Assessing the contribution of precipitation to urban flood inundation using a hydraulic modelling approach

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Abstract

Improving the capacity to model urban flood inundation was identified by Wheater (2002) as a key priority within contemporary flood risk science. Although an increasing emphasis has been placed upon urban environments within flood modelling studies, current approaches remain somewhat rooted within the context of rural areas. This has begun to be addressed through the development of model codes specifically designed for application to urban flooding problems (Yu and Lane, 2006a, Bates et al., 2010). However studies of urban flooding have thus far failed to address the potential importance of rainfall, which is hypothesised to attain a greater significance within urban environments due to the pre eminence of impermeable land cover (Hall, 1984). This is particularly relevant in the light of recent increases in pluvial flooding (Pitt, 2007).

Accordingly, this study provides the first attempt to include rainfall within a hydraulic flood inundation model. An improvised representation of rainfall has subsequently been developed using a negative manipulation of the infiltration and evaporation terms within a simple storage cell model, LISFLOOD-FP. This has facilitated testing of the potential significance of rainfall to flooding within urban areas, with specific reference to the flood event which occurred on 25th-26th June 2007 in Sheffield. The proliferation of uncertainty from various sources has necessitated analysis with respect to bulk contribution of precipitation here. Addition of rainfall to the parameterisation of the model has lead to an increase in model performance from F=0.56 to F=0.60, suggesting that precipitation provided a modest but significant contribution to the aforementioned flood event. The findings of this modelling study are in agreement with several independent assessments of the June 2007 flooding within Sheffield (Dickson and Berry, 2008, Environment Agency, 2007). Moreover, this study illustrates that the utilisation of new, more efficient modelling tools (Bates et al., 2010), may facilitate further comprehensive assessment of the potential contribution of rainfall to urban flood inundation.

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Chapter One

Introduction

1. Introduction

1.1 The contemporary importance of flooding within urban areas

Floodplain inundation constitutes a major environmental hazard in both the developed and developing world (Penning-Rowsell and Tunstall, 1996). While flooding occurs within both rural and urban areas it is the latter, characterised by higher densities of people and property, where overall flood risk is greatest (Mark et al., 2004, Pappenberger et al., 2007a). Intuitively, where a natural hazard and human vulnerability coincide in space and time, a comprehensive understanding of the risk generated precludes the ultimate aim of planning and implementation of mitigation strategies (Blaikie et al., 1994).

Within the context of the UK, Mason et al., (2007a) state that approximately 2 million properties are located on floodplains, with 200,000 of these deficient of protection against a 1 in 75 year flood (Evans et al., 2004). Indeed the flood events of 1998 and 2000 left in the region of 100,000 properties inundated, with 11,000 people forced into temporary accommodation and overall damage costs in excess of £1 billion (Neelz et al., 2006). More recently, widespread and severe flooding experienced in 2007 resulted in fourteen fatalities whilst around 55,000 homes and 6,000 businesses were flooded, with total damage claims linked to this flooding approaching £3 billion (Marsh and Hannaford, 2007). As a direct result, the issue of flooding has relatively recently begun to command an increasing amount of attention from the national media and general public (Wright et al., 2008).

'Making Space for Water' (Department for Environment, 2005) is a strategic document published by the UK government as a proposed response to the aforementioned recent incidents of flooding. This report emphasised the need for a more holistic approach to flood risk management and aimed to encourage the deployment of an integrated portfolio of responses which reflect both national and local priorities. 'Making Space for Water' placed particular emphasis on the value of urban areas within society and has led to the proliferation of a new paradigm in UK flood risk management, which centres around protection of urban areas through a variety of responses including rural land management and sustainable urban drainage.

Consequently, improving knowledge of urban flooding currently represents one of the key priorities and focuses of contemporary fluvial science (Wheater, 2002). Bates and Lane (2000) state that the inherent difficulties associated with studying low frequency high magnitude phenomena such as flooding directly mean that predictive models constitute the most useful tool for their investigation. Thus there is an urgent need to develop the capacity to accurately model flood inundation within urban areas (Hunter et al., 2008).

1.2 A brief introduction to hydraulic flood inundation modelling

A flood inundation model is defined as a site specific application of a hydraulic model code, which provides a representation of flows within a river channel and on the adjacent floodplain, when bank full discharge is exceeded. Within any flood inundation model there is an implicit need to provide a representation of both channel and floodplain flow, both of which exhibit very different hydraulic characteristics. Knight and Shiono (1996) state that whilst within channel flow can be treated one dimensionally, out of bank flows are known to be highly two and even three dimensional with strong shear layers developing between the channel and floodplain (Tominaga and Nezu, 1991). It is clear therefore that the range of hydraulic conditions present within even a relatively simple rural flood event demands significant consideration in terms of model process representation.

Before continuing it is appropriate to define some key terms which are implicit within hydraulic modelling. The basis of a hydraulic model is constituted by a ‘model code’ which is defined as a generic computer program which can be used for different river reaches without modifying the source code (Refsgaard, 2001). A ‘model’ is subsequently defined as a site application of a code to a particular river reach or catchment (Hunter et al., 2007). This context specific application is dependent upon the specification of model parameters and boundary conditions. Boundary conditions define the characteristics of the flow domain to be modelled, representing processes outside the spatial domain of the model (Wainwright and Mulligan, 2004), whilst a parameter is a value which may be constant in the case concerned but may vary from case to case, where a case can represent a different model run or different grid cells/objects within the same model.

1.3 Challenges of urban flood inundation modelling

Urban areas present a multifaceted problem in terms of flood inundation modelling as they can be characterised by complex topographies, in addition to high densities of structural features such as buildings, walls, kerbs, embankments and drainage structures (Mark et al., 2004). These features can potentially have a high order effect on both the flow routing and overall volume of water on the floodplain during overbank events (Haider et al., 2003, Yu and Lane, 2006a), thus further complicating the general challenges presented by flood modelling described above. In addition high velocity hydraulic flows may be propagated in urban areas due to the presence of roads and other smooth surfaces which are associated with low shear values (Fewtrell et al., 2008).

Urban environments are also commonly characterised by large areas of impervious land cover which are associated with significant implications for urban hydrology (Hall, 1984), whilst the presence of drainage systems further complicates the partitioning of water in such environments and constitutes another important consideration when attempting to model flooding within urban areas (Mignot et al., 2006). Effective parameterisation of complex topography and surface features undoubtedly presents the most important challenge faced by urban fluvial flood modellers (Lane, 2005). Therefore a consideration of the most appropriate method to provide a parameterisation of urban topography and surface features precludes the selection of a suitable model for use within this study.

The upscaling of roughness parameters, a technique traditionally used in the absence of high resolution Digital Elevation Models (DEMs) presents one method of representing the effect on flow induced by urban topography and surface features. This practice has been used effectively within past studies in order to represent grain effects on within-channel flow (Lane and Richards, 1998, Lane et al., 1999). In addition Mason et al., (2003) utilise the upscaling of roughness parameters, through manipulation of a sink in the momentum equations, in order to represent the effects of vegetation on floodplain flow.

Although this constitutes one potential method of representing the effects of structural features on hydraulic flows within urban environments, it is argued by Lane (2005) that this practice is not appropriate for application to urban environments due to the complete blockage to flow which is induced by walls, buildings and other surface features (Yu and Lane, 2006a). Within studies of three-dimensional hydraulic models it has been hypothesised that although upscaling roughness heights in order to account for high resolution topographical variability may reduce the flux of water across the floodplain it will almost certainly fail to recognise the full effects of complex topography, particularly mass blockage (Lane et al., 2004) and reduction of the floodplain storage volume (Yu and Lane, 2006a). It has been postulated by Yu and Lane (2006a) that the aforementioned conclusions are equally applicable to two-dimensional hydraulic models. Accordingly, it appears that an approach which facilitates explicit representation of topography and surface features is a necessity when modelling flood inundation within urban areas.

Whilst it is apparent that the parameterisation of topography and surface features is of preeminent importance in urban fluvial flood inundation modelling, it is important to note that research into this area remains in its relatively early stages and consequently there are numerous other important challenges which have yet to be fully explored. Neal et al., (2009a) provides a useful review of studies which have been carried out in the field of urban flood inundation modelling concluding that much work thus far has focused upon; model benchmarking (Hunter et al., 2008), flood simulations with varying return periods (Aronica and Lanza, 2005), sensitivity analysis of simulations to model parameters/discretisation of domain topography (Yu and Lane, 2006a, Fewtrell et al., 2008) and parameterisation of surface/sewer flows through development of new modelling tools (Smith, 2006). These areas of research are undoubtedly of considerable significance, although it is important to recognise that the list above is not exhaustive and that there are further avenues, thus far unexplored, which may potentially increase the performance and utility of urban flood inundation models.

1.4 The potential of hydraulic flood inundation modelling in urban areas

1.4.1 Introduction to hydraulic modelling approaches

Since the inception of modelling within flood risk science three dominant types of model codes have been produced. Initially simple one-dimensional schemes such as HEC-RAS (Priestnall et al., 2000) and more complex full two-dimensional finite-element and finite-volume treatments (Horritt and Bates, 2001a) were predominantly used to predict flood inundation. Over the past decade the shortcomings of one and two-dimensional model codes have given rise to a third type of flood inundation model; storage cell models, typified by LISFLOOD-FP (Bates and De Roo, 2000). These types of models commonly represent channel flows with a simplification of the 1D Saint-Venant equations, whilst calculating floodplain flows through application of uniform flow formulae to regular structured grids (Hunter et al., 2007). Three dimensional approaches to flood inundation modelling have been explored (Younis, 1996). However despite the fact that out of bank flows are known to be highly complex a full three dimensional approach is unnecessary in most instances and should be restricted for application to within channel hydraulics (Horritt, 2000).

Considering the different types of models available for representing flood inundation it is not always clear which particular scheme to use for a given application. Horritt and Bates (2001b) argue that the model process representation required for a specific application is primarily a function of the type/accuracy of predictions required, whilst other factors such as model scale and quality of parameterisation data should also be considered. Whilst modellers historically tended to favour the implementation of the most complex scheme available, Bates and De Roo (2000) postulate that the best model is the simplest which provides the information required by the user whilst reasonably fitting available data. Considering the complex problem presented by modelling flood inundation within urban areas, along with the multitude of different approaches available it is necessary to provide a brief review of these options and select a model appropriate for application to this study, based upon the considerations specified in (Bates and De Roo, 2000, Horritt and Bates, 2001b)

1.4.2 One-dimensional flood inundation modelling

One-dimensional models were initially developed due to ease of parameterisation (Horritt and Bates, 2001a) and have been utilised frequently within flood routing studies (Chow, 1988). These approaches remain popular due to low data demands and high computational efficiency, which has enabled their application over wide spatial scales at low resolutions (Tayefi et al., 2007). Within one-dimensional flood models both the channel and floodplain topography are represented through a series of extended cross sections (Horritt and Bates, 2002) and simplified versions of the St Venant equations are solved at each interval (Moussa and Bocquillon, 1996) for a set of prescribed inflow/outflow boundary conditions. Therefore it is clear that these schemes are characterised by an array of simplifying assumptions, with both channel and floodplain hydraulics receiving identical treatment. Outputs produced by one-dimensional models typically comprise a series of averaged velocity and horizontal water levels at given cross sections (Tayefi et al., 2007). These outputs can subsequently be overlain onto Digital Elevation Models (DEMs) and linearly interpolated in order to generate predictions of flood inundation extent (Bates and De Roo, 2000).

Although one-dimensional models are able to reproduce simple features of flood events such as basic flood wave propagation, it is beyond the capability of these schemes to adequately represent spatially complex topography which is preeminent in prediction of floodplain flow patterns (Horritt, 2000). Consequently where floodplain morphology is relatively simple and highly detailed outputs are not required, one dimensional modelling is often able to produce inundation predictions of an acceptable level of quality with a high level of efficiency (Michaelides and Wainright 2004).

An example of this utility is illustrated by the study of Horritt and Bates (2002), in which the performance of the one dimensional model HEC-RAS provided inundation predictions of a comparable quality to more complex two-dimensional schemes. Therefore within the context of this individual study the simple one-dimensional model constituted the most useful approach. However the authors noted that the specific reach used within this research was characterised by a confined floodplain, effectively minimising the advantages offered by more complex two-dimensional model codes. Horritt and Bates (2002) therefore concluded that the utility of 1D models is greatest where floodplain morphology is simple, whilst their predictions are likely to decline in quality with increasing topographical complexity.

Intuitively, the aforementioned problems associated with simple one-dimensional models are exacerbated within urban areas (Yu and Lane, 2006a). Cross-sectional surveys are unable to capture the topographical complexity of these environments sufficiently and such simplified representations are therefore wholly inadequate for parameterisation of urban areas. In addition flow hydraulics have been shown to be highly two and even three-dimensional in topographically/structurally rich environments (Abderrezzak et al., 2009), this clearly cannot be reflected by the limited process representation available within one-dimensional models. Consequently complex flow hydraulics are commonly parameterised through upscaling of roughness parameters via manipulation of sinks in momentum equations (Yu and Lane, 2006a). As has already been established such an approach is largely inappropriate in urban areas due to the inadequate representation of flow blockage induced by surface features (Lane, 2005). Accordingly, Mason et al., (2007a) stated that highly simplified models are inappropriate for application within urban contexts, with a minimum of a 2D treatment of floodplain flows required for flood inundation modelling within such complex topographical environments.

1.4.3 Two-dimensional flood inundation modelling: finite element/finite difference approaches

The assertions made by Mason et al., (2007a) suggest that two-dimensional hydraulic model codes may offer a more suitable approach to flood inundation modelling within urban areas. Two-dimensional models fall into two main categories; finite-difference and finite-element. These models were developed in response to the aforementioned shortcomings associated with one-dimensional models and constitute a more advanced approach to studying overbank flows in relatively short river reaches (<20km) (Horritt, 2000). These schemes are capable of differentiating between channel and overbank hydraulic conditions and provide a more appropriate representation of flow hydraulics in line with known processes (Horritt and Bates, 2002), including enhanced representation of lateral shear, secondary flows and turbulence (Tayefi et al., 2007).

Two-dimensional models are most commonly parameterised with a DEM, used to generate a mesh which is able to provide a continuous representation of complex floodplain topography (Figure 1.1). The application of inflow/outflow boundary conditions allows computation of depth and depth averaged velocity at each computational node at each iteration (Bates et al., 1995). Therefore unlike their simpler counterparts two-dimensional models include a continuous representation of floodplain topography and their outputs require minimal post processing in order to generate visual representations of inundation (Bates and De Roo, 2000). Intuitively two dimensional models are much more data intensive than 1D schemes, requiring distributed topographic information (Bates et al., 1998), possibly friction data (Horritt, 2000) and distributed validation data. The aforementioned attributes of two dimensional models, specifically their ability to include an improved representation of topography and surface features, in addition to a more realistic process representation constitutes a great asset in terms of potential utility in modelling urban areas. Thus benefits are accrued in terms of outputs which are of a much higher quality than those from 1D schemes (Horritt and Bates, 2002).

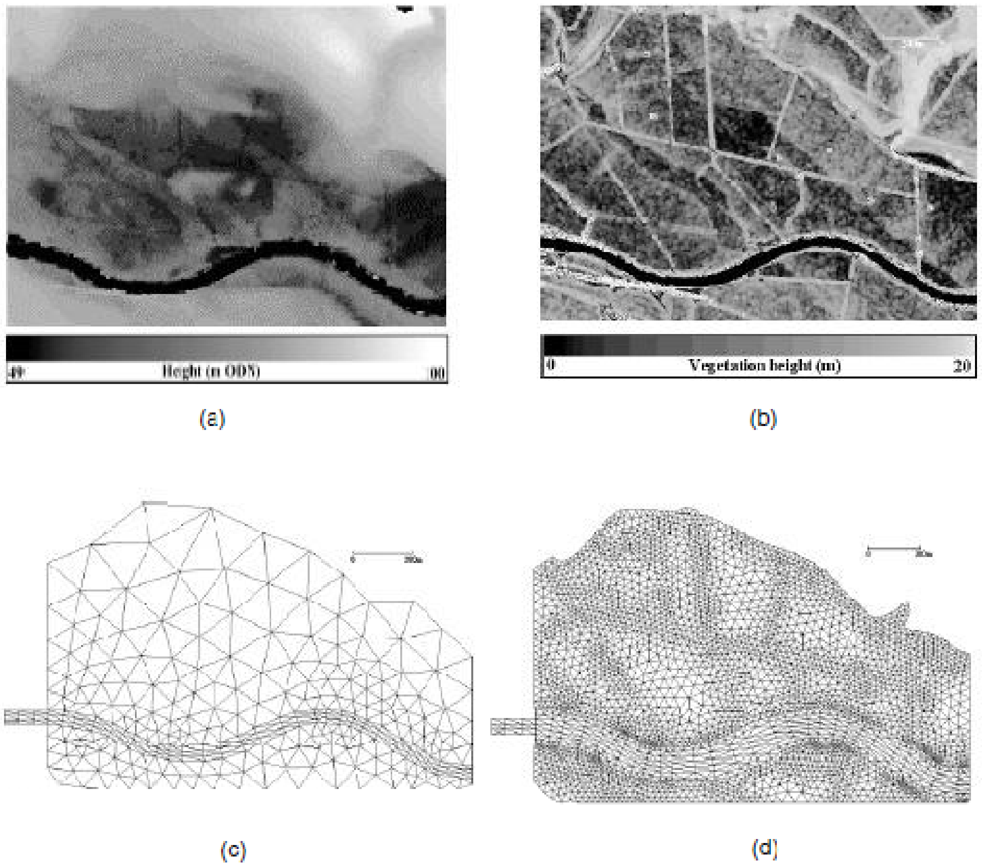


Figure 1.1 Examples of meshes used within two dimensional flood inundation models (c and d) generated from a DTM (a) and vegetation height map (b)

However, two-dimensional approaches to flood inundation are not without their limitations. Horritt (2000) stated that at the time of publishing a lack of distributed calibration/ validation data provided a considerable constraint to the development of two-dimensional models. This dearth of distributed data commonly necessitated the use of point scale hydrometric measurements within validation, which is largely inappropriate given the disparity between the dimensionality of model outputs and observed data (Bates, 2004). Although recent advances in remote sensing have facilitated the production of an increasing number of distributed datasets related to flood events, these are often constituted by single temporal snapshots of inundation extent. Therefore a dearth of validation data remains a clear problem in the application of 2D models (Hunter et al., 2007).

A further drawback of full 2D flood inundation models is low computational efficiency, which strongly limits their applicability within urban areas (Neelz and Pender, 2007). Two-dimensional models are both process and data intensive which can lead to long model run times particularly when applied over large domains (Bates et al., 1995). McMillan and Brasington (2007) state that process intensity of full 2D schemes combined with computational constraints imposed by research budgets routinely forces modellers to use low resolution topographical discretisations, thus largely negating the advantages offered in terms of process representation.

The aforementioned limitations present a particular problem when applying two-dimensional models to urban environments as these areas can only be adequately represented by a model grid of the order of the length scale of buildings <5m (Fewtrell et al., 2008). Where high computational demands necessitate a low resolution discretisation of topography within urban areas, buildings and other sub-grid scale surface features which may have significant impacts upon flow routing are not represented explicitly in the model mesh. As in one-dimensional models these sub-grid scale features are commonly ignored or are incorporated through weakly constrained roughness parameters, a technique which has been found to be largely inappropriate within urban areas (Lane et al., 2004, Yu and Lane, 2006a). Therefore whilst two-dimensional flood inundation models offer more realistic process representation than one-dimensional codes their utility is limited by computational efficiency, which precludes high resolution topographical representations. Ultimately this limits their applicability to urban areas and hence also this particular study.

1.4.4 Two-dimensional flood inundation modelling: storage cell approaches

The storage cell approach to modelling of flood inundation has emerged in response to the lack of utility illustrated by overly simplistic one-dimensional models and the high computational costs associated with two dimensional finite difference/finite element schemes (Bates and De Roo, 2000). The formulation of these approaches is based upon the hypothesis of Bates and De Roo (2000) who give credence to the notion that the best available models are those which provide the information required by the user whilst reasonably fitting available data. Although numerous models exist which fall into this category, the LISFLOOD-FP model developed by Bates and De Roo (2000) is one of the most well documented and tested examples (Bates, 2004, Horritt and Bates, 2001a, Horritt and Bates, 2001b, Horritt and Bates, 2002, Hunter et al., 2005b, Hunter et al., 2008, Hunter et al., 2007, Fewtrell et al., 2008, Mason et al., 2007a, Neal et al., 2009a)

LISFLOOD-FP is a physically based flood inundation model and is an extension of the LISFLOOD catchment model developed by (De Roo et al., 1996). The model aims to incorporate the minimum process representation required to achieve acceptable predictions based upon available data (Bates and De Roo, 2000), particularly focusing upon the reproduction of inundation extent data derived from satellite and aerial imagery. The LISFLOOD-FP model formulation is fundamentally based upon the predominant importance of topography in prediction of floodplain inundation (Bates and De Roo, 2000). Topography can be considered extremely important within flood inundation for two primary reasons; (1) due to its effects on flow routing; and (2) because low floodplain gradients can lead to exaggeration of errors in modelled shoreline location and subsequently inundation extent (Horritt and Bates, 2001a). Given the reliance of this type of model upon topographical data, advances in remote sensing have been implicit in the development of storage cell codes. More specifically the development of LiDAR and aerial imagery platforms, which have facilitated the collection of high resolution DEMs and observed flood extent imagery (Bates, 2004).

Therefore model design is predicated on a sacrifice in terms of hydraulic process representation in order to enable the incorporation of high resolution DEMs, thus facilitating explicit representation of complex topography and surface features whilst retaining a high level of computational efficiency (McMillan and Brasington, 2007). Given the aforementioned design philosophy, LISFLOOD-FP utilises a simplified one-dimensional representation of channel flow which is linked to a two-dimensional storage cell treatment of floodplain hydraulics (Yu and Lane, 2006a). It is important to state that the storage cell concept is not new, having originally been proposed by Cunge (1980), however the ability to combine these approaches with high resolution topographic data constitutes the original and innovative aspect of LISFLOOD-FP (Hunter et al., 2007).

Whilst this simplified storage cell treatment has excelled in reproducing inundation extent when calibrated against observed data (Hunter et al., 2006), the LISFLOOD-FP model has been critiqued due to its poor representations of floodplain hydraulic characteristics particularly the wetting/drying process (Yu and

Lane, 2006a). This can be considered as an inevitable outcome of the model formulation which was specifically designed to reproduce maximum flood extent, with little emphasis placed upon accurate representation of floodplain hydraulic processes (Bates and De Roo, 2000). However these shortcomings have subsequently been addressed by Hunter et al., (2005b) who developed an adaptive time step solution for LISFLOOD-FP which has been included within an updated version of the model code. Comparison of the adaptive time step and original versions of LISFLOOD-FP Hunter et al., (2006) illustrated an increase in absolute performance in addition to a more realistic representation of floodplain wetting/drying, although with an increased computational cost. Subsequently, the LISFLOOD-FP code has been parallelised using OpenMP (Neal et al., 2009), enabling the model to be implemented on up to eight processor cores and achieving a reduction in simulation times. Testing over a range of study areas revealed that speed up was greater for larger model domains, potentially increasing the applicability of the model. Increases in efficiency of LISFLOOD-FP have also been achieved through an inertial formulation of the shallow water equations (Bates et al., 2010), which is detailed further within 1.5.

The LISFLOOD-FP model was originally predominantly applied to rural hydraulic modelling scenarios, where its efficiency facilitated application over long reaches and in some cases even catchments (Horritt and Bates, 2001a). Within these studies the performance level of LISFLOOD-FP was equivalent to or exceeded that of other more complex models (Horritt and Bates, 2001b, Horritt and Bates, 2002).

1.5 Application of storage cell codes to urban flooding

More recently LISFLOOD-FP has begun to be applied to urban contexts, after flood prediction within these areas was identified by Wheater (2002) as one of the key priorities of contemporary fluvial flood modelling. Given the preeminent importance of topography and structural complexity in determining flow upon urban floodplains (Yu and Lane, 2006a), the ability of LISFLOOD-FP to provide a direct representation of these features through incorporation of high resolution DEMs whilst retaining a level of computationally efficiency implies that the model is ideal for application within such contexts. Despite the known complexity of hydraulic characteristics within urban areas, where flows are known to be highly two and even three dimensional (Haider et al., 2003), the simple storage cell approach of LISFLOOD-FP provides a satisfactory representation of overbank inundation when combined with high resolution topographic data. This is illustrated by a number of studies which have successfully applied the LISFLOOD-FP model within urban areas (Fewtrell et al., 2008, Hunter et al., 2008, McMillan and Brasington, 2007, Neal et al., 2009a).

Although the LISFLOOD-FP model has been shown to provide accurate predictions of flooding within urban areas, the model was originally designed for application within rural contexts at coarse resolutions and thus the model structure strongly reflects this (Bates et al., 2010). The main consequence of this is that applications of LISFLOOD-FP within urban environments have been limited to relatively small areas in order to facilitate the use of high resolution grids which are required in order to provide an accurate representation of topography (Fewtrell et al., 2008).

Therefore Bates et al., (2010) conclude that the structure and process representation of flood inundation models originally designed for rural contexts do not necessarily reflect the specific characteristics of the urban environment. Whilst these models have been shown to provide good predictions of flooding within urban areas it is clear that the science of flood inundation modelling must be developed in order to truly reflect the complexity of hydraulic and hydrological processes within these environments. This problem has been partially addressed through development of model formulations which facilitate adequate representation of urban fluvial flood processes, whilst retaining high levels of computational efficiency. This is typified by the sub grid scale approach developed by Yu and Lane (2006a) and more recently an inertial formulation of the shallow water equations (Bates et al., 2010), which represent promising tools in exploring flood processes within urban environments.

Despite the obvious potential of these approaches it is clear that further research is required in order to improve prediction of flooding within urban areas (Bates et al., 2010). In order to maximise the utility of these new model codes it is also necessary to consider factors which were not originally thought to be significant within rural flood modelling studies. It is well known that urban areas are fundamentally different from rural areas, particularly in hydrological terms, which can be attributed primarily to greater proportions of impermeable land cover observed within urban environments (Sullivan et al., 2004). Increases in the incidence of pluvial flooding documented by Pitt (2007) implies that production of large volumes of run off in response to intense/prolonged rainfall precipitation may provide significant contributions to flood inundation within urban areas. Although the hydrological response of urban areas to intense/prolonged rainfall is relatively well documented within literature which focuses upon urban drainage (Djordjevic et al., 1999, Hsu et al., 2000, Aronica and Lanza, 2005), thus far this facet of the flood hydrology of urban areas remains unaddressed within flood inundation modelling studies.

1.6 The potential significance of precipitation within urban areas

As previously stated direct precipitation onto the urban surface is an example of a factor which remains unparameterised within urban flood models, which is surprising given its potential importance within certain contexts. It is well documented that urban environments are characterised by large areas of impermeable land cover, the presence of which has been shown to have high order impacts upon hydrological regime (Sullivan et al., 2004). Specifically, impermeable surfaces preclude infiltration and as a direct consequence close to 100% of precipitation received at the surface is converted to runoff within these areas (Hall, 1984). The hydrology of urban areas is further complicated by the presence of drainage systems, designed to mitigate the impact of excess amounts of run off induced by impermeable land cover (Hsu et al., 2000). This leads to a situation whereby the response of urban environments to rainfall is characterised by two systems; the natural surface water system and the artificial drainage system (Aronica and Lanza, 2005). These systems are expected to function simultaneously in order to ensure adequate drainage and prevent the occurrence of surface flows.

In instances where urban surface run off in response to rainfall is within the design capacity of drainage systems water drains away from the surface into sewers and is routed towards drainage outfalls (Hsu et al., 2000), thus precluding the occurrence of surface inundation. However it is clear that the design capacity of these drainage systems are often limited and rainfalls above design levels may lead to the proliferation of critical conditions (Aronica and Lanza, 2005). Where this occurs water overflows from drains and manholes, whilst further water additions through precipitation remain on the surface and potentially contribute to surface inundation. Aronica and Lanza (2005) also postulate that micro topographical effects within urban areas may lead to local drainage inefficiencies and surface flooding even where rainfall intensities are below design levels.

Underpinned by the simple hydrological principles detailed above it is possible to formulate a simple hypothesis which outlines the generation of pluvial flooding within urban areas. Within this hypothesis storm events produce large volumes of precipitation which fall directly onto urban areas facilitating rapid generation of runoff. Subsequently this runoff, depending on specific topography and urban characteristics, may be either conveyed quickly overland towards the river channel, thus contributing to the volume of overbank inundation, or alternatively overwhelm drainage systems generating localised flooding. It is important to note that this hypothesis is very simple and consequently does not take into account the dynamics of real flood events, which are of predominant importance when considering the contribution of direct precipitation to urban flood inundation.

It is well known that spatially and temporally variable rainfall and subsequent catchment response are important in determining flood wave characteristics. In situations where rainfall events are relatively short and uniform over the catchment, run-off generated in urban areas quickly drains into the channel via overland flow or through conduits such as drains in the period preceding the arrival of the peak discharge, which is attenuated by the river catchment. In this scenario pluvial flooding, or contributions from direct precipitation to overbank flood inundation, are less likely due to the lag time between rainfall and arrival of peak discharge within the urban area.

However certain situations may arise where episodes of prolonged or repeat rainfall perpetuate the production of large amounts of urban runoff which coincide with the passing of peak discharge within the river channel. When this occurs raised water levels within the river channel have a propensity to reduce the capacity of drain outfalls, when combined with large volumes surface water generated through run-off drainage systems become overwhelmed. Within this scenario the reduced functionality of drainages systems facilitates the production of pluvial flooding. Depending upon local topography surface water may remain isolated or combine with overbank flows, leading to increasing levels of inundation and greater flood risk. It is also important to note that although high river stage may contribute to the generation of pluvial flooding in certain instances, it is possible that disconnected urban flooding can be driven by extreme rainfall events alone and therefore may occur independently of fluvial river flooding.

It is clear that the above process is very complex, particularly the interaction between the surface and artificial secondary drainage systems which is clearly key in controlling the flood hydrology of urban areas. This has been addressed by a wealth of modelling studies which attempt to couple surface and subsurface flows in order to generate a representation of the flood response within urban areas. This is typified by the dual drainage concept (Djordjevic et al., 1999). A more detailed and complete review of these can be found within (Smith, 2006). However in instances where rainfall events are intense and prolonged, potentially coinciding with raised river stage, it is clear that drainage systems may become overwhelmed leading to widespread occurrence of critical overland flows. Within these situations the influence of drainage systems is negated and additional water supplied through precipitation has the potential to contribute directly to flood inundation. In addition, mitigation of the influence of drainage systems means that hydraulic flood inundation models present a useful and relatively simple tool to study these phenomena. Intuitively, this suggests that a parameterisation of precipitation within LISFLOOD-FP has the potential to improve predictions of flood inundation during high magnitude rainfall events.

1.7 Research questions and hypotheses

The broad aim of this study is to develop and test an approach which facilitates a representation of precipitation within LISFLOOD-FP and to subsequently assess the contribution of rainfall to flood inundation within urban areas.

1.7.1 Research questions

Is LISFLOOD-FP able to provide an adequate representation of surface flooding in urban areas in response to rainfall?

Is rainfall able to make a significant contribution to flood inundation within urban areas?

Does inclusion of a representation of precipitation lead to improved predictions from hydraulic flood inundation models during high magnitude rainfall events?

1.7.2 Hypotheses

As a consequence of the unique hydrological characteristics, rainfall is able to make significant contributions to flood inundation within urban areas.

Inclusion of a representation of rainfall within LISFLOOD-FP is able to improve model performance where flooding coincides with rainfall events within urban areas.

1.8 Thesis structure

Within this chapter literature relevant to this study has been reviewed and research questions and hypotheses stated. Chapter two introduces the city of Sheffield and the summer floods which occurred in 2007, which have been chosen as an ideal context for this research.

This is followed by an in depth description of the LISFLOOD-FP model structure and process representation within chapter three. Application of the LISFLOOD-FP model code to Sheffield is detailed within chapter four, including site description, data sources, data processing, boundary conditions and validation data.

Formal model testing begins through a basic sensitivity analysis, which makes up chapter five. The LISFLOOD-FP model is then validated within chapter six, utilising independent observed data for the flood event which occurred within Sheffield on 25th-26th June 2007.

Chapter seven details the development and testing of an improvised representation of rainfall within LISFLOOD-FP utilising existing model parameters. Subsequently the rainfall representation developed within chapter seven is applied to the validated model produced within chapter six, in order to determine the contribution of rainfall to the June 2007 flood event within Sheffield within chapter eight.

Results obtained within chapters six, seven and eight are discussed within chapter nine and conclusions are subsequently drawn within chapter ten.

Chapter Two

Sheffield and the summer 2007 floods

2. Sheffield and the summer 2007 floods

Given the overall research aim of this study it was necessary to apply the LISFLOOD-FP model to a river reach in an urban area which would facilitate testing of the proposed hypotheses. After consideration of a variety of factors including flood risk, hydrological characteristics and data availability, the city of Sheffield was selected as an ideal location for this research.

2.1 Flood risk within the city of Sheffield

Sheffield is historically prone to flooding and constituted one of the most severely affected areas during the widespread floods which occurred within the UK during June 2007 (Marsh and Hannaford, 2007). Overall flood risk in Sheffield can be attributed to a number of salient factors. Sheffield is located at the foot of the Pennine hills and is the point of confluence of the Don, with two other fast flowing rivers the Sheaf and the Loxley. These rivers represent the primary physical hazard within Sheffield.

Despite the significant physical hazard presented by these rivers, development on Sheffield's floodplain has been extensive. Consequently a large number of homes and businesses are located in areas at immediate risk from flooding. Overall, Sheffield is the sixth largest metropolitan area within the UK by population and according to 2008 estimates the city is home to approximately 535,000 residents. In monetary terms Sheffield is also extremely influential within the UK, with an economy estimated to be worth around £8.7 billion in 2006. Within the metropolitan area of Sheffield it seems that the contribution of floodplain development to flood risk has been twofold. In addition to simply increasing the elements at risk located on the floodplain, Environment Agency (2007) state that floodplain development has exacerbated the physical hazard through confinement of rivers into channels and culverts, thus limiting their capacity for expansion in the event of increased discharges.

In summation, when considered in a simple risk framework such as that of Blaikie et al., (1994) the city of Sheffield represents an area where a major physical hazard, provided by the River Don, coincides with considerable social and economic elements at risk. Accordingly Sheffield constitutes an urban area with a high level of flood risk and thus on a basic level represents an ideal location for this research.

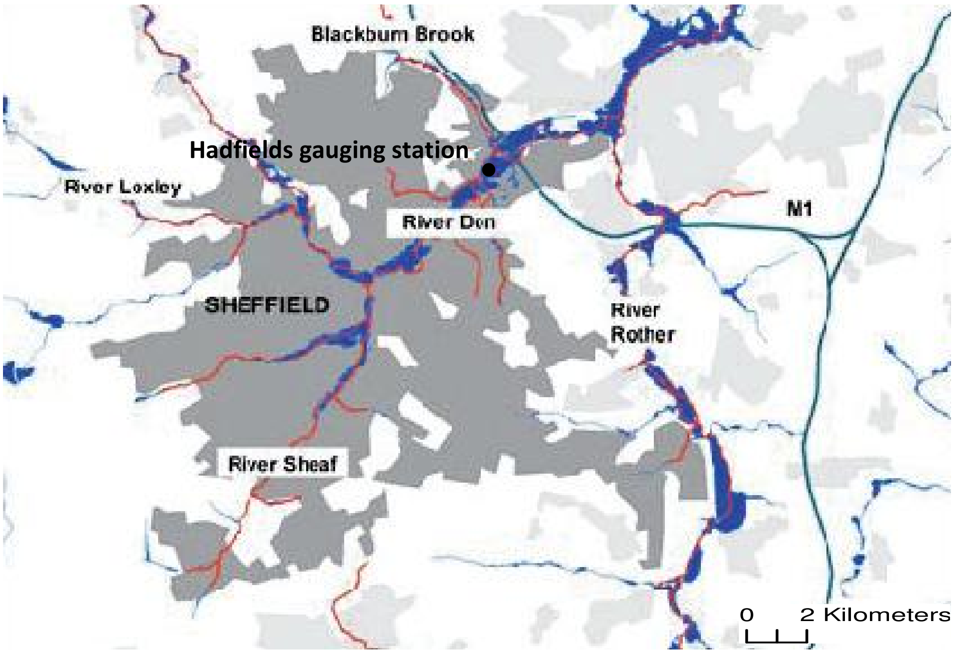


Figure 2.1 Map taken from Environment Agency (2007), illustrating the urban area of Sheffield with its river network in red and flood outlines from 2007 in blue.

2.2 The River Don catchment

The source of the River Don is located within the Southern Pennines, an area of Millstone Grit and Coal Measures forming part of a continuous range of hills which runs down the centre of England (Wass and Faulkner, 2003). From this location the river flows eastwards through the noTable urban areas of Sheffield, Rotherham and Doncaster before its confluence with the River Ouse at Goole in East Yorkshire (Amisah and Cowx, 2000). The river has a number of tributaries, with the most noteworthy of these being the River Rother and the River Dearne which confluence with the Don downstream of Sheffield. Although it is also important to note the presence of smaller fast flowing tributaries of the River Sheaf and the River Loxley, along with Blackburn Brook and Porter Brook, which join the main channel in the region of Sheffield. In terms of flood response the relatively steep upper Don, which includes the urban area of Sheffield, is associated with rapid response to rainfall and flashy hydrographs. In comparison, the lower reaches of the Don are associated with lesser gradients, meaning that significant flood events are often more prolonged than upstream (Wass and Faulkner, 2003).

The Don catchment covers an area of approximately 1,849 km^2 (Amisah and Cowx, 2000) and has been highly urbanised, with the greatest hydrological impact cited in Chesterfield, Sheffield and Rotherham. Inevitably, flood risk mitigation strategies have been implemented along the course of the Don, which comprise ‘a combination of formal washland, flow control structures and river embankments’ (Wass and Faulkner, 2003). In addition around half of the catchment upstream from Hadfields gauging station flows through water supply reservoirs (Wass and Faulkner, 2003). The interaction of extensive urbanisation and flood protection strategies within the catchment have inevitably impacted the flow regime of the river, however Dickson and Berry (2008) state that the upper Don in the region of Sheffield still exhibits a flashy response to storm events.

Figure 2.2 Location of the River Don catchment within the context of the UK (Environment Agency, 2007)

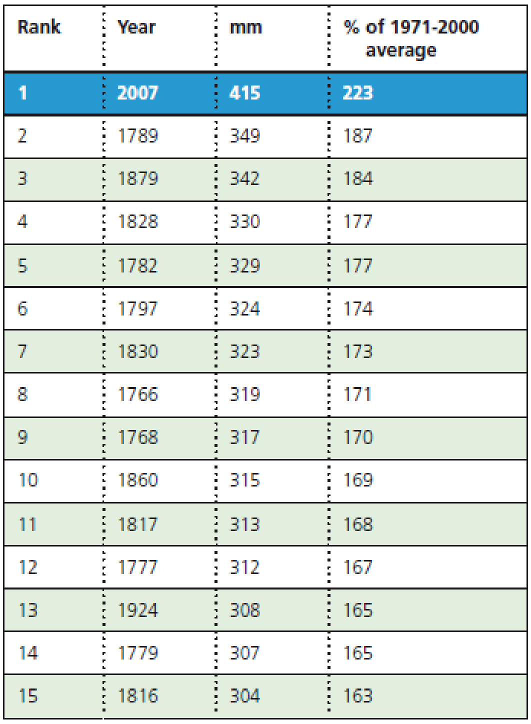
2.3 The summer 2007 floods

2.3.1 A UK perspective

The late spring and early summer of 2007 was marked by an unprecedented frequency, spatial extent and duration of extreme rainfall events. Record rainfall totals were received as Britain experienced its wettest May to July period in the last 250 years (Figure 2.3), generating exceptional hydrological conditions

(Environment Agency, 2007). The occurrence of these conditions was somewhat surprising given that the early spring of 2007 was notably dry, resulting in significant soil moisture deficits which would be expected to provide a buffer to flood risk through the proceeding months.

However weather conditions quickly changed and as a result of high levels of rainfall in the subsequent period catchments quickly wetted up and subsequently demonstrated a response to rainfall which would be typical of winter months (Marsh and Hannaford, 2007). The intensity and duration of storm events produced localised flash flooding, whilst also propagating widespread and prolonged flood inundation along many watercourses during the period from mid June to the end of July (Marsh and Hannaford, 2007). In some areas the severity of flooding superseded that experienced in March 1947, the highest magnitude flood event of the 20th century.



Rank	Year	mm	% of 1971-2000 average
1	**2007**	**415**	**223**
2	1789	349	187
3	1879	342	184
4	1828	330	177
5	1782	329	177
6	1797	324	174
7	1830	323	173
8	1766	319	171
9	1768	317	170
10	1860	315	169
11	1817	313	168
12	1777	312	167
13	1924	308	165
14	1779	307	165
15	1816	304	163

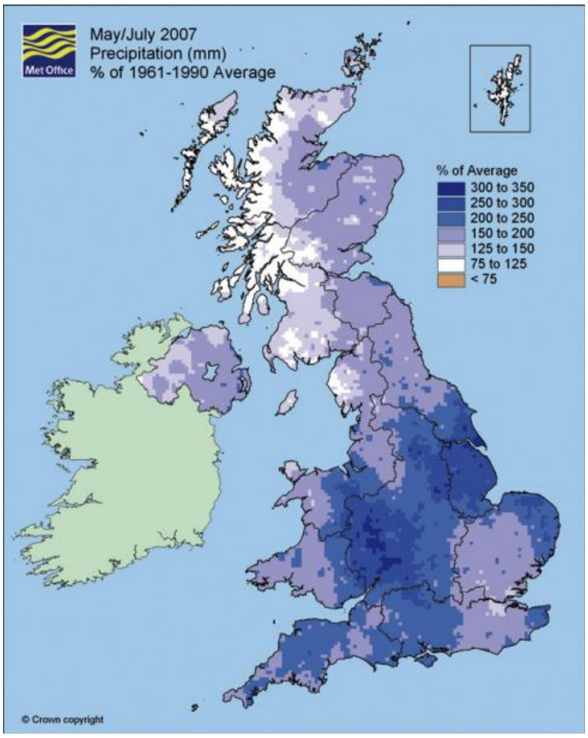


Figure 2.3 Left: Table illustrating the highest May-July rainfall totals for England and Wales. Right: Map of UK showing May-July 2007 rainfall as a percentage of the 1961-1990 average (Marsh and Hannaford, 2007).

Within the north of England two storms which occurred during the spring-summer 2007 were predominantly important in the generation of widespread flooding. The first of these storms occurred between the 13th and 15th of June, producing large volumes of precipitation in a band stretching from the Midlands to North-East

England. Some flooding did occur in direct response to these initial storms, although more importantly the precipitation caused catchments to wet up, leaving them highly susceptible to further rainfall. The arrival of a second low pressure system approximately 10 days later produced volumes of rainfall which far exceeded any previous records and is illustrated within Figure 2.5 (Environment Agency, 2007).

In response to record levels of precipitation falling onto highly responsive catchments, many rivers recorded peak discharges far in excess of previous maxima, which exceeded design capacities of flood alleviation measures and urban drainage systems (Pitt, 2007). Hadfields gauging station in Sheffield (Figure 2.4) recorded water levels which exceeded the highest stage previously recorded on this section of the River Don by 1.7 m (Marsh and Hannaford, 2007), whilst extended periods of high flow prevented drainage of flood waters and consequently were responsible for particularly severe impacts within many urban areas. Additionally it has been argued that a somewhat unique but also significant feature of the summer 2007 flooding was that a high proportion of the damage caused was attributable to inundation from non fluvial sources, primarily from inundation caused by overwhelming of drains/sewers (Marsh and Hannaford, 2007).

In the context of the UK the damage caused by the summer 2007 floods was enormous, indeed this episode of flooding is set apart from past floods due to its impacts upon well populated floodplains and urban centres (Marsh and Hannaford, 2007). Overall there were fourteen recorded fatalities linked to flooding, whilst no fewer than 55,000 homes and 6,000 businesses were flooded. As a direct result insurance claims approached £3 billion by the end of 2007 (Environment Agency, 2007). Despite the high monetary losses the impacts of the 2007 floods were not purely economic, for the majority of those affected the flooding far exceeded any previous experience in terms of scale and magnitude. Many people inhabiting flooded or at-risk low lying areas were evacuated, whilst thousands were displaced indefinitely due to prolonged/ repeated flooding of properties. In addition, flooding affected 300 schools in Yorkshire and Humberside whilst there was also damage to utility infrastructure. In Gloucestershire flooding left 350,000 people without access to mains water supply (Pitt, 2007) , whilst the power supply to 40,000 homes was also disrupted. Therefore it is clear that the summer floods of 2007 were responsible for a huge range of economic and social impacts.

2.3.1 Flood processes and impacts within the city of Sheffield

Whilst it is clear that the impacts of the 2007 summer floods were extensive across England and Wales, the city of Sheffield constituted one of the more severely affected areas during this event. The chain of events which lead to the flooding of Sheffield began with the extraordinary levels of precipitation received during the first half of June 2007. This caused reservoirs within the headwaters of the Don, Loxley and Sheaf catchments to reach maximum capacity, negating their potential to act as buffers to further rainfall (Environment Agency, 2007). The first of two further high intensity storms occurred when 90 mm of precipitation was recorded over the 48 hour period preceding 15th of June. This rainfall caused already elevated river levels across the Don catchment to rise further and in Sheffield, where the three aforementioned rivers confluence, the capacity of drains was exceeded resulting in some localised flooding (Environment Agency, 2007). This was proceeded by a second more intense storm event which occurred on the 25th June in which 100 mm of precipitation fell within the Don catchment and onto the city itself in less than 24 hours. A subsequent dramatic increase in the discharge of the river completely overwhelmed drainage systems, resulting in the widespread incidence of both fluvial and pluvial flooding (Environment Agency, 2007).

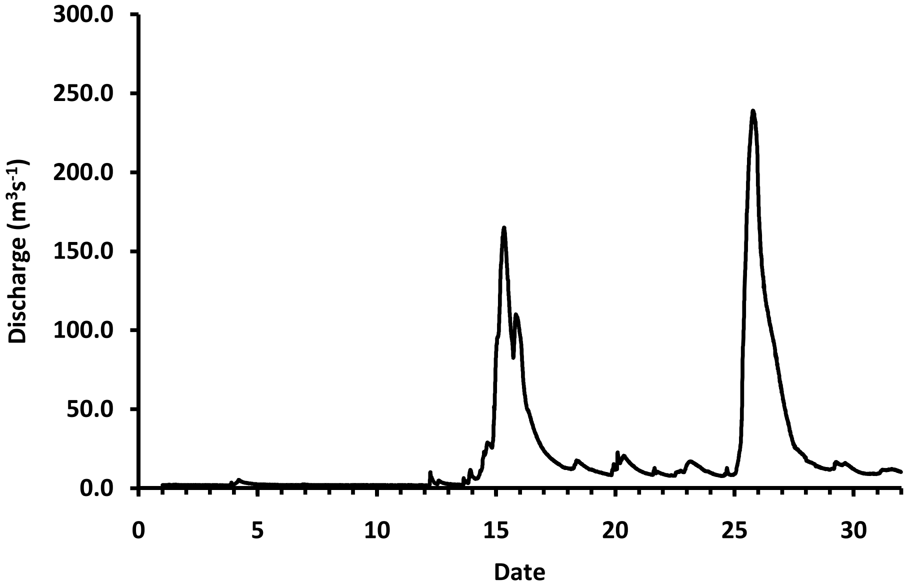


Figure 2.4 Discharge hydrograph observed at Hadfields gauging station in Sheffield for the month of June 2007. Note the two main peak flow events occurring on June 15th and June 25th.

The impacts of this episode of flooding within the metropolitan area of Sheffield were severe; two fatalities were recorded, 1,200 residential properties and 100 businesses were inundated. Furthermore, 200 people trapped by rapidly rising water levels were evacuated by the emergency services whilst hundreds more were left stranded in buildings in flood affected parts of the city. Damage was sustained by a wide range of other structures and services with reports confirming that several small buildings collapsed under pressure from flood waters, whilst approximately 13,000 people were left without power. In addition, the Hillsborough Football Stadium became inundated to a depth of approximately six feet whilst the lower floor of the Meadowhall shopping centre was flooded, causing some shops to remain closed until September (Environment Agency, 2007). Intuitively, the worst flooding occurred within the low lying areas of city which constitute the urban floodplain, which is where many of the cities industrial factories are situated. Damage to the facilities of Clarkson Osborn, a tool making company, were valued at around £15 million whilst other firms such as Sheffield Forgemasters International and Cadbury Trebor Bassett suffered multi million pound losses (Environment Agency, 2007).

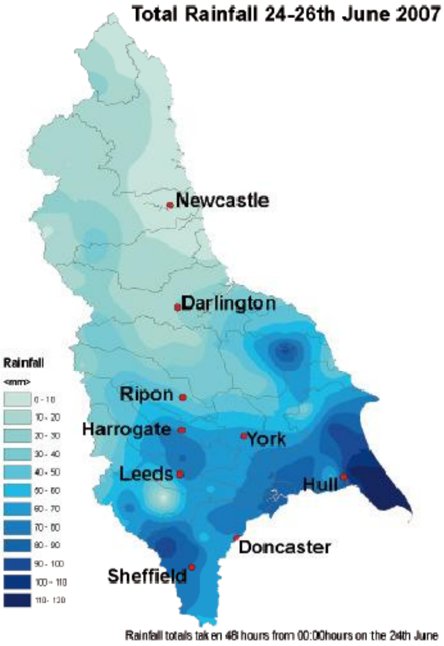


Figure 2.5 Rainfall totals within North England for the 24th-26th June 2007. Taken from (Environment Agency, 2007)

Therefore in addition to the basic justification presented in 2.1, the specific aims of this study in terms of assessing the significance of direct precipitation to predictions of flood inundation, mean that Sheffield represents a very interesting research location. From a UK perspective it is hypothesised that the 2007 floods were characterised by a high proportion of flood damage attributable to non-fluvial flooding (Pitt, 2007). Indeed it has been postulated that pluvial flooding caused by the overwhelming of drains was responsible for around two thirds of the properties flooded across the UK (Marsh and Hannaford, 2007). However within Sheffield there are several differing consensuses regarding the potential importance of rainfall and pluvial flooding.

