around the weir at Maythorne. This is to be expected as the remainders and lowered banks, designed to allow ware to more easily enter the open floodplain, are located downstream. With the meanders and bank lowering located upstream of Cauldwell's Mill encouraging water to enter and remain in the surrounding floodplain, Fig. 4.38 shows a dramatic reduction in maximum stage at the mill of up to 1.04m from the Baseline, showing that less water is forced through the restriction of the mill. Further downstream, the maximum stage during Scenario 3 returns to a generally similar level to that of the Baseline. During Scenario 4, with all techniques from the previous scenarios combined, characteristics in maximum stage from each previous scenario can be seen, with maximum stage remaining fairly similar to that of the Baseline upstream of the weir at Maythorne. At the weir, the maximum stage during Scenario 4 is seen to increase by approx. 100mm before dropping below the results of the Baseline by around 170mm. At the

Cauldwell’s Mill the maximum stage of Scenario 4 follows a similar pattern to that of Scenario 3 while providing a further drop in stage of up to 1.12m from that of the Baseline. Downstream of the mill, the maximum stage during Scenario 4 remains lower than that of the Baseline, following a similar pattern to Scenario 2 before returning to normal at the downstream end of the reach modelled.

Due to a lack of flooding from Potwell Dyke during the 1 in 10-year (10% AEP) event the restoration techniques employed in the test scenarios have no impact on maximum stage along Potwell Dyke. Figure 4.39 shows that the stage remains similar to that of the Baseline throughout the modelled reach for Potwell Dyke with the exception of the very downstream end of the watercourse where it enters a culvert before joining the River Greet. Before entering the culvert, which is excluded from Fig. 4.39, the maximum stage during Scenario 1 is shown to remain unchanged from that of the Baseline. Scenario 3 is shown to increase in stage slightly by 6mm over the Baseline, while Scenarios 2 and 4 show a 14mm decrease from the Baseline.

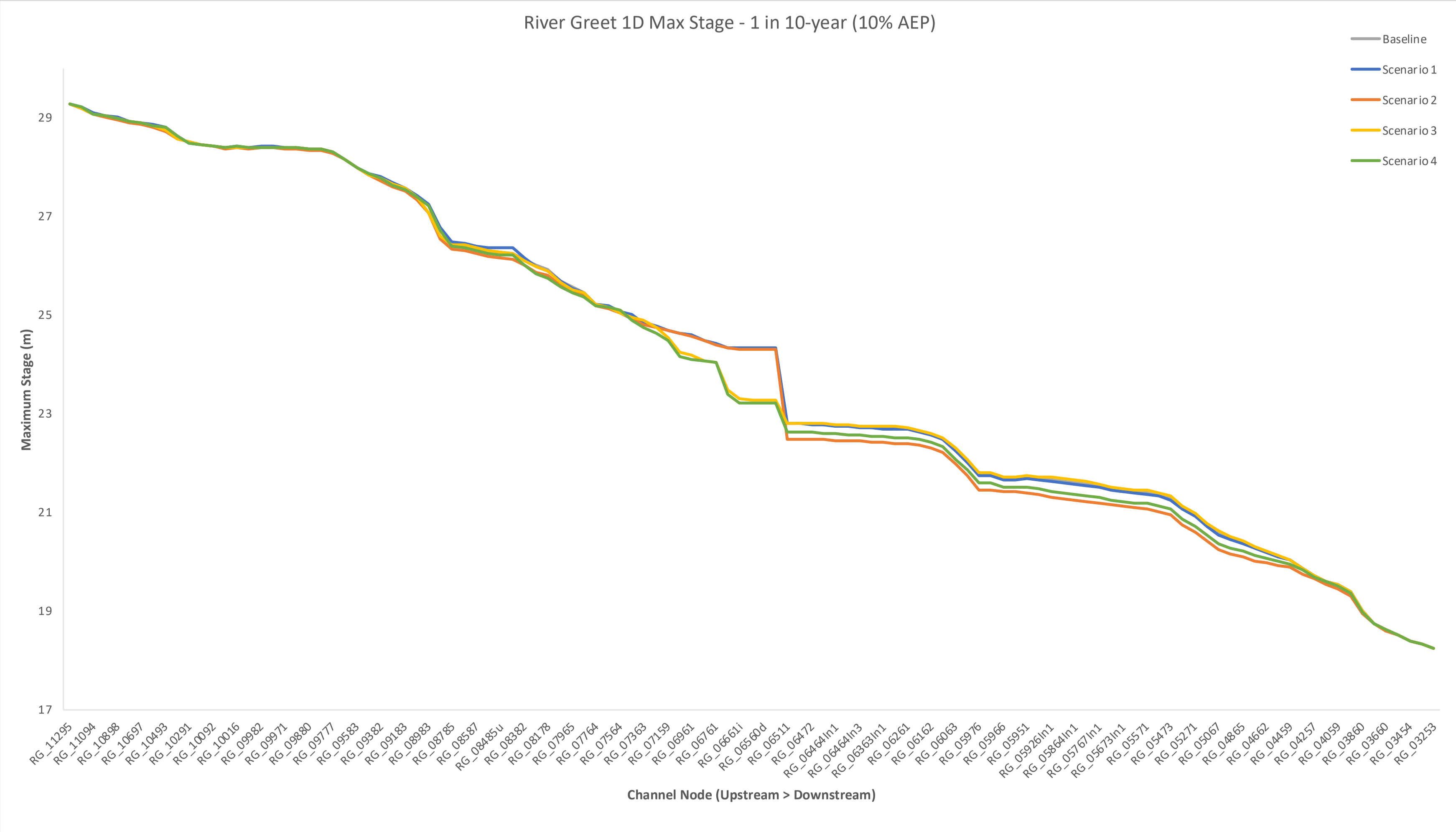


Figure 4.38: River Greet 1 in 10-year (10% AEP) 1D Maximum Stage (m) from upstream to downstream for all model scenarios

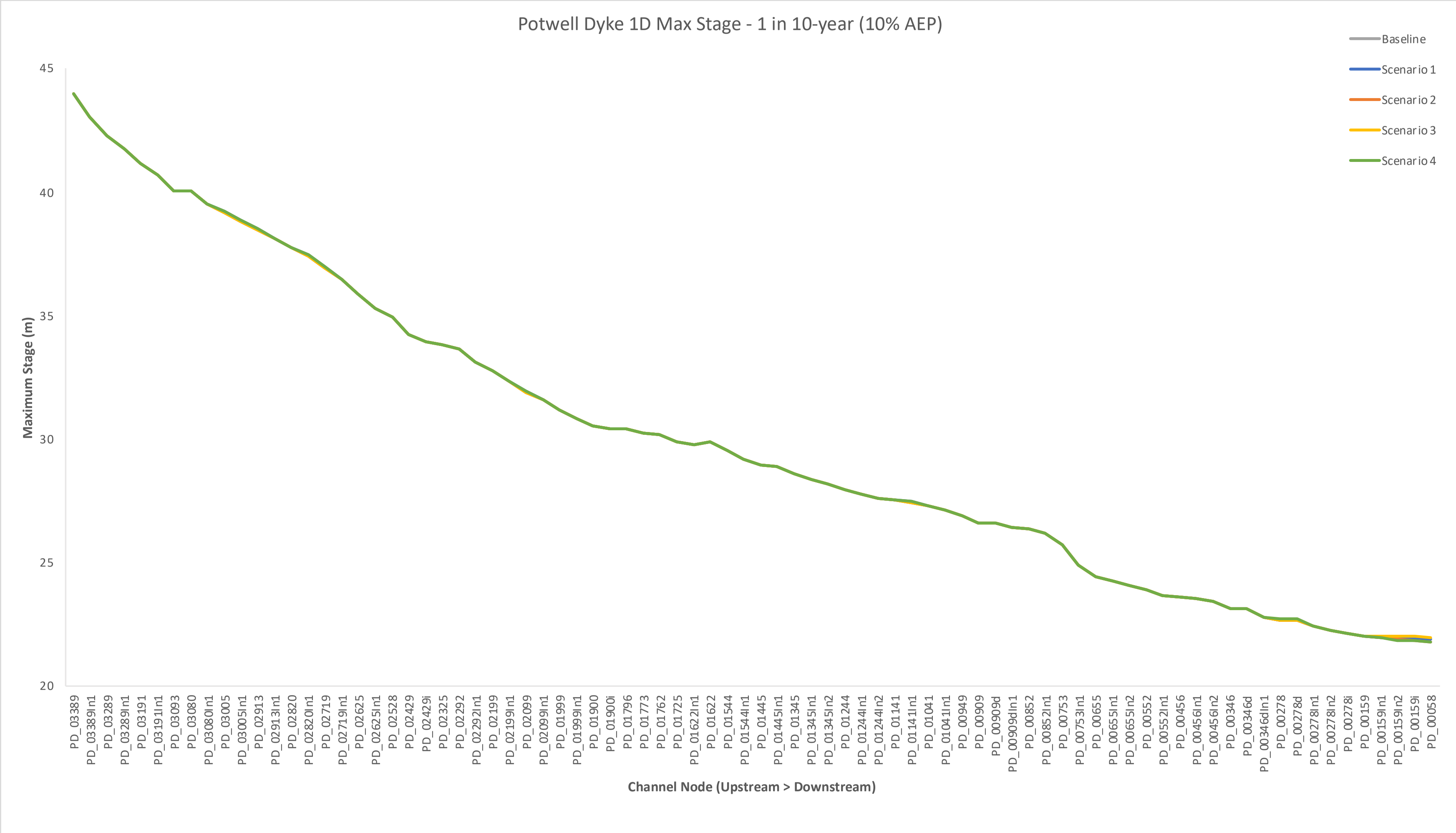


Figure 4.39: Potwell Dyke1 in 10-year (10% AEP) 1D Maximum Stage (m) from upstream to downstream for all model scenarios

Figures 4.40 and 4.41 below show the in-channel maximum stage (m) taken form the results of the 1D model for the River Greet (Fig. 4.40) and Potwell Dyke (Fig. 4.41) for each scenario during the 1 in 50-year (2% AEP) flood event. As with the results for the River Greet during the 1 in 10-year (10% AEP) event (Fig. 4.38), the maximum stage for each test scenario follow the same patterns but to a higher stage due to the increased magnitude of the event. In the area of the weir at Maythorne, Scenario 1 remains higher than that of the Baseline, with an approximate increase in maximum stage of 140mm. At the same location, Scenario 2 is approx. 120mm lower than the Baseline, while Scenario 3 remains at the same stage as the Baseline and Scenario 4 shows an increase of approximately 140mm. At the Cauldwell's Mill, Scenarios 1 and 2 remain at the same maximum stage as the Baseline. Scenario 3 is shown to be 980mm lower than the Baseline, while Scenario 4 is shown to be 1.13m lower.

Figure 4.41 shows that the maximum stage on Potwell Dyke for the test scenarios remains broadly close to that of the Baseline, as has been observed during the 1 in 10-year (10% AEP) event. Immediately upstream of the culvert at the confluence with the River Greet Scenario 1 is, again, shown to remain the same as the Baseline, indicating that woody debris has had little impact upon the small amount of flooding further upstream. At the same location, Scenarios 2 and show a 300mm drop in maximum stage from that of the Baseline, while Scenario 3 shows a marginal increase of 4mm.

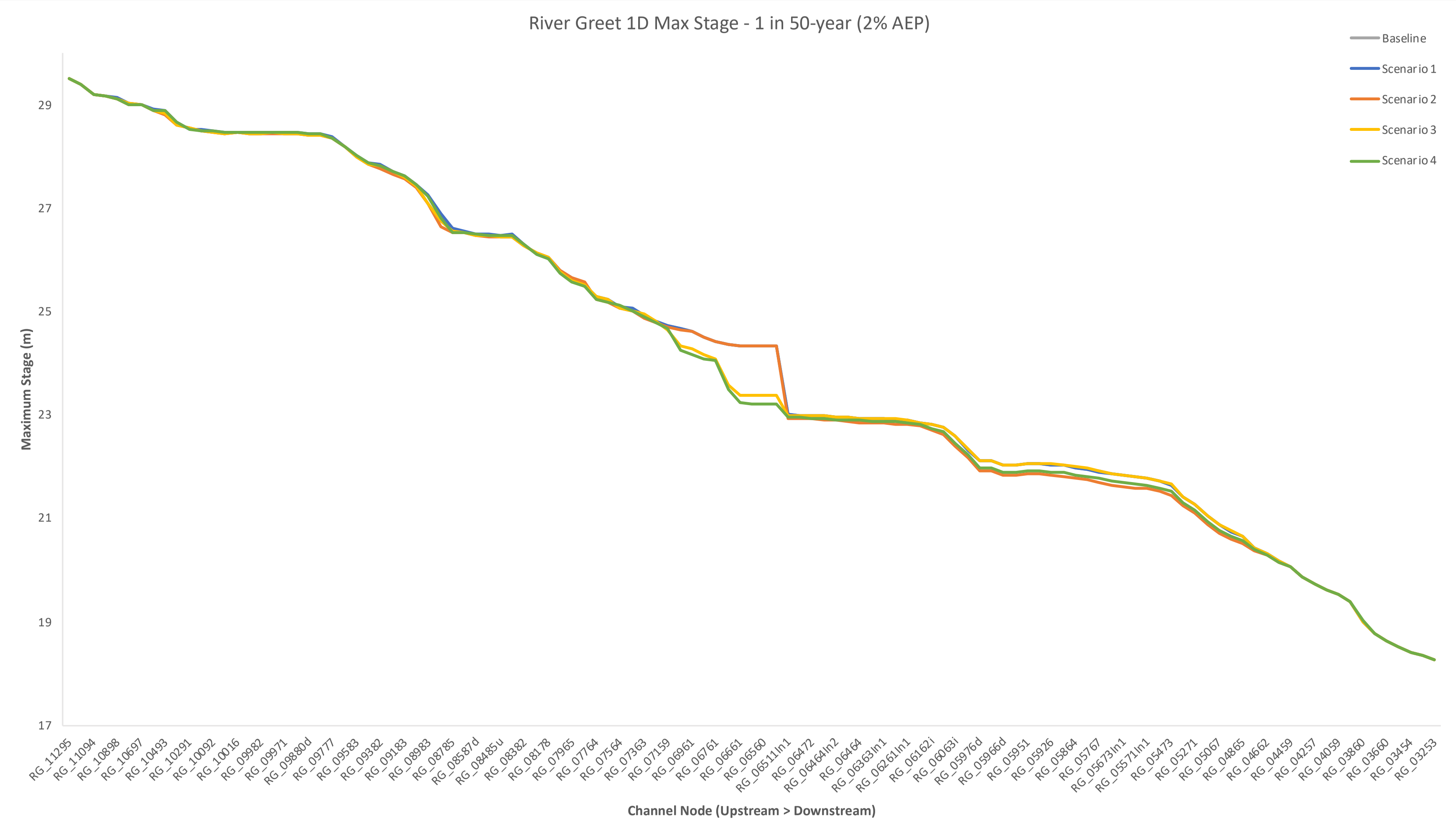


Figure 4.40: River Greet 1 in 50-year (2% AEP) 1D Maximum Stage (m) from upstream to downstream for all model scenarios

