Exploring new technologies for simulation and analysis of urban flooding

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Abstract

Regulatory drivers, climate change and urbanisation put pressure on urban water managers to find sustainable solutions protecting people and properties from floods now and in the future. For this purpose flood model simulations and analysis are conducted to assess impacts of change on existing systems and to test options for adaptation. Recent developments in hydrodynamic models like CityCAT offer innovative concepts for effective and efficient integrated urban flood modelling. The application of new developments however is met by constraints related to the legacy of established modelling strategies, the modelling tools applied, data availability and the specific duties and responsibilities of stakeholders.

The aim of this thesis is to explore new technologies for the simulation and analysis of urban flooding and outline a programme for delivering practical solutions for end-users which addresses these constraints.

To address the important practical challenge of missing and inadequate data, a method for generating synthetic networks of storm drain inlets was developed and demonstrated. Tested in fully coupled CityCAT models to link the surface and sub-surface drainage domain, results have shown that synthetic networks of storm drain inlets provide satisfactory results compared with surveyed inlet networks. The results also highlight the sensitivity of the inlet drainage performance related to their location and elevation.

Additionally, a generic, open-source flood exposure analysis tool was developed. Detailed hydrodynamic model results and exact building geometries are used to assess the potential internal flooding of buildings for entire cities. Newly developed mapping scripts combine exposure results with hydrodynamic model results to assess cause and consequence of floods.

The third part of the thesis presents a strategic-level options appraisal highlighting the practical and financial benefits in relation to a potential industrial application of the new developments. With the availability of open architecture modelling software, this section demonstrates that the model building, simulation and analysis process can be optimised through the application of automated, generic algorithms and cloud computing.

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List of abbreviations

1D	one-dimensional
2D	two-dimensional
1D/1D	1D simulation of sub-surface domain and 1D simulation of surface flow paths
1D/2D	1D simulation of sub-surface domain and 2D simulation of surface domain
AOI	Area Of Interest
BB	Building block (method)
BH	Building hole (method)
CityCAT	City Catchment Analysis Tool
CPU	Central processing unit
CS	Collection Systems (InfoWorks CS)
DWMP	Drainage and Wastewater Management Plans
EA	Environment Agency (England & Wales)
FD	Fully distributed
FEH	Flood Estimation Handbook
FRM	Flood Risk Management
GB	Gigabyte
GIS	Geographic Information System
GML	Geography Markup Language
ICM	Integrated Catchment Modelling (InfoWorks ICM)
ICS	Integrated Catchment Studies
LiDAR	Light Detection and Ranging
MFP	Mixed Flow in Pipes
MLE	Multiple Linking Element
OS	Ordnance Survey
PC	Personal Computer
QGIS	Quantum GIS
R&D	Research and Development
RAM	Random-access memory
RP	Return Period (storm event)
RTK	Real Time Kinematic

SD	Semi distributed
SEPA	Scottish Environment Protection Agency
SLE	Single Linking Element
SUDS	Sustainable Urban Drainage System
SWMM	Storm Water Management Model
SWMP	Surface Water Management Plan
TIN	Triangular Irregular Network
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
VM	Virtual Machine

Chapter 1 Introduction

1.1 Research Context

On a regular basis, urban areas across the world experience flood events with often devastating effects on people, the urban infrastructure and the services provided. Over 50% of the world's population already live in urban areas (Brown, Keath and Wong, 2009) and a continual increase leads to potentially greater exposure to floods. At the same time, the landscapes of urban areas have undergone substantial changes affecting their hydrological runoff regimes (Butler and Davies, 2011). Reduced infiltration as a result of impermeable surfaces such as roofs, roads and pavements enhances the generation of runoff during storm events. Urban creep and the impacts of climate change suggest a further intensification of flooding in urban areas (Skougaard Kaspersen *et al.*, 2017; Chan *et al.*, 2018).

Flood Risk Management (FRM) and sustainable drainage systems are therefore required to manage the conveyance of large quantities of wastewater and stormwater in order to limit the occurrence, magnitude and impact of floods in urban areas. For this purpose, flood modelling and analysis tools are applied in order to better understand the mechanisms and impacts of floods. Specifically to urban areas and the realm of this thesis, this concerns pluvial and sewer flooding.

Traditionally, surface water runoff from impermeable surfaces is drained by a sub-surface drainage system. As shown in Figure 1.1, overland flow on roads is drained by storm drain inlets or gullies (Figure 1.3) to be conveyed by a sub-surface pipe network of a separate (stormwater) or combined sewer system (wastewater and stormwater). Sewer flooding occurs when the sub-surface drainage system becomes pressurised and the exceedance flow surcharges from the sub-surface drainage system onto the surface (Butler and Davies, 2011; Martins, Leandro and Djordjević, 2018) – see also Figure 1.2.

Pluvial flooding on the other hand is the consequence of heavy storms causing large volumes of stormwater to run off on impermeable surfaces which can no longer enter into the sub-surface drainage network; either because the latter has reached or exceeded its capacity or the runoff volumes exceed the drainage capacity of storm drain inlets (Maksimović *et al.*, 2009).

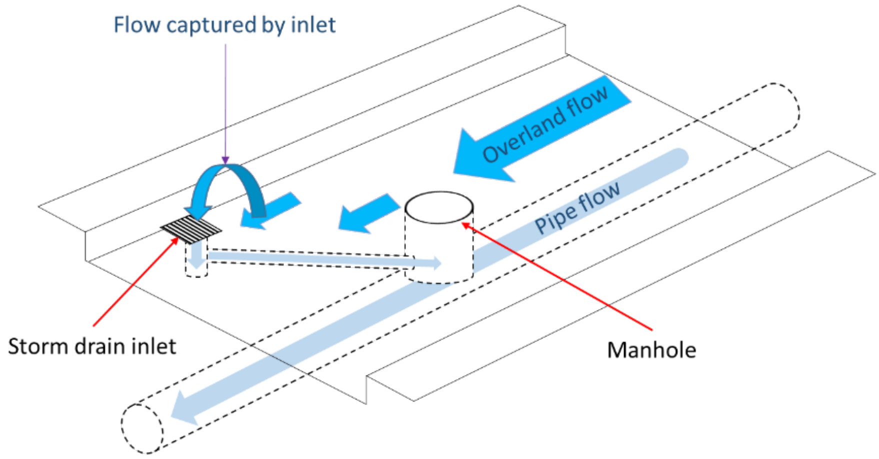


Figure 1.1 Storm drain inlets draining overland flow from the surface into the sub-surface domain.

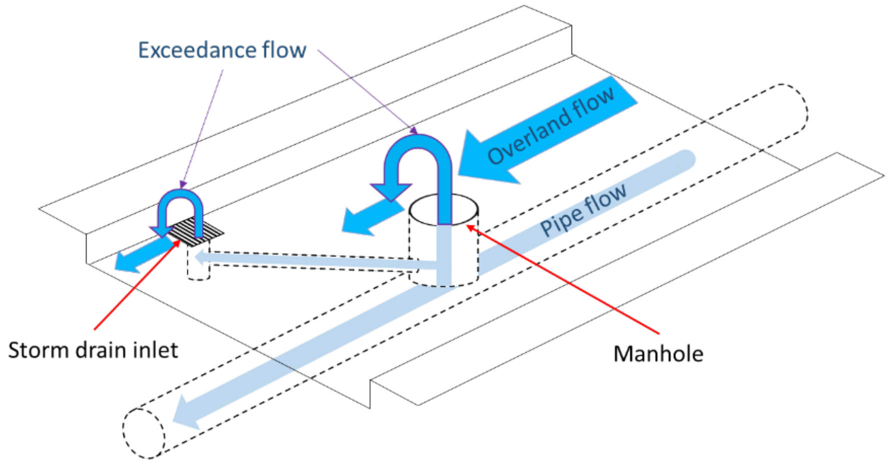


Figure 1.2 Sewer flooding as a result of pressurised sub-surface system causing exceedance flow to surcharge from sub-surface pipe network via manholes and storm drain inlets to become overland flow.

Figure 1.3 Examples of storm drain inlets.

1.2 Identification of problem

Urban flooding is a holistic problem. Pluvial and sewer flooding are rarely isolated incidences nor are they static across space and time. Dynamic interactions take place between what are considered the major and minor drainage systems of the surface and sub-surface respectively (Butler and Davies, 2011; Martins, Leandro and Djordjević, 2018). Hence, each element of the urban fabric and the drainage network (e.g. buildings, roads, storm drain inlets and pipes) plays a crucial role in urban drainage and flooding and therefore needs to be accounted for in flood modelling tools.

Working towards sustainable ways of managing sewer and pluvial flooding, the responsible authorities have to make the critical choice of selecting the appropriate modelling and analysis tools. Appropriate in this context means that the models have the capacity to provide necessary data and information to answer the questions asked. In other words: the models have to be fit for purpose.

The current flood modelling strategies in place within industrial stakeholders are the result of long established routines, shaped by the companies' duties and responsibilities. The strategies are also influenced by the approach and functions of the commercial modelling tools which are applied. In fact, the modelling strategies are often specifically established for a certain modelling approach or tool. With specific duties, responsibilities and certain modelling tools, flood modelling was rather fragmented in the past with individual stakeholders working in isolation from one another (Hall *et al.*, 2003).

Furthermore, some modelling approaches date back decades (Maksimovic and Prodanovic, 2001). The current modelling strategies and the flood modelling sector as a whole have experienced considerable implications on the collection and management of data as modelling tools tend to require a specific set of input data. This particularly concerns the sub-surface drainage network including pipes, manholes and storm drain inlets.

Establishing the modelling strategies also required considerable investments in order to obtain software licenses, to build models[1] as well as to maintain and run them. Nowadays, models are starting to be considered as assets for a company and not just a collection of data. The flood modelling business is therefore inherently conservative as changing the modelling approach or modelling software may lead to a loss of investments and expertise gathered over the years. Water utilities in the UK for instance operate on five-year business plans. Hence,

[1] A model in this work is considered as the entity of all input data and parameters of an urban catchment necessary to run a simulation in a hydrodynamic modelling software.

adopting a new flood modelling tool has to be considered as part of a long-term decision making and investment process.

There is also an increasing number of drivers and challenges with which urban areas and decision makers are faced in relation to urban flooding. Climate change is expected to alter rainfall patterns with some areas likely to see intensified storm events and higher occurrence frequencies (Mailhot and Duchesne, 2010). Urban growth will put more people at risk as urban population is expected to rise from 3.6 billion people in 2011 to 6.3 billion in 2050. (Hammond *et al.*, 2015). Urban sprawl will also increase the area of impermeable surfaces and therefore increase runoff rates which further intensifies pluvial and sewer flooding (Skougaard Kaspersen *et al.*, 2017). Moreover on a governance level, regulatory changes such as the EU Water Framework directive have to be implemented into national legislations asking for a more integrated approach (Orr, Colvin and King, 2007).

Alternative modelling approaches and techniques have become available in recent years. Research and development (R&D) focused on the development of integrated urban drainage models (Bach *et al.*, 2014) or coupled 1D/2D (pipe network = 1D and surface domain = 2D) flood models (Leandro *et al.*, 2009) to better represent the complexity associated with urban drainage and flooding. This produced new modelling approaches and tools such as CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018), which explicitly simulates all storm drain inlets together with the urban fabric.

In addition, the quantity and quality of topography data and terrain data, necessary to conduct detailed flood modelling constantly improves. New computational powers such as cloud computing (Glenis *et al.*, 2013) have become available enabling detailed 1D/2D modelling for entire urban catchments. Likewise, open-source software tools offer alternative ways for data analysis (Olson and Rosacker, 2012) and the engagement of the public in the process of data collection (crowdsourcing) – also in the field of flood modelling (Kutija *et al.*, 2014) – has become more popular in recent years leading to a new way of participatory research (Olson and Rosacker, 2012; Franzoni and Sauermann, 2013).

1.3 Aim and Objectives

In summary, long established and extensively applied state-of-the-art commercial modelling approaches show signs of limitations in addressing the increasing demand and challenges in urban flood modelling. Alternative modelling tools have become available but their potential industrial application is met by constraints related to the legacy of past and current modelling approaches.

1.3.1 Aim

The aim of this thesis is therefore to harness some of the latest research advancements in the field of integrated urban flood modelling through the development of new methods and tools.

1.3.2 Objectives

Working towards the aim of this thesis, the following objectives were identified:

[1] Highlight the major drivers for integrated urban flood modelling;

[2] Review the current urban flood modelling approaches adopted by the industry;

[3] Assess the recent research outcomes and developments in the field of integrated urban flood modelling;

[4] Evaluate the specific attributes which make CityCAT a useful software in addressing some of the key challenges in urban flood modelling;

[5] Identify the challenges and limitations which prevent a full application of new modelling tools such as CityCAT and other developments;

[6] Develop a method to generate synthetic storm drain inlet locations for the purpose of hydrodynamic modelling and evaluate the performance against field surveyed storm drain inlets;

[7] Develop generic and stand-alone tools for analysing and visualising fully coupled 1D/2D flood model simulation results;

[8] Highlight the benefits and practical implications of a potential industrial application of new developments;

1.4 Thesis organisation

This STREAM-IDC EngD thesis is a project between Newcastle University and Scottish Water. The project idea was initially conceived through a discussion at a conference. During the placement at Scottish Water in Edinburgh valuable insights into industry-based flood modelling was gained. Data for the project were provided by Scottish Water and Newcastle

University. Modelling in CityCAT was carried out by Newcastle University. Support from Perth and Kinross Council, Scotland was also received. Outputs from the thesis have been published in (Bertsch, Glenis and Kilsby, 2017), and were presented at various national and international conferences.

1.5 Research contribution

This thesis contributes to the understanding of the important role of storm drain inlets as part of the urban drainage system. Recent developments in the field of integrated urban flood modelling focus on the explicit simulation of storm drain inlets. The thesis found that extensive records about the location of storm drain inlets are not always available. Hence a new method was developed which allows the generation of a synthetic network of storm drain inlets. This can be applied in fully coupled hydrodynamic model simulations. Through the development of this method, it was found that the simulated drainage performance of inlets is highly sensitive to relatively little changes in the location of inlets – particularly in terms of elevation. It was also found that synthetically generated networks provide a sufficient first version of the network allowing for a 1D/2D simulation. For detailed analysis of the captured flows by inlets, it is recommended to conduct a field survey in order to obtain the real network.

The thesis has also developed a series of generic data analysis and mapping tools including a flood exposure analysis tool. Using detailed hydrodynamic flood model results and exact geometries of buildings, the tool has the capacity to assess the internal flooding likelihood of buildings for entire cities. With detailed data becoming more available in the future the tool avoids aggregation of data which inherently leads to loss of information. Using detailed hydrodynamic data highlights the sensitivity of the tool towards its parameters and hence the need to carefully select them. All tools are open-source and written in Python allowing users to alter them towards specific needs.

1.6 Thesis structure

The thesis is formed of seven chapters. The layout of the thesis is present in Figure 1.4. Chapters two – six have their own introduction and conclusion for an easier readability. The method for generating synthetic networks of storm drain inlets in chapter four represents the work published in (Bertsch, Glenis and Kilsby, 2017).

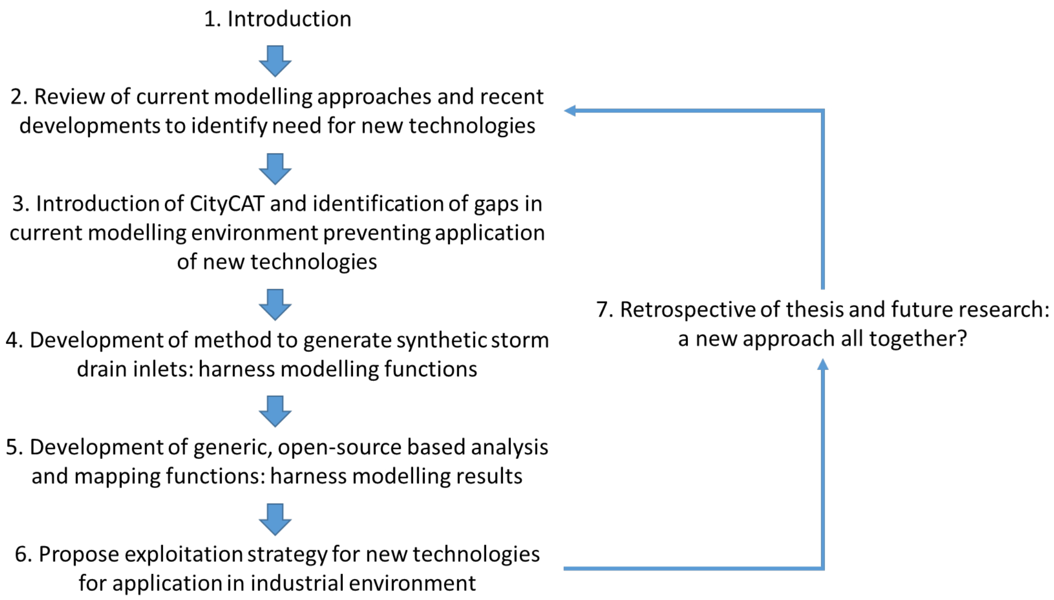


Figure 1.4 Conceptual thesis layout.

Chapter 2

Chapter two presents the literature review. It introduces the main drivers for integrated urban flood modelling, the current industry-based modelling approaches and practicalities as well as latest R&D developments. The purpose of this review is to identify critical gaps and limitations of the current modelling approaches in relation to the challenges and drivers behind urban flooding and management.

Chapter 3

The third chapter first introduces CityCAT and evaluates the usefulness of the software for addressing some of the gaps identified in Chapter 2. Subsequently the implications of the current modelling approaches, preventing a potential application of new developments such as CityCAT are outlined. As a result Chapter 3 defines the need for ways to harness new developments and introduces the deliverables of the thesis: (1) a method to generate missing storm drain inlet data for running fully coupled 1D/2D models and (2) mapping and analysis tools for handling large amounts of detailed hydrodynamic results.

Chapter 4

The consideration of storm drain inlets to link the surface and sub-surface drainage domain has become more common in recent years. As part of this study it was found that comprehensive data records in the form of surveyed storm drain inlets are not always available. This prevents a full application of CityCAT which explicitly models all storm drain inlets across the entire urban domain. Hence a method was developed which allows to generate synthetic storm drain inlet networks for the purpose of hydrodynamic 1D/2D modelling. The chapter describes the establishment of the method and the application with a comparison of synthetic storm drain inlet networks against surveyed inlet locations.

Chapter 5

Hydrodynamic models like CityCAT produce large amounts of detailed model results which are provided in numerical data format. In order to enhance their readability and accessibility for end-users a number of generic, open-source based functions and scripts were developed to support the analysis and visualisation of those data. An exposure analysis tool allows to assess the potential internal flooding likelihood of properties following an industry standard procedure.

Chapter 6

The EngD required management component is presented in Chapter 6. The purpose of this chapter is to outline a potential exploitation strategy of the outcomes of the thesis together with the modelling functions of CityCAT. The chapter identifies the potential benefits, areas of application and costs associated with using CityCAT as an additional modelling software.

Chapter 7

Chapter 7 reflects on the outcomes of the thesis against the objectives outlined in section 1.3.2. The purpose of this chapter is to assess in what way the outcomes of the thesis have the potential to change the approach and perception of the water sector and other stakeholders towards integrated urban flood modelling. This will also contain a section on potential areas for future research in this field.

Chapter 2 Integrated urban flood modelling: review of the state-of-the-art and recent developments

2.1 Introduction

This chapter presents the findings from the literature review. The aim is to identify potential gaps and missing elements which may limit a full and truly effective and efficient integrated urban flood modelling. Those findings will subsequently be taken into the third chapter to introduce CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018) and to form the conceptual background for this thesis.

The first part of this chapter outlines the main drivers and challenges behind integrated urban flood modelling. The emphasis is on the implications of climate change, urban growth and regularity changes. The second part of the review assesses the current best-practice methods adopted by the industry to conduct urban flood modelling. Furthermore, recent advancements and developments in the field of integrated urban drainage modelling from a research perspective are presented. Since this thesis is focusing on the practical implications of flood modelling the following topics are covered:

- Representation and modelling of the urban fabric inside models (semi- vs. fully distributed modelling approach);
- Modelling of pluvial and sewer flooding in 1D/1D (pipe and surface domain = 1D) and 1D/2D (pipe flow = 1D and surface flow = 2D) models and the critical aspect of linking the surface and sub-surface drainage domain;
- Modelling of flow in pipes;
- Further analysis of hydrodynamic model results in flood exposure and risk analysis.

In alignment with the scope of this thesis, the focus of this review is on the modelling of pluvial and sewer flooding. Hence the modelling of fluvial, coastal or groundwater flooding is not considered.

2.2 Drivers behind integrated urban flood modelling

In principle, modelling of the urban drainage system helps to: (a) analyse and assess the impact of change to an existing system and/or (b) assist in the design of a new system (Butler and Davies, 2011). Anthropogenic induced changes including climate change and urban growth have considerably altered urban environments. Urban drainage systems have therefore become increasingly complex to model. Additional regulatory changes are constantly increasing the demand for sophisticated flood modelling and analysis tools to assess a holistic problem in a truly integrated way.

2.2.1 Regulatory and legislative drivers

Today's approach and regulations associated with integrated urban flood modelling and Flood Risk Management (FRM) are the result of a long process with substantial changes through time. The 1980's and 1990's were dominated by a flood defence approach focusing on the economic aspects behind decision making (Johnson, Tunstall and Penning-Rowsell, 2005). The goal was to transfer water away from urban areas by large scale engineering means without considering environmental and socio-economic implications. Early risk management approaches were rather fragmented, lacking a 'whole systems' approach (Hall *et al.*, 2003; Penning-Rowsell, Priest and Johnson, 2014). Also, public awareness about flooding was relatively limited in the past (Hall *et al.*, 2003).

However public perception has changed more recently in response to devastating floods in 1998 and 2000 (Hall *et al.*, 2003; Johnson, Tunstall and Penning-Rowsell, 2005). Furthermore, new regulatory directives such as the EU Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC) were established to provide legal frameworks for a new FRM based approach. In recent years, those directives had to be put into national regulations such as the Flood Risk Management (Scotland) Act 2009 (Scottish Parliament, 2009). Responsible authorities including Water Utilities, local authorities, the Environment Agency (EA) in England & Wales and the Scottish Environment Protection Agency (SEPA) all have specific duties with respect to FRM and are encouraged to collaborate on the issue of flooding.

As a result of the FRM (Scotland) Act 2009, the Scottish Government issued a guidance document in 2011 (Scottish Government, 2011). This document highlights the need to have an integrated urban drainage approach across Scotland. The report sets out five principles (Box 2 in Scottish Government 2011) which should be adopted by the responsible authorities across Scotland (SEPA, Scottish Water, local authorities) in order to support integrated urban drainage and consequently help mitigate the risk of flooding through the delivery of a SWMP (Surface Water Management Plan) (Scottish Government, 2013), these are:

1. Increase amount of permeable surfaces;
2. In situ handling of stormwater runoff from permeable surfaces;

3. Minimise the amount of water drained into the sub-surface system;
4. Maximise options to deal with surface water before it drains into the sub-surface system;
5. Flood plains and flow paths need to be considered in exceedance design.

Besides legislative and regulatory drivers for the sector as a whole, individual stakeholders also have been given specific roles and duties in the context of integrated urban flood modelling and FRM. As one of the responsible authorities defined in the Flood Risk Management (Scotland) Act 2009 (Scottish Parliament, 2009), Scottish Water has the duty to assess the flood risk from the sewerage system for potentially vulnerable areas and each property across Scotland. This responsibility of the sewerage system (operational and maintenance) starts and ends with the property boundary (Scottish Water, 2015). The water from rainwater pipes and sewage from the internal drainage system (e.g. from the kitchen or bathroom) within a property boundary are the responsibility of the homeowner. Once the wastewater enters the main sewer system (combined or separated) and crosses the property boundary Scottish Water is responsible for it.

2.2.2 Climate change and urban growth

Besides the regularity drivers, climate change and urban growth also act as significant drivers for integrated flood modelling. Climate change is likely to increase the intensity and frequency of heavy and intense rainfall events (Mailhot and Duchesne, 2010; van der Pol *et al.*, 2015; Miller and Hutchins, 2017; Chan *et al.*, 2018). Consequently, the likelihood and magnitude of floods intensify. At the same time, urban areas expand exposing more people, infrastructure, the urban fabric (e.g. buildings) and service to the hazard of floods (Brown, Keath and Wong, 2009; Miller and Hutchins, 2017; Paprotny *et al.*, 2018).

Simulating the impacts of climate change on the risk of flooding has therefore become a crucial objective for stakeholders as well as researchers. Looking at the impact of changes in rainfall for instance, one method is to apply rainfall uplift factors which can be derived from climate models (Dale *et al.*, 2017). This is common practice across the UK, in terms of planning for new developments and developing flood mitigation strategies (Digman *et al.*, 2014; Pettit, 2014).

Critically, the impact of climate change and urbanisation varies between cities as some are more vulnerable to climate change or urbanisation while others are affected by both (Skougaard Kaspersen *et al.*, 2017). A study by Skougaard Kaspersen et al. (2017) showed that increasing the impermeable surface area by 1% may cause an additional 10% of the total area to be affected from flooding. A case study analysis by Nie et al. (2009) indicates that increasing rainfall rates by 20%, 30% and 50% may lead to an increase in surcharging water volumes from manholes of 43%, 121% and 181% respectively.

Those examples highlight a non-linear relationship between changes in rainfall or impermeable surfaces and the resulting flood risk – see also Yang et al. (2013). This underlines the need to have flood modelling tools capable of simulating the interactions between the surface and the sub-surface domain in order to assess the complex impacts of climate change and urban growth.

The combination of urbanisation and climate change enhances pluvial and sewer flooding as more people produce more wastewater which has to be drained and eventually treated. More impermeable surface areas mean larger surface runoff volumes have to be managed. As a result of those changing conditions, the design standards for urban drainage systems have to be revised and adapted (Willems, 2013; Pereira *et al.*, 2014). Integrated flood modelling tools can assist in the design of new systems and in the adaptation of existing systems.

Other examples driving integrated urban flood models in the context of climate change and urbanisation are the modelling and assessments of SUDS – sustainable urban drainage systems (Semadeni-Davies *et al.*, 2008b, 2008a; Fletcher *et al.*, 2015) and blue-green infrastructure (Thorne *et al.*, 2018). Mentens et al. (2006) highlight the need to have integrated modelling tools which allow a simulation of multiple blue-green infrastructure features in order to assess the combined impact on the runoff in urbanised areas.

2.3 Modelling approaches and techniques

For the simulation of floods in urban areas multiple approaches, methods and tools are available. Regardless of the model or modelling approach, all approximate the spatial distribution and representation of the topographic features as well as the physical processes. This makes some methods and tools inadequate for simulating the complex and dynamic interactions between the surface and sub-surface domain (Maksimovic and Prodanovic, 2001).While the selection of the modelling tool is influenced by many factors including the available resources, data and expertise, the appropriate modelling tool should be useful in the sense that it can address a specific purpose or goal – whilst acknowledging the simplification and limitations of the model (Box, 1979). For the purpose of strategic, large scale modelling of surface flooding in urban areas for instance the sub-surface drainage network is in some cases not explicitly simulated (Environment Agency, 2013b). Instead, a constant value of 12 mm/h (Environment Agency, 2013b) is subtracted from the input rainfall mimicking the drainage effect of the sewer system. For detailed sewer flood modelling purposes on the other hand, the interactions between the sewer system and the surface domain are modelled with coupled 1D/2D models simulating both pipe flow (1D) and surface flow (2D).

The modelling strategies at industrial stakeholders are also influenced by the modelling tools applied. Many commercial software packages like InfoWorks ICM – Integrated Catchment Modelling (Walker, 2017) offer different modelling approaches ranging from the 1D/virtual manhole method to coupled 1D/2D models. It is therefore within the judgment of the user and the realm of a project to select the appropriate modelling approach and software.

2.3.1 Representation of the urban fabric inside a model

There are multiple ways to classify modelling tools (Salvadore, Bronders and Batelaan, 2015). For the purpose of this thesis the discretisation technique and representation of the urban domain inside the model was chosen as the most meaningful way. In this context, modelling techniques can generally be distinguished between semi-distributed (SD) and fully distributed (FD) (Figure 2.1).

SD models for urban flood modelling purposes are commonly based on the 'sub-catchment/manhole' method (Figure 2.1 - right). In this approach the modelling domain is divided into a number of individual sub-catchments which are linked to manholes (Pina *et al.*, 2016; Cheng *et al.*, 2017; Bermúdez *et al.*, 2018; Gong *et al.*, 2018). To reflect on the area, slope and surface types within the sub-catchments, they are assigned a number of parameters. Based on those parameters a rainfall-runoff hydrograph is calculated for each sub-catchment to transfer water volumes into the manholes and consequently the sub-surface domain (Pina *et al.*, 2016). The sub-catchment/manhole approach is essentially a collection of multiple hydrological models – one for each sub-catchment – followed by a hydraulic model for calculating pipe flow. The delineation of the sub-catchments and parametrisation is usually done manually which may require a considerable amount of time depending on the size and complexity of the overall domain.

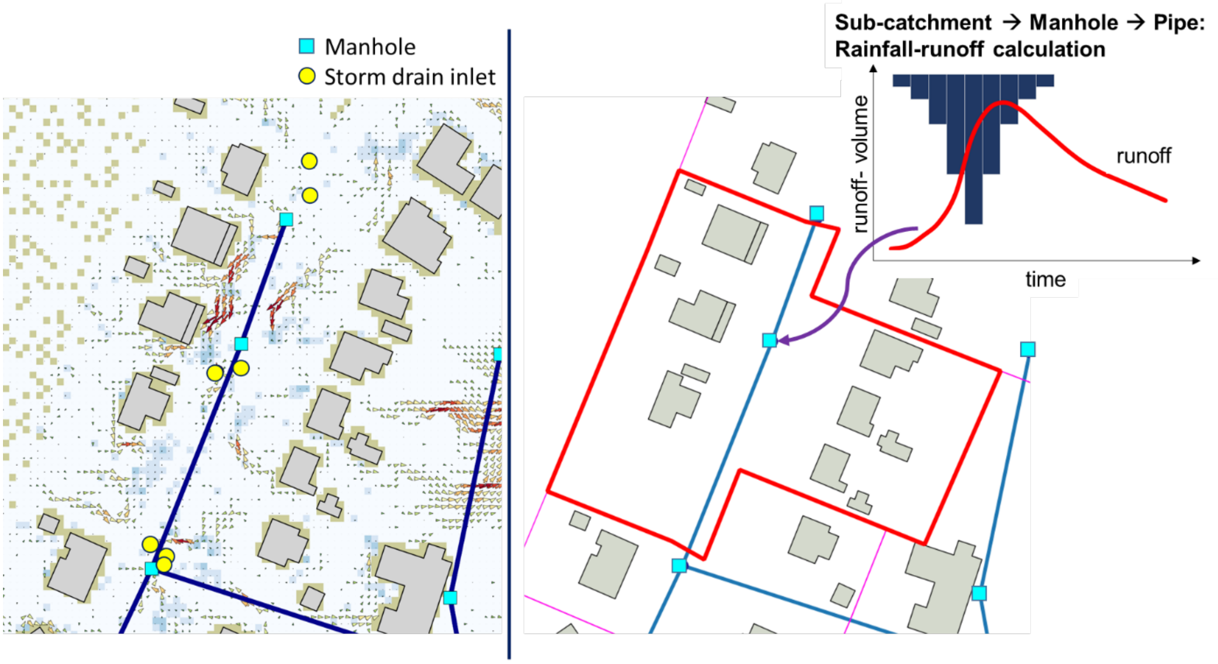


Figure 2.1 Fully-distributed, FD (left) and semi-distributed, SD (right) modelling approach. The FD approach is based on discretised grid with rainfall applied on individual grid elements. 2D surface flow runoff enters inlets. The SD approach has sub-catchments linked to manholes for conveying rainfall-runoff hydrographs into sub-surface sewer system without conducting 2D surface water runoff modelling.

Depending on the modelling software, multiple methods for the generation of the rainfall-runoff hydrograph are available. InfoWorks ICM for instance offers seven different methods (Gong *et al.*, 2018). Specifying the method to calculate the rainfall-runoff hydrograph also requires a parametrisation for calculating initial rainfall losses through infiltration and evaporation (Gong *et al.*, 2018). Selecting the appropriate method and understanding the implications and limitations of the method are therefore important. Apart from the initial losses, the SD method also lacks the capability of explicitly capturing continuous losses throughout the simulation resulting from infiltration or temporal water storage in terrain depressions (Pina *et al.*, 2016).

Instead of using sub-catchments, the FD method has a discretised grid (Figure 2.1 - left) or mesh (see next section) covering the entire modelling domain. Rainfall is applied directly on the individual grid or mesh elements. The physically based FD method therefore allows the simulation of 2D surface flow directly from rainfall. Usually, the final computational grid of a FD model combines multiple layers of information including surface elevation, green areas and buildings for instance.

2D modelling domain in FD models

The 2D computational grid of a FD model is commonly based on a regular spaced grid or a TIN (Triangular Irregular Network) mesh. Whilst regular spaced grids use the exact DTM (Digital Terrain Model), a TIN mesh has to be delineated from the initial DTM. A TIN mesh can be generated automatically in GIS or sometimes within the hydrodynamic modelling software itself. A critical aspect is the optimisation of a TIN mesh. This process may include the merging of small mesh elements or the alignment of mesh elements with walls or curbs. In case of a high spatial resolution and a complex urban topography the generation of a TIN mesh may require several months as the optimisation has to be done manually (Gibson *et al.*, 2016).

For the generation of a TIN mesh, the minimum and maximum area of individual mesh elements can be defined. Small elements allow for a more detailed representation of the terrain and urban fabric but come at the cost of longer mesh generation times and longer simulation times. Examples from the literature show the differences between the minimum and maximum mesh element size can be considerable. In Bermúdez et al. (2018) the minimum and maximum mesh areas are 3.75 m^2 and 50 m^2 respectively. Cheng et al. (2017) use <50 m^2 for mesh elements on roads and 50 m^2 to 100 m^2 for other areas. An average and maximum element mesh size of 25 m^2 and 100 m^2 is applied in (Russo *et al.*, 2015). Selecting the minimum and maximum mesh size should also take into account model stability conditions and time-stepping implications as the latter is determined by the smallest mesh element.