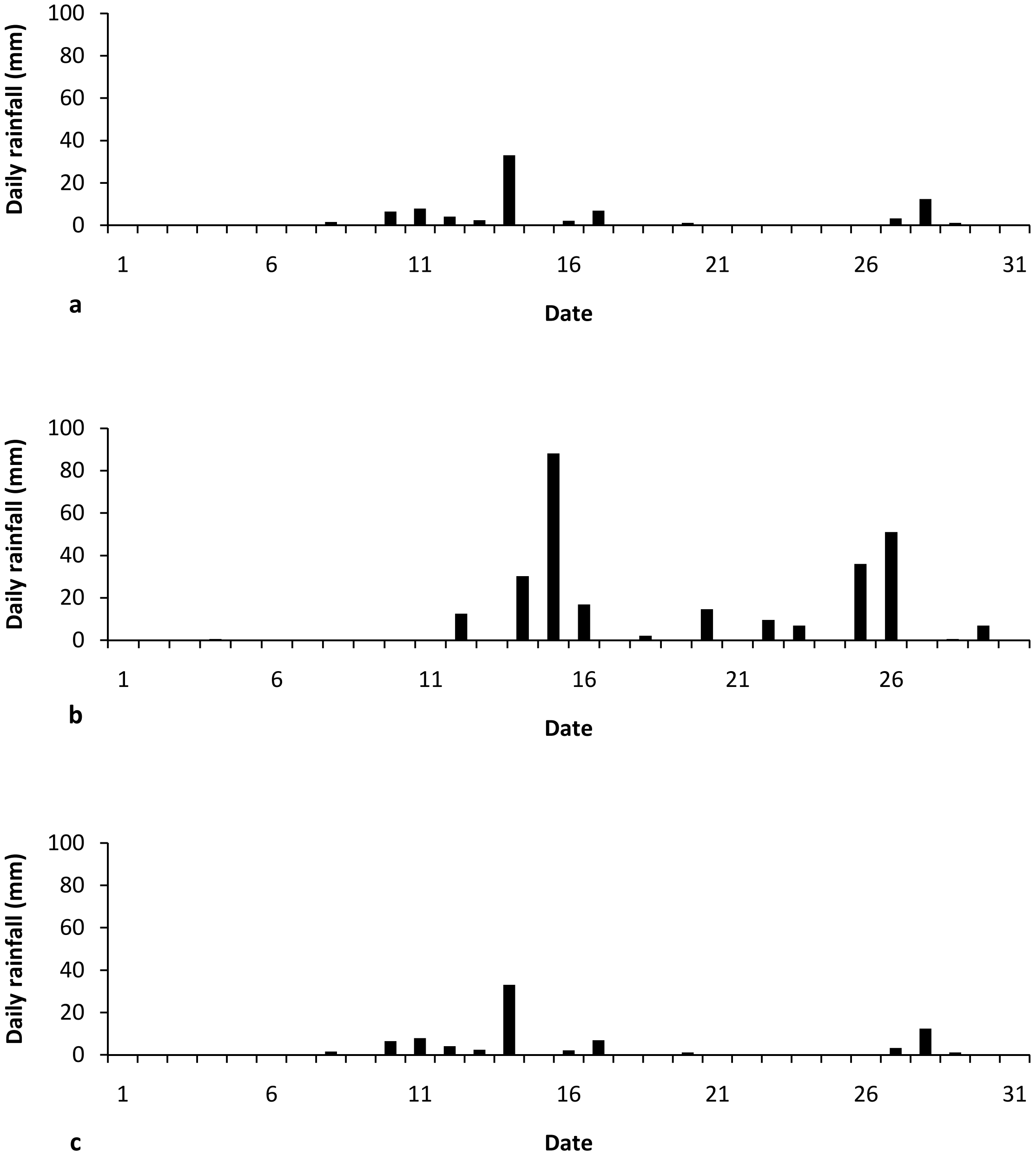


Figure 2.6 Rainfall levels taken from Sheffield MIDAS station src id 525 for spring-summer 2007 (a) May (b) June (c) July

An assessment by Environment Agency (2007) has highlighted the incidence of severe flooding as a direct consequence of heavy rainfall events in 2007, suggesting that precipitation and run off generation may be a key feature of flood hydrology within the city. However, Dickson and Berry (2008) contend these conclusions, stating that surface flooding in response to rainfall was localised and constituted only 5% of the total inundation observed during the June 2007 in Sheffield. Furthermore, this report states that aerial imagery acquired the day after peak flood inundation was incorrectly interpreted by the Environment Agency, leading to overestimation of the incidence and impact of pluvial flooding. Regions of standing water isolated from the channel were assumed to have resulted from the overwhelming of drains by intense precipitation rather than representing areas which had been separated from the main area of inundation as flood waters receded. Although (Dickson and Berry, 2008) acknowledge that disconnected run-off was generated during the event, it is argued that the pluvial flooding experienced was often not of a sufficient level to cause flooding of properties. With seemingly no definitive conclusion reached regarding the importance of precipitation and pluvial flooding within Sheffield in 2007, a modelling study which addresses this issue is clearly increasingly relevant.

2.5 Summary

Overall, the location of Sheffield within the Don catchment means that the city is prone to flooding, with the primary natural hazard provided by the river Don itself. It is clear that this flood risk has been accentuated by large scale development upon floodplains within the city. Therefore on a basic level Sheffield represents an ideal location for this study. Sheffield was affected severely by the summer floods which occurred across the UK within June 2007. In the aftermath of this flood event, reports from the Environment Agency suggested that pluvial flooding in response to high intensity rainfall was responsible for significant inundation during this event (Marsh and Hannaford, 2007). However a subsequent consultancy report has questioned the conclusions of the Environment Agency, stating that pluvial flooding provided only a limited contribution to the observed flood inundation (Dickson and Berry, 2008). Consequently the flood event which occurred within June 2007 in Sheffield provides ideal context for this investigation and enables the research questions and hypotheses to be examined with reference to a specific example.

Chapter Three

LISFLOOD-FP model description

3. LISFLOOD-FP model description

The development process of the original LISFLOOD-FP model is given in (Bates and De Roo, 2000). The model description below is based upon the aforementioned paper, along with subsequent studies which have developed and tested various modifications to the LISFLOOD-FP code, namely (Horritt and Bates, 2001a, Horritt and Bates, 2001b, Hunter et al., 2005b, Hunter et al., 2006). Within this study LISFLOOD-FP Version 2.7.5 was used for simulations within chapter five, whilst version 4.3.6 was used for simulations within chapter six and seven, having been obtained midway through the research.

3.1 LISFLOOD-FP model basis

A raster Digital Elevation Model (DEM) forms the primary component of LISFLOOD-FP (Bates and De Roo, 2000), based upon the preeminent importance of topography in prediction of flood inundation. In order to capture dynamic flood wave behaviour LISFLOOD-FP comprises a process representation which includes separate treatments of in channel and overbank flows (Knight and Shiono, 1996), which has been deemed necessary to provide accurate predictions of flood inundation on all but the simplest of floodplains (Horritt and Bates, 2001a). The model formulation is based upon a one-dimensional representation of in channel hydraulics, coupled to a two-dimensional storage cell representation of over bank flows. This constitutes the simplest available process representation which is able to facilitate dynamic simulations and reflects the models simple design philosophy (Bates and De Roo, 2000).

3.2 One-dimensional approximation of channel flow

3.2.1 Kinematic wave

The kinematic wave approximation, a simplification of the full one dimensional St. Venant equation, constitutes the most basic scheme available for dynamic wave routing of in channel hydraulic flows. This approximation is produced through elimination of the local acceleration, convective acceleration and pressure terms in the momentum equation, whilst also relying upon the assumption that friction and gravity forces are balanced (Bates and De Roo, 2000).

The above treatment produces the discretised equation system (Bates and De Roo, 2000):

- Continuity: Equation 1.1

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

- Momentum: Equation 1.2

$$S_0 - \frac{n^2 P^{4/3} Q^2}{A^{10/3}} - \left[\frac{\partial h}{\partial x}\right] = 0$$

where *Q* is the volumetric flow rate, *A* is the flow cross sectional area, *t* is the time, *q* is a lateral inflow term, S_o is the channel bed slope, *n* is the Manning's friction coefficient, *P* is the wetted perimeter and *h* is the flow depth (Horritt and Bates, 2001a).

The kinematic approximation is therefore based upon the assumption that the channel cross section is wide and rectangular so that the wetted perimeter is approximated by channel width (Bates and De Roo, 2000). An explicit finite difference procedure is utilised within LISFLOOD-FP, more specifically a simple linear scheme (Chow, 1988), in which finite difference equations are derived through the backward-difference method. Whilst providing a simple and efficient way of representing channel flow it is inevitable that the use of the aforementioned simplifications and assumptions will result in some limitations. In the case of LISFLOOD-FP the momentum equation used considers only the down gradient characteristics of hydraulics and consequently backwater effects are discounted, whilst there is also a possibility of shock wave development in areas of flow convergence (Bates and De Roo, 2000).

3.2.2 Diffusive wave channel solver

For some river reaches the assumptions required for implementation of the kinematic approximation are inappropriate. In order to more accurately represent Amazonian flood wave hydraulics, where backwater effects are known to be significant, Trigg et al., (2009) developed a diffusive channel solver for implementation within LISFLOOD-FP. Overall the diffusive solver enables a more complete representation of channel hydraulics, whilst also facilitating representation of full multi-branching river networks and decoupling of the 1D/2D model compents, with little increase in computation cost. Although the diffusive solver is able to represent propagation of the flood wave more accurately, its implementation requires an additional downstream boundary condition. Within this study the kinematic approximation is utilised as backwater effects are not significant within the study reach, whilst a downstream boundary condition is not available.

3.3 Channel representation

Within the original version of LISFLOOD-FP (Bates and De Roo, 2000) the river channel was discretised as a set of cells running through the model domain each containing a value for channel width, slope, bank full depth and friction coefficient, thus providing the information required in order to enable calculation of the kinematic wave approximation. However Bates and De Roo (2000) noted a scaling problem in this approach whereby channel width may deviate from the grid size within some applications. Within the application of the original LISFLOOD-FP model by Horritt and Bates (2001a) a large discrepancy was observed between the relatively coarse grid spacing and the width of the river channel. Consequently in this situation a much greater area of the floodplain is occupied by the channel than is appropriate, potentially precluding the representation of near channel regions which are hypothesised to be significant in storage of overbank flows (Horritt and Bates, 2001a).

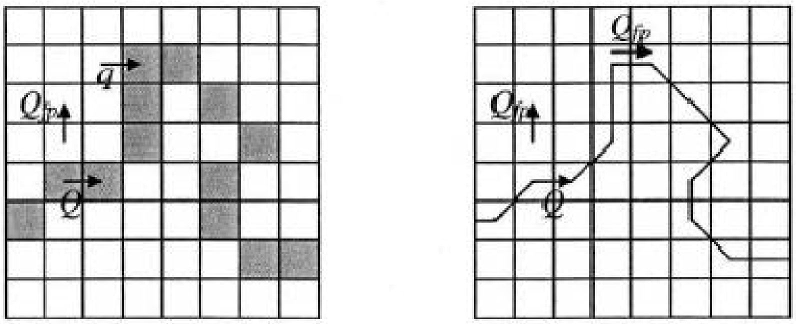


Figure 3.1 Schematic diagram illustrating the channel discretisation used within the original LISFLOOD-FP model (left) and with the NCFS code modification (right). (Horritt and Bates, 2001a).

In response to this scaling problem Horritt and Bates (2001a) developed the near channel floodplain storage (NCFS) model, an alternative channel discretisation which has subsequently been included in updated versions of the LISFLOOD-FP model. Within the NCFS the channel is represented as an additional flow path which lies over the floodplain mesh rather than occupying floodplain pixels directly (Horritt and Bates, 2001a). Consequently this discretisation facilitates flow of water between channel and floodplain nodes according to a Manning's like flow equation, whilst flux of water between floodplain cells which are populated by the channel is also included, thus providing a more adequate representation of water storage in near channel areas.

3.4 Two-dimensional storage cell representation of floodplain flow

In order to calculate floodplain flows the original LISFLOOD-FP model solves a continuity equation relating flow into a cell and its change in volume and a momentum equation for each direction where flow between cells is calculated according to Manning's law (Hunter et al., 2005b).

Effectively floodplain flow is approximated as a two-dimensional diffusion wave (Bates and De Roo, 2000):

- Continuity equation: Equation 1.3

$$\frac{\partial h^{i,j}}{\partial t} = \frac{Q_x^{i-1} - Q_x^{i,j} + Q_y^{i,j-1} - Q_y^{i,j}}{\Delta x \Delta y}$$

- Momentum equation (only x direction): Equation 1.4

$$Q_x^{i,j} = \frac{h_{flow}^{5/3}}{n} \left(\frac{h^{i-1,j} - h^{i,j}}{\Delta x} \right)^{1/2} \Delta y$$

In this set of equations $h^{i,j}$ is water surface free height at node (i, j), Δx and Δy are cell dimensions, n is Manning's friction coefficient, Q_x and Q_y describe the volumetric flow rates between floodplain cells (Horritt and Bates, 2001b). Flow depth h_{flow} represents the depth through which water is able to flow between two cells and is defined as the difference between the highest water free surface in the two cells and the highest bed elevation (Bates and De Roo, 2000). The momentum equation for Q_y is defined analogously to the equivalent equation for Q_x (Hunter et al., 2005b). The equations above are solved explicitly using a finite-difference discretisation of the time derivative term (Hunter et al., 2005b):

- Finite difference discretisation: Equation 1.5

$$\frac{{}^{t+\Delta t}h^{i,j} - {}^{t}h^{i,j}}{\Delta t} = \frac{{}^{t}Q_x^{i-1j} - {}^{t}Q_x^{ij} + {}^{t}Q_y^{ij-1} - {}^{t}Q_y^{ij}}{\Delta x \Delta y}$$

Here ${}^{t}h$ and ${}^{t}Q$ represent depth and volumetric flow rate at time t respectively, whilst Δt represents the model time step (Hunter et al., 2006).

It is inherently difficult to achieve model stability within explicit hydraulic models, particularly in the case of the original LISFLOOD-FP model which required a user defined time step commonly selected through process of trial and error (Horritt and Bates, 2001a). Hunter et al (2005b) show that the stability of model solutions depends upon a combination of water depth, free surface gradients, Manning's *n* and grid cell size. Overall a smaller time step favours model stability, whilst a larger time step ensures greater computational efficiency. The optimum time step is one which is small enough to produce stable model solutions, whilst not being too small and thus rendering model simulations inefficient. Model instability is marked by the prevalence of chequerboard oscillations when excessively long time steps are used and is illustrated in Figure 3.2 (Hunter et al., 2006).

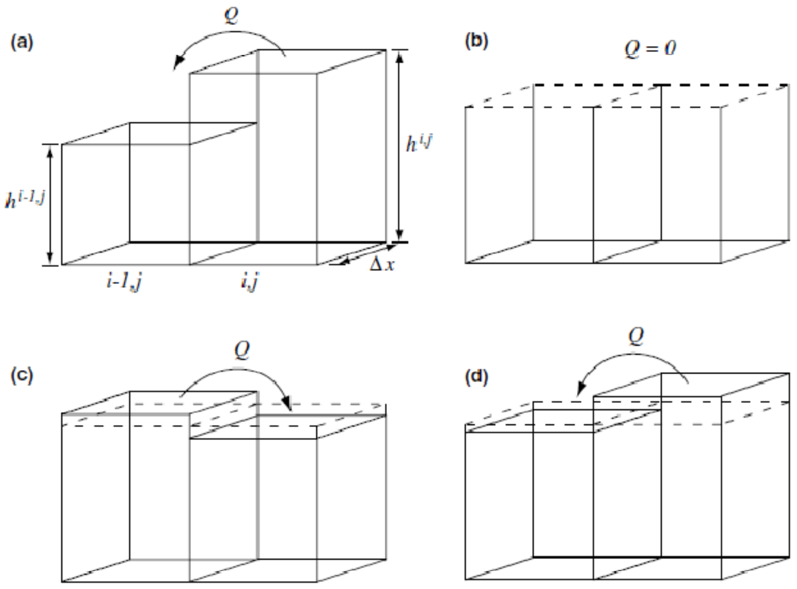


Figure 3.2 Development of chequerboard oscillations a) End of first time step, water level in cell i,j exceeds that of $i-1,j$. b) End of next time step, water level equal so flux between i,j and $i-1$ should equal zero c) Low free surface gradient between the two cells leads to development of oscillations, at the end of previous time step the flux from i,j to $i-1,j$ causes the level in $i-1,j$ to jump too high, resulting in erroneous flow reversal at the following time step d) At the end of time step $t+2\Delta t$, the level in $i-1,j$ has caused a large discharge toward i,j whose levels rise too high and causes a second successive flow reversal (Hunter et al., 2005b).

In order to prevent the occurrence of instability, detailed in Figure 3.2, a flow limiter was included within the model code which imposes a maximum flow between cells, thus preventing ‘over or undershoot of the solution’ particularly in areas of deep water (Hunter et al., 2005b).

- Flow limiter: Equation 1.6

$$Q_x^{i,j} = \min\left(Q_x^{ij} \frac{\Delta x \Delta y\left(h^{i,j} - h^{i-1j}\right)}{4\Delta t}\right)$$

The flow limiter operates as a function of flow depth, grid cell size and time step and functions by ensuring that the change in cell depth during one iteration is not sufficient to reverse the flow in or out of the cell at the next time step (Hunter et al., 2005b). Fluxes calculated by the flow limiter replace those calculated by the Manning equation in the standard flow equations and are highly dependent on model parameters. Accordingly where the flow limiter is invoked floodplain flows exhibit a high level of sensitivity to both grid cell size and time step and are insensitive to floodplain roughness (Hunter et al., 2006).

3.5 Performance of the original formulation of LISFLOOD-FP

The original version of LISFLOOD-FP, the formulation of which has been detailed above, has been tested and compared to numerous other one- and two-dimensional flood inundation models (Horritt and Bates, 2001a, Horritt and Bates, 2001b, Bates and De Roo, 2000, Hunter et al., 2005a). Within these studies the performance of LISFLOOD-FP has been equivalent to or better than its alternatives in terms of predicting maximum flood extent when calibrated with respect to observed data. In light of the original design philosophy of LISFLOOD-FP the predictive performance illustrated within these studies proves that the model accomplishes and perhaps exceeds its original aims. However Hunter et al., (2005b) state that despite the ability of storage cell codes such as LISFLOOD-FP to replicate maximum flood extent data, their inherent simplifying assumptions lead to various theoretical and practical constraints.

Horritt and Bates (2002) demonstrate that in instances where the flow limiter is heavily invoked, LISFLOOD-FP demonstrates a high sensitivity to time step and grid cell size whilst a lack of sensitivity is shown with respect to floodplain friction parameters. This is a characteristic which is relatively common among storage cell models. Significantly, where the flow limiter is invoked predictions of inundation are not independent of grid resolution and time step, with potential negative impacts upon model performance (Horritt and Bates, 2002). This problem is particularly prevalent when calibrated parameters from one event are applied to predict another independent event. In such instances variance in model performance indicates non-stationarity within optimum parameter sets (Hunter et al., 2006).

In addition, Werner et al., (2005b) illustrate the poor performance of LISFLOOD-FP compared to other flood inundation models when applied without calibration to a given river reach. Here the model was shown to substantially under predict both bulk and spatially distributed flood characteristics. Finally, Horritt and Bates (2001a) established that the optimal calibrations for flood wave travel time and inundated area were located in different areas of the parameter space. Therefore whilst the model is able to simulate either dataset independently, the two cannot be easily reconciled. Given the shortcomings evident in the formulation of the original LISFLOOD-FP model, Hunter et al., (2005b) proposed an adaptive time step numerical scheme which aimed to improve model performance. The adaptive time step solution was designed to enhance the simulation of floodplain conveyance, primarily through a more physically realistic representation of the propagation and recession of the inundation front (Hunter et al., 2006).

3.6 Summary

LISFLOOD-FP is a storage cell model predicated upon a simple design philosophy, which reflects the preeminent importance of topography within flood prediction. Accordingly the model formulation is based upon a sacrifice in terms of process representation in order to facilitate the incorporation of a high resolution DEM. The fixed time step version of LISFLOOD-FP is able to accurately predict flooding when calibrated with respect to synoptic images of flood inundation extent (Bates and De Roo, 2000, Horritt and Bates, 2001b). However the model has been shown to offer poor dynamic performance, particularly when utilised without calibration with respect to inundation extent (Hunter et al., 2006). Subsequently Hunter et al., (2005b) developed an adaptive time step solution which has been shown to provide an absolute increase in performance, in addition to a much improved representation of inundation dynamics both for analytical solutions and a real test scenario (Hunter et al., 2006).

Chapter Four

Model application

4. Model application

4.1 Study site

Given the high resolution topographic data used within this study it was not feasible to model the entire urban area of Sheffield. Therefore a relatively short ~4 km reach of the Don was selected on the eastern edge of the metropolitan area, downstream of the Hadfields Weir gauging station (BNG 439000, 391000). The Don flows from west to east through the ~2.8 km^2 study area and at this point the river is typically 20-30 m wide and heavily engineered. Bankful depth is typically 5-8m and average slope falls within the limits for the application of the kinematic approximation (Woolhiser and Liggett, 1967).

The model domain is relatively large compared to other studies eg (McMillan and Brasington, 2007, Fewtrell et al., 2008) and includes a significant portion of land outside the recognised floodplain. Inclusion of such areas, which are often associated with very little fluvial flood risk, is usually inadvisable due to increased computational costs associated with a larger grid. However, given the overall aim of this study the use of a larger domain is necessary in order to encompass areas which may potentially contribute to surface runoff in response to rainfall.

The study area exhibits a high degree of topographical complexity, encapsulating the rivers floodplain which is approximately 500 m in width and well constrained as well as the valley sides which exhibit much greater relief. Superimposed upon this relatively complex topography are a variety of land uses typical of the periphery of an urban area. The low lying floodplain and main region of potential inundation is characterised primarily by a variety of relatively large industrial buildings. These structures are accompanied by relatively large areas of impermeable land surfaces such as roads and car parks, whilst there is also a significant area of green space including grasslands and some wetland around the channel.

In terms of noteworthy structures, the Meadowhall shopping centre is located in the southwest corner of the domain and is undoubtedly the most significant location within the study area, whilst a sewage treatment plant is located adjacent to the river at BNG 440100, 392000. As previously stated, the valley sides account for a substantial area of the model domain and although these areas are associated with little flood risk from the river Don itself, they remain highly significant given the aims of this particular study. The area outside the floodplain corridor is characterised by more extreme relief, generating much higher slope gradients than those on the floodplain. In addition, outside the limits of the floodplain land use is more highly dominated by impermeable land cover types such as residential housing estates, roads and some industrial buildings.

4.2 Model configuration

Where a flood inundation model is applied to a specific context it is necessary to define the relevant characteristics of this catchment/reach through the imposition of model boundary conditions and selection of parameters. Flood inundation models commonly require three primary boundary conditions to be specified (Hunter et al., 2007): (i) topographic data to construct the model grid (ii) inflow/outflow data (iii) a value of roughness for each grid cell. The specification of these boundary conditions along with further model parameterisation is detailed below, with the exception of roughness values which are treated as calibration parameters within LISFLOOD-FP.

4.2.1 Topographic data

The primary requirement of LISFLOOD-FP is a raster digital elevation model (DEM), which are most commonly generated from high resolution airborne laser altimetry data (LiDAR) surveys (Bates and De Roo, 2000). LiDAR and photogrammetry are the only technologies currently available which are able to supply data of an appropriate resolution and accuracy to hydraulic models (Gomes Pereira and Wicherson, 1999). LiDAR surveys have become routine over the past decade generating a wealth of high resolution topographical data, currently it is estimated that that 62% of the land surface of England and Wales has been surveyed. LiDAR is therefore able to capture the topographical richness of a variety of land surface types at typical horizontal resolutions of 2 m with a vertical accuracy of 15 cm RMSE (Bates, 2004), although topographical data with a resolution of 1 m or less is now available for many urban areas (Environment Agency, 2010).

Despite the potential utility offered by LiDAR data, considerable post processing is normally required in order to convert raw data into a useful DEM which can then be used to parameterise a flood inundation model (Cobby et al., 2003). Mason et al., (2007a) state that the fundamental requirement of LiDAR post-processing is to separate ground hits from hits on surface objects. Where the land surface is covered with vegetation a portion of the laser pulse is reflected by the top of the canopy, whilst part will penetrate to the ground (Bates, 2004). Where this occurs the first laser returns allow the generation of a Digital Surface Model (DSM) which includes a representation of these trees and vegetation, whilst the second returns which correspond to the land surface can be interpolated in order to generate high resolution ‘bare earth’ Digital Terrain Models (DTMs) (Cobby et al., 2001).

Within this study topographic data were provided by the Environment Agency’s Geomatics Group in the form of a Digital Surface Model (DSM) and a Digital Terrain Model (DTM) both of 1 m spatial resolution. This LiDAR data has been post processed to standard data quality requirements set by the Environment Agency’s National Centre for Environmental Data Surveillance, using a combination of Terrascan software and Arcview 3.3 (Plant, 2010). EA post processing ensures a minimum vertical precision of 0.15m throughout, with potential improvements in relatively flat areas with solid reflectance surfaces. The DSM comprised the complete LiDAR dataset including surface features such as buildings and vegetation, whilst the DTM constituted a bare earth representation of topography with the aforementioned surface features removed. As this data is already post processed the basic problem presented by raw LiDAR data in terms of separating ground hits and hits from surface objects has already been addressed, precluding the need to employ the use of a LiDAR segmenter such as that developed for urban areas in (Mason et al., 2007a)

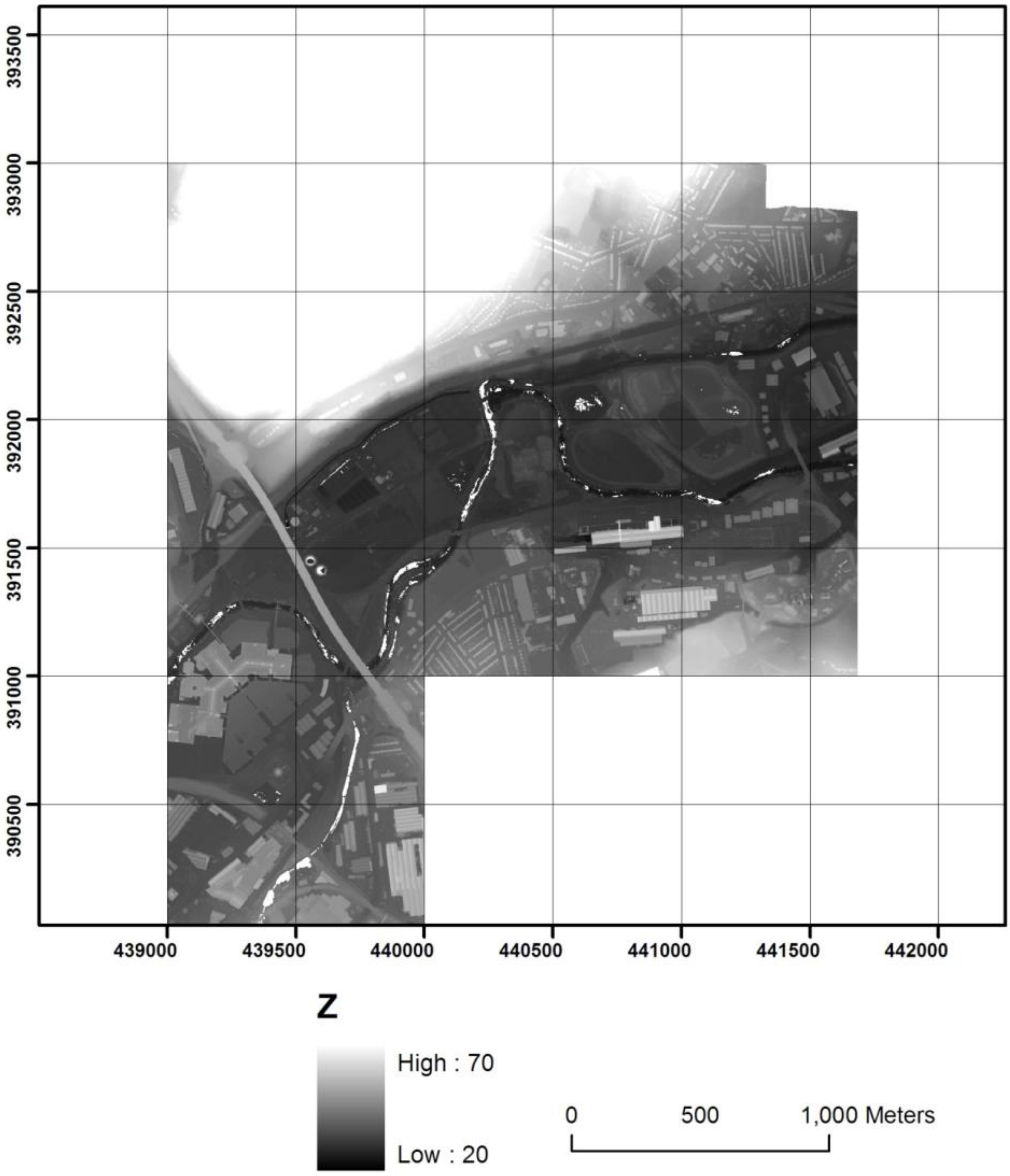


Figure 4.1 Digital Surface Model for study area (1m spatial resolution), including surface features.

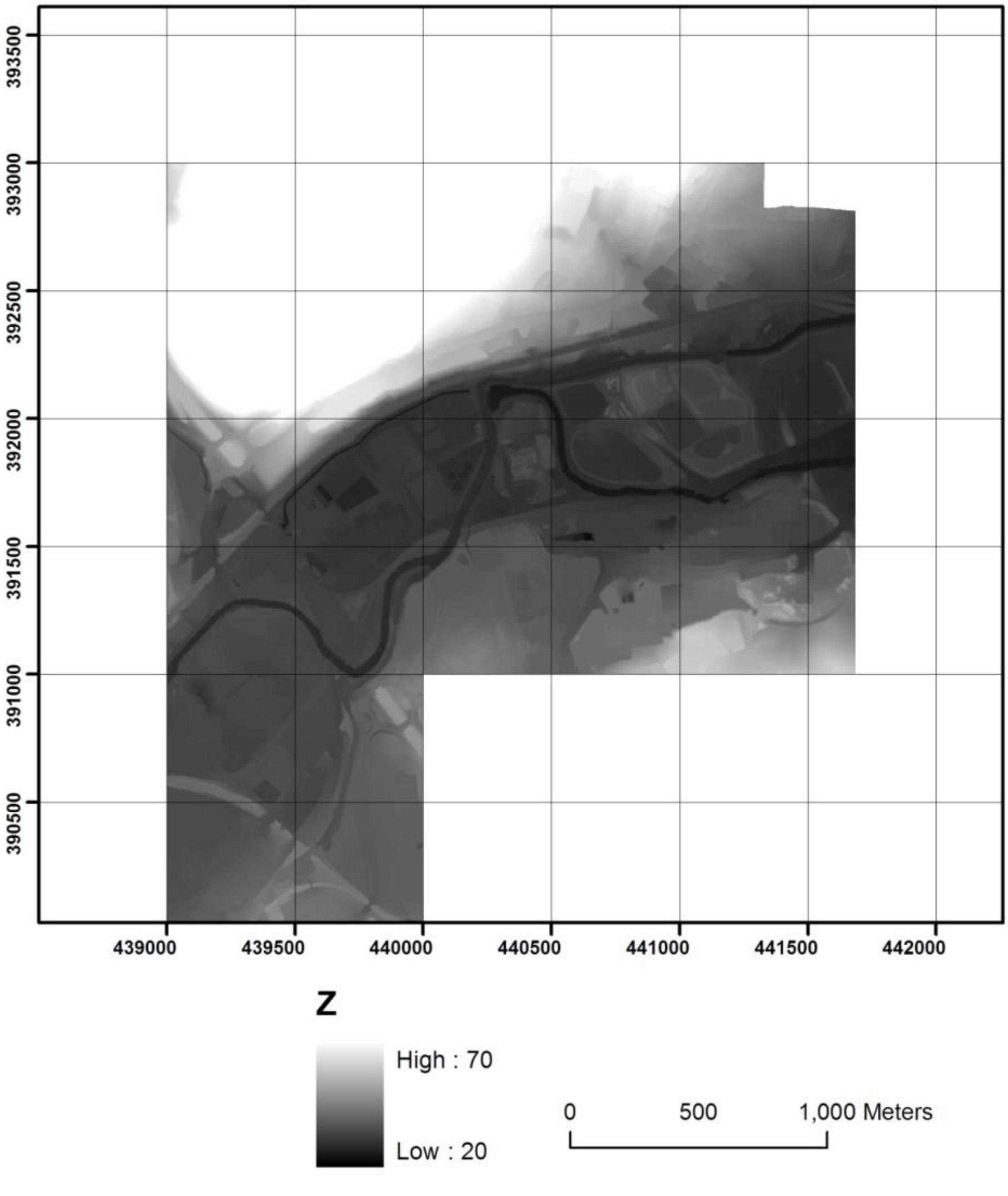


Figure 4.2 Bare earth Digital Terrain Model for study area (1m spatial resolution), with surface features removed.

4.2.2 Topographic data processing

Although the topographical data supplied by the EA had been pre processed further treatment was required in order to convert the data into a suitable DEM for application within LISFLOOD-FP. The data was originally supplied as individual 1 km^2 tiles, which were converted into a mosaic using ArcGIS (Figure 4.1 and 4.2). Large areas of no data were located in the south east of the domain as topographical data was not possessed for these areas. LISFLOOD-FP requires a grid with regular dimensions, hence in order to achieve this it was necessary to include these unknown areas. Accordingly elevation values within the no data areas were raised to a uniform value of 999 m, far in excess of the actual floodplain topography, in order to prevent flow of water into these areas. This treatment was also applied to the smaller no data region located in the north east corner of the domain.

Yu and Lane (2006a) state that a proper topographical representation of urban environments for use within flood inundation models must retain buildings and certain structures whilst removing tree canopies. The rationale for this decision is that it is only tree trunks which influence floodplain flow/storage. Given that the area occupied by tree trunks is only a fraction of the area of the canopy, the inclusion of these features would lead to an incorrect representation of the floodplain surface. The raw DSM data possessed within this study contains a representation of both buildings and trees, whilst the post-processing technique used in production of the DTM resulted in removal of all surface features. Accordingly neither the DSM or DTM alone provides an adequate representation of the topography of an urban environment (Yu and Lane, 2006a). Consequently further post-processing is required in the context of this study in order to generate a DEM which provides an appropriate representation of the topographical and structural complexity of the urban environment for utilisation within LISFLOOD-FP.

In response to this problem the DSM and DTM have been integrated using OS MasterMap data (Figure 4.3), facilitating the generation of the final DEM with which to populate the LISFLOOD-FP model. OS MasterMap is a useful data source which provides a comprehensive and up to date classification of areal themes across the UK (scale 1:1250), including features such as roads, structures, watercourses and buildings which are topologically structured. Particularly useful within this application is the buildings theme, which comprises all buildings with a surface area greater than 8 m^2, with the exception of outbuildings within private gardens where the minimum surface area is 12 m^2 (Mason et al., 2007a). The methodology employed here was similar to that utilised in previous urban flood modelling studies such as Fewtrell et al., (2008), in which the OS MasterMap data is used to generate a ‘mask’ (Figure 4.4) through which kerbs, pavements and buildings are reinserted into the bare earth DTM.

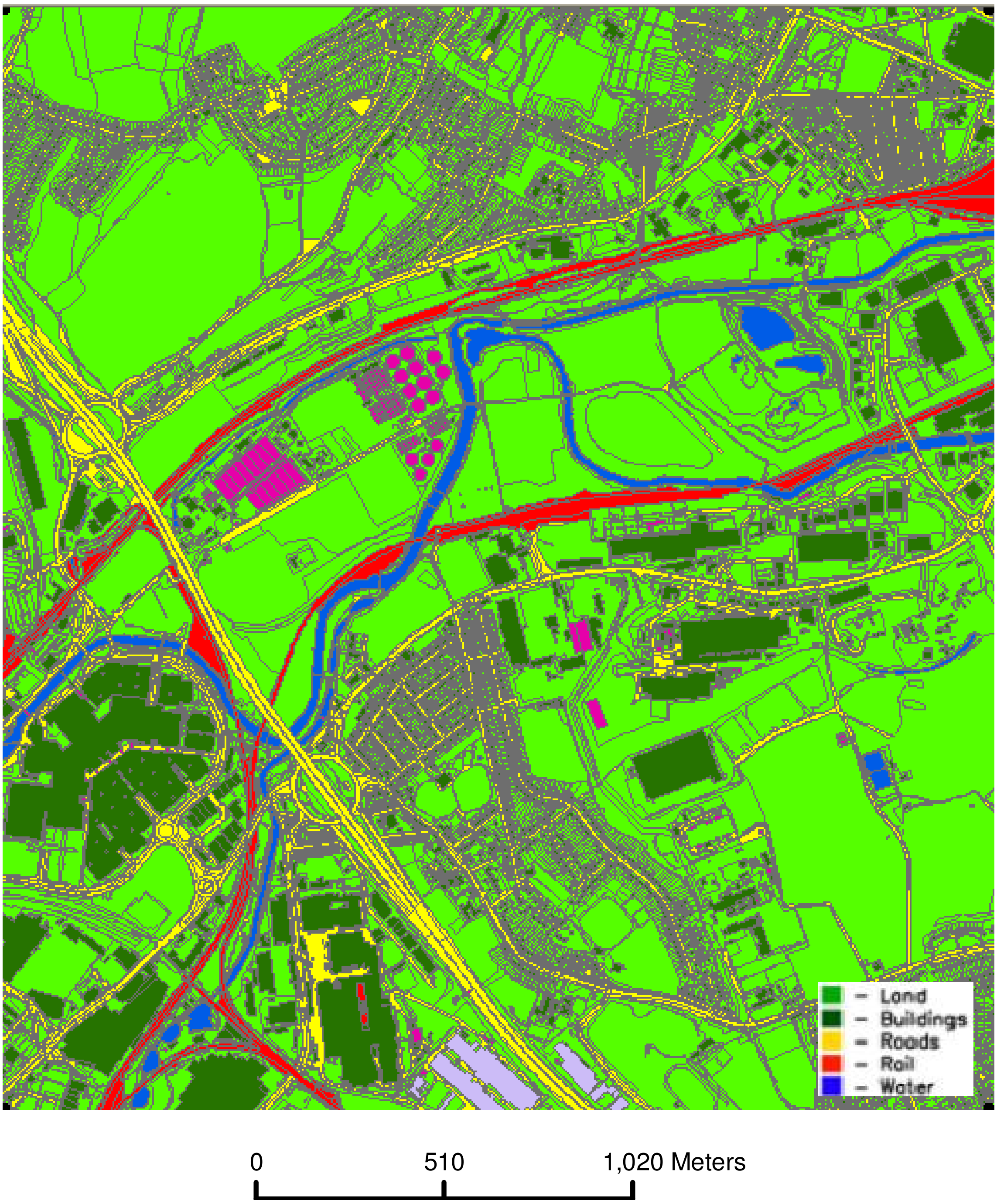


Figure 4.3 OS MasterMap data for the study area.

Although based upon the same principles, the technique used here differs from that utilised in Fewtrell et al., (2008) in several ways. Firstly the processing technique used here facilitates the inclusion of actual building heights as determined from the LiDAR survey (McMillan and Brasington, 2007) rather than arbitrary heights for different building types. This approach was chosen as it constituted the most simple in this context, although the difference is insignificant given that flood levels on the order of building height are unrealistic.

In order to reinsert buildings into the DTM OS MasterMap data was loaded into ArcGIS, a standard Geographical Information Systems package, within which buildings were converted into a binary grid of a commensurate size and resolution of the DTM and DSM (Figure 4.4). Grid cells were assigned a value of 1 if corresponding to the location of a building or 0 for any other areal theme. The final DEM (Figure 4.5) was generated through integration of the DSM and DTM in the software package MATLAB. Other topographic features such as bridges/ flyovers which potentially lead to unrealistic blockage of flow were generally classified as structures within the OS MasterMap, hence this methodology also precluded their inclusion within the final DEM (Mason et al., 2007a). One exception to this was provided by a bridge over the river Don which was included in the mask as part of the Meadowhall building. This bridge was removed from the DEM manually after the aforementioned processing had been undertaken.

Figure 4.4 Final binary building mask derived from OS MasterMap data

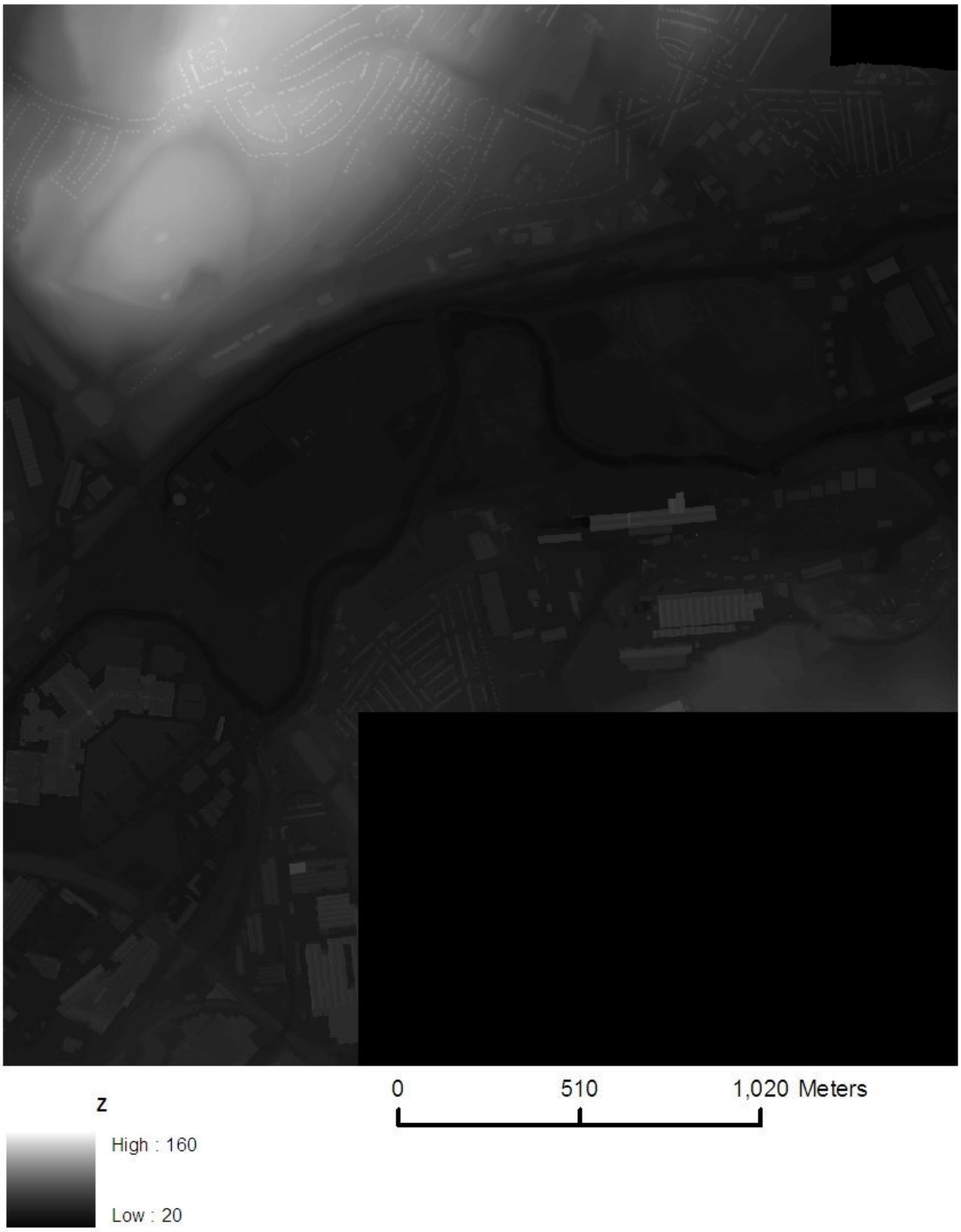


Figure 4.5 Digital Elevation Model (1m spatial resolution) obtained through integration of the DSM and DTM.

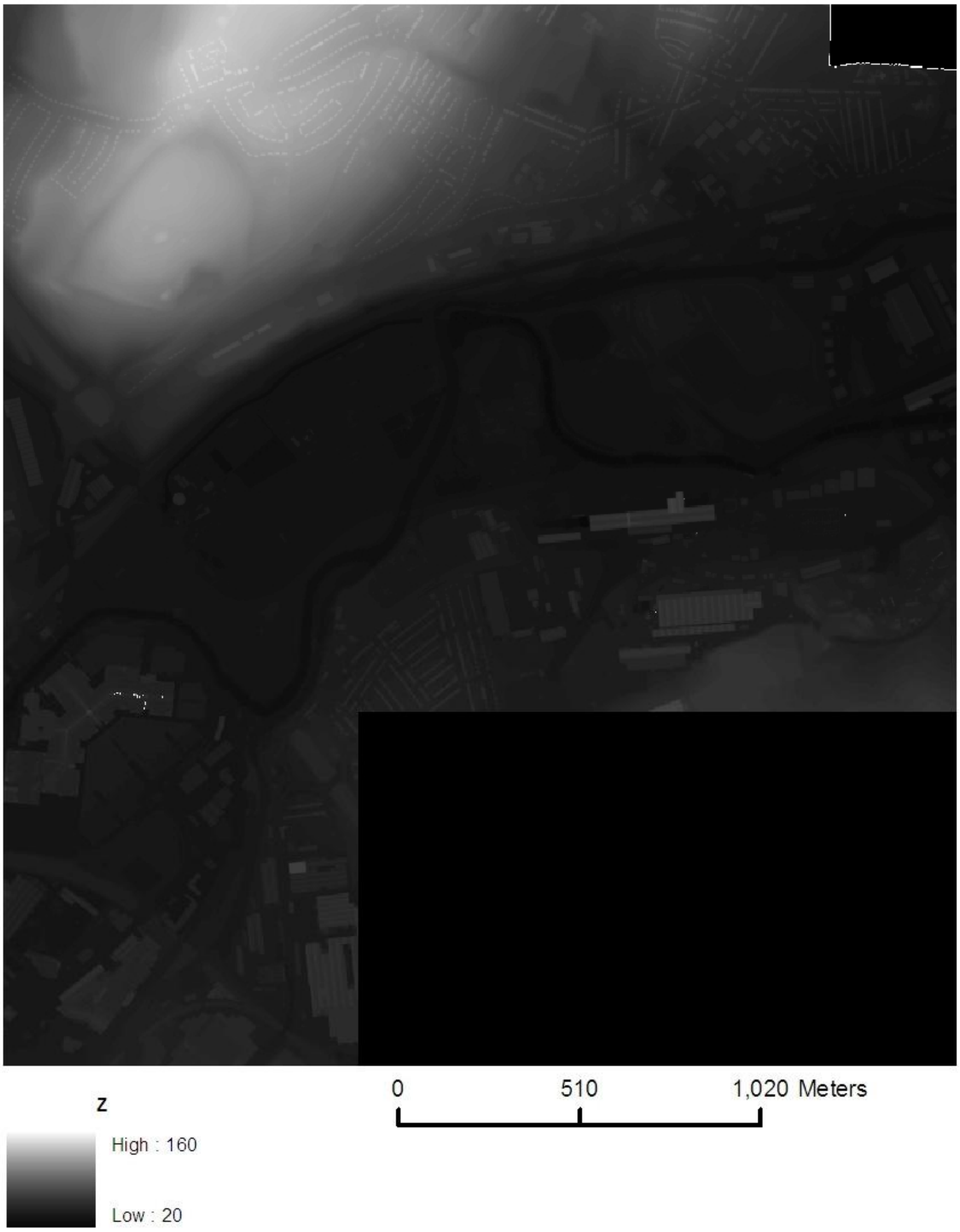


Figure 4.6 Digital Elevation Model (4m spatial resolution) obtained through integration of the DSM and DTM and resolution reduction.

4.2.3 Resolution reduction

The topographic data was supplied at a resolution of 1m and as the study area is relatively large the original DEM contained a total of 8,055,000 cells. Whilst the use of very high resolution topographical data is desirable within urban environments, it is clear that such a large number of grid cells is impracticable within this study. In order to generate more feasible grids the original 1m DEM was aggregated into progressively coarser resolution DEMs as in Fewtrell et al., (2008); 2 m (2,013,000), 4 m (503,250), 8 m (125,625) and 16 m (31,229) through employment of resolution reduction code within MATLAB. It was decided that a 4m resolution grid would be used within this study, as it offered significant computational advantages compared to 1 m and 2 m grids whilst providing an adequate representation of structural and topographical complexity at the building scale (Wright et al., 2008).

Resolution reduction can be achieved through numerous different interpolation methods which use different configurations of cell values in order to generate a coarser grid (Fewtrell et al., 2008). Given the topographical complexity observed in urban environments, careful consideration of the method of interpolation is important as the chosen technique will have a high order impact upon the representation of buildings at coarser scales (Fewtrell et al., 2008). Yu and Lane (2006a) found inconsistent results when analysing outputs from model simulations using reduced resolution grids which had been generated through bilinear, nearest neighbour and cubic spline resampling techniques. Further, Fewtrell et al., (2008) concluded that no off the shelf resampling techniques are able to provide a significant improvement in model performance. However the authors state that a bilinear approach appeared to offer an advantage in prediction in areas of shallow flow. Therefore due to the importance of pluvial flooding and surface run-off within this study, bilinear interpolation was chosen as the most appropriate technique with which to perform resolution reduction.

4.2.4 Flow boundary conditions

Flow boundary conditions for hydraulic flood inundation models are usually constituted by upstream/ downstream hydrographs. The upstream boundary condition used within this study takes the form of an inflow hydrograph obtained from Hadfields weir, an Environment Agency maintained gauging station within the urban area of Sheffield. The location of the study reach facilitated the direct input of gauging station records into the model domain, precluding the need to use additional calculations in order to generate an inflow hydrograph and preventing the introduction of further uncertainties. Stage and discharge records are available from this gauging station at 15 minute time intervals.

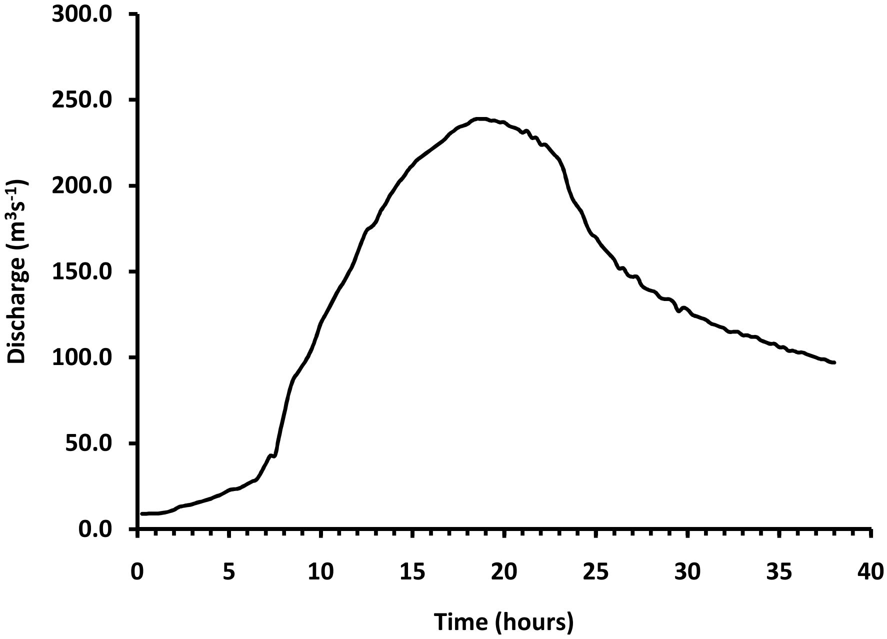


Figure 4.7 Discharge hydrograph from gauging station at Hadfields Weir for the period of second flood peak from 00:00 June 25th 2007 to 14:00 June 26th 2007.

The original data was supplied as a stage and discharge time series for the month of June 2007 (Figure 2.4), however in order to reduce model simulation times this was sub sampled in order to produce an event discharge hydrograph. This hydrograph (Figure 4.7) represented the period corresponding to the second flood peak which occurred from 00:00 June 25th to 14:00 June 26th. This hydrograph encapsulates the period of rapid rise of the flood hydrograph to the time of aerial imagery and is the shortest possible in order to reduce model run times and.

A downstream flow boundary condition was not included here as this is not required within the parameterisation of the LISFLOOD-FP model, which allows water to leave freely, with outflow from the domain calculated according to the local water slope between penultimate and final cells (Bates and De Roo, 2000).

4.2.5 Channel specification

LISFLOOD-FP facilitates the specification of a uniform or non-uniform channel (Bates et al., 2005). Where a uniform parameterisation is chosen channel width, slope and value of Manning's *n* are assumed constant along the reach, although in a non-uniform channel representation one or more of these characteristics can be distributed. Both approaches have been implemented within past studies using LISFLOOD-FP, with choice depending upon the requirements of the individual modelling application. Uniform channel representations have been primarily used when LISFLOOD-FP has been applied over relatively large scales, usually within rural contexts (Horritt and Bates, 2001b, Wright et al., 2008). Distributed channel parameterisations have also been utilised within many flood inundation modelling studies, although by contrast this approach is generally used where reaches are shorter (McMillan and Brasington, 2007).

Initially a distributed channel representation was favoured here, in order to incorporate the full complexity of channel morphology through the 4km reach. However initial simulations illustrated that a distributed representation led to the proliferation of model instabilities in the region of a weir located within the centre of the model domain. These instabilities were attributed to a rapid change in bed elevation associated with the weir, leading to bed slopes exceeding the limit permitted by the kinematic approximation to channel flow (Woolhiser and Liggett, 1967). Attempts were made to resolve this through the implementation of weir linkages between cells, although this became problematic due to the high grid resolution. Consequently, a uniform channel specification appeared to be the most practical method to generate stable model simulations.

Where a uniform channel representation is implemented the model code requires the specification of the following information at the upper and lower nodes; X,Y coordinates, width, channel friction (Manning's *n*) and a value for bed elevation. Intervening nodes require only X,Y coordinates to be specified, with the other aspects of channel geometry generated through interpolation by the model code (Bates et al., 2005). In total 57 nodes have been specified for the ~4 km channel reach with an average spacing of 70 m. Channel width and bed elevation for the upper and lower nodes were extracted from cross sections of an Environment Agency ISIS model for the Don catchment, a technique also used in (Neelz et al., 2006).

4.2.6 Rainfall data

Precipitation data for the 2007 flood event can be obtained from two primary sources, rain gauges and rainfall radar. Rain gauges provide hourly or daily rainfall volumes at specific locations within a catchment, which are commonly utilised within rainfall-runoff modelling studies. Daily records are usually sufficient for rainfall estimation within large catchments, whilst hourly and sub-hourly records are more suitable for estimation of rainfall within smaller catchments. It is important to acknowledge the potential errors associated with rainfall data obtained from gauges, which can be attributed to the design and specific location of the gauge. Rain splash and wind effects are often problematic, particularly during high intensity rainfall.