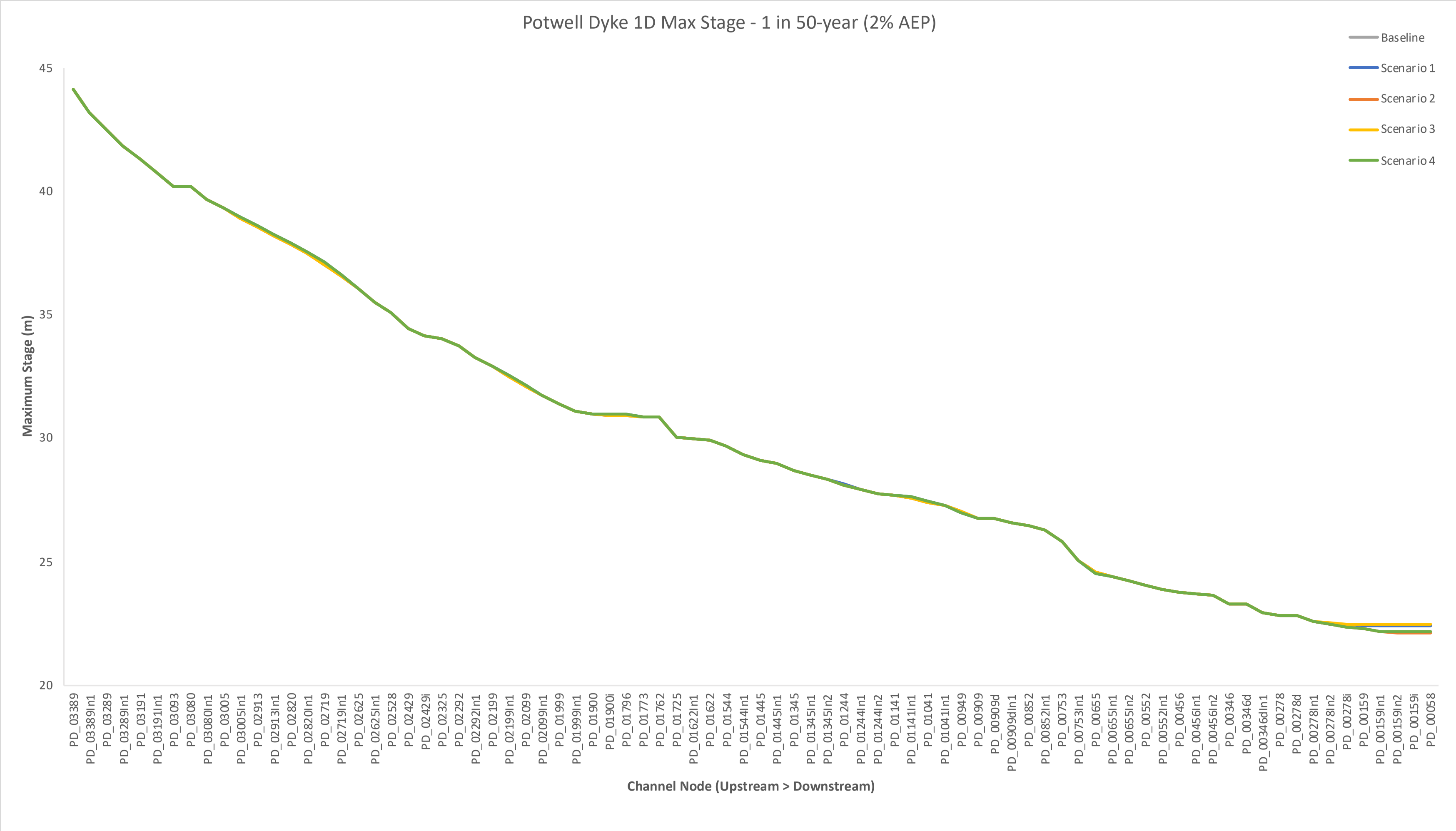


Figure 4.41: Potwell Dyke1 in 50-year (2% AEP) 1D Maximum Stage (m) from upstream to downstream for all model scenarios

Finally, Figures 4.42 and 4.43 below show the in-channel maximum stage (m) taken form the results of the 1D model for the River Greet (Fig. 4.42) and Potwell Dyke (Fig. 4.43) for each scenario during the 1 in 100-year (1% AEP) plus 30% climate change flood event. The relationship shown to occur between the results of the 1 in 10-year (10% AEP) and the 1 in 50-year (2% AEP) is also shown to occur during the 1 in 100-year (1% AEP) plus 30% climate change event as expected due to the the incremental increase in event magnitude. Figure 4.42 shows that the maximum stage for Scenario 1 follows that of the Baseline much more closely, indicating that woody debris has very little effect during a flood event of this size. At the weir near Maythorne, while the maximum stage for Scenario 1 remains higher than that of the Baseline, the difference is shown to be only 7mm at most. At the same location, Scenario 2 remains lower than the Baseline by approximately 260mm. Scenario 3 still remains at the same stage as the Baseline around the weir. However, while, Scenario 4 showed an increased compared to the Baseline during the 1 in 50-year (2% AEP) event, during the 1 in 100-year (1% AEP) plus 30% climate change event, the maximum stage for Scenario 4 at the weir is shown to be approximately 210mm lower than that of the Baseline. At the Cauldwell's Mill, Scenarios 1 and 2 are again shown to remain at the same maximum stage as the Baseline. The difference between Scenario 3 and the Baseline is shown to have reduced further and is now 390mm lower than the Baseline. The same also applies to Scenario 4, which is shown to be 600mm lower than the Baseline, adding further confirmation that the features and techniques tested become less effective as the event magnitude increases. During the smaller flood events the maximum stages of Scenarios 2, 3 and 4 were generally shown to have some difference to the Baseline immediately downstream of the mill. However, during the 1 in 100-year (1% AEP) plus 30% climate change event, the maximum stages of all test scenarios remains essentially the same as the Baseline immediately downstream of the mill and throughout the rest of the reach downstream. Another observation during this event is that, upstream of Cauldwell's Mill the maximum stage for the Baseline and Scenarios 1 and 3 appear to be relatively erratic, while in contrast, the maximum stage for Scenarios 2 and 4 appear less so, suggesting that the use of wetland ponds providing storage outside of the channel has had a calming effect on river stage within the channel.

Figure 4.43 shows that Potwell Dyke follows the same relationship as with the previous events, with the maximum stage for Scenario 1 generally the same as that of the Baseline still. However, in three locations upstream, the maximum stage in Scenario 1 is shown to increase up to 120mm, likely caused by flows being held back by woody debris. Scenarios 2 and 3 are shown to be essentially the same as the Baseline, while Scenario 4, which includes the woody debris and woodland from Scenario 1, shows the same small increase in maximum stage in the three locations upstream. The most notable change for this event on Potwell Dyke is at the very downstream end of the reach, just before the culvert at the confluence with the River Greet. Whereas, in the lower order flood events, differences were shown to occur for Scenarios 2, 3 and 4 from the Baseline due to the influence of the maximum stage on the River Greet, with the maximum stage on the River Greet for all test scenarios matching that of the Baseline restoration features have less of an effect, this has resulted in the stages for all test scenarios upstream of the culvert matching the Baseline as well.

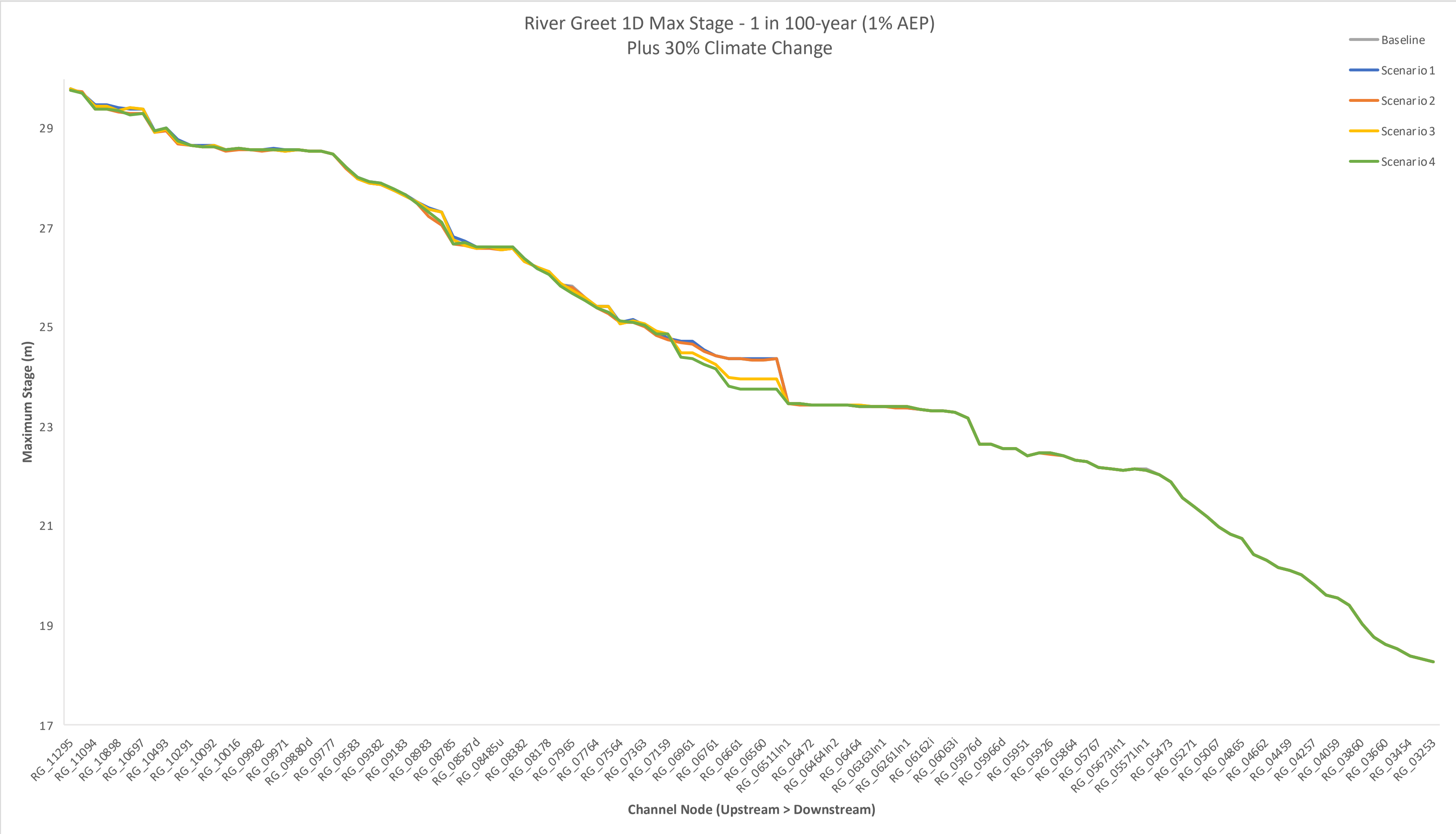


Figure 4.42: River Greet 1 in 100-year (1% AEP) plus 30% Climate Change1D Maximum Stage (m) from upstream to downstream for all model scenarios