Representation of buildings

Hydrodynamic flood modelling in densely built-up urban areas requires the acknowledgment of obstacles such as buildings. Schubert & Sanders (2012) compare different ways of representing building footprint areas inside a hydrodynamic model and the implications on the complexity of the model set-up process. For industrial modelling purposes two approaches are commonly applied. The first one represent buildings as void space which has the cells from within the building footprint removed from the computational 2D domain (grid or mesh). As a result, surface flow is routed around the building footprint. The advantage of this method is the reduction in computational cells to be simulated, which reduces the computational time of a simulation and is particularly beneficial for densely built-up areas.

The second approach uses 'stubby' buildings (Pettit, 2014; SEPA, 2018). In this method the grid cells within the building footprint area remain part of the computational grid, however, their elevation is altered in the DTM. A common example is to raise the elevation by 0.3 m in order to reflect the difference between ground elevation (outside) and floor level (inside) of a building (Pettit, 2014). Buildings are considered as flooded once the water level overtops the additional elevation of the 'stubby' buildings.

The representation method of buildings inside a model has further implications on the calculation of rainfall-runoff from roofs. Models which have the building footprint area removed from the computational grid need to have a method implemented to keep the roof-runoff volumes inside the system i.e. the computational domain. In the 'stubby' buildings approach rainfall runoff can be calculated from the cells within the building footprint as they are not removed from the grid.

2.3.2 Modelling of pluvial and sewer flooding

1D and virtual reservoirs

An early and much simplified approach for simulating sewer flooding is the concept of virtual reservoirs based on a SD model (Maksimovic and Prodanovic, 2001) – see Figure 2.2. As introduced previously, sub-catchments are linked to manholes and the calculation of rainfall-runoff is based on hydrographs. Additionally, the sub-catchments manholes are also assigned with a virtual flood reservoir or flood cone. In the case of a pressurised manhole, the surcharging exceedance flow fills the virtual reservoir. Once the state of the drainage system goes back to non-pressurised, the water from inside the virtual reservoir can drain back into the sub-surface system. Alternatively the water can also 'get lost' mimicking a surcharge onto the surface without returning into the sub-surface system. However, an actual 2D simulation of the surcharging water is not conducted.

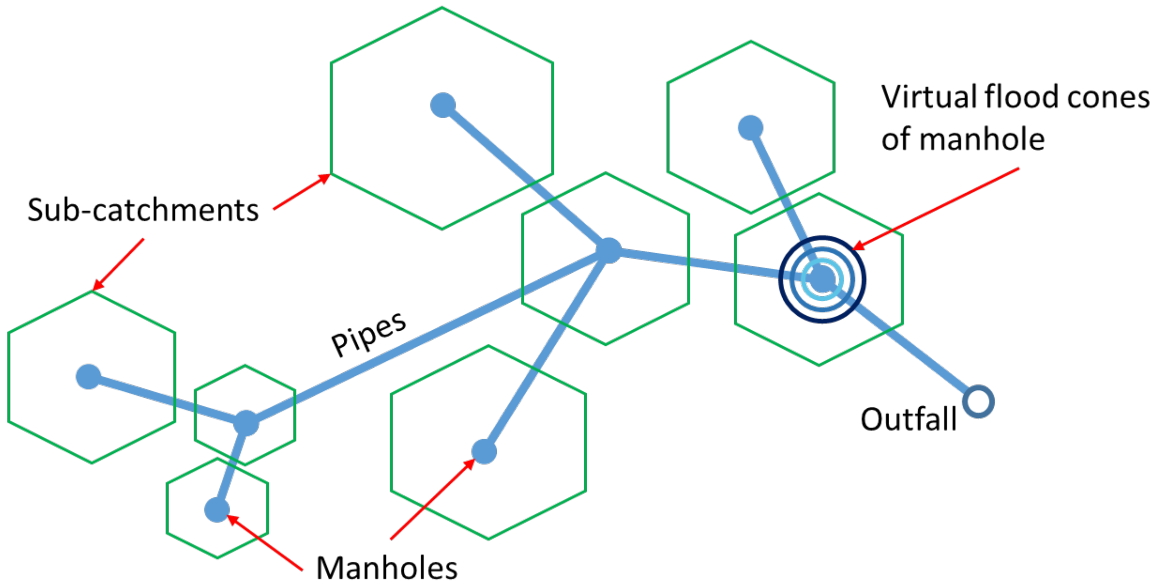


Figure 2.2 Simulation of sewer flooding based on virtual reservoir modelling method.

Although the approach of virtual reservoirs requires very little computational resource the location and severity of sewer flooding is only indicated by pressurised manholes and the surcharging water volumes present in the virtual reservoirs. Furthermore, this method lacks any coupling of the surface and sub-surface domain and pluvial flooding cannot be assessed with this method.

Coupled 1D/1D modelling approach

Alternative modelling methods to simulate sewer flooding instead of the virtual reservoir method were introduced with the emergence of the dual-drainage concept in the late 90's (Djordjević, Prodanović and Maksimović, 1999). Generally, the dual-drainage concept has a major (surface runoff routes) and minor (sub-surface pipe system) drainage system (Djordjević *et al.*, 2005).

Associated with the dual-drainage concept was the development of the 1D/1D modelling approach (Figure 2.3). In a 1D/1D model the major and minor system are linked through nodes – usually manholes (Mark *et al.*, 2004; Djordjević *et al.*, 2005; Leandro *et al.*, 2009). In principle the 1D/1D modelling approach treats roads as channels and consequently simulates flow in form of an open channel flow. Potential surface water runoff pathways delineated from a DEM are also represented one dimensionally. Linking the 1D pipe network with the 1D surface channels allows the simulation of the exchange of water between the major and minor drainage system (Leandro *et al.*, 2009).

To introduce runoff into the sewer system, 1D/1D modelling tools such as SIPSON – Simulation of Interaction between Pipe flow and Surface Overland flow in Networks – (Djordjević *et al.*, 2005) also rely on the generation of rainfall-runoff hydrographs as previously introduced. 1D surface channels can also be linked to ponding areas which have to be identified prior to a simulation using GIS tools (see for instance Maksimović *et al.*, 2009). This allows representation of the temporal storage of water in terrain depressions during the simulation.

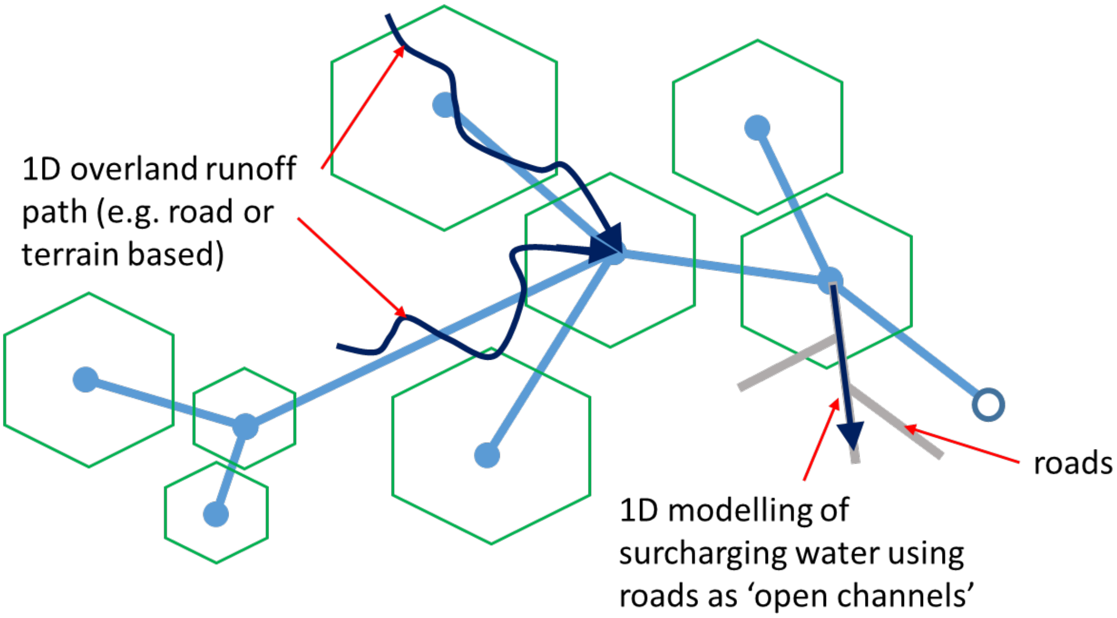


Figure 2.3 Simulation of sewer flooding based on coupled 1D/1D modelling method.

As long as surface flow is confined within the 1D channels of roads (i.e. within kerbs) and the surface runoff, the 1D/1D modelling approach can be applied for simulating sewer flooding (Leitão *et al.*, 2010; Simões *et al.*, 2011). However, in case of large flood events with water overtopping the height of kerbs and extending beyond roads the flow dynamics cannot be captured with a 1D/1D model (Mark *et al.*, 2004). Furthermore, pluvial flooding cannot be simulated across the entire domain as no 2D modelling is conducted.

SD coupled 1D/2D modelling approach

In a 1D/2D model, manholes are linked to a 2D surface grid/mesh domain. Potential exceedance flow can surcharge onto the surface and is routed as 2D overland flow (Figure 2.4). This allows for a more realistic assessment of sewer flooding problems as terrain information is directly incorporated into the modelling. Often, 1D/2D models are SD in terms of the sub-catchment/manhole method (Salvadore, Bronders and Batelaan, 2015). To introduce the exceedance flow from the sub-surface domain onto the surface domain, weir equations are commonly applied using the diameter of the manhole as crest length (Cheng *et al.*, 2017; Bermúdez *et al.*, 2018).

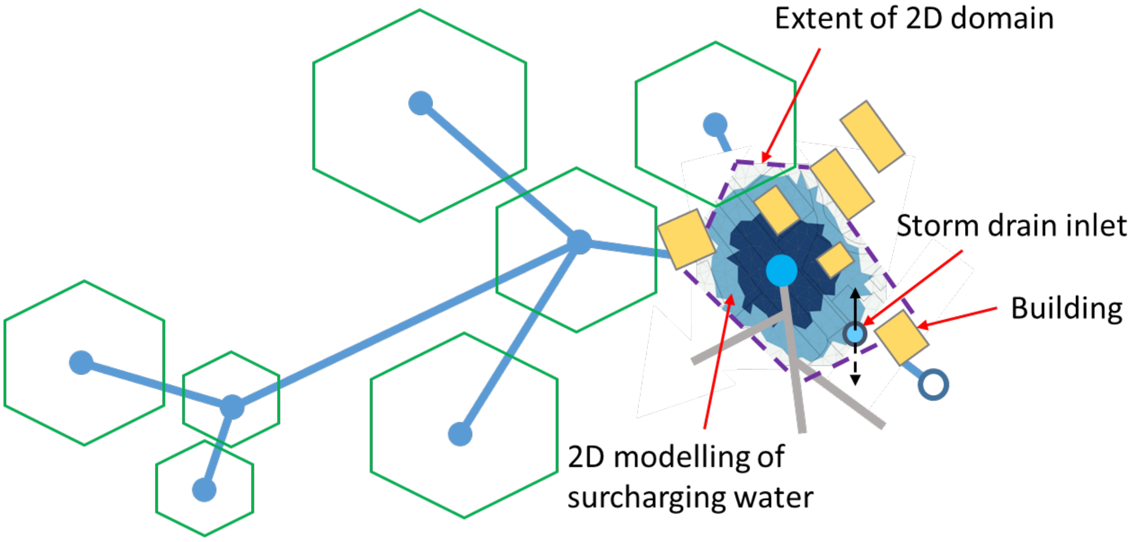


Figure 2.4 Simulation of sewer flooding based on coupled 1D/2D modelling method.

The 1D/2D modelling approach is embedded in many commercial modelling tools such as InfoWorks ICM (Innovyze, 2018). By only linking a selected number of manholes to a 2D domain, the grid/mesh resolution of those 2D areas can be kept relatively high allowing for a more detailed analysis of sewer flooding. This makes the 1D/2D approach particularly attractive for authorities responsible for sewer flooding such as water utilities in the UK.

Considering larger domains however examples from the literature have relatively coarse grid resolutions. For a 27.5 km^2 domain Bermúdez et al. (2018) have used a mesh size ranging from 3.75 m^2 to 50 m^2 for instance. In Cheng et al. (2017) the modelling domain with an area of 23.7 km^2 has mesh resolutions from <50 m^2 for roads with up to 100 m^2 for other areas. Those resolutions may not be suitable for the purpose of detailed urban flood modelling as they could miss narrow flow pathways between buildings or other features of the urban topography (Mason, J-p. Schumann and Bates, 2010).

Fully coupled 1D/2D modelling approach

The modelling approaches introduced so far consider the hydrological and hydraulic phases separately in the sense that rainfall is converted into surface runoff hydrographs to provide the input for the hydraulic calculations (Djordjević *et al.*, 2005). Furthermore, the coupling of the sewer system with the surface domain allows exceedance flow from the sewer system onto the surface and only in some case back into the sewer system. None of the modelling methods introduced so far allow simulation of pluvial flooding.

To simulate pluvial flooding from rainfall induced surface runoff various FD 2D modelling tools are available (Hunter *et al.*, 2008; Fewtrell *et al.*, 2011; Environment Agency, 2013a). They are however not coupled with the sewer system. To mimic the drainage effect of the sewer system in such models the rainfall input is reduced by a constant value (Environment Agency, 2012; Webber *et al.*, 2018). For the generation of surface water flood maps the Environment Agency for instance applies a value of 12 mm/h (Environment Agency, 2012). Since this value is applied uniformly across space and time the major limitation of this method is the inability to reflect any variability in the efficiency of the drainage network. The varying impact of the sub-surface drainage domain on surface water depth is illustrated in chapter 5.

A case study by Van Dijk et al. (2014) compares a surface flood model using a constant drainage reduction value of 20 mm/h with a coupled 1D/2D model. Particularly at locations in transitional zones between flat and steep areas Van Dijk et al. (2014) conclude that the application of a constant drainage value has its greatest limitation. This is because the drainage catchments of the surface and sub-surface domain show less overlapping in those areas.

In order to simulate pluvial and sewer flooding explicitly in a single model and to appropriately connect the surface and sub-surface domain a more integrated modelling approach is required. For this purpose, FD and fully coupled 1D/2D models have been developed with a range of specific capabilities:

- Fully distributed 2D modelling domain (TIN mesh or regular spaced grid) based on terrain derived catchments;
- Transformation of rainfall into surface runoff for each cell of the 2D modelling domain with subsequent 2D overland flow routing;
- Simultaneous solution for calculating 2D surface flow and 1D pipe flow to capture bidirectional flow;
- Linking the surface and sub-surface domain with storm drain inlets and manholes;
- Capacity to simulate shock waves, flow around complex geometries (e.g. buildings) and calculate the wetting and drying of cells.

As shown in Figure 2.5, the results from a fully coupled 1D/2D model yield information on water depth and flow vectors for each cell of the computational domain. In order to access the capacity of fully coupled 1D/2D models, detailed data about the terrain, topography and sub-surface drainage system including pipes, manholes and inlets are required. Compared to previously introduced modelling methods, fully coupled 1D/2D models require greater computational resources.

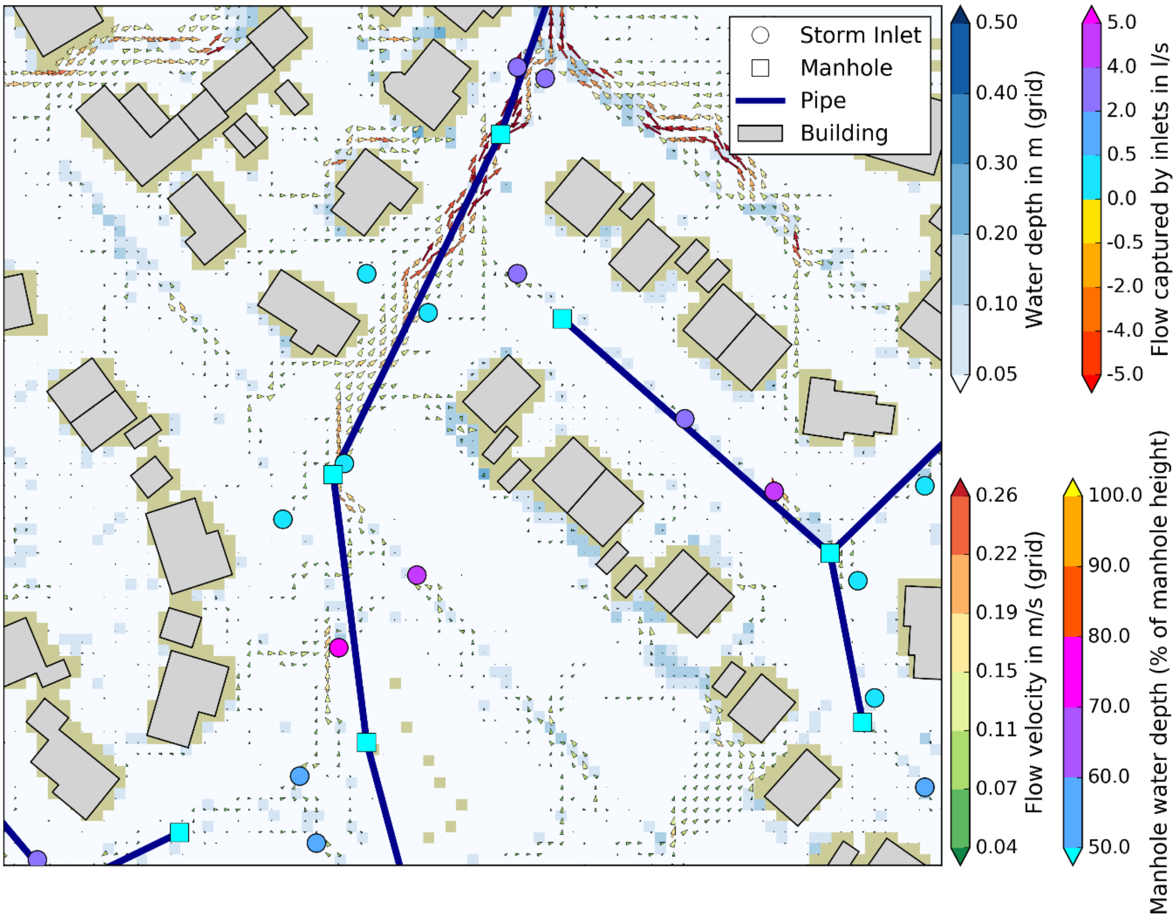


Figure 2.5 Illustration of model components of a fully distributed, fully coupled 1D/2D hydrodynamic model.

A critical component for FD, fully coupled 1D/2D models is the numerical scheme implemented. They require the ability to appropriately solve the propagation of shock waves (Hunter *et al.*, 2008), flow around complex obstacles such as building as well as the drying and wetting of cells (Brufau, García-Navarro and Vázquez-Cendón, 2004). Since this thesis is focusing on the practical implications of urban flood modelling the mathematical background and numerical schemes of modelling tools is not discussed any further.

An early example of adopting the concept of fully coupled 1D/2D models is presented in Dey & Kamioka (2007). Their model combines various modelling engines (e.g. from SWMM) for a simultaneous modelling of 1D pipe flow, 1D river flow and 2D overland flow. Overland flow can be rainfall induced or originate from overtopping rivers and surcharging manholes. In order to link the surface and sub-surface domain, Dey & Kamioka (2007) apply manholes and simulate the flow through manholes using a weir equation.

Further case studies and practical applications of the work presented in Dey & Kamioka (2007) however could not be found. In general, examples from the literature on large scale and detailed FD fully coupled 1D/2D FD urban flood modelling are rare. Also for industrial modelling purposes the application of fully coupled 1D/2D models for analysing pluvial and sewer flooding is rather the exception than the norm. One of the reasons is that fully coupled 1D/2D models are still relatively new and track records of industrial applications are rare. Another reason is the demand of high quantity and quality of data which may not always be available. Furthermore, the higher demand of computational resources is a major limiting factor in terms of the costs and resources required for running flood simulations.

To a certain extent, the limited application of a fully coupled 1D/2D model is also an institutional one. As mentioned earlier FRM involves stakeholders with different duties and responsibilities. In the UK, no single authority has the responsibility to assess pluvial and sewer flooding. Hence, from an institutional perspective the need for fully coupled 1D/2D models has so far not been widely recognised.

Manholes and inlets: the linking elements

Current and past modelling approaches rely heavily on manholes to link the surface and sub-surface domain. In reality however the actual surface water drainage is performed predominantly by storm drain inlets. With the advancement of fully coupled 1D/2D models, more recent research aims to appropriately link the surface and sub-surface domain with both manholes and storm drain inlets (Leandro *et al.*, 2007).

Early work on the application of inlets was performed by Leandro et al. (2007) and the method of single-linking-elements (SLE) and multiple-linking-elements (MLE). A SLE is formed of a rectangular gutter, an inlet, a manhole and the pipe connection between manhole and inlet (Leandro *et al.*, 2007). The calculation of flow entering an inlet is based on a weir equation. Initially, the MLE method was developed for coupling 1D/1D models used in the SIPSON modelling tool (Leandro *et al.*, 2007). The MLE node combines the information of multiple SLE nodes (Leandro *et al.*, 2007). Therefore, the performance of the MLE methodology suffers in situations where the different SLE nodes are considerably different in terms of their elevation or if they are non-symmetrically distributed around the eventual MLE location.

Using a weir equation to calculate the flow captured by inlets can also be found in Palla et al. (2016). Critically however, the simulations in Palla et al. (2016) only allow one-directional flow from the surface into a virtual sub-surface system without simulating the actual pipe system. Therefore sewer flooding cannot be simulated with the methodology presented in Palla et al. (2016).

Russo et al. (2015) apply two different approaches for calculating the flow exchange between surface and sub-surface in an InfoWorks ICM model. For one set of manholes a weir equation is applied. For the other set of manholes, a head/discharge curve based on the piezometric head inside the manhole and the water level on the surface is used. This however does not take into account the approaching velocity of overland flow. In reality, at a certain velocity parts of the approaching flow are no longer captured by an inlet. This velocity is also referred to as 'splash-over velocity' (Gómez and Russo, 2011; Comport and Thornton, 2012). In (Russo *et al.*, 2015) the InfoWorks ICM model is further simplified by grouping nodes of similar types. Consequently, the head/discharge curve for the final node is multiplied by the number of grouped inlets. Establishing the head/discharge curves and combining multiple nodes has to be done manually resulting in a labour intensive model building.

2.3.4 Simulating pipe flow

The simulation of pipe flow in coupled models of commercially applied modelling tools such as InfoWorks ICM (Innovyze, 2018) or SWMM (United States Environmental Protection Agency, 2018) is commonly using the Preissmann slot method. In principle, the Preissmann slot method introduces an artificial slot on top of the pipe soffit level (Preissmann, 1961). The purpose of using the Preissmann slot method is to model pressurised flow as open-channel flow based on the continuity and momentum equations of the shallow water equations (see for instance Ferreri, Freni and Tomaselli, 2010; Malekpour and Karney, 2015). Using the same equations for modelling both pressurised and non-pressurised flow results in relatively short simulation run times.

The Preissmann slot method however has several limitations. The Preissmann slot method is not capable of dealing with sub-atmospheric pressures (Vasconcelos, Wright and Roe, 2006; Malekpour and Karney, 2015). In the situation of a sub-atmospheric pressure, the Preissmann slot method switches from a pressurised to a non-pressurised flow which is only possible through adequate ventilation of the pipe system (Vasconcelos, Wright and Roe, 2006; Malekpour and Karney, 2015). Furthermore, the Preissmann slot method can lead to spurious numerical oscillations during the transition of flow phases (Vasconcelos, Wright and Roe, 2006; Malekpour and Karney, 2015). Also the selection of the slot width has an impact on the simulation. While narrow slot widths result in small computational time steps and thus longer simulation times, wider slot widths increase the amount of water stored inside the slot which slows the advancement of the inflow front (Vasconcelos, Wright and Roe, 2006). The application of the Preissmann slot method for modelling pressurised pipe flow can therefore cause model instabilities and produce erroneous results (Ferreri, Freni and Tomaselli, 2010; Innovyze, 2013).

Heavier and more intense rainfall due to climate change as well as larger areas of impermeable surfaces will increase the volume of stormwater that needs to be drained by urban drainage system. In comparison, the sub-surface drainage system remains relatively static and its capacity does not increase at the same rate. From a modelling perspective, the likelihood of simulating pressurised pipe flow within an existing system therefore increases. New mathematical models for simulating pressurised pipe flow have been developed in recent years to overcome the limitations of the Preissmann approach (Bourdarias, Ersoy and Gerbi, 2012).

2.3.5 Flood exposure and risk analysis

Hydrodynamic flood models primarily provide information on the depth and flow vectors of water. For the purpose of flood risk analysis this information is applied to study the wider implications of floods on people, properties and other parts of the human and natural environment.

Flood risk is generally described as the product of the three elements: hazard, vulnerability and exposure (Kron, 2002; Molinari *et al.*, 2014; Koks *et al.*, 2015). Hazard is about the physical element of the flood event reflecting its probability of occurrence and magnitude (Kron, 2002; Merz, Thieken and Gocht, 2007; Chen *et al.*, 2016). The vulnerability aspect describes the ability or inability of a flooded object to cope with the effects of a flood event (Koks *et al.*, 2015). Resilience and preparedness of individuals or a community in a flood prone area affect their vulnerability and consequently risk as a whole (Vis *et al.*, 2003;

Thieken *et al.*, 2007; Merz *et al.*, 2010). Exposure refers to the number of people and value of assets exposed to the hazard (Molinari *et al.*, 2014; Hammond *et al.*, 2015; Koks *et al.*, 2015).

A thorough flood risk analysis requires socio-economic parameters to reflect on the vulnerability (Cutter, Boruff and Shirley, 2003; Van Ootegem *et al.*, 2015). Depending on the scale of the investigation (i.e. level of detail and size of the area) and the methods applied, a vulnerability analysis may require a considerable amount of data, including for instance: hazard data, detailed building characteristics and building inventory information as well as flood damage and repair costs (Apel *et al.*, 2009). Such data sets however might not be available or easy accessible (Apel *et al.*, 2009; Schröter *et al.*, 2014).

Compared to an extensive flood risk analysis, flood exposure analysis has the advantage of highlighting affected areas of buildings while requiring less input data. Furthermore, a flood risk analysis is commonly based on the results from a previously conducted flood exposure analysis. For the purpose of calculating flood exposure, the hazard information (e.g. inundation depth) is related to the exposed unit (e.g. building) by means of spatial intersection or proximity analysis. Depending on the scale of application, exposure analysis are often conducted with aggregated hydrodynamic data and simplified representations of the exposure unit (Fuchs, Keiler and Zischg, 2015; Röthlisberger, Zischg and Keiler, 2017). Although this approach is feasible for large scale analysis, the associated loss of information when aggregating or simplifying data has to be remembered. With the increasing availability of detailed hydrodynamic data from fully coupled 1D/2D models the need for flood exposure analysis tools capable of handling such data also increases.

A common challenge in the context of conducting flood exposure or risk analysis from hydrodynamic models is the compatibility of data. Commercial flood modelling tools often require a software specific add-on or extension package to access and analyse the model results. Thus, users have to obtain a license even though they may not conduct the flood modelling analysis themselves. On the other hand, the modelling software-specific exposure analysis tool will not accept data from other hydrodynamic modelling tools. Therefore, generic flood exposure analysis tool are required which can access model results from different modelling tools.

2.5 Conclusions: The gaps identified

The literature review presented in this chapter first introduced the main drivers for integrated flood modelling analysis. Common best-practice approaches in the industry and recent research developments in the field were presented and critically evaluated. Although progress has been made over the last years with regards to the development of fully coupled 1D/2D models, the review has identified certain gaps still limiting fully effective and efficient integrated urban flood modelling:

- The shared responsibility amongst stakeholders limits the need for fully coupled 1D/2D hydrodynamic models as no single authority is required to assess both pluvial and sewer flooding. Hence modelling of pluvial or sewer flooding is done in a rather isolated manner and only recent frameworks like the Integrated Catchment Studies (ICS) (Scottish Government, 2013) and Drainage and Wastewater Management Plans (DWMP) (Richard, 2018; South West Water, 2018) looking at a more integrated approach.

- The application of storm drain inlet networks for industrial purpose in coupled 1D/2D models is rarely done due to the modelling tools used, missing data and the demand of strong computational resources coupled with longer simulations times.

- Commercial modelling tools offer relatively fast simulation times (e.g. semi distributed modelling approach, Preissmann scheme, limited number of nodes, mesh dimensions). However, considerable time may be required for the model generation as multiple steps involved have to be done manually such as the 2D mesh optimisation, defining and parametrisation of sub-catchments, establishing head/discharge curves for inlets or the grouping of nodes.

- Detailed hydrodynamic model results are rarely used for large scale exposure analysis. Instead, aggregated information is applied leading to a loss of information. Additional analysis of hydrodynamic results are also strongly dependent on the modelling tool applied leading to compatibility problems between data and software.

Associated with the points listed above, Table 2.1 summarises the major current best-practice methods specifically focusing on the simulation of pluvial and sewer flooding in terms of their approximations, limitations and options to overcome those limitations.

Table 2.1 Summary of approximations behind commonly applied modelling methods for simulating pluvial and sewer flooding, the limitations and potential solutions.

Approximations	***Limitations***	***Solutions***
Representation of surface domain by sub-catchments	• Terrain incl. infiltration and topography not explicitly simulated • Manual derivation and parametrisation of sub-catchments is labour intensive	• Explicit representation of terrain and topography in FD models • Use of terrain-derived catchments in GIS
Rainfall-runoff modelling via hydrographs based on sub-catchment parameters	• Separation of hydrological and hydraulic phase • Rainfall induced surface runoff not simulated • Pluvial flooding not captured • Losses (e.g. temporal storage of water, continuous infiltration) not captured	• Application of FD and fully coupled 1D/2D models which simultaneously solves the surface runoff and sub-surface flow in pipes
Linking of surface and sub-surface domain via manholes	• Mostly one-direction flow (surface → sub-surface) • Storm drain inlets not applied for large scale domains	• Explicitly simulate manholes and inlets in fully coupled 1D/2D models
2D sewer flood modelling for specific areas only	• Interaction of rainfall induced 2D overland flow and sewer flooding not captured • TIN mesh optimisation is labour intensive	• Fully coupled 1D/2D models • Using regular spaced grids ($\Delta x = \Delta y$) and automated model building algorithms
Head/discharge curves to drain surface water via manholes	• Approaching flow velocity ignored • Manual establishment of head/discharge curves can be time consuming	• Application of storm inlets to drain surface water
Grouping multiple nodes into single one	• Merging leads to loss of information	• Explicit modelling of all storm drain inlets
Preissmann slot method applied to mimic open-channel flow for pressurised pipe flow	• Not suitable for heavy pressurised pipe flow	• Alternative ways of modelling pressurised flow
Reduce amount of rainfall to mimic sub-surface system in pluvial, 2D flood models	• Dynamic (spatial and temporal) interactions between the surface and sub-surface domain are not captured	• Application of fully distributed and fully coupled 1D/2D models

Chapter 3 Alternative solutions and means to harness them

3.1 Introduction

The literature review in the previous chapter assessed the drivers and needs for flood modelling analysis and introduced commonly applied modelling approaches and software tools. The review also reflects on recent developments in the field of urban flood modelling. The conclusions were drawn that modelling of large urban catchments at high resolutions in fully coupled 1D/2D models using all storm drain inlets is still in its infancy. Particularly for industrial purposes where the application of matured approaches such as the sub-surface/manhole modelling is still popular.

Over the recent years, CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018) a fully coupled 1D/2D urban flood modelling tool has been developed at Newcastle University. CityCAT explicitly simulates all storm drain inlets and manholes to link the surface and sub-surface domain. Furthermore, infiltration over green areas is simulated and roof runoff can be captured in different ways. This allows for an effective modelling of the holistic problems behind pluvial and sewer flooding. The automatic generation of the final computational grid and the multi-threaded capability for efficiently using powerful computational facilities such as server or cloud computing also allow for a highly efficient modelling approach.

To unlock the full potential of CityCAT high resolution data are required. Furthermore, analysis tools capable of accessing the large quantity of model results are needed. Exploring a potential industrial application of CityCAT however showed that this is met by constraints. This is largely due to the implications of the modelling approaches and techniques in place. To overcome those constraints, this chapter presents the framework behind the developments of this thesis which are presented in chapters 4-6.

This chapter first introduces the modelling approach behind CityCAT and its unique modelling functions. The emphasis is to demonstrate the useful aspects of the software from a practical perspective. The second section outlines the key implications of the current modelling approaches on a potential industrial application of CityCAT. The purpose behind this is to identify the need for developing methods to generate missing data and analysis and visualisation tools to harness both the modelling functions and model results of CityCAT.

3.2 CityCAT – City Catchment Analysis Tool

CityCAT is a fully distributed and fully coupled 1D/2D hydrodynamic modelling platform. To simulate hydrologically connected areas CityCAT applies terrain based surface runoff catchments which can be derived automatically in GIS software. CityCAT is based on a regular spaced grid and allows the simulation of large areas at high resolutions (e.g. 67 km^2 domain at $\Delta x = \Delta y = 2$ m). A schematic representation of the components of a 1D/2D CityCAT model is shown in Figure 3.1.

The software architecture in CityCAT is entirely object-oriented also including the numerical algorithms (Glenis, Kutija and Kilsby, 2018). Computational objects such as cells and cell-interfaces have properties, fields and methods. Those are applied to establish the interconnections between the computational objects automatically during the model building stage. This includes for instance the assignment of the appropriate Riemann solver depending on the boundary condition of the cells. Compared to a procedural code structure this means that during the simulation no 'if-then-else' queries are required making the object-oriented approach considerably more efficient (Glenis, Kutija and Kilsby, 2018).