Rainfall radar provides the other primary source of rainfall data, operating through sending electromagnetic pulses into the atmosphere at low angles and measuring returns, which are dependent upon rainfall intensity. Consequently, rainfall radar provides a much higher spatial and temporal distribution of rainfall intensity than gauge data. Rainfall radar data are subject to several limitations, primarily that rainfall intensity is measured at some distance above the ground. There may be substantial changes in rainfall at the ground surface due to strong winds or orographic effects. Further, radar data must be calibrated to account for the precipitation type, which generate different radar returns.

Within this study rainfall data was provided from the Met Office MIDAS dataset, which was acquired from the British Atmospheric Data Centre website (Met Office, 2006). The MIDAS dataset consists of a range of daily and hourly weather observations from 154 rainfall gauging stations across the UK. For this particular study daily rainfall records were taken from the Sheffield MIDAS station src id 525 (BNG Easting: 433930 Northing: 387280). This station is located approximately 5km south west of the study area and represents the closest active station, thus providing the an estimation of precipitation which is sufficient for this study. Appropriate calculations were subsequently made in order to convert the supplied daily rainfall totals into a uniform rate per model time step, thus facilitating an assessment of the contribution of direct rainfall to flood inundation observed within the model domain for June 2007.

4.3 Validation data

Traditionally calibration and validation data for hydraulic models were constituted by bulk flow measurements (Bates et al., 1998). Where internal state variables were measured, data were generally acquired for a limited number of points and thus showed only mixed success when compared to grid scale model predictions (Lane et al., 1999). Given the distributed outputs produced by contemporary flood inundation models such as LISFLOOD-FP, it is widely acknowledged that distributed data is required for adequate calibration and validation of these models (Bates, 2004). Data suitable for use in calibration and validation exists in many forms, although inundation extent has proved to be the most useful source of distributed data in terms of flood routing and forecasting, illustrating a greater level of utility than other measures such as water depth or flow velocity (Bates, 2004). Whilst inundation data are temporally zero dimensional, their two dimensional spatial format provides opportunity for distributed calibration and validation of distributed predictions across a large modelled reach (Bates, 2004). Additionally, inundation extent can usually be considered as a sensitive test of hydraulic models, this is due primarily to the potentially large errors in shoreline location associated with small errors in predicted water surface elevation, which proliferate as a result of relatively flat floodplain gradients.

Remotely sensed inundation extent data was first used for validation of a hydraulic model in Bates et al., (1997), who utilised Landsat images in order to validate predictions from a finite-element model for the Missouri River, USA. Since this initial study, observed flood inundation extent derived from several sources including synthetic aperture radar (SAR) and aerial photography have been used for calibration/validation of hydraulic models (Wright et al., 2008). SAR approaches ie Horritt et al., (2001) have been favoured due to their high resolution outputs (satellite SAR~ 12.5 m, airborne SAR~0.5 m). In addition, the flexibility afforded by day/night and all weather capability affords SAR a significant advantage over other sensors such as those operating at visible/infrared wavelengths which are prone to interference from cloud cover (Horritt, 2000).

Despite excellent general utility and widespread use within rural areas it is important to note that SAR imagery is not necessarily always the most reliable source of flood extent data (Bates, 2004). In some instances the water surface may be roughened by wind or rain, whilst increased backscatter may also be induced by emergent vegetation/buildings thus reducing the clarity of SAR images. Flood outlines are generally obtained from SAR images through automated processing techniques such as the statistical active contour (Horritt, 1999). Significantly, complex radar returns from buildings and other features often preclude the use of such automated techniques within urban areas (Neelz et al., 2006), whilst gaps between buildings are commonly smaller than image resolution (Neal et al., 2009a).

The practical limitations associated with the use of satellite and airborne SAR imagery, particularly within urban areas, means that aerial photography can provide another source of data from which flood inundation extent can be derived. Aerial photography is more adept for imaging of floods in urban areas, as unlike SAR, this imaging platform is not affected by issues such as complex and scattered radar returns. Accordingly, Neelz et al., (2006) utilised aerial imagery in an urban area where the use of SAR was considered inappropriate. In the aforementioned study multiple images were joined, orthorectified and georeferenced using ERDAS IMAGINE Orthobase, yielding a flood outline accurate to approximately 2-4 m horizontally. Yu and Lane (2006a) also used aerial imagery to manually delineate flood shorelines, using a supervised classification to divide the floodplain into functional units. Therefore aerial photography perhaps offers greater potential for derivation of flood inundation extent within urban areas.

Despite facilitating a stringent test of model predictions and constituting perhaps the most useful source of validation data, the utility of flood extent data is limited by its temporal availability, precluding validation of inundation dynamics (Bates et al., 2006). Any imagery provides a snapshot of flood extent, although this often does not correspond to the peak flood extent. This is particularly significant for models such as LISFLOOD-FP which require calibration in order to reproduce maximum flood extent, perhaps the most important feature of a flood event (Yu and Lane, 2006a). This shortcoming has lead to the development of further techniques which facilitate acquisition of data suitable for validation of flood inundation models.

Where suitable inundation extent is not available, other types of data can be used for calibration and validation of flood inundation models. This is exemplified by the use of water levels as a performance measure in Neal et al., (2009a). Indeed

Hunter et al., (2005a) state that water levels offer significant potential in reducing calibration parameter uncertainty. An obvious source of water level data is gauging stations which often provide continuous records of stage, however gauges are necessarily located on watercourses and hence are limited in spatial coverage (Neal et al., 2009a).

Werner et al., (2005a) used maximum flood levels measured on buildings as a performance measure in a GLUE framework. This study illustrated that distributed flood level measurements may facilitate reduction of uncertainty in calibration parameters where bias towards high friction values is generated as the floodplain basin becomes fully inundated, resulting in low sensitivity of inundation extent to channel/floodplain roughness. Furthermore, Mignot et al., (2006) used 99 flood marks to calibrate a two-dimensional shallow water model of Nimes, France for a large flood event in 1988. Consequently it is clear that wrack and water marks are able to provide a very useful source of calibration and validation data for flood inundation models, as unlike most aerial imagery, the maximum flood extent/depth is captured spatially. Therefore wrack and water marks are particularly useful when utilised as an independent dataset for validation.

Water level measurements as described above can be classified as post event data, in that they are acquired through surveys commissioned after the recession of the flood wave. This is advantageous as correct prediction of the flood is not required and it is unnecessary to be on-site during potentially hazardous peak flood conditions. However data of this kind is also associated with numerous limitations. Firstly, flood level measurements are one dimensional in time and hence cannot be used for validation of temporal dynamics (Bates et al., 2006). In addition, although the measurement of water/ wrack marks can be made to high levels of vertical accuracy (<1 cm), deciding the elevation appropriate for survey is associated with a much greater degree of uncertainty. It is commonly difficult to distinguish whether marks have been deposited at the maximum water level or as floodwaters recede. In the case of the latter water levels will be underestimated and vice versa (Neal et al., 2009a). Therefore the nature of these measurements means that it is extremely difficult to provide a true estimate of uncertainty, the magnitude of which tends to vary for different events, according to the conditions at peak levels of inundation in terms of wrack/water mark deposition and the skill of the surveyor (Neal et al., 2009a).

Additional sources of distributed calibration/validation data have been obtained through integration of remotely sensed SAR imagery and LiDAR data (Schumann et al., 2007a, Pappenberger et al., 2005, Mason et al., 2007), surveys of riparian residents (McMillan and Brasington, 2007) and application of microwave Doppler radar remote velocity measurement (Costa et al., 2000). Although these techniques offer utility in specific contemporary contexts, the aforementioned data sources are currently in the embryonic stage and their use has not been widespread. Therefore overall it is clear that inundation extent derived from remotely sensed imagery and post event water levels constitute the two main sources of calibration/validation data for contemporary hydraulic flood modelling studies.

4.3.1 Flood extent data

Flood extent data for the June 2007 floods in Sheffield was supplied by the Environment Agency in the form of a GIS ready shapefile (Figure 4.10), circumventing the need to undertake image processing as outlined previously within this chapter. This data was obtained by the EA Geomatics Group at 14:00 on the 26th June 2007, using a combination of oblique and vertical aerial photography which was fully orthorectified offering resolutions of approximately 37 megapixels (10-25 cm ground resolution) (Chick, 2010a). These images were subsequently utilised in combination with ArcGIS in order to draw flood outlines, which form the basis of the shapefile utilised within this study. In order to facilitate comparison with outputs from the LISFLOOD-FP model the flood extent data was subsequently converted into a binary grid of a commensurate size and resolution to the model grid, with flooded cells given a value of 1 and dry cells 0 (Figure 4.8 and 4.9).

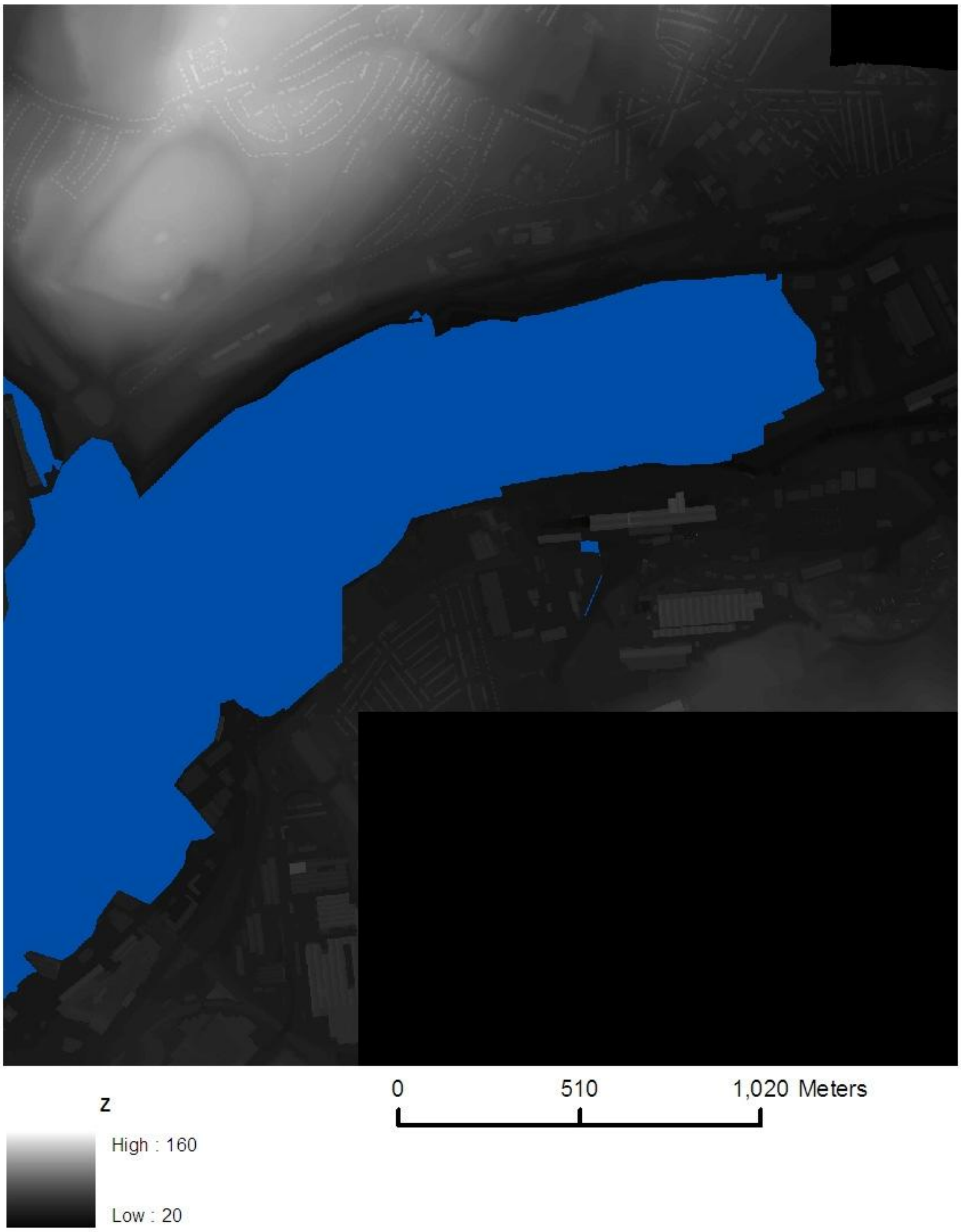


Figure 4.8 DEM of model domain overlain with the June 2007 flood extent captured through aerial imagery and delineated by the Environment Agency (blue)

As previously stated the pre-processed nature of this flood extent data is advantageous in that it precludes the need to undertake time consuming image analysis. However there are also numerous disadvantages to using pre processed data of this kind, within this particular study these uncertainties are twofold.

Firstly the supplied inundation extent data consists of a flood outline with the entire area bounded by this outline classified as inundated. Intuitively, the lack of spatial detail within the dataset implies that the entire surface of the area within the outline was flooded at the time of imagery. Despite the high magnitude of flooding observed within Sheffield in 2007 the relatively high elevation of features such as embankments mean that it is extremely unlikely that this area was completely inundated. The lack of spatial detail within the flood outline therefore constitutes a considerable source of potential uncertainty when comparing predicted and observed flood extent.

The second issue associated with the observed inundation extent data can be attributed to the location of the study area on the eastern margin of the metropolitan area of Sheffield. An additional shape file illustrating the extent of the urban area of Sheffield was included within the June 2007 floods dataset which was supplied by the Environment Agency (Figure 4.10). A simple visual comparison of the city boundary and the flood extent outline suggests that no overbank flooding was observed outside the extent of the urban area. It is extremely unlikely, given the magnitude and widespread impact of this particular flood event, that flooding occurred exclusively within the urban limits of Sheffield.

Although it is impossible to quantify this without the original aerial imagery, it seems more feasible that the Environment Agency exclusively delineated floods occurring within the city limits for this particular dataset. This is problematic here as the city boundary runs through the study area and consequently a significant portion of the domain lies outside the city limits. This could potentially lead to the propagation of large uncertainties and bias during implementation of model performance measures, as a scenario arises in which any flooding predicted by the model outside of the city boundary will be classed as over prediction.

In addition to the uncertainties highlighted above which are relatively unique to this study, there are two additional more generic sources of error associated with this data. The first can be attributed to the inherent subjectivity associated with delineation of shorelines which is undertaken manually for this dataset. Determination of the flood extent is carried out visually and thus determining whether an area is flooded is an individual decision (Chick, 2010a). The second major source of uncertainty stems from the timing of the collection of aerial

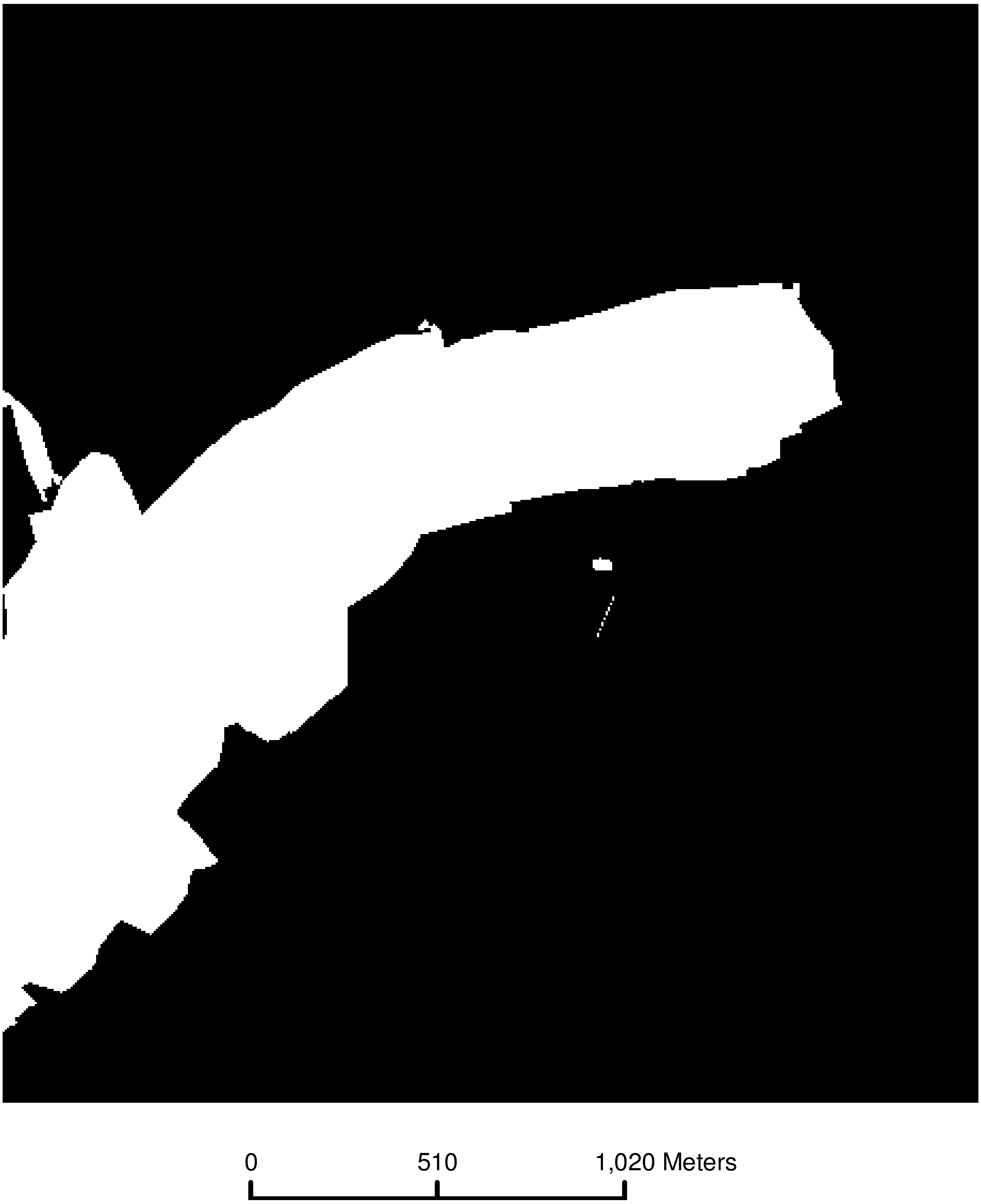


Figure 4.9 Flood outline supplied by the Environment Agency, converted into raster format and subsetted to the same extent as the model domain.

imagery, which took place on the falling limb of the hydrograph. Ideally flood extent is obtained at peak discharge as this is more likely to correspond with maximum flood extent. Capture of peak inundation extent occurs in some instances, often during well predicted or prolonged episodes of flooding with multiple discharge peaks which facilitate the mobilisation of aircraft required to collect aerial imagery (Wright et al., 2008). However the rapid onset of flooding, particularly in flashy catchments such as the Don, often means that flood extents are observed on the falling limb of the event where dewatering has begun to occur and floodwaters may have receded (Yu and Lane, 2006a). This has potentially significant consequences and should be considered during model validation.

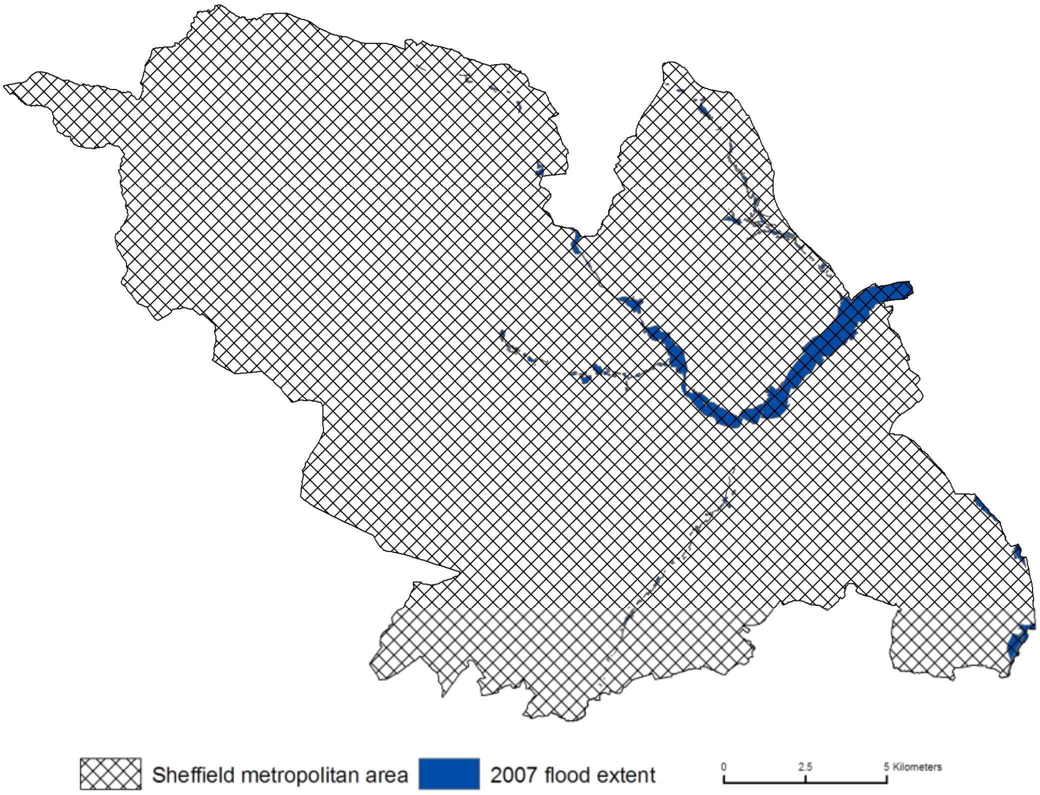


Figure 4.10 Full extent of the 2007 flood extent supplied by the Environment Agency including the Sheffield metropolitan boundary

4.3.2 Flood level data

Flood level measurements were also supplied by the Environment Agency, which provide a useful source of validation data that is independent from inundation extent. This dataset comprises water levels surveyed at 26 locations within the study area in the aftermath of the June 2007 flood event (Figure 4.11). The measurements were undertaken by surveyors contracted by the Environment Agency after water levels had receded to safe levels. As maximum flood levels could not be observed directly, wrack marks were used as the primary proxy measurements which were complemented by water marks located on the side of buildings (Chick, 2010a).

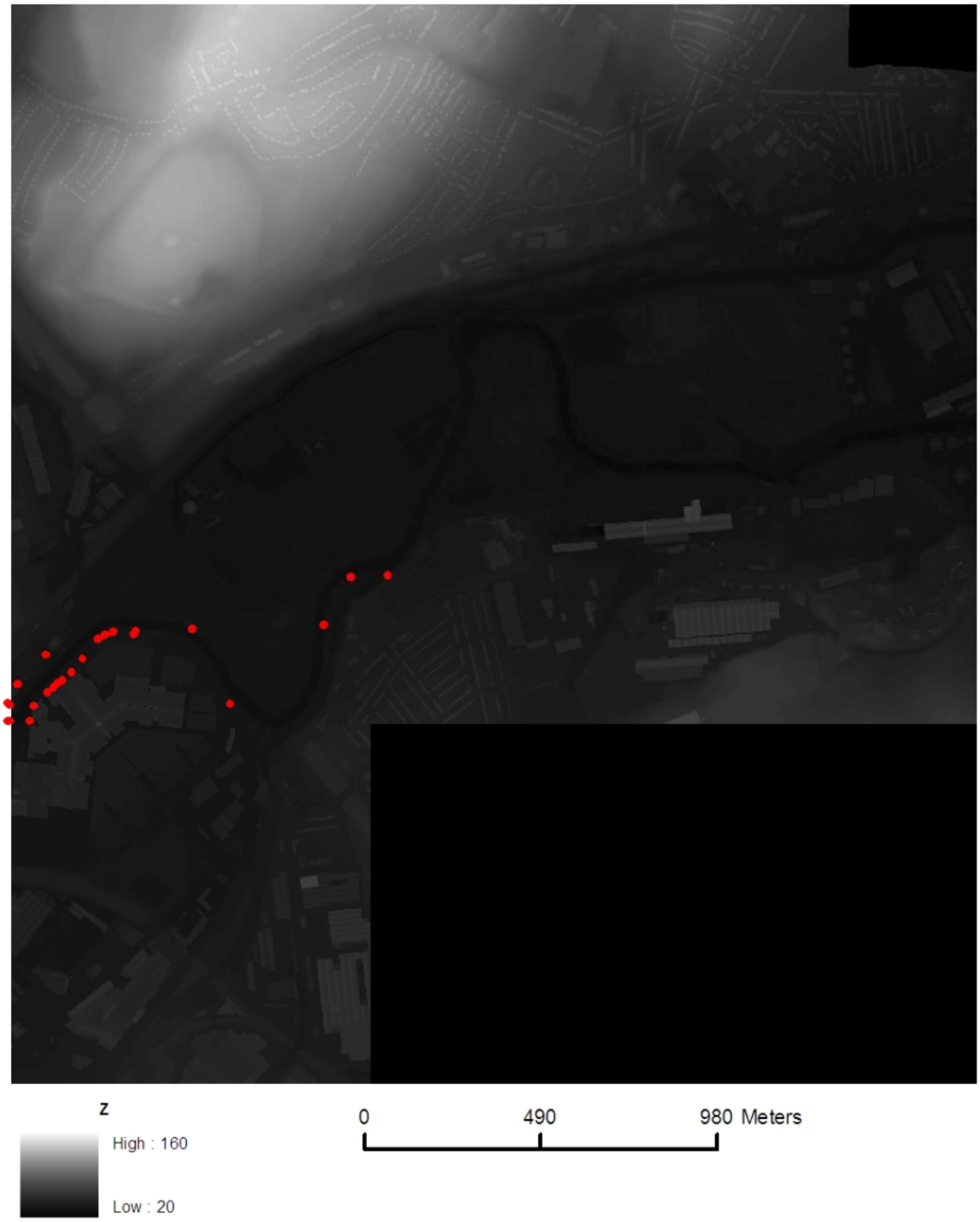


Figure 4.11 DEM of the model domain with overlain water level measurements (red points).

In order to maximise the accuracy of this survey a technique known as Network Real Time Kinematic (RTK) was utilised (Neelz et al., 2006). This method facilitates rapid topographical survey whilst benefitting from real time corrections from passing Global Navigation Satellite Systems (GNSS) satellites through the use of a GPRS enabled mobile phone. In terms of errors the Network RTK is associated with a vertical accuracy of approximately 50mm (Chick, 2010a). Where

RTK could not be employed a level and staff were used to determine the height of wrack marks, associated with standard errors.

Although the methods used to survey wrack marks were undoubtedly highly accurate and associated with minimal errors, it is important to note that ground based wrack marks are inherently uncertain (Neal et al., 2009a). Wrack marks are deposited by flood waters and are assumed to denote the maximum extent of the inundation front during a flood event. However this can rarely be verified and it is possible that wrack marks are deposited before/after maximum flood extent is reached, thus leading to the propagation of additional uncertainty (Chick, 2010b). Similarly when post event data consist of wet marks on buildings or walls capillary action within the brickwork can cause the water line to grade out. This can result in vertical errors of the order 50 mm, although this Figure can potentially increase with a larger lag time between retreat of the flood and survey (Chick, 2010b). Although these water levels are undoubtedly associated with a considerable level of uncertainty it is clear that they are invaluable as a source of independent validation data, especially given the issues identified with flood inundation extent data.

4.4 Summary

The LISFLOOD-FP model code has been applied to a ~4 km reach of the River Don on the east side of the metropolitan area of Sheffield. The model has been populated with the best available data from a range of sources, with the set up reflecting the specific aim of this study and previous implementations of the LISFLOOD-FP model. Crucially, inundation extent and water levels provide two independent sources of validation data for this model application which should facilitate a rigourous test of model performance. However it is important to consider the considerable uncertainties associated with these datasets.

Chapter Five

Model calibration and validation

5. Model calibration and validation

Model validation constitutes a precursor to a thorough investigation of the contribution of rainfall for the flood event which occurred within Sheffield on 25th-26th June 2007. Accordingly, the focus of this chapter is to establish the maximum performance of LISFLOOD-FP for the aforementioned event without including precipitation. This will subsequently allow the contribution of rainfall to be elucidated within subsequent chapters.

5.1 Calibration and validation in hydraulic flood inundation modelling

Calibration and validation constitute an integral stage within the application of a hydraulic model code to a specific river reach. Calibration is broadly thought of as the process by which model parameters are fitted to improve the correspondence between model predictions and observations, whilst validation is the process by which model predictions and observations are compared in order to assess the performance of the model (Hall et al., 2005). However it is important to state that these processes are not straightforward, indeed there are numerous different methodologies available which can be used to calibrate different model parameters, with the choice of calibration strategy dependent upon the model, purpose of application and availability of appropriate datasets. Calibration and validation of hydraulic models of river flooding is an inherently problematic process, with these issues being recognised in many studies (Aronica et al., 1998, Romanowicz et al., 1996, Hunter et al., 2007).

Historically, the calibration and validation of hydraulic flood inundation models has generally been undertaken with respect to stage and discharge levels obtained from networks of gauging stations (Bates et al, 1992). However bulk flow measures are unable to facilitate a rigorous assessment of the distributed outputs which these models often provide (Hunter et al., 2007). Advances in remote sensing have been integral to the development of the science of flood modelling, facilitating the production of high resolution DEMs which have been used to parameterise floodplain topography. The perceived increase in quality of distributed predictions which proliferated as a result of improved representation of floodplain topography thus demanded a commensurate increase in sources of data for validation.

Although the use of bulk flow data has continued (Bates et al., 1998), distributed validation datasets have been acquired through remote sensing techniques such as Synthetic Aperture Radar (SAR) (Horritt, 2000, Bates et al., 2006), aerial photography (Yu and Lane, 2006a) and LiDAR surveys (Lane et al, 2003). Whilst collection of post event water levels have also been utilised in several studies (Dutta et al, 2000; Romanowicz and Beven, 2003), along with water elevation measurements (Aronica et al., 1998). In some cases ‘soft’ data, for example observations of flood characteristics from local residents, have been utilised in model assessment frameworks (McMillan and Brasington, 2007).

However it is important to note that despite the range of validation data types utilised within recent flood modelling studies, availability of these datasets is often limited (Hunter et al., 2007). This is compounded by the complex nature of errors associated with different datasets and the model characteristics which they are able to test. Inundation extent was initially considered a highly sensitive test of distributed model performance as small changes in water depth lead to propagation of large variations in modelled shoreline due to low topographical gradients upon floodplains (Bates and De Roo, 2000). However subsequent studies have revealed that high flood magnitudes and/or topographical constraints on narrow floodplains may decrease the sensitivity of this test (Horritt and Bates, 2002). Limitations of other datasets include the limited spatial dimensionality of internal flow measurements and limited temporal dimensionality of discrete water level data (Hunter et al., 2007).

The aforementioned validation issues are clouded further by the errors associated with the capture of datasets. Observed inundation extent delineated from SAR can be prone to misclassification (Horritt et al., 2001), whilst aerial photos can be equally difficult to classify and may required time consuming and subjective manual processing (Chick, 2010a). The acquisition of this data is also problematic given the repeat overpass times of satellites and mobilisation times associated with airborne surveys (Bates, 2004). Water levels obtained through post event trash line surveys are also inherently uncertain due to a lack of knowledge of the conditions under which they were deposited (Neal et al., 2009a). In summation it is clear that the accuracy and availability of validation data are rarely optimal within studies of flood inundation.

The pre eminent issue arising from the aforementioned limitations associated with validation data is that a rigorous assessment of model performance may not be possible in all instances. This manifests in terms of the equifinality problem Beven (2001), whereby many different model parameter sets fit the available validation data equally well. This raises issues regarding whether the model is producing the right results for the right reasons Beven (1989), effectively constraining the ability of a modeller to draw firm conclusions in relation to flood dynamics. Further, multiple behavioural models may produce different results when used in predictive mode for future flood events, thus increasing uncertainty and decreasing the confidence which can be placed within these models and their predictions (Hunter et al., 2007).

5.2 LISFLOOD-FP calibration issues

LISFLOOD-FP is no exception to other hydraulic models and also requires calibration when applied to a given channel reach. As outlined in previous chapters LISFLOOD-FP is a model code which was originally designed in order to facilitate accurate reproduction of flood inundation extent using the simplest available process representation (Bates and De Roo, 2000). Horritt and Bates (2002) state that as a consequence of model design philosophy, LISFLOOD-FP is more dependent upon calibration than other full two dimensional codes such as TELEMAC-2D. Generally within applications of LISFLOOD-FP values of channel and floodplain friction are not well constrained and thus treating these model parameters as calibration coefficients allows the user to compensate for shortfalls in the model process representation (Horritt and Bates, 2001b). Adjustment of friction values in order to account for multiple processes enables an optimum level of fit to be achieved between predicted and observed flood inundation. This approach is often the only solution to roughness parameterisation in LISFLOOD-FP, although this process often constitutes a major source of error (Horritt and Bates, 2001b)

The reliance of the LISFLOOD-FP model upon calibration is well documented (Horritt and Bates, 2001a, Horritt and Bates, 2001b, Horritt and Bates, 2002). When calibrated with respect to inundation extent data the performance of LISFLOOD-FP has been observed to be equal or superior to other hydraulic models (Horritt and Bates, 2001b). Further, where appropriate calibration data is available flood inundation extent is often predicted to a level of accuracy comparable to the margins of error between actual flood extent and delineated aerial imagery (Hunter et al., 2005b). Where this is the case the model can be considered at the limit of its predictability (Horritt and Bates, 2001a). However in contrast, when applied without calibration with respect to inundation extent, the model is shown to dramatically under/over predict flood extent, in comparison to HEC-RAS and TELEMAC-2D which can adequately reproduce inundation extent from either discharge and inundated area data (Horritt and Bates, 2002). Therefore it is clear that calibration with respect to inundation extent, through optimisation of roughness parameters precludes an appropriate application of LISFLOOD-FP.

The concept of equifinality has meant that numerous studies have implemented a GLUE approach to model calibration (Aronica et al., 2002). This approach is utilised by Bates et al., (2004), who generated a wide range of feasible realisations of the model using Monte Carlo simulations. This calibration methodology led to the production of 500 randomly and uniformly selected combinations of channel and floodplain friction values, with behavioural simulations selected from the entire ensemble. The authors state that this approach is predicated on the notion that conceiving of inundation risk as a probability can be considered as a much more accurate and defensible representation of the problem of flood risk prediction. Calibration schemes utilising large numbers of simulations within a Monte Carlo framework have gained much credence within flood inundation modelling (Pappenberger et al., 2007a). This methodology is appropriate where a model is very efficient, thus allowing large numbers of simulations to be undertaken at a reasonable computational cost.

The other main approach to calibration of LISFLOOD-FP is utilised in Horritt and Bates (2001b), who take a more pragmatic approach based upon some prior knowledge of model response. Within this methodology an initial, relatively brief, search of the entire parameter space is followed by a more thorough investigation of the area around the optimum calibration, from which one optimum parameter set is selected. This constitutes a much more efficient approach to calibration and is ideal if model simulations are computationally intensive, precluding the implementation of a set of Monte Carlo simulations. Whilst offering distinct advantages in terms of efficiency this type of calibration methodology, which determines a single optimum parameter set, has been criticised by authors including Bates et al., (2004) who postulate that such deterministic predictions are likely to misrepresent uncertainties in the modelling process.

5.3 Calibration and validation methodology for this application

Accordingly calibration and validation will be undertaken here with respect to the flood event which occurred within Sheffield from 00:00 on 25th to 14:00 26th June 2007 (Figure 4.7). The model will be calibrated with respect to inundation extent acquired at 14:00 on the 26th June (Figure 4.8), which corresponds to the falling limb of the discharge hydrograph. In line with previous LISFLOOD-FP modelling studies, channel and floodplain friction parameters are unconstrained and hence are utilised within calibration. The relatively large high resolution grid utilised within this study means that model simulations are computationally intensive, thus precluding a Monte Carlo approach to model calibration and validation. Instead a pragmatic approach similar to that taken by Horritt and Bates (2001b) is favoured. Accordingly a brief initial search of the parameter space is undertaken in order to identify the region of the optimum, followed by a more intensive investigation of this region. Although a more thorough assessment of uncertainty would be desirable, the purpose of this calibration is to identify a parameter set which provides the best available fit with observed data, in order to ultimately assess the potential contribution of direct precipitation. Therefore given that the model will not be applied in order to provide formal predictions of flooding, the pragmatic approach can be considered more acceptable.

The extent of the parameter space is defined with channel and floodplain friction varying between 0.01 and 0.1. Definition of such a broad range ensures that the optimum is included within the broad envelope. The results illustrated within the previous chapter illustrate that within this model application sensitivity to channel friction is very high, whilst response to floodplain friction is minimal. The lack of sensitivity to floodplain friction illustrated in the previous chapter suggested that inclusion of this parameter within calibration would not be worthwhile. However given that a lower time step is utilised here (see below) there is a possibility that sensitivity to floodplain friction may increase as the flow limiter is invoked less.

This is reflected within this calibration strategy and accordingly the initial search of the parameter space is undertaken through varying the value of n_{ch} with regular increments of 0.02. After identification of the optimum region further simulations are undertaken, here n_{ch} is varied with uniform increments of 0.005. For each value of n_{ch} three simulations are run using n_{fp} values of 0.01, 0.05 and 0.1. These extreme values were chosen as it seemed unlikely that smaller variations in n_{fp} would be result in significant model response. The optimal model is subsequently validated with respect to flood level measurements provided by the Environment Agency which provide an independent dataset thus facilitating a more rigorous test of model performance.

5.4 Selection of model time step

The sensitivity analysis undertaken in the previous chapter revealed that it was not possible to employ the use of the adaptive time step solution within this application of LISFLOOD-FP. The optimum time step calculated by the ATS reduces quadratically with grid cell size Hunter et al., (2005b) and consequently becomes very low when working with fine grids such as the one used here. The ATS has been utilised within past LISFLOOD-FP applications in urban areas at fine grid scales (Fewtrell et al., 2008, Hunter et al., 2008), however it is important to note that the size of the model domain used within these studies was relatively small ~0.4 km^2 thus offsetting some of the increased computational cost. The overall research aim of this study necessitates the use of a comparatively large model grid (~ 2.8 km^2) at high resolution, thus rendering simulations utilising the adaptive time step impracticable.

Therefore it is clear that the specific requirements of this study necessitate the use of the fixed time step version of LISFLOOD-FP. This is not desirable as Hunter et al., (2006) illustrated that the fixed time step model is outperformed by the adaptive time step in terms of absolute performance, whilst also providing a more intuitive representation of floodplain wetting and drying. When applied with a fixed time step LISFLOOD-FP is commonly characterised by the influence of the flow limiter, and hence is unable to accurately represent inundation dynamics. However Hunter et al., (2006) illustrate that it is possible to calibrate the fixed time step model with respect to observed inundation extent in order to give an adequate level of performance (~6% lower than the ATS). Therefore given that within this model application the calibration will effectively be used as a benchmark in order to determine the potential contribution of direct rainfall, use of the fixed time step version of LISFLOOD-FP if not desirable, is acceptable. The main consequence of this is that the model is likely to offer a poor representation of inundation dynamics, thus limiting the scope of conclusions.

The issue of time step selection is problematic within LISFLOOD-FP. Hunter et al., (2005b) states that explicit numerical models are inherently unstable and reports that past applications of the fixed time step version of LISFLOOD-FP have required a process of trial and error in order to attain stable model solutions. However stability depends upon water depth, free surface gradients, Manning's *n* and grid cell size and thus optimal time step varies spatially and temporally within a simulation (Hunter et al., 2005b). Difficulty in defining appropriate time steps within early versions of LISFLOOD-FP led to the development of chequerboard oscillations where chosen time steps were too large. In response to this problem a flow limiter was included within LISFLOOD-FP in order to maintain the stability of simulations, although at the cost of increased sensitivity to model parameters particularly resolution and time step (Hunter et al., 2006). Given the problematic nature of time step selection the lowest feasible time step was chosen for use within this study in order to attempt to minimise the influence of the flow limiter.

When selecting a feasible time step for use within this calibration it was necessary to consider the testing of direct precipitation later in this study. In order to isolate the contribution of rainfall to modelled inundation and determine the potential significance of this parameter, it is required that model set up (including time step) remains constant. It is well known that simulation times within LISFLOOD-FP are a function of the number of wet cells within the domain (Hunter et al., 2005b), thus where precipitation is included the increase in numbers of wet grid cells are likely to lead to substantially longer model run times. Accordingly, a series of model tests suggested that a time step of 0.1 s represented the smallest feasible time step within this study in order to retain an acceptable level of computational efficiency.

5.5 Accuracy assessment measures

A standard measure of fit is given by (Bates and De Roo, 2000, Horritt and Bates, 2001a, Aronica et al., 2002, Horritt and Bates, 2002, Cobby et al., 2003, Bates et al., 2004)

$$F = \frac{\mathrm{Num}(\mathrm{S}_{\mathrm{mod}} \cap \mathrm{S}_{\mathrm{obs}})}{\mathrm{Num}(\mathrm{S}_{\mathrm{mod}} \cup \mathrm{S}_{\mathrm{obs}})}$$

Within this measure S_{mod} and S_{obs} are the sets of cells/pixels classified as wet by the model and satellite observations, respectively, and Num gives the number of members of the set (Bates and De Roo, 2000). *F* represents the area correctly predicted as wet by the model as a fraction of the area observed to be wet where *F*=1 (100%) perfect fit to *F*=0 if no part of the domain is correctly classified by the model. This statistic penalises under and over prediction of flood extent and allows meaningful comparison of the model performance for models of different reaches(Bates and De Roo, 2000). Importantly this performance measure avoids the biases associated with fit statistics which calculate the number of correctly classified wet/dry pixels as a percentage of total cells within the domain (Horritt and Bates, 2001b).

Model validation will be undertaken through comparison of modelled and observed water levels at 26 locations within the domain for the event which occurred on the 25th-26th June 2007. The observed water levels are thought to correspond to the maximum depth of inundation through the course of the flood event (Chick, 2010a). Accordingly, validation consists of comparisons between observed flood levels and the maximum modelled water level extracted from the inundation time series at each location. The differences between observed and predicted levels are subsequently averaged for each model simulation (Neal et al., 2009a).

5.6 Calibration results

5.6.1 Initial search of the parameter space

The initial model simulations, illustrated in Table 5.1, revealed that the optimum region of performance was located at the upper end of the parameter space between n_{ch} = 0.08-0.1. The significant increases in the fit statistic, particularly for n_{ch} values between 0.02 and 0.08, illustrate a very steep gradient within the parameter space which is indicative of a high level of sensitivity to channel roughness specification. Overall, the absolute values of the performance statistic can be considered to be relatively low, indeed Table 6.1 illustrates that the optimum region of the parameter space yields a maximum fit between predicted and observed inundation of 0.50.

Given that optimum performance was located at the upper limit of the parameter space, this suggested that expansion of the range of channel roughness could be worthwhile. However given that the channel roughness envelope is already wider than that used within other studies, in addition to the potential uncertainties associated with the validation data it was decided to proceed with a more intensive search of the parameter space between n_{ch} 0.08 and 0.1.

n_{ch}	n_{fp}	*F*
0.02	0.05	0.06
0.04	0.05	0.09
0.06	0.05	0.28
0.08	0.05	0.45
0.1	0.05	0.50

Table 5.1 Table illustrating results of the initial search of the parameter space, given in terms of the performance statistic *F.*

5.6.2 Intensive investigation of the optimum parameter space

Table 5.2 illustrates the results associated with the more intensive investigation of the optimum region of the parameter space. The model shows a progressive and steady increase in *F* towards the upper end of the range of n_{ch} values. Overall the maximum value of the performance statistic *F* was 0.50, which was observed for simulations where n_{ch}=0.1 and n_{fp}=0.01, 0.05, 0.1, thus suggesting that these simulations represent the optimum parameter set for the observed flood extent. Significantly, the maximum model performance illustrated here can be considered relatively low, as the performance statistics indicate that the model is only correctly predicting 50% of the observed inundated areas correctly. This level of performance is lower than past LISFLOOD-FP applications Table 5.5. In addition, it is clear from Table 5.2 that the model exhibits a negligible response to floodplain friction specification, with perturbation over the complete range of n_{fp} (0.01-0.1) associated with each value of n_{ch} resulting in a maximum variation of 0.01 in the performance statistic *F.*

n_{ch}	n_{fp}		
	0.01	0.05	0.1
0.08	0.45	0.45	0.45
0.085	0.46	0.46	0.46
0.9	0.48	0.48	0.47
0.095	0.49	0.49	0.49
0.1	0.50	0.50	0.50

Table 5.2 Results of calibration for the optimum area of the parameter space, presented in terms of performance statistic *F*

5.7 Discussion

5.7.1 Uncertainties in inundation extent data

In light of the relatively low values of *F* obtained within this calibration it is necessary to elucidate the factors responsible for this sub-par model performance. Visual analysis of Figure 5.1, which illustrates predicted inundation extent overlain upon the observed data, reveals the presence of several areas in which the model consistently under predicts flooding. The most striking of these areas is characterised by several topographically isolated basins towards the east of the floodplain. The observed flood extent delineates this entire area as inundated during the June 2007 flood event, however several analyses provide significant evidence which strongly suggests that inundation of this area by overbank flows would be highly unlikely, even in light of the magnitude of the flooding which occurred in 2007.

A more in depth analysis of the topography of the aforementioned region, illustrated in Figure 5.2 reveals the presence of large bounding embankments in the region of under prediction. The elevation of these embankments is ~32-33m, which would preclude inundation even during very extreme overbank flows. This assertion is supported by the post event flood level data corresponding to this event which suggests that maximum water levels were less than the height of the embankments. This is particularly significant given that water level measurements correspond to locations upstream of the weir located within the centre of the study area (Figure 4.11). The weir is associated with a significant drop in the level of the river channel and thus maximum flood levels would be expected to be even lower in the region of the floodplain basins.

Field observations revealed that perennial water bodies are located within these topographical basins even during times of no flooding, given this evidence it is hypothesised that these areas have almost certainly been misclassified during delineation of flood extent from aerial imagery. This alludes to a considerable level of uncertainty within the observed inundation extent which, given the relatively large spatial extent of these areas in relation to the total flooded area, is clearly one major contributor to the relatively poor performance of the model. Further visual analysis of the topography of the study area illustrates the presence of further areas of high elevation which are similarly unlikely to have been inundated

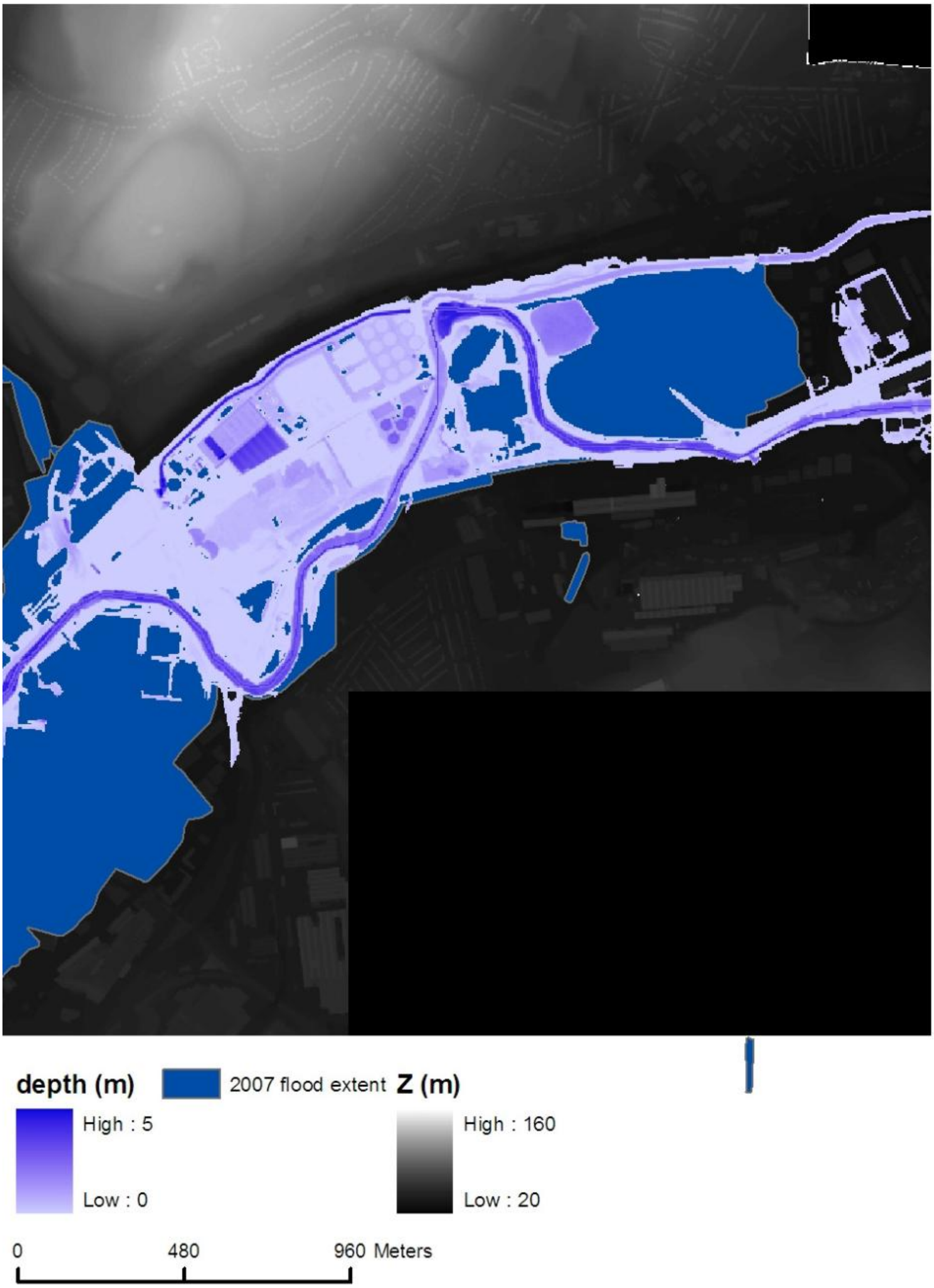


Figure 5.1 Observed flood extent for the 2007 flood event overlain with predicted inundation extent from the optimum parameter set.

during the 2007 flood event. This further highlights the potential issues associated with undertaking model validation with respect to observed flood extent which is constituted by an indiscriminately filled in flood outline with no internal spatial detail.

Further visual analysis of Figure 5.1 reveals the presence of additional areas which are associated with consistent over prediction by the model and are located towards the eastern limit of the domain. This is constituted by within bank flow, in addition to overbank flow occurring along a street and around buildings to the north and south of the river channel. It is hypothesised that poor performance within these areas can also be attributed to additional uncertainties associated with the validation data. Holistic comparison of the observed inundation extent for the 2007 flood event and the Sheffield metropolitan boundary (Figure 4.10) reveal that no areas are identified as flooded outside the city limits within this dataset. It is known that this was not the case during the 2007 events, with further flooding occurring downstream in areas such as Doncaster.

Therefore it is thought that the flood extent featured in this data set is limited to inundation observed within the geographically defined limits of the city. This claim is strongly supported by the fact that the river channel is delineated as dry within the observed data, this seems particularly surprising given that discharges were still well above baseline levels at this point in the hydrograph. This introduces further uncertainty here as the Sheffield metropolitan boundary intersects the study area, consequently a significant proportion of the model domain lies outside the city limits. Therefore it is hypothesised that any cells predicted as wet by the model which fall outside the city limits are automatically considered incorrect when implementing performance measures, potentially leading to undue penalisation of the model.

This issue was addressed relatively easily through application of a simple mask to the model outputs prior to the implementation of performance measures. More specifically, when applied this mask effectively removed any flooded areas from model predictions which fell outside the city limits. Therefore application of this mask effectively reduces uncertainty and precludes undue penalisation of the model highlighted above. The model performance after application of the mask is illustrated within Table 5.3. Clearly the results show a modest increase in *F*, with the optimum calibration increasing from 0.50 to 0.56 where the mask is applied.