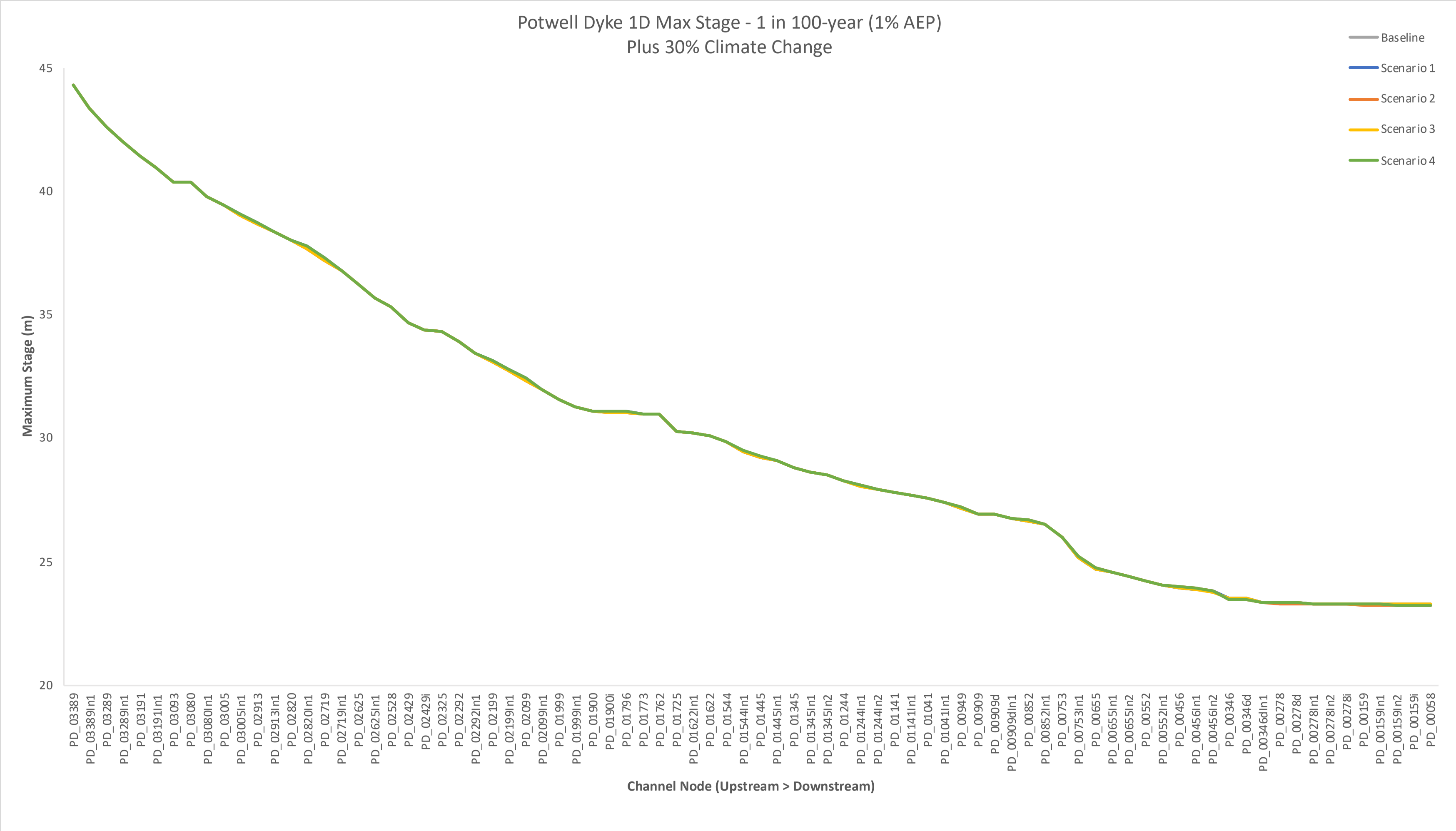


Figure 4.43: Potwell Dyke1 in 100-year (1% AEP) plus 30% Climate Change1D Maximum Stage (m) from upstream to downstream for all model scenarios

5 Discussion

5.1 Model Calibration & Verification

5.1.1 Sensitivity Testing

In order to ensure that the model is sensitive to changes in hydraulic parameters and behaves correctly, simulations were completed using the Baseline 1D model and the 1 in 100-year (1% AEP) plus 30% climate change hydrological event with modifications made to the in-channel Manning's n roughness coefficient. All in-channel Manning's n roughness values within the channel were changed by +20% overall for one simulation and -20% overall for a second simulation. Table 5.1 below presents the maximum stage from these 1D-only test simulations for a selection of cross-sections/nodes on the River Greet and Potwell Dyke.

Table 5.1: 1 in 100-year (1% AEP) Max Stage 1D-only Sensitivity Results - test with +20% Manning's n and -20% Manning's n

River Node	Baseline Max Stage (m AOD)	+20% Manning's n Max Stage (m AOD)	Percentage Change from Baseline	-20% Manning's n Max Stage (m AOD)	Percentage Change from Baseline
RG_11195	32.072	32.166	0.09%	31.981	-0.09%
RG_06860	32.008	32.074	0.07%	31.941	-0.07%
RG_03555	19.782	19.951	0.17%	19.582	-0.20%
PD_03289	42.527	42.598	0.07%	42.432	-0.09%
PD_01773	31.178	31.19	0.01%	31.166	-0.01%
PD_00058	22.825	22.901	0.08%	22.776	-0.05%

The results show that, with an increase in Manning's n of 20%, the maximum channel stage increases slightly. Conversely, with a decrease in Manning's n of 20%, the maximum stage decreases slightly. In completing this process there is no specific increase or decrease that is to be expected. Instead, it is expected that the amount of change is approximately the same for both the increase and the decrease. Some exceptions are also to be expected due to the effects of nearby structures. A such, the results shown in Table 5.1 are acceptable as they confirm that the model is sensitive to changes in hydraulic parameters.

5.1.2 Mass Balance & Model Health

The relative health of the model can be checked following a completed model simulation by observing the Mass Balance outputs for the 2D component of the model. The Mass Balance outputs provide information relating to the total volume of water within the model and should generally show that the input volume is equal to the output volume plus any volume that is stored within the 2D domain. However, variations will occur due to approximation in the calculations carried out by the model, particularly in the way in which volumes are calculated and these are perfectly normal. More crucially, though, variations can also occur due to model issues such as irregularities and stability problems which will indicate poor model performance (Flood Modeller, n.d.; TUFLOW, 2018). With a normal TUFLOW Classic model, a simulation is able to continue with some mass error in volumes, reporting the cumulative mass balance error in the results output from a simulation to give indications of stability issues. However, the TUFLOW HPC module used for this study has been created in a way that enables a simulation to run while maintaining a cumulative mass error of 0% by using adaptive timestepping. As a model simulation progresses using HPC, the maximum available timestep possible is used while maintaining 0% mass error. If the model should encounter any stability issues that may jeopardise the mass error, the timestep is decreased, allowing for extra steps of full calculations, to allow the model to overcome the stability issue (Reference TUFLOW, 2018). A large number of adaptive timestepping messages occurring in quick succession will indicate a potential model instability. Figure 5.1 below shows a plot of the number of nRS_HCN adaptive timestepping messages that have occurred during each model simulation.

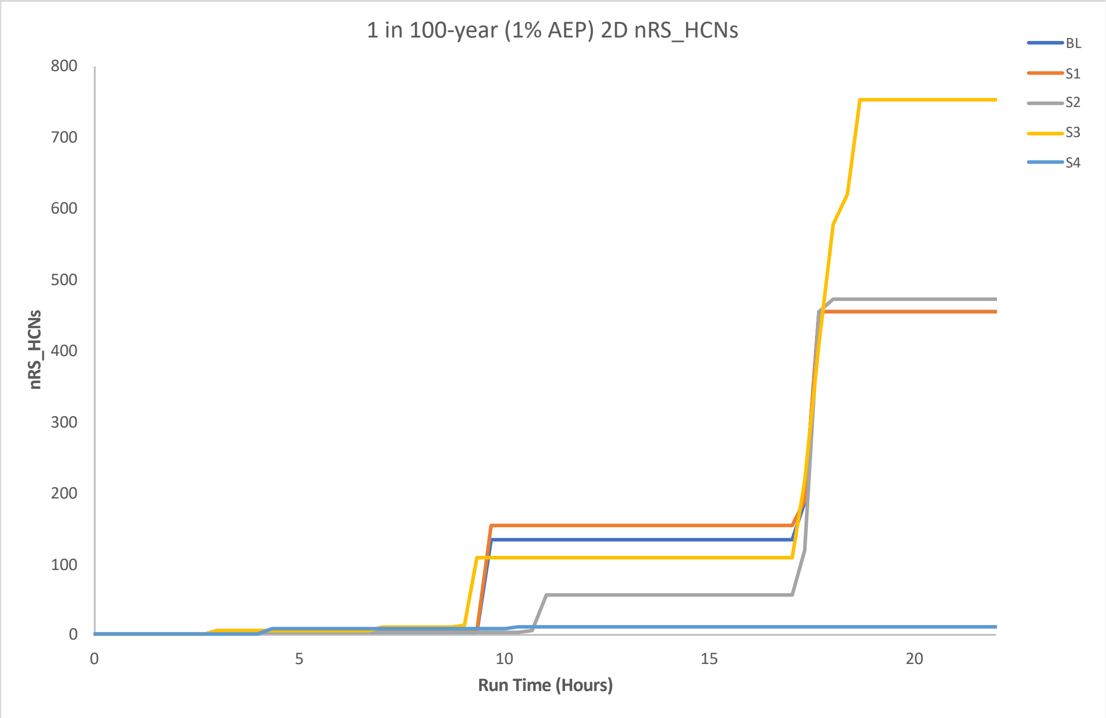


Figure 5.1: Number of nRS_HCN messages occurring during 1 in100-year (1% AEP), indicative of model instabilities

At approximately 9 hours run time the number of messages occurring during the Baseline and Scenarios 1 and 3 are seen to increase before settling at around 10 hours. Scenario 2 is also shown to increase to a delayed and lesser extent. Most notably, though, is that at approximately 12 hours the number of messages rises significantly, especially for Scenario 3. This sharp increase suggests that a possible model instability is occurring during these simulations. Interestingly, the number of adaptive timestepping messages occurring for Scenario 4 is shown to remain low throughout. However, because the model simulations were able to complete fully without crashing, any potential causes for the changes in timesteps and any potential instabilities that caused these alterations are difficult to determine. This analysis is generally best employed where a simulation suddenly crashes as it will help isolate the primary cause. The fact that the timestepping messages are shown to settle before the simulations are completed suggests that the model was able to overcome the calculation difficulties it encountered.

5.1.3 Checks Against EA Flood Mapping

In order to determine that the results of the 1D-2D linked model are suitable, the full extents of flooding for the 1 in 100-year (1% AEP) event have been compared to the full extents of Flood Zone 3 (1% AEP or greater) from the Environment Agency's Risk of Flooding from Rivers and Sea mapping. Figure 5.2 below shows that, while there are some similarities between the extents of Flood Zone 3 and the modelled Baseline event from this study, particularly in the downstream end of the study area on the River Greet, in many places the the extent of flooding during the Baseline model is much greater than that of Flood Zone 3. Flooding on Potwell Dyke is shown to be substantially lower than that of Flood Zone 3, with the flooding occurring on Nottingham Road bearing the only similarity. While similarities are desired, as this suggests that flooding within the study model comforts to topographical features in the same way as Flood Zone 3, differences, such as those observed in Fig 5.2, are not necessarily negative.

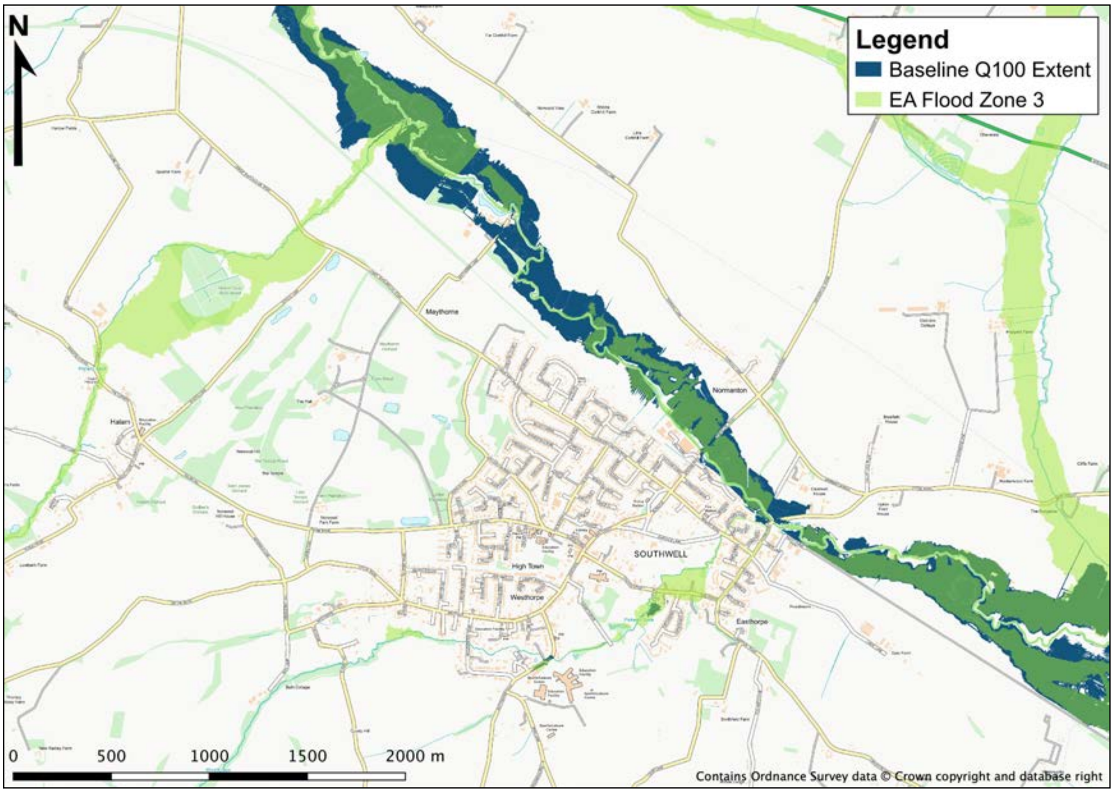


Figure 5.2: Baseline 1 in 100-year (1% AEP) peak flood extents in comparison to the EA's Flood Zone 3 (1% AEP) flood extents

There are a number of causes for the differences observed, such as differences in the way hydrological event information is derived. The most likely reason for the differences is due to the difference in model accuracy and input information between that of this study and those of the River Greet and Potwell Dyke used to generate the EA’s flood zones. By using a high-resolution grid for the 2D domain flooding is less likely to be under-represented. The models used for the generation of the EA’s flood zones are also much smaller, covering a shorter reach of each watercourse. As such, the information available when the generation of the flood zones were completed on behalf of the EA is much more limited, resulting in much smaller flood extents (as seen upstream on the River Greet in Fig. 5.2). Furthermore, the flooding issues associated with Potwell Dyke comprise numerous contributing factors. The model and simulations completed as part of this study have demonstrated the issue of fluvial flooding, with contributing factors such as hydraulically restrictive structures and surcharge from the River Greet up the culvert at the downstream end of Potwell Dyke. However, due to running through an urbanised area, Potwell Dyke acts as the receptor for a large number of outfalls from drainage systems, such as surface water sewers, individually drained buildings and surface water water drainage ditches, open drains and culverts which have not been modelled due to the sheer complexity that this would create. While the model used to generate the EA’s flood mapping for Potwell Dyke also did not comprise these additional flow inputs into the watercourse, it is possible that some compensation was made to the hydrological input at the upstream boundary of the model.