The fully-distributed modelling approach of CityCAT means that infiltration is calculated for green areas using the Green-Ampt method (Warrick, 2003). Grid cells within building footprint areas are treated specially. They are removed from the computational grid reducing the number of computational cells. Particularly for densely built-up urban areas this can reduce the simulation time considerably. The water volumes of the building-footprint cells however is not lost but kept in the domain where it is distributed to the cells adjacent to a building. Optionally, the building footprint cells can be assigned with a water storage volume enabling to simulate blue-green infrastructure with CityCAT.

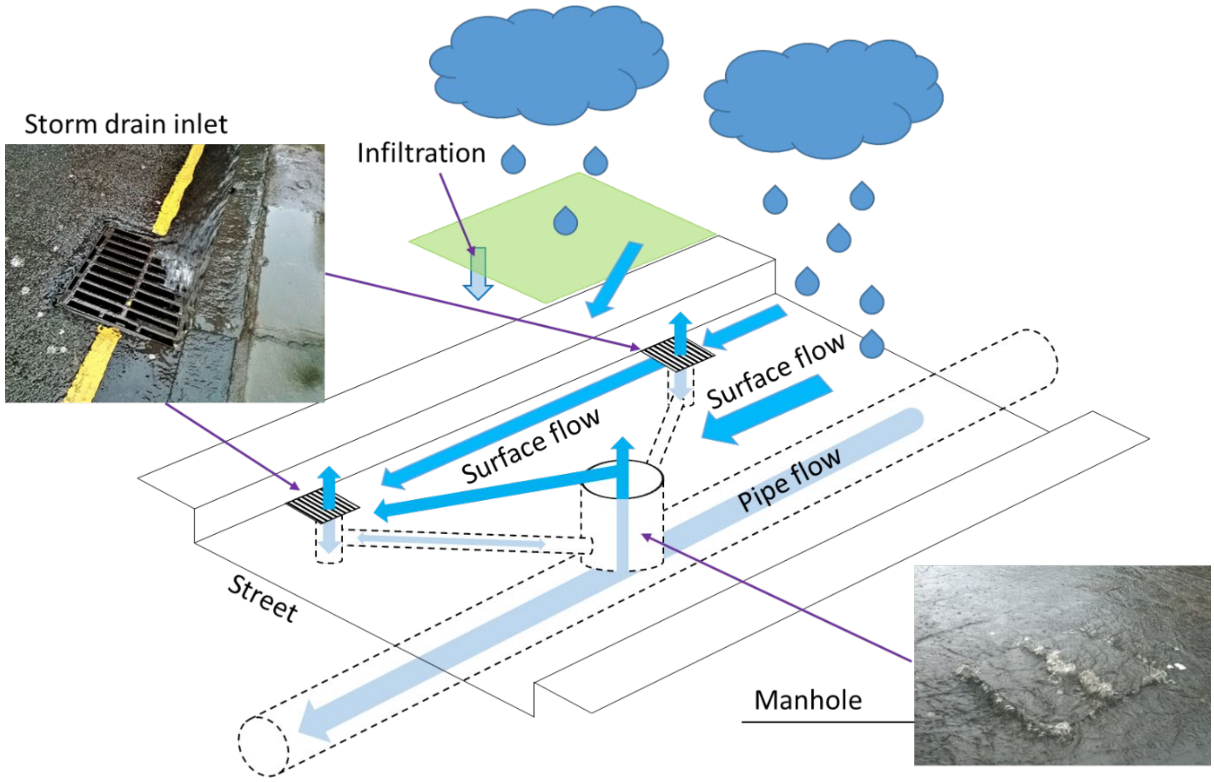


Figure 3.1 Schematic representation of the urban drainage system as modelled in CityCAT. Coupling the surface and sub-surface domain by explicitly simulating manholes and inlets captures flow in both directions. Rainfall induced surface runoff follows the 2D terrain and can infiltrate over green areas. Building roof runoff not shown.

CityCAT explicitly simulates each storm drain inlet to connect the surface and sub-surface drainage domain. Inlets are automatically linked to a near manhole following a set of conditions including the slope of the connection pipe and the distance between ground elevation and crown of the connection pipe. The calculation of flow captured by inlets is based on a weir equation. The actual efficiency of the inlet however is determined by five different equations including parameters related to: the inlet grating type, the dimension of the gully box, the capacity of the connection pipe as well as the pressure inside the sub-surface system and the water level and flow velocity on the surface grid.

The calculation of pipe flow in CityCAT is not based on the Preissmann slot method. Instead, the MFP (mixed flows in pipes) mathematical model introduced by Bourdarias, Ersoy and Gerbi (2012) is used. The MFP model combines the shallow water equations for non-pressurised flow and a set of conservative equations derived from the compressible Euler equations to handle pressurised flow (Bourdarias, Ersoy and Gerbi, 2012). To apply the MFP model, CityCAT automatically discretises the pipe sections into sub-sections (finite volumes) depending on the length and slope of the pipe section.

Compared to the Preissmann slot method, the MFP method allows for simulation of both sub-atmospheric pressures as well as the transition phase of flow conditions (pressurised – non-pressurised and vice versa). The MFP method is therefore suitable to handle the complex flow dynamics which occur in the event of sewer surcharging and flooding. Computationally, the MFP method is more demanding than the Preissmann slot method resulting in longer simulation times.

Modelling storm drain inlets provides the quantitative exchange of flow between surface and sub-surface domain in both directions. For large urban areas there may be several thousand inlets. Hence, simulating the entire drainage domain in form of a fully coupled 1D/2D model with all storm drain inlets allows CityCAT to assess both pluvial and sewer flooding in a truly integrated way.

The final computational grid of a CityCAT model is generated automatically. This process involves the allocation of green areas and buildings. Furthermore, the inlets are linked to the nearest manhole following pre-defined rules. The modelling approach adopted in CityCAT is computationally much more intensive compared to commercially available software packages. A CityCAT version for servers and cloud computing has therefore been developed (Glenis *et al.*, 2013; Glenis, Kutija and Kilsby, 2018).

Figure 3.2 shows the components of a CityCAT model including terrain information (horizontal resolution = 2m), buildings and green areas as well as the sub-surface drainage network components of storm drain inlets, manholes and pipes. Figure 3.3 shows the fully coupled 1D/2D simulations results for the same domain shown in Figure 3.2. The hydrodynamic model results show the surface water runoff along two major pathways depicted by the inundation depths and flow vector fields. Many of the storm drain inlets on roads along those runoff pathways capture more than 6.0 l/s. The maps shown in Figure 3.2 and Figure 3.3 were produced with the Python mapping scripts developed in this work and presented in chapter 5.

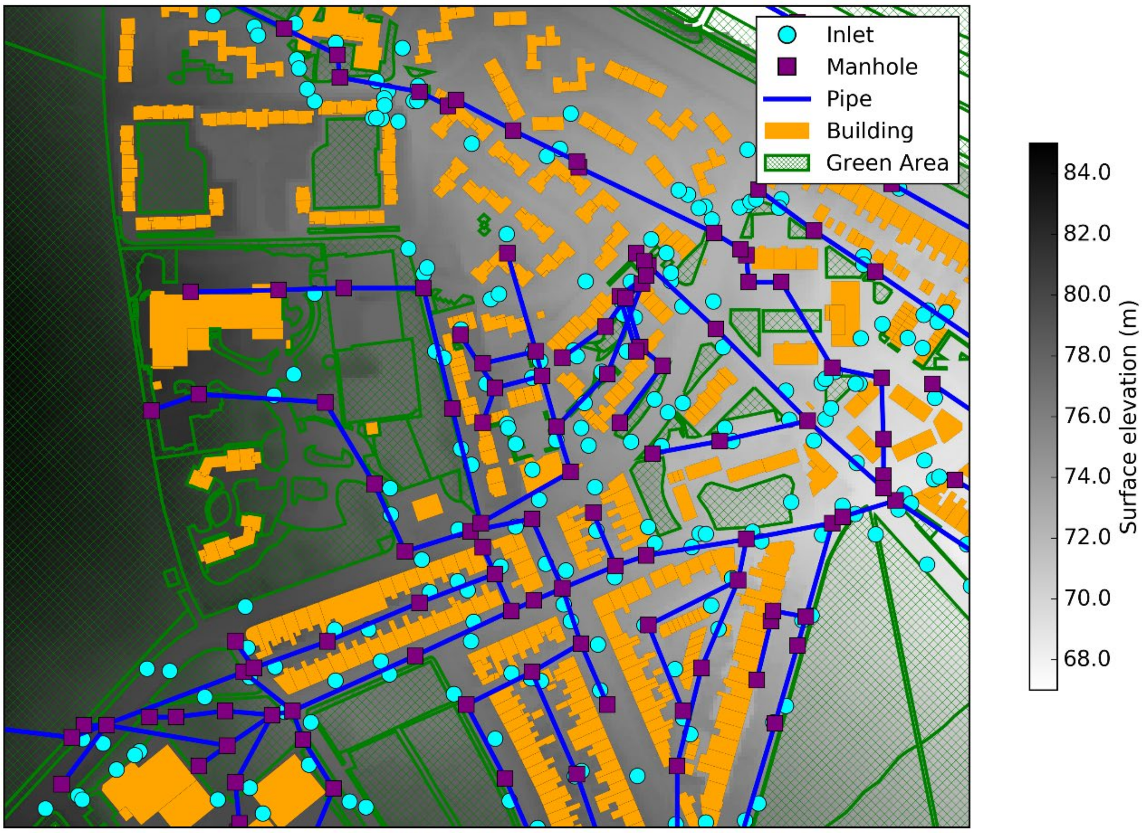


Figure 3.2 Map showing components of a 1D/2D CityCAT model: Terrain (background), inlets, manholes, pipes, buildings and green areas.

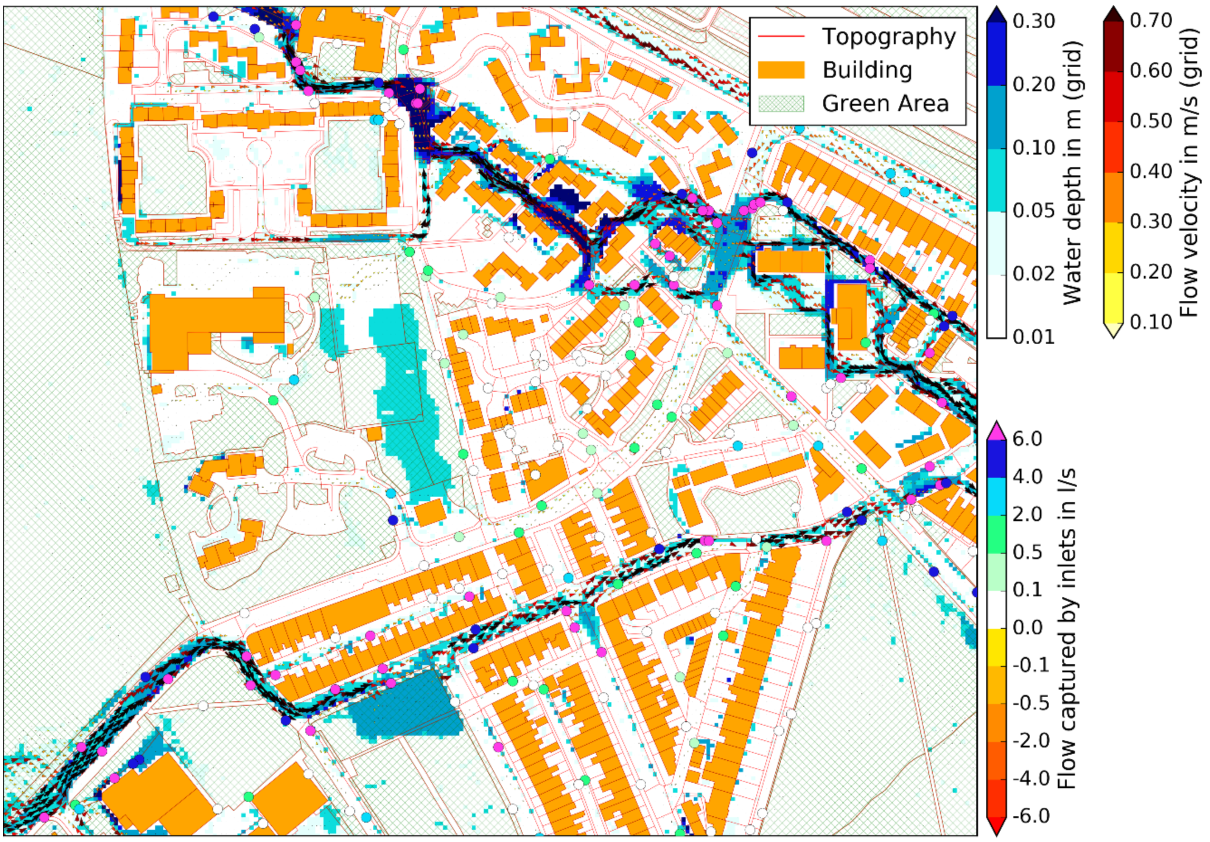


Figure 3.3 Map showing 1D/2D CityCAT model results. Hydrodynamic results: surface water inundation depth, surface flow vector field, flow rate captured by inlets – negative values indicate surcharging condition.

3.3 Implications of current environment on potential application of new developments

Exploring a potential industrial application of CityCAT in this thesis revealed certain barriers and limitations related to the current environment of flood modelling. The modelling strategies in place in water utilities and their consultants have been formed over many years incorporating the specific duties and responsibilities. Considerable investments were made for purchasing modelling software licenses and for the building and maintenance of hydraulic models. As a result, the modelling strategies, modelling skills and the data requirements are strongly influenced by the specific modelling tools applied.

3.3.1 Data

A fully coupled 1D/2D CityCAT model requires several sets of data. For the simulation of the surface domain in densely built-up urban areas detailed terrain and topography data are required. Those data are becoming increasingly available and are easily accessible. Examples for the UK are the UK Government Survey Open Data LiDAR database (DEFRA, 2018) and the OS MasterMap data (Ordnance Survey, 2018). Beside flood modelling, terrain and topography data are also required for other purposes such as environmental studies and for mapping. Therefore records are likely to have been established already in the past.

The other set of data required for detailed 1D/2D models concern the sub-surface drainage system including pipes, manholes and storm drain inlets. Compared to the widely used terrain and topography data, sub-surface drainage network information tend to be used more specifically in the context of the modelling and analysis of sewer systems. The collection, storage, maintenance and application of sub-surface drainage network data is therefore often associated with a specific stakeholder or authority. In the UK those are generally water utilities in the context of sewer flooding and wastewater drainage. Occasionally, local authorities and highway drainage authorities are involved in the process of managing sub-surface drainage network data.

Research for this thesis has shown certain gaps in data quantity and quality associated with the sub-surface drainage network. One major challenge compared to above-ground features is the actual data collection of below-ground assets. Particularly the surveillance of pipe dimensions is associated with considerable costs and resources. Consequently, sub-surface drainage data are sometimes simply missing.

To fill the gap of missing data for the purpose of hydrodynamic modelling, sub-surface network information has to be added manually. For this purpose design manuals are commonly applied. Alternatively, missing data may be completed by using available data from other parts of the network. To complete a missing pipe section diameter value, the available diameter of the up- or downstream pipe section could be used for instance.

Another approach to work-around missing data is to use simplified models. Particularly the sub-catchment/manhole approach allows to do so. For areas where pipes are missing larger sub-catchments can be established and the sub-catchment parameters adapted. A similar approach can be taken for missing manholes information whereby multiple manholes are grouped and represented by a single node – with the linked sub-catchment parameters changed accordingly. Such simplification processes however are only possible for semi-distributed models as missing data can be incorporated through model parametrisation. Fully-distributed and fully coupled models such as CityCAT require the exact location of pipes, manholes and inlets. Consequently, the conversion of the sub-surface drainage network data from an over-simplified semi-distributed model to a fully-distributed model does not provide enough information.

Storm drain inlets

The future application of fully coupled 1D/2D models is also faced with a particular problem of missing networks of storm drain inlets. The literature review in chapter 2 has shown that until recently, storm drain inlets have not been used and even now their application in simulations of entire cities is limited. Past modelling approaches and tools simply did not consider storm drain inlets at all. Hence, from a hydraulic and flood modelling perspective there was no need to obtain records about storm drain inlets in the past. Also other applications such as inlet maintenance for instance do not necessarily require exact locations of inlets. An estimation on the number of inlets per street or post code would suffice in order to schedule the necessary operations.

The implication of missing storm drain inlets is summarised schematically in Figure 3.4. As mentioned above storm drain inlet records are missing or the available data are not complete (i.e. cover the entire urban catchment) because past modelling tools did not rely on inlets. Today storm drain inlets are not simulated on large scale catchments because (1) they are missing and (2) the modelling approaches and tools applied do not explicitly consider inlets. As a result, there are no simulation results available on the performance of inlets (i.e. drainage performance). Such information however would be crucial for the development and adaptation of surface water management and urban drainage plans for instance. Missing a baseline model of the current storm drain inlet network and their drainage performance also means that no updates can be incorporated.

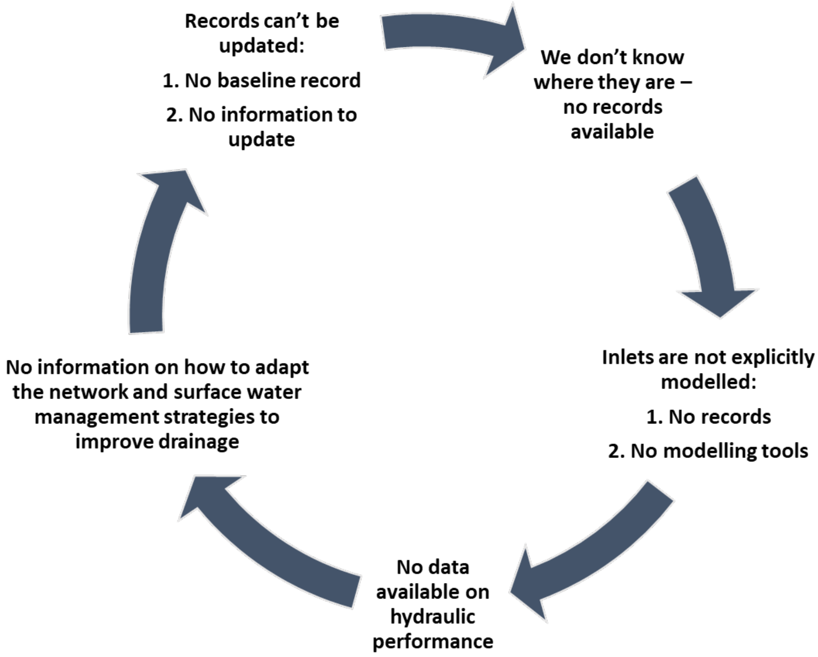


Figure 3.4 Current situation of storm drain inlet data availability, modelling capacities and practical implications.

As shown in Figure 3.4 the reason for missing storm drain inlets is very much a technical one. However there is also an institutional dimension to it. The literature review mentioned the issue of an isolated approach towards flood modelling and risk management in the past. This was consequently reflected in the specific duties and responsibilities of the stakeholders involved. Storm drain inlets are therefore not just physically at the interface of two drainage domains but also in terms of the responsibility of different authorities. UK water companies are generally concerned about stormwater once it has entered the sub-surface drainage system. Local authorities on the other hand are more concerned about the drainage of the surface water. Hence, storm drain inlets are located at the fringes of different responsible authorities.

3.3.2 Analysis tools

With the emergence of new modelling tools, the demand for analysis tools capable of handling detailed hydrodynamic model outputs has increased, particularly in the context of flood risk management, as results from a flood model are one part of further analysis including flood exposure and damage assessments for instance.

Similar to the situation on data availability outlined in the previous section, the current modelling approaches and strategies have also had a considerable impact on the analysis methods and tools applied. Commercially available flood modelling software offer robust and user-friendly products, technical and sales support. Furthermore they often have a long-established record of industrial applications demonstrating their benefits. However, using commercial modelling tools may limit the application of advanced analysis tools. To access model results for post-processing analysis often requires specific add-on tools which are compatible with the actual flood modelling software. On the other hand, those add-on tools are often limited to work with results from the associated modelling software. Hence results from other modelling tools cannot not be post-processed and analysed.

Also, the modelling approach and the results generated determine the options for post-processing the model results. The modelling approach of virtual reservoirs for instance would only allow to assess sewer flooding based on a proximity analysis between the surcharging manholes and nearby properties. The sub-catchment/manhole method on the other hand does not allow to assess the exposure to pluvial flooding. This requires additional 2D simulations using different software with the results to be merged afterwards.

One further reason to explore the application of generic open-source analysis tools is the collaboration amongst multiple users and stakeholders. Certain modelling platforms not only require a license to run a simulation but also to access previously run simulations. Hence, even users who do not intend to run a simulation but only want to access, view or analyse the results are required to have a license.

3.4 Conclusions and requirements

This chapter first introduced the fully distributed and fully coupled 1D/2D CityCAT modelling software. The purpose was to highlight the useful functions to close the gaps identified in the previous chapter regarding the increasing demand for truly integrated urban flood modelling. Particularly the fully distributed modelling approach of high resolution computational grids and the explicit modelling of all storm drain inlets offer a new dimension to urban flood modelling.

In a second step, the implications and legacies of past and current modelling approaches were identified. Critically, missing data and a lack of appropriate analysis and visualisation tools act as barriers and limitations considering a potential industrial application of CityCAT. The subsequent chapters aim to address those limitations by developing and demonstrating new methods and tools to harness CityCAT and the hydrodynamic results produced.

The first aspect (chapter 4) are missing storm drain inlet data required for fully coupled 1D/2D CityCAT models. Currently, field surveys have to be conducted in order to establish records. For large domains this can only be achieved with considerable time and cost resources. Those resources may however not be available straight away as business cases have to be filed and the work has to be commissioned. Depending on the area, special surveying equipment may also be required to overcome GPS signal issues.

Alternative methods for establishing the locations of storm drain inlets is through image processing from aerial photography (Vitry *et al.*, 2018) or street level images. Extracting data and information from images however may suffer from low-quality images and obstructions such as debris, vehicles or vegetation. Furthermore, the application of unmanned aerial vehicles to generate high-quality aerial photography may be limited due to legislative restrictions of using them in a densely built-up urban environment (Leitão *et al.*, 2016).

Hence the aim was to develop an automated desk-based method which allows to generate a synthetic network of storm drain inlets which can be applied in fully coupled 1D/2D models. A synthetically generated network can be used as a first iteration of a model and continuously improved as surveyed data become available.

The second part (chapter 5) will focus on the development of generic mapping and analysis tools using open-source platforms. The aim is to make the large quantity of fully coupled model results easily accessible for end-users. Applicable for large domains covering entire cities, the tools were developed to make use of high model results and detailed topographic data. The tools access common data formats such as csv-files and can be applied independently of the modelling-platform. Furthermore, the open-source codes of the tools can be adapted towards specific user requirements. A number of case studies are presented to demonstrate the functions of the tools in combination with the benefits of CityCAT allowing for a more in-depth analysis of cause and consequence behind pluvial and sewer flooding.

Chapter 4 Generation of synthetic storm drain inlet networks

4.1 Introduction

In order to access the full capabilities of CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018), a comprehensive record of storm drain inlet locations is required. Experience from this thesis has shown, however, that such records are not always available. For certain areas, no records exist at all, while other areas have only incomplete or outdated records. Consequently, missing storm drain inlet data prevent a full application of CityCAT. Currently cost-intensive field surveys have to be conducted in order to record the necessary data. In order to fill the gap of missing data based on a low-cost approach, the main aim of this study is to develop and evaluate an automated, GIS (Geographic Information System) routine to generate synthetic storm drain inlet locations for existing pipe networks. For evaluation purposes a detailed field survey was conducted in order to have a record of actual storm drain inlet locations for a catchment. From a practical perspective, the question is whether the routine can provide a straightforward and low cost alternative when compared to resource intensive field work when establishing a network of storm drain inlets.

Missing input data is often one of the biggest challenges when building flood models. Apart from storm drain inlet locations, this may also concern dimensions and locations of manholes and pipes. Taking the idea proposed in this work of using surrogate data and generic methods, the tool that is developed could potentially be extended in future work to assist in generating other crucial information that is required for high-resolution urban flood models.

The chapter will first outline the assumptions behind the initially developed methodology which is based on a GIS routine. Based on preliminary hydraulic model results that are obtained from CityCAT simulations, improvements to the initial methodology are presented. Finally, model results for a synthetically generated and surveyed storm drain inlet network are compared in order to validate the GIS routine and to study the sensitivity of the whole network drainage efficiency (for sub-surface and surface) to the density and placement of inlets.

4.2 Development of methodology

4.2.1 Background

A variety of methods have been developed over the last decades for the design of sewer systems (Argaman *et al.*, 1973; Diogo and Graveto, 2006; Guo *et al.*, 2007; Guo, Walters and

Savic, 2008; Möderl, Butler and Rauch, 2008). Although these methods vary, they are primarily aimed to provide assistance in the development of new sewer systems in the form of manholes and pipes. This study will focus on the design (location and density) of storm drain inlets for existing sewer systems.

The design and spacing of storm drain inlets in reality takes into account a large number of parameters, those are for instance: slope and cross-fall of the road, the storm drain inlet grating type and efficiency, surface roughness, flow width and velocity in the kerb channel, maintenance factors, design storm, and contributing catchment area per storm drain inlet (Highways Agency, 2000; Spaliviero, May and Escarameia, 2000). In this context Despotovic et al. (2005), identify three major factors contributing to the inlet capacity and efficiency: lateral street slope, longitudinal street slope, and pavement roughness. If all of those variables were to be incorporated in a GIS routine, a significant amount of high quality input data would be required that is not usually available.

A further challenge in developing a generic GIS routine for locating storm drain inlets is the change of design criteria over time (Marsalek *et al.*, 1993; Delleur, 2003; Mailhot and Duchesne, 2010). More recent design criteria shifted towards separated drainage systems and the need to accommodate larger runoff volumes. In this context, for example, in Scotland, newly built sustainable drainage systems have to accommodate storm events with return periods of up to 200 years (Fletcher *et al.*, 2015). Most installed sewer systems however are based on older design manuals, dating back several decades, which adopted return periods between 1 and 30 years (Butler and Davies, 2011). Therefore, a generic tool to generate storm drain inlet locations for existing sewer systems has to find a balance in terms of the different design criteria over time.

4.2.2 Initial assumptions behind methodology

With the above considerations in mind, it has been decided to initially adopt a robust and simplified approach for the GIS routine that is developed. Furthermore, the routine should be universally applicable and therefore rely only on a minimum number of input data. Crucially however, the tool needs to incorporate information on the existing sub-surface system. The three assumptions behind the initial version of the GIS routine are therefore:

1. **All storm drain inlets are on roads and of the same grating type**: In reality storm drain inlets can be found in various places, but predominantly on roads—next to or underneath the kerb. Several studies were carried out investigating the impact of

different locations, grating, and cover types on the drainage efficiency of storm drain inlets (Despotovic *et al.*, 2005; Almedeij, Alsulaili and Alhomoud, 2006; Gómez and Russo, 2009, 2011). However, for simplification purposes, it is assumed that all storm drain inlets are located on roads and are of the same type (see Chapter 1 Figure 1.3, left).

2. **All storm drain inlets are spaced at an equal distance**: The approach of an equidistant spacing of 50 m between storm drain inlets is obtained from Butler & Davies (2011).

3. **All storm drain inlets are close to the existing pipe network:** It is assumed that storm drain inlets are located at a certain distance to the nearest pipe. The pipe network in form of a polyline shapefile is used to conduct a spatial proximity analysis. A threshold distance of 20 m between storm drain inlet and pipe has been selected.

Based on those assumptions, two sets of input data are required: (1) a polygon shapefile representing the road network, and (2) a polyline shapefile representing the pipe network. With the above assumptions, no terrain information is accounted for at this stage. The integration of terrain information will be presented after the preliminary results.

4.2.3 Placement of storm drain inlets

In the first step, the synthetic storm drain inlets are placed along a reference line. For this purpose, the road polygons are dissolved (i.e. no internal boundaries) into one single polygon (Figure 4.1a). Inside this polygon a buffer is created applying a distance of 0.25 m in order to assure that all of the storm drain inlets are placed inside the road. The buffer polygon is subsequently converted to a line feature, which is subsequently referred to as the reference line (Figure 4.1b). Finally, point features (i.e. storm drain inlets) are placed along the reference line at an equidistant spacing of 50 m (Figure 4.1b).

4.2.4 Alignment of storm drain inlets with pipe network

The pipe network is applied next. As shown in Figure 4.1c, a 20 m buffer is created around the entire pipe network. Any storm drain inlet that is located outside the 20 m buffer will be discarded (Figure 4.1c). Synthetic storm drain inlets in the final layer therefore meet the following conditions: they are located inside the road polygon, 0.25 m inside the kerb and 50 m apart from each other, and they are within 20 m of the pipe network.

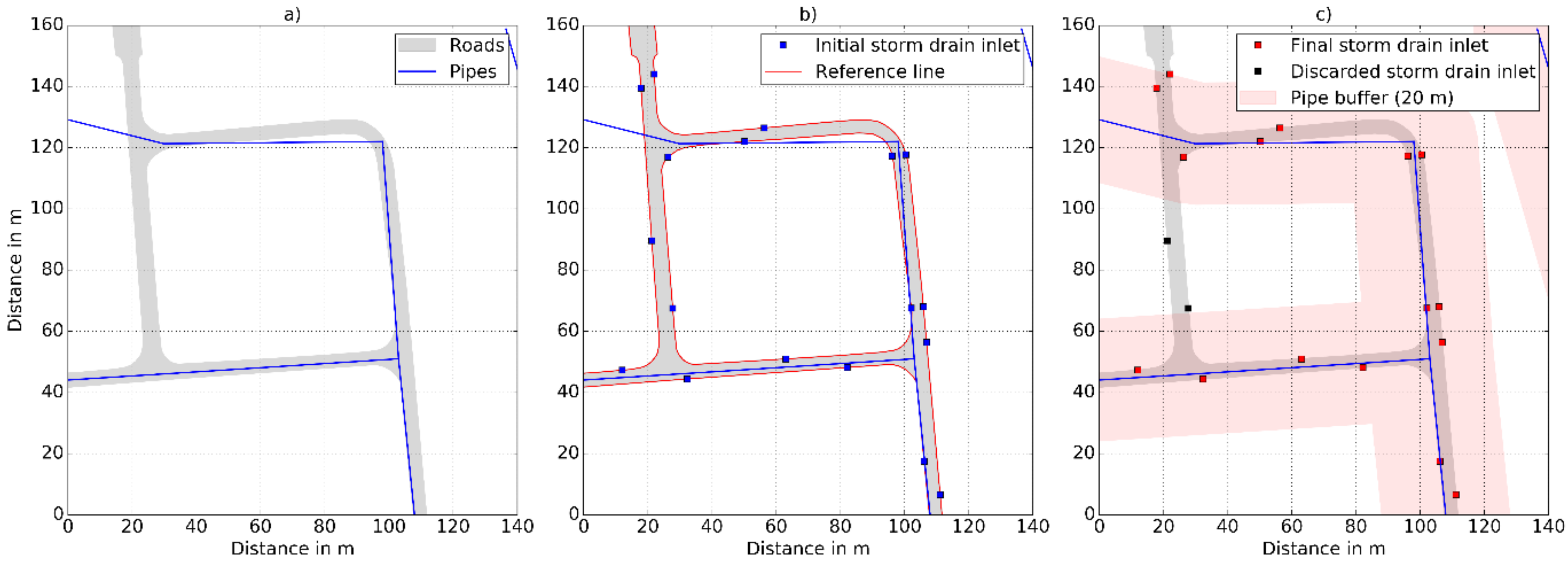


Figure 4.1 Generation of a synthetic storm drain inlet network: (a) Input data consisting of dissolved road polygon shapefile and pipe network polyline shapefile. (b) Creating reference line (0.25 m inside of road polygon shapefile) and placing points on reference line at an equidistant space of 50 m. (c) Storm drain inlets at a distance >20 m to nearest pipe segment are discarded.

4.3 Case study

Having outlined the principles behind the initial GIS routine in general, a case study is conducted. For validation purposes, a field study was completed to survey the actual storm drain inlet network. The study area is located in central Scotland. The topography of the area is relatively flat. The drainage network, including pipes and manholes, were obtained from an InfoWorks CS model, which was made available by Scottish Water. By incorporating additional drainage network elements from GIS records, the final drainage network that was applied consists of 294 manholes and 10,898 m of pipes. For the purpose of this study, only storm and combined drainage pipes were applied. Furthermore, no base flow or dry weather flow was taken into account.

4.3.1 Synthetic storm drain inlet locations: Application of methodology

Following the workflow of the GIS routine outlined, the first step was to obtain the road data. For this purpose, the OS (Ordnance Survey) MasterMap Topography layer was downloaded from Edina Digimap (Digimap, 2012). From the initial data set, all of the road polygons (‘featureCod: 10172’) were extracted. Applying the steps of the initial GIS routine, the network generated contained 376 synthetic storm drain inlets (Figure 4.2b).

4.3.2 Surveying of actual storm drain inlet locations: Field work

Approximately 13 km of roads were surveyed, requiring four full working days, including travelling time and post-processing of the data collected. The GPS equipment that was applied to record the storm drain inlet locations was the hand held device Leica GS15 with SMARTNET correction (Leica Geosystems, 2015). The network based Real Time Kinematic (RTK) function of the device combines satellite and GPRS signals to achieve greater accuracy. Overall, the positional accuracy observed during the field work was approximately +/−10 cm, which is thought to be sufficient for the purpose of this study. At a few storm drain inlet locations signal problems were experienced. Those locations were manually highlighted on a map and later added to the RTK-surveyed storm drain inlets in GIS. If a parked vehicle made it impossible to survey the actual inlet, its location was taken at the closest distance possible and subsequently adjusted in GIS.