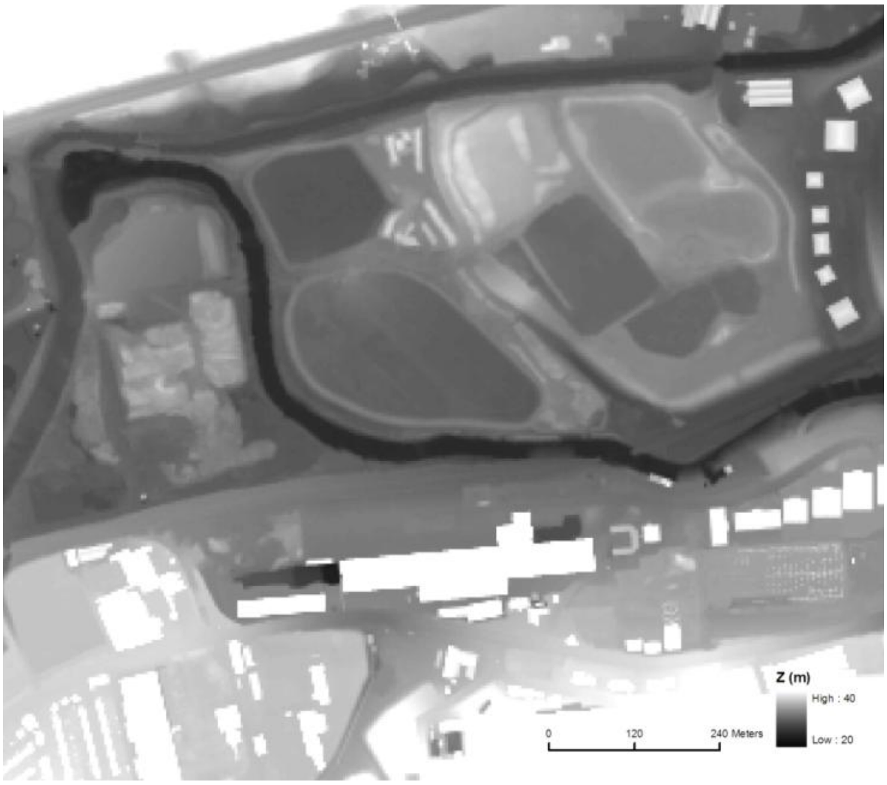


Figure 5.2 Topography of the eastern region of the flood plain illustrating basins bounded by areas of high elevation which are thought to be misclassified in observed data.

5.7.2 Lack of model parameterisation

The other primary region of systematic under prediction by the model is located to the south of the large structure (Meadowhall shopping centre), which is located within the south west of the domain (Figure 5.1). Despite being delineated as inundated within the observed data, no flood waters were observed within this region of the model domain for the complete range of calibration simulations. The lack of inundation in this particular area is unsurprising for these simulations as the large building which lies between the area of under prediction and the river would act as a blockage to flow. This is particularly prevalent here due to the proximity to the edge of the domain which effectively prevents flood water reaching this location (Figure 4.1).

A subsequent analysis of the location of the model domain within the holistic context of the Sheffield flood event provides a clear explanation for the observed under prediction. The areal extent of the observed flooded area extends beyond the western limit of the model domain (Figure 5.1 and 4.10). Considering the location of the domain, the course of the river upstream of the study area and the orientation of the flooded area, it appears that the study area is likely to have received considerable contributions of water from overbank flows occurring upstream during the flood event. Given the location of the region of under prediction in question it seems clear that this area would have received considerable contributions from upstream overbank flows. However this is an effect which has not been encountered within previous applications of LISFLOOD-FP and thus cannot be easily parameterised here.

n_{ch}	n_{fp}		
	0.01	0.05	0.1
0.08	0.48	0.48	0.48
0.085	0.50	0.50	0.50
0.9	0.52	0.52	0.51
0.095	0.54	0.54	0.54
0.1	0.56	0.56	0.56

Table 5.3. Results of calibration for the optimum region of the parameter space given in terms of performance statistic *F*, but corrected in order to discount flooding outside the city boundary

5.7.3 Channel representation

The aforementioned issues of validation data uncertainty and lack of model parameterisation can be attributed as a factor in the relatively poor levels of fit between predicted and observed inundation within Table 5.3. However an inappropriate representation of the river channel flow is perhaps the largest contributor to poor model performance within this calibration exercise. LISFLOOD-FP Version 2.7.5 utilises a kinematic wave representation of channel flow, which considers only down gradient hydraulic characteristics and is prone to development of shockwaves in areas of flow convergence (Bates and De Roo, 2000).

The development of instabilities during model testing using the kinematic wave precluded the use of a distributed channel representation, necessitating the use of a highly simplified, uniform channel. It is thought that the averaging of bed slope and channel width increased conveyance through the study reach, limiting the exchange of water with the floodplain. This manifests in terms of poor performance the excessively high optimum values of n_{ch} shown within Table 5.2, which fall outside the range of channel roughness commonly used within flood inundation models. Later versions of LISFLOOD-FP incorporate a diffusive channel solver (Trigg et al., 2009) which provides a more stable and realistic channel representation than the kinematic wave approximation. The implementation of the diffusive wave would be beneficial within this study, removing the need to oversimplify the channel representation and leading to a more realistic representation of flood hydraulics.

5.7.4 Conclusions

Overall, outputs from the accuracy assessment measures illustrated within Table 5.2, suggest that the model performs relatively poorly for the flood event which occurred within Sheffield on the 25th-26th June 2007. Initial maximum model performance of F=0.50 falls considerably below the level for an acceptable simulation F=0.65 (Hunter et al., 2006) and other applications of the LISFLOOD-FP model (Table 5.5). Subsequent investigation has revealed that a significant level of the poor model performance can be attributed to inappropriate application of the kinematic wave approximation, which necessitated an oversimplified representation of the river channel. This has caused the model to be non-behavioural, at the upper end of the parameter space.

Further, significant uncertainties have been identified within the observed flood inundation extent data, making formal assessment of model performance through performance measures very difficult. In addition it has been shown that further model under prediction can be attributed to a lack of parameterisation of overbank flows from upstream. One element of uncertainty in the validation data has been minimised, through the application of a simple mask, which propagated a significant increase in performance F=0.56. However other uncertainties are more difficult to address and remain untreated here.

5.8 Model validation

5.8.1 Validation methodology

Subsequently the model has been validated with respect to a series of 26 water levels which are located predominantly within the upper reach of river, in close proximity to the main channel (Figure 4.11). When utilising this data it is important to consider the inherent degree of uncertainty associated with post event surveys.

This is particularly prevalent here considering loss of topographical detail experienced when the model grid is resampled to coarser resolution, with any changes in topography as a result of aggregation likely to influence water level at specific locations. Nevertheless this dataset presents a source of independent validation data and therefore facilitates a more rigorous test of model performance (Hunter et al., 2007). The differences between predicted and observed water levels were subsequently averaged for each simulation and are illustrated within Table 5.4.

n_{ch}	n_{fp}		
	0.01	0.05	0.1
0.08	0.59	0.60	0.61
0.085	0.76	0.76	0.77
0.9	0.95	0.94	0.94
0.095	1.12	1.12	1.12
0.1	1.30	1.30	1.30

Table 5.4 Results of validation against water level data, value expressed as mean difference between observed and maximum predicted water depth for 26 locations within the domain (m).

5.8.2 Validation results

Table 5.4 illustrates that the model consistently and significantly over predicts water depths within the domain when calibrated with respect to inundation extent. The results show that at the lower limit of the optimum parameter space the model, on average, over predicts maximum flood levels by approximately 0.60 m. The magnitude of this over prediction increases gradually as the value of channel roughness increases, illustrating a maximum average error of 1.30 m for the optimum parameter set. Therefore it is clear that the model exhibits a high level of sensitivity to n_{ch} with respect to water depth, whilst displaying almost no response to variations in floodplain roughness. This manifests in terms of a steady increase in over prediction of depth when moving towards the upper end of the parameter space.

5.8.3 Discussion

On a basic level the results of validation with respect to water levels reveals the poor dynamic performance of the LISFLOOD-FP within this application, despite the conclusions of the calibration exercise which suggest that the model is performing acceptably in relation to inundation extent. Model behaviour elucidated through comparison to water levels indicates that the progressively higher values of *F* observed towards the top end of the parameter space within calibration were effectively achieved through forcing excessive increases in the height of the free surface (through increases in n_{ch}) in order to generate more extensive inundation. On a basic level this indicates the proliferation of equifinality (Beven, 2001), strongly suggesting that the model is achieving acceptable performance in terms of predicting inundation extent for the wrong reasons.

The model behaviour observed within this study can be compared directly to that reported in Hunter et al., (2006) and appears to be somewhat typical for a fixed time step implementation of LISFLOOD-FP. Here a large flood event of sufficient magnitude to fill the valley bottom results in shorelines being located upon relatively steep slopes. Where this is the case inundation extent becomes a relatively insensitive measure of model performance (Hunter et al., 2007). Therefore progressively higher n_{ch} values result in relatively small increases in the areal extent of inundation at the expense of large increases in water level. This effect is likely to be accentuated in this specific case due to the topographical complexity observed within urban environments (Yu and Lane, 2006a).

However, within this specific model application a number of factors appear to further complicate assessment of model performance. It is pre-eminently important to consider that within this study the model was calibrated with respect to aerial imagery acquired at 14:00 on the 26th June, which corresponds to the falling limb of the hydrograph. Fixed time step implementations are known to offer poor representations of inundation dynamics, particularly wetting and drying of the floodplain (Hunter et al., 2005b). Therefore the poor dynamic performance of fixed time step implementations of LISFLOOD-FP makes calibration particularly problematic when inundation data do not correspond to peak inundation extent.

Whilst it is clear that a more accurate representation of flood dynamics is desirable within flood inundation modelling studies, this is most important when applying the calibrated model to different flood events. This is particularly important when these events may be of a lower magnitude and hence may not fill the valley. In such applications the poor dynamic performance of the model could potentially be highly problematic, as correct timing of the diffusion of the flood wave becomes critical (Yu and Lane, 2006a).

Reach name (and length)	Validation data	Maximum LISFLOOD-FP performance (*F*)	Number of calibration simulations
Meuse (35 km)	Inundation extent from aerial imagery and SAR, point hydrometry	82 %	1
Thames (3 km)	Inundation extent from aerial imagery and SAR,	84 %	25
Severn (60 km)	Inundation extent from SAR, point hydrometry	73 %	500
Imera (15 km)	Ground surveyed flood extent	85 %	500
Don (4km)	Inundation extent from aerial imagery, post event water levels	50 %	20
Don (4km)	Inundation extent from aerial imagery, post event water levels (corrected for uncertainty)	56 %	20

Table 5.5 Comparison of *F* values calculated for different applications of LISFLOOD-FP, adapted from (Bates et al., 2005)

Within this particular model application calibration is undertaken primarily in order to produce a baseline simulation in order to facilitate elucidation of the potential contribution of direct precipitation to inundation within the domain. Therefore the reasonable performance offered by the model in terms of replicating synoptic inundation extent should be sufficient within the specific context of this study. Whilst the poor dynamic performance is clearly not desirable, it can be considered acceptable and somewhat inevitable given the overall aims of this study which demand the use of a large high resolution grid, which effectively precludes use of the adaptive time step solution. However it is critical to consider the uncertainties and poor representation of flood dynamics highlighted within this model validation exercise, which will impart strict limitations upon the scope of conclusions regarding the potential contribution of direct rainfall later in this study.

5.9 Summary

Although optimum model performance attained here does not meet the F value of 0.65, reported by Hunter et al., (2006) as the minimum for an acceptable simulation, the poor levels of fit between predicted and observed flooding can be partially attributed to the significant uncertainty associated with the observed inundation extent data.

The relatively low values of *F* are also partially attributable to a lack of parameterisation of key sources of overbank flooding, namely flood waters flowing into the region of the model domain from upstream floodplains. This is a function of the specific location of the model domain in relation to overall flood extent within the city of Sheffield for this event and has not been documented in previous applications of LISFLOOD-FP.

Given the above shortcomings in both the validation data and acknowledged lack of model parameterisation, it can be tentatively suggested that model performance for the optimum parameter set (n_{ch}=0.1, n_{fp}=0.05) is as good as realistically can be expected and is acceptable when considered purely in terms of synoptic inundation extent.

However model validation has highlighted that a significant over prediction of maximum depth is required (through forcing of high channel roughness values) in order to produce an acceptable representation of inundation extent at the time of aerial imagery on the falling limb of the hydrograph. Hence it appears that the morphology of the floodplain and uncertainty in inundation extent data effectively masks a poor representation of flood dynamics associated with the fixed time step implementation of LISFLOOD-FP. This is inevitable given the influence of the flow limiter, which is indicated through the lack of sensitivity to floodplain friction and rapid diffusion of the flood wave. This validation exercise thus provides a further indication of the value of independent data for model assessment (Hunter et al., 2007) and elucidation of equifinality (Beven, 2001).

Chapter Six

Development and testing of a representation of rainfall within LISFLOOD-FP

6. Development and testing of a representation of rainfall within LISFLOOD-FP

6.1 Introduction

Development of an appropriate representation of direct rainfall into the LISFLOOD-FP model domain is of preeminent importance in fulfilling the primary research aim within this study. An initial investigation into the structure and parameters included within LISFLOOD-FP (Bates et al., 2005), suggested that the infiltration term offered promise, facilitating removal of a spatially and temporally uniform volume of water from each grid cell through the course of a simulation. Intuitively, a negative manipulation of this parameter could potentially facilitate addition of a spatially and temporally uniform volume of water to each cell, thus facilitating a basic representation of precipitation without the need for recoding and recompiling of the model source code which was not possible here.

An updated version of the LISFLOOD-FP model code received shortly before testing commenced included evaporation as a new parameter. Evaporation was included within LISFLOOD-FP in order to facilitate a more appropriate representation of flood inundation in tropical rainforest environments (Wilson et al., 2007). This parameter is of a similar nature to infiltration, representing a spatially uniform loss of water from grid cells through the course of the model simulation (Bates et al., 2005). However in contrast to infiltration, LISFLOOD-FP facilitates a time varying specification of evaporation which is temporally interpolated. This suggests that a negative manipulation of this model parameter, in a similar manner to infiltration, could facilitate incorporation of temporally variable rates of precipitation within LISFLOOD-FP.

An alternative method for representing rainfall was offered by specifying a series of point based sources of water within the model domain. The LISFLOOD-FP .bci file allows the specification of non-channel boundary conditions, including time-varying point based additions of water which could be manipulated in order to represent precipitation. Point based additions of water through the .bci file are difficult to initialise, however, requiring specification of density and spatial distribution of inputs and further calculations in order to ensure correct rates/ volumes of rainfall input. Consequently, a negative manipulation of infiltration/ evaporation was chosen as the most appropriate method of rainfall representation.

This chapter provides a thorough investigation into the use of negative manipulation of the infiltration/evaporation terms to parameterise precipitation within LISFLOOD-FP. Initially the most appropriate basic approach to representing rainfall through use of the infiltration and evaporation terms is established. This is followed by a series of tests which examine model response to perturbations of a range of model input factors in the context of providing a meaningful and intuitive representation of precipitation. The findings of this chapter are subsequently synthesised in order to test the potential contribution of direct precipitation to a real flood event within the following chapter.

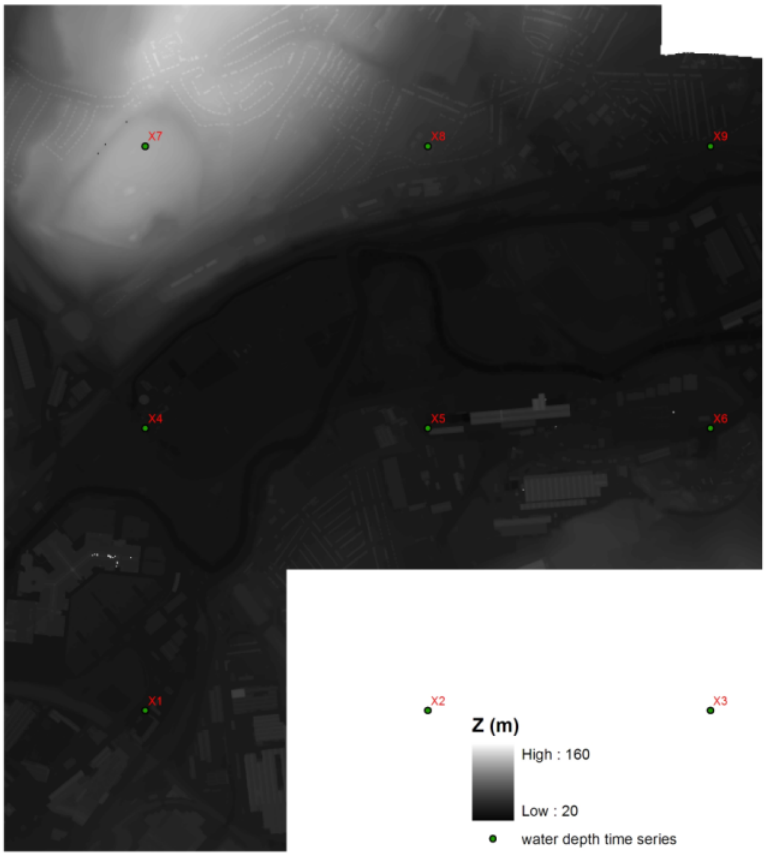


Figure 6.1 Model domain illustrating locations of water depth time series extraction for simulations 1-4

6.2 Developing an appropriate representation of rainfall

Here, a logical progression in the representation of precipitation is developed based upon analysis of four primary model simulations detailed in Table 6.1. These simulations are characterised by steady inflow discharge which is less than bankfull, precluding overbank flood inundation, ensuring that any inundation observed upon the floodplain can be attributed to input from negative manipulation of infiltration. The model simulations detailed here were designed exclusively to test the viability of the rainfall representation, therefore an arbitrary total rainfall input of 50 mm over the course of the simulation. Analysis of results is based upon visual representations of inundation characteristics along with a number of water depth time series sampled at regularly spaced discrete points across the model domain (Figure 6.1) and mass balance outputs and are summarised in Table 6.1.

Simulation number	Parameter	Initial depth mask	Initial depth (mm)	Rainfall rate (mm/day)	Simulation time (minutes)
1	Infiltration	None	5	45	406
2	Infiltration	Spatially uniform	5	45	1315
3	Infiltration	Corrected	5	45	674
4	Evaporation	Corrected	5	45	680

Table 6.1 Summary of simulations undertaken within process of deriving an appropriate representation of precipitation in 6.2

6.2.1 Simple negative manipulation of the infiltration term

Figure 6.2 provides a visualisation of the inundation extent observed when a simple negative manipulation of the infiltration term was used in order to provide a representation of precipitation in simulation one. The observed distribution of flood inundation, which is essentially confined to within bank flow, is somewhat surprising given that a spatially and temporally uniform rate of precipitation which was imposed. Further, Figure 6. Illustrates the volume of water within the model domain through simulation1, taken from LISFLOOD-FP mass balance file. This graph illustrates an initial decline in water volume, after which a steady state volume is reached. Theoretically the imposed negative infiltration value should be associated with an addition of 50 mm of rainfall over the whole 24 hour model simulation. Under such rainfall conditions some evidence of water flow outside the limits of the channel within Figure 6.2 along with an increase in volume within Figure 6.2.1 would be expected.

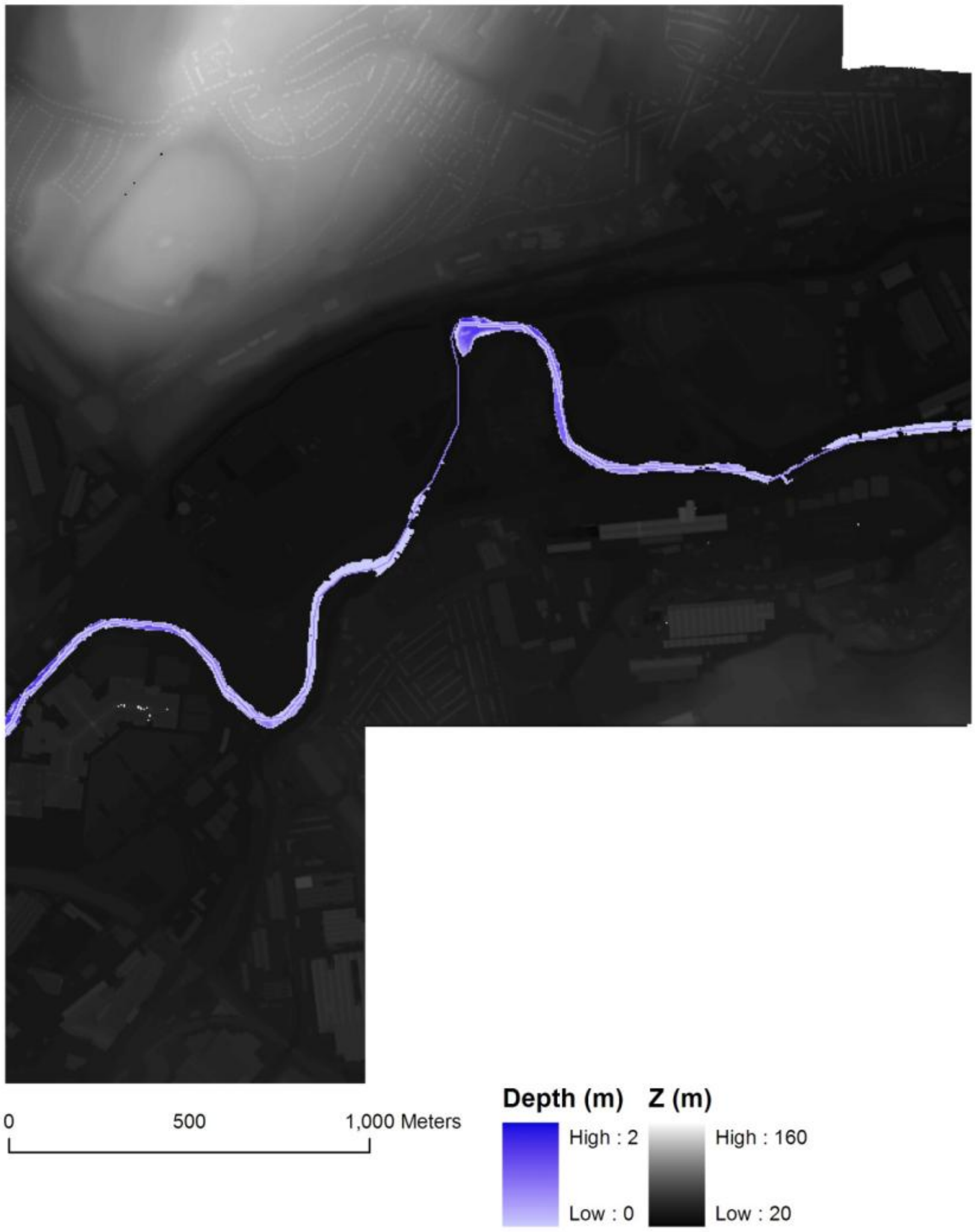


Figure 6.2 DEM of the model domain, overlain is the inundation extent observed 80000 seconds (~22 hours) into simulation 1. It is clear from this image that the presence of water within the domain is confined to the channel.

Figures 6.2 and 6.2.1 therefore highlight a fundamental flaw when using a simple negative manipulation of the infiltration term to represent rainfall within the model domain. This flaw can be attributed to the assumption within the model code which governs that the process of infiltration is only able to occur where a grid cell is already wet. Whilst this is intuitively correct for infiltration, this assumption imposed a strict limitation upon the use of the infiltration term to represent rainfall, as effectively water can only be added to cells which are already wet. Given that a large proportion of the model domain is unlikely to be affected by fluvial flood inundation throughout the model simulations, the volume of water which could potentially be supplied to the domain through direct rainfall would potentially be significantly underestimated using this approach. Therefore it was necessary to seek an alternative method of representing direct rainfall within this study.

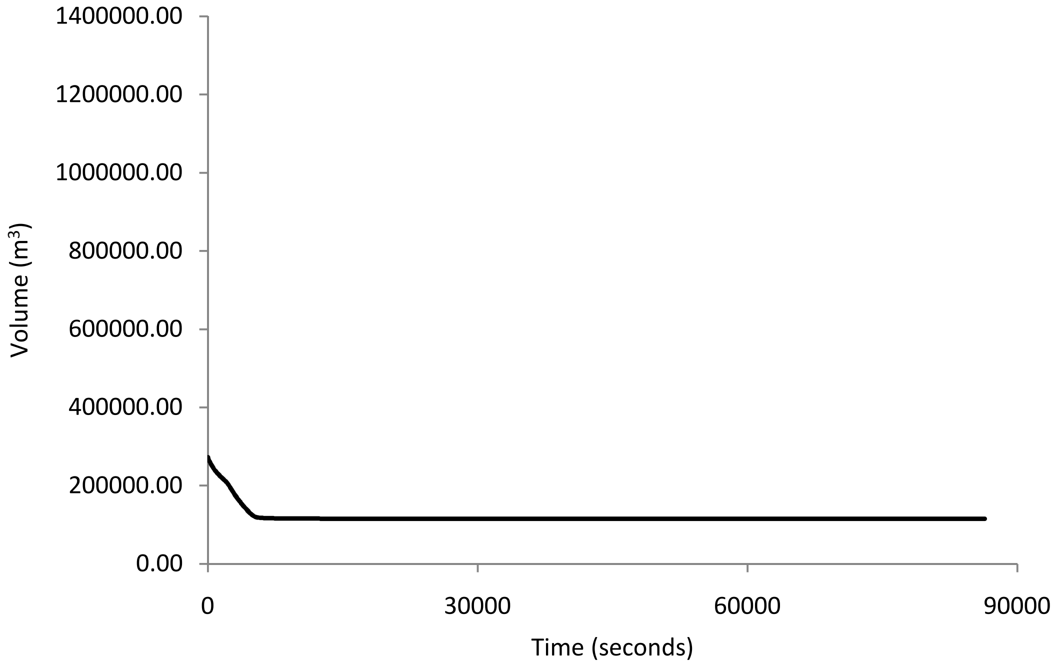


Figure 6.2.1 Volume of water within the model domain through the course of simulation 1, taken from LISFLOOD-FP mass balance file.

6.2.2 Negative infiltration with an initial water depth mask

In response to the fundamental limitations of using a simple negative manipulation of the infiltration term identified in 6.2.1, an initial depth mask was used within simulation two in order to facilitate an improved representation of precipitation. The use of an initial depth mask is predicated upon the rationale that the imposition of a shallow water depth across the entire domain at the outset of a simulation facilitates negative infiltration as all cells are effectively considered to be wet by the model code.

Subsequently the initial depth was imposed here through utilisation of the .start file within LISFLOOD-FP. The .start is a file of a commensurate size and resolution to the model grid which facilitates specification of water depths at the onset of the simulation. This file was originally included in the LISFLOOD-FP model in order to allow previous results files to be utilised as initial conditions for model simulations, thus making the .start file ideal for use within an improvised representation of rainfall.

Accordingly, a spatially uniform mask (10 mm initial depth) was generated and utilised within simulation two, which was characterised by a parameterisation otherwise identical to that used in 6.2.1. Figure 6.3 provides a visual illustration of the inundation characteristics observed 80000 seconds (~22h hours) into the simulation. This Figure clearly illustrates a much greater inundation extent than that observed for simulation 1. Large areas are characterised by very shallow water depths whilst there also appears to be some relatively localised pooling of water. Therefore Figure 6.3 suggested that the application of the initial water depth mask was promising in terms of facilitating an improved representation of rainfall within the domain. This is supported by Figure 6. which illustrates the change in volume of water within the model domain through the course of simulation 2. A simple comparison with Figure 6.2.2 , illustrates that the initial depth mask is facilitating the addition of water, through negative infiltration, into the model domain.

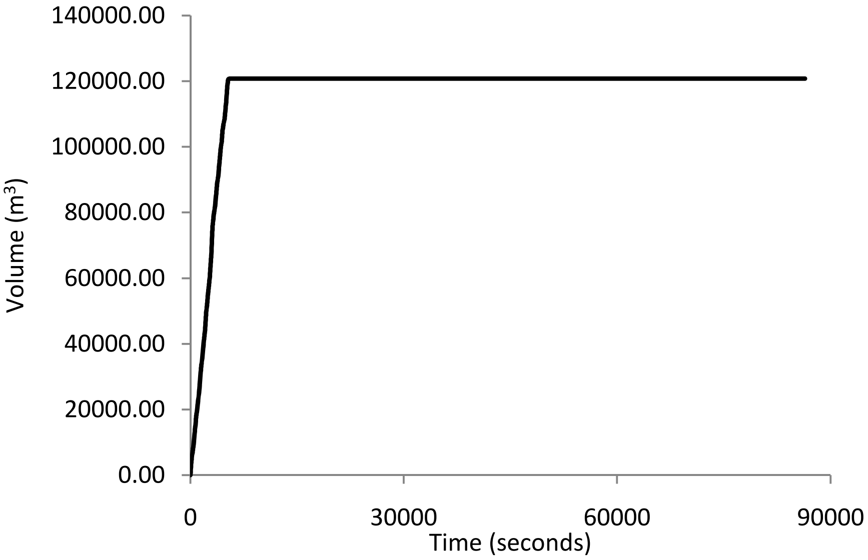


Figure 6. 2.2 Volume of water within the model domain through the course of simulation 2, taken from LISFLOOD-FP mass balance file.

Whilst the imposition of an initial depth showed promise, it was also clear that the DEM utilised within this study makes the application of a spatially uniform water depth mask across the entire domain problematic. As outlined in model application the DEM is characterised by two large areas of unknown elevation in the north east and south east corners, which have been assigned unique values of 999 in order to differentiate them from the rest of the known model grid (Figure 4.1 and 4.2).

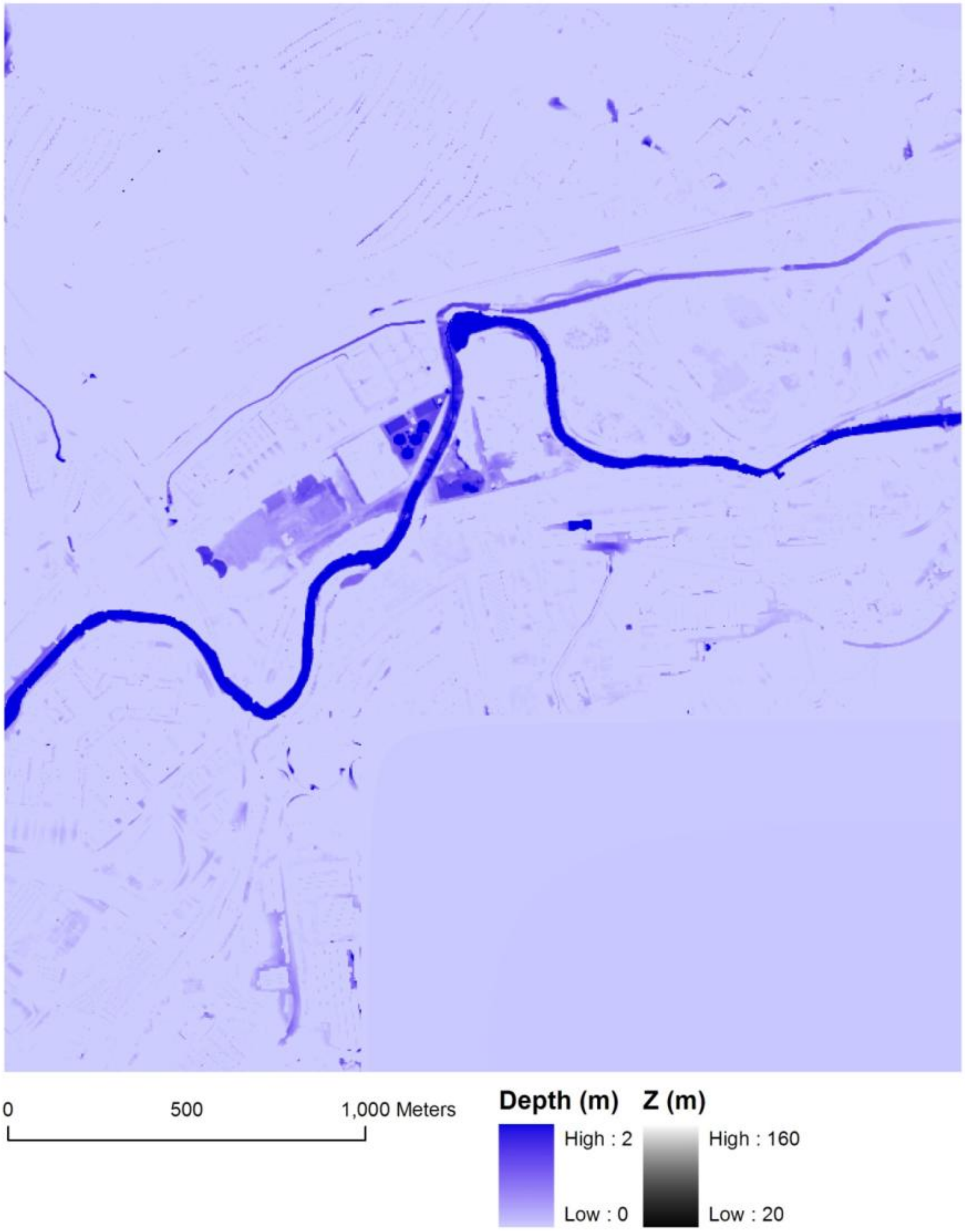


Figure 6.3 Flood inundation for simulation 2, taken from 80000 seconds (~22 hours) into the simulation with spatially uniform initial depth mask

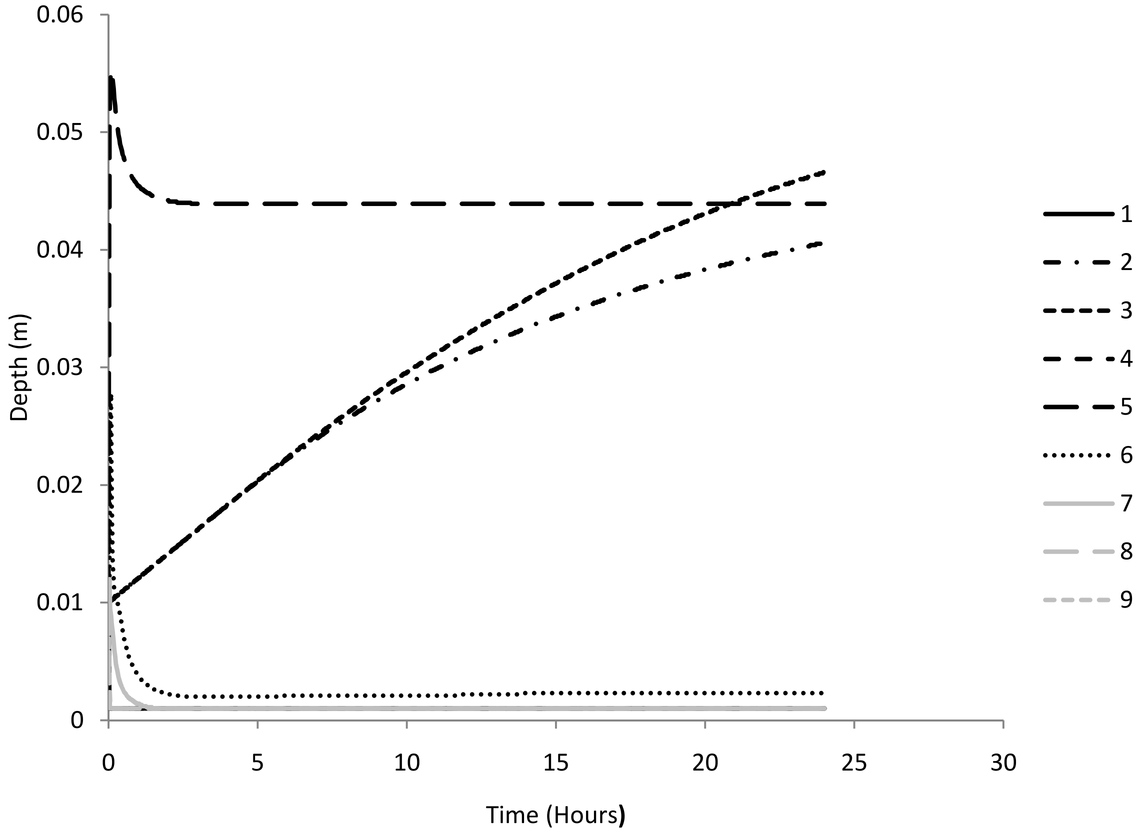


Figure 6.4 Water level time series for simulation 2 extracted from locations shown in Figure 6.1

The implications of this are twofold; firstly these unknown areas will inevitably supply water to the known model domain, where elevation values are much lower. This is problematic as the nature of the elevation in these areas is unknown and hence it is largely inappropriate to assume that the topography would facilitate contributions of water to the known portion of the study area. Secondly, the topographical nature of these areas is likely to result in the proliferation of a range of highly unrealistic hydraulic conditions. Large elevation differences of the order of hundreds of metres exist between cells at the transition from the unknown to known areas of topography. Within a hydraulic model this difference is likely to manifest as an erroneously high water surface slope. In addition the uniform elevation of 999 m within unknown areas will lead to very low water surface slopes and further unrealistic flow conditions, evidence of which is shown within Figure 6.3 and 6.4. In addition, a uniform initial depth mask is likely to be associated with unnecessary increases in computational cost as the simulation time of LISFLOOD-FP is strongly a function of the number of wet cells (Hunter et al., 2005b) this is illustrated in Table 6.1.

It is important to note that similar, albeit less exaggerated effects may also be observed more widely across the domain where the presence of structural features such as buildings produce water surface slopes of an order which are not traditionally considered in the formulation of floodplain flow equations (P.D Bates personal communication).

6.2.3 Negative infiltration with a refined initial water depth mask

In response to the aforementioned problems which proliferated during implementation of a uniform initial depth across the domain, the mask was modified for use within simulation three. Water depths of zero were assigned to areas of unknown elevation and to buildings, with the aim of precluding the widespread occurrence of unrealistic hydraulic flows.

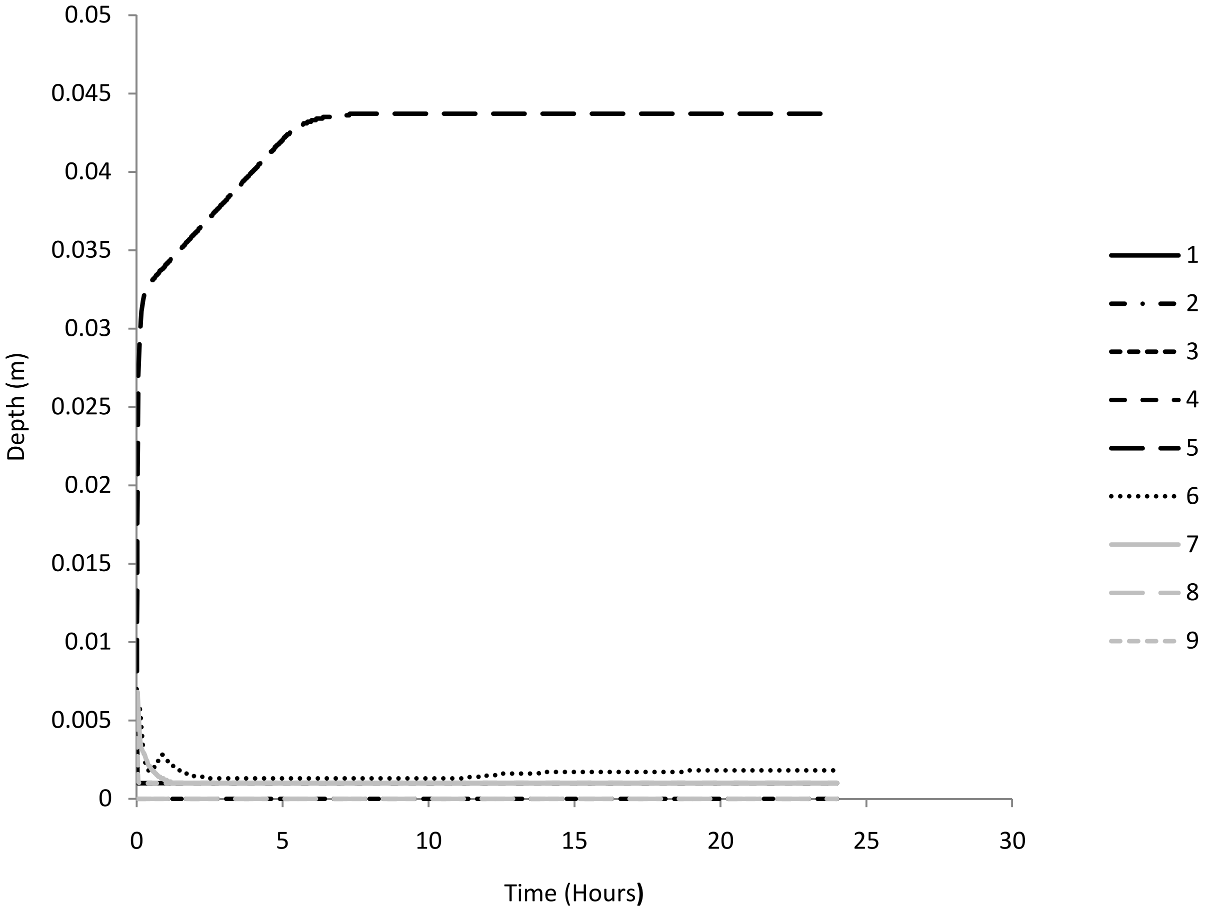


Figure 6.5 Water level time series for simulation 3, extracted from locations illustrated within Figure 6.1.

Figure 6.5 and 6.6 illustrate that the modification to the initial depth mask is effective in preventing the occurrence of flows within these areas, whilst similar inundation characteristics are maintained within other locations across the domain. Therefore it appears that the use of the corrected initial depth mask within simulation three facilitates an appropriate basic representation of direct precipitation which is lacking within simulation one, without the excessive computational costs associated with simulation two (Table 6.1).

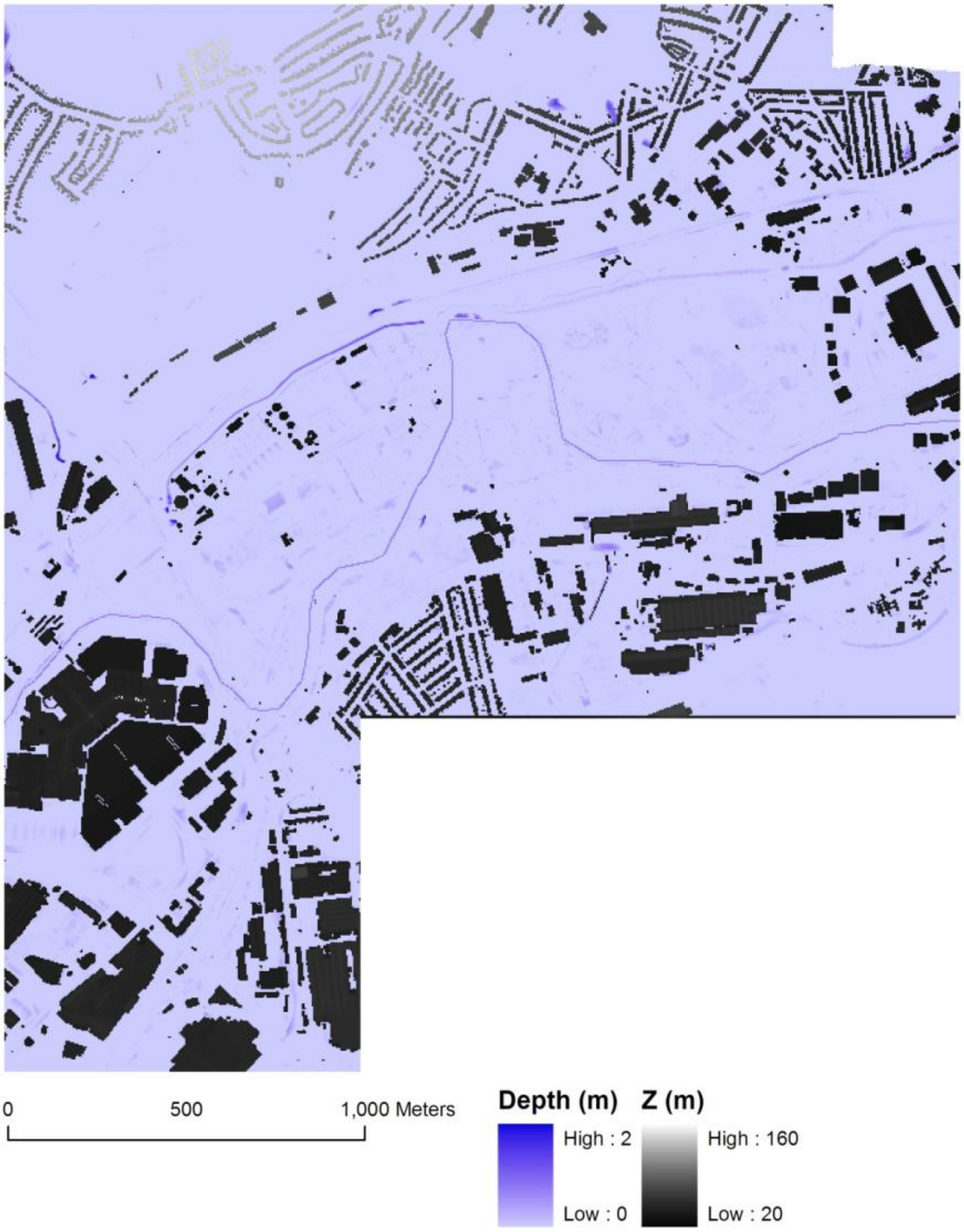


Figure 6.6 Flood inundation extent taken from 80000 seconds (~22 hours) into simulation 3, populated with initial depth mask corrected for buildings and unknown areas.

6.2.4 The potential for time-varying precipitation rates using evaporation

A negative manipulation of the evaporation rate within LISFLOOD-FP was also identified as a potential method to parameterise rainfall within the model domain. Theoretically the representation of rainfall provided through use of evaporation should be equivalent to that achieved through manipulation of

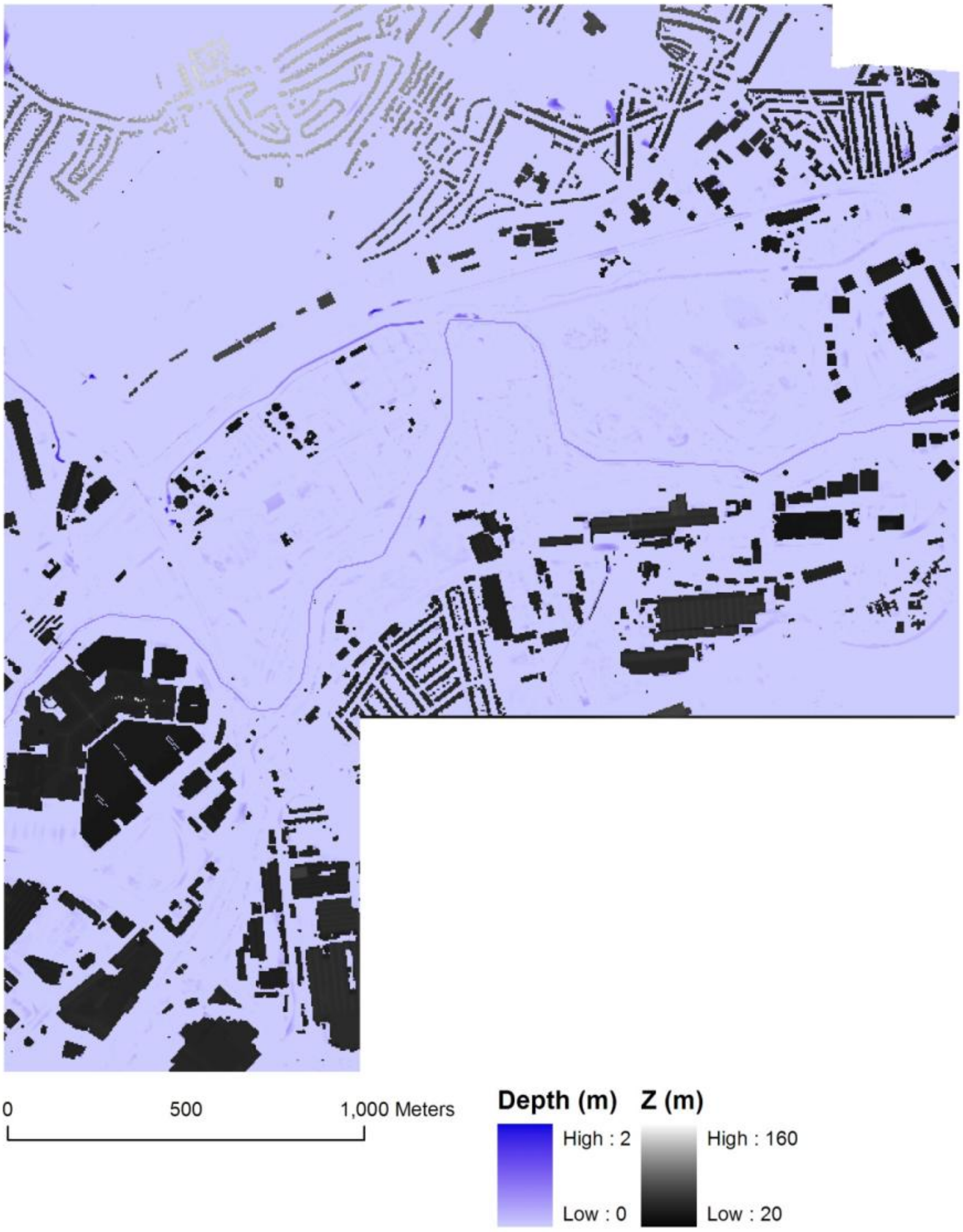


Figure 6.7 Flood inundation for simulations taken from 80000 seconds (~22 hours) into simulation 4, populated with initial depth mask corrected for buildings and unknown areas, using evaporation to represent rainfall.

infiltration, as both operate through removing (or adding if given a negative value) a uniform volume of water from cells across the model domain at each time step.

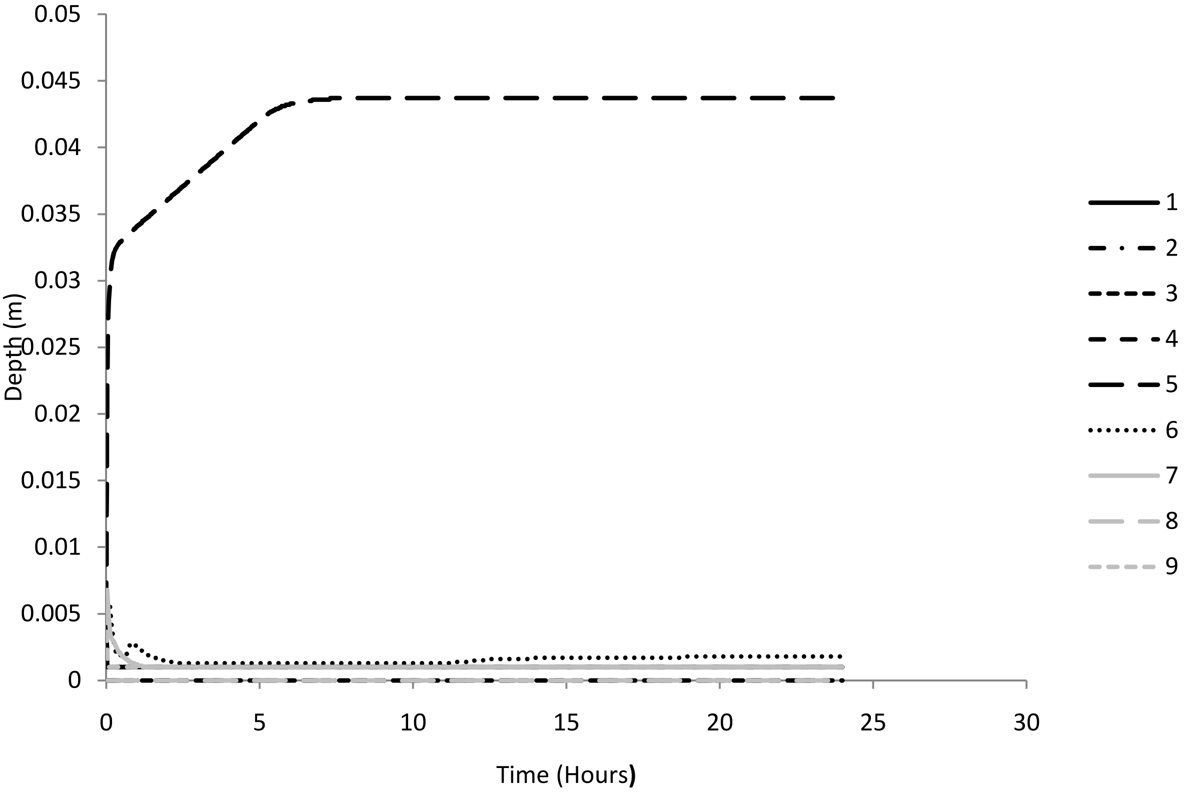


Figure 6.8 Water level time series for simulation 4. Graph shows identical depths to those observed in 6.6 suggesting that the representation of rainfall using negative manipulations of the infiltration and evaporation terms are equivalent.

However the evaporation and infiltration terms differ in that the former should be able to facilitate specification of time varying precipitation rates. This is potentially very useful within this study as rainfall rates are rarely uniform through the course of prolonged flood events. Given the potential utility of this parameter simulation four was undertaken in order to establish model stability with negative evaporation values. Within this simulation an identical rainfall rate to that used within simulation three was imposed, thus facilitating a direct comparison between the two representations of precipitation.