5.2 Higher Resolution to Reduce Uncertainty

The aim of the study has been to provide evidence that modelling river restoration and natural flood management techniques at a high resolution will demonstrate that they are effective in reducing flood risk to urbanised catchments. By modelling a study area at a higher resolution it is believed that improvements in the accuracy of results and how certain mechanisms, such as flood flow routing, are represented (Coulthard et al., 2007; Harnett and Nash, 2017).

5.2.1 Benefits of a Reduced Cell Size

TUFLOW carries out calculations for water volume, depth, velocity and conveyance at each 2D cell for each timestep throughout the simulation, as defined by the user. Therefore, by decreasing the size of a single cell and increasing the total number of cells, together with increasing the number of timesteps occurring during a simulation, the number of calculations is greatly increased. This has a dramatic effect on the length of time taken to run a simulation but also requires more advanced and capable computer processing power.

Cell size and the margins for determining how small the cell size should be to be considered as "high resolution" within a 2D model domain is relatively subjective. The 2D cell size needs to be small enough to replicate the environmental processes and behaviours being simulated yet, in balance, the cell size also needs to be large enough to minimise the run times of simulations (TUFLOW, 2018).

Minor flow paths within the floodplain, such as within field drains, ditches and other topographical depressions, may be represented more coarsely than in reality or perhaps completely omitted. Where these flow paths have less significance, such as during higher order flood events where the area becomes completely inundated, it may not be necessary to provide enough detail within the 2D domain to accurately represent them, but it is evident that a finer resolution will produce less errors and greater detail (eg. Altenau et al., 2017). However, during low-order flood events, where smaller flow paths can be critical to how and where flooding begins to occur, or in areas such as urban areas where small, high velocity flow paths present a danger, representation of these flow paths with enough accuracy should be regarded as highly important in order to better understand them.

This has been demonstrated in this study, particularly in the results from Scenario 2, where wetland ponds were added to provide additional flood storage within the natural floodplain. Some of these wetland ponds were linked by swale channels in order to allow water to be conveyed from one pond to the next in order to encourage full utilisation of the ponds first ahead of the rest of the natural floodplain. By modelling at a high resolution of $1m^2$ grid cells, flow velocities, as well as other factors, can be more closely examined due to the greater detail results obtained. With this greater detail of information, more informed decisions can be taken with greater confidence (Bevan, 2007; Dottori et al., 2013; WMO, 2009).

5.3 Implications of Using Models

By decreasing the size of each individual cell within the 2D model the number of cells required to cover the study area is increased. This presents issues with time and cost, where more complex and detailed models will take longer and cost more to build but they will also take longer to simulate, which is often unfeasible where results are required urgently. For smaller catchments which will still have a relatively short simulation time this is less of a concern. However, for larger catchments which may need to run for longer periods of time, it is often necessary that the spatial resolution must be compromised by reducing cell size and, therefore, reducing the accuracy in order to improve simulation run times (Coulthard et al., 2007).

While the use of a higher resolution model grid results in greater detail for model inputs and outputs, therefore reducing uncertainty, reducing the cell size and, therefore, increasing the total number of cells that must be calculated at each timestep will result in increased model run times and increased hardware requirements to run each simulation. In the case of this study, TUFLOW HPC was utilised in order to greatly reduce run-times. Where the Classic version of TUFLOW will utilise a single CPU core, HPC allows for multi-core usage on modern CPUs or it can utilise the user's graphics module, which often comprise of hundreds or even thousands of small processing cores, allowing for simultaneous calculations as opposed to one at a time. Without utilising the HPC module for TUFLOW, it is estimated that each simulation for this study would take approximately 7-12 days each to fully complete, with 7 simulations per scenario and 5 scenarios to simulate. In addition, it is often the case that events and scenarios are run multiple times where issues and errors are encountered. With HPC, simulation times for each event were reduced to approximately 20 hours, which is remarkably close to running the 22 hour flood event in real time. As such, when deadlines set for the assessment of any flood study, including those employing the use of natural flood management techniques, modelling flood events can often stretch those deadlines. By increasing the resolution and increasing the simulation run times, deadlines become more difficult to meet.

While flooding from the River Greet is very prominent throughout the study, the flooding that occurs from Potwell Dyke is relatively minimal in comparison to the Environment Agency's Risk of Flooding from Rivers and Sea flood mapping, which is based on an existing model of the watercourse.There are a couple of reasons why this is the case. Firstly, as Potwell Dyke has a relatively small contributing catchment, much of the flooding that occurs from the channel is attributed to short-term, intense rainfall. However, as the model forming part of this study was largely based upon the River Greet, the critical storm duration is largely tied to that of the River Greet's full catchment, including Potwell Dyke. As a result, intense rainfall is spread over a longer time period. Second, as Potwell Dyke is a relatively small watercourse which receives a large number of surface water outfalls from local sewers and drains, individual building drainage and runoff from nearby developments. As a result, Potwell Dyke is a critical receptor as it is generally too small to receive larger volumes in quick succession from these numerous sources, placing the watercourse under substantial stress. Finally, due to being a small watercourse comprising of a number of culverts and small bridge structures, Potwell Dyke is particularly susceptible to blockages, which form part of the Environment Agency's worst-case modelling scenarios when generating flood zones. A more suitable assessment for Potwell Dyke, under these circumstances, would be to model it alone at a high resolution and include an assessment of potential blockages. However, this would form a full study in itself.

5.4 Evidence that Modelling Restoration is Effective

One the key benefits to modelling river restoration and natural flood management techniques at a high resolution is the fact that the smaller cell size allows for more accurate representation of smaller objects, such as individual pieces of woody debris. Objects represented within TUFLOW, and other fixed grid 2D models, must be at least one full cell in size. Where a particularly coarse grid resolution is used, objects that are smaller than one cell will either be over represented or completely ignored, while conversely, any objects slightly larger than a single cell but smaller than two cells will be under-represented. Further benefits of a higher resolution model grid become apparent when representing larger objects as the edges of such objects become less pixellated and more refined. This is also the case when results are represented, as changes in flood characteristics, such as depth and velocity, are more detailed and detail that would otherwise be ignored by a larger grid resolution are accounted for, reducing the overall uncertainty of the results obtained. Aside form using a high-resolution grid, modelling the techniques under the different scenarios employed by this study has shown to represent the features and relevant hydraulic characteristics, such as changes in flows and velocities which is comparable to other similar studies (eg. Sersawy and El Barbary, 2016).

5.4.1 Benefits of Scenario 1

In general, the results of Scenario 1 have shown that the effects of natural flood management techniques used have increased gradually as the magnitude of the flood event increased, due largely to the impact increased roughness values provided by woodland and woody debris have had on flow velocities. In a number of locations, especially in Location A, woodland placed along the banks of the River Greet have been shown to dramatically decrease the velocity of water as is spills over the banks. While this is unlikely to prevent flooding further downstream, it does show the potential to decrease the danger of fast moving flows and increase the time taken for an area to flood fully, by which time water may be given the chance to subside following the peak of the flood event. Areas indicated to benefit from increased woodland in this way were observed to benefit from greater exponential decreases in flood velocities directly from the river channel into the floodplain during greater magnitude flood events. While Location A comprised a rural area which does not include any development affected by flooding, the results of Scenario 1 demonstrate that by lining river banks with dense woodland urbanised areas where flooding directly from the channel is a likely risk could benefit exponentially.

5.4.2 Benefits of Scenario 2

The results obtained for Scenario 2 have shown that introducing natural flood management techniques that provide an additional storage provision, such as wetland ponds, could prove to be highly effective throughout most flood events but particularly for the lower magnitude events. During the 1 in 10-year (10% AEP) event the presence of wetland ponds has resulted in significant reductions in maximum flood depth and have, in-places, completely prevented flooding shown to occur in the Baseline. And while during the larger 1 in 100-year (1% AEP) plus 30% climate change event the complete removal of flooding in comparison to the Baseline is far less apparent, the wetland ponds were still able to reduce maximum flood depths throughout the majority of the study area despite being largely inundated by floodwater.

5.4.3 Benefits of Scenario 3

The general aim of Scenario 3 was to reduce the impacts of flooding, and particularly the depth of flooding experienced, in critically sensitive areas by allowing flooding into less sensitive areas by introducing meanders with lowered banks and profiled floodplains. The results observed from Scenario 3 have shown that, by lowering bank levels and allowing water to spill in the floodplain sooner, flooding was encouraged in parts of the adjacent floodplain, with increases in maximum flood depth shown to occur. At the same time, areas of the floodplain, generally adjacent to the opposite bank to the lowered banks, decreases in maximum depth were observed. During all three flood events, the maximum flood depth was shown to increase immediately downstream of each of the three meanders, while some increase has been shown to occur to the opposite side of the river, with the changes shown to be more dramatic during the 1 in 10-year (10% AEP) event and less dramatic during the 1 in 100-year (1% AEP) plus 30% climate change event. While the techniques demonstrated in Scenario 3 were located in a rural area, the results suggest that with careful planning these methods could directly benefit urbanised areas. This would be possible by re-meandering and lowering the outer banks of the meander directly opposite an urban area, drawing flood water away from the opposite bank.

5.4.4 Benefits of Scenario 4

In theory, by combining the use of woody debris and woodland, wetland ponds and re-meandering and bank lowering in previous scenarios, Scenario 4 has the potential to offer the benefits of each scenario complementing each other. Scenario 4 would generally be more representative of real-world restoration projects (reference studies). To an extent, the results obtained for Scenario 4 indicate indicate the benefits of Scenarios 1, 2 and 3 working together in order to reduce the impacts of flooding over the Baseline. This is particularly the case during the 1 in 10-year (10% AEP) event and, to a lesser extent, the 1 in 50-year (2% AEP) event, where increases in maximum flood depth are shown to occur adjacent to the right bank at the upstream extent, where woody debris has been previously shown to reduce velocities while increasing the amount of water retained in the area. At Location B, the increased velocities occurring along the flow path appear to have been reduced somewhat as a result of the attenuation provided upstream. Drastic increases are predictably shown to occur within the wetland ponds, indicating that they are being properly utilised throughout all events. The pattern of increases immediately downstream of meanders introduced and modified as part of Scenario 3, and decreases in the floodplain opposite the meanders, is observed during Scenario 4. The extent of the increase downstream of the meanders has been mitigated somewhat by the presence of wetland ponds downstream providing storage, resulting in decreases in maximum flood depth downstream of Normanton Road. Despite the positive results in places during the lower order events, a similar pattern of reduced beneficial effects is still observed during the 1 in 100-year (1% AEP) plus 30% climate change event. This suggests that, even though various techniques mitigating flooding in different ways are able to compliment one another effectively for smaller events, as a flood event increases in magnitude the techniques are generally shown to become less effective due to becoming inundated.

5.5 Evidence that Modelling Restoration is Ineffective

5.5.1 Disadvantages of Scenario 1

Results obtained for Scenario 1 suggest that the use of woody debris, at least in the instances employed for this study, have little effect overall. Where woody debris was scattered throughout the floodplain and spread across wide areas in an attempt to reduce flow velocities through those areas, the results indicate that flow velocities and depth were relatively unaffected. In addition, woody debris that was formally arranged, such as with Location B, where barriers were formed in an attempt to reduce flow velocity along an established flow path through Maythorne, also appeared to be ineffective. Maximum velocity along this flow path was shown to have increased significantly, resulting in increased maximum flood depth within the village. At first it would appear that the placement of woody debris barriers have had a direct negative impact upon maximum velocity and depth in the area. However, on closer inspection, the significant increases are likely the direct result of significant reductions in maximum velocity and depth further upstream at Location A by reducing the effects of flooding upstream of Maythorne. While reducing the effects of flooding in Location A has been achieved, due to a lack of storage provision for the water that has been removed, flooding has worsened downstream in Location B. While the woody debris barriers placed in Location B have, therefore, not directly worsened conditions in Maythorne, they do appear to have done little to mitigate the increase caused by significant reductions in flooding upstream.

5.5.2 Disadvantages of Scenario 2

The main disadvantage to the addition of wetland ponds and attenuation volumes in general is that they require a considerable amount of space to be dedicated to them in the real-world which would otherwise be utilised for things like agriculture and livestock (Naiman et al., 2005). While an attenuation pond is very effective at increasing the density of water storage in a a given space, that space generally needs to be dedicated to its primary function of attenuation. As such, the space remains unoccupied and unused for purposes such as development and agriculture for the majority of the time, sacrificing the land to mitigate a flood which may only happen on rare occasions. Additionally, attenuation volumes become ineffective once at full capacity and subsequently inundated by additional flood water and must be sized accordingly for the maximum flood event to be mitigated. This means that, if a volume is designed to accommodate a 1 in 1,000-year (0.1% AEP) flood event, during smaller magnitude events the volume will not be utilised fully.

5.5.3 Disadvantages of Scenario 3

While the results from Scenario 3 generally demonstrated that re-meandering and, in particular, reconnecting the channel to the floodplain would allow more flooding of less sensitive floodplain, the results also indicate that the effects of this method would be particularly difficult to manage. Large areas of maximum flood depth increase were observed in return for relatively minimal gains in maximum flood depth decrease. This is particularly the case during the 1 in 10-year (10% AEP) event, where the effects of Scenario 3 are more drastic. During the 1 in 100-year (1% AEP) plus 30% climate change event, the vast majority of the study area sees no change in maximum flood depth (indicated by no change highlighted in Fig. 4.33), suggesting that while the benefits are less prolific the negative effects are also less substantial. While the placement of re-meandering and bank lowering directly opposite an urbanised area has been suggested, this would generally be very difficult to put into practice. In the study area of Southwell most of the development has taken place to in the floodplain adjacent to the right bank of the River Greet, with the floodplain adjacent to the left bank left largely undeveloped, suggesting there would be room to place a new meander directly opposite Southwell. However, in reality, urbanised areas built within floodplains tend to span both sides of the floodplain, constraining the river channel and leaving very little open space for river restoration projects to take place (reference). As such, re-meandering and reconnecting a river to its floodplain while reducing flood risk to urbanised areas would present too great a risk of increase to urbanised areas immediately downstream of the lowered banks to be worthwhile.