In a final step, the locations of the surveyed storm drain inlets were aligned with the below ground pipe network. Although a surveyed storm drain inlet would indicate the existence of below ground drainage features, a number of inlets were surveyed in areas without any GIS records of a pipe in close proximity. To avoid unrealistic long connections between those storm drain inlets and a manhole, and not to estimate any pipe dimensions and locations, it was decided to discard those storm drain inlets. This was done applying the same 20 m buffer that has been used for aligning the synthetic storm drain inlet locations (Figure 4.1c). As shown in Figure 4.2a, the post-process surveyed network consists of 445 storm drain inlets.

4.3.3 Hydrodynamic model for case study area

Finally, the surveyed and synthetically generated storm drain inlet networks were applied in hydrodynamic model simulations using CityCAT. The drainage network elements applied included the storm drain inlet locations, pipes, and manholes. For the purpose of this study, uniform dimensions for all inlets (0.3 m × 0.3 m) and linking pipes (90 mm diameter) between the inlet and manhole were applied. The simulations were conducted using LiDAR (Light Detection and Ranging) terrain data with a resolution of 2 m × 2 m, and a uniform rectangular numerical grid was generated with $\Delta x = \Delta y = 2$ m. With a catchment area of approximately 2.1 km^2 the numerical grid is formed of 525,554 cells. Buildings and green areas were extracted from MasterMap topography data. The 20 and 50 year return period storm event of 60 minutes duration applied (Figure 4.3) were generated using the Flood Estimation Handbook (FEH) procedure (Reed and Robson, 1999). Surface roughness coefficients (Manning's n values) of 0.02 and 0.035 for impermeable, and permeable surfaces were applied, respectively.

Based on interviews with the Local Council, Scottish Water, and residents during the field survey, it was found that the hydrodynamic model results identified most areas that had been affected from pluvial flooding in recent years. Detailed investigations into the simulated and observed inundation depths, however, were limited due to a lack of detailed data, and are therefore not presented in this study.

4.3.4 Preliminary results

As shown in Figure 4.2b, the initial GIS routine produced 376 storm drain inlets in comparison to the 445 surveyed ones (Figure 4.2a). There are two reasons that are thought to be responsible for this difference. As described earlier, newly built area drainage networks are designed to accommodate larger storm runoff volume. The area highlighted in Figure 4.2a and Figure 4.2b is a newly built area with a much greater density of storm drain inlets in comparison to the overall catchment. The second reason is the small scale terrain depression, which quickly results in an accumulation of surface water. Those areas are sometimes referred to as in-sag locations (Highways Agency, 2000), which would see additional inlets installed to cope with the surplus of water.

The network drainage efficiency has been assessed by calculating the inflow volumes for the network at each time step in CityCAT. The initial network, with fewer storm drain inlets and not specifically accounting for ponding areas results in a clear under-representation of the captured flow (Qi) by the storm drain inlets (Figure 4.3). The flow captured (Qi) represents the portion of flow entering the storm drain inlets and is the difference between the flow approaching a storm drain inlet and the pass-over flow (Despotovic *et al.*, 2005). The graph in Figure 4.3 shows the total volume of water that is drained by all storm drain inlets for the synthetic and surveyed storm drain inlet networks for both of the storm events. Figure 4.3 not only shows an under-representation of the captured flow, but also a later onset of drainage when comparing the synthetic storm drain inlets with the actual ones.

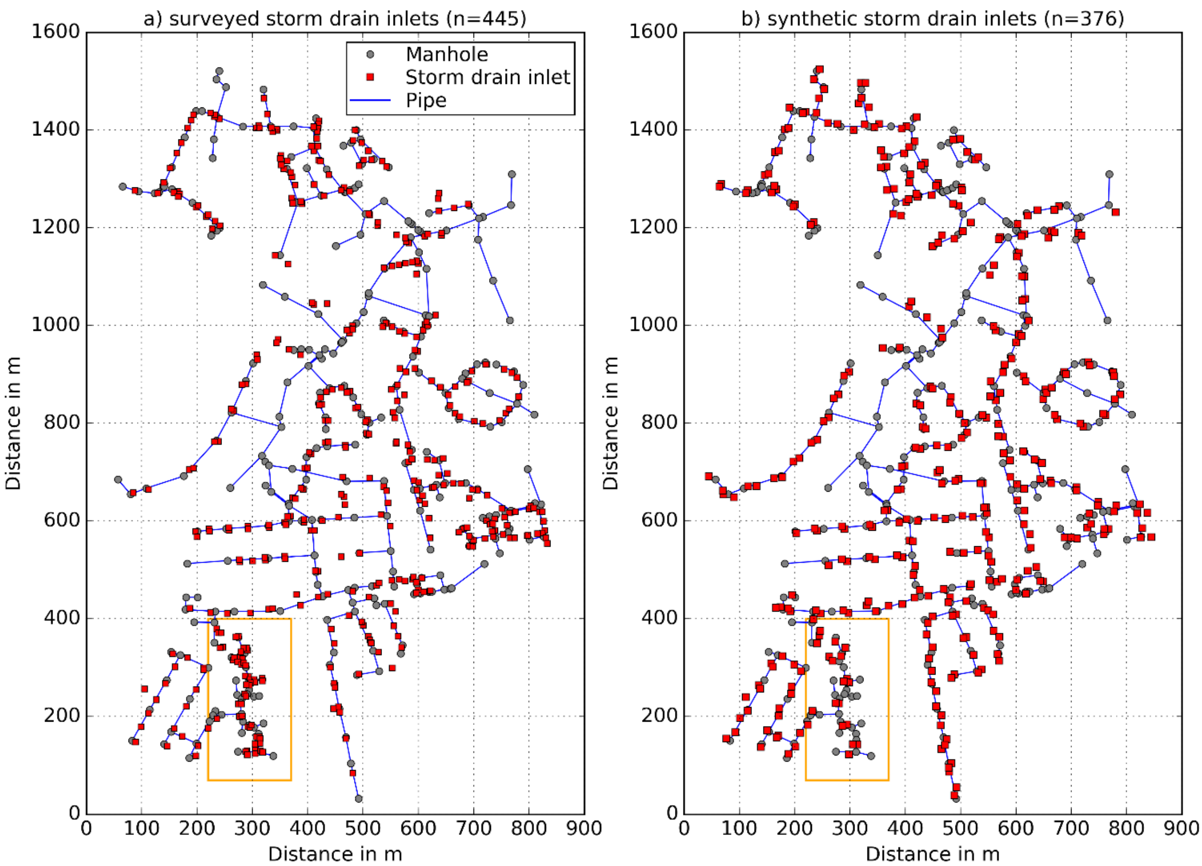


Figure 4.2 Surveyed storm drain inlet network (a) and preliminary synthetic storm drain inlet network based on initial method (b).

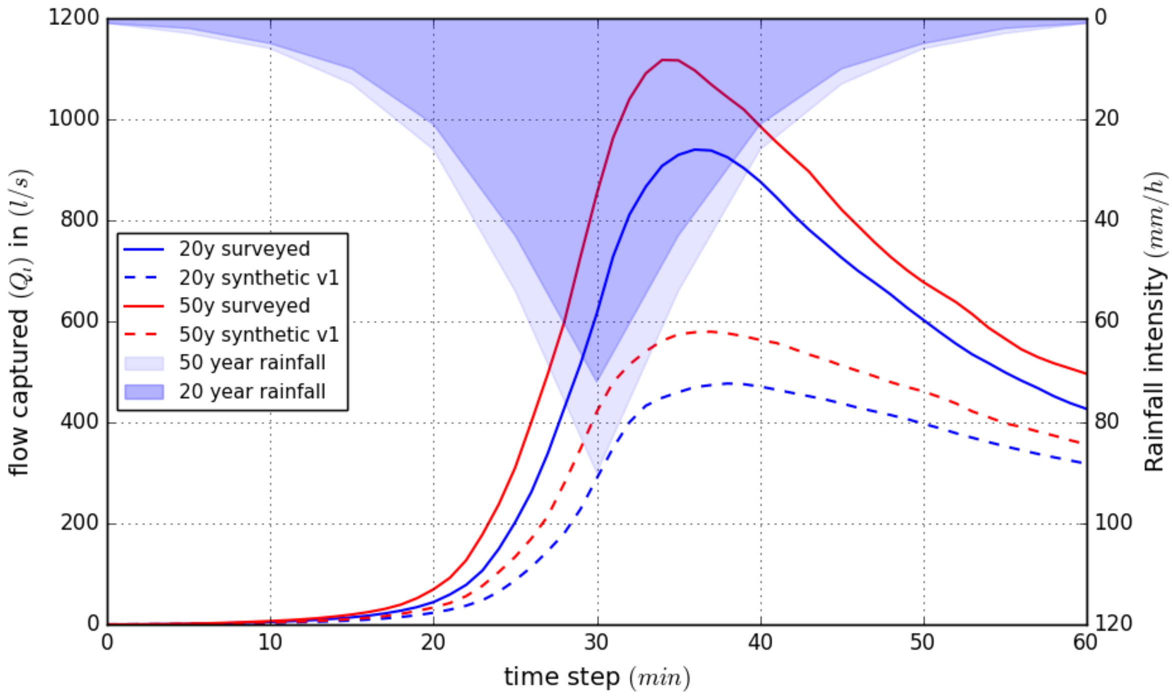


Figure 4.3 Comparison of captured flow rates (Qi) for surveyed and synthetic storm drain inlet network based on initial method for a 20 and 50 year RP storm event.

4.4 Adaptations to initial methodology

Based on the preliminary results, it becomes evident that adaptations to the initial GIS routine are required. Those adaptations should aim to better approximate the total number of storm drain inlets, as well as the drainage performance of a synthetically generated storm drain inlet network. Terrain information is likely to be crucial, so the adaptions made focus on the following aims:

1. Increase the total number of synthetic storm drain inlets to match the actual number
2. Increase the drainage efficiency of synthetic storm drain inlets by re-distributing them applying terrain information
3. Increase the drainage capacity within surface water accumulation areas by adding more synthetic storm drain inlets

4.4.1 Storm drain inlet density

In order to increase the total number of storm drain inlets, it was decided to specifically address areas that were built under more recent building standard. As outlined initially, the drainage network and its capacity within those areas is likely to have been designed to cope with larger runoff volumes when compared to older ones. It is therefore required to understand which areas across the catchment are relatively newly built. The spacing of storm drain inlets within those areas of interest (AOI) is subsequently reduced in order to increase the storm drain inlet density. For this purpose, the reference line inside the AOI was separated from the rest. Any existing synthetic storm drain inlet from the first network version that was found to be inside the AOI was deleted. Subsequently, new storm drain inlets were placed at a spacing of 20 m. Finally, the storm drain inlets from the AOI were merged with the remaining storm drain inlets from the first version.

4.4.2 Adjusting the locations of storm drain inlets

Apart from having too few storm drain inlets, the preliminary model results also suggested that the initially placed storm drain inlets are insufficient in terms of their drainage. It was therefore decided to re-distribute the initially placed storm drain inlets to lower elevated cells within the immediate surrounding of the storm drain inlets. First, a 3 m buffer was created around each storm drain inlet to extract the reference line. Around each of those 6 m long sections a second buffer area with a distance of 1.5 m was created (Figure 4.4b). Within each of those buffer areas the lowest terrain point was identified (Figure 4.4b). Finally, the shortest distance between the lowest terrain point and the reference line was calculated in order to identify the final location of the adjusted storm drain inlet (Figure 4.4c).

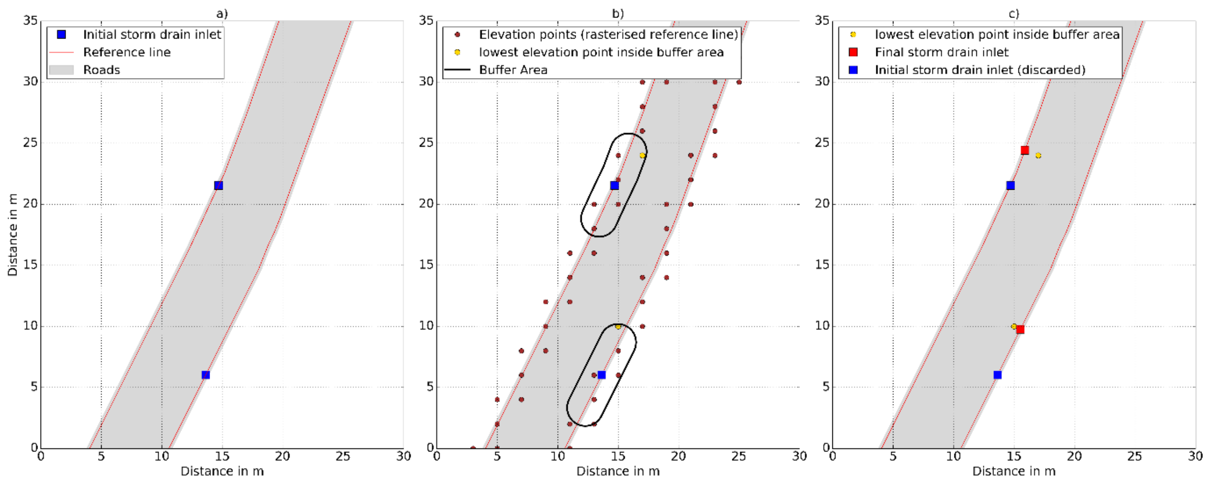


Figure 4.4 Re-distribution process of initial storm drain inlets: (a) initial network, (b) identify lower lying cells around initial inlet based on terrain data and (c) final, re-distributed inlet location with initial one discarded.

Based on the criteria outlined above an adjusted storm drain inlet can be at a maximum distance of 4.5 m to its initial one. The more important change between the initial and adjusted storm drain inlet, however, is the difference in their elevation. A comparison between the terrain elevation at the initial location and the adjusted one found an average drop in elevation of 6.9 cm (Figure 4.5). The maximum drop in elevation between an initial and adjusted inlet is 0.91 m. At that location, the elevation of the initial storm drain inlet was affected by an embankment feature close to the road.

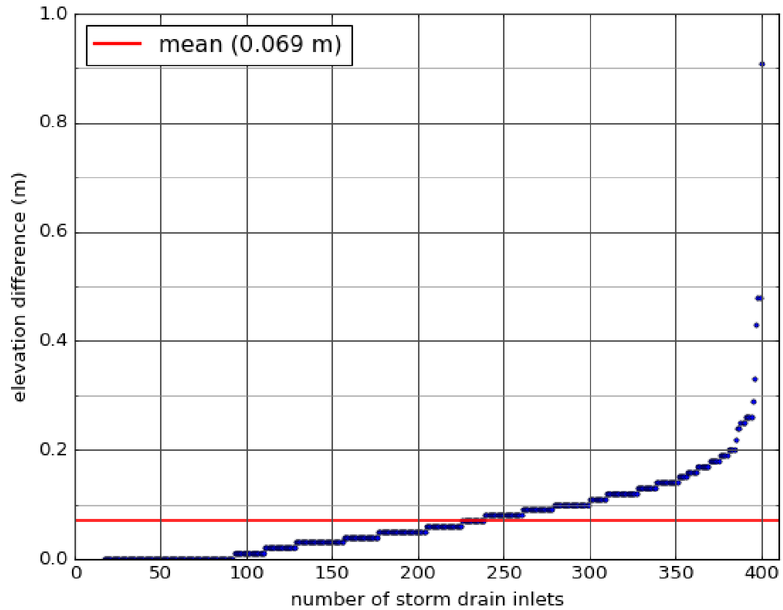


Figure 4.5 Difference of elevation between the initial storm drain inlet location and adjusted one.

4.4.3 Surface water accumulation areas

The final improvement made to the initial GIS routine concerns surface water accumulation areas. In reality, those areas of local terrain depressions would likely have more storm drain inlets that are installed to cope with the surplus of water. To add additional storm drain inlets, areas of depression had to be identified first. For this purpose model results obtained from a CityCAT 2D (surface only) simulation were applied. The simulation was run for a 20-year return period on a 2 m LiDAR grid and included buildings as well as green areas. The results of the final time step (after 60 minutes) were subsequently used.

In a first step, all of the cells with an inundation depth ≥ 0.05 m were merged together to form continuous polygons (Figure 4.6a,b). Any polygon with an area < 200 m^2 and not intersecting with the reference line were discarded. For each polygon left the lowest terrain point inside the road polygon was identified (Figure 4.6b). The threshold values of 0.05 m and 200 m^2 are thought to be a reasonable combination to reflect the actual surface water ponding areas and not being misguided by potential erroneous terrain data. Subsequently, at the shortest distance between the lowest terrain point and the reference line, an additional storm drain inlet was placed (Figure 4.6b). Around this storm drain inlet, a buffer with a distance of 150% of the terrain resolution was created (Figure 4.6c). At the lower lying intersection point of this buffer line with the reference line a second additional storm drain inlet was added (Figure 4.6c). Adding a second storm drain inlet aims to reflect so called twin-gullies, which are commonly installed in sag locations (Highways Agency, 2000).

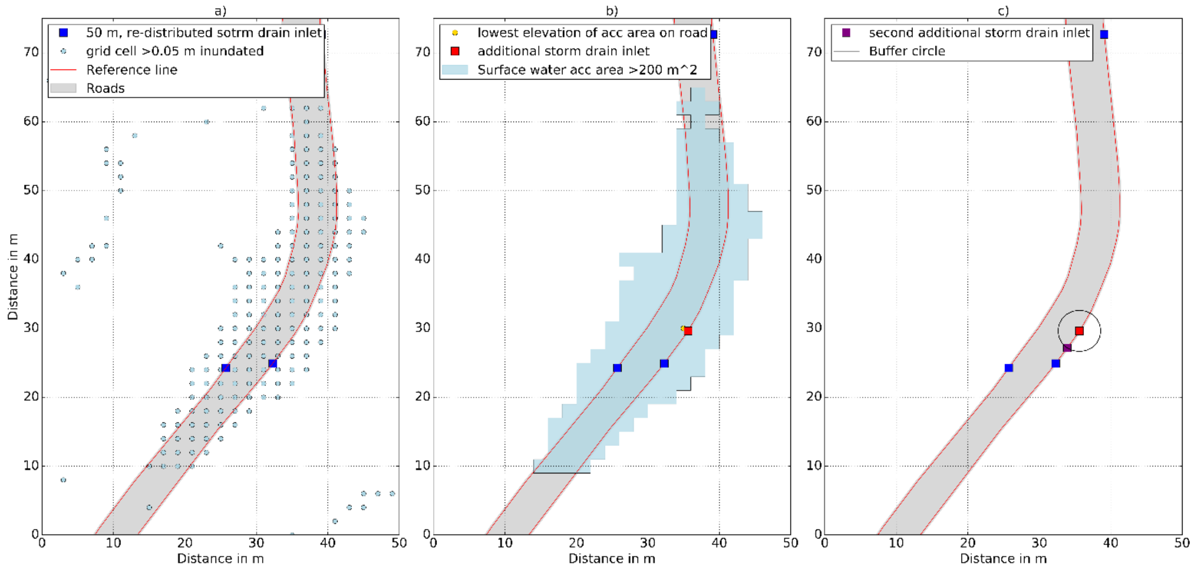


Figure 4.6 Placement of additional twin storm drain inlets in surface water accumulation areas (in-sag locations): (a) extracted cells with inundation depth >0.05 m from 2D model results are accumulated and converted to polygons in (b). For each polygon >200 m² intersecting with reference line the lowest elevation point inside the road polygon is identified to locate two additional inlets (c). All four storm drain inlets shown in (c) are applied for hydrodynamic simulation.

4.5 Final results and discussion

4.5.1 Final synthetic storm drain inlet network

Applying all of the adaptions outlined to the initially introduced case study area the final synthetic storm drain inlet network presented in Figure 4.7 consists of 443 storm drain inlets. In comparison to the 376 and 445 storm drain inlets of the initial synthetic network and surveyed one, respectively, the adaptations show a substantial improvement in terms of the number of storm drain inlets.

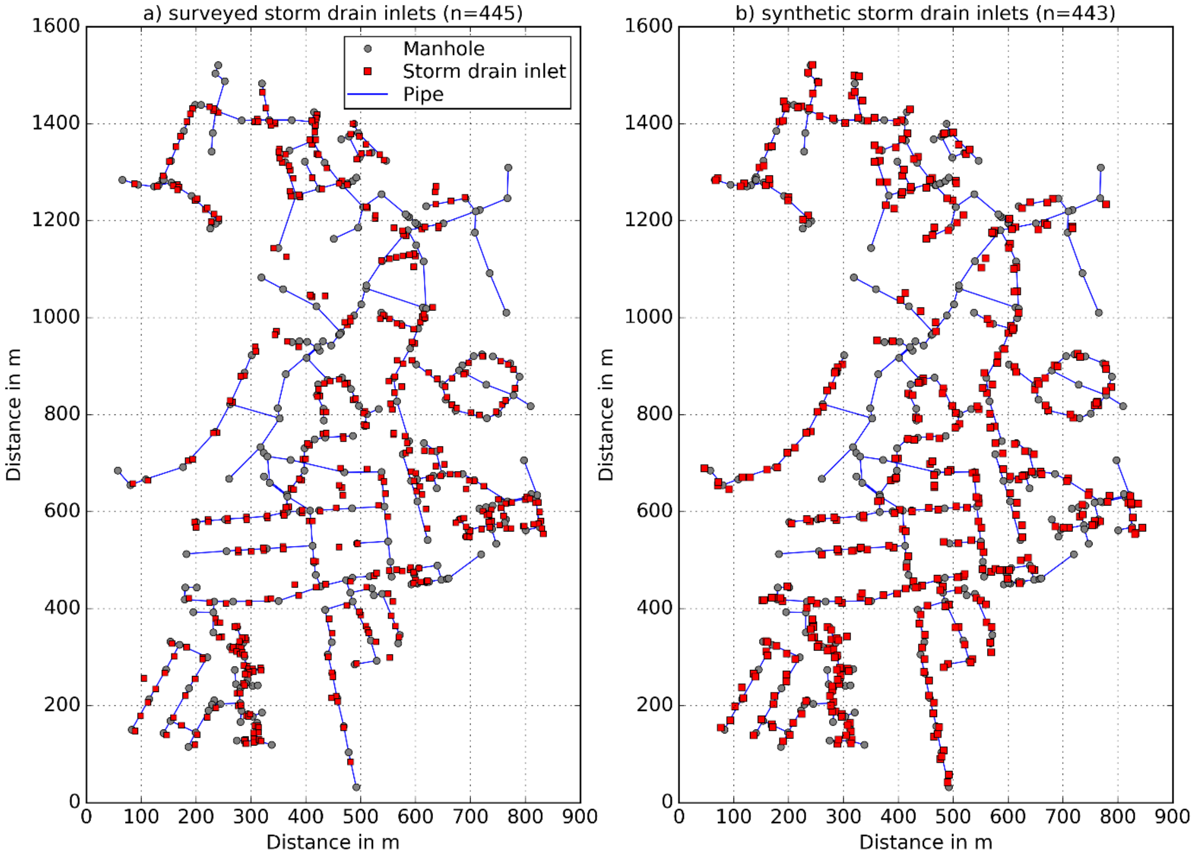


Figure 4.7 Surveyed storm drain inlet network (a) and synthetic storm drain inlet network final version (b).

In order to compare the hydraulic performance of the synthetic storm drain inlet network against the surveyed, two different sets of results are presented in the following looking at:

1. The surface/sub-surface interface by comparing the total volume of water entering all storm drain inlets (as shown previously in Figure 4.3).
2. The surface domain by comparing surface water inundation depth grids.

4.5.2 Surface/sub-surface domain interface: Drainage performance of storm drain inlets

The results shown in Figure 4.8 highlight a different significance of the adaptions that were made to the GIS routine. Increasing the density of inlets by placing inlets every 20 m in the AOI described in section 4.4.1 resulted in 25 additional inlets. Considering the peak values of the simulated captured flow rates however this only led to a slight increase from 477 l/s to 490 l/s shown by the results of the synthetic network v2 in Figure 4.8. Adding inlets in surface water accumulation areas (additional 42 inlets) and adjusting the position of inlets applying terrain information, the respective synthetic networks v3 and v4 lead to a much bigger increase of the captured flow rates with peak flows of 707 l/s and 961 l/s respectively (Figure 4.8).

As described earlier, the average elevation difference between the initial and adjusted storm drain inlet of 6.9 cm was relatively small, suggesting that together with the 42 storm drain inlets added in surface water accumulation areas, the system drainage performance is quite sensitive to small scale topographical changes and positioning. These issues are also highlighted in other studies (Aronica and Lanza, 2005; Palla *et al.*, 2016).

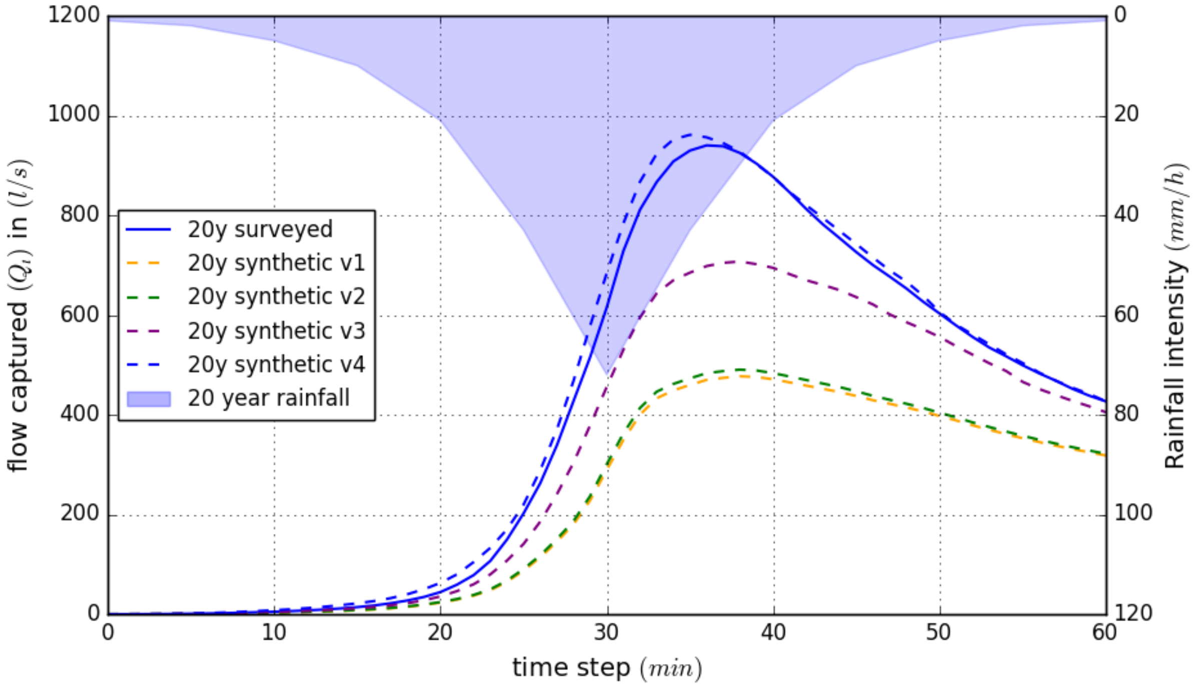


Figure 4.8 Comparison of captured flow rates (Qi) for surveyed and synthetic storm drain inlet networks after different adaptations (v1-v4) for a 20 year RP storm event.

In comparison to the preliminary results (Figure 4.3), the final synthetic network model (v4) shows a significant improvement (Figure 4.9) in terms of the drainage efficiency when compared with the surveyed network model, in terms of both the total volume drained and the shape and timing of the inflow hydrograph (Qi) for both storm events. For the 20 year rainfall event, the simulated peak flow rates are 940 l/s for the surveyed network of inlets and 961 l/s for the final synthetic network (v4). The simulated peak flow rates for the 50 year rainfall event are 1117 l/s for the surveyed network of inlets and 1102 l/s for the final synthetic network (v4).

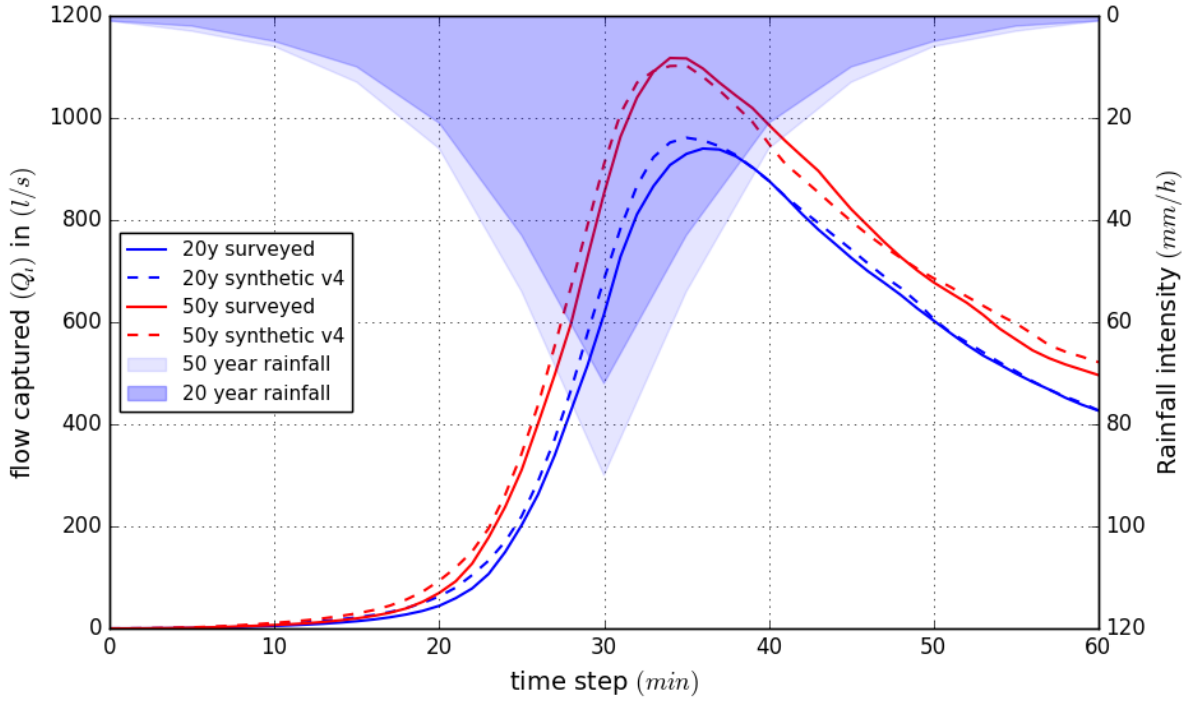


Figure 4.9 Comparison of captured flow rates (Qi) for surveyed and synthetic storm drain inlet network based on adapted method for a 20 and 50 year RP storm event.

4.5.3 Surface water domain: inundation depth on grid

The final results that are presented investigate the impact of the different storm drain inlet networks on the surface water inundation depth. The map in Figure 4.10 was produced by subtracting the maximum surface water grid obtained for the simulation using the surveyed storm drain inlet network from that using the synthetic network. Only the results for the 20-year storm event are presented.

A negative difference indicates a greater surface water depth for the simulation based on the surveyed storm drain inlet network when compared to the one that is obtained from the simulation using the synthetic storm drain inlet network. Whereas, a positive difference means a greater surface water depth for the simulation based on the surveyed storm drain inlet network.

Overall, the differences in surface water depth mostly range between −0.01 and 0.01 m, respectively. Areas with a difference in surface water depth beyond −0.01 m and 0.01 m are scattered across the entire catchment. For a majority of those areas, the absolute difference in surface water depth is within 0.05 m. On a catchment level, the results shown in Figure 4.10 can be considered satisfactory in terms of the surface water drainage that is achieved by the synthetic storm drain inlet network. The results also underline the significance of storm drain inlets that are situated in surface water accumulation areas. At the same time, this highlights the critical aspect of over-estimating the number of synthetic storm drain inlets added in surface water accumulation areas.

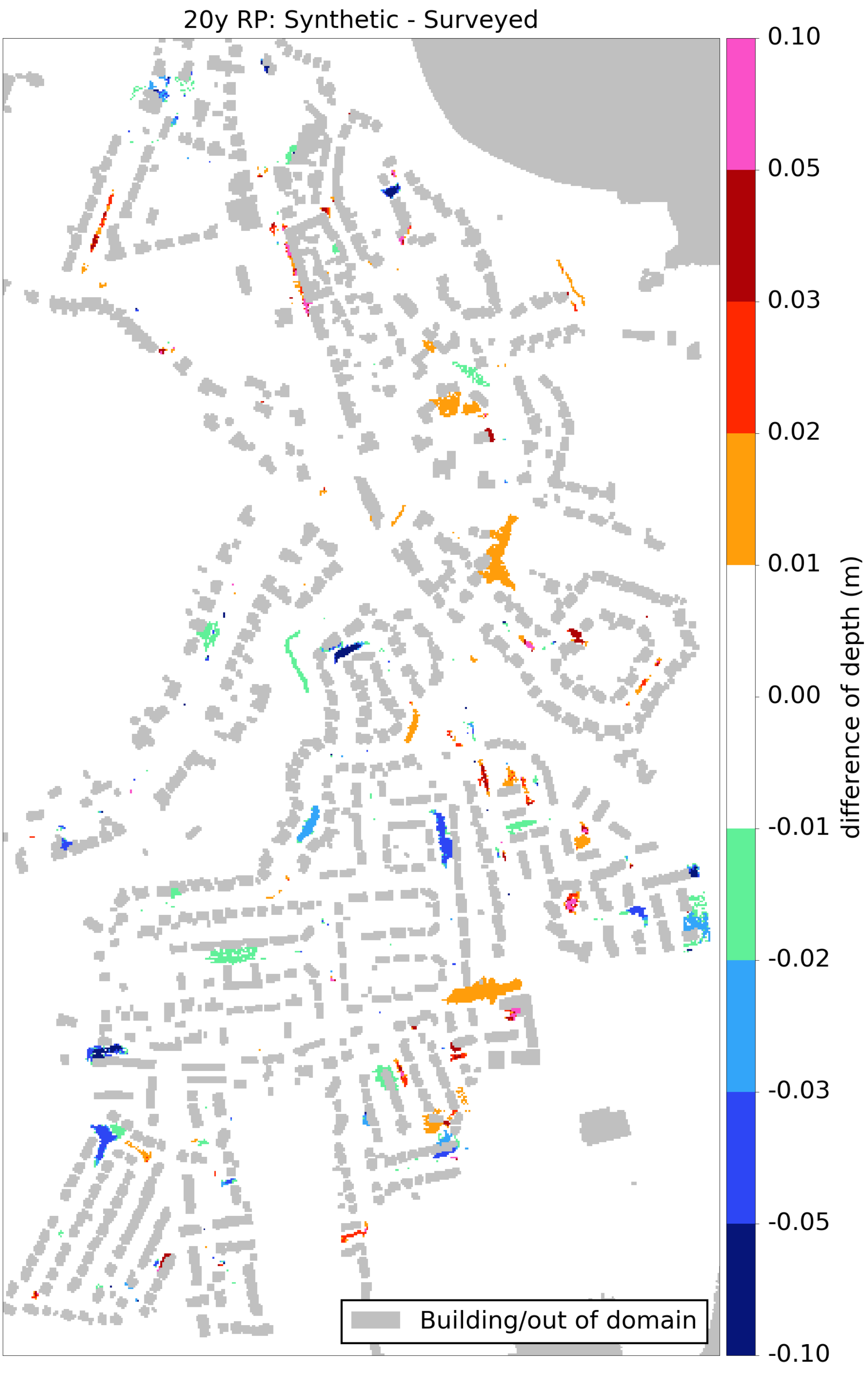


Figure 4.10 Comparison of maximum surface water depth between simulations using final synthetic storm drain inlet network and surveyed one. Based on maximum depths for a 20 year RP event of 60 minutes duration. Positive values: surface depth greater for simulation using synthetic storm drain inlets. Negative values: surface depth greater for simulation using surveyed storm drain inlets.