The visual representation of areal flood inundation extent illustrated in Figure 6.7 and inundation time series in 6.8, both corresponding to simulation four show high levels of similarity to those produced within simulation three, shown in Figures 6.5 and 6.6. This strongly suggests that negative manipulation of the evaporation term presents a viable approach to parameterisation of rainfall, although with the additional potential to facilitate time varying rates. Therefore given that no substantial increases in computational cost were associated with time varying rainfall representation (Table 6.1) it appears that the evaporation parameter offers a greater level of utility in representing direct rainfall.

6.2.5 Summary

Overall, initial testing suggests that the use of an initial depth mask is a precursor to an adequate representation of precipitation within LISFLOOD-FP. In addition a correction in order to prevent flows on tops of buildings and unknown areas of elevation in the domain was shown to be beneficial in terms of preventing erroneous flow hydraulic conditions and reducing computation costs. Use of such a mask in conjunction with a negative manipulation of the infiltration/evaporation parameters appears to offer the best representation of precipitation available without a recode of LISFLOOD-FP.

A thorough analysis of more detailed model response to parameterisation of precipitation was surplus to requirements within this initial testing. However the identification of some of the basic inundation characteristics in response to the rainfall parameterisation is useful in order to inform the model testing which follows. It is clear from initial results that inundation characteristics in response to precipitation are not uniform across the domain. Rather the domain is characterised by extensive areas of very shallow flow, whilst the majority of the water volume appears to be located in relatively localised areas of pooling which are associated with much greater depths. Given this basic model response to parameterisation of precipitation it is clear that a change in analysis technique is required in order to elucidate more complex and intricate model behaviour. As inundation characteristics are highly non-uniform, the sampling strategy for inundation time series should reflect this. In addition, clearer representations of the areal extent of flooding within the domain are also required in order to aid interpretation.

6.3 Model sensitivity to rainfall representation

Having established an adequate parameterisation of precipitation within LISFLOOD-FP in 6.2, further testing was required in order to elucidate more complex model behaviour in response to rainfall. A thorough understanding of the model response to parameterisation of precipitation will facilitate the implementation of the most physically realistic rainfall representation available for application to the 2007 flood event in Sheffield within the following chapter.

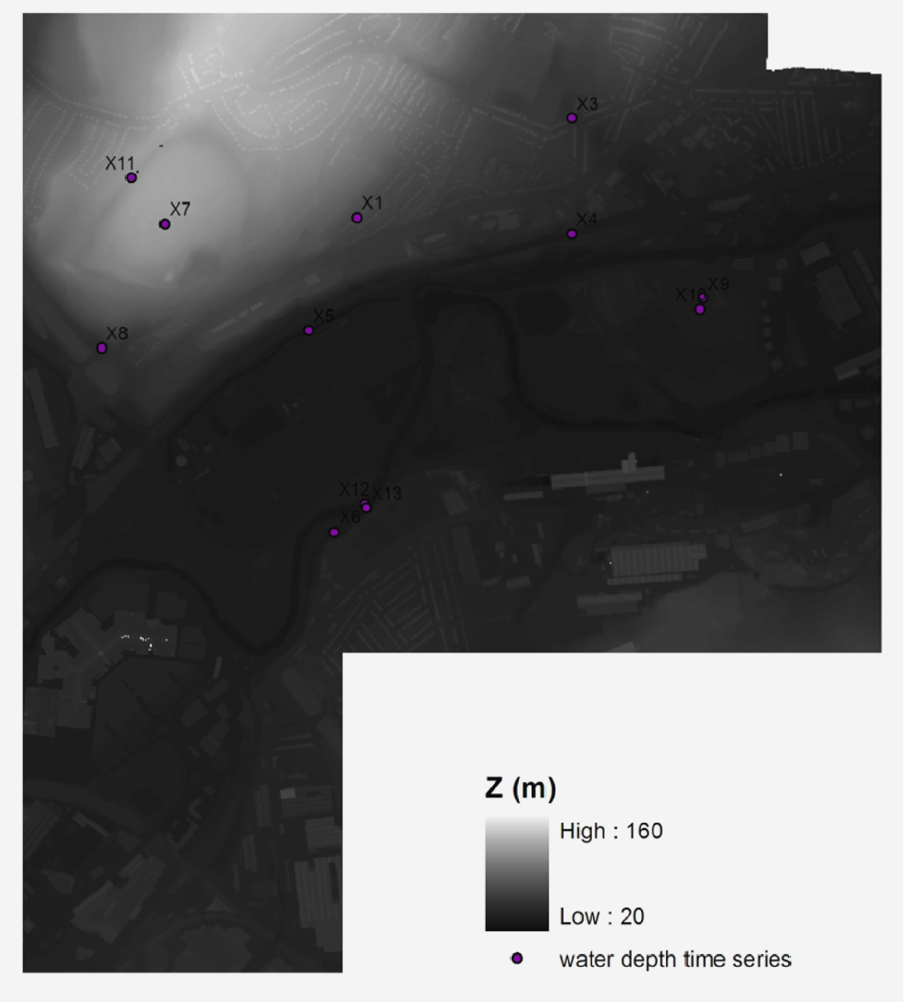


Figure 6.9 Model domain illustrating locations of water depth time series extraction for simulations within 6.3

It is clear from initial testing within 6.2 that the nature of flood inundation in response to rainfall is fundamentally different to overbank inundation. Intuitively surface flows in response to rainfall tend to be much more shallow, thus reliance upon model behaviour observed within the initial sensitivity analysis in chapter five is largely inappropriate here. In order to provide a comprehensive test of model behaviour in response to precipitation a variety of factors will be tested within this analysis, including standard model boundary conditions/parameters; grid resolution, time step and floodplain friction. In addition, rainfall specific input factors will be investigated, including the partitioning of water between initial imposed depth and subsequent rainfall rate and uniform/ time varying precipitation rates. A one at a time (OAT) approach is utilised in this analysis, in a similar manner to the initial model sensitivity analysis in chapter five. This facilitates testing of model response to perturbations in individual parameters and allows the significance of these to be assessed. Within these simulations a steady state discharge of 100 m^3/s (below bankfull) is utilised in order to preclude the occurrence of overbank flows, ensuring that any flood inundation observed can be attributed solely to inputs from precipitation.

It became clear in 6.2 that more refined analysis techniques were required in order to reflect the specific characteristics of flood inundation in response to rainfall. Accordingly, analysis here will be based upon thematic maps which delineate the areal extent of meaningful flow depths within the domain, placing particular emphasis upon areas where depth is in excess of 30 cm. This water level is commonly regarded as the threshold depth for flooding of buildings (Neal et al., 2009a). Although analysis of thematic maps is useful in providing a clear visual quantification of the areal extent of flooded areas, it is strictly limited temporally and hence does not allow analysis of dynamics through the course of the simulation. Therefore the thematic maps will be supplemented by analysis of water depth time series selected from areas of hydrological interest (Figure 6.9) within the domain, which are useful in elucidating the dynamics of inundation. In combination, these two analysis techniques should facilitate thorough testing of model response to parameterisation of precipitation.

6.3.1 Time step

Figure 6.13 and Table 6.2 initially suggest that the LISFLOOD-FP model shows relatively little sensitivity to time step in terms of the areal extent of inundated areas in response to rainfall. Visually, the thematic maps for the four varying time steps appear very similar. Table 6.2 provides a quantification of the inundated areas, illustrating an increase of only 3 m^2 in flooded areas with a depth in excess of 30 cm over the complete range of time step values, further suggesting that sensitivity is relatively low. It is relevant to note that these Figures only provide a snapshot of inundation taken from towards the end of the model simulation (~22 hours), whilst in addition the classification used could mask finer details of model response. However additional evidence from the water depth time series illustrated in Figure 6.10-6.12 offer conflicting evidence with respect to the model response to time step.

Time step (s)	0	0.001	0.0011-0.0049	0.005-0.149	0.15-0.299	>0.30
0.1	1683.6	2055.3	447.7	765.4	256.5	375.6
0.5	1683.6	2054.8	447.7	763.8	263.6	376.8
1	1683.6	2054.6	447.1	762.9	268.2	377.3
5	1685.0	2052.2	445.5	765.6	271.4	378.4

Table 6.2 Areal extent (m^2) of classified flood depths in response to changing time step, providing a quantification of Figure 6.13

Figure 6.10 exhibits identical trends for all time steps, thus suggesting that sensitivity to this factor is minimal. However in contrast to Figure 6.10, variation in water depths illustrated in Figure 6.11 suggests the model does in fact exhibit some response to changing time step. A clear difference in water levels can be observed between the simulations with different time steps, particularly where the time step is reduced to 5 s. Overall the increase in time step from 0.1 to 5 seconds is associated with a decrease in depth exceeding 30 cm at point 5.

This is interesting as it appears that sensitivity to time step depends upon the specific location from which water depth is extracted. A hypothesis explaining this sensitivity has been generated after consideration of the location from which the water level time series was taken and the process representation of LISFLOOD-FP. The inundation time series illustrated in Figure 6.11 is taken from point 5, which is located within a small channel at the northern limits of the floodplain. As a result of its location within the domain (Figure 6.9), this area is likely to receive water from a relatively large upslope contributing area on the valley side. By contrast less sensitivity was observed within the time series taken from point 2, which is located within a topographical depression in an upslope area likely to be characterised by a smaller and more proximal contributing area.

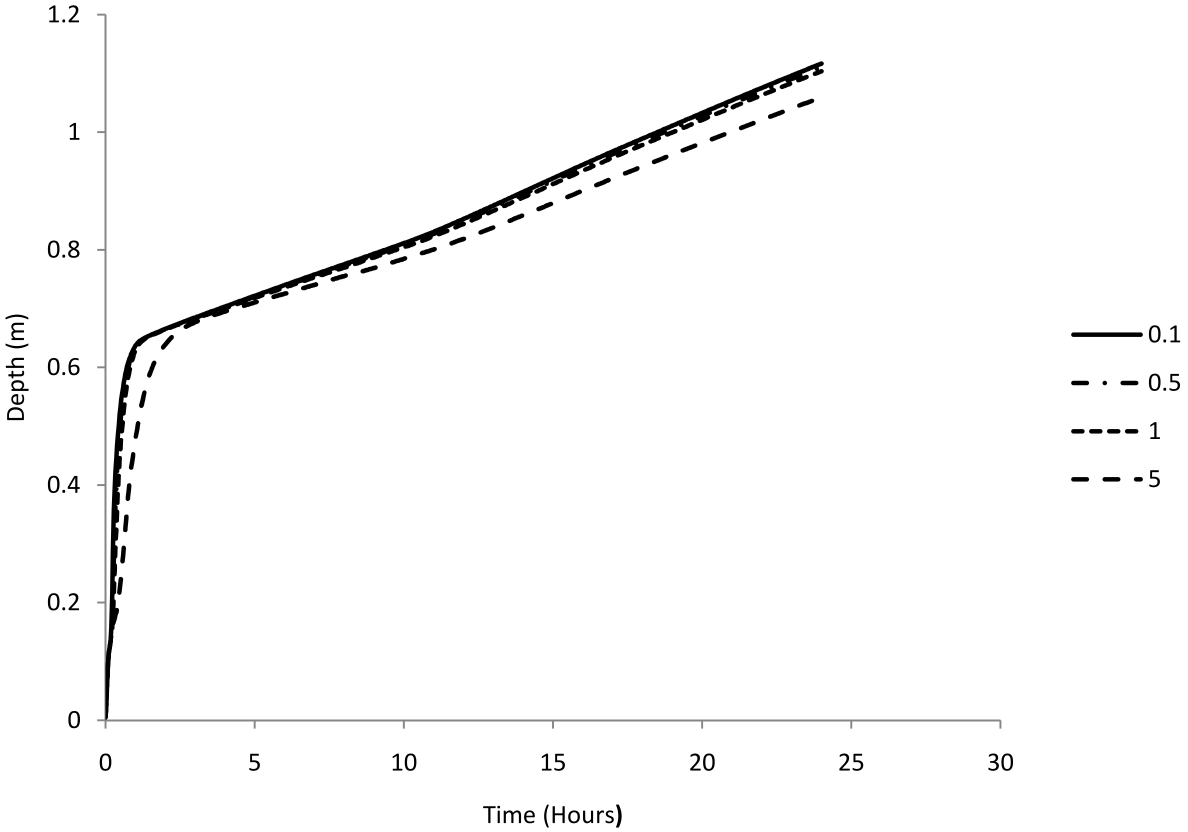


Figure 6.10 Water depth time series taken from point 3 illustrating sensitivity to time step (seconds)

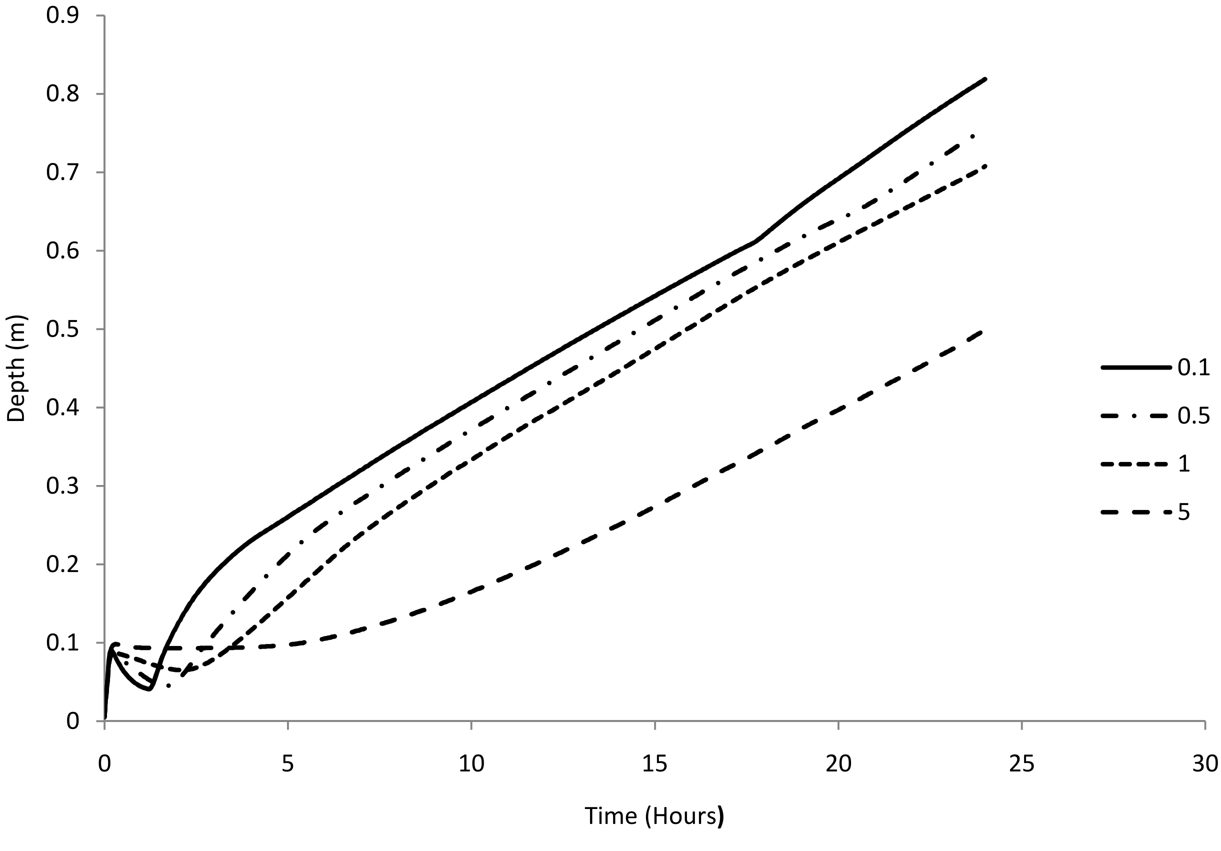


Figure 6.11 Water depth time series taken from point 5 illustrating sensitivity to time step (seconds)

It has been demonstrated previously in this study that when applied with a fixed time step, LISFLOOD-FP exhibits resolution and time step dependence due to the influence of the flow limiter. Usually where the flow limiter is invoked this manifests as a constraint to lateral diffusion of the flood wave where time steps are greater, due to dependence upon model parameters. Therefore intuitively where water is added directly to upslope areas through a parameterisation of precipitation, the flow limiter is likely to attenuate flow to lower topographical areas. This is reflected in the increased sensitivity to time step observed at point 5 which receives water from a wider contributing area than point 3, thus providing more opportunity for attenuation of flow. In order to test this hypothesis a time series was taken from point 9 (Figure 6.12), which is located within a small basin located within to the east of the floodplain. The topography of this basin is such that its contributing area is strictly limited to the basin itself, thus providing less opportunity for attenuation of water supply. The lack of sensitivity illustrated at this location (Figure 6.12) consequently supports the aforementioned hypothesis.

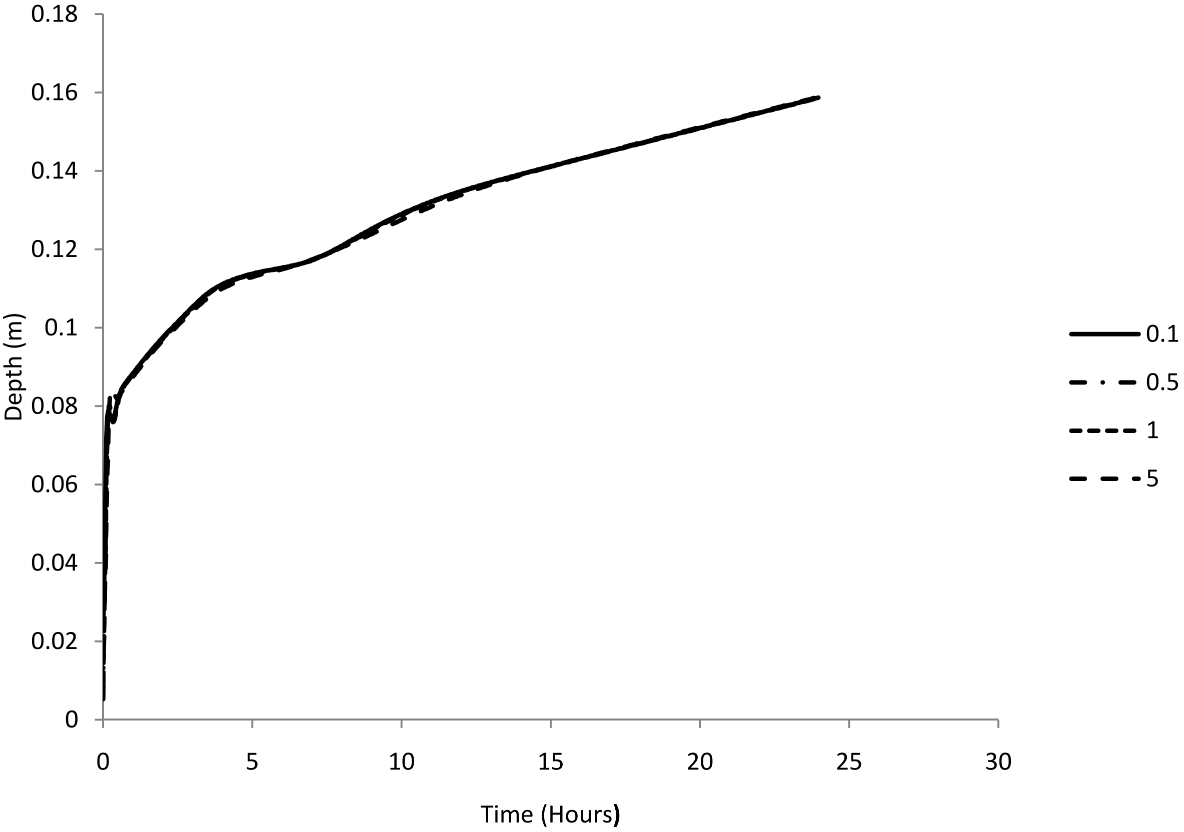
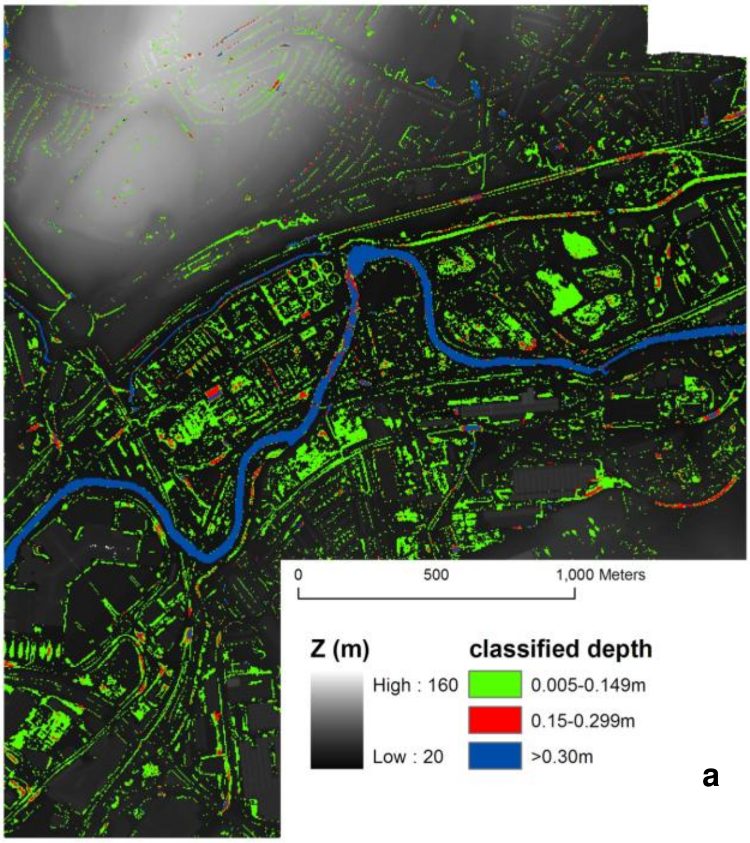


Figure 6.12 Water depth time series taken from point 9, illustrating sensitivity to time step (seconds)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classified depth
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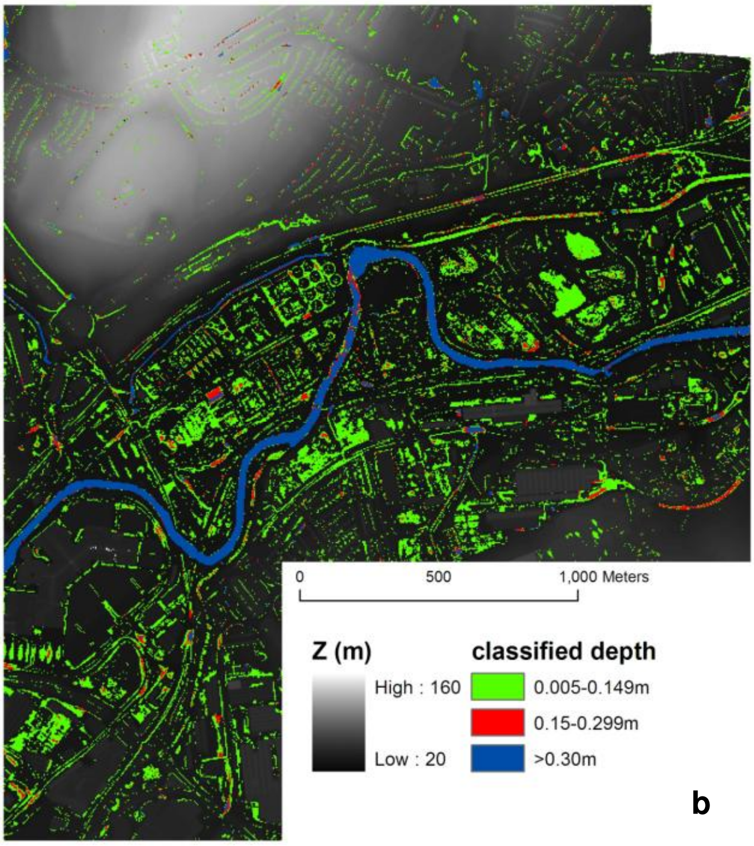
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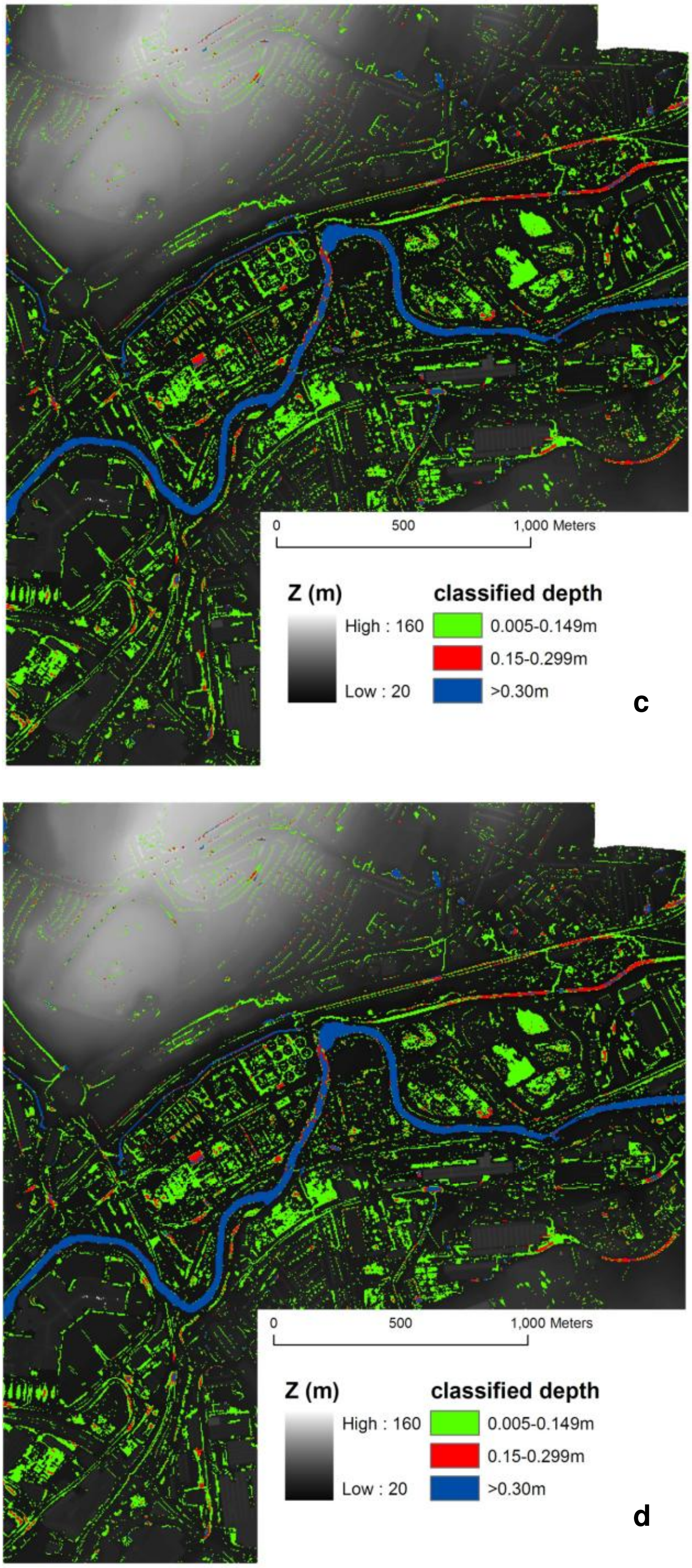
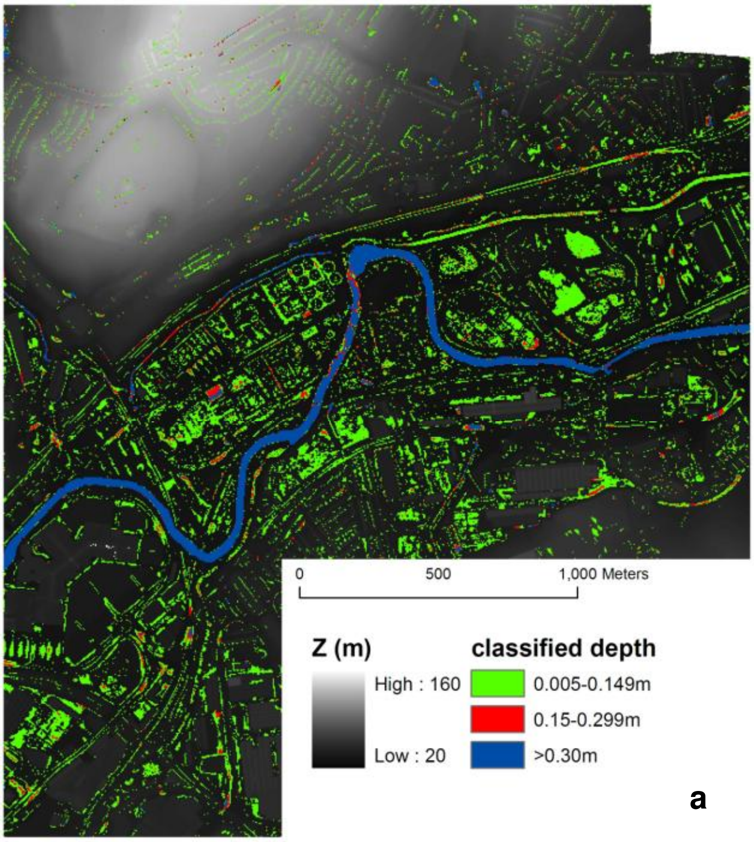


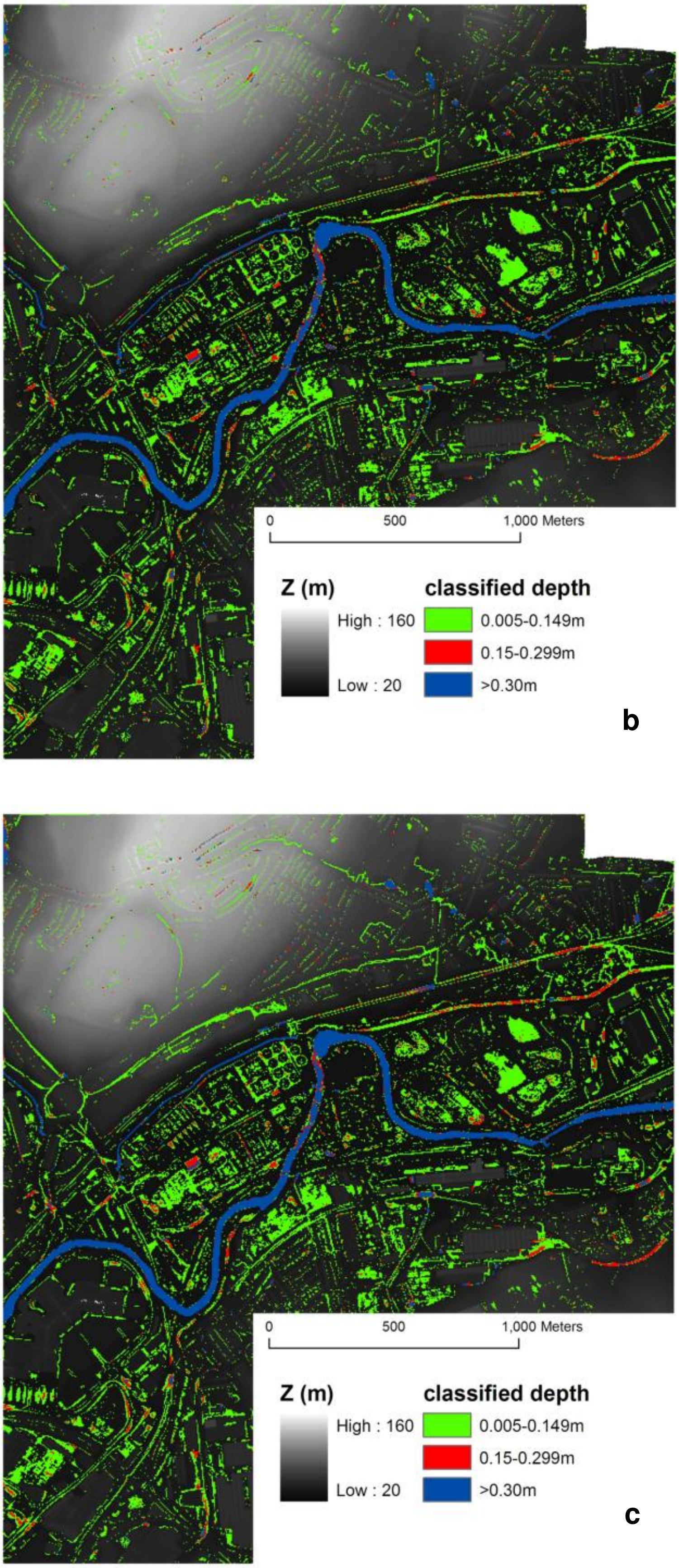
Figure 6.13 Thematic maps illustrating the areal extent of classified flood depths for varying time steps, taken from 80000 seconds (~22 hours) into simulation. (a) 0.1s (b) 0.5s (c) 1s (d) 5s

Overall this analysis tentatively suggests that the spatial extent and depths of flow are relatively insensitive to time step in locations which receive water from a relatively small and proximal contributing area. However the inundation time series taken from point 5 illustrates that sensitivity to time step may occur where a particular area receives water from a large contributing region. This suggests that time step may potentially be important in determining the velocity and hence timing of surface flows in response to precipitation. This is potentially very important when attempting to determine the dynamic contribution of rainfall to flood inundation. For example, the attenuation effect observed where time step is high could potentially lead to an underestimation of the contribution of rainfall to overbank flooding within a formal modelling scenario.

6.3.2 Floodplain friction

Figure 6.14 and Table 6.3 illustrate that the areal extent of meaningfully flooded areas exhibit a greater level of variance to perturbations in floodplain friction than to time step. Careful visual analysis reveals that Figure 6.14 shows an increase in meaningfully flooded areas with increasing floodplain roughness, whilst this trend is confirmed within Table 6.3 which reveals that model response is relatively coherent.





Figures 6.14 Thematic maps illustrating the areal extent of classified flood depth for varying floodplain friction, taken from 80000 seconds (~22 hours) into the simulations. (a) n_{fp}=0.02 (b) n_{fp}=0.06 (c) n_{fp}=0.1

From the Table it is clear that the spatial extent of all inundation depths in excess of 0.001 m increases with floodplain roughness. This effect is most pronounced for the lower brackets of water depth and is least where inundation is in excess of 30 cm.

n_{fp}	0	0.001	0.0011-0.0049	0.005-0.149	0.15-0.299	>0.30
0.02	1683.7	2099.4	297.72	731.2	231.8	363.2
0.06	1683.5	2055.3	447.7	765.3	256.4	375.5
0.1	1683.4	2010.4	555.8	801.2	276.5	385.6

Table 6.3 Areal extent (m^2) of classified flood depths in response to changing floodplain friction, providing a quantification of Figure 6.14.

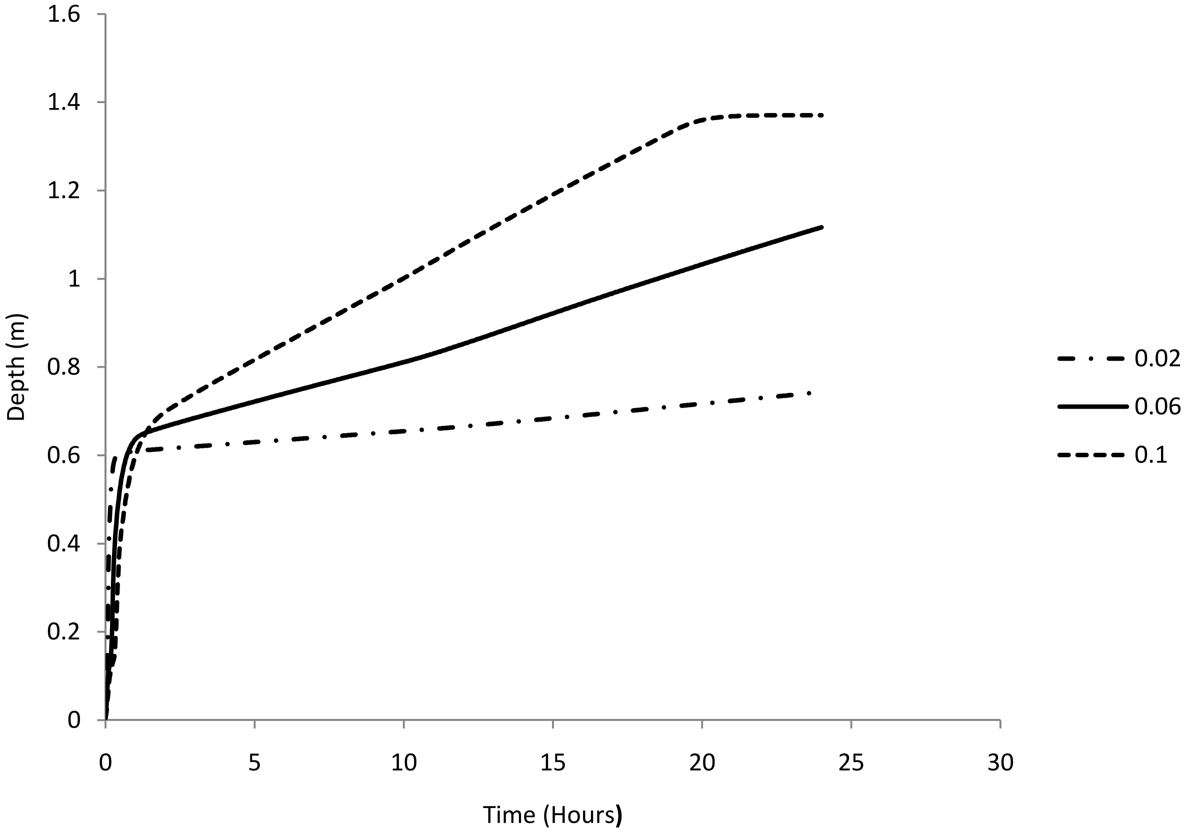


Figure 6.15 Water depth time series illustrating sensitivity to floodplain friction (Manning's *n*) taken from point 3

The initial indications of sensitivity to floodplain friction elucidated from Figure 6.14 and Table 6.3, which provide a temporal snapshot of flood inundation, are corroborated by the dynamic response illustrated in Figures 6.15 and 6.16. Within Figure 6.15 a rapid initial increase in depth is observed which is of a relatively similar magnitude for all values of n_{fp}. However after this initial rise the sensitivity to floodplain roughness becomes apparent, with the simulated water depths diverging in a relatively uniform manner. It is important to note that greater water depths are associated with increases in n_{fp}.

The time series illustrated within Figure 6.16 is characterised by a small peak and subsequent decline in depth within the first few hours of the simulation. This is followed by a steady increase in water depth through the remainder of the simulation with a relatively uniform variation observed between the different values of n_{fp}. As in Figure 6.15, depth of inundation increases in response to higher roughness values.

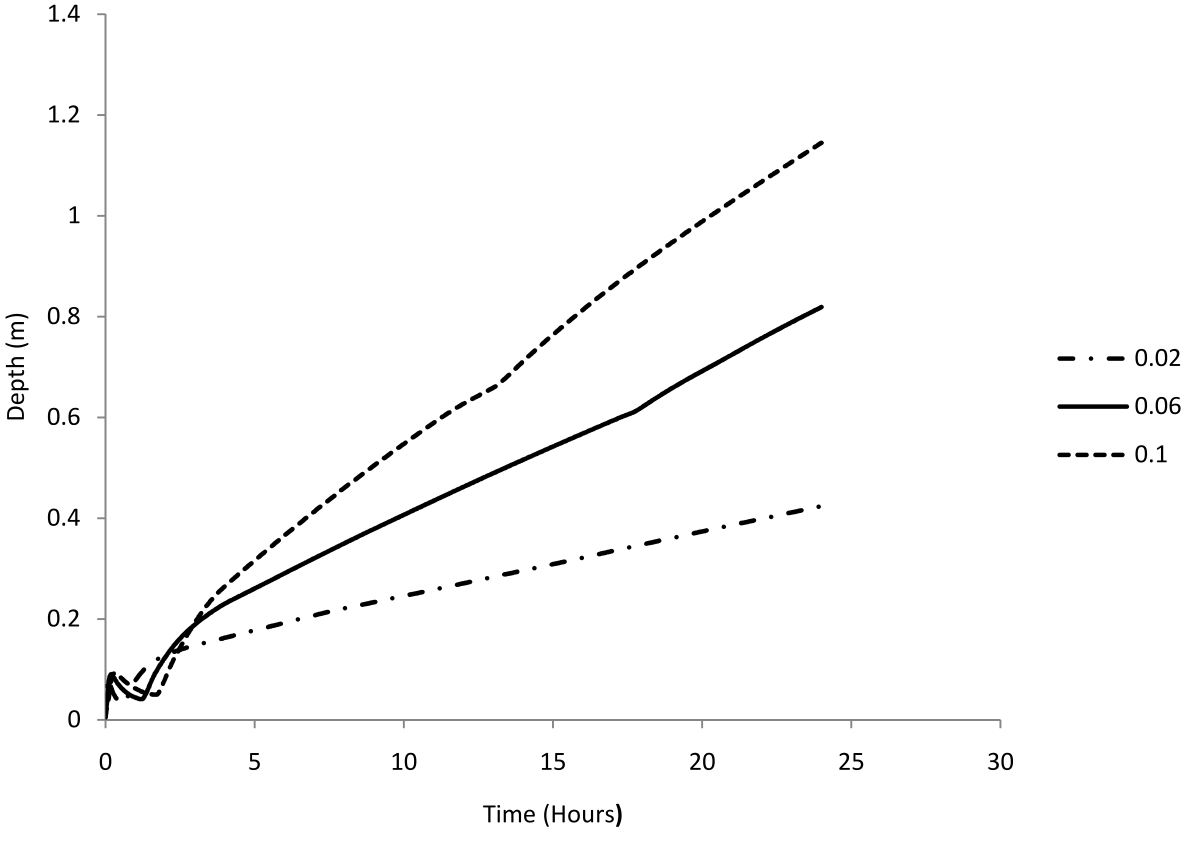


Figure 6.16 Water depth time series illustrating sensitivity to floodplain friction (Manning's *n*) taken from point 5

Therefore overall the results of this analysis suggest that surface flows in response to rainfall exhibit a significant level of sensitivity to floodplain friction. Overall higher values of floodplain friction lead to an increase in flow depth within Figure 6.15 and 6.16, which represents the expected response when considered in terms of floodplain flow equations within LISFLOOD-FP. This sensitivity appears to be relatively coherent when compared to the response to variations in time step. Significantly, further detailed analysis of Figures 6.15 and 6.16 illustrates a more rapid initial increase in depth for low values of floodplain friction, whilst a slight lag can be observed for higher values. This is also intuitive, suggesting that lower values of roughness effectively facilitate more rapid routing of the water supplied to the domain through the initial depth mask.

6.3.3 Resolution

A visual assessment of the thematic maps within Figure 6.18 is problematic here due to the difference in resolution, which results in a considerable loss of spatial detail at coarser scales. It appears that the spatial extent of meaningfully flooded areas increases at finer grid scales, although the difference in resolution makes visual comparison difficult. In order to aid analysis, Table 6.4 provides a quantification of the areal extent of water depths observed within these images. It is clear that surface flows in response to rainfall exhibit a moderate level of sensitivity to grid resolution, although the sensitivity appears to be less coherent than that displayed for floodplain friction in 6.3.2. Generally the spatial extent of meaningful flood depths (> 0.005 m) appears to increase at finer grid resolutions, thus supporting the visual analysis. However there are several anomalies, indeed Table 6.4 suggests that the 16 m grid is associated with the greatest spatial extent of flood depths in excess of 30 cm. Visual analysis of the thematic maps suggest that this is a function of an increase in areal extent of the channel at 16 m resolution although this cannot be quantified here. Overall Figures 6.18 and Table 6.4 tentatively suggest that an increase in DEM resolution is associated with an increase in the spatial extent of meaningfully flooded areas.

Grid resolution (m)	0	0.001	0.0011-0.0049	0.005-0.149	0.15-0.299	>0.30
2	1644.1	2072.9	436.0	802.5	272.8	377.9
4	1683.5	2055.3	447.7	765.3	256.4	375.5
8	1739.3	2005.0	486.6	739.2	265.0	374.8
16	1810.1	1950.0	483.7	682.2	256.0	387.9

Table 6.4 Areal extent (m^2) of classified flood depths (m) in response to changing grid resolution, providing a quantification of Figure 6.18

Figure 6.17 constitutes a water level time series extracted from point 2, which is located upslope of a row of buildings on the north valley side of the domain (Figure

6.9). The water levels observed at this point are highly inconsistent with respect to changing resolution and thus present a prime example of the loss of spatial detail associated with use of coarser grid resolutions. Accordingly it seems that the topographical representation of buildings within the 4 m and 8 m grids are conducive to blockage of flow and accumulation of water at this specific location (Figure 6.18). However the minimal water depths observed at this location suggest that this blockage does not occur for the 2 m and 16 m simulations.

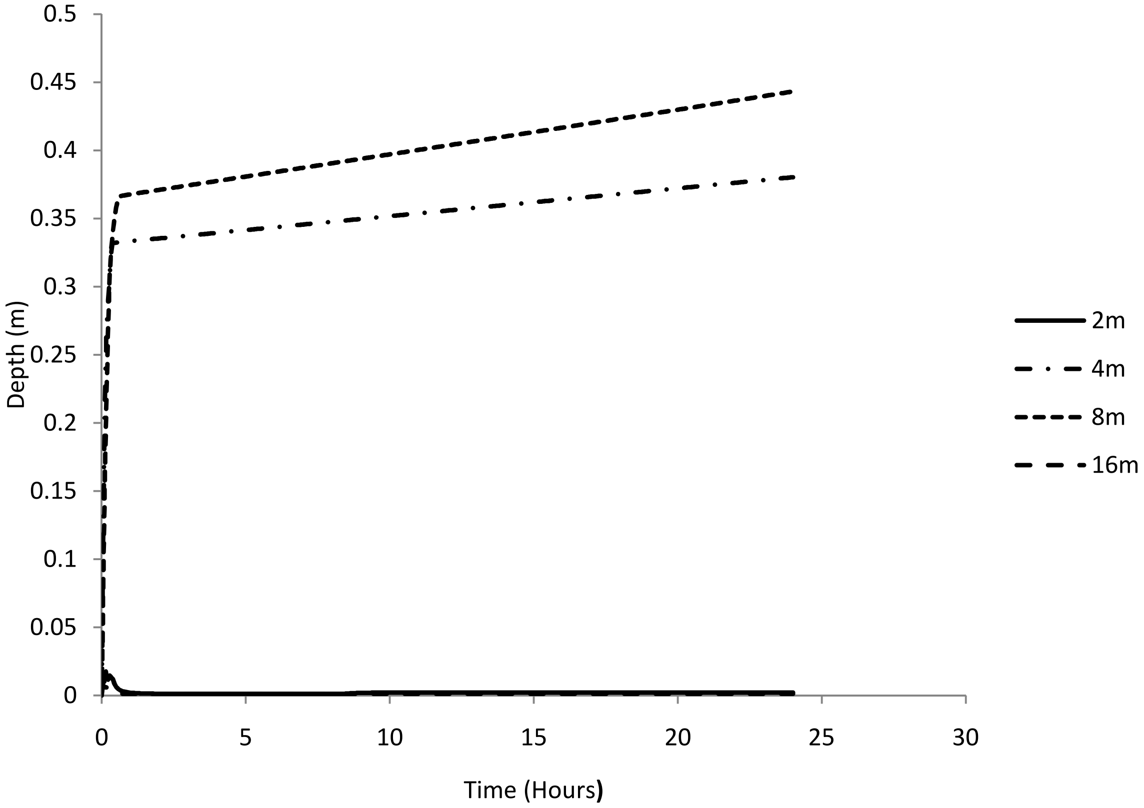
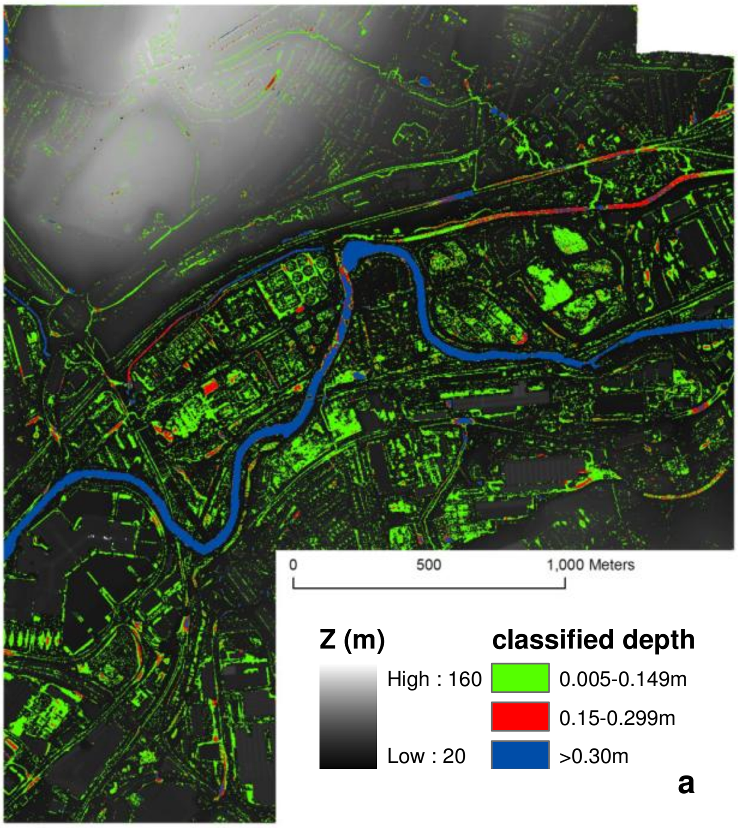


Figure 6.16 Water depth time series showing response to variation in grid resolution (m), taken from point 2.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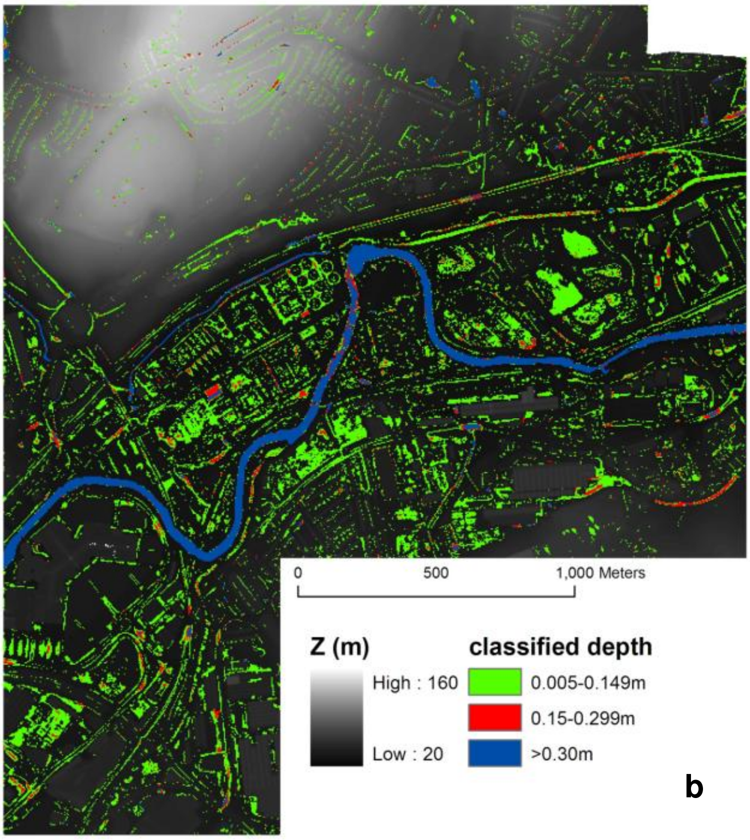
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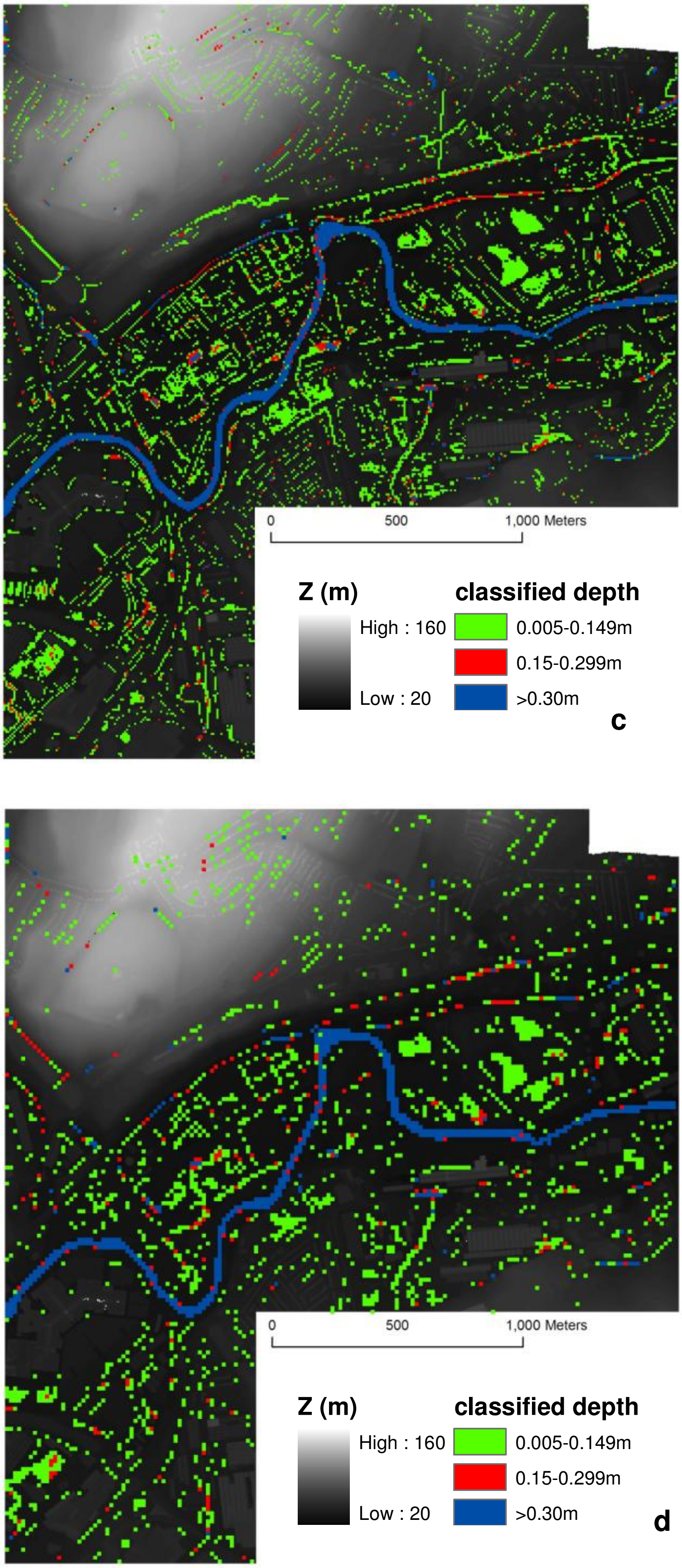


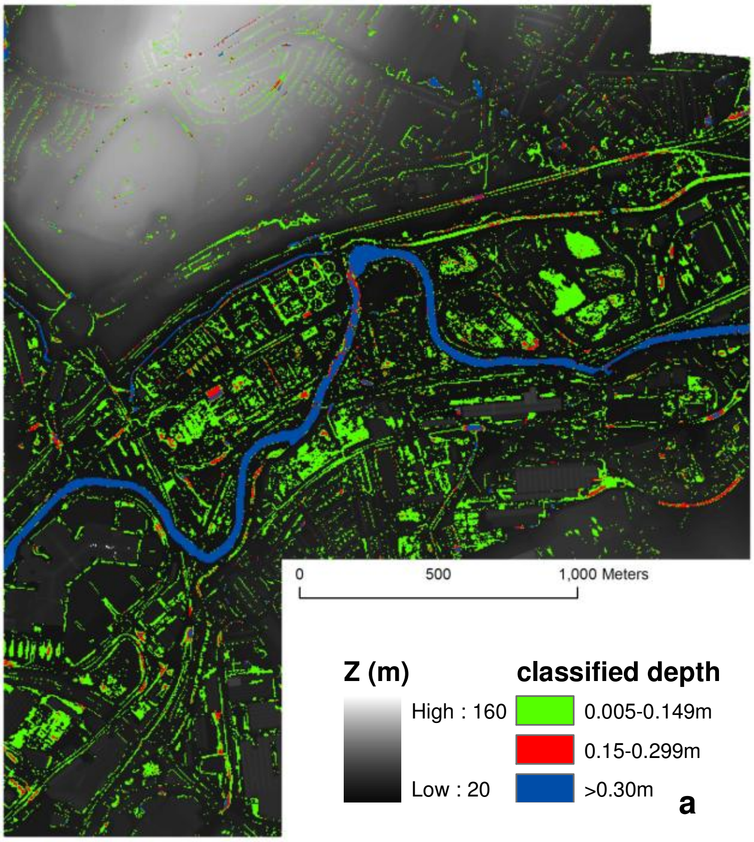
Figure 6.18 Thematic maps illustrating the areal extent of classified flood depth for varying grid resolution, taken from 80000 seconds (~22 hours) into the simulations (a) 2m (b) 4m (c) 8m (d) 16m

Overall it can be concluded that the model exhibits considerable sensitivity to grid resolution. The initial analysis of thematic maps tentatively suggests that finer grids are associated with a greater areal extent of meaningfully flooded areas. However analysis of water depth dynamics within Figure 6.17 suggests that the significance of grid resolution extends beyond a simple consideration of the overall areal extent of flooded areas. It is clear that grid scale is of preeminent importance in providing a topographical representation of structural features within the urban environment, which are clearly of preeminent importance in controlling the routing of water through the model domain.