5.5.4 Disadvantages of Scenario 4

The key disadvantage to combining all tested techniques together in Scenario 4 is that the effects of woody debris indicate increases in maximum flood depth, appearing to have worsened conditions, with general increases upstream. As such, when the results of Scenario 4 are directly compared with those of Scenario 2, it appears that wetland ponds alone are able to offer more beneficial decreases in maximum flood depth throughout the wider study area. While the aim of the woody debris was to decrease velocities, increase flood depths and retain greater amounts of floodwater, the results of Scenario 2 show that reductions in maximum flood depth can be offered in all areas by simply providing enough flood attenuation without adversely increasing maximum flood depth to other areas in the way that woody debris has been shown to do. Therefore, while the increases in maximum flood depth shown in the upstream region of the River Greet during Scenario 4 are not necessarily negative, and are indeed intended, the results show that it is likely that Scenario 4 would have indicated more favourable results than it did simply by excluding the use of woody debris and woodland altogether.

5.6 Real-World Empirical Assessment

One of the key observations from the modelling completed for this study is that restoration and natural flood management techniques are shown to be somewhat effective during smaller flood events and, in general, incrementally less effective as the magnitude of the flood event increases. This same observation generally holds true for more conventional flood defences such as earth embankments and bunds, which are simply only effective when they are built high enough to contain a set level of river stage. However, when this set level is exceeded, the defence will be overtopped and/or inundated and essentially fails to serve its intended purpose (Jongejan et al., 2020). Therefore, the results of this study suggest that river restoration and natural flood management techniques should be considered as flood defences designed to mitigate lower order, modest flood events rather than the ultimate solution in solving all flooding.

Hydrodynamic modelling, particularly when studying the effects of flooding, is often seen as the primary method of assessment (Strayer and Dudgeon, 2010). However, flood modelling, and the modelling of any environmental processes, should be considered as a single advisory tool designed to improve and assist decision-making rather than being the sole tool for making an informed decision. The results of any modelling study should be used to complement existing observations and analyses to either confirm or deny initial thoughts about the processes occurring. This is largely due to the fact that modelling of any kind involves varying levels of uncertainty and, while it is sometimes possible to minimise uncertainties through more accurate input data or increased model resolution, understanding those uncertainties is arguably more important (eg. Liu et al., 2020).

While the results of this study have generally demonstrated positive outcomes can be achieved by modelling river restoration and natural flood management techniques, and that there are benefits to doing so at a high resolution, a number of flaws exist. Firstly, the potential to reduce flood the impacts of flooding to developments is limited, which is largely due to a lack of detailed design and more careful consideration when selecting techniques. In Scenario 1, for example, single cell woody debris was placed through parts of the model domain at randomly, focusing on desired areas. By employing detailed design methodology for the placement of the woody debris in the model the positive effects would have the potential to be more effective. This highlights the need for formal frameworks which detail the design and planning requirements for river restoration and natural flood management and for the modelling of such techniques.

6 Conclusions

6.1 Study Summary

The purpose of this study has been to assess how effective river restoration and natural flood management techniques are at reducing flood risk to an urbanised area by utilising a high-resolution hydrodynamic model. Due to the rising concern regarding urbanisation the impacts of flooding in urban areas, such as impacts upon infrastructure, normal services and the danger to populations (Zhou et al., 2019), and with the increasing threat of climate change (Kay et al., 2011), there has been a general shift away from hard engineering options to more natural and holistic methods for managing flood risk (Soar and Thorne, 2001). Advances in hydrodynamic modelling have meant that it is possible to predict and assess the impacts of fluvial flooding in urbanised areas while observing simulated flow routes within floodplains based upon topographies captured using remote sensing technology (Nguyen et al., 2016). Modelling at a high-resolution has become possible due to advancements made to the level of detail captured by remote sensing technologies, particularly LiDAR, which is capable of recording topography at resolutions of 1m and below, resulting in greater accuracy and reduced uncertainty in results (Fewtrell et al., 2008; Liu et al., 2015; Gallegos et al., 2009; Marks and Bates, 2000; Mason et al., 2007, 2014; Neal et al., 2009a; Ozdemir et al., 2013; Schubert et al., 2008). This study has utilised a high-resolution 2D grid comprising 1m cells in order to more accurately represent fine details associated with river restoration and natural flood management techniques and to demonstrate how greater model detail and accuracy in outputs reduces the levels of uncertainty surrounding the use of such techniques.

6.2 Summary of Aims & Objectives

Following construction of a baseline model of the study area of Southwell, including the River Greet and Potwell Dyke, a series of scenarios where common river restoration and natural flood management techniques were modelled, simulated and analysed in comparison to the baseline, with a final scenario which combined the tested techniques together. These scenarios were modelled in order to demonstrate the following hypothesis:

a) River Restoration and Natural Flood Management techniques will be shown to be effective at reducing flood risk to an urbanised area.
b) By combining River Restoration and Natural Flood Management techniques together, the methods tested will be shown to be more effective at reducing flood risk to an urbanised area than when tested individually.

The study has shown that river restoration and natural flood management techniques are effective at reducing flood risk, confirming the first hypothesis tested, though this has been demonstrated to be particularly the case for lower magnitude flood events. The study has also demonstrated that the techniques could be employed to reduce flood risk to an urbanised area, though this would be subject to a detailed design process which was outside the scope of this study. Scenario 4 tested the previous scenarios in combination in order to demonstrate that river restoration and natural flood management techniques will compliment one another, working together to provide greater benefits to reduce flood risk. The findings of these scenarios are summarised below.

6.3 Summary of Findings

6.3.1 Scenario 1

Scenario 1 was aimed to demonstrate how effective the use of woody debris scattered throughout parts of the upstream floodplain and woodland placed along the river banks would be at reducing flooding downstream. The theory behind this technique is that flow velocities of floodwater entering and moving through the floodplain would be reduced, keeping flood volumes in the upstream reaches for longer and, therefore, reducing the effects of flooding downstream. By modelling these features at a high-resolution it was possible to more accurately reflect more realistic dimensions for woody debris, while the edges of the riparian woodland could be better defined. The results of Scenario 1 were generally mixed, with decreases and increases in both flood depth and velocity occurring in various places. The results also showed that the effects of woody debris and riparian woodland increased exponentially with the magnitude of the flood event, with greater decreases in maximum velocity and increases in maximum depth occurring as intended during the 1 in 100-year (1% AEP) plus 30% climate change event. In particular, riparian woodland was able to dramatically reduce the velocity of water as is spilled out-of-bank and into the floodplain, resulting in increased levels of maximum depth in Location A. However, the results also showed that the increase in maximum volume upstream resulted in a flow path of running through the village of Maythorne downstream being exacerbated, and attempts to reduce velocities using woody debris barriers had marginal effects. By utilising a high-resolution model grid comprising 1m^2 cells, the results were greatly refined, resulting in higher detail for flow paths such as the one running through Maythorne. Had a higher resolution model been used, this flow path would certainly have been less detailed and the level of certainty that the flow path would occur under these circumstances would have been reduced.

6.3.2 Scenario 2

The aim of Scenario 2 was to demonstrate the effectiveness of wetland ponds which were to provide additional floodplain attenuation upstream, thereby reducing the impact of flooding further downstream. By modelling at a high-resolution it was possible to accurately define the edges and overall shapes of the ponds and to also include small swales linking some of the ponds, which were added to allow ponds to fill sequentially while minimising spill out of the previous pond. The results generally indicated that the inclusion of wetland ponds was highly effective at reducing flood risk throughout the study area. This was particularly the case for the 1 in 10-year (10% AEP) flood event, where flooding was shown to have decreased significantly from the Baseline, with flooding in many places completely prevents. The benefits of wetland ponds became less effective as flood magnitude increased through the events tested. However, during the 1 in 100-year (1% AEP) plus climate change event an increase in maximum depth was shown to occur in Maythorne and upstream of the village due to the pond upstream reaching peak capacity and resulting in spill downstream. This was in contrast to the decreases shown for the smaller events, suggesting that a greater amount of attenuation volume was required for the pond upstream. This points to the relative convenience of attenuation volumes such as wetland ponds, which can be sized appropriately according to a volume of floodwater identified in the Baseline model. Conversely, the key drawback to what has been proven to be a highly effective technique is that attenuation volumes require a considerable amount of space to be put aside and dedicated to them. While the swales linking some of the ponds were shown to convey flows from one pond to the next effectively in the lower events before ponds were essentially inundated by floodwater, they were primarily included to demonstrate the fine level of detail that could be represented with a high-resolution 2D grid. Without this high-resolution grid, swales and other linear drainage features smaller than a single grid cell would generally need to be modelled as a small 1D channel with input and output flow boundaries to allow water to flow through.

6.3.3 Scenario 3

Scenario 3 included the modelling of two new meanders in the River Greet, with the out meander bank lowered and the surrounding floodplain profiled to result in a gradual incline back up to existing floodplain levels. The bank and floodplain was also lowered and profiled at a third, existing river meander. The aim of doing so was to demonstrate that water could be encouraged to enter and utilise the surrounding floodplain, drawing flooding away from more sensitive areas. By modelling this technique in high-resolution it was possible to accurately define the new river meanders as a greater number of cells border the river channel. Flows out of the river channel and into the floodplain were, therefore, represented with a greater number of cells in the 2D domain. In general, this technique appeared more effective during the 1 in 10-year (10% AEP) event, with increases shown for intentionally flooded areas and significant decreases on the opposite side of the channel. This suggests that, with more suitable detailed design, remaindering and bank lowered could be employed strategically to deflect flooding away from critical areas. While reductions in maximum depth were still observed during the 1 in 100-year (1% AEP) plus 30% climate change event, they were largely outweighed by increases that would suggest the method wouldn't be practical for larger events. As a high-resolution was used for the 2D model domain a greater number of cells were involved in representing the flows out of the channel and into the lowered and profiled floodplain. As such, this resulted in greater accuracy in the results and improved confidence. While this restoration technique would prove more difficult to control, as it forces deliberate flooding into the floodplain upstream of an urban area, the use of a high-resolution grid lowers the uncertainty and risk involved when assessing how this technique would positively or negatively affect downstream areas, enabling better planning in a real-world scenario.

6.3.4 Scenario 4

Scenario 4 combined the restoration and natural flood management techniques tested in Scenarios 1, 2 and 3 together in order to test how effective these methods would work together. This scenario was primarily focused on testing the previous scenarios together, rather than having a specific emphasis on utilising a high-resolution grid. However, Scenario 4 was able to take advantage of the high-resolution aspects of the previous scenarios. The results for Scenario 4 show that the individual effects of each technique used are working together, with the strongest benefits observed during the 1 in 10-year (10% AEP) event, and to a lesser extent exponentially for the 1 in 50-year (2% AEP) and 1 in 100-year (1% AEP) plus 30% climate change events. The flow path through Maythorne, which was exacerbated by increases in volume upstream due tot the placement of woody debris and woodland, was greatly reduced within Scenario 4 due largely to the provision of attenuation during the 1 in 10-year (10% AEP) event. Most notably, however, is that Scenario 4 highlights that the use of woody debris to decrease velocities and increase volumes upstream, and the use of meanders and bank lowering, would need to better better planned to be more effective in the circumstances of this study. Wetland ponds have proven to be highly effective due to the attenuation provision that they offer. However, during Scenario 4 the wetland ponds were essentially shown to attenuate the deliberate increases caused by the other management techniques. While this is not necessarily a negative effect, as the wetland ponds could simply be included to mitigate the negatives effects of other techniques to make them more efficient, in hindsight the wetland ponds needed to offer greater attenuation volumes during Scenario 4 to manage increases caused by woody debris, woodland and the re-meandering/bank lowering in addition to offering the reductions in flood depth and extent observed with Scenario 2.

6.4 Benefits & Disadvantages of Modelling in High-Resolution

Modelling river restoration and natural flood management techniques, and hydrodynamic studies in general, in high-resolution is beneficial due to the level of detail that can be applied to defined specific features, resulting in greater accuracy in outputs. Under or over-representation of features is less-likely to occur where the size of a single cell is reduced. A high-resolution grid will also provide a much greater level of detail to model-wide outputs. Where a larger grid may result in flooding that appears coarse to the edge of the flood extents or with changes in flow, velocity and depth, a high-resolution grid will appear very detailed, better reflecting changes occurring on a small scale. Due to the increased detail and accuracy provided by a high-resolution model, the level of uncertainty relating to model outputs is reduced.

However, due to the greatly increased number of individual cells forming the model domain grid, a high-resolution model comes with a few caveats. Chiefly, the level of detail involved means that a greater amount of time is required to build and simulate the model as a direct result of greater demands upon computer resources. With calculations occurring during every simulation timestep at every cell simultaneously, significant computer processing power is required in order to keep simulation times to a realistic timeframe. This issue is significant where projects deadlines have to be met, often rendering a high-resolution model impractical. The amount of time taken to run a high-resolution model can be dramatically reduced through the use of computational parallelisation, allowing calculations during a simulation to be split across multiple computer processing units or by running multiple simulations simultaneously. This, however, requires even greater levels of computational hardware and software which will likely come at a greater cost.

As a result of computational power, time and cost demands, practitioners are likely to strike a compromise and settle for a grid resolution that does not impact upon these constraints while is still able to produce reasonable results, albeit those with less accuracy and a greater level of uncertainty which require greater amount of expert analysis to assess them.

6.5 Potential Future Improvements

Restoration and Natural Flood Management techniques appear to be more effective during low-order flood events. These techniques effectively act as soft-intervention and are, therefore, best suited to low-order flood event mitigation where volumes and flood extents are lower and more manageable. The results of this study, however, highlight the need for careful planning and consideration when implementing river restoration and natural flood management as the effects appear to be relatively unpredictable in certain circumstances. In order to maximise understanding of how effective river restoration and natural flood management will be, and how much protection they can offer during both low-order and high-order flood events, modelling such processes is imperative and doing so at a high-resolution results in greater levels of detail and confidence and lower levels of uncertainty.