4.6 Conclusions

A GIS routine was developed, allowing the generation of a synthetic storm drain inlet network for the purpose of fully coupled 1D/2D urban flood modelling using CityCAT. Simultaneously, actual storm drain inlet locations were surveyed during a field survey for validation and calibration purposes. Preliminary modelling results for a case study in Scotland using the simplest design assumptions based on a synthetic storm drain inlet every 50 m revealed an under-representation of the total flow captured when compared against a surveyed storm drain inlet network (Figure 4.3). Consequently, improvements to the GIS routine were made in order to account for higher densities of storm drain inlets in specific areas, but more importantly, to include terrain information. This was achieved in two ways. Firstly, the initially placed storm drain inlets were re-located to lower lying neighbouring cells. Secondly, two additional storm drain inlets were added in areas of calculated surface water accumulation.

The updated model results showed significant improvements in terms of the flow that was captured (Figure 4.9) and the remaining surface water inundation depths on a catchment level (Figure 4.10). The GIS method developed therefore provides a reasonable and robust way of generating synthetic storm drain locations at relatively low costs when compared to field work. The results also stress the significance of having high-resolution terrain data since the re-distribution of storm drain inlet locations was conducted on a micro scale level. The resulting maximum horizontal and average vertical shift of 4.5 and 0.069 m, respectively, led to a considerable increase in the flow that was captured, and therefore highlight the sensitivity of the drainage efficiency to relatively small changes in the location and elevation of storm drain inlets.

Despite the results that were achieved, a synthetically generated storm drain inlet network should only be considered as a first iteration towards the final storm drain inlet network that is applied in a 1D/2D simulation. Particularly for critical locations, such as surface water accumulation areas, or when studying the impact of clogged storm drain inlets (see for instance Leitão et al. 2017), it is necessary to have the exact location of a storm drain inlet. Also, when conducting detailed surface–sub-surface flow pathway analysis, the application of surveyed storm drain inlets is recommended. Having the capabilities of conducting such detailed analysis in CityCAT underlines at the same time the benefits of having a generic way of generating a synthetic network of storm drain inlets. As shown in this work, different densities of storm drain inlets can be generated for individual areas. Simultaneously, single storm drain inlets could be added or removed. Changing inlet densities and locations together with pipe dimensions could be applied in future work to evaluate not only the hydraulic, but also the cost implications, which was beyond the scope of this work.

Generally, more studies are required in order to validate the hydrodynamic results presented against measured flow data of actual storm events. This would allow for a wider and systematic sensitivity analysis addressing the location and spatial density of storm drain inlets, as well as the impact of their geometry and blockages. Critically, the GIS routine should also be applied and tested on urban catchments with different characteristics in terms of size, topography, etc. to avoid a potential over-calibration towards the catchment tested in this work. In general, further research in this area could focus on two things. Firstly, on improving the GIS routine that is developed in this work. This could range from including additional data or applying different means of placing the storm drain inlets by using more sophisticated statistical analysis tools. Secondly, moving away from the synthetic network to find different ways of recording the actual locations of storm drain inlets. Surveyed inlet locations are preferred in order to replicate the complex hydraulics of the actual urban drainage system. Methods to generate synthetic inlet locations are informed by design standards that may have changed over time and are often unique to specific locations. Furthermore, certain situations in reality might require adaptation of the design and planning standard in order to place storm drain inlets. Such locations are difficult to capture with a generic method for generating synthetic storm drain inlet locations. From a practical perspective, storm drain inlet locations could be collected as part of drainage maintenance work or other regular work that is carried out on roads.

Alternatively, an automated process could be developed allowing for a detection of storm drain inlet locations based on image processing of the application of Google Street View images, similar to algorithms that are applied for face or license plate recognition (Frome *et al.*, 2009). Image processing to identifying storm drain inlet locations based on UAV (Unmanned Aerial Vehicle) orthoimages was conducted in a more recent study de Vitry et al. (2018).

Chapter 5 Mapping and analysing fully coupled 1D/2D flood model results

5.1 Introduction

With the increasing capacity of hydrodynamic modelling tools to simulate large domains at high resolutions, the quantity of model results also increases. Advanced hydrodynamic modelling tools such as CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018) produce surface water grids formed of millions of cells. Hydrodynamic model results are usually provided in numerical format. Hence, further analysis and mapping tools are required to make them readable and accessible for researchers and end-users such as water utilities, consultants, environmental agencies, spatial planners and insurance companies.

Commercially available flood modelling software however often require specific (and proprietary) add-on packages to post-process, analyse and visualise their results. At the same time, results from a different modelling tool can often not be accessed by another modelling software. Thus, compatibility issues may prevent further analysis of the results. On the other hand, a lack of appropriate analysis tools capable of handling large quantities of high resolution data may lead to aggregation and simplification and therefore a loss of information.

In order to increase the accessibility, readability and interchangeability of fully coupled 1D/2D hydrodynamic model results a number of open-source Python-based scripts were developed in this chapter. The tools allow for an automated and time-saving processing of large quantities of data. By mapping multiple time steps the dynamics behind urban floods can be analysed. Comparing different scenarios, the impact of change can be visualised. A flood exposure analysis tool was developed which applies exact shapefile geometries of buildings and high resolution flood information. It enables the assessment of the likelihood of internal flooding of properties following industry standards. The open-source codes can be adapted towards specific user needs and further functions can be added. The Jupyter notebook with the source code for the flood exposure tool can be downloaded under the BSD-license from the following GitHub repository: https://github.com/hydrob.

The following section first introduces Python and Jupyter as the programming platforms applied. Subsequently the functions of the mapping and visualisation scripts are illustrated. Finally the flood exposure analysis tool is presented. Appendix A contains additional material to illustrate the functions of the scripts developed.

5.2 Programming platforms Python and Jupyter

For the purpose of developing open-source applications a series of programming languages are available. For this thesis it has been decided to develop codes in Python (https://www.python.org/) and for the Jupyter Notebook environment (http://jupyter.org/). Python is a widely used, free of charge and well-documented programming language which has a considerable number of relevant libraries for the specific purposes of this work. Furthermore the initial plotting script for CityCAT (section 5.3.2) was written in Python and thus provided a practicable starting point for further developments.

Jupyter Notebook is a browser based, open-source environment available under the modified BSD license (https://opensource.org/licenses/BSD-3-Clause). A single notebook can be written in different programming languages including Python. The live-code written inside a notebook can be enhanced using explanatory text, visualisation objects and interactive widgets. Jupyter notebooks therefore offer a range of beneficial features for the purpose of data handling, data analytics and visualisations.

The Jupyter notebook developed in this work is based on the Python version 3.5. To install the Jupyter environment and Python the Anaconda distribution (https://www.anaconda.com/download/) offers an easy to follow solution and is supplied with a range of required modules including Matplotlib (Hunter, 2007). Some of the modules required for the flood exposure tool however are not included in the Anaconda distribution. Further packages and dependencies are required:

- Geopandas (http://geopandas.org/)
- Fiona (https://pypi.python.org/pypi/Fiona)
- Rtree (https://pypi.python.org/pypi/Rtree/)
- Shapely (https://pypi.python.org/pypi/Shapely)

5.3 Mapping tools

5.3.1 Initial Python plotting script

The mapping tools developed in this work are based on an initial Python plotting script written by Vassilis Glenis and Greg O'Donnell, at Newcastle University. This script can be used to plot the inundation depth of a 2D CityCAT simulation (Figure 5.1). The mapping script can iterate through a specified folder which contains the depth grids for all time steps– see also Appendix A. This automatically generates a map with the same layout for each time step. A zoom function can focus on a specific area (Figure 5.2). The highlighted area in

Figure 5.2 represents a pluvial flooding location which is applied to illustrate the adaptations and additions made to the initial plotting script.

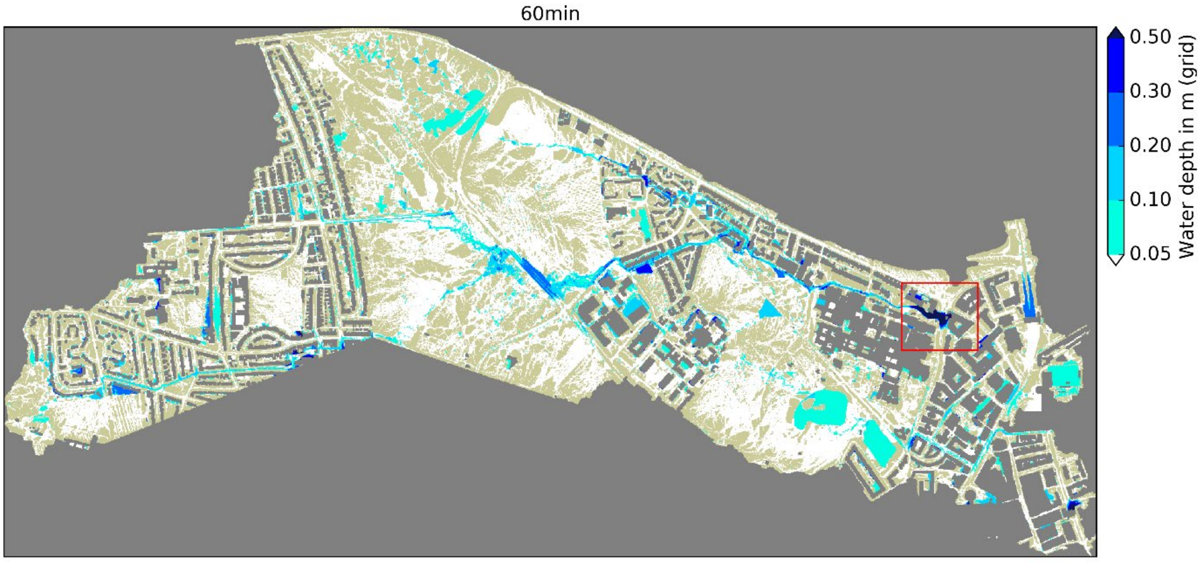


Figure 5.1 Map produced with initial plotting script showing the simulated surface water depth of a 50 year RP event with 60 minutes duration for the entire catchment at t=60 minutes. Red box indicates zoom extend shown in Figure 5.2.

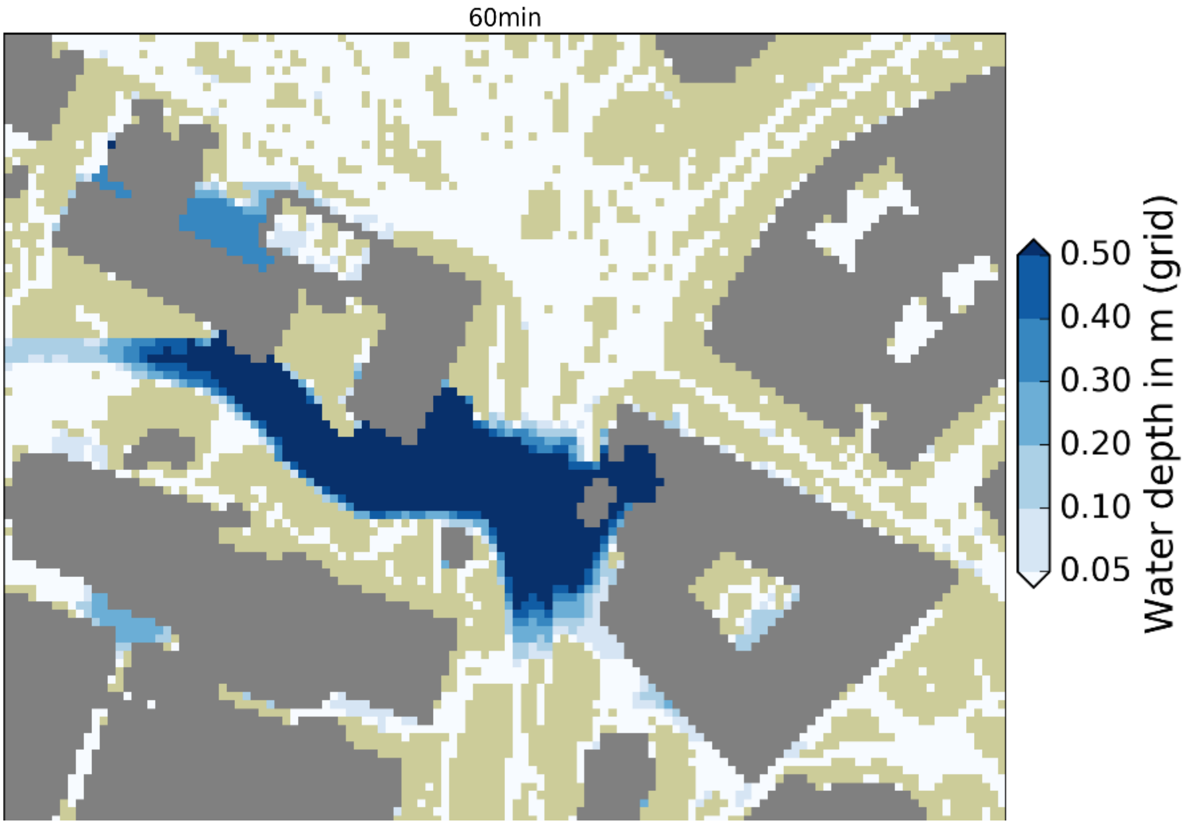


Figure 5.2 Surface water inundation depth grid from fully coupled 1D/2D hydrodynamic model results of a 60 minute storm event at t=60 minutes.

5.3.2 Hydrodynamic aspect of floods – fully coupled 1D/2D model results

The first function which was added to the initial mapping script plots the surface flow vector field. For this purpose the Matplotlib Quiver plotting function is used, with the length and colour of the arrow used to reflect the vector velocity. The Quiver function automatically calculates a flow vector based on two flow components in x and y direction respectively. The information on the flow vector components is given in the same file as the inundation depth grid (Appendix A).

In a second step, the plotting script was extended with a function to visualise the drainage performance of storm drain inlets. The storm drain inlet information on the flow captured or surcharging (l/s) is accessed from separate files whereby each file contains the information for all inlets with the time step correspondent to the surface water grids (Appendix A). To improve the clarity of the maps shown in Figure 5.3 to Figure 5.6 the script also applies the Geopandas library to plot shapefiles of the topography including buildings and green areas for instance.

Pluvial flooding

The pluvial flooding area highlighted in Figure 5.1 and Figure 5.2 is used subsequently to illustrate the different mapping functions. A storm event with 50 year return period of 60 minutes duration was simulated. The simulations were performed with a fully coupled 1D/2D hydrodynamic model in CityCAT. The maps presented in Figure 5.3 - Figure 5.6 show the results after 15, 30, 45 and 60 minutes respectively.

The results after 15 minutes (Figure 5.3) show that surface water is mostly located on impermeable surfaces such as roads and pavements while infiltration occurs on permeable surfaces. Furthermore surface water flow velocities are relatively small at this time step and not yet visible (the legends have been optimised to suit all time steps shown in Figure 5.3 - Figure 5.6). The drainage performance of all storm drain inlets in the area is relatively low ranging between 0.0 and 0.5 l/s and the flooded area has not been formed after 15 minutes (Figure 5.3).

At the peak intensity of the storm event at 30 minutes (Figure 5.4), surface water is also visible on permeable surfaces indicating: (a) already saturated soils or (b) an exceedance of the infiltration capacity. The pluvial flooding location has become visible and three surface water runoff pathways following the roads have been established – from the north, south and west. Furthermore, seven storm drain inlets in the area have reached a drainage rate of more than 5.0 l/s, with five of those inlets located within the pluvial flooding zone.

After 45 minutes of the simulation (Figure 5.5) the pluvial flooding zone is clearly visible and the drainage rate of additional storm drain inlets has increased. The dominant surface water runoff path leading to the pluvial flooding zone is now from a westerly direction. Crucially this runoff pathway can be traced back to the upper parts of the catchment and conveys considerable volumes of water. Furthermore, along the runoff pathway, several terrain-related depressions act as temporary storage features. Also the pluvial flooding zone can be considered a temporary storage feature. After 60 minutes of the simulation (Figure 5.6) the water inundation depth exceeds 0.5 m causing water to spill and drain in a south-easterly direction. This example highlights the important capability of fully distributed models to simulate entire terrain-derived catchments in order to capture all necessary surface water runoff pathways and the temporary storage of water in terrain depressions.

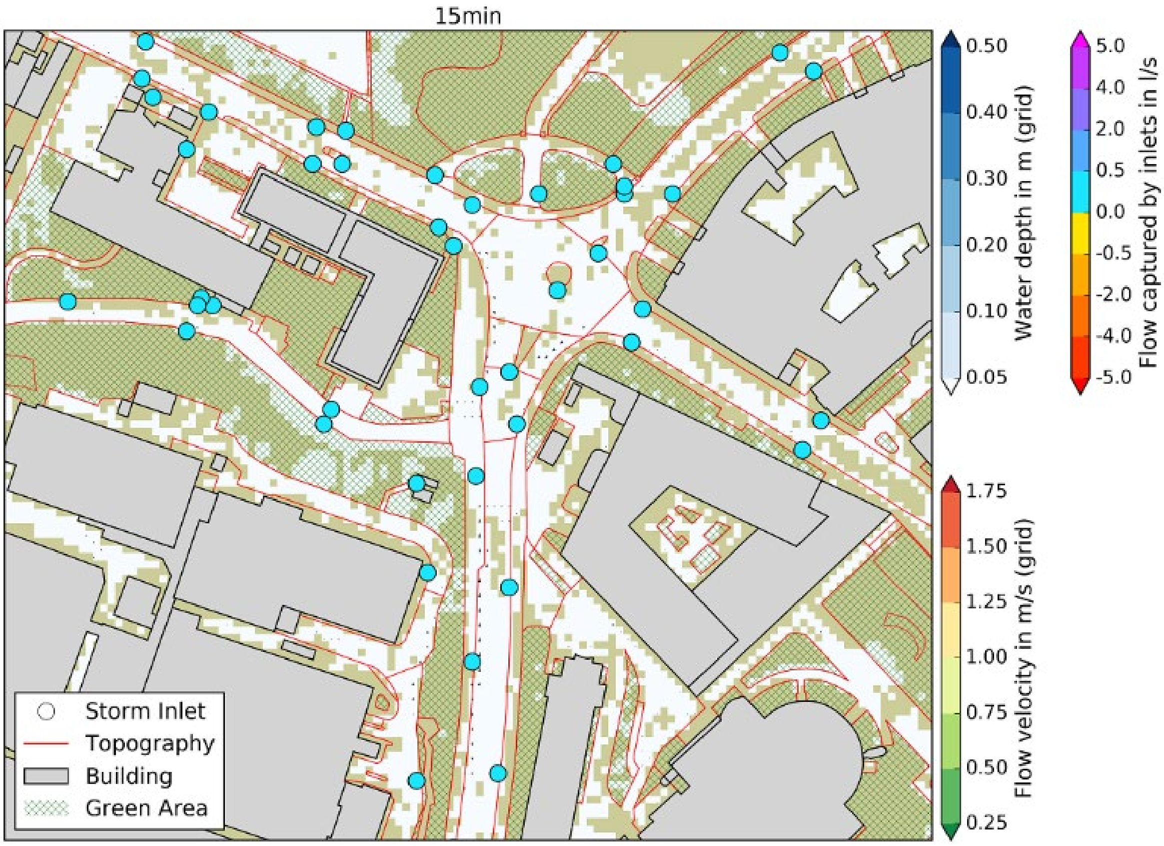


Figure 5.3 Fully coupled 1D/2D hydrodynamic model results for a 60 minutes, 50 year RP storm event at t=15 minutes.

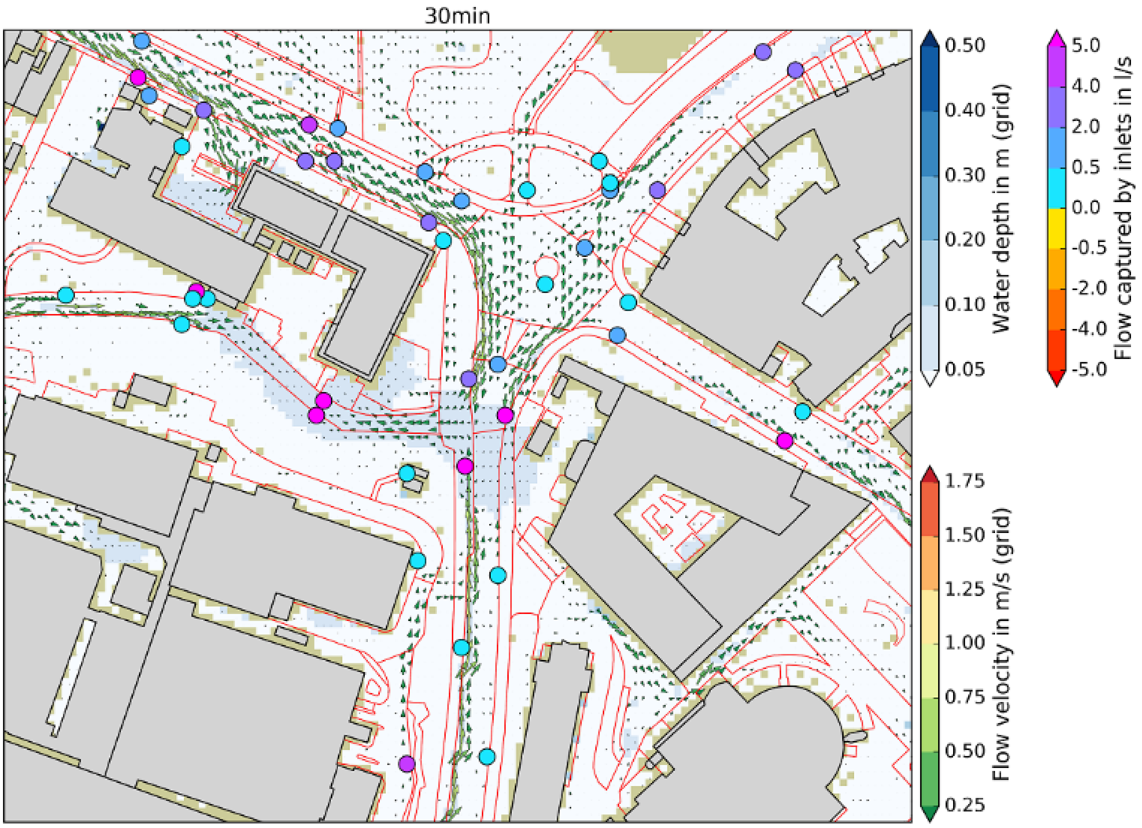


Figure 5.4 Fully coupled 1D/2D hydrodynamic model results for a 60 minutes, 50 year RP storm event at t=30 minutes.

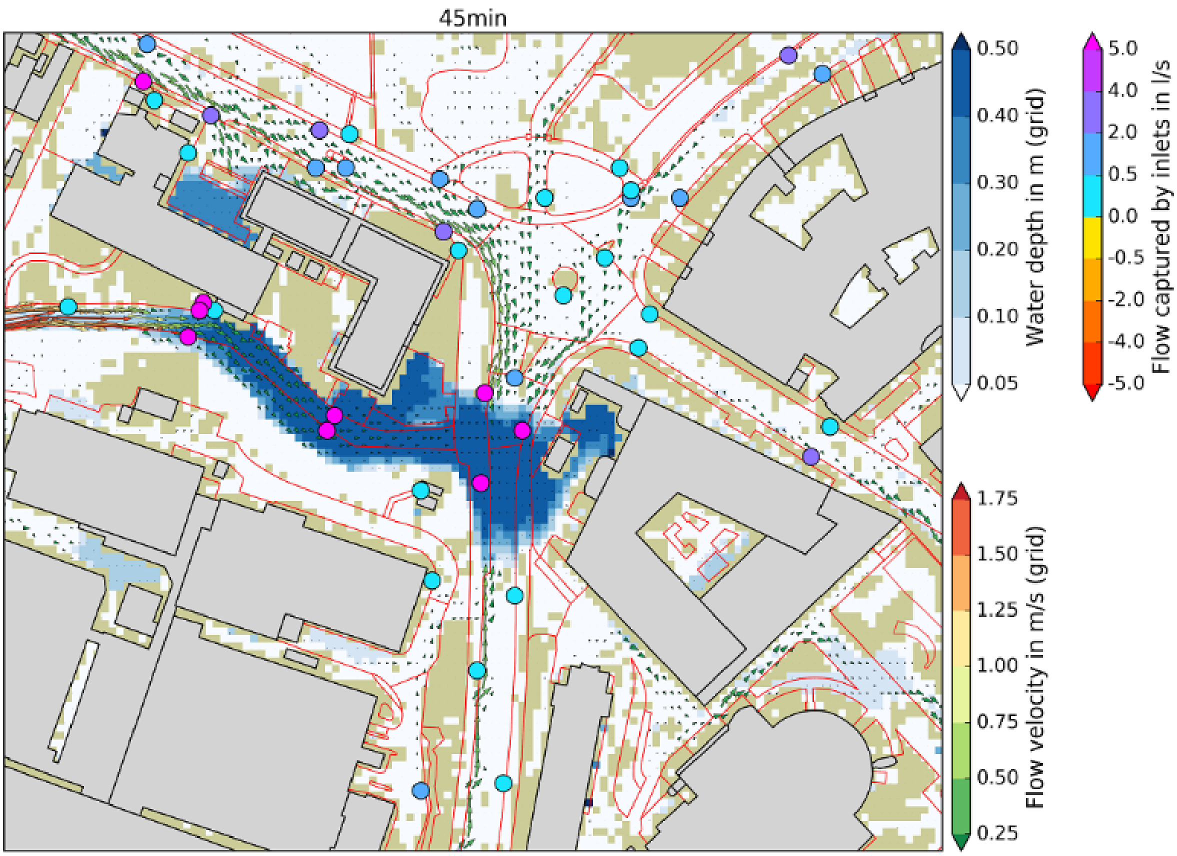


Figure 5.5 Fully coupled 1D/2D hydrodynamic model results for a 60 minutes, 50 year RP storm event at t=45 minutes.

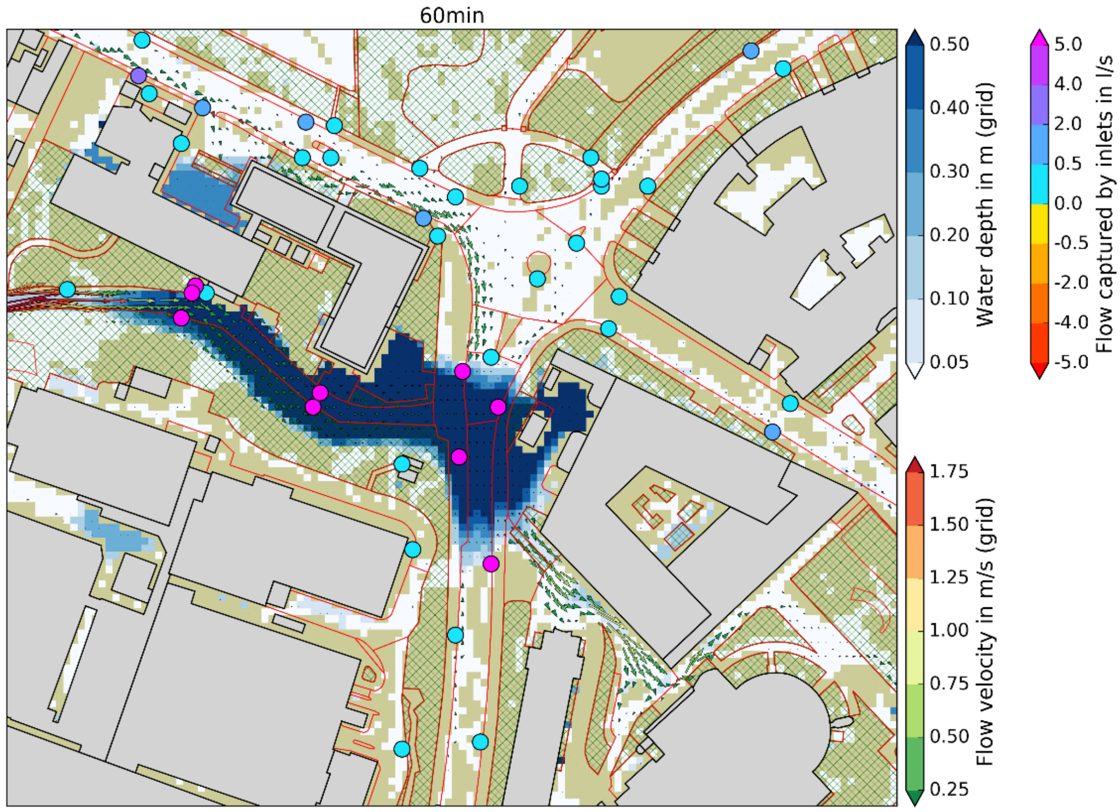


Figure 5.6 Fully coupled 1D/2D hydrodynamic model results for a 60 minutes, 50 year RP storm event at t=60 minutes. Increasing inundation depth causes water to spill from pluvial flooding area in south-easterly direction.

Sewer flooding

Besides the drainage performance of inlets, the water level inside manholes is an important indicator for potential sewer flooding. For this purpose, the mapping scripts allow plotting of the water level inside manholes as percentage of the manhole height. Hence, pressurised manholes are assigned with values in the excess of 100%. The information on the manhole height and the water level are accessed in a similar approach to the storm drain inlet files (Appendix A).

To demonstrate the example of a pressurised sub-surface system, a 50 year return period storm event of 60 minutes duration was simulated in a fully coupled 1D/2D CityCAT model. After 30 minutes (Figure 5.7) all visible storm drain inlets (circles) and manholes (squares) are non-pressurised. The simulated flow captured by inlets ranges between 0.0 and 5.0 l/s. At 55 minutes simulation time (Figure 5.8) two manholes have become pressurised with water levels of 107.9% and 155.9% respectively. As a result of the pressurised manholes, the connected storm drain inlets surcharge, indicated by negative flow values of 0.2, 2.2 and 4.3 l/s. Focusing on the inlet with a surcharging flow rate of 4.3 l/s the exceedance flow is visible as it has become part of the surface water flow vector grid. This example highlights the important ability of fully coupled 1D/2D models to simulate manholes and inlets explicitly and simultaneously solve the flow equations for the surface and sub-surface domain.

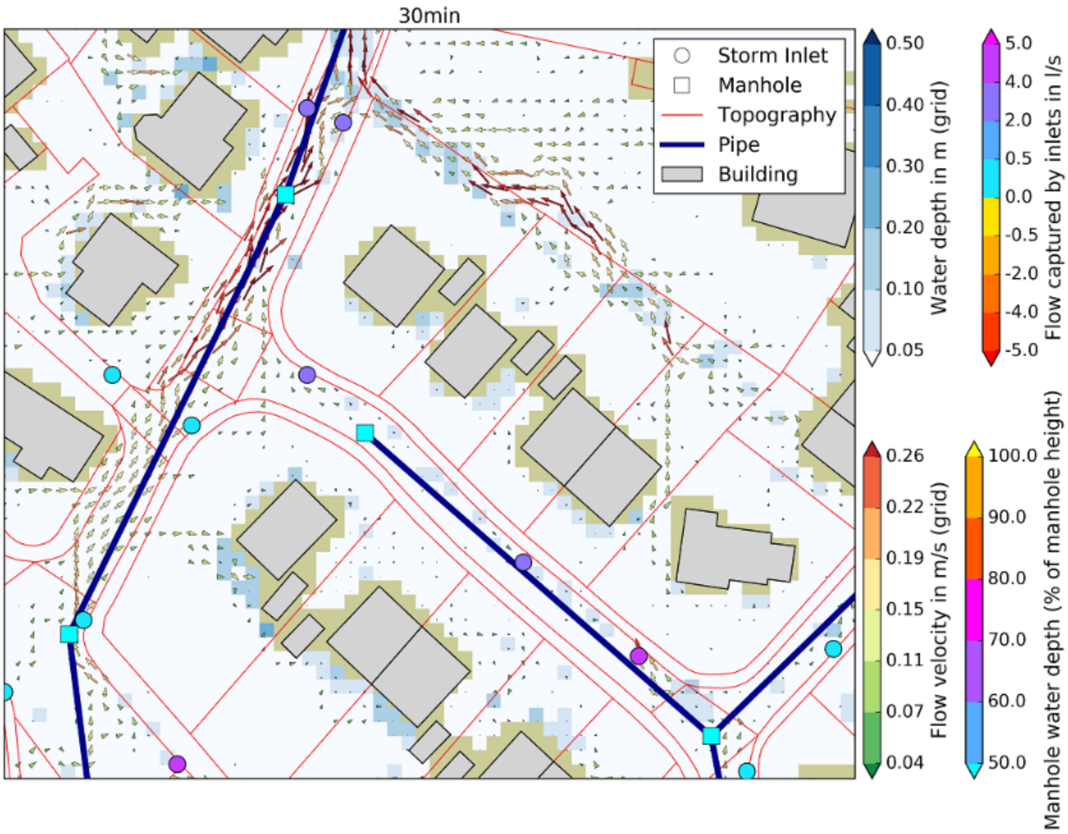


Figure 5.7 Drainage performance of the sub-surface drainage network and surface runoff pathways at t=30 minutes.