6.3.4 Uniform versus time-varying precipitation

It was demonstrated in 6.2 that a negative manipulation of the evaporation parameter was able to offer a representation of precipitation similar to that provided by the infiltration term, although with the additional capability of facilitating time varying additions of water to the domain. Given the temporal variability of rainfall observed over the timescales of typical hydraulic model simulations, it was considered appropriate to investigate whether a relatively crude time varying rainfall rate would potentially be beneficial.

In order to test model response to time varying precipitation rates, three model simulations have been undertaken. The first simulation is characterised by a rainfall rate of 72.5 mm/day during the first 12 hours, followed by a rate of 22.5 mm/day from 12-24 hours. The second simulation exhibits a uniform rate of 45 mm/day through the course of the whole simulation. The final model run is associated with an initial rate of 22.5 mm/day up to 12 hours, followed by precipitation of the order 72.5 mm/day for the remainder of the simulation. Therefore each simulation is associated with addition of the same overall volume of water over the 24 hour period, although this is supplied through varying rainfall rates.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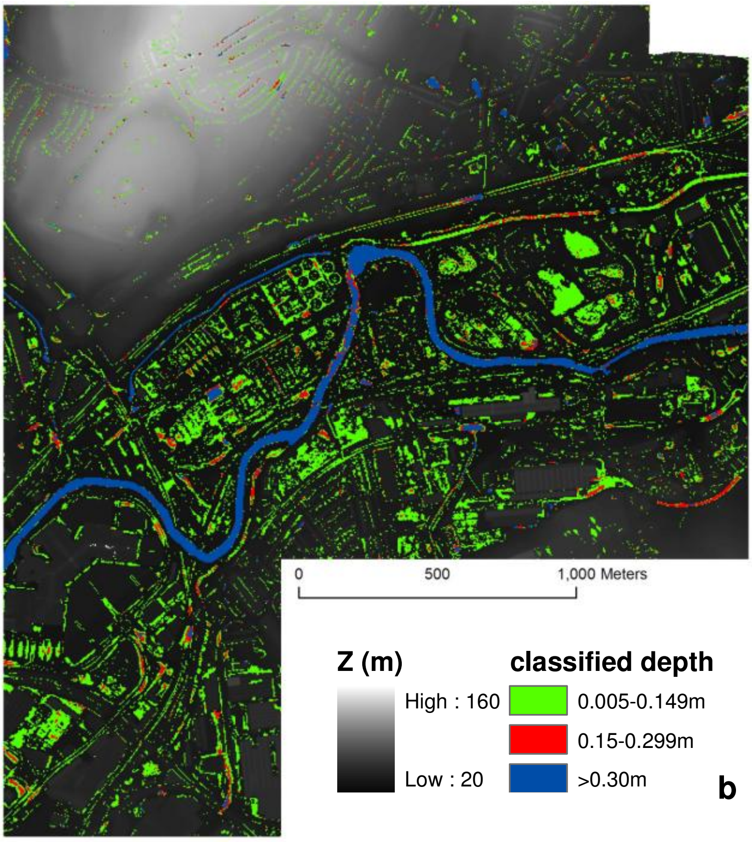
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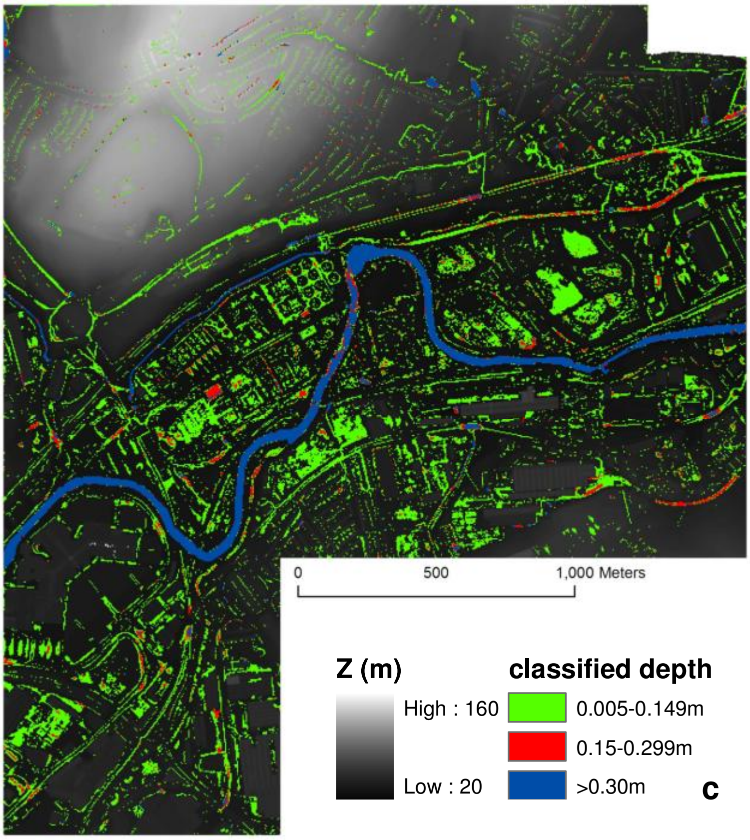


Figure 6.19 Thematic maps illustrating the areal extent of classified flood depth for time varying precipitation. Taken from 80000 seconds (~22 hours) into the simulations (a)72.5 mm/22.5 mm (b) 45 mm/45 mm(c) 22.5 mm/75.5 mm

Table 6.5 provides a quantification of the model response to time varying rainfall rates from a temporal snap shot of the inundation extent approximately 22 hours into the simulation. The simulation characterised by initially high rainfall rate is associated with the greatest areal extent of flooded areas with depths exceeding 0.15m and the least extensive flooding in depth categories from 0.0011 to 0.149 m. The reverse is true for the simulation with a lower initial rate of rainfall delivery which illustrates the greatest areal extent of flooded areas with depths between 0.0011m and 0.149 m.

Within the first simulation a large proportion of the total water volume is added within the first twelve hours, therefore by 22 hours into the model run the majority of this water has been routed to topographically low areas where pooling occurs. By contrast, areas of high water depth are less spatially extensive within the third simulation as a greater proportion of the overall volume of water supplied is still in the process of being routed to topographically low areas at the time which these statistics were extracted. On a basic level this illustrates that crudely distributed rainfall parameterisation may be beneficial in comparison to a uniform rate, particularly if attempting to determine the potential contribution of rainfall to flood inundation midway through a model simulation, at peak overbank flood extent for example.

Rate (0-12 hours)	Rate (12-24 hours)	0	0.001	0.0011-0.0049	0.005-0.149	0.15-0.299	>0.30
72.5	22.5	1683.4	2075.4	353.5	748.6	274.5	387.6
45	45	1683.5	2043.9	468.3	775.8	270.9	382.1
22.5	72.5	1683.5	2018.7	543.4	795.3	267.8	378.5

Table 6.5 Areal extent (m^2) of classified flood depths (m) in response to time varying precipitation (mm/day), providing a quantification of Figure 6.19

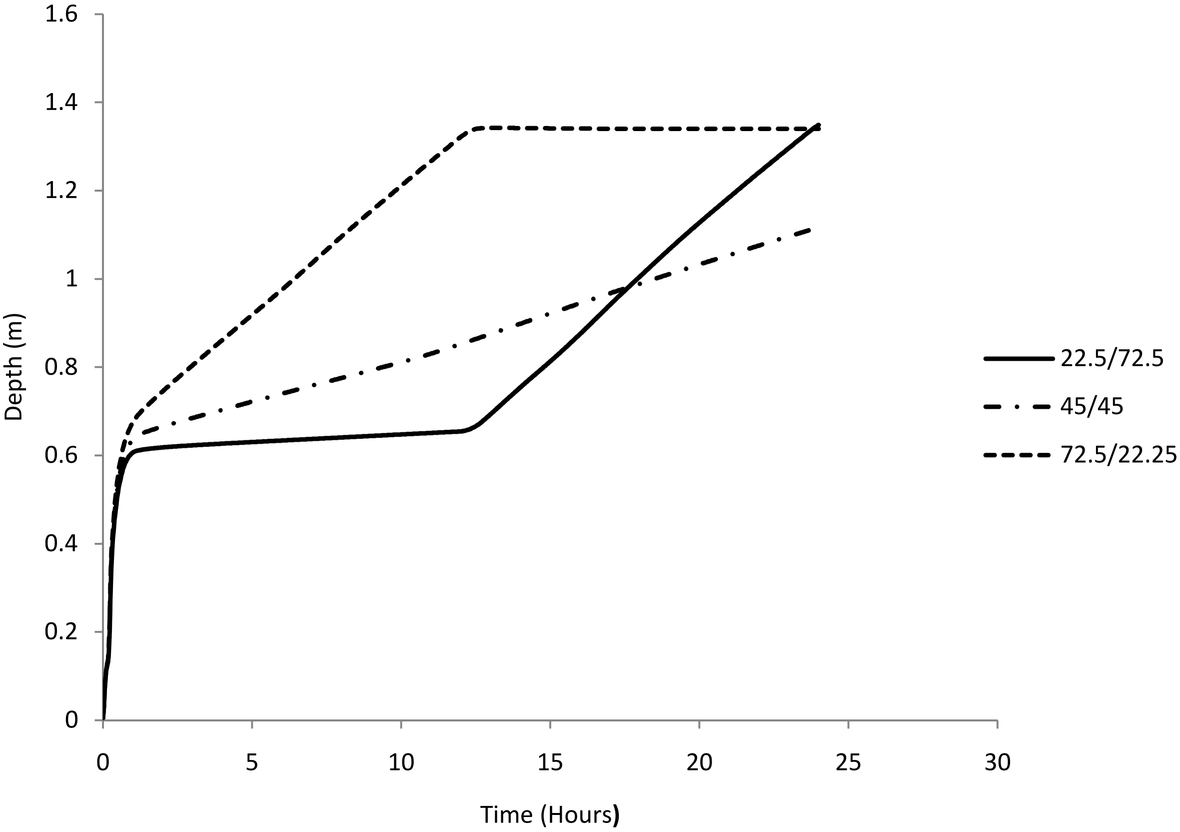


Figure 6.20 Model response to a uniform and crude time varying precipitation (mm/day) taken from point 5

The inundation time series displayed in Figures 6.20 and 6.21 illustrate that water depths modelled for time-varying simulations diverge considerably from the uniform simulation at both locations within the domain. Within both graphs simulation one is characterised by an initial rapid rise in depth through the first half of the simulation, with this rate decreasing significantly within the second half of the simulation. Comparatively simulation 3 exhibits almost exactly the opposite effect, with water depth rising very slowly within the first half of the simulation, followed by a rapid increase in depths from 12-24 hours. These depth time series support the notion that time varying parameterisation of rainfall can be associated with significantly different inundation characteristics, particularly when considered dynamically through the course of the simulation.

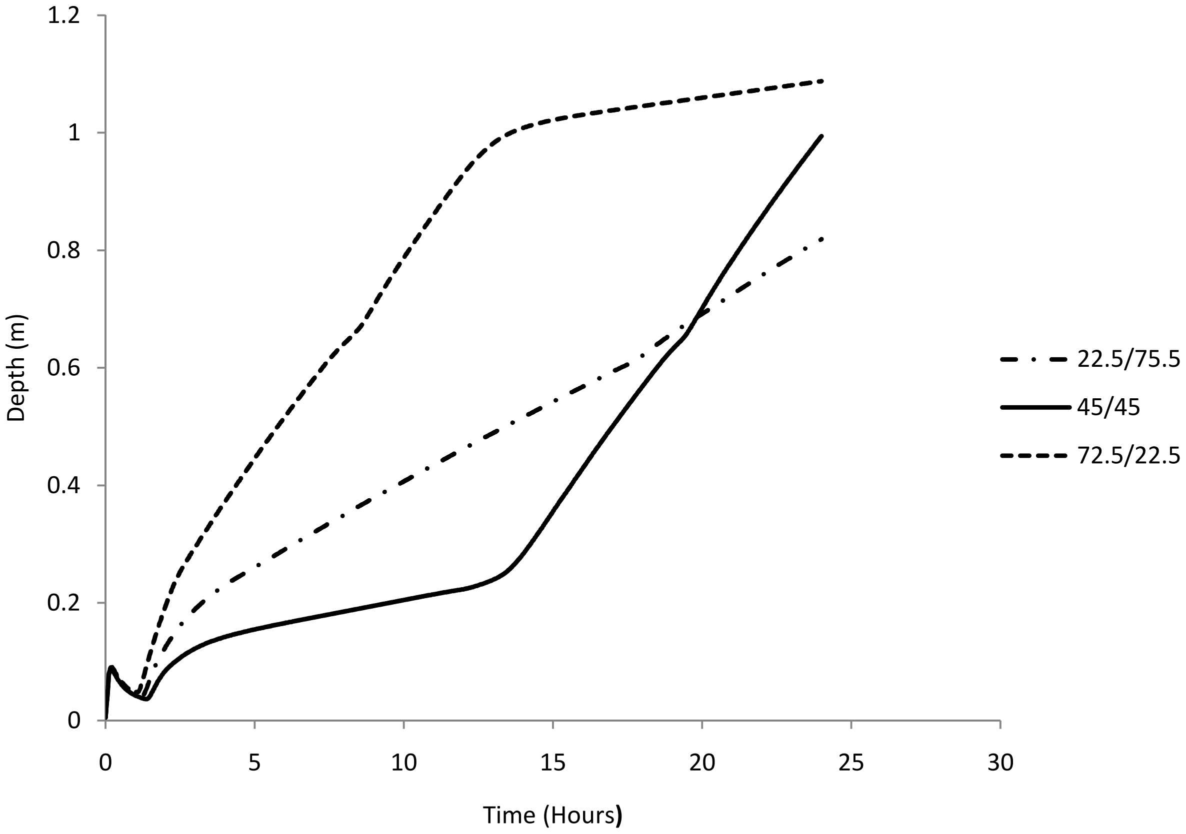


Figure 6.21 Model response to a uniform and crude time varying precipitation (mm/day) taken from point 3

Therefore it appears that a time-varying representation of precipitation has the potential to produce inundation characteristics which vary significantly from a uniform prescribed rainfall rate at a given point within a model simulation. This tentatively suggests that a time varying parameterisation may potentially offer a higher level of utility than a uniform one, particularly where the contribution of rainfall to inundation extent is required midway through a model simulation.

6.3.5 Partitioning of total rainfall delivery

It is difficult to know the optimum depth to impose across the domain at the outset of a simulation. The purpose of the initial depth is to facilitate addition of water through the course of the study. It is clear that this is not a process, intuitively it seems that the shallowest possible depth would be desirable for this purpose. Therefore here a range of different initial depths are tested in order to determine the most suitable mask. Subsequent rainfall rates are adjusted in order to ensure that the same overall net volume of water is supplied to the model domain.

Initial depth (m)	Rainfall rate (mm/day)	0	0.001	0.0011-0.0049	0.005-0.149	0.15-0.299	>0.30
0.001	0.049	1696.7	2247.7	8.0	65.0	70.1	334.4
0.005	0.045	1683.6	2055.3	447.7	765.4	256.5	375.6
0.01	0.04	1682.8	2043.7	439.1	773.6	307.8	397.0
0.025	0.025	1680.8	2035.2	388.8	765.0	375.7	455.4
0.05	0	1678.2	2054.5	201.6	721.8	429.6	518.2

Table 6.6 Areal extent (m^2) of classified flood depths (m) in response to partitioning of total water supply between initial water depth and subsequent rainfall rate (mm/day), providing a quantification of Figure 6.24

Thematic maps illustrated in Figure 6.24 and area and volume outputs from the LISFLOOD-FP mass balance file show that the model exhibits perhaps the greatest level of sensitivity to the partitioning of rainfall delivery between the initial imposed depth and rainfall rate for the remainder of the simulation. Strikingly the thematic map illustrates that no inundation in excess of the original imposed depth was present ~22 hours into the simulation (excluding within bank flows) where an initial depth mask of 0.001 m was utilised. For initial depth masks of 0.005 m and above, model response to variations in the partitioning of water between initial imposed depth and subsequent rainfall rate can be considered to be relatively coherent. Within Table 6.6 the areal extent of inundation in excess of 0.15 m depth increases progressively with initial imposed water level, whilst the reverse is true for areas characterised by depths of 0.0011-0.149 m. Therefore a simple analysis clearly reveals that the model exhibits a high level of sensitivity to initial imposed depth despite adjustment of subsequent rainfall rates in order to standardise the net input of water into the model domain.

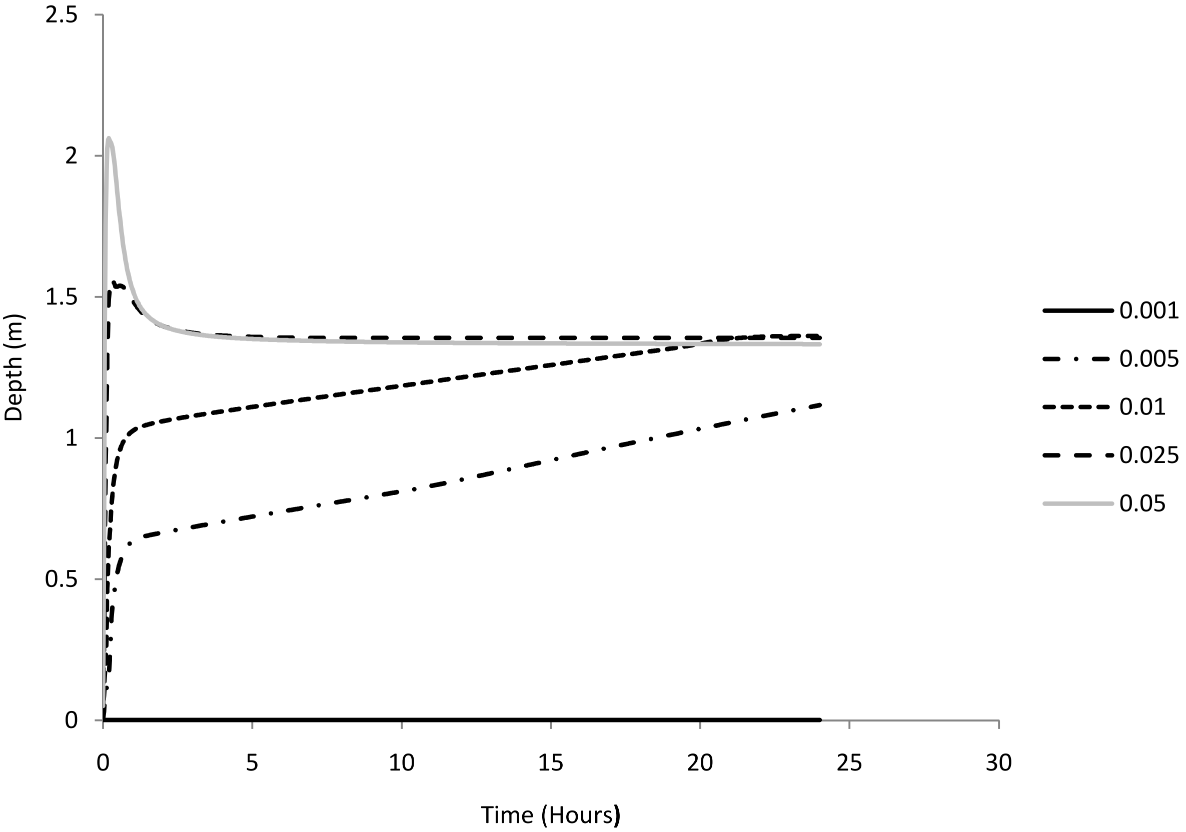


Figure 6.22 Inundation time series extracted from point 3 illustrating model response to changes in the partitioning of overall water supply to the domain between initial imposed depth (m) and subsequent rainfall rate (mm/day)

Figures 6.22 and 6.23 add weight to the notion that partitioning of greater proportions of the overall input volume of water to the initial water depth mask leads to the generation of increased flood inundation. Simulations characterised by greater initial depths are associated with a rapid initial rise in water levels, followed by a plateau for the remainder of the simulation which is characterised by a minimal change in depth.

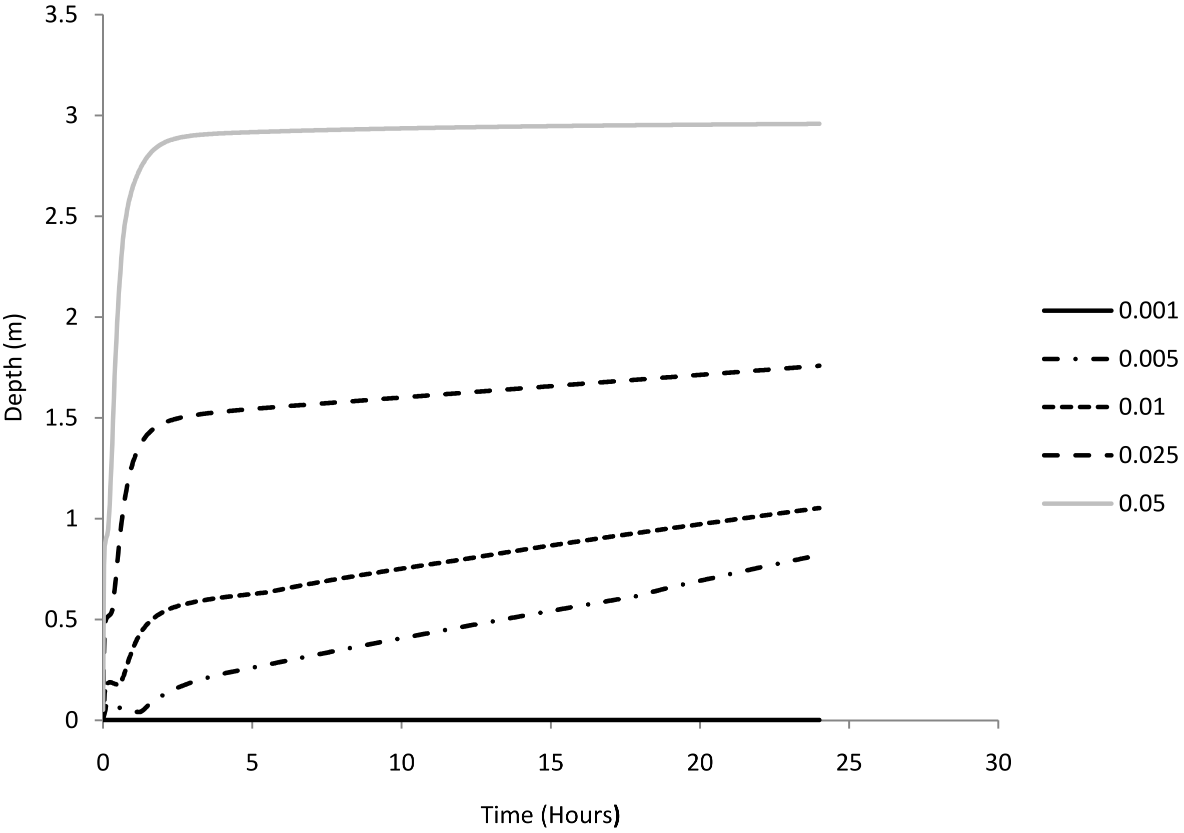
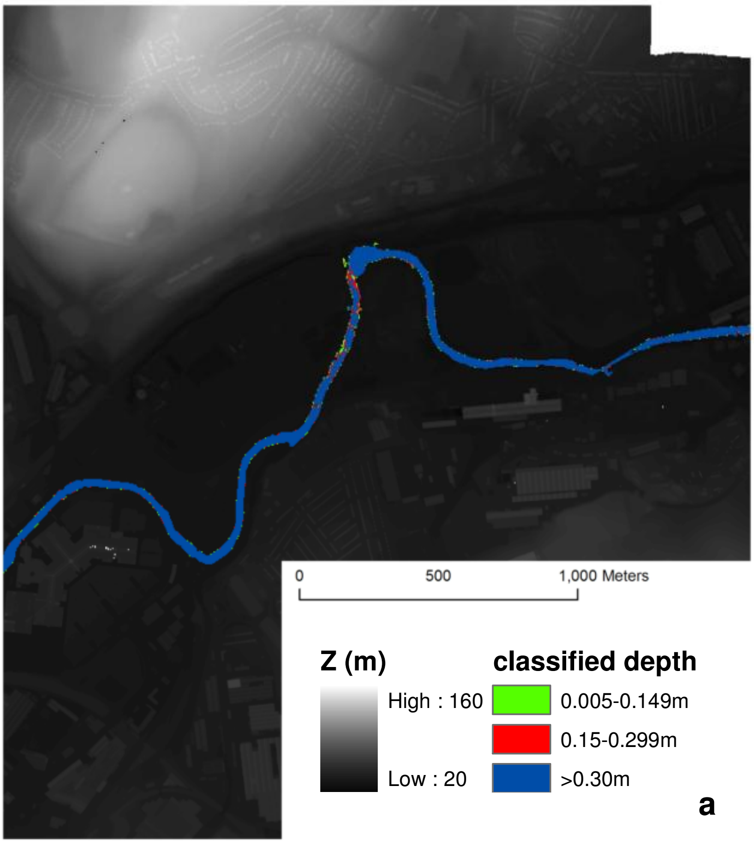


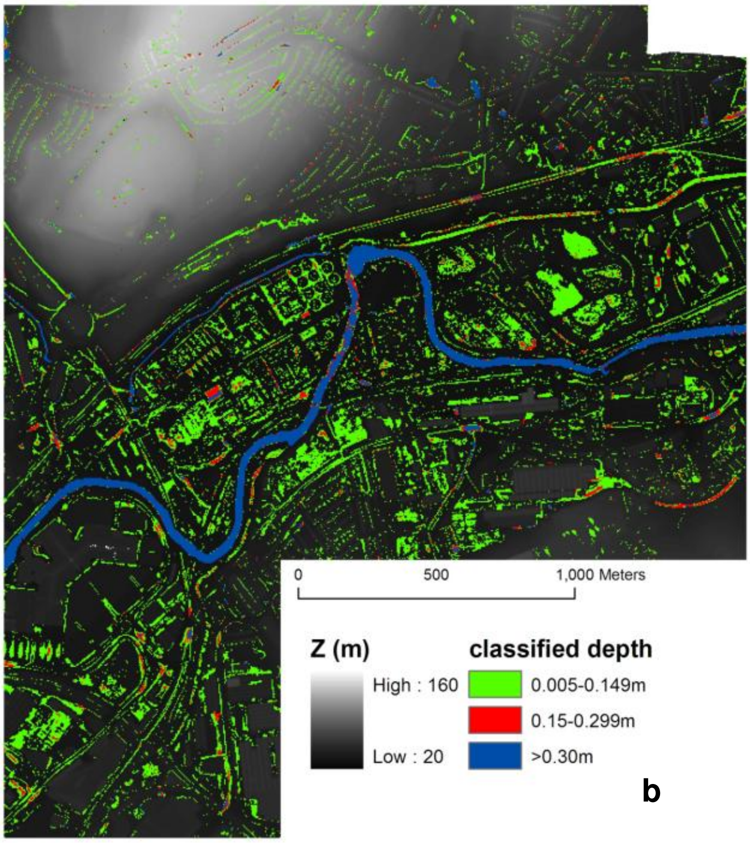
Figure 6.23 Inundation time series extracted from point 5 illustrating model response to changes in the partitioning of overall water supply to the domain between initial imposed depth (m) and subsequent rainfall rate (mm/day)

Although a rapid rise in water level is also observed at the onset of simulations where a lower proportion of overall water supply is partitioned to initial depths, this rise is of a much smaller magnitude. Intuitively, due to higher subsequent imposed rainfall rates, water depths increase steadily through the remainder of the simulation. This model behaviour is clearly evident within Figure 6.23, although overall variance in depth is limited within 6.22 due to the specific topography which precludes inundation to depths greater than 1.5 m. In addition Figures 6.22 and 6.23 confirm that the initial depth mask of 0.001 m effectively precludes addition of water to the domain through a representation of rainfall as water levels remain minimal through the course of the simulations.

Significantly, Figure 6.23 illustrates the presence of a significant disparity between the final water levels observed for these simulations. This is particularly important given that despite variance in partitioning between initial depth and subsequent rainfall rate, overall net input of water into the model domain should be identical for all simulations.

In summation it is clear that increasing the proportion of water input to the domain through the initial depth mask leads to an increase in areal extent of meaningful flood depths. Inundation depth time series, which illustrate the temporal dynamics of model response to partitioning of total input water volume (Figures 6.22 and 6.23) corroborate the basic trends illustrated within Figure 6.24. Indeed the huge disparity observed between final water levels in Figure 6.23 suggest that the class definition used for the thematic maps may not reflect the true level of sensitivity exhibited by the model.

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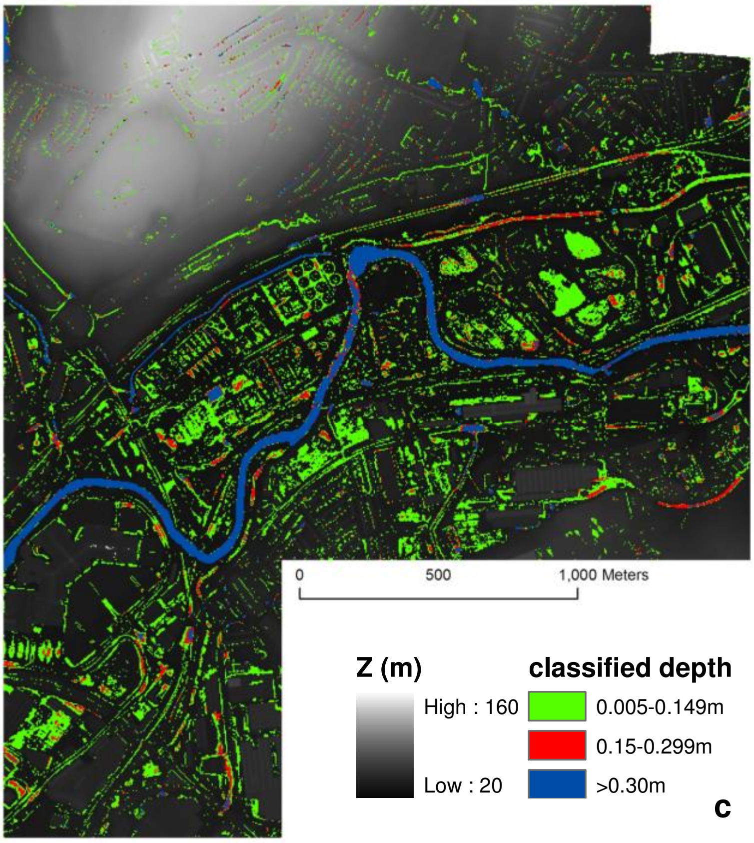
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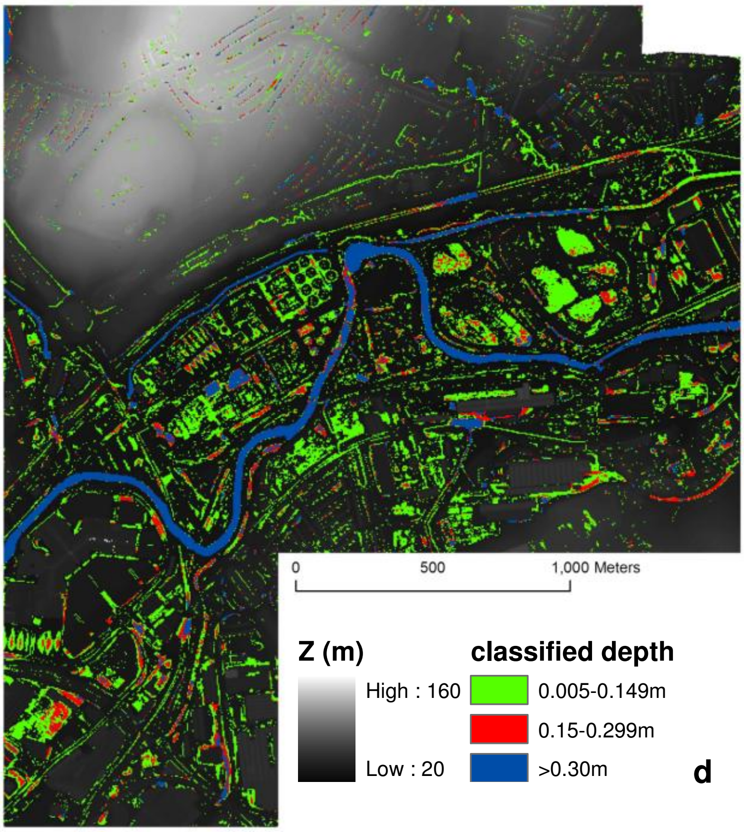


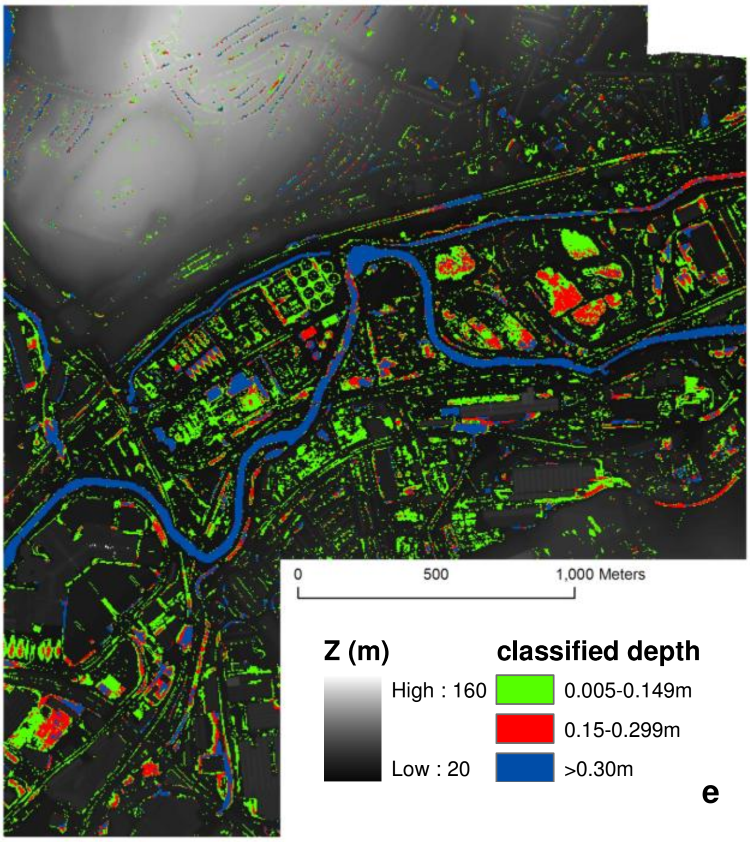


Figure 6.24 Thematic maps illustrating the areal extent of classified flood depth in response to changing partioning of total supplied water volume between the initial depth mask and subsequent rainfall rate. Taken from 80000 seconds (~22 hours) into the simulations.

The model behaviour exhibited here can be explained through the synthesis of several key observations; with perhaps the most crucial of these being the lack of inundation occurring within simulations where the initial imposed depth was 0.001 m. This lack of inundation illustrates that a water depth of 0.001 m within a given cell precludes further addition of water to that cell through a representation of rainfall. This is of pre eminent importance here as evidence suggests that initial imposed depths are quickly routed to areas of low topography, resulting in water levels of 0.001 m for large areas of the model domain very early in the simulation. This is supported by the model behaviour illustrated within Figures 6.25 and 6.26 . Figure 6.25 Illustrates the rapid decline in inundation extent at the onset of simulations, as water from the initial depth mask is quickly routed down slope. Therefore addition of water through parameterisation of rainfall is precluded within these areas, effectively reducing the overall volume of water supplied to the domain. Intuitively this effect becomes more prevalent as an increasing proportion of total water volume is partitioned to rainfall rate, this is reflected in the results which have been elaborated within this chapter.

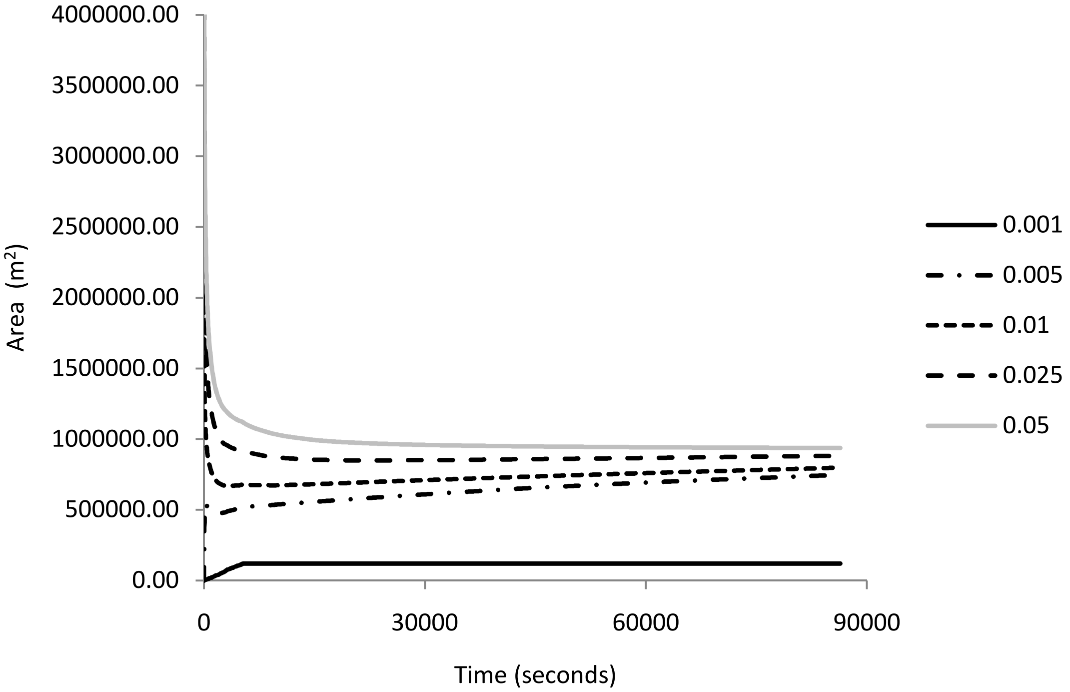


Figure 6.25 Inundation area for simulations with changing partitioning of total supplied water volume between the initial depth mask (shown in legend) and subsequent rainfall rate, taken from LISFLOOD-FP mass balance file.

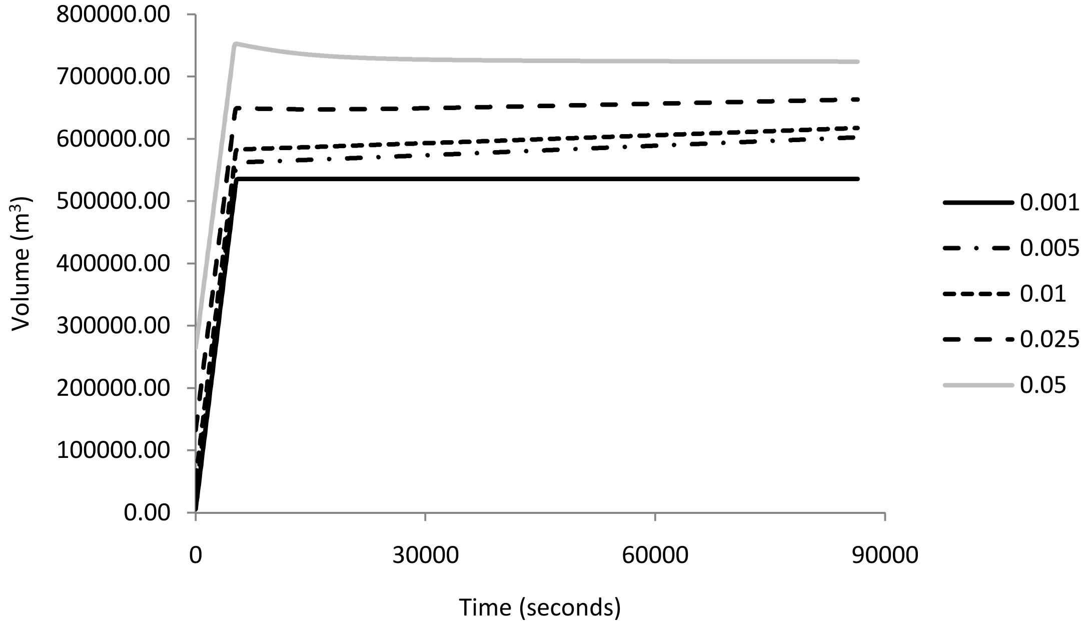


Figure 6.26 Volume of water in model domain for simulations with changing partitioning of total supplied water volume between the initial depth mask (shown in legend) and subsequent rainfall rate, taken from LISFLOOD-FP mass balance file

6.4 Summary

This chapter provides a thorough description of the development of the best available representation of rainfall and subsequent testing of LISFLOOD-FP model response, elucidating further important model behaviour when attempting to represent surface flows and inundation in response to rainfall. Grid resolution appears to be particularly significant in terms of providing a topographical representation of structures, which impart a significant influence upon routing of flows. The dynamics of flow routing are less clear within this analysis. There is some evidence of time step dependence ie Figure 6.11, illustrating the influence of the flow limiter and hence a potentially unrealistic representation of surface flow dynamics. However Figures 6.15 and 6.16 clearly illustrate significant sensitivity to floodplain friction, which illustrates that the flow limiter may not be as influential as for overbank flows. This is somewhat surprising given the widespread influence of the flow limiter observed previously within this study and can be attributed to the shallow flow depths and lower velocities associated with flows sourced from precipitation input.

In addition to model sensitivity, it is important to consider the physical realism and general applicability of the improvised method of representing precipitation. Initial testing within 6.2 suggested that an improvised representation of precipitation, through negative manipulation of the evaporation term in conjunction with a refined initial depth mask offered a physically realistic, time varying method by which to parameterise rainfall. However subsequent results have suggested that the total volume of precipitation supplied to the domain is not invariant with respect to partitioning of overall rainfall totals between the initial depth mask and subsequent rainfall rate, as illustrated within Figure 6.25.

Effectively, the improvised representation of precipitation based upon negative manipulation of the infiltration/evaporation terms within LISFLOOD-FP is unable to effectively reconcile total volume and rate of rainfall. This has significant implications when attempting to determine the contribution of rainfall to a real flood event within the following chapter. Therefore, although a point based representation of rainfall using the .bci file may have been more difficult to set up initially, this method may offer greater potential in providing an accurate time varying representation of precipitation. Importantly, point inputs of water using this method are not dependent upon cells being wet, thus allowing rate and overall volume of rainfall to be reconciled.

Chapter Seven

Contribution of rainfall to an observed flood event: Sheffield 2007

7. Contribution of rainfall to an observed flood event: Sheffield 2007

7.1 Introduction

In order to determine the potential contribution of rainfall to the June 2007 flood event and urban flooding more generally, the optimum calibration established in chapter six was parameterised with a representation of precipitation based upon the approach developed within the previous chapter. Six model simulations were undertaken, reflecting three two day rainfall events observed within June 2007 (Table 7.1). Within this set of simulations all boundary conditions and parameters remained constant, thus ensuring that any variation in model response could be attributed directly to inputs from precipitation.

Simulations one and two were associated with rainfall levels recorded in Sheffield on the 25th and 26th June, this corresponds to the period of the hydrograph used as a boundary condition within calibration, thus facilitating an assessment of the contribution of rainfall to the actual flood event. Simulations three and four correspond to a very high magnitude precipitation event which occurred on the 15th and 16th of June, whilst precipitation totals for simulations five and six are taken from a precipitation event of lower magnitude which occurred on the 22nd and 23rd of June. This range of simulations was undertaken in order to determine the potential contribution of rainfall of varying intensities to flood inundation. It is important to note that daily rainfall totals were taken from a BADC MIDAS located approximately 5 km south west of the study area. Rainfall was assumed to occur at a constant rate within the 24 hour period and as model simulations were 38 hours in duration, rainfall totals were adjusted to reflect this.

It is important to note that the results produced here will be used in order to make inferences and conclusions regarding the potential contribution of rainfall to the flood event which occurred on the 25th-26th June 2007 within Sheffield. Therefore it is important to acknowledge the key assumption implicit within this application of LISFLOOD-FP. For the purposes of this study it is assumed that no infiltration or removal of surface water through drains occurs for the duration of the simulations. Therefore, effectively 100% of the precipitation received within the domain is converted to surface run off. This assumption is necessary here as it is impossible to account for the influence of drainage systems within LISFLOOD-FP. Although this assumption is clearly a significant one due to the preeminent influence which drainage systems impart upon the routing of water within urban areas (Aronica and Lanza, 2005), it is justified in light of the hydrologic conditions experienced within the city of Sheffield during the 25th and 26th of June 2007. Environment Agency (2007) state that high levels of rainfall (Figure 7.1) and elevated stages in the Don observed within the period prior to the 25th of June left the cities drainage system exceptionally sensitive to further addition of water. Therefore the onset of high intensity rainfall, in combination with a rapid rise in the stage of the Don experienced on the 25th June, led to rapid overwhelming of the cities drainage system (Environment Agency, 2007). Therefore the assumption of 100% run off conversion is justified for the relatively short (38 hour) duration of these model simulations.

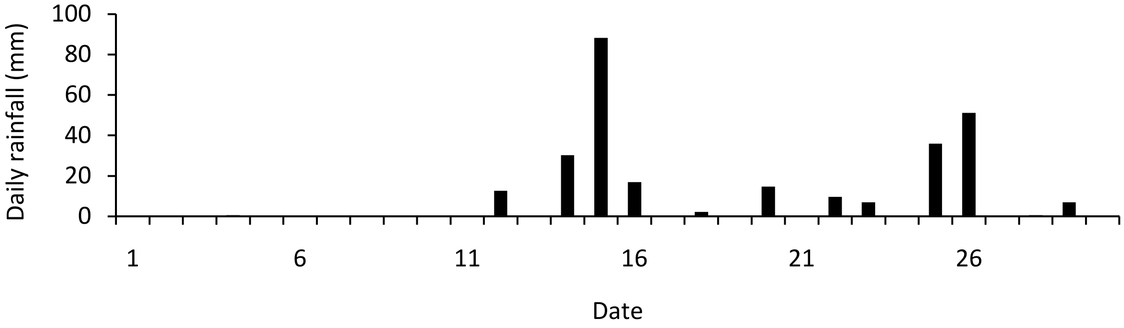


Figure 7.1 Daily rainfall recorded at UKMO MIDAS station within Sheffield, located approximately 5km south west of the study area, for June 2007.

It is also important to consider the issues faced within the previous chapter when attempting to derive the most appropriate representation of rainfall within LISFLOOD-FP. Development and testing elucidated that providing a physically realistic representation of precipitation can be considered relatively problematic without a model recode, predominantly due to the proliferation of areas of shallow depths (0.001 m) which effectively preclude addition of further water to the domain. This has resulted in the proliferation of a predicament in which an adequate representation of total volume and rate of rainfall is unable to be reconciled. More specifically, a physically realistic representation of rainfall rate results in a significant underestimation of the total volume of water supplied to the domain. A solution to this problem was found through supplying the total volume of rainfall at the onset of the simulation through the initial depth mask, although this is clearly also inherently problematic as it provides a poor dynamic representation of rainfall.

Given that neither of these approaches can be considered physically realistic and are inherently problematic, each two day rainfall scenario is represented by both of the aforementioned rainfall representations within this analysis.

Simulation number	Date rainfall (June 2007)	Total precipitation (mm)	Initial depth (mm)	Rainfall rate 0-24 hours (mm/day)	Rainfall rate 24-38 hours (mm/day)
Original	n/a	0.0	0.0	0.0	0.0
1	25/26	65.8	65.8	0.0	0.0
2	25/26	65.8	10.0	26.0	51.1
3	15/16	98.1	98.1	0.0	0.0
4	15/16	98.1	10.0	78.2	16.9
5	22/23	13.6	13.6	0.0	0
6	22/23	13.6	10.0	0.0	6.5

Table 8.1 Simulations of the calibrated model for flood event occurring on the 25th/26th June 2007, including observed rainfalls corresponding to this flood event (1 and 2), along with two other two day rainfall totals from June 2007.