There are limited ways in which to model river restoration and natural flood management techniques within existing model packages, with the tools and methods available which are generally suited to modelling large, solid objects such as bunds, levees and infrastructure. Current methods involving simple ground model and roughness modifications for entire grid cells may be relatively effective at replicating certain objects within the floodplain but they still result in a degree of uncertainty. Further development of modelling packages has the potential to add specific tools which are better suited to the modelling of general and specific restorative objects and techniques. Doing so may remove the need to model at increasingly high resolutions in order to replicate potentially intricate objects with a series of cells arranged ind a grid.

Due to the limited ways in which river restoration and natural flood management can be modelled, and due to the limited number of real-world projects incorporating such techniques when compared to those of traditional flood management methods, there is a clear lack of a formal framework for river restoration and natural flood management modelling. Frameworks have been proposed, such as those suggested by The River Restoration Centre (2017). However, there is little evidence to suggest that this or any other framework has been adopted as the baseline process for modelling such features. A formal framework, which in the UK should be endorsed by DEFRA and the Environment Agency, would form the basis for appropriate detailed planning of restoration features, how they should be represented through modelling and how they should be assessed. This would likely translate to how such features would be designed and implemented in the real-world and would further reduce uncertainty regarding the potential positive and negative effects that could occur.

This study has also highlighted a potential need to model multiple hydrodynamic and hydraulic models in combination. Currently, different sources of flood risk are modelled and assessed separately, due largely to the fact that many of these models calculate flows in different opposing ways. For example, a hydrodynamic river model used to assess the level of fluvial flooding will often use lumped hydrology as an input, while a hydraulic sewer model will usually used a rainfall-runoff input which is integrated into individual subcatchments, entering the system at different points. The results of this study have shown limits levels of flooding from Potwell Dyke, due largely to the study focussing on fluvial processes only while Potwell Dyke is known to flood due to numerous contributing factors, such as pluvial flooding. Therefore, there is potential scope for a study which is able to assess multiple types of flooding together in order to gain a true representation of the processes actually occurring.

Ultimately, further research into the benefits of modelling at a high-resolution is required. While this study explores how high-resolution modelling can be used to make a more detailed assessment of how effective river restoration and natural flood management techniques can be in a given location, it does not make a direct comparison between a high-resolution model and a lower resolution used for the assessment of such techniques.

References

Acreman, M.C., Riddington, R. and Booker, D.J. (2003). Hydrological impacts of floodplain restoration: A case study of the River Cherwell, UK. *Hydrology and Earth System Sciences,* 7(1), 75–85.

Acreman, M.C. and Ferguson, A.J.D. (2010). Environmental flows and the European water framework directive. *Freshwater Biology*, 55(1), 32–48.

Altenau, E. H., Pavelsky, T. M., Bates, P. D. and Neal, J. C. (2017). The effects of spatial resolution and dimensionality on modeling regional−scale hydraulics in a multichannel river. *Water Resources Research*, 53(2), 1683–1701.

Angel, S., Parent, J., Civco, D.L., Blei, A. and Potere, D. (2011). The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. *Progress in Planning,* 75(2), 53–107.

Arnell, N.W., Halliday, S.J., Battarbee, R.W., Skeffington, R.A. and Wade, A.J. (2015). The implications of climate change for the water environment in England. *Progress in Physical Geography: Earth and Environment*, 39(1), 93–120.

Arnone, E., Pumo, D., Francipane, A., La Loggia, G. and Noto, L.V. (2018). The role of urban growth, climate change and their interplay in altering runoff extremes. *Hydrological Processes,* 32, 1755– 1770.

Ashley, R.M., Balmforth, D.J., Saul, A.J. and Blanskby, J.D. (2005). Flooding in the future–predicting climate change, risks and responses in urban areas. *Water Science & Technology*, 52, 265–273.

Bannister, N., Mant, J. and Janes, M. (2005). *A Review of Catchment Scale River Restoration Projects in the UK.* The River Restoration Centre: Cranfield.

Berndtsson, R., Becker, P., Persson, A., Aspegren, H., Haghighatafshar, S., Jönsson, K., Larsson, R., Mobini, S., Mottaghi, M., Nilsson, J., Nordström, J., Pilesjö, P., Scholz,M., Sternudd, C., Sörensen, J. and Tussupova, K. (2019). Drivers of changing urban flood risk: A framework for action. *J. Environ. Manag.*, 240, 47-56.

Boyd, E.H. (2017). *Building Flood Resilience into the Fabric of Britain* [online]. Environment Agency: Bristol. Available at: https://environmentagency.blog.gov.uk/2017/02/17/building-flood-resilience-into-the-fabric-of-britain/ [Accessed 18 July 2019].

Braud, I., Breil, P., Thollet, F., Lagouy, M., Branger, F., Jacqueminet, C., Kermadi, S. and Michel, K. (2013). Evidence of the impact of urbanization on the hydrological regime of a medium-sized periurban catchment in France. *J. hydrology*, 485, 5-23.

Braud, I., Ayral, P.-A., Bouvier, C., Branger, F., Delrieu, G., Le Coz, J., Nord, G., Vandervaere, J.-P., Anquetin, S., Adamovic, M., Andrieu, J., Batiot, C., Boudevillain, B., Brunet, P., Carreau, J., Confoland, A., Didon-Lescot, J.-F., Domergue, J.-M., Douvinet, J., Dramais, G., Freydier, R., Gérard, S., Huza, J., Leblois, E., Le Bourgeois, O., Le Boursicaud, R., Marchand, P., Martin, P., Nottale, L., Patris, N., Renard, B., Seidel, J.-L., Taupin, J.-D., Vannier, O., Vincendon, B. and Wijbrans, A. (2014). Multi-scale hydrometeorological observation and modelling for flash flood understanding. *Hydrology and Earth System Sciences*, 18, 3733–3761.

Brookes, A. (1999). 17. Floodplain Restoration and Rehabilitation. pp. 553-576 in Walling, D.E., Anderson, M.G. and Bates, Paul D. (eds.), *Floodplain processes*. Wiley: Chichester, New York.

Brown, R.A. and Pasternack, G.B. (2009). Comparison of methods for analysing salmon habitat rehabilitation designs for regulated rivers. *River Res. and Applications*, 25, 745–772.

Bubeck, P., Kreibich, H., Penning-Rowsell, E., Botzen, W.J.W., de Moel, H. and Klijn, F. (2013). Explaining differences in flood management approaches in Europe and the USA: A comparative analysis. *Compr. Flood Risk Manage*. 1199–1209.

Bunn, S.E. and Arthington, A.H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, 30, 492–507.

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J. and Kendall, C. (2005). Effects of suburban development on runoff generation in the Croton River basin, New York, USA. *J. Hydrol.*, 311, 266–281.

Ceola, S., Montanari, A. and Koutsoyiannis, D. (2014). Toward a theoretical framework for integrated modeling of hydrological change. *WIREs Water*, 1, 427-438.

Charlton, M.B. and Arnell, N.W. (2014). Assessing the impacts of climate change on river flows in England using the UKCP09 climate change projections. *J. Hydrol.*, 510, 424–435.

Chave, P. (2001). *The EU Framework Directive: an introduction*. IWA Publishing: Cornwall.

Chow, V. T. (1959). *Open-channel hydraulics*. McGraw-Hill: New York.

Christierson, B.V., Vidal, J.P. and Wade, S.D. (2012). Using UKCP09 probabilistic climate information for UK water resource planning. *J. Hydrol.*, 424–425, 48–67.

Conner, J.T. and Tonina, D. (2014). Effect of cross-section interpolated bathymetry on 2D hydrodynamic model results in a large river. *Earth Surface Processes and Landforms*, 39, 463–475.

Coulthard, T.J., Hicks, D.M. and Van De Wiel, M.J. (2007). Cellular modelling of river catchments and reaches: Advantages, limitations and prospects. *Geomorphology*, 90, 192–207.

Crooks, S.M. and Kay, A.L. (2015). Simulation of river flow in the Thames over 120 years: evidence of change in rainfall-runoff response? *Journal of Hydrology: Regional Studies*, 4 (B), 172–195.

Crowder, D.W. and Diplas, P. (2000). Using two-dimensional hydrodynamic models at scales of ecological importance. *J. Hydrol.*, 230, 172–191.

Dawson, R.J., Ball, T., Werritty, J., Werritty, A., Hall, J.W. and Roche, N. (2011). Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change. *Glob. Environ. Chang.*, 21, 628–646.

DEFRA (2012). *Tackling water pollution from the urban environment − consultation on a strategy to address diffuse water pollution from the built environment*. DEFRA: London.

DEFRA (2013). *Environmental Statistics - Key Facts*. DEFRA: London.

DEFRA (2017). *UK Climate Change Risk Assessment 2017*. DEFRA: London.

EA. (2009). *Flooding in England: A National Assessment of Flood Risk*. Environment Agency: Bristol.

EA. (2014). *Flood and coastal erosion risk management: Long-term investment scenarios (LTIS)*. Environment Agency: Bristol.

Egger, C. and Maurer, M. (2015). Importance of anthropogenic climate impact, sampling error and urban development in sewer system design. *Water Res.*, 73, 78–97.

El Sersawy, H. and El Barbary, Z. (2016). Hydraulic Evaluation of River Restoration Using Numerical Modelling Approach. *IJSRSET, Engineering and Technology*, 1, 607-617.

Evans, E., Ashley, R., Hall, J., Penning-Rowsell, E., Saul, A., Sayers, P., Thorne, C. and Watkinson, A. (2004). *Foresight. Future Flooding. Executive Summary*. Office of Science and Technology: London.

Fletcher, T.D., Andrieu, H. and Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Adv. Water Resour.*, 51, 261–279.

Flood and Water Management Act 2010. HMSO: London.

Flood Modeller (n.d.). *Flood Modeller 1D Mass Balance Calculations* [online]. Jacobs: Dallas, USA. Available at: http://help.floodmodeller.com/floodmodeller/Technical_Reference/1D_Simulation_Details/1D_Mass_balance.htm. [Accessed 20 July 2019].

Ford, A., Barr, S., Dawson, R., Virgo, J., Batty, M. and Hall, J. (2019). A multi-scale urban integrated assessment framework for climate change studies: A flooding application. *Computers, Environment and Urban Systems*, 75, 229-243.

Gard, M. (2009). Comparison of spawning habitat predictions of PHABSIM and River2D models. *International Journal of River Basin Management*, 7, 55–71.

Gard, M. (2014). Modelling changes in salmon habitat associated with river channel restoration and flow-induced channel alterations. *River Res. and Applications*, 30, 40–44.

Gore, J.A., Crawford, D.J. and Addison, D.S. (1998). An analysis of artificial riffles and enhancement of benthic community diversity by physical habitat simulation (PHABSIM) and direct observation. *Regul. Rivers: Res. Mgmt.*, 14, 69-77.

Gourley, J.J., Erlingis, J.M, Hong, Y. and Wells, E.B. (2012). Evaluation of tools used for monitoring and forecasting flash floods in the United States. *Weather and Forecasting*, 27, 158–173.

Haaland, C. and Van den Bosch, C.K. (2015). Challenges and strategies for urban green-space planning in cities undergoing densification: A review. *Urban Forestry & Urban Greening*, 14, 760–771.

Hall, J. (2003). Quantified scenarios analysis of drivers and impacts of changing flood risk in England and Wales: 2030–2100. *Global Environmental Change Part B: Environmental Hazards*, 5, 51–65.

Hall, J., Sayers, P. and Dawson, R. (2005). National-scale assessment of current and future flood risk in England and Wales. *Natural Hazards*, 36, 147–164.

Hall, M.J., (1977). The Effect of Urbanization on Storm Runoff from Two Catchment Areas in North London. *AHS-AI SH*, 123, 144–152.

Hammond, M.J., Chen, A.S., Djordjević, S., Butler, D. and Mark, O. (2015). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, 12, 14–29.

Hannaford, J. (2015). Climate-driven changes in UK river flows: a review of the evidence. *Prog. Phys. Geogr.*, 39, 29–48.

Hardy, R.J., Bates, P.D. and Anderson, M.G. (1999). The importance of spatial resolution in hydraulic models for floodplain environments. *J. Hydrol.*, 216, 124–136.

Harper, D., Ebrahimnezhad, M. and Climent I Cot, F. (1998). Artificial riffles in river rehabilitation: setting the goals and measuring the successes. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 8, 5-16.

Hendry, K., Cragg-Hine, D., O'Grady, M., Sambrook, H. and Stephen, A. (2003). Management of habitat for rehabilitation and enhancement of salmonid stocks. *Fisheries Research*, 62, 171–192.

Hlodversdottir, A.O., Bjornsson, B., Andradottir, H.O., Eliasson, J. and Crochet, P. (2015). Assessment of flood hazard in a combined sewer system in Reykjavik city centre. *Water Sci. Technol.*, 71, 1471–1477.

Hollis, G.E. (1975). The effect of urbanization on floods of different recurrence interval. *Water Resour. Res.*, 11, 431–435.

Hollis, G.E. (1988). One year irrigation experiment to assess loses and runoff volume relationships for a residential road in Hampshire, England. *Water Resour. Res.*, 11, 61–74.

Hollis, G.E. and Ovenden, J.C. (1988). The quantity of stormwater runoff from ten stretches of road, a car park and eight roofs in Hertfordshire, England during 1983. *Hydrol. Processes*, 2, 227–243.

Hunt, A. and Watkiss, P. (2011). Climate change impacts and adaptation in cities: A review of the literature. *Climatic Change*, 104, 13–49.

Huong, H.T.L. and Pathirana, A. (2013). Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam. *Hydrology and Earth System Sciences*, 17(1), 379-394.

HR Wallingford (n.d.) *Tools for the design and evaluation of sustainable drainage systems (SuDS)* [online]. HR Wallingford: Wallingford. Available at: http://www.uksuds.com/. [Accessed: 28th December 2019].

Institute of Hydrology (1975). *Flood Studies Report*. Natural Environment Research Council: Swindon.

Institute of Hydrology (1999). *Flood Estimation Handbook*. Centre for Ecology & Hydrology: Wallingford.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. Ed. by Core Writing Team, R.K. Pachauri and L.A. Meyer. pp151.