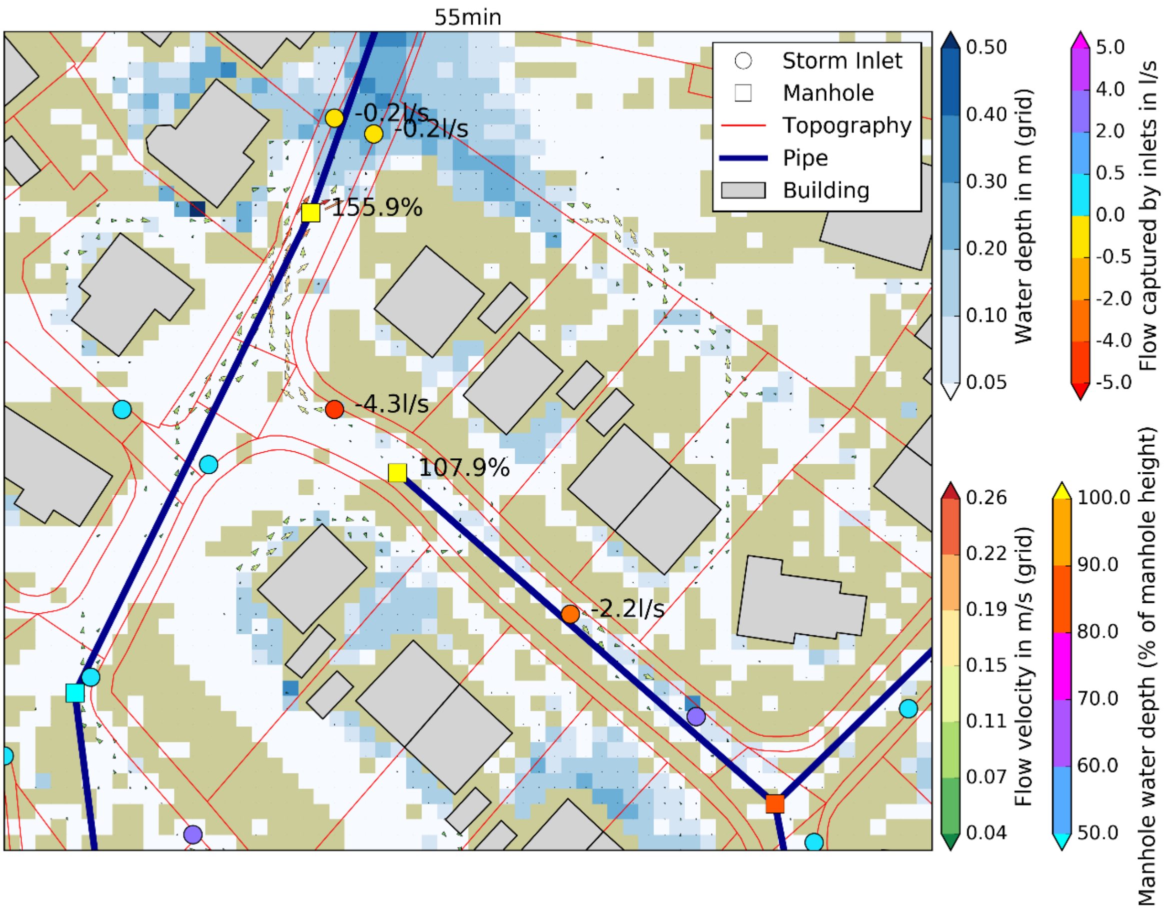


Figure 5.8 Sewer flooding: pressurised manholes and surcharging inlets with the resulting surface flow vectors at t=55 minutes. Negative inlet flow values indicate surcharging conditions. Manhole is considered pressurised if simulated water level inside manhole exceeds manhole height.

5.3.3 Comparing scenarios: visualising impact of change

The previously presented mapping functions assist in analysing the performance of drainage systems and in understanding the mechanisms behind flood events. Another crucial aspect in flood analysis is the assessment of change i.e. the ability to compare different scenarios. For this purpose, a number of additional data analysis tools were developed in Python. The functions are illustrate in the following two sections focusing on:

1. Difference of surface water depth between a 2D only and a fully coupled 1D/2D model simulation
2. Impact of different pipe dimensions on the drainage performance of storm drain inlets

Example 1 – Model comparison: 1D/2D vs 2D

The first mapping script visualises the difference of the surface water depth grids between two scenarios. For this purpose a 50 year return period storm event of 60 minutes duration was simulated for a 2D model only and fully coupled 1D/2D model – both in CityCAT. The horizontal resolution of the terrain model is $\Delta x = \Delta y = 2$ m. The catchment, with an area of

2.8 km^2, is located east of the city centre of Newcastle upon Tyne, UK. The pipe network of the 1D/2D model has a length of 16.6 km and the 911 storm drain inlets were synthetically generated following the methodology presented in chapter 4.

To visualise the difference between two surface water depth grids the script first calculates the differences for each cell by iterating through the two grids. Therefore both grids must be identical in terms of dimension and number of grid cells. The tool is applicable for individual grids or entire time-series.

The maps presented in Figure 5.9 and Figure 5.10 show the surface water depth difference at t=30 minutes and t=60 minutes respectively. Both maps also show the storm drain inlets and the pipe network to visualise the extent of the sub-surface drainage network of the 1D/2D model. At storm peak (30 minutes - Figure 5.9) the differences across the grid are less than 0.05 m. Areas of negative values show the reduction in surface water depth for the 1D/2D model over the 2D model as a consequence of the drainage effect of the sub-surface network. At the end of the simulation (60 minutes - Figure 5.10) large areas along the entire sub-surface network are affected by the drainage effect. Furthermore, the magnitude of the difference is greater than 0.3 m in areas of local terrain depressions.

The impact of the drainage performance of the sub-surface drainage system can be further analysed as the plotting tools also allow to visualise the results from a flood exposure analysis (methodology explained in section 5.4). The maps in Figure 5.11 and Figure 5.12 show the internal flooding likelihood of buildings for the 2D and 1D/2D model simulation respectively. The 2D simulation resulted in 123 and 116 buildings classified with a high and medium likelihood respectively. The 1D/2D simulation on the other hand resulted in 100 and 123 buildings classified with a high and medium likelihood respectively.

The ability to visualise the difference in surface water depth allows visualisation of the dynamic and non-uniform drainage effect of the sub-surface drainage system in both a spatial and temporal dimension. This highlights the particular benefit of fully coupled 1D/2D models of simulating all storm drain inlets explicitly for the entire domain. Furthermore, in combination with the flood exposure results, the mapping scripts also visualise the impact of change and the cause and consequences of urban floods.

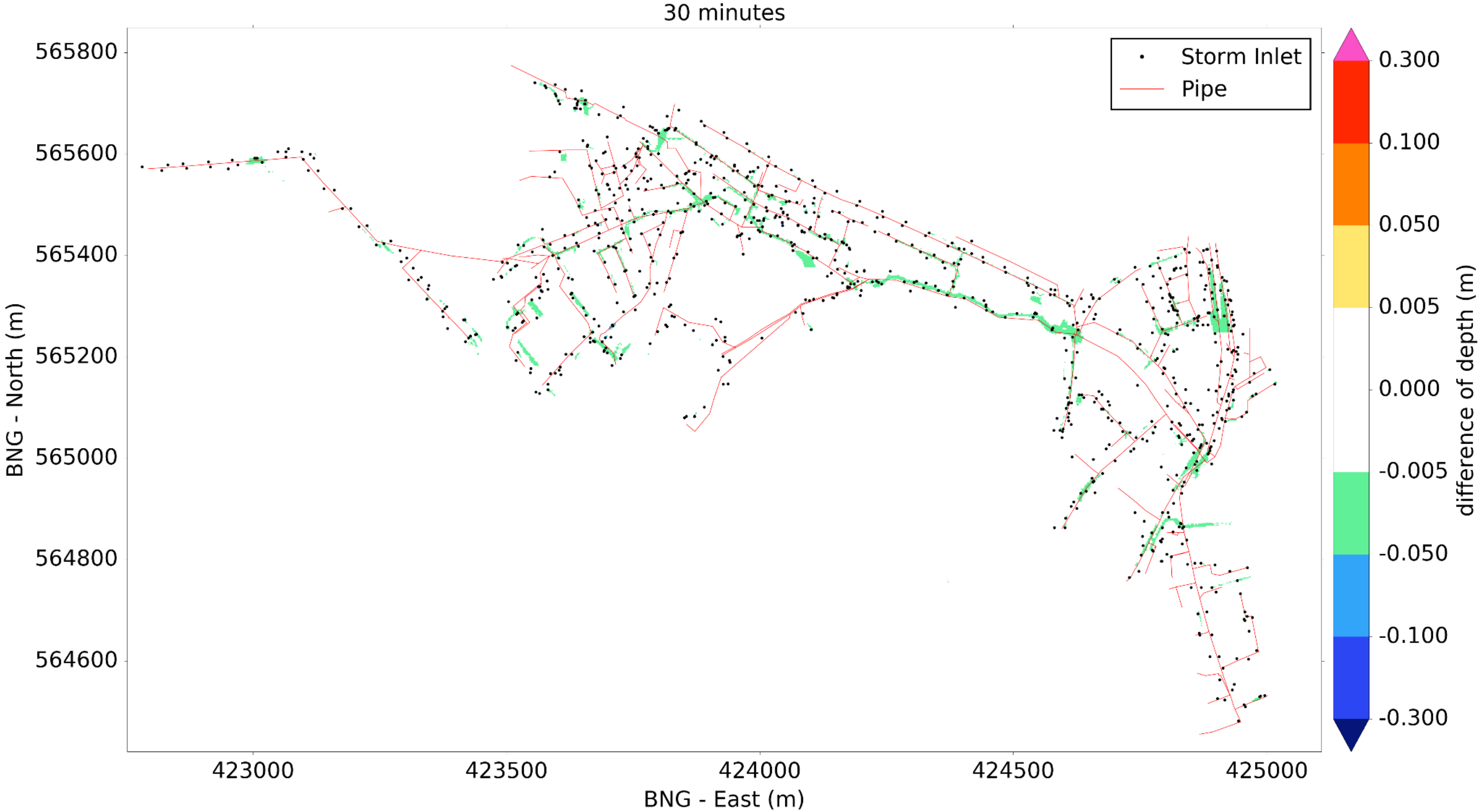


Figure 5.9 Difference of surface water depth between a 2D and 1D/2D simulation at t=30 minutes of a 50 year return period storm event of 60 minutes duration. Negative values highlight drainage effect of sub-surface network.

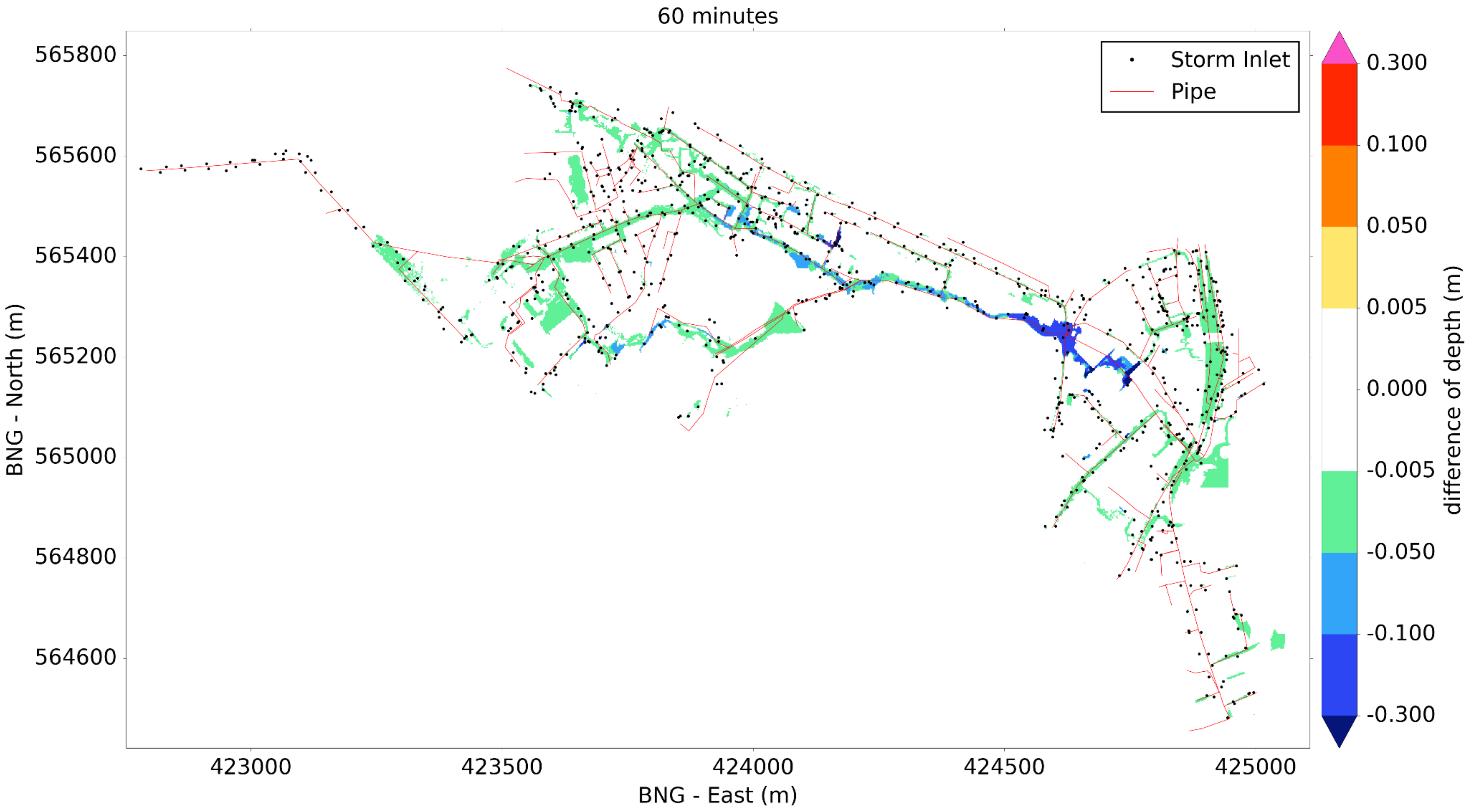


Figure 5.10 Difference of surface water depth between a 2D and 1D/2D simulation at t=60 minutes of a 50 year return period storm event of 60 minutes duration. Negative values highlight drainage effect of sub-surface network.

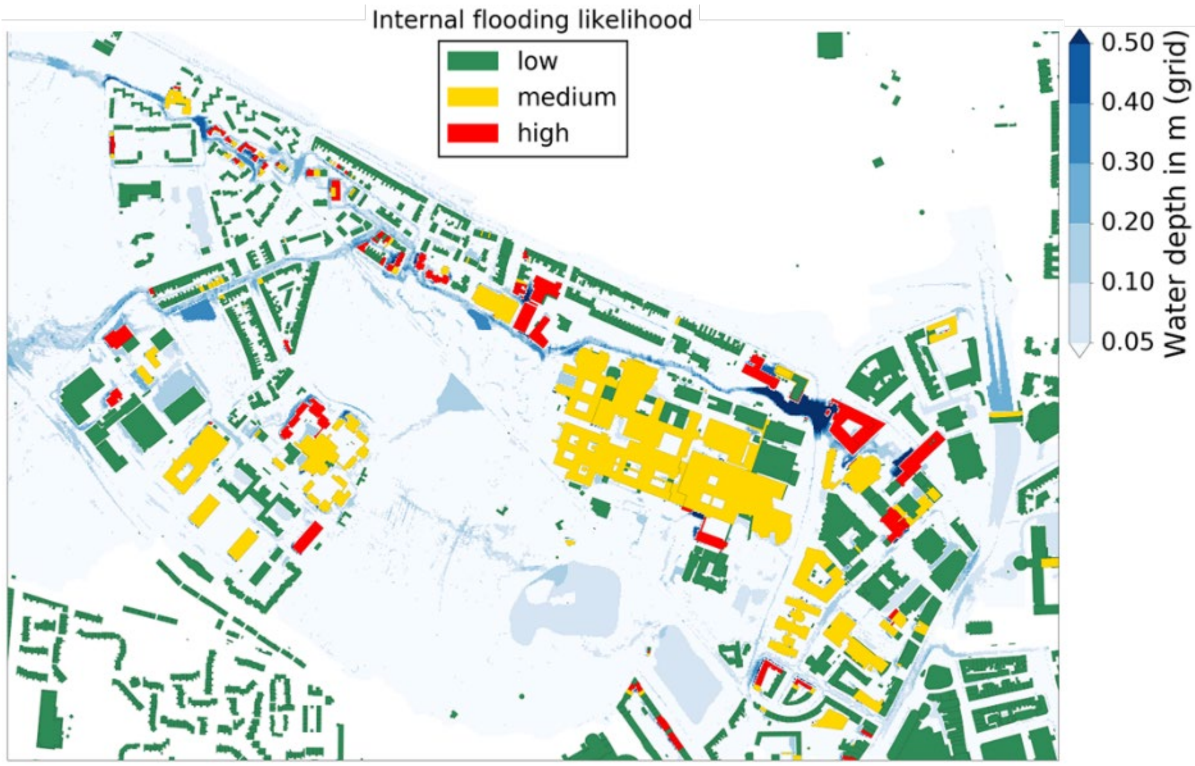


Figure 5.11 Internal flooding likelihood of buildings for 2D simulation of 60 minutes, 50 year RP storm event.

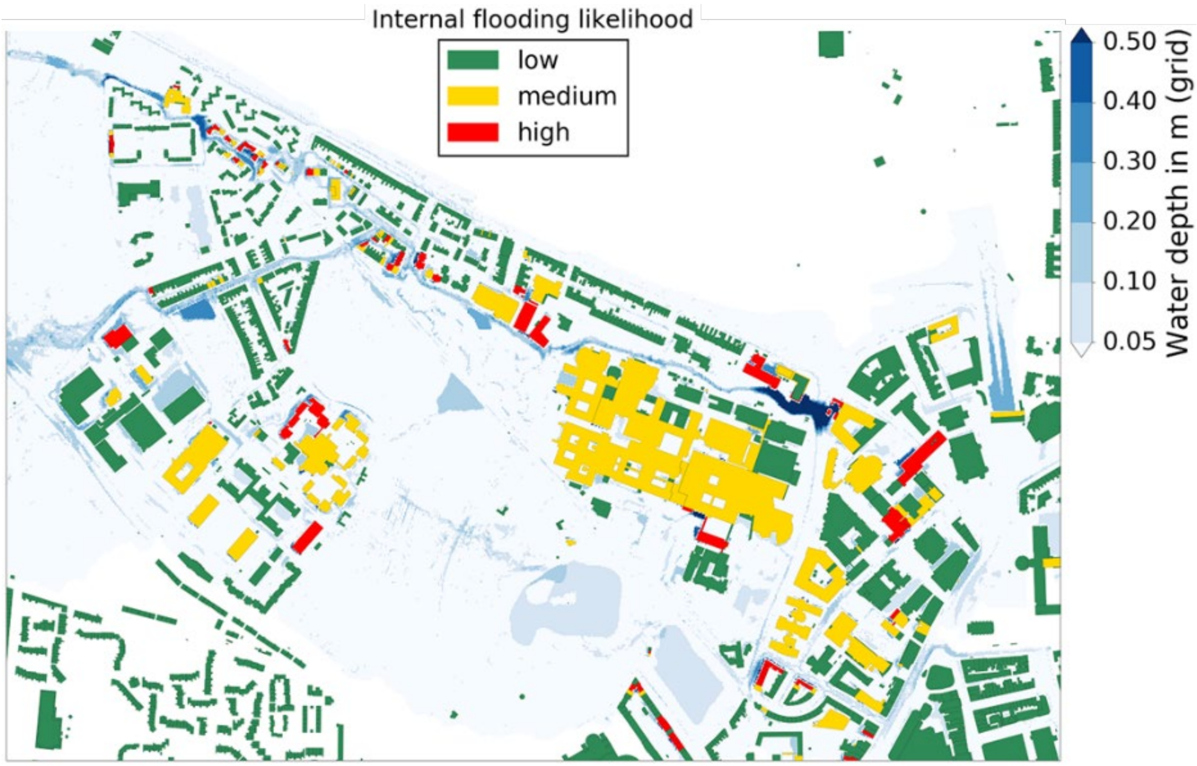


Figure 5.12 Internal flooding likelihood of buildings for fully coupled 1D/2D simulation of 60 minutes, 50 year RP storm event.

Example 2 – Storm drain inlet performances

The second example presents data analysis tools which were developed to analyse the drainage performance of the sub-surface network and particularly that of storm drain inlets. For the purpose of illustrating the functions of the analysis tools, two fully coupled 1D/2D CityCAT models were simulated using: (A) observed pipe diameters and (B) increased pipe diameters according to Table 5.1. By increasing the pipe diameters in scenario B, the aim is to analyse the impact of an increased capacity of the sub-surface system on the drainage performance of storm drain inlets. The surface catchment has an area of 2.1 km^2 and a horizontal grid resolution of $\Delta x = \Delta y = 2$ m. The pipe network has a length of approximately 10.9 km. Furthermore, 294 manholes and 445 surveyed storm drain inlets were simulated. The inlet grating types, manhole and connection pipe dimensions are the same in both scenarios.

Table 5.1 Specification of observed and increased pipe diameters of scenario A and B respectively used in fully coupled 1D/2D hydrodynamic simulation.

scenario A current pipe diameter (m)	**scenario B increased pipe diameter (m)**	**increase (m)**	**increase (%)**
0.100	0.200	0.100	100.0
0.150	0.250	0.100	66.7
0.200	0.300	0.100	50.0
0.225	0.350	0.125	55.6
0.300	0.400	0.100	33.3
0.375	0.500	0.125	33.3
0.450	0.600	0.150	33.3

The scatter plots in Figure 5.13 show the simulated drainage performance (flow captured in l/s) of the individual storm drain inlets for scenario A (X-axis) and scenario B (Y-axis) at t=30 and t=49 minutes. The scatter plots also show three surcharging zones for inlets surcharging in: both scenarios = red, scenario A = orange and scenario B = yellow.

At t=30 minutes (Figure 5.13 – left), the simulated flows captured are similar for both scenarios. This can also be observed in Figure 5.14 showing the cumulative flow captured by all inlets for each time step of the simulation. After 33 minutes of the simulation however, the increased pipe diameter start to have a visible effect on the drainage performance of the storm drain inlets. The graphs in Figure 5.14 also show that the impact of the increased pipe diameters on the drainage performance varies across time.

Regarding the cumulative flow captured, the greatest difference was simulated at t=49 minutes with 142.6 l/s. As shown in Figure 5.13 – right, several inlets have dropped below the identity line (equal drainage of inlets in both scenarios). This indicates an increased drainage performance for inlets simulated in scenario B. Furthermore, apart from one inlet (surcharging in both scenarios) all surcharging inlets in scenario A show a positive drainage performance in scenario B. Hence increasing the pipe diameters has the potential to reduce potential sewer flooding.

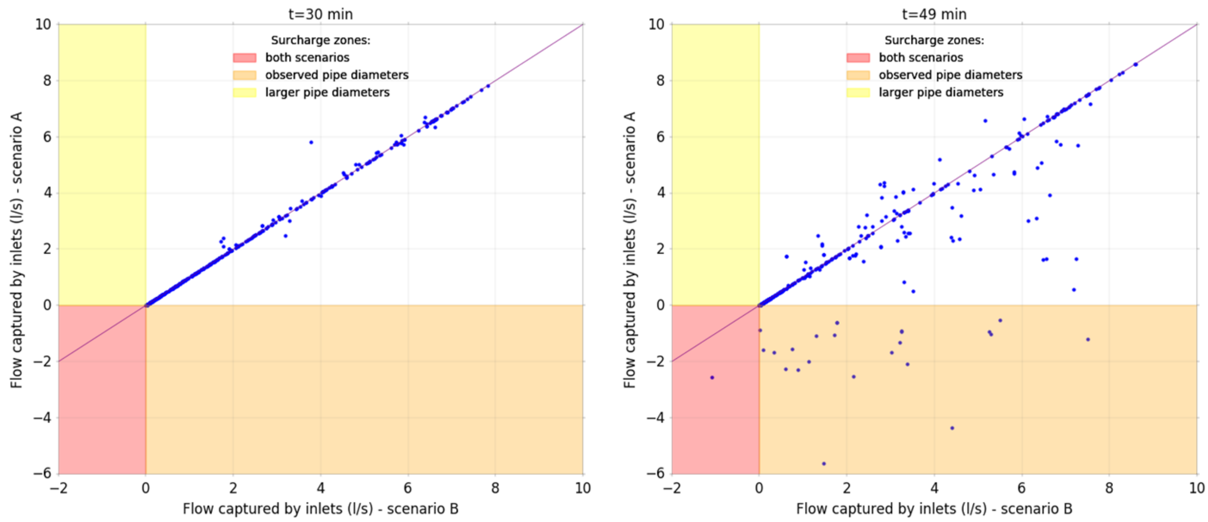


Figure 5.13 Simulated flow captured (l/s) by individual storm drain inlets at t=30 (left) and 49 minutes (right). X-axis: drainage for sub-surface network with recorded pipe diameters (scenario B). Y-axis: drainage for sub-surface network with increased pipe diameters (scenario A).

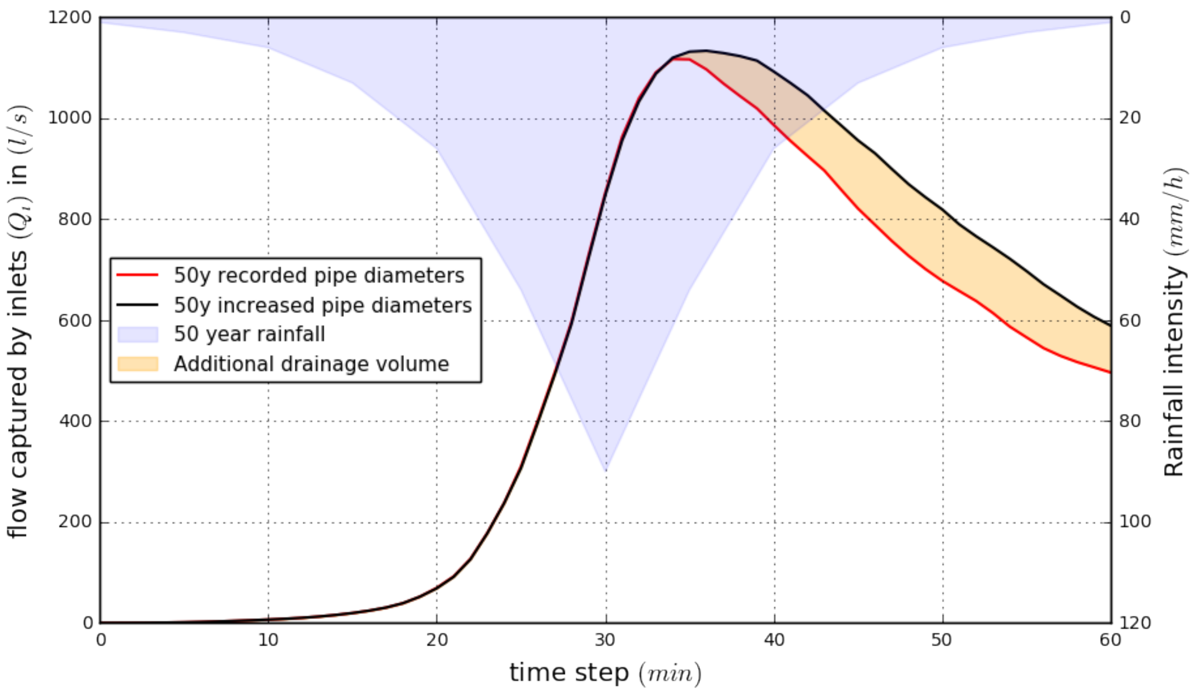


Figure 5.14 Simulated cumulative flow capture by all storm drain inlets for 50 year return period storm event of 60 minutes duration. Scenario A: sub-surface drainage network with recorded pipe diameters (red line). Scenario B: sub-surface drainage network with increased pipe diameters (black line).

Figure 5.14 compares the storm drain inlets and pipe network for scenario A (left) and B (right) at t=49 minutes. The most common pipe diameters across the network are 0.150 m and 0.225 m for scenario A and consequently 0.250 m and 0.350 m for scenario B respectively. Surcharging storm drain inlets are highlighted in both maps. Comparing the surcharging inlets in scenario A with the flow rates captured of the same inlets in scenario B shows that the impact of increased pipe diameters varies across space.

Figure 5.15 suggests that most surcharging storm drain inlets are linked to manholes which are connected to pipes with diameters of 0.150 m. The increase in diameter for 0.150 m pipes was 66.7%. In comparison, the largest increase in terms of the drainage capacity between scenario A and B was simulated with 142.6 l/s at t=49 minutes. This only represent an 18.8% increase of the drainage performance of scenario A at that time. This shows that the additional capacity of the sub-surface network was not matched by the drainage performance of the inlets. This is also supported as scenario B (Figure 5.15 – right) still has a considerable amount of inlets with flow rates of less than 0.5 l/s.

The results presented in Figure 5.13 to Figure 5.15 illustrate that the simulated drainage performance of inlets is affected by more than just the pipe diameters. The flow conditions on the surface, the dimensions and size of the manhole and the connection pipe as well as the flow conditions inside the pipe all affect the drainage performance of inlets. Thus high resolution fully coupled 1D/2D hydrodynamic models are required in order to capture the necessary information about the flow dynamics and interactions between the surface and sub-surface domain.

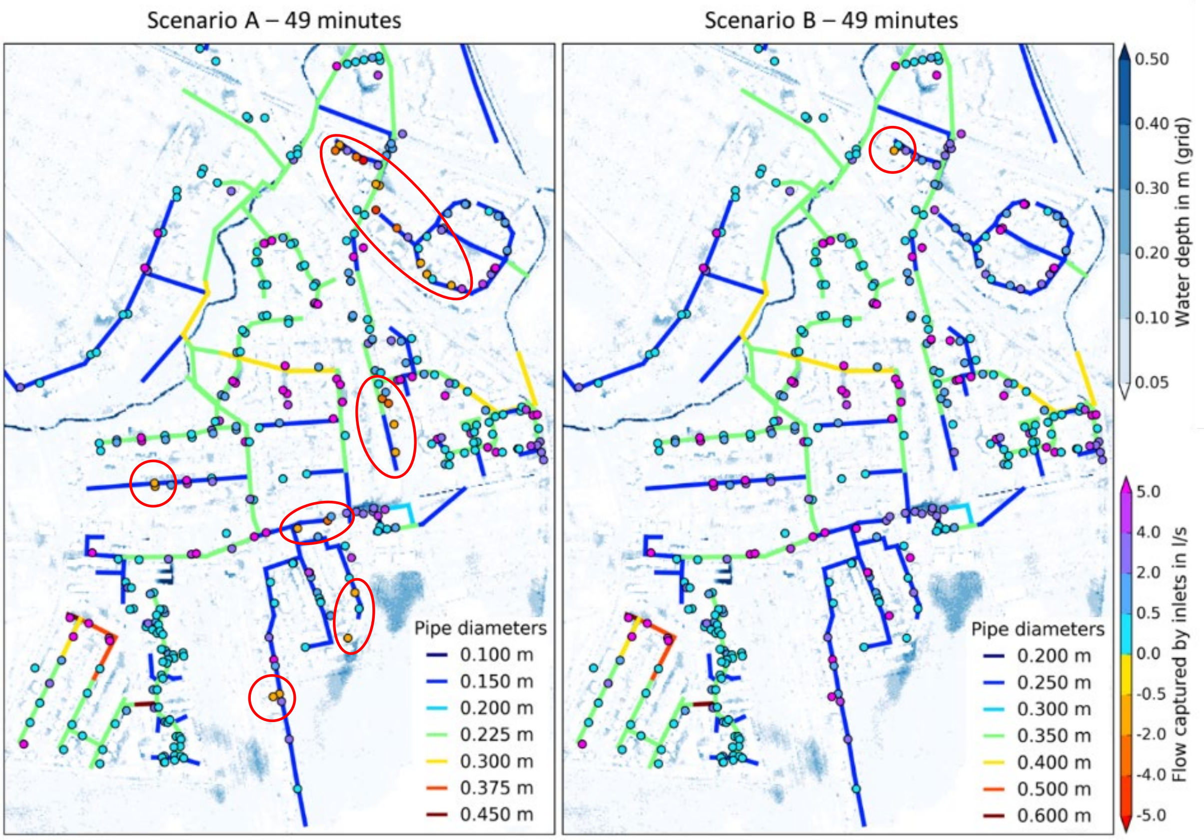


Figure 5.15 Impact of different sub-surface pipe diameters on flow captured by storm drain inlets for a 50 year return storm period event of 60 minutes duration at t=49 minutes. Left: simulation results based on current pipe diameters. Right: simulation results for changed pipe diameters according to Table 5.1.

A close up in Figure 5.16 shows the impact of the increased drainage capacity of the sub-surface system on the drainage performance of individual inlets. The current pipe diameters cause surcharging conditions with an exceedance flow of 4.3 l/s and 2.3 l/s (Figure 5.16 - lefts). The resulting sewer flooding visible as 2D surface flow. With increased pipe diameters, the previously surcharging inlets show positive drainage rates of 4.4 l/s and 0.6 l/s respectively (Figure 5.16 - right).