7.2 Areal extent of inundated areas

Table 7.1 and Figures 7.2-7.8 illustrate the areal extent of different flood depths within the model domain for simulations one to six. Comparison of the areal extent of flood inundation produced by simulations with varying levels of precipitation and the original calibration simulation constitutes a relatively simple method to assess the potential contribution of rainfall to flood inundation within urban areas. It is important to note that these Figures and associated statistics are derived from flood inundation characteristics at the end of the simulation corresponding to the time of capture of aerial imagery used for validation at 14:00 on 26th June 2007. Therefore this snapshot provides an estimation of the overall synoptic contribution of precipitation to flood inundation.

A more in depth assessment of the dynamic contribution of rainfall is rendered inappropriate here for a number of reasons; Firstly, model validation revealed that the fixed time step implementation of LISFLOOD-FP used here is effectively reproducing the synoptic extent of inundation, although is associated with a poor representation of the dynamics of inundation. Hence, it seemed appropriate to assess the contribution of rainfall at the time of imagery used for calibration. In addition, the inability to provide a physically realistic representation of rainfall within LISFLOOD-FP renders a dynamic assessment of precipitation contribution more problematic. Therefore it is clear that assessing the bulk contribution of rainfall to flood inundation represents the most defensible approach to addressing the research questions and hypotheses in this study.

An initial assessment of Table 7.2 reveals that where rainfall is included within the model there is a considerable decrease in the spatial extent of areas associated with no inundation, typically up to 1000 m^2. As would be expected from prior model testing, representation of precipitation within these simulations results in a large increase in the spatial extent of areas with the minimum depth of 0.001 m when compared to the original calibration simulation. However the increase in spatial extent of minimum depths which are observed within these simulations can be regarded as a largely insignificant relic of the rainfall representation. In order to assess the true contribution of rainfall to inundation within urban areas it is necessary to place a greater emphasis upon more significant flood depths. Significant flood depths are those which exceed the minimum depth threshold, particularly those above 0.30 m, which is generally considered to be the threshold depth required for inundation of buildings.

Simulation	0	0.001	0.0011-0.0049	0.005-0.149	0.15-0.299	>0.30
Original	2641.5	672.0	105.5	341.3	267.5	650.8
1	1673.1	1998.7	191.0	680.6	462.0	738.1
2	1678.6	1964.5	445.7	750.8	380.7	683.8
3	1670.0	1992.2	191.5	666.2	456.8	777.9
4	1677.8	1987.2	317.7	717.2	424.6	701.8
5	1678.9	2041.1	194.6	683.4	337.6	669.8
6	1679.4	2044.4	225.7	675.9	321.4	664.0

Table 7.2 Areal extent (m^2) of classified flood depths (m) for simulations 1-6

7.2.1 Observed flood event in Sheffield 25th-26th June 2007

A comparison of the extent of meaningful flood depths associated with the original calibration and simulations one and two enables an assessment of the potential contribution of precipitation to inundation for the real flood event which occurred on the 25th and 26th June 2007. This 38 hour event was characterised by a high peak discharge, in addition to high rainfall intensities- 36.0 mm/day from 0-24 hours and 51.1 mm/day from 24-36 hours, with a total rainfall contribution of 65.8 mm for the simulation. As expected the addition of precipitation is somewhat problematic as the two different representations of rainfall lead to markedly different synoptic inundation characteristics (Table 7.2, Figures 7.3,7.4) Given that this analysis is unable to elucidate the dynamic precipitation contribution, the benefits offered by the physically realistic rainfall rate within simulation two are effectively minimised here. Therefore it seems that simulation one, which is characterised by bulk addition of the entire volume of rainfall within the initial depth mask, is likely to reflect the true contribution of precipitation most appropriately within this analysis.

Accordingly, analysis of Table 7.2 illustrates that simulation one produces a significantly greater areal extent of deeper flood waters than simulation two. Indeed this simulation results in an increase in flooded areas >0.30 m and 0.15-0.299 m, of ~80 m^2 and 190 m^2 respectively when compared to the original calibration simulation. By contrast, within simulation two the increase in areal extent of flooding of equivalent depths is smaller at ~30 m^2 and 113 m^2. Comparatively the spatial extent of lower water depths (0.0011-0.149 m) is more extensive within simulation two, although it is clear that this difference is attributable to the representation of precipitation within these two simulations. It is hypothesised that the continual supply of rainfall within simulation two means that a significant volume of water is in the process of being routed at the end of the simulation when these statistics were extracted, thus explaining the more extensive areas of shallow flood inundation.

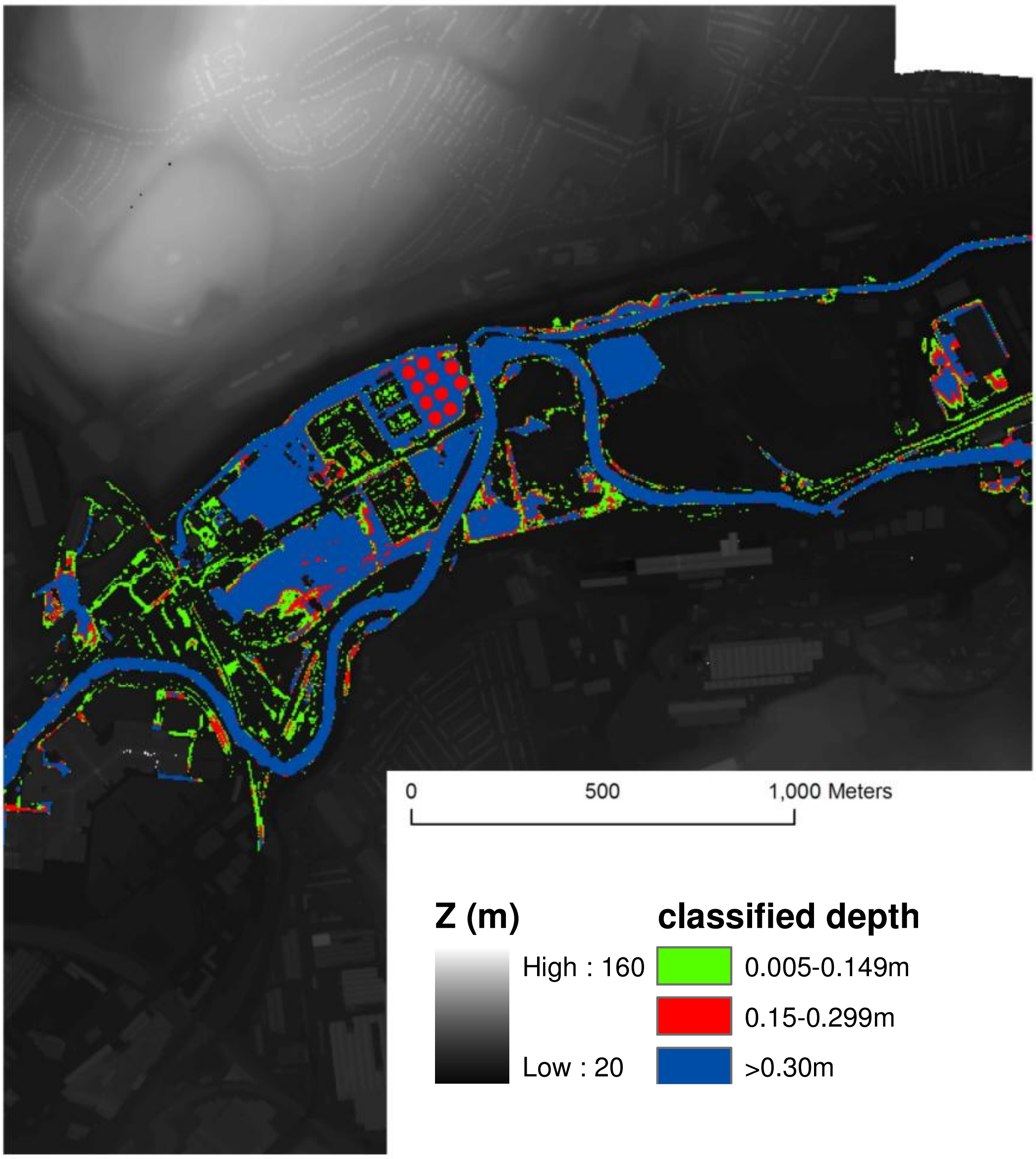


Figure 7.2 Thematic map illustrating the areal extent of classified flood depths for the original calibration simulation

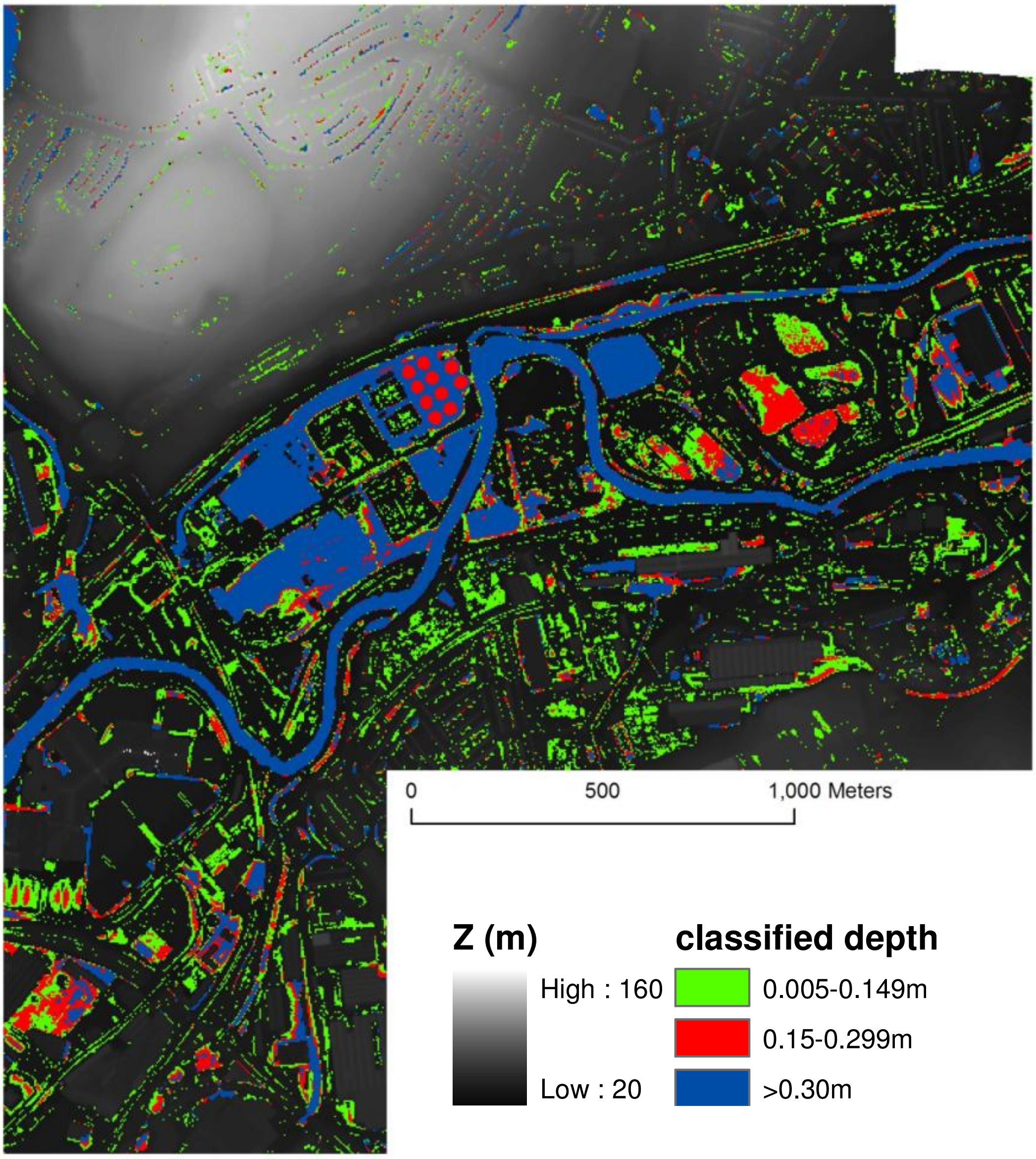


Figure 7.3 Thematic map illustrating the areal extent of classified flood depths for simulation 1

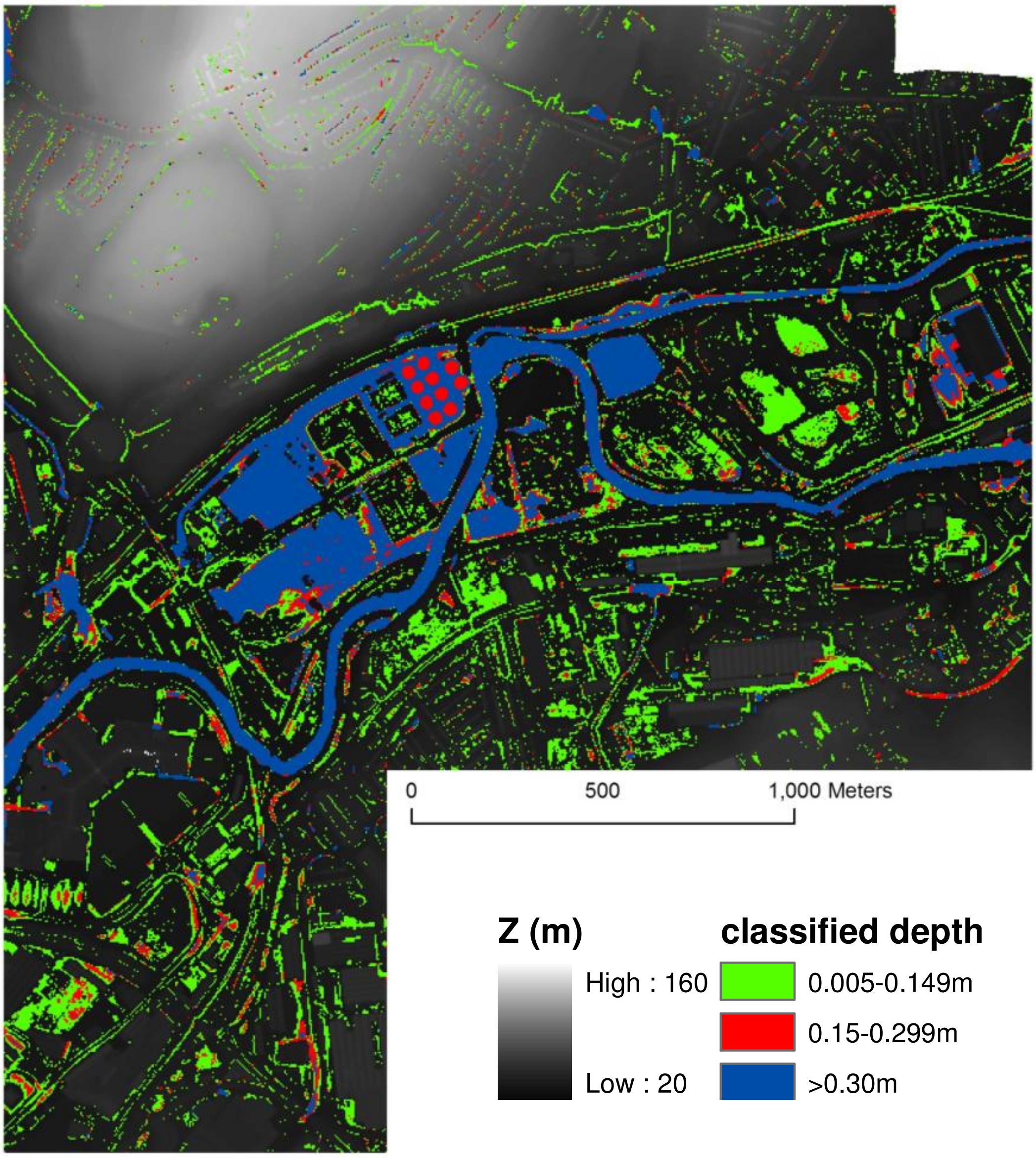


Figure 7.4 Thematic map illustrating the areal extent of classified flood depths for simulation 2

Overall, from this simplistic analysis it is clear that both representations of precipitation clearly lead to an increase in the areal extent of meaningful flood depths within the model domain for the June 2007 flood event. Simulation one, which is thought to represent the total supply of precipitation to the domain more appropriately, appears to be associated with a more marked increase in overall inundation extent/depth. However it is important to note that the nature of this analysis fails to consider inundation dynamics and hence masks the lack of physical realism associated with this approach.

It has been established that the high levels of precipitation associated with the modelled flood event which occurred on the 25th/26th June yielded an increase in the spatial extent of meaningful water depths. Subsequently a more detailed visual analysis of Figures 7.2-7.4 facilitates the identification of the spatial distribution of areas which became inundated in response to rainfall parameterisation. These thematic maps illustrate that a representation of precipitation leads to a distinctive model response in terms of the spatial distribution of inundated areas. Areas of insignificant flow depth (>0.005) are removed from the maps in order to facilitate a clearer representation of more significantly flooded areas. A basic visual analysis of Figures 7.2-7.4 reveals that flood inundation in response to rainfall is characterised by relatively localised areas of significant depth, which are distributed across the entire model domain.

Meaningful flow depths produced in response to rainfall occur both within the limits of the traditionally defined floodplain and also on the valley sides. However, within both of these geomorphologically distinct areas pooling occurs within locations which are conducive to accumulation of flow, for example topographical depressions or in locations where structural features lead to the blockage of flow down slope. Therefore these results suggest that surface run off produced in response to precipitation is routed strongly according to local topography. The widespread proliferation of flow accumulation on some of the valley slopes within the domain suggests that a significant volume of water sourced from rainfall was retained in locations close to its original source within the June 2007 flood event.

However within some regions of the study area, for instance the relatively steep slopes on the north side of the model domain, it is clear that that local topography is not conducive to retaining water. This is indicated by the lack of inundation observed within these areas at the time of aerial imagery. Intuitively this suggests that some areas of the domain, particularly those characterised by steep topography, are likely to supply water to the region of the floodplain. However given that analysis of the dynamic contribution of rainfall is not considered here it was not possible to quantify the precise nature of spatial fluxes of water.

Therefore from analysis of thematic maps and associated areal statistics it is clear that a representation of rainfall leads to a modest but potentially significant increase in inundation which occurred on 25th-26th June 2007. The thematic maps (Figures 7.2-7.4) suggest that increases in flood inundation both inside and outside the limits of the traditionally defined floodplain, where local topography is conducive to flow accumulation. Consequently this suggests that precipitation was able to contribute to fluvial flooding in addition to inundation independent from the river channel. However, the classes used within the thematic maps make determination of the contribution of rainfall to fluvial flooding problematic.

7.2.2 Other rainfall intensities experienced within June 2007

Simulations three to six were undertaken in order to assess the potential contribution of varying levels of precipitation to inundation during an overbank flood event. These simulations are characterised by the same hydrograph and model set up as simulations one and two, although are parameterised with rainfall totals selected from two other rainfall events of markedly different intensities which occurred within June 2007 (Table 7.1). Therefore unlike the previous analysis, the precipitation levels used here do not correspond to the observed hydrograph and hence do not represent a real flood event. The purpose of these simulations is largely as a test, in order to determine the contribution of varying precipitation intensities to urban flooding. Again these simulations are reliant upon the assumption of critical drainage and 100% run off.

Simulations three and four corresponded to a very high intensity rainfall event which occurred on the 15th and 16th June 2007. Table 7.2 illustrates that this two day period constitutes the highest overall contribution of precipitation at 98.1 mm, this is partitioned into rainfall rates of 88.2 mm/day for 0-24 hours and 16.9 mm/day for 24-38 hours. Accordingly this can be regarded as an extremely high magnitude summer rainfall event. Simulations five and six were associated with a rainfall event of a much lower intensity which occurred on the 21st/22nd June 2007, which is characterised by rainfall rates of 9.6 mm/day- 0-24 hours and 6.9 mm/day- 24-38 hours. This can therefore be classified as a much lower magnitude precipitation event, with a greater likelihood of occurrence through the summer months.

On a basic level these sets of simulations illustrate the same response to representation of rainfall as simulations one and two, with the domain being characterised by large areas of minimal flood depths (Table 7.2), whilst more significant flood inundation is localised (Figures 7.5-7.9). Analysis of Table 7.2 and Figures 7.2-7.9 further illustrate the contrast between the different methods of representing rainfall. It is important to notice that the increase in meaningful inundation extent produced within simulation one was higher than that for simulation four, despite the disparity in the rainfall totals for the two day periods. This shows that the method of representing rainfall is of preeminent importance here.

Intuitively, the high rainfall totals associated with simulations three and four produce a significant increase in the areal extent of meaningfully flooded areas which supersedes that observed within simulations one and two. Indeed the areal extent of areas flooded to a depth>0.30m is 779.9 m^2, this exceeds the original calibration simulation by ~127 m^2 and simulation one by ~40 m^2. Table 7.2 illustrates that simulations five and six are associated with a much smaller contribution from precipitation. Indeed total supplied rainfall volume of 13.6 mm leads to an increase in flood depths >0.30 m of only ~19 m^2 and 13 m^2 for simulations five and six respectively. For depths of 0.15-0.299m the observed increase in spatial extent is ~70 m^2 and 45 m^2 for simulations five and six respectively. Therefore increases in inundation extent in response to the lower rainfall intensities within simulations five and six are very small and can be considered largely insignificant.

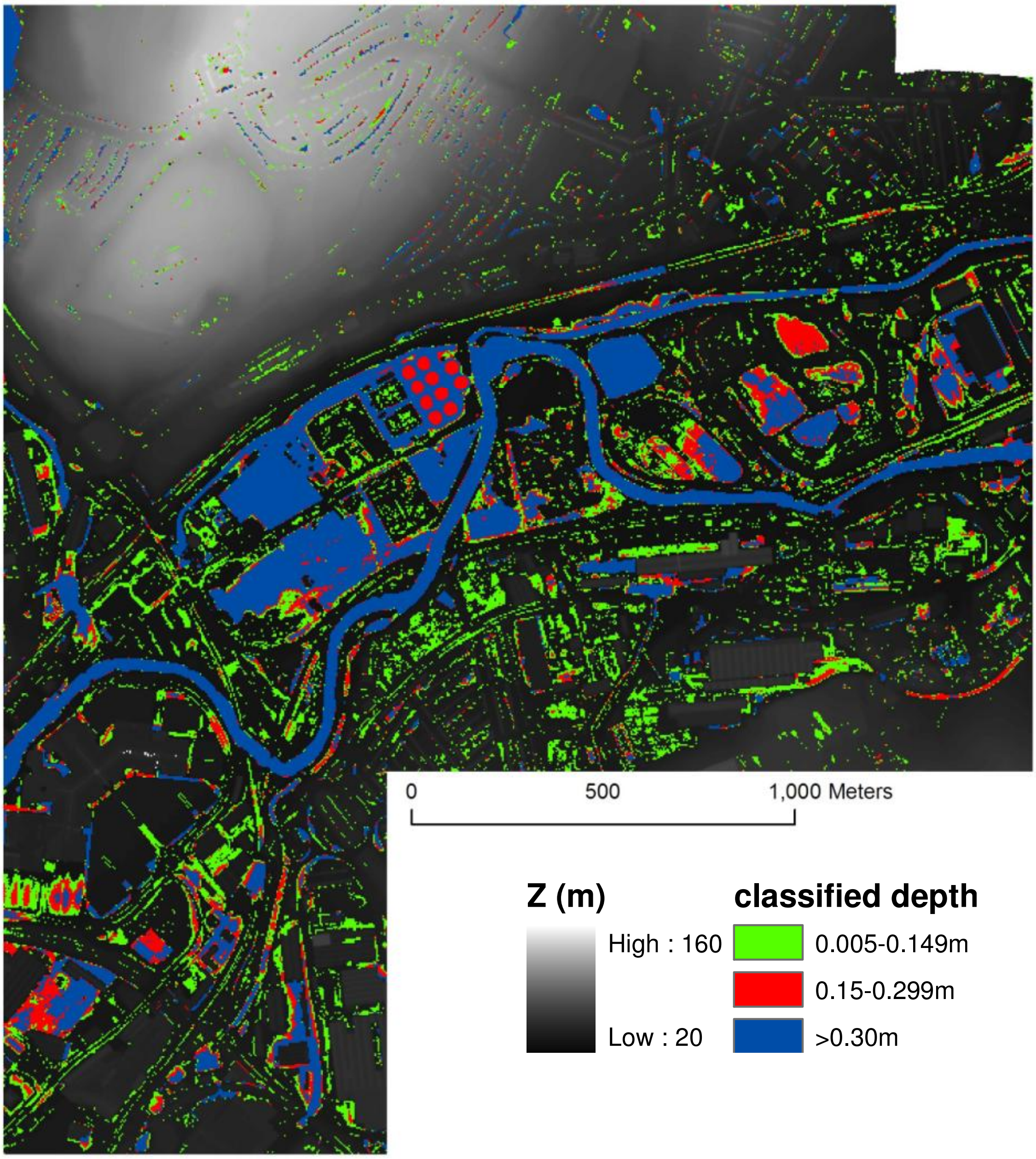


Figure 7.5 Thematic map illustrating the areal extent of classified flood depths for simulation 3

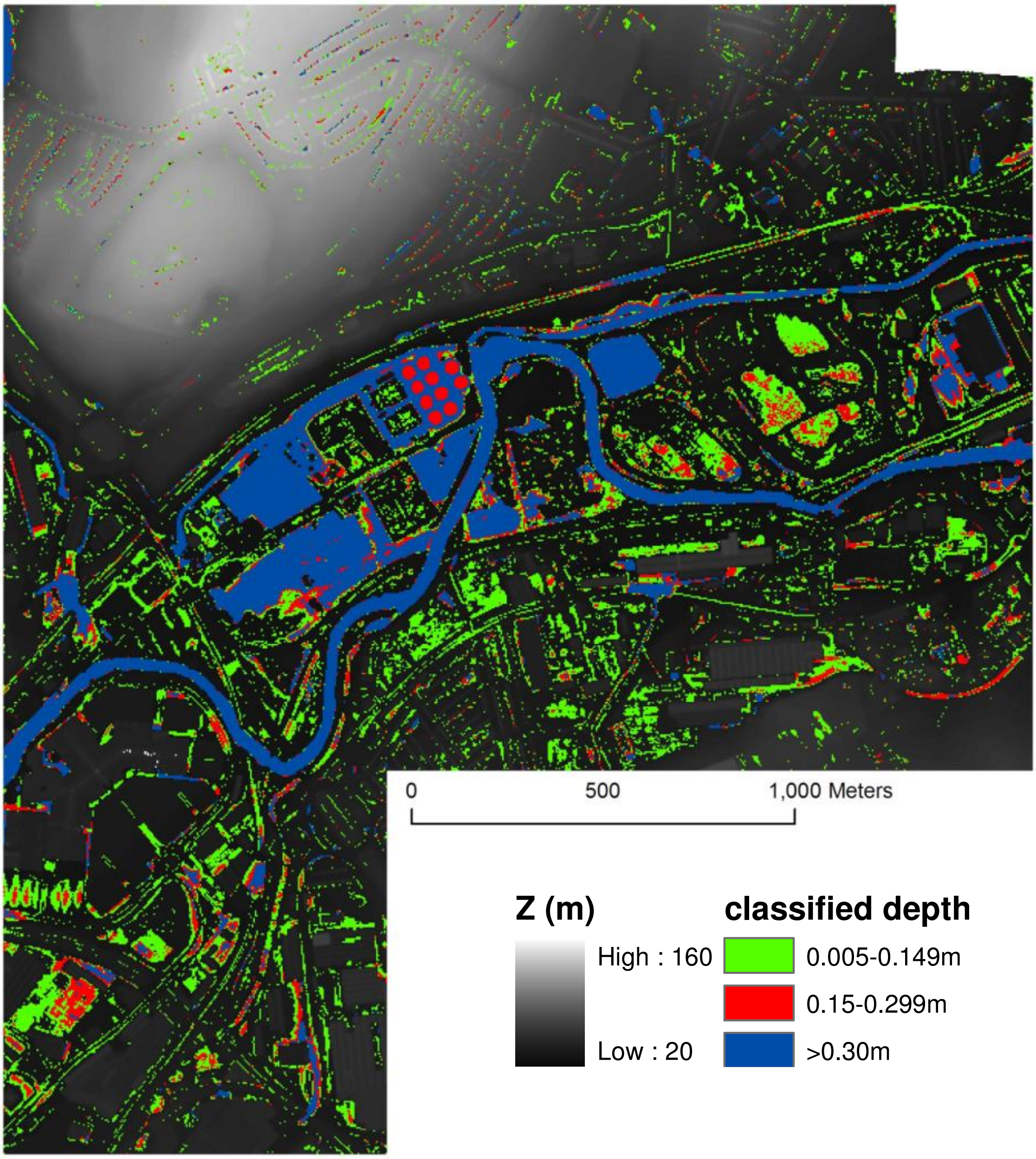


Figure 7.6 Thematic map illustrating the areal extent of classified flood depths for simulation 4

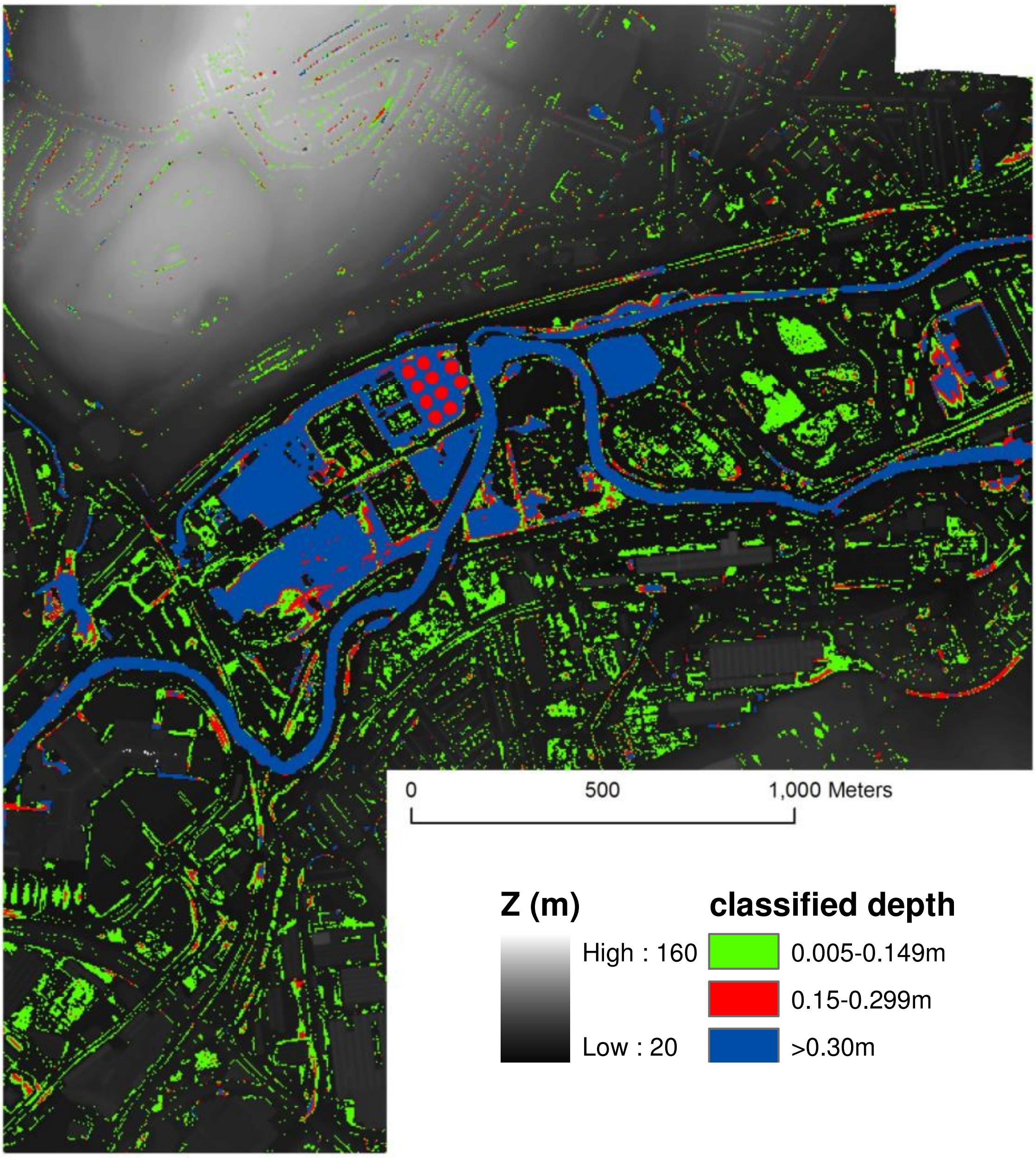


Figure 7.7 Thematic map illustrating the areal extent of classified flood depths for simulation 5

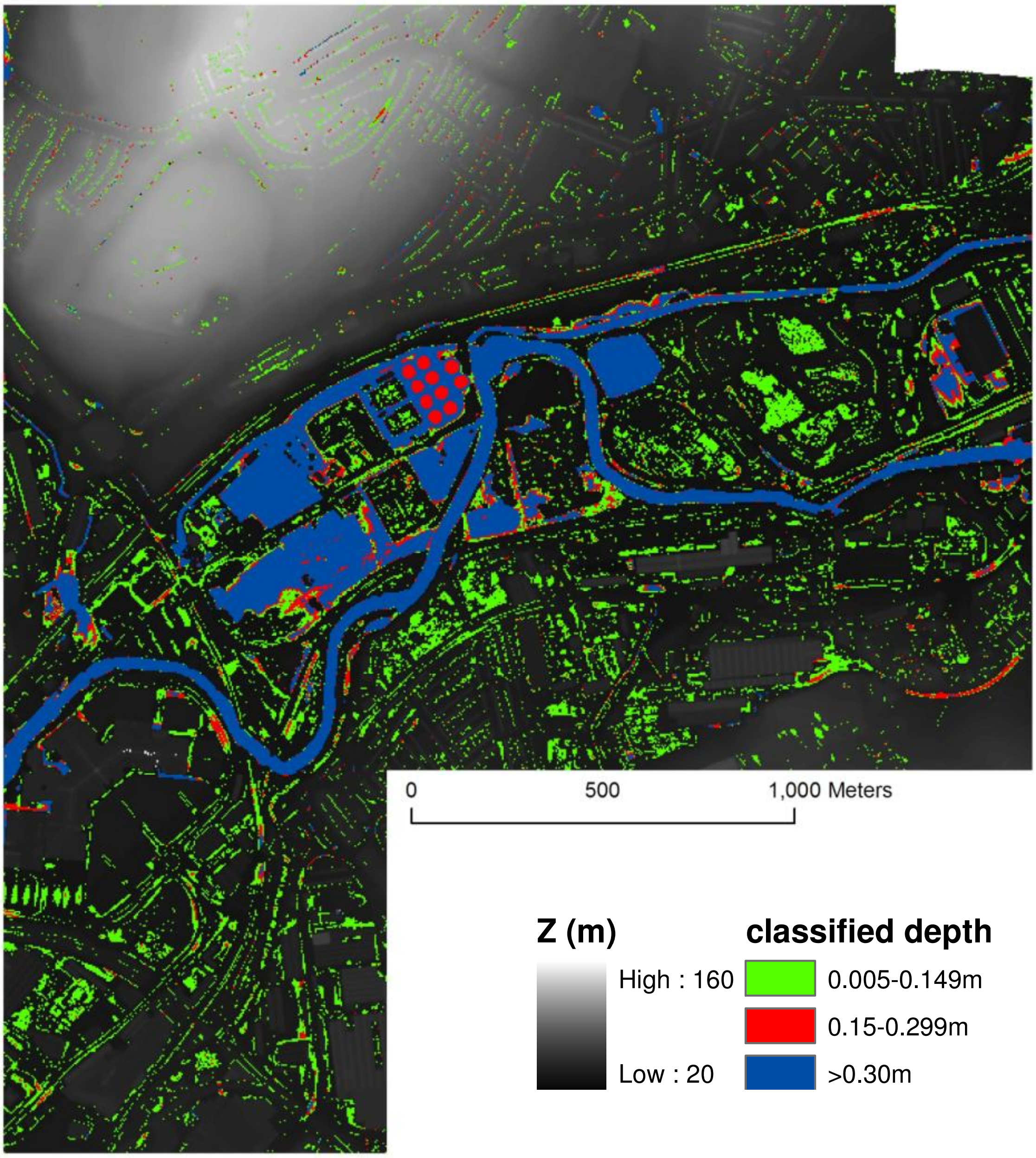


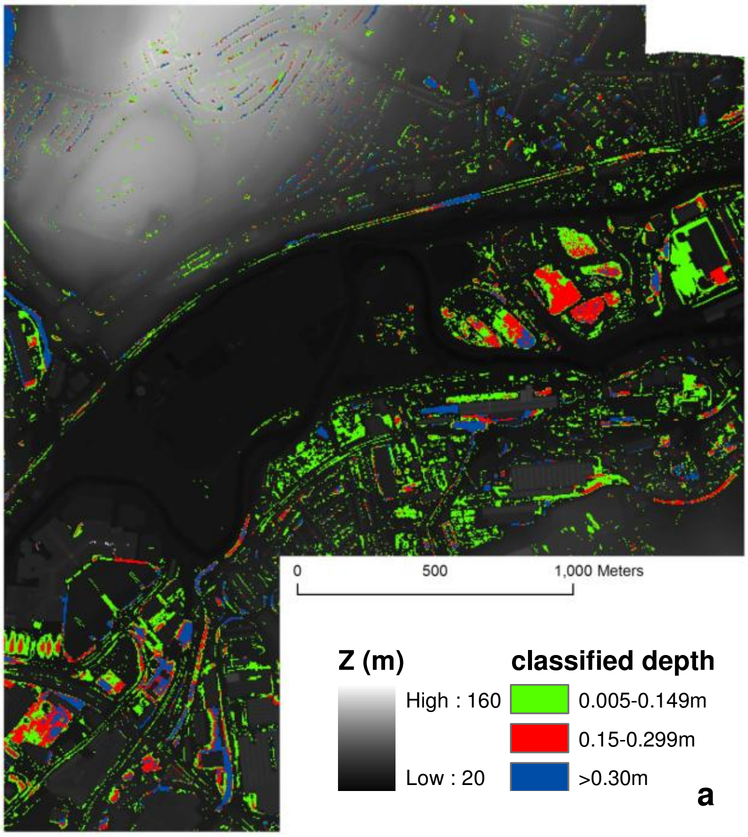
Figure 7.8 Thematic map illustrating the areal extent of classified flood depths for simulation 6

7.3 Contribution of precipitation to fluvial flood inundation

The results illustrated within the previous sections have demonstrated that a representation of rainfall is associated with a localised, but potentially significant contribution to flood inundation within the domain. This was witnessed for both the observed flood event which occurred 25th-26th June 2007 and the test scenario. Visual analysis of Figures 7.2-7.9 suggest that the contribution of precipitation is most marked within areas which were not flooded within the original optimum calibration simulation. However, it became apparent that in some areas water supplied through rainfall was not retained on the valley sides, suggesting that precipitation may have contributed to fluvial inundation within the June 2007 flood event. However due to the classification scheme used within the thematic maps it was difficult to elucidate the magnitude of this contribution.

Therefore in order to facilitate the elucidation of the contribution of rainfall to these areas, Figure 7.9 was generated. Figure 7.9 comprises a set of images which have been produced through subtraction of the grid of water depths for the original calibration simulation from the grid of water depths produced by simulations one to six. Intuitively, this provides a visual representation of the contribution of rainfall to flooding in excess of that observed for the original calibration simulation at the time of aerial imagery.

An initial visual analysis of Figures 7.9 reveals some clear patterns in the contribution of precipitation to fluvially flooded areas. First, where 100% of rainfall is supplied to the domain through the initial mask (a,c,e) the lack of depth variation in areas of overbank flooding indicates that the contribution of precipitation can be considered minimal. In comparison (b,d,f), which correspond to simulations in which precipitation is supplied at a physically realistic rate, do indicate some contribution from precipitation to areas of overbank flooding. However even within b,d and f, the overall contribution of rainfall to fluvially flooded areas appears to be relatively small in comparison to areas which do not experience overbank flooding.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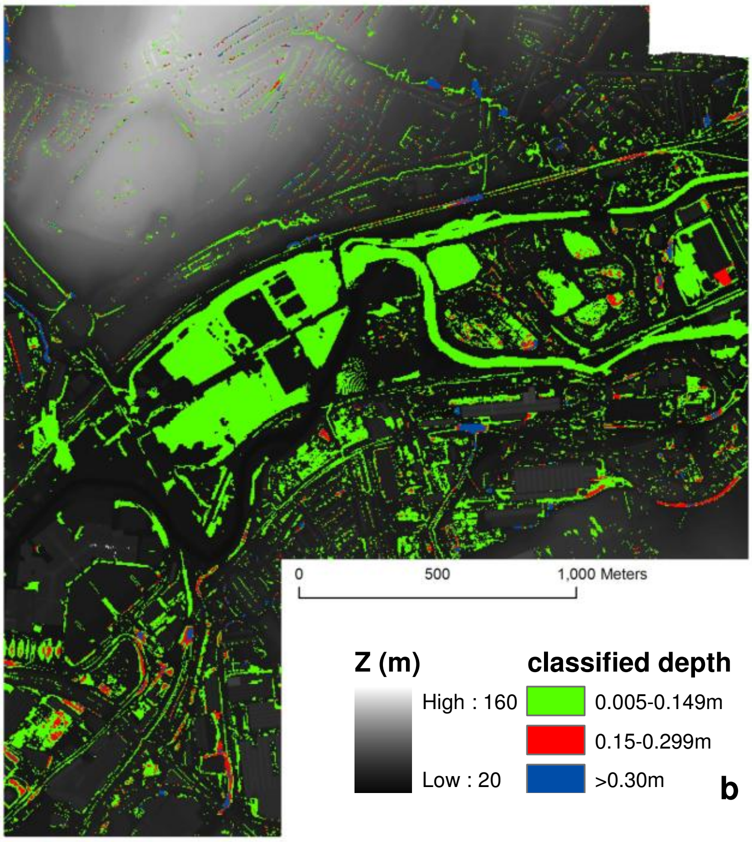
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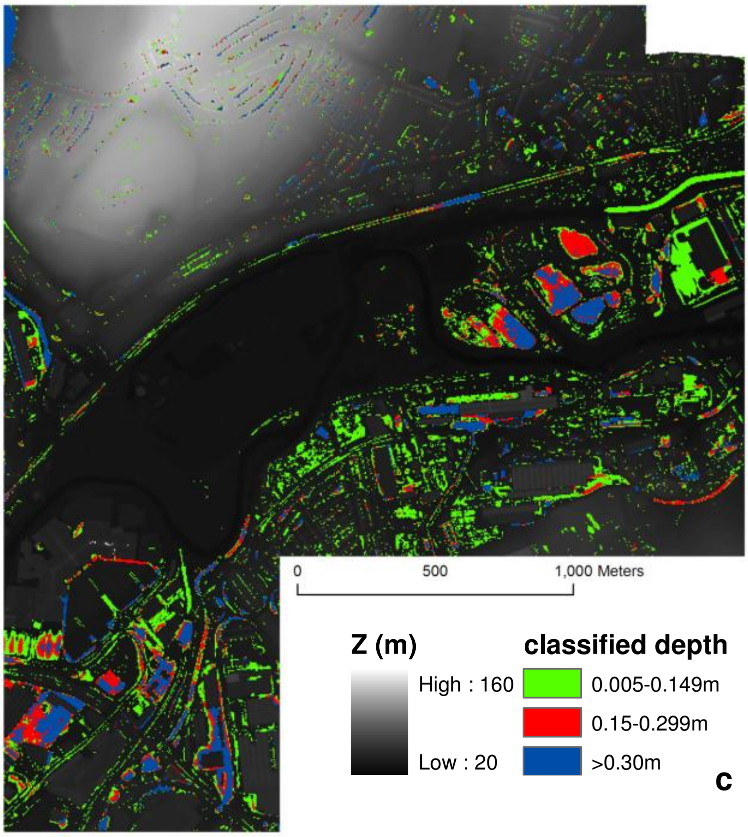
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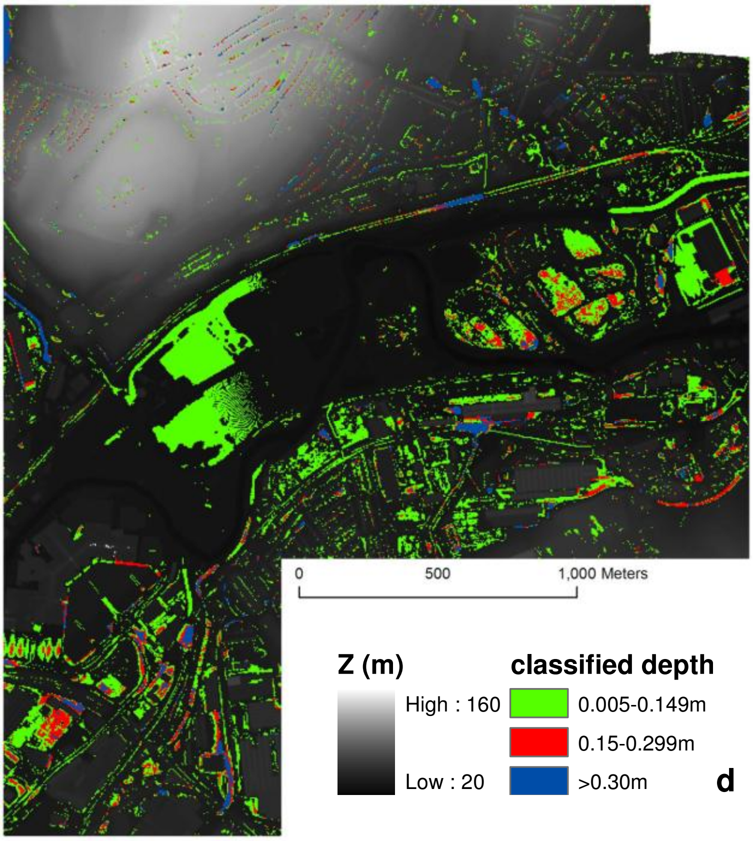
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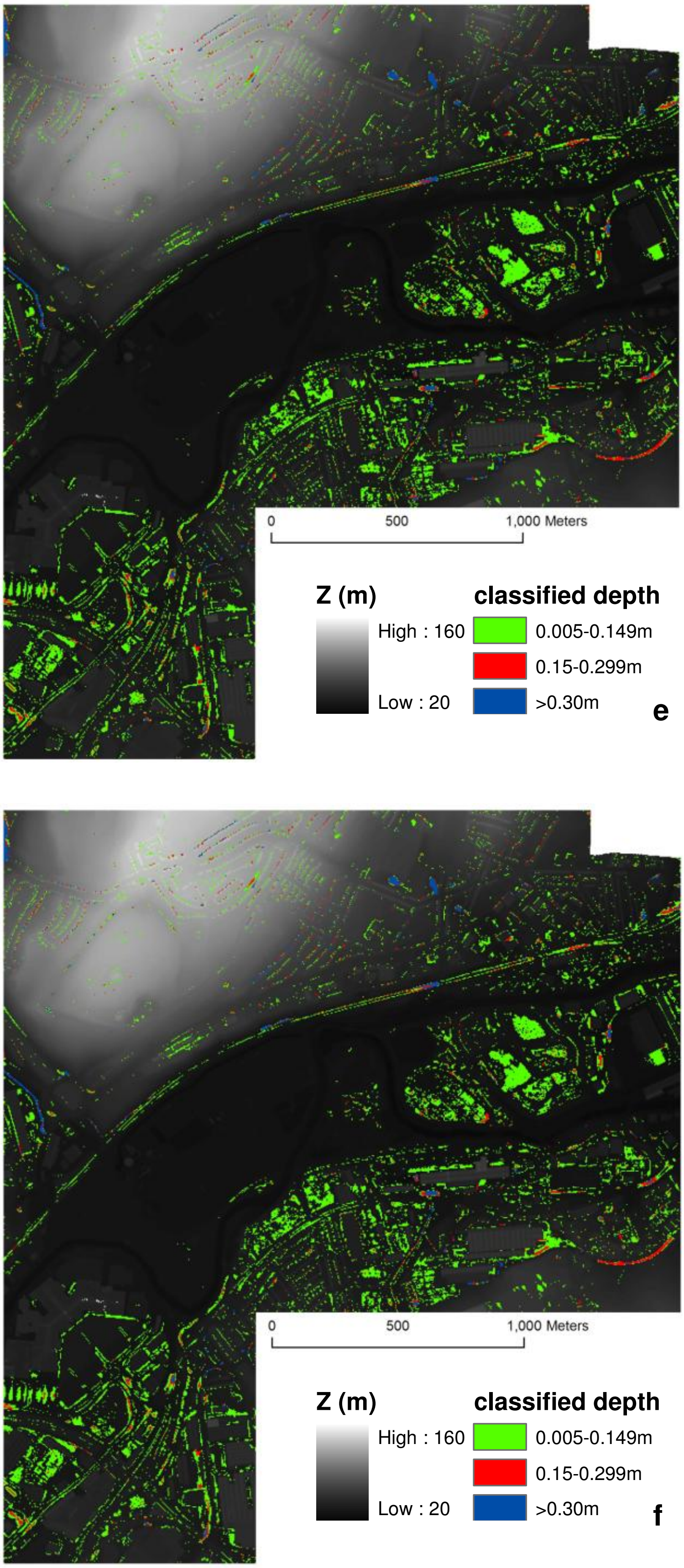

Figure 7.9 Thematic maps generated through subtraction of grid of flood inundation obtained from the original calibration simulation and simulations with parameterisation of rainfall, thus illustrating contribution of precipitation to fluvial flooding for simulations: (a) 1 (b) 2 (c) 3 (d) 4 (e) 5 (f) 6

Further analysis reveals that the difference in depth observed for fluvially flooded areas appears to be most pronounced within simulation two, which is parameterised by the second greatest total precipitation supply at 65.8 mm but the highest intensity of precipitation for 24-38 hours at 51.1 mm/day. Simulation four, which is associated with the greatest net volume of precipitation at 98.1 mm, but lower precipitation intensity during the latter part of the simulation- 16.9 mm/day exhibits a smaller contribution of precipitation within fluvially flooded areas. Depth variation in the main body of flood inundation is very small for simulation six, which is parameterised by both the smallest overall precipitation contribution at 13.6 mm and the lowest intensity of rainfall from 24-38 hours at 6.5 mm/day.

Therefore, the above analysis demonstrates evidence that the contribution of precipitation within fluvially flooded areas is highly dependent upon recent rainfall intensity, rather than overall volume of precipitation through the course of the simulation. However, overall water depth variations within fluvially flooded areas in response to precipitation appear to be relatively low for all simulations. Indeed, the maximum depth variation observed in response to precipitation within these areas were produced within simulation two and generally exceeded no more than several centimetres. The contribution of precipitation to fluvially flooded areas appears to be less than for areas outside the floodplain. Unlike the hillslope areas, where water collects and is stored within topographical depressions, water added to the fluvially flooded area as precipitation drains away rapidly into the river channel. This can be attributed as the reason for the relatively small contribution which rainfall provides to fluvially flooded areas.

Overall, this analysis suggests that the contribution of precipitation to water levels within fluvially flooded areas is largely insignificant for the real flood event which occurred on the 25th-26th June 2007, in addition to the hypothetical rainfall scenarios demonstrated in simulations three to six. However it is important to note that this analysis is based upon a temporal snapshot at the end of the simulation and thus although some dynamic contributions of rainfall can be inferred, these cannot be accurately assessed.

7.4 Implementation of performance measures

The performance statistic *F* was implemented for simulations one and two within this section of the analysis in an attempt to quantify the contribution of precipitation to inundation for the flood event which occurred on the 25th-26th June 2007, with respect to observed data. Prior analyses have shown that precipitation makes a modest but significant contribution to flood inundation characteristics for this event. Therefore hypothetically, implementation of accuracy assessment measures should elucidate whether representation of rainfall is able to improve the performance of LISFLOOD-FP for this specific event.

In order to ensure direct comparability of fit statistics for simulations one and two with the optimum calibration determined in chapter 6, the grids of flood depth were pre-processed using equivalent methods. Hence the Sheffield boundary mask was applied in order to reduce uncertainty, whilst minimum threshold depths of 0.001m were removed across the domain. The only exception to this is where depths of 0.001m were observed within the original optimum calibration simulation. This processing was undertaken in order to ensure that any changes in *F* could be attributed directly to the contribution of precipitation rather than be influenced by any other factors.