IUCN (2009). No time to lose: make full use of nature-based solutions in the post-2012 climate change regime. In: Position Paper on the Fifteenth Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP 15). International Union for Conservation of Nature: Gland, CH: IUCN.

Jacobson, C.R. (2011). Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. *J. Environ. Manage.*, 92, 1438–1448.

Jiang, Y., Zevenbergen, C. and Ma, Y.C. (2018). Urban pluvial flooding and stormwater management: A contemporary review of China's challenges and “sponge cities” strategy. *Environ. Sci. Pol.*, 80, 132-143.

Johnstone, D. and Horan, N. (1996). Institutional developments, standards and river quality: A UK history and some lessons for industrialising countries. *Water Science and Technology.* 33. 211-222.

Jongejan, R.B., Diermanse, F., Kanning, W. and Bottema, M. (2020). Reliability-based partial factors for flood defenses. *Reliability Engineering & System Safety*, 193, 106589.

Jongman, B., Ward, P. and Aerts J.C.J.H. (2012). Global exposure to river and coastal flooding: Long term trends and changes. *Global Environmental Change,* 22, 823-835.

Karamouz, M., Hosseinpour, A. and Nazif, S. (2011). Improvement of urban drainage system performance under climate change impact: Case study. *J. Hydrol. Eng.*, 16, 395-412.

Kaspersen, P.S., Ravn, N.H., Arnbjerg-Nielsen, K., Madsen, H. and Drews, M. (2017). Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding. *Hydrology and Earth System Sciences*, 21(8), 4131-4147.

Kay, A.L., Crooks, S.M., Pall, P. and Stone, D.A. (2011). Attribution of Autumn/ Winter 2000 flood risk in England to anthropogenic climate change: a catchment-based study. *J. Hydrol.*, 406, 97-112.

Kay, A.L., Rudd, A.C., Davies, H.N., Kendon, E.J. and Jones, R.G. (2015). Use of very high resolution climate model data for hydrological modelling: baseline performance and future flood changes. *Clim. Change*, 133, 193-208.

Kendon, E.J., Roberts, N. and Fowler, H. (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nat. Clim. Change,* 4, 1-7.

Kleidorfer, M., Mikovits, C., Jasper-Tonnies, A., Huttenlau, M., Einfalt, T. and Rauch, W. (2014). Impact of a Changing Environment on Drainage System Performance. *Procedia Engineering,* 70 (2014), 943-950.

Knighton, D. (1998). *Fluvial forms and processes, a new perspective*. Arnold: London

Kundzewicz, Z. W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K. and Sherstyukov, B. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological Sciences Journal*, 59, 1-28.

Legleiter, C.J., Kyriakidis, P.C., McDonald, R.R. and Nelson, J.M (2011). Effects of uncertain topographic input data on two-dimensional flow modeling in a gravel-bed river. *Water Resour. Res.*, 47, W03518.

Lehane, B.M., Giller, P.S., O'Halloran, J. Smith, C. and Murphy, J. (2002). Experimental provision of large woody debris in streams as a trout management technique. *Aquatic Conserv: Mar. Freshw. Ecosyst.*, 12, 289-311.

Liu, J., Shao, W., Xiang, C., Mei, C. and Li, Z. (2020). Uncertainties of urban flood modeling: Influence of parameters for different underlying surfaces, *Environmental Research*, 182, 108929.

Mahmood, M.I., Elagib, N.A., Horn, F. and Saad, S.A.G. (2017). Lessons learned from Khartoum flash flood impacts: An integrated assessment. *Science of the Total Environment*, 601, 1031-1045.

Marshal, D.C.W. and Bayliss A.C. (1994). *Report No. 124 Flood estimation for small catchments*. Institute of Hydrology. Natural Environment Research Council: Swindon.

McGrane, S.J., Hutchins, M.G., Miller, J.D., Bussi, G. and Kjeldsen, T.R. (2016). During a winter of storms in a small UK catchment, hydrology and water quality responses follow a clear rural-urban gradient. *J. Hydrol.*, 545, 463–477.

Miller, J. D., Kim, H., Kjeldsen, T.R., Packman, J., Grebby, S. and Dearden,R. (2014). Assessing the impact of urbanization on storm runoff in a peri-urban catchment using historical change in impervious cover. *J. Hydrol.*, 515, 59–70.

Miller, J. D. and Hutchins, M. (2017). The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *Journal of Hydrology: Regional Studies*, 12, 345–362.

Murphy, J., Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K., Clark, R., Collins, M., Harris, G. and Kendon, L. (2010). *UK Climate Projections Science Report: Climate Change Projections.* UK Met Office Hadley Centre: Exeter.

Naiman, R.J., Décamps, H., McClain, M.E., Linkens, G.E. (2005). 10 - Restoration, pp. 291-325 in Naiman, R.J., Décamps, H., McClain, M.E., Linkens, G.E. (eds.) *Riparia: Ecology, Conservation and Management of Streamside Communities*. Academic Press: New York.

Nguyen, P., Thorstensen, A., Sorooshian, S., Hsu, K., AghaKouchak, A., Sanders, B., Koren, V., Cui, Z. and Smith, M. (2016). A high resolution coupled hydrologic–hydraulic model (HiResFlood-UCI) for flash flood modeling. *J. Hydrol.*, 541, 401-420.

ONS. (2014). *National Population Projections: 2014-based Statistical Bulletin* [online]. ONS: London. Available at: https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2015-10-29. [Accessed 07 August 2019].

Pasternack, G.B., Gilbert, A.T., Wheaton, J.M. and Buckland, E.M. (2006). Error propagation for velocity and shear stress prediction using 2D models for environmental management. *J.Hydrol.*, 328, 227–241.

Praskievicz, S. and Chang, H. (2009). A review of hydrological modelling of basin-scale climate change and urban development impacts. *Prog. Phys. Geogr.*, 33, 650–671.

Pretty, J.L., Harrison, S.S.C., Shepard, D.J. Smith, C., Hildrew, A.G. and Hey, R.D. (2003). River rehabilitation and fish populations: assessing the benefit of instream structure. *Journal of Applied Ecology*, 40, 251-265.

Priestley, S. (2015). Water Framework Directive: achieving good status of waterbodies, Briefing Paper Number CBP7246, 27th November 2015 [online]. House of Commons Library: London. Available at: http://researchbriefings.files.parliament.uk/documents/CBP-7246/CBP-7246.pdf. [Accessed 26th August 2019].

Priestley, S. (2016). Winter floods 2015–16. Briefing Paper Number CBP7427. 21st January 2016 [online]. House of Commons Library:London. Available at: http://researchbriefings.files.parliament.uk/documents/CBP-7424/CBP-7424.pdf. [Accessed 3rd September 2019].

Prosdocimi, I., Kjeldsen, T. and Miler, J. (2015). Detection and attribution or urbanization effect on flood extremes using nonstationary flood-frequency models. *Water Resour. Res.*, 51, 4244–4264.

Reynard, N.S., Prudhomme, C. and Crooks, S. (1999). Climate change impacts for fluvial flood defence. *Report to Ministry of Agriculture, Fisheries and Food, Final Report FD0424-C.* Centre for Ecology and Hydrology: Wallingford.

Reynard, N. S., Kay, A. L., Anderson, M., Donovan, B. and Duckworth, C. (2017). The evolution of climate change guidance for fluvial flood risk management in England. *Progress in Physical Geography: Earth and Environment*, 41, 222–237.

Richards, K.S. (1982). *Rivers: Form and Process in Alluvial Channels*. Methuen: London.

River Restoration Centre (2017). *River Restoration and 2D modelling Science Digest* [online]. The River Restoration Centre: Cranfield. Available at: https://www.therrc.co.uk/sites/default/files/general/river_restoration_and_2d_modelling.pdf [Accessed 07 December 2019].

Rosbjerg, D. (2017). Optimal adaptation to extreme rainfalls in current and future climate. *Water Resour. Res.*, 53, 535–543.

Rubinato, M., Nichols, A., Peng, Y., Zhang, J.-m., Lashford, C., Cai, Y.-p., Lin, P.-z. and Tait, S. (2019). Urban and river flooding: Comparison of flood risk management approaches in the UK and China and an assessment of future knowledge needs. *Water Sci. and Eng.*, 12 (4), 274-283.

Salvadore, E., Bronders, J. and Batelaan, O. (2015). Hydrological modelling of urbanized catchments: a review and future directions. *J. Hydrol.*, 529, 62–81.

Sayers, P.B; Horritt, M; Penning-Rowsell, E; McKenzie, A. (2015). Climate Change Risk Assessment 2017: Projections of future flood risk in the UK. Committee on Climate Change: London.

Schumm, S.A. (1973). Geomorphic Thresholds and Complex Response of Drainage Systems, pp. 299-310 in: Morisawa, M., Ed., *Fluvial Geomorphology.* Publications of Geomorphology, State University of New York: Binghamton.

Sheeder, S.A., Ross, J.D., Carlson, T.N. (2003). Dual urban and rural hydrograph signals in three small watersheds. *J. Am. Water Resour. Assoc.*, 38(4), 1027–1040.

Sheng, J. and Wilson, J.P. (2009). Watershed urbanization and changing flood behavior across the Los Angeles metropolitan region. *Nat. Hazards*, 48(1), 41–57.

Soar, P.J. and Thorne, C.R. (2001). *Channel restoration design for meandering rivers*. ERDC/CHL Report CR-01-1. U.S. Army Engineer Research and Development Center: Vicksburg, MS.

Southwell Flood Forum (n.d.). *Southwell Flood Forum Community Protection and Support* [online]. Southwell Flood Forum: Southwell. Available at: http://www.southwellfloodforum.org.uk/ [Accessed: 7th December 2019].

Strayer, D.L. and Dudgeon, D. (2010). Freshwater biodiversity conservation: recent progress and future challenges. *Journal of the North American Benthological Society*, 29, 344–358.

TUFLOW (2018). *TUFLOW Classic/HPC User Manual* [online]. BMT: Teddington. Available at: https://www.tuflow.com/Download/TUFLOW/Releases/2018-03/TUFLOW%20Manual.2018-03.pdf. [Accessed 4th July 2019].

UK Met Office (2011). *Climate: Observations and Projections and Impacts*. UK Met Office Hadley Centre: Exeter.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S.E., Sullivan, C.A., Liermann, C.R. and Davies, P.M. (2010). Global threats to human water security and river biodiversity. *Nature*, 467, 555–561.

Voskamp, I. M. and Van de Ven, F.H.M. (2015). Planning support system for climate adaptation: Composing effective sets of blue-green measures to reduce urban vulnerability to extreme weather events. *Building and Environment*, 83, 159-167.

Waddle, T. (2010). Field evaluation of a two-dimensional hydrodynamic model near boulders for habitat calculation. *River Research and Applications*, 26, 730–741.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M. and Morgan, R.P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society*, 24 (3), 706–723.

Watts, G., Battarbee, R. W., Bloomfield, J. P., Crossman, J., Daccache, A., Durance, I., … Wilby, R. L. (2015). Climate change and water in the UK – past changes and future prospects. *Progress in Physical Geography: Earth and Environment*, 39(1), 6–28.

Wheater, H.S. (2006). Flood hazard and management: a UK perspective. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences.* 364 (1845), 2135–2145.

Wheater, H. and Evans, E. (2009). Land use, water management and future flood risk. *Land Use Policy*, 26 (S1), S251-S264.

Wheaton, J.M., Pasternack, G.B. and Merz, J.E. (2004). Spawning habitat rehabilitation – II. Using hypothesis development and testing in design, Mokelumne River, California, U.S.A. *International Journal of River Basin Management*, 2, 21–37.

Whitehead, P.G., Battarbee, R.W., Crossman, J., Elliott, J.A. and Wilby, R. (2013). *A climate change report card for water. Working Technical Paper 9. River and lake water quality − future trends*. Natural Environment Research Council: Swindon.

Wilby, R.L., Beven, K.J. and Reynard, N.S. (2008). Climate change and fluvial flood risk in the UK: more of the same? *Hydrol. Process.*, 22, 2511-2523

WMO (2009). Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. *Climate data and monitoring WCDMP-No. 72, WMOTD No.1500*. World Meteorological Organization: Geneva.

Wright, K.A., Goodman, D.H., Som, N.A, Alvarez, J., Martin, A. and Hardy, T.B. (2017). Improving hydrodynamic modelling: an analytical framework for assessment of two-dimensional hydrodynamic models. *River Res. Applic.*, 33, 170–181

Wu, X.S., Wang, Z.L., Guo, S.L., Liao, W.L., Zeng, Z.Y. and Chen, X.H. (2017). Scenario-based projections of future urban inundation within a coupled hydrodynamic model framework: a case study in Dongguan City, China. *J. Hydrol.*, 547, 428–442.

Yin, J., Yu, D.P., Yin, Z., Liu, M. and He, Q. (2016). Evaluating the impact and risk of pluvial flash flood on intra-urban road network: a case study in the city center of Shanghai, China. *J. Hydrol*., 537, 138–145.