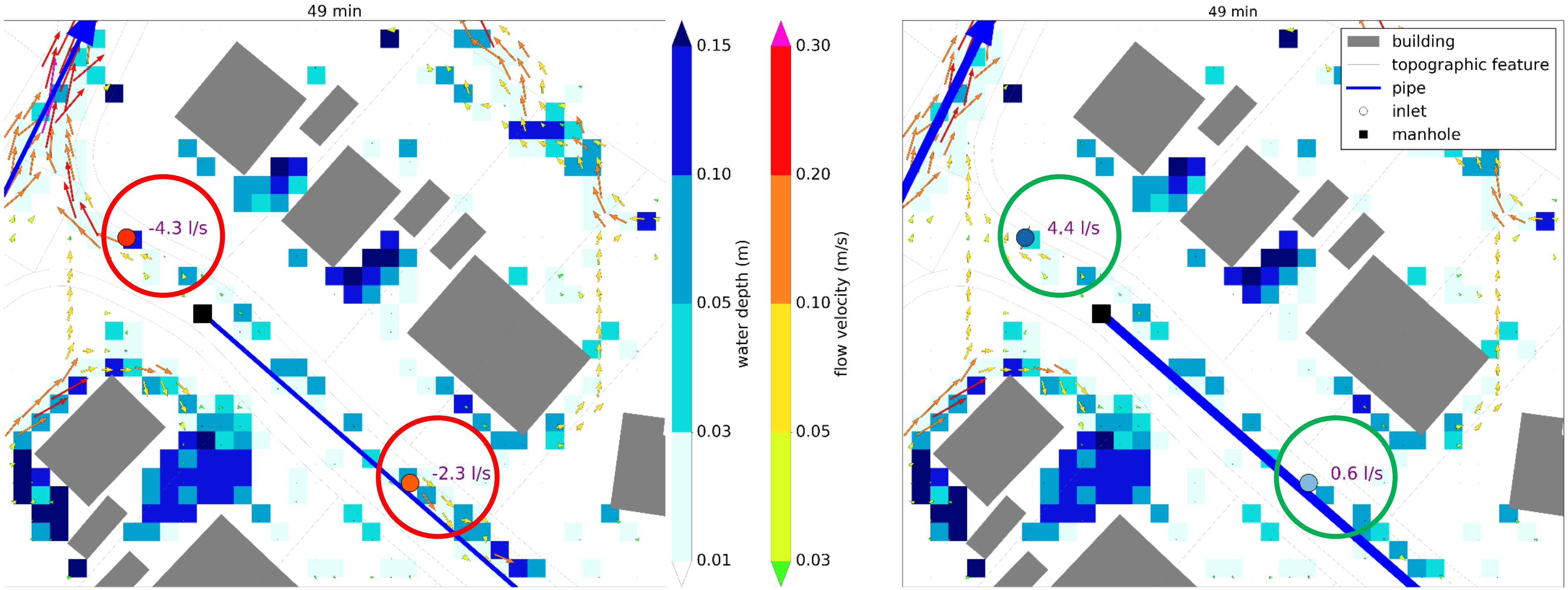


Figure 5.16 Impact of different sub-surface pipe diameters on individual storm drain inlets. Current pipe diameters (left) lead to surcharging condition at inlets with exceedance flow visible as 2D surface flow. Increased pipe diameters (right) show positive drainage rates.

5.4 Exposure analysis tool

The tools presented so far assist in the generation of maps helping to visualise the hydrodynamic data obtained from models including: surface inundation depth, surface flow vector fields, drainage rates of inlets and manhole pressures. A second important element in the post-processing of hydrodynamic model results is to conduct further analysis in order to assess the impacts and wider implications of floods. One common analysis in this context is to assess exposed elements of the urban fabric to the hazard of floods. Hence, this thesis developed a flood exposure analysis tools using high resolution data and exact building geometries.

5.4.1 Flood exposure assessment

For the purpose of identifying potentially flooded buildings, flood exposure assessments can be used as a more easily achieved alternative to a comprehensive and data intensive FRM analysis. Flood exposure analysis tools generally relate the hazard information (e.g. inundation depth) to the exposed unit by means of spatial intersection or proximity analysis. For the purpose of this work, the exposure units are buildings. Critical factors in developing an appropriate exposure analysis method are: (1) the spatial scale at which the analysis is conducted, (2) the purpose of the analysis and (3) the format and resolution of the information of the hazard and exposure elements. With regards to the scale, de Moel et al. (2015) distinguishes between: (1) the continental or global, (2) national, (3) regional and finally (4) the local scale. Depending on the scale and purpose of a flood exposure analysis, the exposed unit and the hazard information are commonly processed as shown in Figure 5.17.

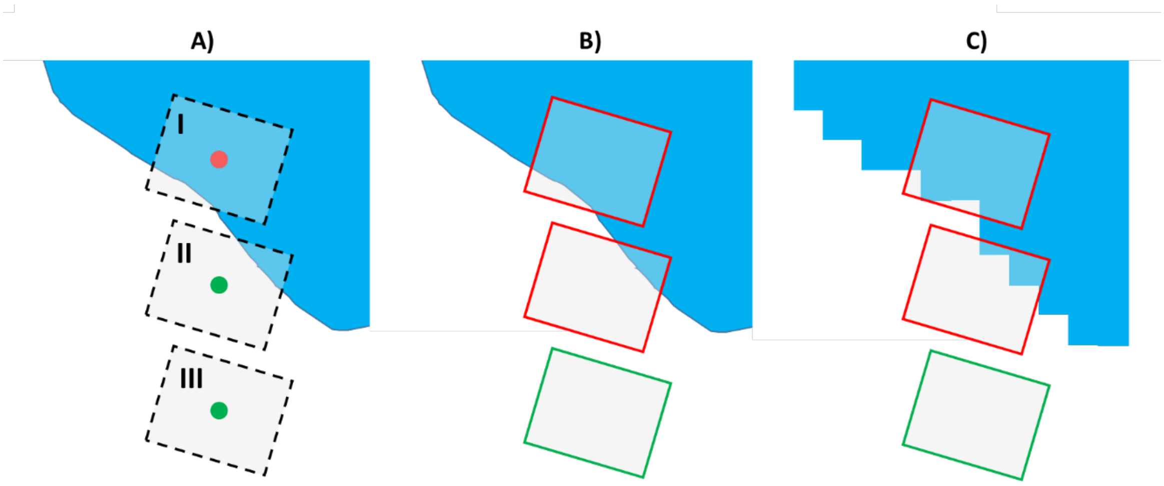


Figure 5.17 Schematic representation of different approaches relating building geometry to hazard information for conducting exposure analysis: (A) aggregated hazard map (polygon) and buildings as single point resulting in flooding of building I; (B) aggregated hazard map (polygon) and exact building geometry as polygon resulting in flooding of building I and II; (C) hazard as detailed grid and exact building geometry in form of polygon resulting in flooding of building I and II.

A) Building = point feature; hazard = aggregated map

Buildings are represented as single points (exposure point) whereas the hazard information is aggregated to polygons or grids (hazard maps). An example of this application can be found in Fuchs et al. (2015). Depending on the location of the exposure point, inside or outside a hazard zone, a building is considered as exposed or not. This method is computational less intensive and generally applied for large scale analysis as the hazard information is aggregated and the building geometry is ignored.

B) Building = polygon geometry; hazard = aggregated map

This approach applies the actual geometry of a building to intersect the hazard map. Based on the intersecting area, potentially flooded buildings are identified. An example application of this method can be found in Röthlisberger et al. (2017).

C) Building = polygon geometry; hazard = individual grid/mesh elements

The most detailed approach applies the building geometry in combination with discretised, individual rectangular or TIN (Triangular Irregular Networks) elements. This approach is generally applied for micro scale exposure analysis purposes as shown in Mazzorana et al. (2014); Ernst et al. (2010); Arrighi et al. (2013).

A crucial requirement for the third approach is to have detailed 2D hydrodynamic model results and building geometries, making the analysis computationally intensive. Hence applications and case studies for relatively large areas are rare. However, an increasing availability of detailed 2D hydrodynamic models applicable for larger urban catchments such as CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018) also increases the requirement for analytical tools capable of processing and accessing those data. Also, flood exposure analysis tools are often based on specific hydraulic models and their hydrodynamic results produced (Ernst *et al.*, 2010; Arrighi *et al.*, 2013). Making the flood exposure tool dependent upon a specific hydraulic model also limits a potential wider application of the exposure tool itself. An example is the commercial flood risk assessment tool RiskMaster (Innovyze, 2017) by Innovyze which analyses hydraulic results from other Innovyze modelling software.

5.4.2 Aim

The aim of this work is therefore to develop a generic, open-source based flood exposure analysis tool for detailed hydrodynamic model results and exact building geometries applicable for large areas. The use of high-resolution hydrodynamic results means that no information is lost. This allows stakeholders involved in flood risk management such as insurance companies, water utilities or environment agencies to conduct the analysis at the same level of detail for large domains. The outputs of the tool provide information on the potential internal flooding likelihood of each building based on a single or series of flood events. This allows stakeholders to analyse and reflect on the impact of change. A simple damage estimation function has been implemented to demonstrate the flexibility of the tool towards potential user adaptations. This is enabled by developing the tool within the open-source environments Python and Jupyter.

In the following sections the term 'internal flooding' is explained followed by a description of the method behind the tool. Subsequently the programming aspects, I/O data (input/output) requirements and the user interface are introduced before the results of a performance test are presented. Finally the damage estimation and the mapping function are introduced.

5.4.3 Internal Flooding

The question of when a building is considered to be flooded is crucial in this analysis. For this purpose the term 'internal flooding' has been adopted from Scottish Water and other stakeholders working on FRM across Scotland. Originally Scottish Water defined internal flooding as a situation whereby wastewater has entered a property (Scottish Water, 2017). This may be from the outside of the building, as a result of sewer flooding or the inside of a property, i.e. the internal drainage system. External sewer flooding on the other hand describes the flooding of the curtilage (e.g. garden) of a property. To classify a building as internally flooded from an outside source, Scottish Water applies a critical threshold of 0.3 m at the property boundary or its outside walls (Figure 5.18). If the threshold of 0.3 m is exceed for a 1 in 30 year storm return period event the building is registered to be at risk from internal flooding. Any property internally flooded for a 1 in 10 year flood event is considered a high priority object and the aim is to reduce the number of high risk properties. Simultaneously, efforts are undertaken to prevent new properties falling into the high risk category as a result of increasing hazards, vulnerability or exposure threats (Figure 5.18).

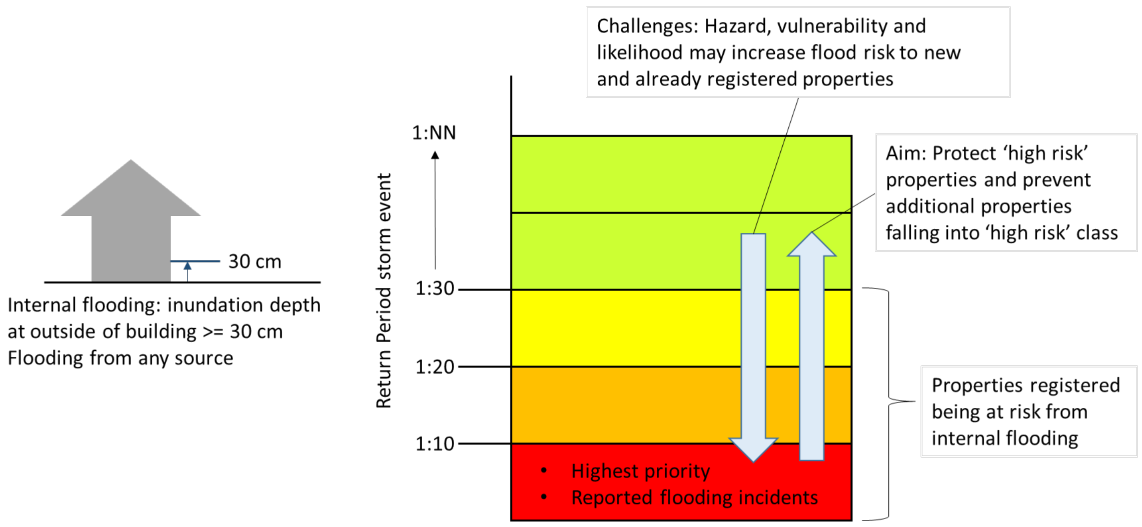


Figure 5.18 Concept of internal flooding following the definition adopted from industry.

5.4.4 Model concept

The internal flooding concept outlined above has been adopted for the purpose of this work with slight modifications. A building is considered internally flooded if water enters the building from any outside source. This allows the application to simulation results of truly coupled 1D/2D hydrodynamic tools such as CityCAT. The internal drainage system of a building is not considered in this work.

The calculations of the internal flooding likelihood of a building is based on two layers representing: (1) the exact building geometry and (2) a regularly spaced inundation depth grid. Additional information about the buildings (e.g. basement or floor levels, existing flood defence features, exact locations of air valves, doors or windows) or the hazard (e.g. flow velocity) are not included at this stage. Work by Mazzorana et al. (2014) and Custer & Nishijima (2015) are examples using detailed building-related features in the context of flood impact assessments. Critically for a generic tool however, this requires a considerable amount of data which might not always be available.

The treatment of building geometries in hydrodynamic models can follow fundamentally different approaches (Schubert and Sanders, 2012). Essentially the cells inside the building footprint can be represented as void space inside the computational grid (BH – Building Hole method) or altered in terms of elevation (stubby buildings) or assigned with specific roughness or porosity parameters (BB – Building Block method) (Schubert and Sanders, 2012). The parameters for a BB method must be selected carefully as they alter the flow dynamics and hence the inundation depth inside, as well as outside the building footprint.

Consequently the results of a flood exposure analysis are also affected. In principle the tool developed in this work should preferably be applied to hydrodynamic model results based on the BH method. Furthermore, the building layer used for the exposure analysis ought to be the same that was used in the hydrodynamic model in order to extract the relevant data as described in the next section.

Buffer analysis

Model results based on the BH method do not provide hydraulic information within the building footprint. Calculating the internal flooding likelihood has to be based on cells adjacent to the outside of the building footprint instead. Hence the principle of GIS-based (Geographic Information System) buffer analysis is applied. As shown in Figure 5.19, a buffer is created around a building in order to extract inundation depths from the adjacent cells based upon which the mean and maximum inundation depth are calculated. Those two values are subsequently applied in order to classify a building according to the scheme presented in Table 5.2.

As outlined earlier the depth of 0.3 m plays a significant role in the assessment of the potential internal flooding likelihood. The critical question in this context is however which depth this refers to: the mean, maximum or minimum of relevant grid cell water depths. If only the maximum depth is considered the results might be skewed towards outliers. Those may be caused by erroneous cell elevations and therefore unrealistically large inundation depths. If the 0.3 m threshold refers to the mean or minimum inundation depth the threat of flooding may be underestimated. It has therefore been decided to use both the mean and maximum inundation depth for the classification shown in Table 5.2. This combination allows some quantification of the potential internal flooding likelihood, rather than binary assessment of flooded – not flooded. Furthermore a building is considered to be internally flooded if the mean and maximum inundation depth are >= 0.1 m and >= 0.3 m respectively. This nominal classification is conducted for the purpose of calculating the potentially exposed value and for generating a summary of results across multiple events.

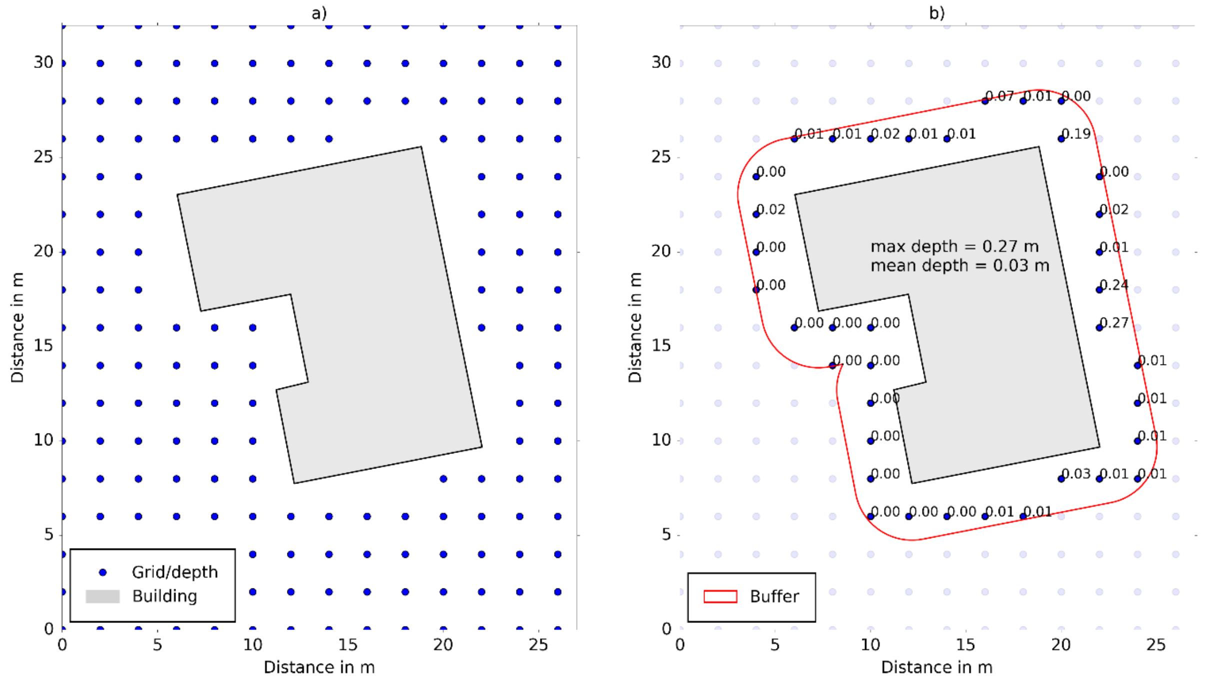


Figure 5.19 Concept of using a buffer to extract inundation depth from grid cells generated by a hydrodynamic model using the BH method.

Table 5.2 Classification scheme applied to assess the potential internal flooding likelihood of a building. The classification scheme presented can be adapted in the source code to accommodate alternative user needs.

class	*mean (m)*	*max (m)*	*internally flooded*
low	0.0 - <0.1	<0.3	no
medium	0.0 - <0.1	≥0.3	no
	≥0.1 - <0.3	<0.3	
high	≥0.1	≥0.3	yes

5.4.5 Tool workflow

Using a buffer analysis to generate the desired output requires a sequence of steps which have to be performed as schematically outlined in Figure 5.20. As shown the user provides the inundation depth grid layer and a building geometry layer. The tool automatically generates a buffer for each building with the size defined by the user. This must be done carefully as the buffer distance can have a considerable impact on the final results – see discussion 5.4.10. Generally a buffer distance equal to 150% of the horizontal resolution of the inundation depth grid is recommended. This ensures that only the cells, closest to the building footprint are spatially intersected. Following the calculation of the mean and maximum inundation depth for each buffer the output files are generated.

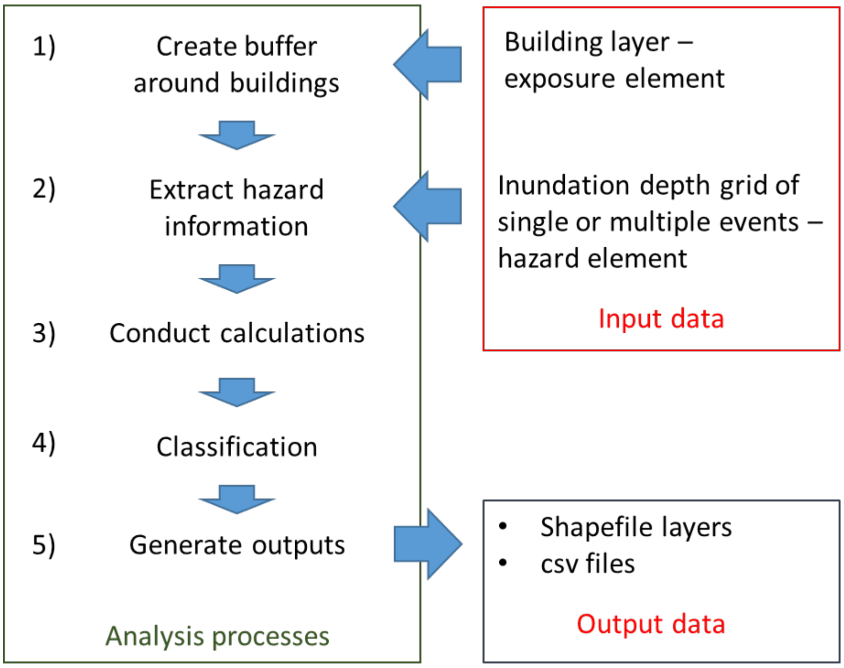


Figure 5.20 Schematic workflow of the analysis tool developed to assess the potential internal flooding likelihood of buildings.

5.4.6 Programming of the tool

To provide the exposure analysis tool as an open-source application Python (https://www.python.org/) and the Jupyter Notebook environment (http://jupyter.org/) were chosen. Jupyter Notebook is a browser based, open-source environment available under the modified BSD license (https://opensource.org/licenses/BSD-3-Clause). A single notebook can be written in different programming languages including Python. The live-code written inside a notebook can be enhanced using explanatory text, visualisation objects and interactive widgets. Jupyter notebooks therefore offer a range of beneficial features for the purpose of data handling, data analytics and visualisations. Python itself is a well-documented and popular programming language with an extensive library offering a range of modules required for the purpose of this tool. The exposure tool accepts common files in the form of .csv (Comma Separated Values) for the inundation depth grid and .shp (Shapefile) for the building geometries.

Input data

Before looking at the algorithmic part of the tool, this section introduces the requirements for the input data. All input files are stored in two folders as shown in Figure 5.21. The folder and filenames of each event as well as the building shapefile can be user specific. In the example shown in Figure 5.21 the folders are referred to as the ‘Events’ and ‘Buildings’ folder respectively.

The folder ‘Events’ contains the inundation depth grids of all flood events to be analysed. They are required to be in .csv (comma separated variable) file format. In each file, the first three columns are read by the tool where the first and second columns contain the X and Y coordinates of the cells and the inundation depth (in metres) is in the third column. Any additional column will be ignored.

The folder ‘Buildings’ contains the building shapefile layer. A building shapefile layer can be obtained from various sources such as the OS MasterMap data (Ordnance Survey, 2018) for the UK or any other open source data providers (*Geofabrik*, 2018; Open Street Map, 2018). Apart from the three mandatory .shp, .shx and .dbf files the projection file (.prj) is also required. It is crucial to have a unique identifier (ID) for each individual building polygon within the shapefile attribute table. This is used in order to conduct the classification. The name of the ID column can be user specific and will be selected through the user interface.

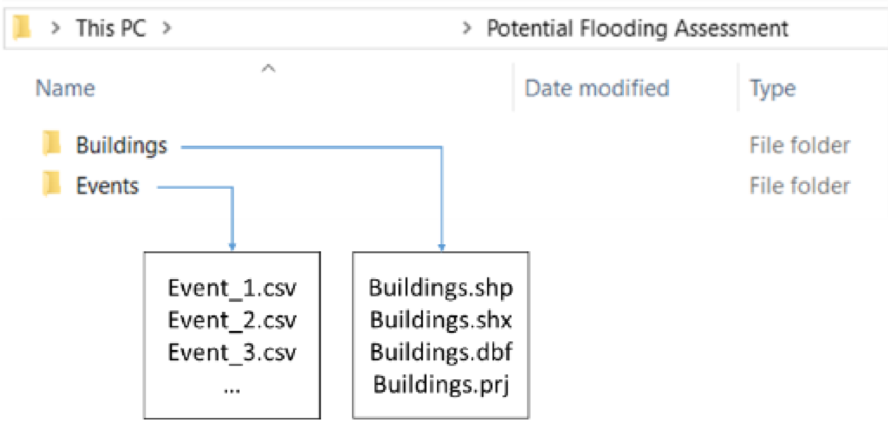


Figure 5.21 Folder structure required to apply potential internal flooding assessment tool.

Interface

The interface has been developed for the Jupyter notebook using the embedded widget functions. Figure 5.22 shows a snapshot of the interface developed. It contains four input fields for the analysis and a further two for the mapping function. The user pastes the path of the ‘Events’ folder and the file path of the building shapefile into field one and two respectively. Subsequently, by updating the drop down menu (point 3) it will be populated by all the columns found in the building shapefile attribute table. From this list the user selects the ID column. Finally a buffer distance (in % of the grid resolution) is specified in field four.

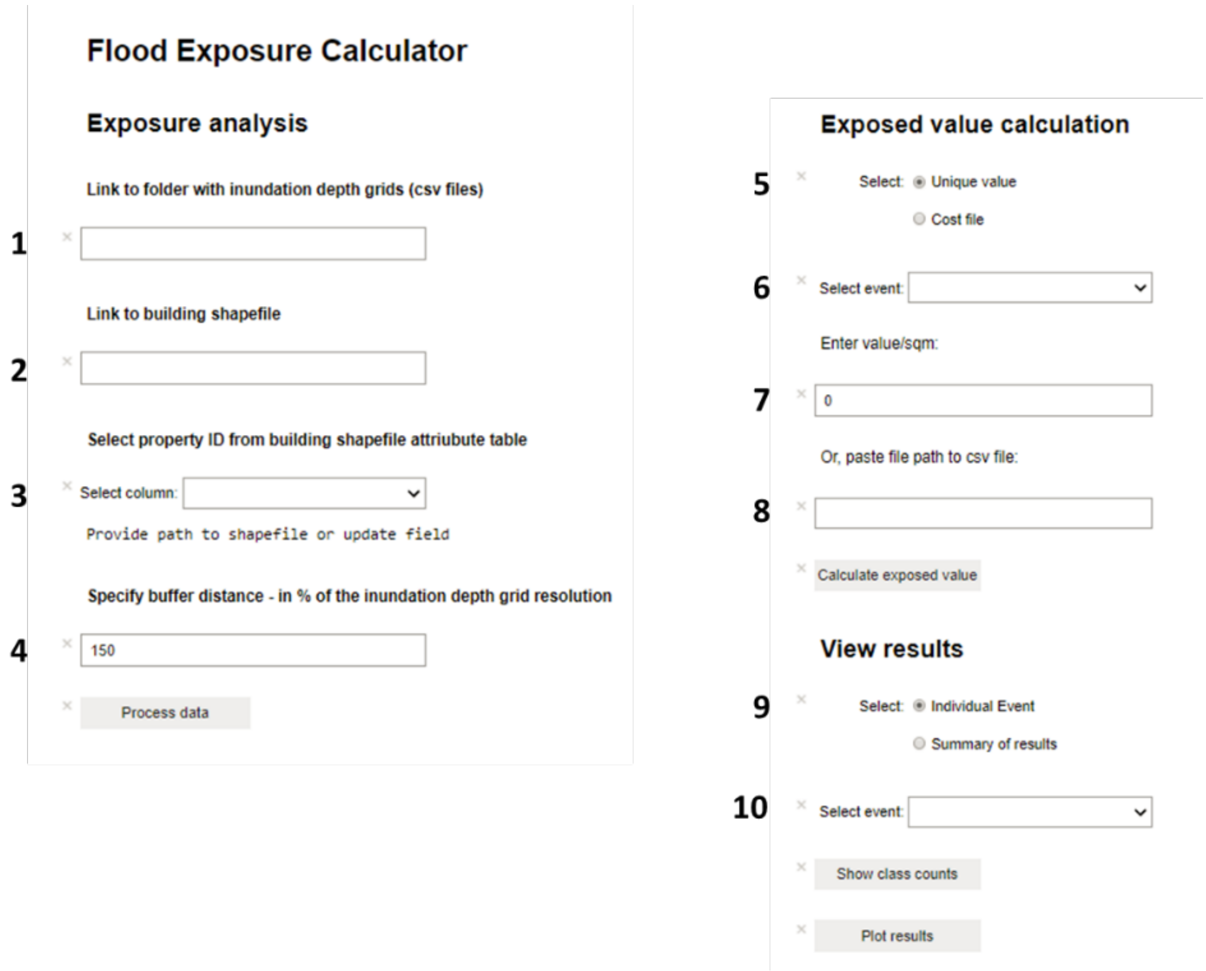


Figure 5.22 Snapshot of flood exposure tool user-interface in Jupyter.

Analytical steps

A number of automated processes are carried out by the tool as shown in Figure 5.23. Prior to any analytical processes three different output folders named ‘Outputs_Events’, ‘Outputs_Summary’ and ‘Outputs_Temp’ as shown in Figure 5.24 are generated automatically. The ‘Outputs_Temp’ folder contains temporary data files which are generated throughout the process and may be deleted after the completion of the analysis.

In a first step, a buffer shapefile layer is generated based on the building shapefile layer. Each buffer is assigned with the ID of the corresponding building. Second a point-based shapefile layer is generated for each event.csv in the ‘Events’ folder. Those event shapefiles are all stored in the ‘Outputs_Temp’ folder. Subsequently the buffer shapefile is applied for conducting the spatial intersection with each of the event shapefile layers (Arnott, 2014). In case a buffer polygon does not intersect with any points then the building is automatically assigned with the category ‘low’ in terms of internal flooding likelihood presented in Table 5.2. For each event an intersection .csv file is generated. Subsequently the intersected depths are grouped by the buffer ID and the mean and maximum inundation depth are calculated. Those two values are then assigned to the corresponding building polygon in a newly created copy of the building shapefile layer. Based on the mean and maximum inundation depths the classification according to Table 5.2 is conducted and assigned to the individual building polygons. Those results are also made available in .csv format and both the shapefile layer and the .csv file of the results are stored in the 'Outputs_Events' folder. In case there are multiple events to be analysed the processes are repeated for each event.

Finally, a summary file is created. For this summary file the tool iterates through all individual event results and counts how many times a building is classified as internally flooded in accordance with Table 5.2. The summary of the results are also provided in .shp and .csv format and stored in the 'Outputs_Summary' folder. Once the processing is complete a message under the 'Process data' button (Figure 5.22) informs the user about the total time required for conducting the analysis.

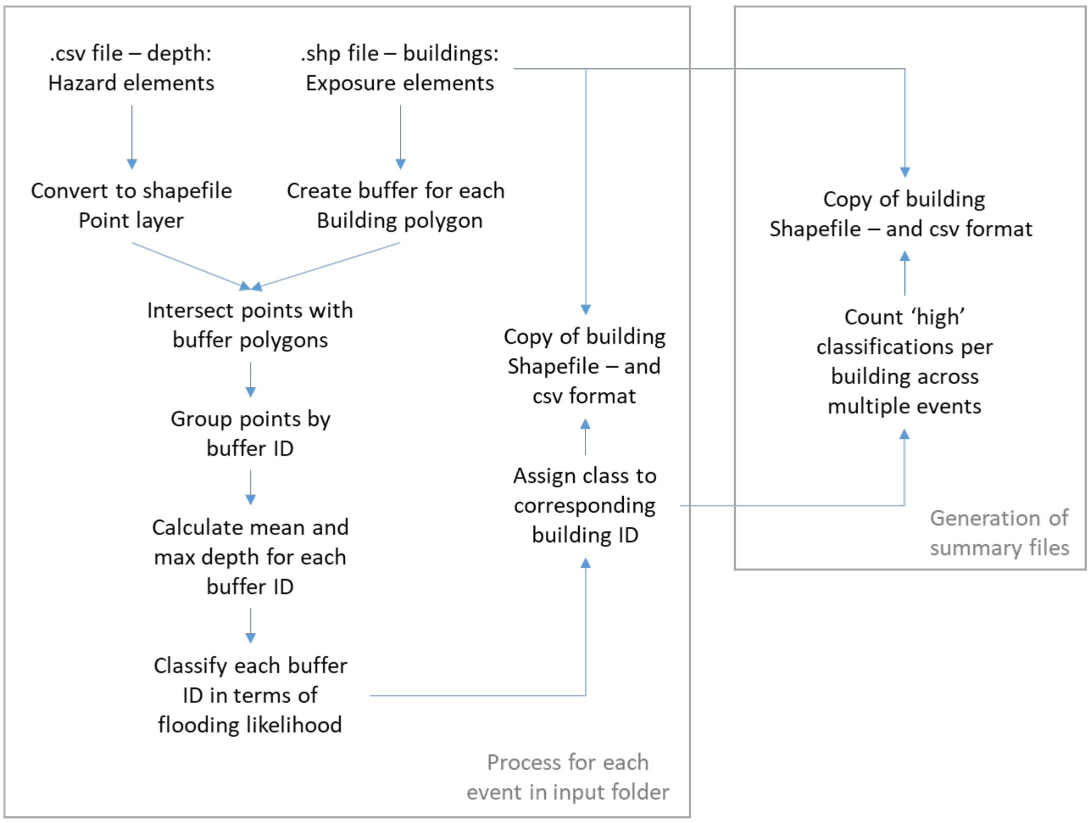


Figure 5.23 Workflow for assessing the potential internal flooding of buildings.