Initial evaluation of Table 7.3 reveals that inclusion of rainfall within the model led to an increase in the level of fit when compared to the original calibration simulation. For simulation one, which is associated with the addition of the total volume of water through the initial depth mask F=0.60, representing an increase in F of ~0.04. For simulation two which corresponds to the more physically realistic representation of rainfall F=0.058, which constitutes an increase of 0.02 in relation to the baseline simulation. In order to place this into context, this increase in the fit statistic is marginally lower than that observed through reduction of uncertainty by implementation of the Sheffield boundary mask. Therefore this increase in model performance can be considered modest.

Simulation number	Total precipitation (mm)	F	F difference
Original	0.0	0.56	0.0
1	65.8	0.60	0.04
2	65.8	0.58	0.02

Table 7.3 Comparison of fit statistics calculated for the original calibration simulation and simulations 1 and 2

Given that values of *F* within Table 7.3 suggest that inclusion of rainfall leads to an increase in model performance for the flood event which occurred on 25th-26th June 2007, further analysis is necessary in order to elucidate areas in which this improvement occurs. Figures 7.10 and 7.11 are thematic maps which effectively provide a visualisation of the performance measure calculation, illustrating 4 classes which reflect areas in which the flooding is correctly predicted, over predicted or under predicted. These Figures illustrate that both simulation one and two are associated with a significant increase in the overall area of the domain which is predicted correctly as wet, which is accompanied by a significant decrease in the overall areal extent of areas of under prediction.

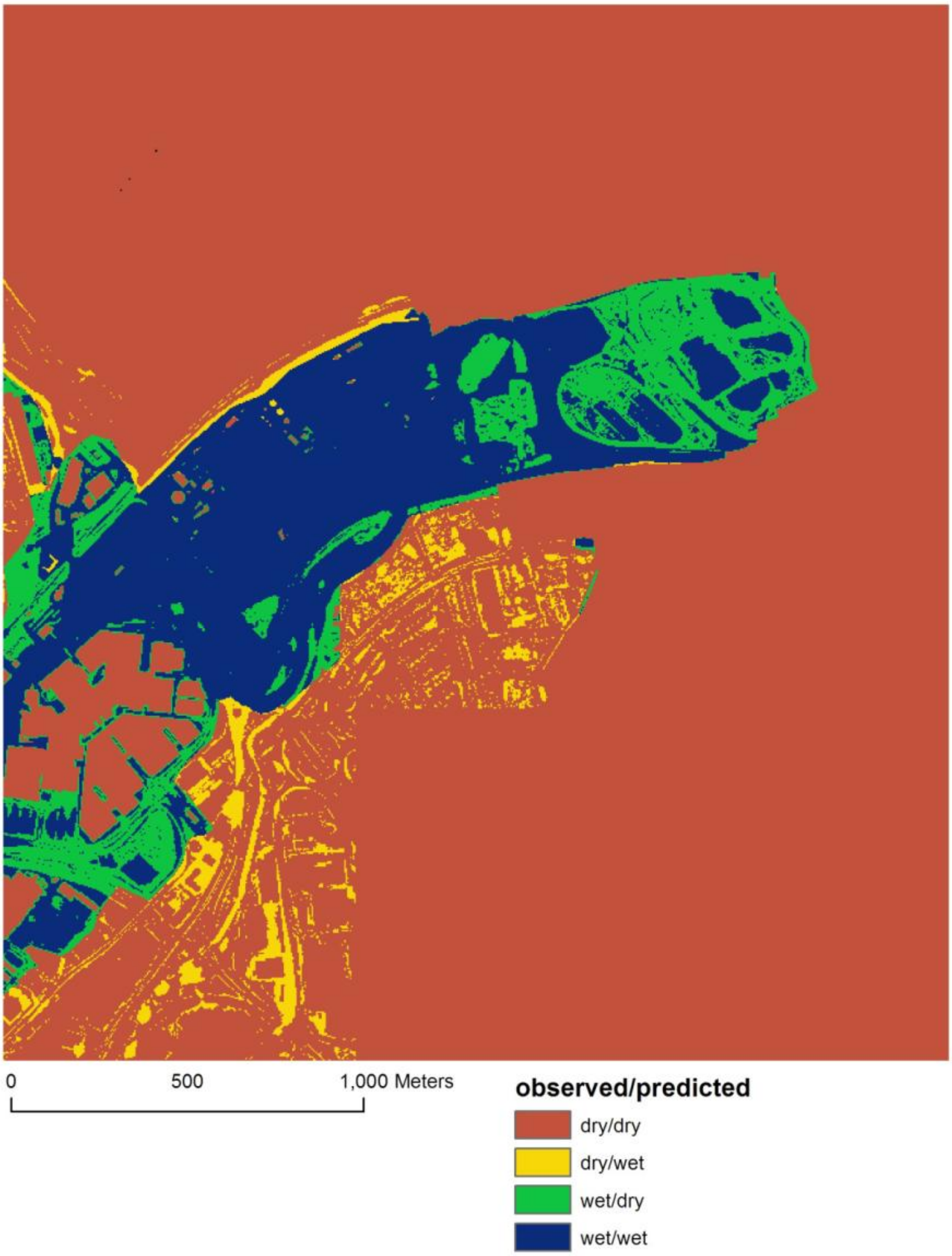

Figure 7.10 Visual illustration of performance measure implemented for simulation 1

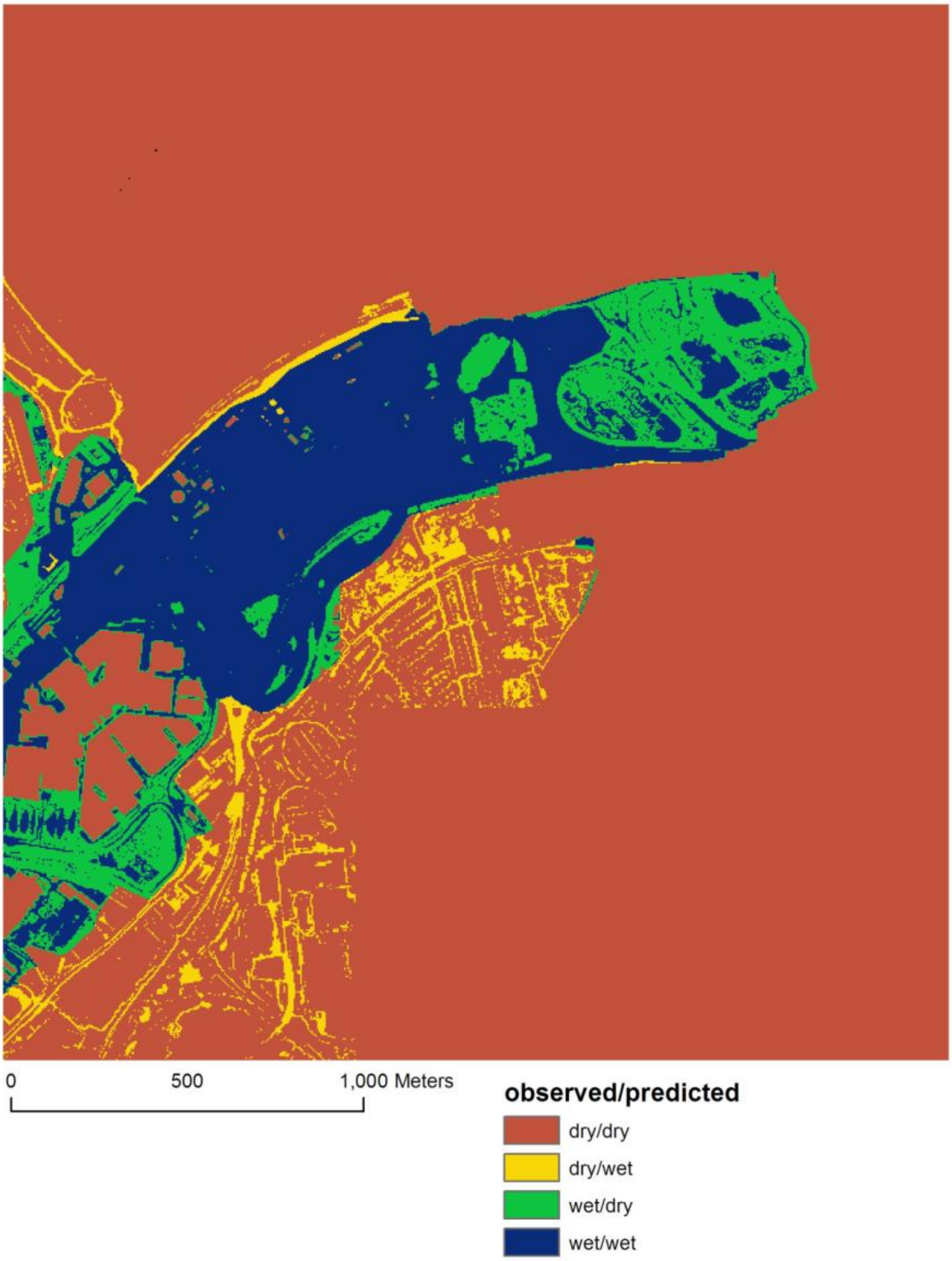

Figure 7.11 Visual illustration of performance measure implemented for simulation 2

The spatial extent of the increase in areas which are correctly predicted as wet perhaps suggest that a greater increase in the overall performance statistic would be expected. However Figures 7.10 and 7.11 also reveal that representation of rainfall simultaneously produces a significant increase in the areas of over prediction. Consequently, the spatial extent of over prediction rises considerably from the original calibration, in which the presence of these areas was scarce. Therefore it is clear that the observed change in performance statistic *F* is effectively the result of significant increases in both correctly predicted wet cells and over predicted wet cells in response to parameterisation of rainfall.

Further visual analysis of Figures 7.10 and 7.11 and comparison to the inundation extent produced within the original calibration simulation (Figure 6.1), is able to elucidate the spatial distribution of areas which are sensitive to rainfall parameterisation and contribute to the observed increase in the accuracy assessment measure *F*. Indeed it is clear that the main body of flooding within the centre of the floodplain is relatively insensitive to parameterisation of rainfall for this test as the majority of this area is characterised by pre existing fluvial flooding. By contrast, increased model performance (a function of greater number of correctly predicted wet cells), occurs within two main areas of the model domain. The most significant increase in correctly predicted wet cells occurs within the numerous topographically confined basins on the east of the floodplain. Whilst the second region which exhibits a marked increase in the number of correctly predicted wet cells is located within the west of the domain, predominantly to the south of the Meadowhall shopping centre. Further, Figure 7.10 and 7.11 also clearly highlight the spatial distribution of areas in which a representation of rainfall leads to over prediction of flood extent. Areas in which flooding becomes over-predicted in response to a representation of rainfall are clearly located away from the main body of inundation and the defined floodplain.

7.5 Summary

Analysis of thematic maps within 7.2 provided evidence to suggest that rainfall made a significant contribution to flood inundation which occurred on 25th-26th June 2007 within Sheffield. Results suggest that shallow flows generated through rainfall are strongly routed according to local topography, leading to localised accumulation of flow. The thematic maps illustrate that areas of inundation of significant depths (>0.30 m) are located across the domain, suggesting that rainfall was responsible for localised flooding on valley sides. Although there is some evidence to suggest that rainfall was able to contribute to fluvial flood inundation, subsequent analysis within 7.3 suggests that this was relatively minimal. Finally implementation of performance measures has yielded an increase in *F* where rainfall is included in the model. However it is important to note that this increase in performance was relatively small at 0.04.

Chapter Eight

Discussion

8. Discussion

8.1 Is LISFLOOD-FP able to provide an adequate representation of surface flooding in response to rainfall?

On a basic level there are two major facets which are required in order to provide an adequate representation of surface flooding in response to rainfall within LISFLOOD-FP. The first is provision of a physically realistic representation of rainfall into the domain, whilst the second is an appropriate routing of this rainfall. Whether LISFLOOD-FP is able to provide a realistic representation of rainfall will form the basis of the initial part of this discussion.

It was not possible to modify the LISFLOOD-FP model code in order to add an extra parameter for precipitation. This necessitated the use of an improvised approach, utilising a negative manipulation of the infiltration and evaporation terms which were added to the model for application to seasonal flooding within rainforest environments (Wilson et al., 2007). The evaporation term appeared to offer promise, facilitating the representation of time-varying precipitation. This was potentially useful here as the main flood event modelled within this study lasted for a duration of 38 hours. As daily rainfall data for June 2007 was possessed, a crudely distributed time-varying rainfall is advantageous over a uniform representation. This is particularly pertinent given the results displayed within Figures 6.20 and 6.21, which illustrate that depth of inundation was very responsive to rainfall rate. This provided an initial suggestion that negative manipulation of the evaporation term could potentially provide a physically realistic representation of rainfall within LISFLOOD-FP.

However despite these promising findings, it quickly became clear that providing a representation of precipitation within LISFLOOD-FP without a recode was inherently problematic. Model testing, which was undertaken in order to determine the optimum partitioning of the total volume of water supplied to the domain between the initial depth mask and subsequent rainfall rate, revealed that the synoptic inundation characteristics were not independent of this partitioning. Results within 6.3.5 illustrated that greater spatial extent and depth of inundation was observed as an increasing proportion of total precipitation was supplied through the initial depth mask, whilst a depth mask of 0.001 m effectively precluded the addition of rainfall into the domain. A synthesis of the results suggested that rapid routing of water from the initial depth mask to areas conducive to accumulation of flow occurred, thus resulting in the proliferation of large areas of cells with the minimum water depth of 0.001 m. Effectively this resulted in a situation whereby rainfall, supplied through the subsequent rainfall rate, only occurred in localised areas where flood depths exceeded the minimum threshold depth.

The issues elaborated above led to a predicament in which a physically realistic representation of both the rate and total volume of rainfall could not be reconciled simultaneously. The implementation of a shallow initial depth mask, in order to facilitate a physically realistic rainfall rate for the remainder of the simulation, resulted in a significant underestimation of the total supply of water to the domain. This could only be remedied through increasing the proportion of rainfall volume supplied through the initial depth mask and adjustment of subsequent rainfall rates in order to ensure, theoretically, that the correct total volume of water was supplied. Subsequently, it became clear that the only way to ensure supply of the total volume of precipitation was to apportion 100% of the rainfall volume to the initial depth mask. This is clearly highly unrealistic physically, as floodplain flows within LISFLOOD-FP are highly dependent upon free surface gradients (Hunter et al., 2005b), hence the input of a large initial depth of water is likely to lead to rapid diffusion (Yu and Lane, 2006b), potentially erroneous flow dynamics and ultimately a misrepresentation of the contribution of rainfall to flood inundation.

Therefore despite initial promise, it is eminently clear that without a recode of LISFLOOD-FP, a physically realistic representation of rainfall is not possible. Within this particular study the impacts of inadequate representation of rainfall contribute to uncertainty and hence potentially undermine conclusions regarding the overall synoptic contribution of rainfall to flood inundation characteristics. It is important to note that the fixed time step version of LISFLOOD-FP used within this study offers a relatively poor representation of floodplain wetting/drying due to the influence of the flow limiter (Hunter et al., 2006), thus limiting the opportunity to make conclusions regarding the dynamic performance of the model. This effectively conceals the shortcomings associated with this improvised representation of rainfall to a large extent, as conclusions within this study are based primarily upon the overall synoptic contribution of rainfall.

However it is clear that in instances where dynamic contributions of precipitation to flood inundation are required, in future studies for example, that a representation of rainfall which is able to reconcile both total volume and rate of rainfall is crucial in order to make valid conclusions. Although the LISFLOOD-FP source code was not accessible here, the findings of this study suggest that a physically realistic representation of rainfall is eminently achievable. This could be provided through a parameter akin to evaporation, although with adjustments in order to facilitate addition of water to cells which are not already wet and a treatment to avoid the problems experienced within minimal cell depths.

Having assessed the physical realism of the supply of water into the model domain, it is appropriate to discuss the subsequent routing of this surface water. It is inherently difficult to assess the accuracy of surface flow representation provided by LISFLOOD-FP in the absence of appropriate validation data (Hunter et al., 2008). However the results obtained within testing in chapter seven are able to yield some information regarding the adequacy of the routing of surface flows in response to rainfall. It is well known that representation of flow processes within urban areas is fundamentally reliant upon a high resolution representation of topography (Yu and Lane, 2006a, Smith, 2006), which allows complex flow paths around buildings, and micro topographical features ie kerbs to be resolved. This is strongly reflected within 6.3.3, as Figure 6.18 illustrates the model response to changes in resolution. It is clear that flow patterns in response to precipitation are highly sensitive to grid resolution, corroborating the findings of Mark et al., (2004) who suggest that DEMs of 1-5 m resolution are required in order to capture relevant topographic features within urban environments.

Significantly, evidence within 6.3.3 suggests that the specific nature of surface flows in response to precipitation, which are characterised by very shallow depths and pooling of water according to local micro topography (Aronica and Lanza, 2005), demand the highest possible resolution of topography. Figure 6.18 provides evidence to suggest that residential buildings exert a blocking effect upon flows (Lane, 2005), from upslope contributing areas which can potentially lead to localised accumulation of water of significant depths. The occurrence of this effect is highly dependent upon grid resolution. Specifically Figure 6.18 illustrates the occurrence of flow accumulation adjacent to a building within simulations populated with a 4m and 8m resolution DEM, although no inundation occurs at this location where a 2 m grid is used. Visual analysis suggests that this can be attributed to the increased ‘roughness’ of building edges at coarser scales which encourage flow accumulation. This effect is negated where structures are represented more realistically at higher resolutions.

This can be considered significant as flow depths in excess of 0.30m are shown to accumulate in these areas, potentially leading to incorrect classifications of the flood status of buildings. This suggests that in instances where rainfall is included within flood inundation models, grid resolutions < 2 m may be required in order to represent micro topography correctly (Abderrezzak et al., 2009),The findings of this study suggest that a building scale (1 m-5 m) representation of topography (Mark et al., 2004), may not be sufficient when dealing with shallow diffuse flows. Therefore it seems that the potential ability to incorporate very fine grids means that LISFLOOD-FP is able to adequately represent routing of surface water according to micro topography. This is a feature which has been lacking from past representations of surface flow within urban areas (Bergmann and Richtig, 1990, Ishikawa and Sakakibara, 1984).

The above discussion suggests that LISFLOOD-FP is able to provide a sufficiently accurate representation of surface flow routing in response to rainfall, when populated with a high resolution DEM. However an adequate representation of overall surface flow also demands a realistic representation of flow velocities (Fewtrell et al., 2008) and other characteristics which determine the timing of routing around the domain. A lack of observed data makes assessment of the dynamics of surface flow difficult (Hunter et al., 2007), although this is commonplace as Hunter et al., (2008) states that ‘despite the occurrence of urban floods, almost no field observations of urban flooding and no mechanisms for their routine monitoring or post event reconstruction is available’. This situation is complicated further by the nature of flows in response to precipitation, which are distributed widely across the entire domain. Therefore although it is effectively impossible to accurately assess the dynamics of surface flows in response to precipitation with respect to observed data, inferences can be made regarding the dynamics of surface flows through a synthesis of observed results and model behaviour.

Figure 6.11 illustrates that water depth time series extracted from areas of flow accumulation which are characterised by a large contributing area illustrate considerable time step dependence. This suggests that the flow limiter exerts a predominant influence upon floodplain flows for this fixed time step implementation of LISFLOOD-FP. It has been demonstrated within Hunter et al., (2006) that where the flow limiter is invoked floodplain flow dynamics become highly unrealistic, this manifests in terms of rapid diffusion of the flood wave (Yu and Lane, 2006a). An almost instantaneous routing of surface water supplied to the domain through rainfall to areas of flow accumulation is observed within Figures 6.10-6.12. Therefore it seems that the representation of floodplain flow within this fixed time step application of LISFLOOD-FP is leading to the proliferation of unrealistically high flow velocities for surface water flows in response to rainfall, in a situation similar to that observed for overbank flows (Hunter et al., 2006). Accordingly this suggests that the dynamics of surface flow routing are relatively poor here, although again poor dynamic performance is largely masked by analysis techniques and other uncertainties within this study.

It is important to consider that the poor routing of flow detailed above can be attributed to the fact that the fixed time step version of LISFLOOD-FP was used. Hunter et al., (2006) compared the performance of the fixed and adaptive time step version of LISFLOOD-FP developed within (Hunter et al., 2005b) when applied to a rural floodplain. The authors concluded that the adaptive time step facilitated both a better absolute performance in addition to a much more intuitive representation of inundation dynamics particularly floodplain wetting and drying.

Accordingly the adaptive time step version of LISFLOOD-FP has been applied to surface flow in urban areas (Fewtrell et al., 2008, Hunter et al., 2008). These studies illustrate that the adaptive time step version of LISFLOOD-FP is able to provide plausible results for shallow flows sourced from a surcharged culvert, akin to the nature of flow observed in this study in response to precipitation. Hunter et al., (2008) overcame the lack of observed data for surface flow in urban environments through rigorous testing of model performance over a plausible range of friction parameters. A similar methodology could be used within future studies in order to test model response and performance when a representation of rainfall is included. Therefore although implementation of LISFLOOD-FP with a fixed time step leads to poor representations of the dynamics of surface flows here, it is clear that use of the adaptive time step solution is likely to facilitate a more realistic and adequate routing of surface flows. Therefore a combination of a high resolution grid and the adaptive time step solution would likely provide an adequate representation of surface flows in response to rainfall.

Importantly, this study has raised several overarching issues regarding the feasibility of a parameterisation of precipitation within LISFLOOD-FP in order to investigate urban flood inundation dynamics in response to rainfall. The findings of this study confirm the original notion considered from the outset; that the nature of precipitation in urban areas demands that LISFLOOD-FP is populated with a large high resolution grid. This is necessary in order to encompass areas outside of the traditionally defined floodplain, which can be characterised by localised flood inundation through the influence of micro topography. In addition it has been shown that these micro topographical effects simultaneously demand a grid resolution ~2 m in order to accurately represent routing of surface flows in response to rainfall. It has also become clear that the poor dynamic performance of fixed time step implementations of LISFLOOD-FP (Hunter et al., 2006), mean that the adaptive time step solution is required in order to adequately reproduce dynamics of surface flow as in (Hunter et al., 2008).

This is clearly problematic here, as Hunter et al., (2005b) state that the adaptive time step solution of LISFLOOD-FP reduces quadratically with grid cell size. Whilst the adaptive time step is viable where grid scales are relatively coarse (for which it was originally formulated), where resolution <10 m significant increases in simulation times occur. Therefore although the ATS version of LISFLOOD-FP has been applied to urban flooding problems (Hunter et al., 2008, Fewtrell et al., 2008), lack of computational efficiency has limited these studies to very small areas ~0.5 km^2. Indeed these applications have exhibited simulation times which exceed those from full 2D solutions of the shallow water equations (Bates et al., 2010). Informal testing revealed that implementation of the ATS was simply not viable for this study, in which the model grid is ~2.8 km^2. In addition it is necessary to consider that the simulation time of LISFLOOD-FP is strongly a function of the number of wet cells (Bates and De Roo, 2000), which inevitably increases dramatically where precipitation is included

Within this study the use of the fixed time step version of LISFLOOD-FP was unavoidable, effectively representing a sacrifice in terms of dynamic performance in order to facilitate a representation of precipitation. Therefore it is clear that the specific requirements (large high resolution grid and adaptive time step solution) necessary in order to adequately model precipitation within urban areas using LISFLOOD-FP lead to the proliferation of a situation where these demands cannot be simultaneously reconciled. Within this study this manifests in terms of poor dynamic model performance, which propagates considerable levels of uncertainty and undermines the validity of conclusions. Overall the numerous issues highlighted within the discussion above strongly suggests that the version of LISFLOOD-FP utilised within this study is unable to provide an adequate overall representation of surface flooding in response to precipitation.

However it is important to consider that new approaches to flood inundation modelling which have been formulated specifically for application within urban areas, typified by Bates et al., (2010), offer great potential in overcoming some of the key problems encountered within this study. This new approach is based upon an inertial acceleration term and has been integrated into the process representation of the most recent version of LISFLOOD-FP. Within the new set of equations minimum stable time step scales with $1/\Delta x$ according to the Courant-Friedrichs-Lewy condition, rather than $(1/\Delta x)^2$ for previous ATS versions of LISFLOOD-FP (Bates et al., 2010). Overall therefore this approach is associated with the well recognised benefits of storage cell codes (Hunter et al., 2007), whilst providing a marked increase in computational efficiency. Although the new inertial version of LISFLOOD-FP was not received until mid way through this research, informal testing revealed that the new equations facilitate stable representations of flow over the grid size/resolutions required for this study with simulation times similar to the fixed time step implementation used within this study. Therefore this suggests that application of the new version of LISFLOOD-FP could potentially facilitate an adequate representation of urban flood inundation in response to rainfall.

8.2 Is rainfall able to make a significant contribution to flood inundation within urban areas?

The prior discussion has highlighted the numerous issues faced when attempting to develop a representation of precipitation within LISFLOOD-FP for application to urban flood inundation. Given that inferences will be made here regarding the contribution of direct precipitation to an observed flood event it is necessary to fully consider the potential uncertainties associated with this approach from the outset. Overall it has been concluded that the fixed time step model offers poor dynamic performance as in Hunter et al., (2006), whilst it has not been possible to develop a rainfall parameterisation able to reconcile the accurate representation of both total rainfall volume and rate through the simulation through manipulation of infiltration/evaporation terms (Wilson et al., 2007). Therefore assessment of the dynamic contribution of rainfall to flood inundation has been deemed highly inappropriate. This is reflected in the following discussion which primarily considers the bulk contribution of rainfall at the time of aerial imagery 14:00 hours on 26th June 2007. Although not ideal, as this corresponds to the falling limb of the hydrograph and hence does not consider the contribution of rainfall at maximum inundation extent, this was considered more appropriate and defensible than attempting to draw conclusions regarding the dynamic contribution of rainfall through the course of the simulation.

In addition, computational constraints have necessitated a deterministic modelling approach utilising optimum parameter sets (Horritt and Bates, 2001a), rather than the GLUE methodology (Aronica et al., 2002), which is able to provide a more defensible representation of flood inundation (Bates et al., 2004). Further, a 4 m grid resolution was utilised for the model simulations in 6.3, in spite of previous recommendations. This was necessary due to computational constraints inherent within this study, although potentially results in an inadequate representation of micro topography (6.3.3). Accordingly this is reflected in the scope of conclusions which are drawn in relation to the hypothesis. Indeed, making explicit predictions of flooded properties is considered inappropriate and is therefore avoided.

A final major uncertainty is the assumption of complete blockage of drains and 100% run off which is necessary within this study, as drainage cannot be represented within LISFLOOD-FP. This is largely justifiable for the event which occurred on the 25th-26th June 2007 due to the exceptional antecedent conditions (Dickson and Berry, 2008, Marsh and Hannaford, 2007). Although evidence suggests that the drainage system was highly inefficient during this event, it seems relatively unlikely that 100% run off was observed for this event. Therefore the results here can be regarded as a maximum potential surface flooding, although with considerable associated uncertainty. Again this is reflected within the nature of the conclusions which are drawn in the following discussion. Therefore it is clear that high levels of uncertainty are preeminent and largely unavoidable within this study. Although Lane (2005) states this should not be a deterrent in attempting to find meaningful signals in data.

The results obtained here, detailed within chapter eight, suggest that the study area illustrates a distinctive and potentially significant response to precipitation for the flood event which occurred on the 25th-26th June 2007. Results from simulation one illustrated in Table 7.2, indicate that representation of precipitation is associated with an increase in all meaningful flood depths (ie above 0.005m) across the domain. The magnitude of increase was most significant for the class 0.005-0.15 m at ~340 m^2, was lower for moderate inundation (0.15 m-0.30 m) at ~200 m^2 and lowest for depths exceeding 0.30 m (threshold for flooding of buildings) at ~80 m^2. Hence at the end of the simulation, inundation directly attributable to precipitation constituted 50% of water between depths 0.005-0.149 m, 42% of depths 0.15-0.30 m and ~12% of depths in excess of 0.30 m. Although these Figures should not be regarded as explicit contributions, it is clear that this modelling exercise for the flood event occurring on the 25th-26th June 2007 in Sheffield suggests that precipitation is able to make a meaningful contribution to flood inundation when considered simply in terms of aerial extent.

Synoptic maps of inundation extent have been used to determine the distribution of flooded areas in response to rainfall. Visual analysis of Figures 7.2-7.4 reveals that the response to rainfall is dominated by the proliferation of areas of localised pooling which occur across the domain, with the distribution of these areas controlled predominantly through micro topography (Smith, 2006). This micro topography consists primarily of topographical depressions which are conducive to accumulation of flow, in addition to structural features such as buildings which appear to block the routing of flow down slope. This occurs in a manner which is similar to that seen for fluvial floodplain flows (Yu and Lane, 2006a), although with micro topography exhibiting increased influence due to the shallow nature of flows in response to distributed precipitation (Aronica and Lanza, 2005). In areas where the density of these features is relatively high, predominantly to the south of the domain, a relatively large proportion of the water supplied through rainfall is retained in areas away from the traditional floodplain. Consequently this suggests that rainfall contributed to the occurrence of localised flooding of significant depth within areas outside the traditional floodplain within the event which occurred from 25th-26th June 2007 in Sheffield. However in other regions, for example the area of high relief to the north of the domain, a lack of inundation on the valley sides suggests that water was routed down slope to the region of the floodplain (Hsu et al., 2000), thus suggesting that rainfall may have contributed to fluvial flood inundation during June 2007. However analysis within 7.3 suggests that the contribution of rainfall to areas of fluvial inundation was relatively minimal within this event.

Overall, despite the high levels of associated uncertainty it is clear that this modelling study is able to offer some insight into the flood event which occurred on the 25th-26th June 2007 in Sheffield. Specifically, the results suggest that precipitation provided a modest but significant contribution to the overall flood inundation, with the predominant impact being the occurrence of localised flooding in areas outside of the traditional flood plain. This is potentially very important as it is unlikely that these areas would be considered to be at risk from fluvial flooding in traditional flood risk maps. In contrast it appears that water sourced from precipitation was only able to make a relatively insignificant contribution to fluvial flood inundation within the June 2007 floods in Sheffield, due to the disparity in total volume of water supplied from these respective sources.

When considered in the context of prior assessments of the 2007 flooding in Sheffield, the findings of this modelling study appear to offer a contribution to the scientific debate surrounding this event, although this is not clear cut. Specifically the results of this study appear to add some weight to the conclusions of the Sheffield Flood Risk Assessment (Dickson and Berry, 2008). This report suggests that the contribution of surface water flooding in response to intense rainfall was largely overestimated in an appraisal of the event (Environment Agency, 2007). Estimates from the Environment Agency report suggest that around two thirds of overall inundation was attributable to pluvial inundation as a direct result of widespread overwhelming of the cities drainage system as a direct consequence of rainfall within the urban area. However estimates provided by Dickson and Berry (2008) suggest that approximately 95% of inundation within the city was attributable to fluvial sources. The remaining 5% was indeed the result of surface flooding, although this was much more localised than that reported by Environment Agency (2007). In addition it was reported that despite relatively high incidence of surface flooding this was rarely of sufficient depth to enter houses (Dickson and Berry, 2008).

Elements of both arguments appear to be reflected within with the synoptic inundation maps. Figures 7.2-7.4 and Table 7.2 suggest that rainfall contributes to the widespread incidence of inundation at depths of between 0.005-0.15 m and 0.15 m-0.30 m, constituting 50% and 42% of the areal extent respectively. This reflects the conclusion of Environment Agency (2007), who state that pluvial flooding was responsible for two thirds of overall inundation. However the model also predicts that the contribution to flood depths capable of causing inundation of buildings (>0.30m) were much more localised at ~12%, more strongly reflecting Dickson and Berry (2008). Uncertainties inherent within the modelling approach utilised here mean that it is impossible to accurately validate either of the arguments regarding the Sheffield 2007 floods, in addition it is important to consider that the study area only constitutes a relatively small area of Sheffield which is not necessarily representative of the city as a whole. However, it can be concluded that the key findings here reflect elements of the conclusions of Dickson and Berry (2008) and Environment Agency (2007).

The focus of the previous discussion has largely centred around the contribution of rainfall to the specific flood event which occurred within Sheffield on 25th-26th June 2007. Although this is well justified, in order to fully address the research question and hypothesis it is necessary to discuss the findings of this study in the wider context of urban flood inundation. This is particularly pertinent given the recent emphasis which has been placed upon the importance of pluvial flooding within urban areas (Pitt, 2007). In addition, an assessment of the more general significance of rainfall to flood inundation within urban areas is relevant in determining whether inclusion of precipitation can be considered worthwhile within hydraulic modelling studies.

It has been established, despite the inherent uncertainty within this study, that precipitation provided a significant albeit modest contribution to the 2007 flood event in Sheffield. However before these findings are taken to constitute evidence of the wider significance of precipitation within urban areas, it is necessary to consider the hydrological circumstances which led to the occurrence of flooding within June 2007. Precipitation totals observed during the 48 hour period from 25th-26th June 2007 within Sheffield were exceptional and in themselves constitute a 1 in 150 year event (Marsh and Hannaford, 2007). However, Dickson and Berry (2008) state that these precipitation levels, despite being very high, were within the range which could usually be handled by the drainage system within Sheffield. Therefore the magnitude of this flood event, particularly the contribution from surface flooding in response to rainfall, was largely attributable to the precipitation and hydrological conditions which occurred prior to the actual flood event (Dickson and Berry, 2008), which propagated inefficiencies within the drainage system. These antecedent conditions were similarly unique, indeed the period from May-July 2007 was the wettest in the past 250 years across the UK the period (Marsh and Hannaford, 2007). This emphasises that surface flooding in response to rainfall is dependent upon both antecedent conditions, which reduce drainage capacity, in addition to the occurrence of high levels of rainfall coinciding with the passing of the flood wave within the urban area.

The results illustrated in 7.2.2 for simulations 5 and 6, which are associated with a lower magnitude of rainfall (total supplied 13.6 mm over 38 hours), further emphasise the preeminent importance of both antecedent conditions and high intensity rainfall which coincides with the flood wave. Despite 100% run off conversion which is assumed within these simulations the areal extent of flood inundation >0.30 m increases by less than 20 m^2 , which can be considered insignificant given the size of the model domain. Therefore even where the drainage system is blocked, high intensity precipitation is required in order to make significant contributions to surface flooding.

Therefore the modelling approach utilised within this study illustrates that surface flooding in response to direct precipitation provided a modest but significant contribution to overall inundation for the flood event which occurred within the city of Sheffield on the 25th-26th June 2007. The study further suggests that response to precipitation manifests in terms of localised flooding outside the extent of the traditionally defined floodplain according to micro topography (Aronica and Lanza, 2005), with rainfall making minimal contributions to inundation within fluvially flooded areas. Although associated with significant uncertainty, which has ultimately restricted the ability to generate more firm conclusions, these findings illustrate a basic agreement with the findings of Dickson and Berry (2008) and Environment Agency (2007).

Although the results obtained for the flood event which occurred within Sheffield in June 2007 support the hypothesis ‘As a consequence of the unique hydrological characteristics, rainfall is able to make significant contributions to flood inundation within urban areas', it is clear that unique hydrological conditions were a precursor to the contribution of rainfall within this event (Marsh and Hannaford, 2007). The proliferation of surface flooding was highly dependent upon both antecedent conditions and the occurrence of a high intensity rainfall event in coincidence with passing of the flood wave. Therefore this brings into question the validity of the hypothesis when applied to urban flood inundation more generally.

8.3 Does a representation of precipitation lead to improved predictions from hydraulic flood inundation models during high magnitude rainfall events?

Despite the numerous uncertainties which are inherent within this study, the prior discussion suggests that high levels of precipitation provided a significant contribution to the flood event which occurred within Sheffield on the 25th-26th June 2007. Given the availability of validation data for this event it was considered appropriate to investigate whether inclusion of a representation of precipitation within the model could produce an improvement in performance for a flood event where rainfall has been hypothesised to be significant (Environment Agency, 2007). This was subsequently undertaken in 7.4 through application of standard performance measures (Bates and De Roo, 2000), to outputs from the original validated model produced in chapter 6 and two simulations exhibiting an identical set up, but including a representation of rainfall.

Results illustrated in Table 7.3 exhibited an increase in *F* in response to the two rainfall representations, with increases of fit of 0.04 and 0.02 for the bulk and distributed rainfall representations respectively. Although these increases in *F* are relatively small, without further analysis it could be simply concluded that the addition of another model parameter leads to an increase in model performance, reflecting the importance of the natural process of rainfall to flood inundation within this event. However, given the high levels of uncertainty inherent within multiple facets of this study it is important to consider the performance measures critically. Accordingly, further analyses have revealed that the increase in model performance observed was a strong function of an increase in the overall number of wet cells across the entire model domain, rather than a clear response to rainfall representation. More specifically, Figures 7.10 and 7.11 illustrate that a significant increase in the number of correctly predicted wet cells occurred in response to rainfall, although this was accompanied by a significant albeit slightly smaller increase in the number of over predicted wet cells. This suggests that the modest increase in the performance measure may be an indication of equifinality (Beven, 2002), rather than a meaningful increase in model performance in response to inclusion of a new important parameter.

In order to thoroughly assess whether representation of precipitation is able to improve model performance and hence investigate the stated research question and hypothesis it is necessary to consider model calibration and validation issues prior to the inclusion of rainfall. The maximum model performance observed within this calibration exercise was F=0.56, which can be considered as a relatively low level of fit. The performance statistic F is based upon the number of correctly predicted wet cells, consequently minimising bias generated through the presence of large dry areas within the model domain (Horritt and Bates, 2001b). This facilitates meaningful comparison of F between modelling studies (Bates and De Roo, 2000). Comparison of the optimum calibration within this study to that observed in prior applications of LISFLOOD-FP, detailed in Table 5.5, is largely unfavourable.

Indeed the optimum parameter set derived through calibration here failed to produce an acceptable simulation based upon the criteria of F>0.65 (Hunter et al., 2006). Further investigation and validation against observed water levels as in Neal et al., (2009a) revealed that the model offered a poor representation of inundation dynamics, a situation somewhat expected given the findings of Hunter et al., (2006) for a fixed time step implementation of LISFLOOD-FP. However despite poor dynamic performance in the aforementioned study, the model was still able to replicate the observed inundation extent acceptably. Therefore the apparent inability to achieve a reasonable level of fit here, despite the wide envelope of the parameter space which exceeded that of many comparable studies (Hunter et al., 2006, McMillan and Brasington, 2007), suggested that deficiencies were present in either the model set up or the available validation data.

In light of subsequent interrogation of calibration output images (Figure 5.1), it has been concluded that uncertainties within the validation data are perhaps the largest contributor to poor model performance observed within Table 5.2. This is not surprising, as Hunter et al., (2007) state that all validation data are limited spatially or temporally and are hence inherently uncertain. Within this study uncertainty can be attributed to the fact that the observed inundation extent is constituted by a flood outline which contains no internal spatial detail. The outline was supplied through the Environment Agency as a GIS ready shapefile which delineated flooding across the entire metropolitan area of Sheffield based upon aerial imagery captured at approximately 14:00 on the 26th June 2007. It is known that the flood extent was delineated manually (Chick, 2010a), although more precise details regarding its derivation are unclear. However, given the time consuming nature of manual delineation of flood outlines based upon aerial imagery (Yu and Lane, 2006a) and the overall areal extent of the flooding across the city (Figure 4.10) it appears that extraction of the inundation extent data was relatively crude and ignored internal spatial detail relevant to a study on this scale.

Use of such validation data is not well documented within the literature, indeed most recent studies utilise relatively well defined flood outlines derived through specially designed techniques ie statistical active contour (Horritt, 1999), or classification techniques (Yu and Lane, 2006a). However the issues here are twofold; firstly considerable evidence (Figure 5.2) suggests that large area of floodplain bounded by topographical basins has been misclassified as flooded. Similarly, the nature of this validation data does not consider local topographical highs which are likely to remain dry even through high magnitudes of overbank flooding, effectively leading to systematic penalisation of the model when performance measures are implemented. An allied issue is that validation data of this nature tend to generate bias towards high n_{ch} values within calibration (Werner et al., 2005a).

One other primary region of marked under prediction was identified, located south of Meadowhall, at the western limit of the model domain. Synthesis of available data and study area morphology indicate that poor model performance within this area could be attributed to the specific location of the study area in combination with the upstream course of the river and orientation of upstream overbank flooding. Significantly, the large building constituted by the Meadowhall shopping centre was located adjacent to the edge of the model domain, resulting in blockage of flow to the area in question. Therefore the lack of flooding predicted by the model within this area can clearly be attributed to inflows from upstream overbank inundation, which are not accounted for within this model. This issue has not previously been documented within studies utilising LISFLOOD-FP, which usually encompass the full extent of the flooded area. This is an issue which may arise more frequently as flood inundation models are increasingly applied to urban areas (Bates et al., 2010).

Therefore, effectively a situation proliferated here whereby quantitative accuracy assessment statistics indicated that the optimum model calibration offered inadequate levels of fit with validation data when compared against other studies. Whilst it is clear from validation against independent water levels that the model exhibited a poor representation of inundation dynamics (Hunter et al., 2006), a large proportion of the error reported by accuracy assessment was either attributable to aforementioned deficiencies within validation data itself or through a relatively clear and acknowledged lack of parameterisation of water sources within the model. In essence, this resulted in the proliferation of a situation whereby the optimal calibration was characterised by relatively large areas of ‘under prediction’, potentially sensitive to addition of a distributed source of water such as rainfall.

Subsequent implementation of accuracy assessment measures indicated a modest increase in model performance in response to representation of rainfall, with *F* rising to 0.60. A simple analysis of the output image produced within calculation of the accuracy assessment measure (Figure 7.10 and 7.11) with Figure 5.1 facilitates elucidation of the contribution of rainfall to change in *F* across the domain. It is eminently clear from this comparison that increases in model performance (indicated through changes from under prediction, to correct prediction as wet) occur predominantly within the two primary regions (the confined topographical basins and region south of Meadowhall), which are identified as under predicted within the original model calibration and validation.

Therefore it appears that an increase in model performance in response to representation of rainfall occurs primarily within regions where under prediction in the original calibration simulation has been accounted for by other factors, namely uncertainty in validation data and known lack of model parameterisation. It can be argued that rainfall may exert some real influence upon inundation within these areas, ie through contributing to raised water levels in ponds located within the topographically confined basins, or through combining with overbank flows from upstream in the region south of Meadowhall. However it is impossible to assess this quantitatively here. Although analysis suggests that the actual contribution of rainfall in these areas is likely to be significantly lower than that indicated by the increase in model performance. Overall, this suggests that an increase in quality of validation data and other simple model parameterisation is required before the contribution of precipitation can be determined reliably through implementation of performance measures.

Significantly, Figures 5.10 and 5.11 illustrate that representation of rainfall leads to a significant increase in the number of cells in which flooding is over predicted. These occur primarily across the area which can be considered outside of the traditional limits of the floodplain. Processing procedures prior to implementation of performance measures involved the removal of areas of minimal 0.001m depths from the grid of inundation taken from time corresponding to aerial imagery. Accordingly, any depths above this are retained and are treated as flooded when implementing the binary accuracy assessment. Examination of Figures 7.3 and 7.4 illustrate that the magnitude of water depths within the areas which are considered 'over predicted' are generally very low, whilst the aerial extent of deeper water which would be recognisable from aerial photography is generally spatially limited. This is problematic as it seems that even if model predictions in these areas were correct, that the minimal depths observed would be insufficient to be identifiable through visual analysis of aerial photography. Overall this highlights further issues when attempting to implement binary accuracy assessment measures for shallow flows in response to rainfall, as the threshold depth required for delineation of flooded areas from aerial imagery is unknown. It is clear that the uncertainties here are very large and that a thorough and reliable assessment is impossible without access to the original aerial imagery.

Overall, the high levels of uncertainty in both the validation dataset and the model itself undermine the ability to make any firm conclusions in terms of a potential increase in model performance in response to inclusion of a representation of precipitation. However it is clear that the prior analysis and discussion provide a strong suggestion that inclusion of a representation of rainfall produces an increase in model performance through compensating for more fundamental deficiencies within the model parameterisation and uncertainties within the validation data.

Therefore rather than generating a meaningful increase in model performance through inclusion of an important environmental process, it appears that representation of precipitation within LISFLOOD-FP at best compensates for deficiencies in validation data and to some extent a known lack of representation of other processes elsewhere within the model. Effectively this results in a situation in which the model is not producing the right results for the right reasons (Beven, 2001). Overall, it seems that any potential signal produced by rainfall is lost amongst the large amounts of uncertainty. Therefore it is clear that application of performance measures is largely inappropriate here. Accordingly, whilst the hypothesis which states that 'Inclusion of a representation of rainfall within LISFLOOD-FP is able to improve model performance where flooding coincides with rainfall events within urban areas', may appear to be superficially correct according to performance measures alone, it is clear that a more thorough consideration of model performance reveals the proliferation of significant equifinality (Beven, 1989) and thus casts doubt upon the validity of the stated hypothesis.

In summation, within this study it was possible to determine the potential contribution of precipitation to flooding within urban areas using a simple deterministic approach (Horritt and Bates, 2001b). However subsequent application of performance statistics highlighted that a more structured and rigorous analysis, in combination with an improvement in available validation data (Hunter et al., 2007), is required in order to determine the potential utility of rainfall as a parameter within flood inundation models. Given the inherent uncertainties in validation data and difficulties in quantification of these uncertainties it appears that methods which assess simulation likelihood, typified by GLUE (Aronica et al., 1998, Bates et al., 2004, Pappenberger et al., 2007b) which embrace equifinality, may present an ideal approach to further investigation of precipitation within flood inundation models. Although implementation of GLUE was unfeasible here due to computational constraints implicit in providing a representation of precipitation, more efficient modelling techniques (Bates et al., 2010), may help to facilitate a more thorough investigation of the importance of rainfall within future studies.

Chapter Nine

Conclusions and future research

9. Conclusions

9.1 Key findings

Within this study a basic representation of rainfall has been developed for application within LISFLOOD-FP. This has been achieved through the imposition of an initial depth mask and a simple negative manipulation of the infiltration and evaporation parameters (Wilson et al., 2007), facilitating a uniform/time varying representation of precipitation respectively. This representation of rainfall has subsequently been tested, revealing that LISFLOOD-FP has the potential to provide an adequate representation of surface flood inundation in response to precipitation, primarily due to the ability to incorporate high resolution representation of topography. Further, results suggest that the nature of flows in response to rainfall are sensitive to blockage by structural features (Yu and Lane, 2006a), although are more strongly controlled by micro topography (Aronica and Lanza, 2005, Smith, 2006). Although Mark et al., (2004) state that a building scale (1-5 m) representation of topography is required when modelling floods within urban areas, this study illustrates that a minimum DEM resolution of 2 m is ideally required in order to accurately represent flow routing in response to rainfall due to the increasing significance of micro topography.

However several key limitations have arisen, which ultimately limit the utility of the approach utilised within this study. Firstly the improvised representation of rainfall using infiltration and evaporation parameters results in a situation whereby an accurate representation of both total volume and rate of precipitation cannot be reconciled. Consequently, addition of the entire volume of rainfall through the initial depth mask appeared to offer the most viable approach to representation of precipitation. Secondly, the specific requirements necessary when attempting to determine the contribution of rainfall to urban flood inundation, primarily a large high resolution grid effectively preclude the use of the adaptive time step solution within LISFLOOD-FP due to the quadratic decrease in time step with increasing grid resolution (Hunter et al., 2005b). Consequently the fixed time step version of LISFLOOD-FP was utilised here, which provides a poor representation of inundation dynamics despite being able to accurately reproduce synoptic images of inundation extent (Hunter et al., 2006). Ultimately the aforementioned limitations have restricted the scope of this study, effectively precluding assessment of the inundation dynamics and placing a greater emphasis upon the bulk contribution of rainfall to flood inundation.

Despite the clear limitations it has been possible to draw several conclusions regarding the contribution of rainfall to the modelled flood event which occurred on the 25th-26th June 2007 within Sheffield through the modelling approach utilised here. Overall, results suggest that rainfall offers a significant but relatively modest contribution to flood inundation. The primary response appears to be the proliferation of localised areas of pooling outside the traditionally defined floodplain where micro topography facilitates flow accumulation (Aronica and Lanza, 2005). The spatial extent of surface run off is relatively high although only a small proportion of flows of sufficient depth to cause inundation of buildings (>0.30m) can be attributed to rainfall. Therefore the findings of this study appear to reflect different facets of the conclusions of both the Sheffield Strategic Flood Risk Assessment Dickson and Berry (2008) and Environment Agency (2007). However uncertainty ultimately limits the scope of conclusions within this study.

The findings of this modelling exercise clearly suggest that rainfall provided a modest but significant contribution to the flood event which occurred within Sheffield on the 25th-26th June 2007. However it is important to put this event into context when attempting to make more general conclusions relating to the significance of precipitation to urban flood inundation. It is clear that both drainage ineffiencies propagated through the wettest May-July period in the last 250 years (Marsh and Hannaford, 2007), in addition to the occurrence of a 1 in 150 year rainfall event in coincidence with passing of the flood wave, were preponderant in the production of significant surface flooding within the modelled event. Therefore this suggests that instances in which rainfall is able to make a significant contribution to urban flood inundation are likely to be limited to exceptional hydrological scenarios.

Within the final part of this study an attempt was made to quantify the potential contribution of rainfall through implementation of simple performance measures (Bates and De Roo, 2000). Although inclusion of a representation of precipitation resulted in a modest increase in the performance statistic, further analysis revealed that this increase was largely attributable to the large uncertainties associated with validation data and other acknowledged lack of parameterisation. Hence it became clear that improvement in model performance illustrated increasing equifinality (Beven, 2001), rather than a meaningful response to inclusion of an important physical parameter Therefore it is clear that the high level of uncertainty associated with validation data, in addition to the limitations of the model itself make formal model assessment with performance measures highly inappropriate within this context. It is clear that further research is required before formal accuracy assessment, such as that attempted here, becomes meaningful.

9.2 Further research

Within this study it has been possible to assess the basic contribution of rainfall to urban flood inundation. The conclusions elaborated above illustrate that the research questions and hypotheses have been addressed, albeit relatively simplistically. However it is clear that the full potential of this study has been limited through several key factors. These limitations appear to be relatively easily resolvable and hence intuitively represent key avenues for future research.

The first limitation can be attributed to the improvised use of the infiltration and evaporation terms (Wilson et al., 2007), in order to represent rainfall. These terms can only function within LISFLOOD-FP when cells are wet, thus leading to a situation whereby accurate representation of total volume and rate of rainfall cannot be reconciled. Hence the development of a specific rainfall parameter within LISFLOOD-FP is crucial for similar future studies. Findings of this study suggest that a rainfall parameter could potentially be of a very similar nature to evaporation, although which facilitates addition of water to both wet and dry cells. Such a parameter could potentially also offer utility for modelling of tropical rivers over large spatial and temporal scales ie (Wilson et al., 2007)

The second limitation was posed by the specific demands necessitated when providing a representation of rainfall within urban environments, which ultimately precluded the use of the adaptive time step solution and resulted in a poor representation of inundation dynamics (Hunter et al., 2006). However the new inertial formulation of LISFLOOD-FP (Bates et al., 2010), offers a much more efficient approach to modelling flood inundation within urban areas. Therefore combination of this new approach with a physically realistic representation of precipitation is likely to facilitate the elucidation of dynamic contributions of rainfall to flood inundation within urban areas over wider spatial scales. This may potentially allow benchmarking of LISFLOOD-FP for surface flows in response to rainfall (Hunter et al., 2008) and the investigation of the contribution of rainfall within a GLUE framework (Aronica et al., 2002).

The third major limitation within this study has been the provision of high quality validation data. This provides further suggestion that a dearth of validation data is perhaps the most significant limitation within the field of hydraulic modelling (Hunter et al., 2007), with this being particularly pertinent for surface flows within urban areas (Hunter et al., 2008). Collection of more high quality validation datasets for urban flood inundation events is therefore necessary in order to facilitate further model testing as elaborated above.

Whilst the avenues for future research are clearly defined here, the conclusions of this study also highlight an overarching issue when considering the contribution of rainfall to urban flood inundation. Although rainfall provided a significant contribution to the flood event which occurred within Sheffield on 25th-26th June 2007, it is clear that this was predicated upon extreme hydrological conditions, which resulted in inefficiency within the cities drainage infrastructure. Indeed, given that LISFLOOD-FP is unable to provide a representation of urban drainage the model can only be applied within these specific situations. Therefore the significance of rainfall representation within hydraulic flood inundation models represents an interesting dilemma in terms of future research, as rainfall is only likely to become significant within low frequency high magnitude events. Therefore alternatively it is possible that the efficient inertial flow equations provided by LISFLOOD-FP (Bates et al., 2010), could find a greater level of utility if used to represent surface flow within dual drainage models (Smith, 2006).

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