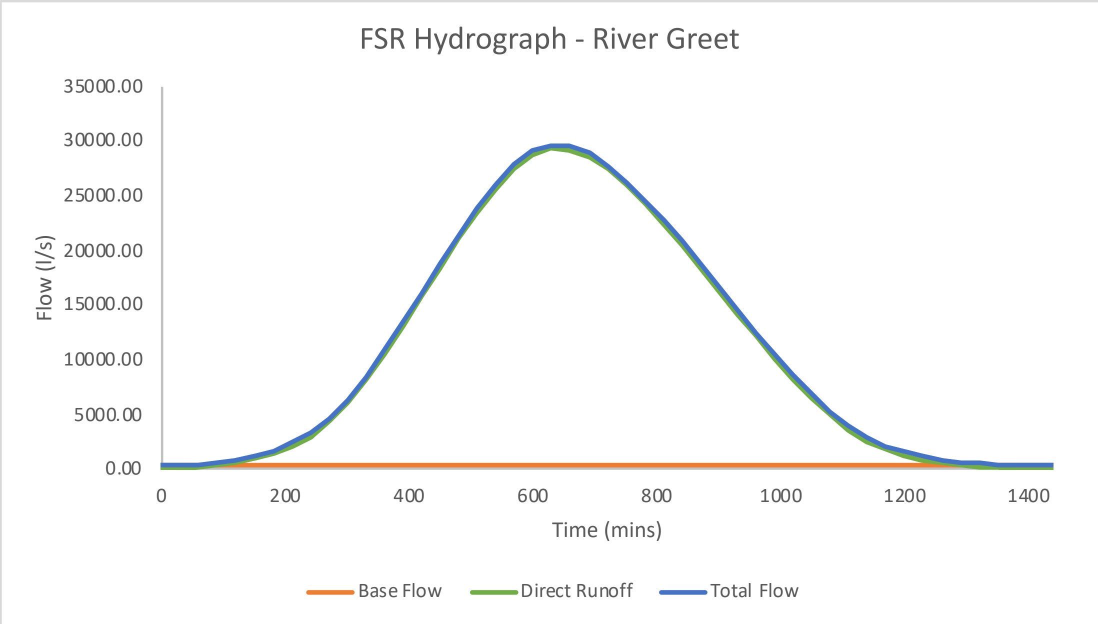
Zhou, Q.Q., Leng, G.Y. and Huang, M.Y. (2018). Impacts of future climate change on urban flood volumes in Hohhot in northern China: benefits of climate change mitigation and adaptations. *Hydrology and Earth System Sciences*, 22, 305–316.

Zhou, Y., Shen, D., Huang, N., Guo, Y., Zhang, T. and Zhang, Y. (2019). Urban flood risk assessment using storm characteristic parameters sensitive to catchment-specific drainage system. *Science of The Total Environment*, 659, 1362-1369.

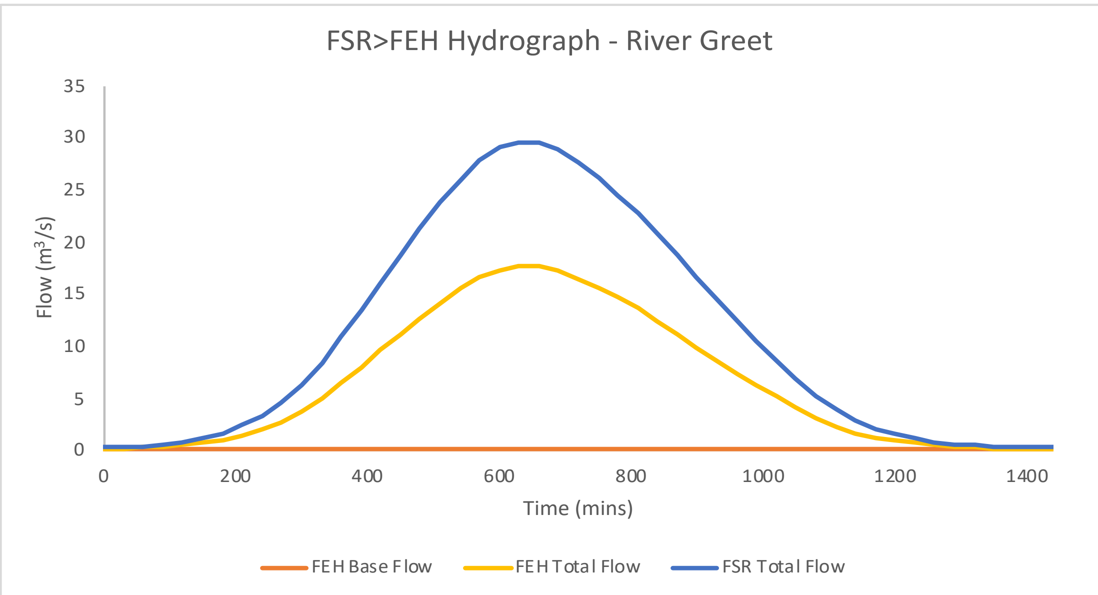
Appendices

Appendix A

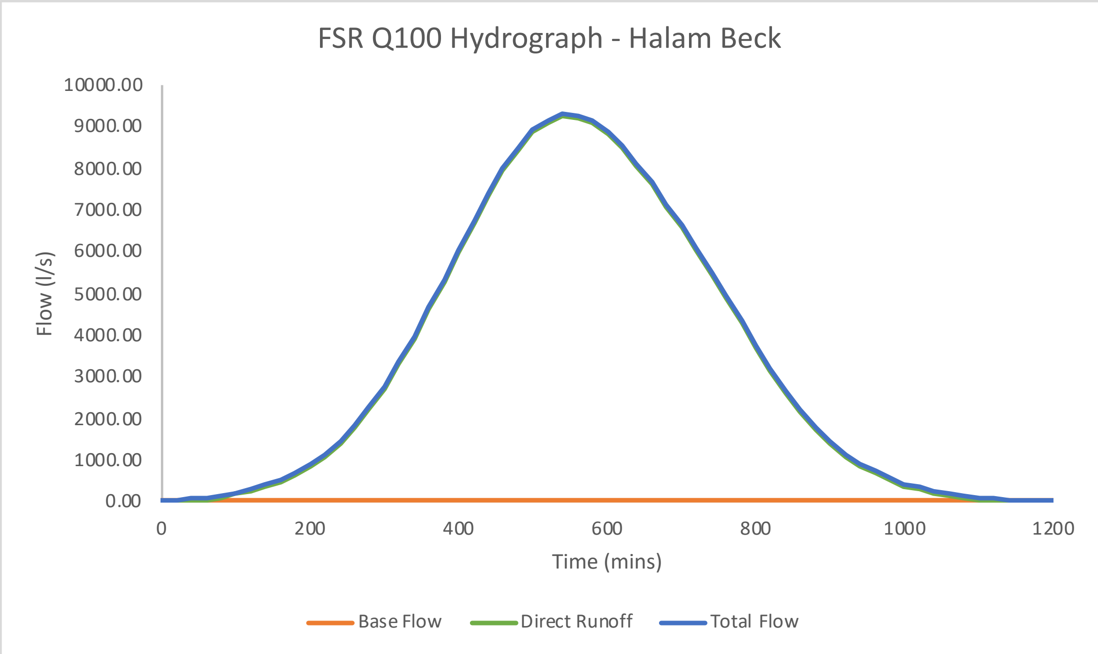
Model Input Hydrographs



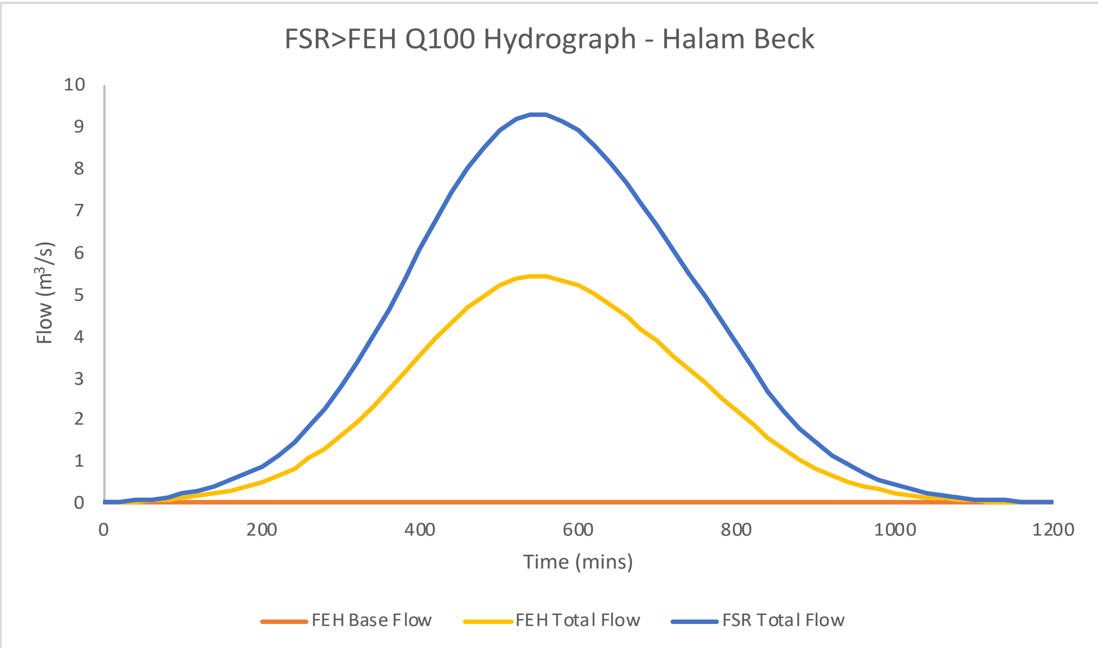
Hydrograph of in-channel flow (l/s) taken at the upstream extent of the River Greet, accounting for the full contributing catchment upstream



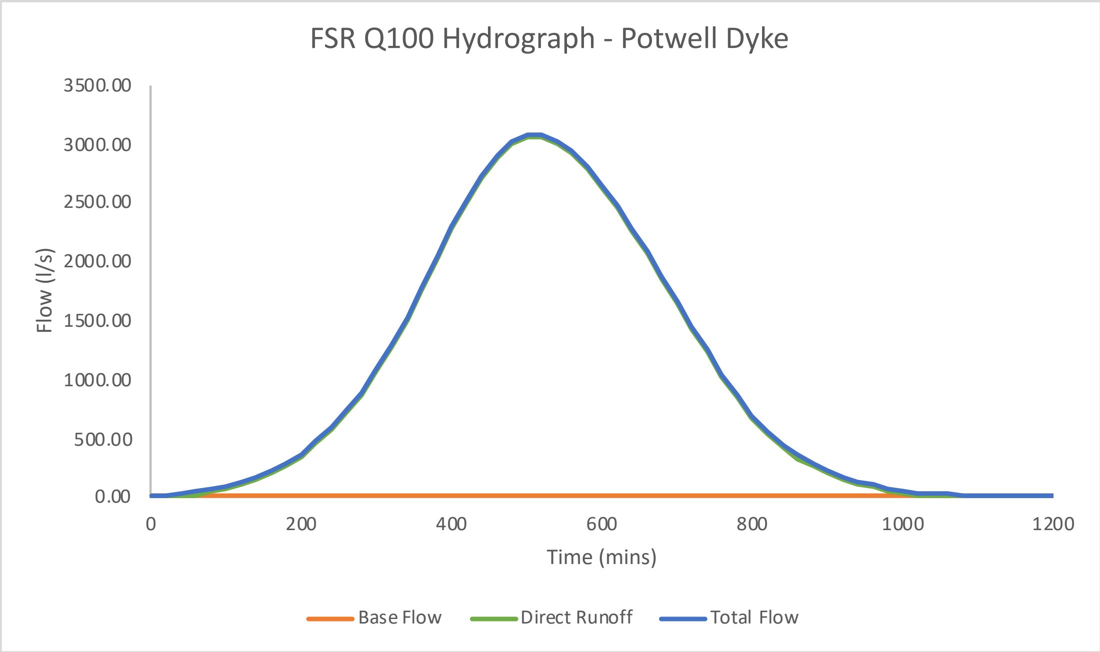
Hydrograph of in-channel flow (m^3/s) where FSR flow rate has been checked against FEH flow rate for the River Greet and apportioned down 40.45%.



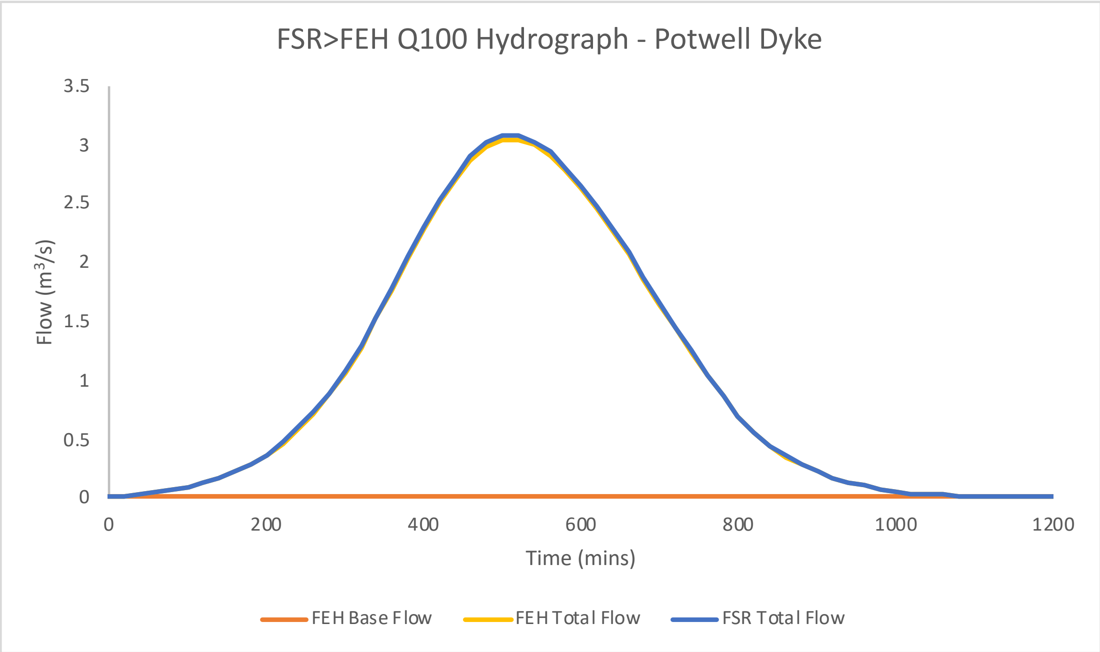
Hydrograph of in-channel flow (l/s) of Halam Beck, a minor tributary of the River Greet, accounting for the full contributing catchment upstream



Hydrograph of in-channel flow (m³/s) where FSR flow rate has been checked against FEH flow rate for Halam Beck and apportioned down 41.56%.



Hydrograph of in-channel flow (l/s) taken at the upstream extent of Potwell Dyke, accounting for the full contributing catchment upstream



Hydrograph of in-channel flow (m^3/s) where FSR flow rate has been checked against FEH flow rate for Potwell Dyke and apportioned down 44.14% and then increased 77.4% to prevent the modelled channel running dry