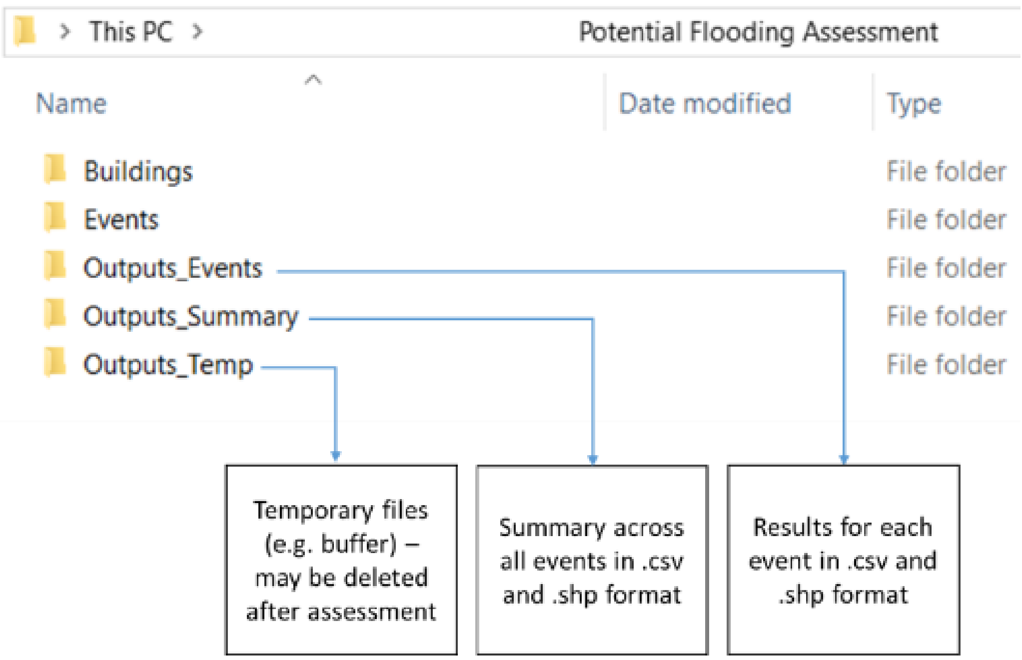


Figure 5.24 Automatically generated output folders and their content.

5.4.7 Exposure tool performance test

To analyse the performance of the flood exposure assessment tool three case studies are presented. Due to data constraints reasons the locations have been anonymised. However, it can be seen in Table 5.3 that the three urban catchments analysed are considerably different in terms of the number of grid cells and buildings. While area B and C are densely built-up cities, area A can be characterised as a village. For A and C the inundation depth grid has a horizontal resolution of 2 m x 2 m whereas B has a 1 m x 1 m horizontal resolution. Applying a buffer distance equal to 150% of the grid resolutions therefore results in a 3 m and 1.5 m buffer for area A, C and area B respectively. The hydrodynamic simulations were carried out using CityCAT.

Table 5.3 Computational performance of the flood exposure analysis tool for three case studies conducted.

	Number of grid cells (file size)	*grid resolution (m x m)*	*Number of building polygons*	*approx. run time (min)*
Area A	525,554 (15 MB)	2 x 2	1,644	3
Area B	2,600,205 (105 MB)	1 x 1	7,096	12
Area C	16,743,301 (474 MB)	2 x 2	157,718	75

All three case studies presented in Table 5.3 were run on a standard PC, 2.6 GHz Intel Core i7-5600 CPU with 8.00 GB RAM and a 64-bit Windows 10 operating system. As shown in Table 5.3 the time required to run the assessment required approximately three, 12 and 75 minutes for areas A, B and C respectively. The tool uses approximately 30% of the CPU throughout the process which is a Python specification. The most memory intensive process is the spatial intersection which required approximately 1GB RAM in case of area C. Most disk space is required for the temporary files as they include the shapefile of the buffer polygons and the point shapefile layer of each flood event. However, those files may be deleted after the analysis has finished.

5.4.8 Exposed value assessment

So far, the flood exposure tool has used only the bare information of building geometry and inundation depth. In order to demonstrate the adaptability of the tool towards specific user needs a simple monetary value assessment of the exposed assets is presented. For this purpose only internally flooded buildings according to the classification presented in Table 5.2 are considered. Furthermore, the exposed value is calculated based on a value/m^2 approach. The area (m^2) of each building polygon is automatically calculated during the analysis steps and can be found in the *_floodstats.csv file in the Outputs_Events folder – *denotes the filename of the corresponding event.csv file.

To calculate the damage, a single flood event is selected from the drop-down menu shown under point five of the interface (Figure 5.22). The exposed value can be calculated in two ways. First by entering a single value/m^2 under point seven of the interface. This value is subsequently applied uniformly on all internally flooded buildings and a total damage across all buildings is presented. This approach allows for a rapid approximation of the exposed building values.

Alternatively a more detailed, building ID dependent value/m^2 can be applied. This requires a separate .csv file which contains building ID and the specific value/m^2 in the first and second column respectively. The file path to this csv file has to be provided in field eight. The total damage is subsequently calculated after matching the *_floodstats.csv and the csv file containing the damage values using the building ID as a key. The advantage of applying the separate damage csv file is that different classes of building (residential, industrial, hospitals etc.) can be specified, or unusually valuable building contents can be accounted for.

5.4.9 Accessing results

Since the results are generated in .csv and .shp file formats they can be accessed and visualised by many widely used applications such as ArcGIS, QGIS, or Excel. Within the Jupyter notebook itself the results can be accessed in different ways. The exposed values calculated are presented instantly. Considering the results of the exposure analysis there are two ways of accessing the results. First, a tabular summary for each event can be generated. For this purpose a single flood event can be selected from the drop-down menu under point ten of the user interface. The table shows the total number of buildings in each internal flooding likelihood class for the selected event.

Second, a mapping function was developed. Fundamental to the mapping tool are the Geopandas and Matplotlib modules which are applied for reading and plotting respectively, the shapefiles. From the drop-down menu under point ten of the user interface (Figure 5.22), the user can choose between individual events or the summary layer. If an individual event has been selected, the map will show the results of the internal flooding assessment together with the corresponding inundation depth as backdrop (see example in Figure 5.25). For plotting the summary of the internal flooding analysis, the inundation depth backdrop map can be selected from the drop-down menu – point eight (Figure 5.26).

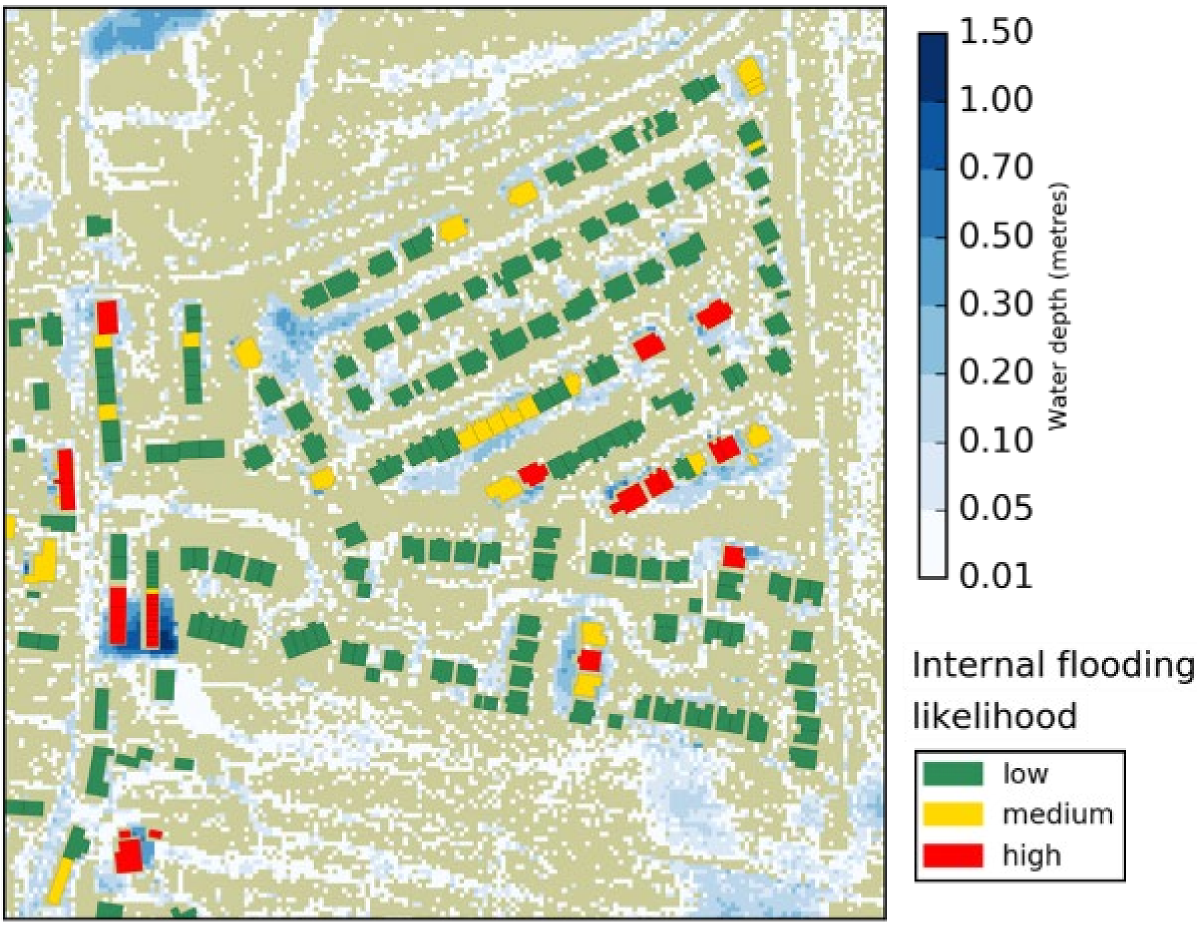


Figure 5.25 Map showing the results of an internal flooding assessment for a single event including the corresponding inundation depth as backdrop map.

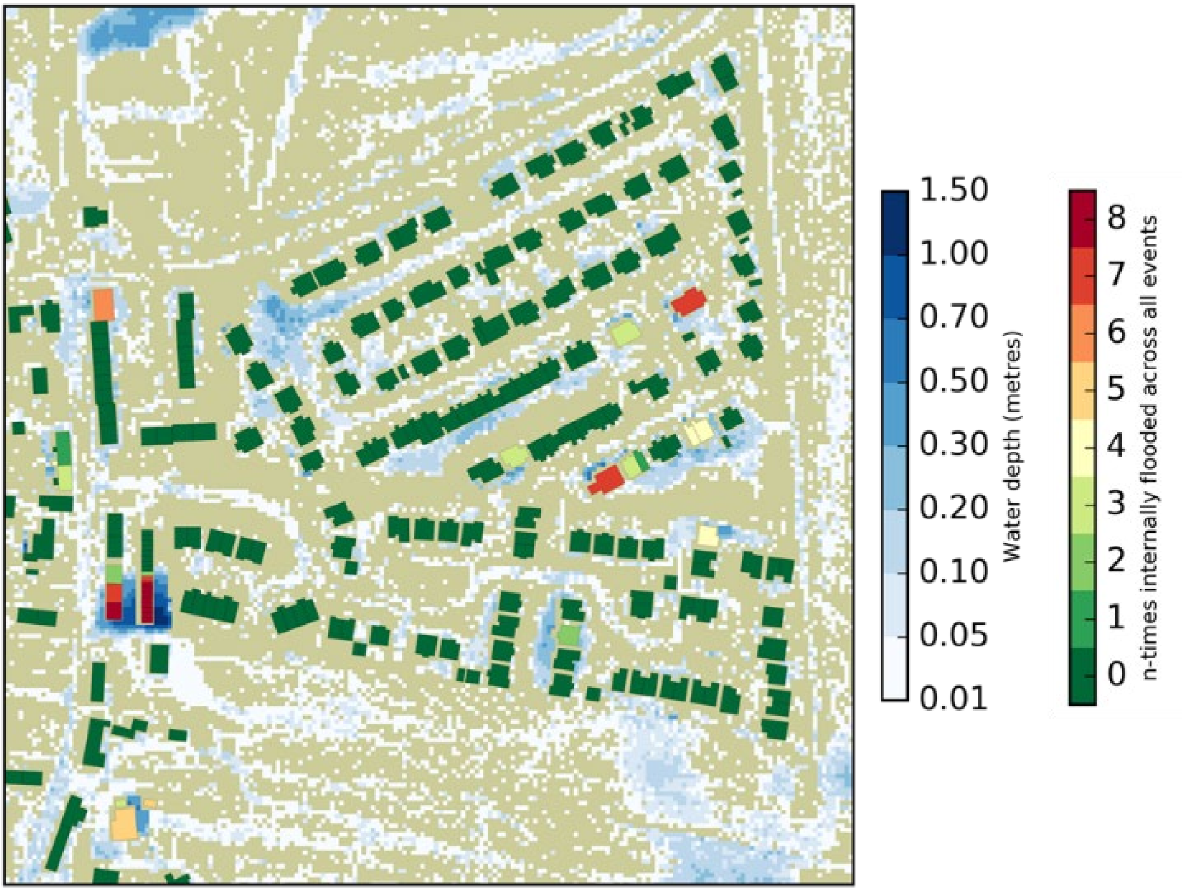


Figure 5.26 Map showing the cumulative results counting the number of occurrences of a building classified as internally flooded for all events analysed. Total number of events analysed in this example n=8.

5.4.10 Discussion and sensitivity analysis

Recent developments in 2D and 1D/2D hydrodynamic flood models have resulted in a step change in the availability of detailed flood maps for large urban areas. Simultaneously, insurers and lead flood authorities are looking for alternative analysis and visualisation tools to inform the decision making processes behind FRM to prepare for future challenges. To bridge this gap a flood exposure analysis tool has been developed to assess the potential internal flooding likelihood of buildings. Based on a buffer analysis, the tool applies an inundation depth grid with the exact geometry of buildings. This prevents a loss of information which occurs when aggregating hazard data or simplifying building geometries. The case studies presented in this paper demonstrate that the tool is capable of analysing more than 150,000 building as part of a single layer in combination with an inundation depth grid made of more than 16.7 million cells and a resolution of 2 m x 2 m. The generic nature of the tool makes it independent from the hydrodynamic model software which has been used to generate the inundation depth grid. This makes a validation of the exposure tool difficult as the exposure results are directly affected by the hydrodynamic model results. An in depth validation of the exposure tool would therefore require a validation of the hydrodynamic model used to generate the inundation depth grid in the first place. Nevertheless a validation of the exposure tool using real flood losses or incident data is the next objective for future work.

Sensitivity Analysis

Using high resolution data and exact building geometries implies that the analysis results are sensitive to changes in the classification scheme applied and other tool parameters. To illustrate this issue, a sensitivity analysis was conducted. Table 5.4 lists the definitions of four scenarios looking at different buffer widths and an alternative classification schemes to the one presented in Table 5.2. The results of the sensitivity analysis are presented in Table 5.5.

Table 5.4 Definition of scenarios A-D to conduct sensitivity analysis for: (a) different buffer widths and (b) classification schemes. Buffer width in % of grid resolution with $\Delta x = \Delta y = 2$ m.

Scenario	***buffer width***	***classification scheme***
A	150%	Table 5.2
B	300%	Table 5.2
C	150%	Table 5.2 – max depth only
D	150%	Table 5.6 – 0.15 m threshold for mean depth

Table 5.5 Results for scenarios A-D of exposure tool sensitivity analysis.

Scenario	***buildings per class***			***buildings***
	low	*medium*	*high*	*total*
A	1,528	70	46	1,644
B	1,526	89	29	1,644
C	1,429*		215	1,644
D	1,557	64	23	1,644

*For the maximum depth, the classification scheme in Table 5.2 only applies a single threshold value of 0.3 m and therefore low and medium is merged into one class.

Buffer distance

The process of extracting inundation depth information around building is inevitably sensitive to the value of the buffer distance. A buffer distance 150% of the horizontal resolution of the inundation depth grid has been proposed to extract the inundation depth off cells adjacent to the outside of the building geometry. A buffer distance less than 150% may lead to the risk of neglecting relevant cells in the analysis. If on the other hand a buffer distance greater than 150% of the inundation depth grid resolution is applied the analysis may include cells which are too far away from a building to be relevant.

To demonstrate the sensitivity of the analysis results due to the buffer distance, two different buffer distances of 150% and 300% were applied for a 2 m depth grid, thus resulting in buffer distances of 3 m and 6 m respectively. Based on the 150% buffer, 46 buildings have a 'high' likelihood of internal flooding (Table 5.5). In comparison the 300% buffer resulted in 29 buildings classified as 'high'. This reduction can be attributed to a change in the mean depth. The maximum depth can only increase or remain unchanged with the application of a wider buffer. For the mean depth however, additional cells extracted by the 6 m buffer can lower the mean depth which happened in this case. The impact of different buffer distances on the analysis results can also be seen in terms of the spatial distribution shown in Figure 5.27. In general this example demonstrates that the exposure analysis results are relatively sensitive to the buffer distance. Hence the selection of the appropriate buffer distance should be done carefully do minimise an over- or under-representation of the internal flooding likelihood.

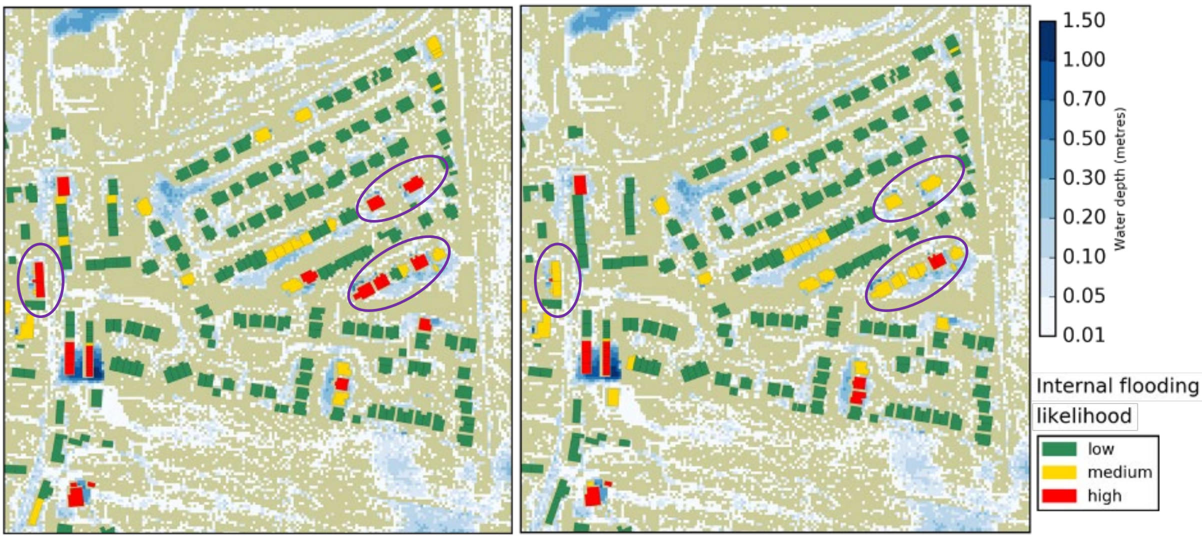


Figure 5.27 Impact on internal flooding assessment results as a consequence of different buffer distances: scenario A with 3 m (left) and scenario B with 6 m (right) for a 2x2 m grid.

Use of maximum depth only

Applying both the mean and maximum inundation depth for the classification as shown in Table 5.2 prevents the results from being skewed towards the maximum depth and hence the potential occurrence of outliers. To study the impact of deeply inundated cells on the internal flooding likelihood only the maximum depth inside the buffer was used. According to Table 5.2 the maximum depth only applies a single threshold value of 0.3 m. Consequently, the results presented in Table 5.5 have the classes low and medium merged into one. As shown in Table 5.5 using only the maximum depth leads to 215 buildings classified as highly likely to be internally flooded. This is a considerable increase compared to the 46 and 29 buildings of the previous scenarios.

Analysing the impact of outliers on the analysis results it is important to understand their origin. Outliers may be the result of individual, isolated erroneous cells in the terrain model causing large inundation depths. Such erroneous cells can be caused by the complex shape of a topographic features including buildings, vegetation cover and sudden changes in terrain heights (Meng, Currit and Zhao, 2010). Random measurement errors caused by other airplanes, birds or a malfunction of the measurement device may also lead to erroneous heights of individual cells (Meng, Currit and Zhao, 2010).

On the other hand a deeply inundated cell may of course be part of a larger surface water accumulation area posing a severe threat to the affected building. The spatial intersection method of a buffer analysis could therefore be adapted. First, the neighbouring cells around the most deeply inundated cells inside a buffer zone could be analysed to identify whether the cell is isolated or part of a larger accumulation area. Alternatively, a second buffer could be generated in order to spatially intersect a larger area around the building. A comparison of the extracted depths within the two buffer zones can help identify whether the hazard increases or decreases with a greater distance from the building.

Classification threshold values

The third sensitivity test concerns the threshold values applied in the classification scheme of Table 5.2. As mentioned, the 0.3 m threshold is an industry standard value for assessing the internal flooding likelihood. Hence, for the classification scheme of scenario D, the threshold of 0.3 m was still applied for the maximum depth but the mean depth threshold was changed from 0.10 to 0.15 m according to Table 5.6.

Changing the mean threshold value from 0.1 m to 0.15 m (Table 5.6) leads to a reduction of buildings highly likely to be internally flooded from 46 (scenario A) to 23 (scenario D) (Table 5.5). Analysing high resolution data, this example demonstrates that relatively little changes in the classification scheme – in this case 0.05 m – can considerably impact the result of the analysis.

Table 5.6 Altered classification scheme to assess likelihood of internal flooding for scenario D - Table 5.4

class	*mean (m)*	*max (m)*	*internally flooded*
low	0.0 - <0.15	<0.3	no
medium	0.0 - <0.15 ≥0.15 - <0.3	≥0.3 <0.3	no
high	≥0.15	≥0.3	yes

5.5 Conclusions

Fully coupled 1D/2D hydrodynamic modelling tools produce large quantities of results. In order to harness and access those results, this chapter introduced newly developed, open-source based visualisation and analysis tools which can be applied independently from the modelling platform or GIS software. The tools handle the raw data from standard formats such as csv-files and shapefiles. By only reading the desired information, large files (>1 GB) and entire time series can be processed automatically without the need to be previously imported into a GIS platform.

The first part of this chapter introduced a series of data visualisation tools. Combined with detailed results from fully coupled 1D/2D hydrodynamic modelling software such as CityCAT, the functions of the developed tools allow to:

- Identify potential areas of pluvial flooding by visualising surface water depth grid and flow vector fields for single time steps and time series.
- Assess locations of potential sewer flooding by visualising drainage performance of storm drain inlets and pressure inside manholes.
- Calculate the impact of change by comparing the surface water depth grids of different scenarios (e.g. 2D vs 1D/2D models).
- Analyse the critical spatial and temporal variability of the drainage performance of storm drain and the sub-surface drainage domain as a whole.
- Evaluate cause and consequence behind urban floods.

In the second part of the chapter, a generic, open-source flood exposure assessment tool for regular spaced inundation depth grids has been developed. Capable of handling large (up to 100 km^2) yet detailed grids (2 m x 2 m horizontal resolution) the tool can be applied on entire cities of more than 10^5 buildings. This allows users such as insurance companies, water utility companies or environmental agencies to harness the increasing availability of detailed 2D and 1D/2D hydrodynamic model results. Furthermore, the open-source Python code can be adapted in order to meet specific user requirements. This may include for instance a change of the classification scheme presented in Table 5.2 and Table 5.6. In a study presented by (Nie *et al.*, 2009) a threshold water depth of 0.9 m is applied to assess the risk of basement flooding. This is due the fact that house owners in Norway are required to build their basement at least 0.9 m above the drainage system in order to avoid frequent flooding.

The exposure analysis is based on a regular spaced inundation depth grid and a building geometry layer. Using the latter, a buffer is generated for each building polygon to subsequently extract inundation depth information. For each buffer the mean and maximum inundation depth are calculated based upon which a classification into the internal flooding likelihood is conducted. The internal flooding principle has been adopted from an industry standard approach.

The application of the common shapefile format for the building geometries adds to the wide applicability of the tool. As the results show, however, this is relatively time consuming. Future work will therefore focus on improving the efficiency of the tool. This also concerns the step of converting the inundation depth grid into a shapefile layer and the application of the current spatial intersection method. Crucially, the next steps should focus on validation and calibration of the tool introduced in this work. In its current version the tool applies only inundation depth as the hazard component. This could be extended in the future by including other hazard elements such as flow velocities and debris factors. A temporal dimension could be considered as well by including the duration of the exposure time. In order to increase the number of potential applications the tool could be adapted to handle non-regular spaced grids such as TIN (Triangular Irregular Network) meshes.

Regarding the damage calculation more detailed depth-damage functions could be applied instead of using single damage/area values. Applications of depth-damage functions can be found in a range of flood damage assessment tools including HAZUS-MH (Scawthorn *et al.*, 2006), FLEMOps (Thieken *et al.*, 2008) and FLEMOcs (Kreibich *et al.*, 2010b, 2010a) or the Multi-coloured Manual (MCM) (Penning-Rowsell *et al.*, 2005). Critically, depth-damage functions are often area and flood event specific as the number of people, properties and exposed values for instance change over time and between areas. Therefore depth-damage functions are difficult to transfer across in space and time between catchments (Merz *et al.*, 2010; Wagenaar *et al.*, 2016). Another important consideration using depth-damage functions is whether the mean or maximum depth flood depth is applied for the assessment as this would have considerable implications on the results.

By assessing the internal flooding likelihood of buildings thorough spatially intersecting a hazard and exposure element, the developed tool could be adapted and applied on other features of the urban fabric. This may include the curtilage of buildings looking at the aspect of external flooding. Alternative areas of application could be the impact analysis of flood s on roads or other elements of the infrastructure.

Chapter 6 Practical implications of an industrial application of new developments

6.1 Introduction

The thesis so far has focused on technical aspects related to new capabilities of a flood and urban drainage model. In doing so, the thesis has shown the usefulness of CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018) and its fully coupled flood modelling approach allowing analysis of pluvial and sewer flooding in a single model. The need for high resolution data to link the surface and sub-surface network in the form of storm drain inlets was also highlighted. Furthermore, the requirement for post-processing analysis and visualisation tools capable of handling large and detailed model results was demonstrated.

Exploring a potential future industrial application of CityCAT however has a series of further implications. From a managerial perspective this mainly concerns the impact and resources required in relation to the current way of conducting business. The purpose of this chapter is to highlight practical and financial implications of implementing and applying CityCAT in combination with the thesis deliverables: (a) the methodology to generate synthetic networks of inlets, (b) the mapping scripts and (c) the flood exposure analysis tool.

A full scale industrial implementation and application of CityCAT requires detailed planning and a wide-ranging analysis of factors such as model licensing, model ownership, legal responsibilities or the development of a detailed modelling strategy. To stay within the scope of this project of focusing on the practical implications such detailed planning is not feasible at this stage. Instead, a strategic-level options appraisal was conducted to identify the most practicable initial route for using CityCAT in an industrial environment. To support the options appraisal the chapter identifies the business areas which are expected to benefit most from an application of CityCAT from a practical and financial perspective. This also includes a cost estimation of a CityCAT model to demonstrate the monetary benefits of the: (1) model building process using automated functions and (2) model simulation on the cloud.

This management chapter is part of the specific requirements of an Engineering Doctorate degree through the STREAM-IDC program. The chapter is aimed at end-users conducting urban flood modelling on a regular basis and the industrial flood modelling sector as a whole.

6.2 Options appraisal

An options appraisal is a method to compare different options for the purpose of achieving an objective (Scottish Government, 2016). The aim of the options appraisal conducted in this work is to assess the feasibility of three different levels of implementing CityCAT as a flood modelling tool at industry based end-users. The details of the options appraisal are presented in Appendix B. In summary, the appraisal considered the following three options:

A. Do nothing option: CityCAT will not be considered at all
B. Fully replace existing modelling tools with CityCAT
C. Additional application of CityCAT on specific selected case studies and situations

From the option appraisal (Appendix B) it was concluded that the most practicable option of implementing CityCAT is Option C. This option allows a company to use CityCAT on specific case studies which are expected to benefit most. Those will be presented in section 6.3.

An additional application of CityCAT means that existing modelling strategies and the associated financial investment and knowledge gathered are not compromised. In fact it allows users to benefit from the best of both worlds as shown in Figure 6.1. The fast simulation times of commercial modelling tools can assist in: (1) identifying areas of potential sewer flooding or (2) areas of pluvial flooding with an initial 2D surface only simulation. A fully coupled CityCAT model could subsequently be applied to investigate in more detail cause and consequence of flooding by modelling both pluvial and sewer flooding in a single model. While certain data from the initial model runs can be used for CityCAT (e.g. converting InfoWorks models), missing data such as storm drain inlets can be generated synthetically.

The implementation of CityCAT as an additional modelling tool ensures that stakeholders involved, such as water utilities or local authorities, meet their duties and responsibilities related to FRM. At the same time they get a more fundamental and deeper understanding of the hydraulic dynamics of the system through the application of fully coupled 1D/2D CityCAT models.

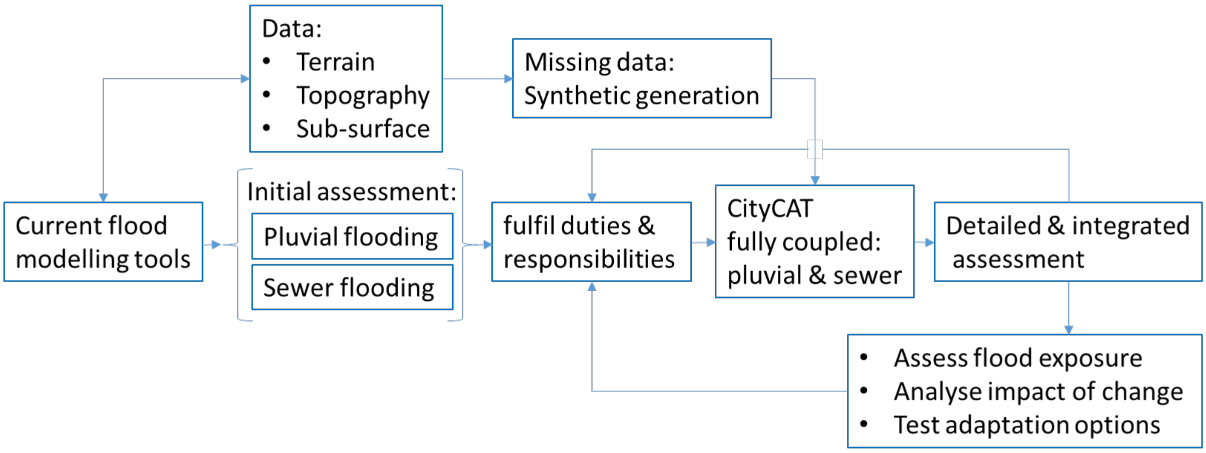


Figure 6.1 Complementary application of CityCAT to existing modelling tools uses the best of both worlds: fast run times of commercial modelling tools for initial assessment and detailed, fully coupled modelling in CityCAT.

6.3 Business areas benefitting from new developments

The current state-of-the-art flood modelling analysis methodologies adopted across the water sector are well tested and have been applied for a long period of time. As highlighted in the literature review in chapter 2, the current modelling methodologies have intrinsic limitations to address and meet some of the challenges and requirements of future flood modelling. In order to support the conclusion from the options appraisal this section identifies the different business areas across the water sector which are expected to benefit from an additional application of CityCAT.

6.3.1 Practically – effective analysis of urban flooding

Driven by recent changes in governance and legislation seeking a more integrated assessment and management of floods, end-users of flood models are encouraged to explore and consider alternative modelling tools in order to meet their duties and responsibilities. Effective modelling tools are required to simulate the entire urban drainage system more realistically allowing users to gain a more holistic understanding of the mechanisms behind floods and to enhance informed decision making. From a practical aspect, Surface Water Management Plans (SWMP) and Integrated Catchment Studies (ICS) are specific examples which are expected to benefit from using CityCAT.

A SWMP is a strategic-level approach with the aim to deliver information on the situation of flooding in a pre-defined area in order to support the management of surface water using sustainable measures (Scottish Government, 2013). The ICS are a collaborative approach between the responsible authorities Scottish Water, SEPA and the local councils to support detailed planning for a SWMP. A core element of the ICS is the detailed modelling of the urban drainage system. For this purpose InfoWorks ICM is used. However, as outlined in chapter 2, the modelling strategies built around InfoWorks ICM may have limitations particularly related to: (1) detailed modelling of pluvial flooding, (2) application of large numbers of storm drain inlets and (3) the separation of the hydrological and hydraulic phase.

Another key element of a SWMP is a risk based approach i.e. modelling the hazard of floods and the impact on people and properties (Scottish Government, 2013). Delivering a SWMP would therefore benefit from the combined capacity of CityCAT and the developed flood exposure tool of providing detailed assessment of both the flood mechanisms and the element of risk. Table 6.1 highlights the specific features of CityCAT which are expected to benefit some of the specific goals of the SWMP and the ICS strategies.

Table 6.1 Specific SWMP and ICS objectives benefiting from modelling & analysis capacities of CityCAT & tools developed. For the SWMP and ICS objectives see Scottish Government (2013).

SWMP and ICS objectives	Capacity of CityCAT
Increase amount of permeable surfaces	• CityCAT explicitly simulates permeable and impermeable surfaces • Surface types are easily adaptable for a CityCAT model • Impact of increased infiltration on flood depth, flow vector field as well as flood risk can be assessed with CityCAT and the analysis tools developed
In situ handling of stormwater runoff from permeable surfaces	• Blue-green features are simulated directly in CityCAT, e.g.: green roofs, altering surface types, swales by adapting the terrain model • Impact of stormwater runoff measurements on flood depth, flow vector field as well as flood risk can be assessed with CityCAT and the analysis tools developed
Minimise the amount of water drained into the sub-surface system and maximise options to deal with surface water before it drains into the sub-surface system	• Detailed modelling of surface water runoff pathways entering storm drain inlets → understanding where water comes from and where it enters the sub-surface system

	• Fully integrated and coupled modelling of surface, sub-surface domain in combination with blue-green features • Impact of adaptations to surface and sub-surface system on flood depth, flow vector field, drainage performance of inlets as well as flood risk can be assessed with CityCAT and the analysis tools developed
Fully integrated ICS models to support detailed SWMP	• CityCAT simulates pluvial and sewer flooding in single model

6.3.2 Financially – efficient analysis of urban flooding

The application of CityCAT is also expected to have a positive financial impact due to: (1) efficient model building processes and (2) the capacity to use cloud computing for model simulation. A generic comparison of the time and costs for building and running a model in CityCAT and commercial modelling tools is summarised in Figure 6.2.

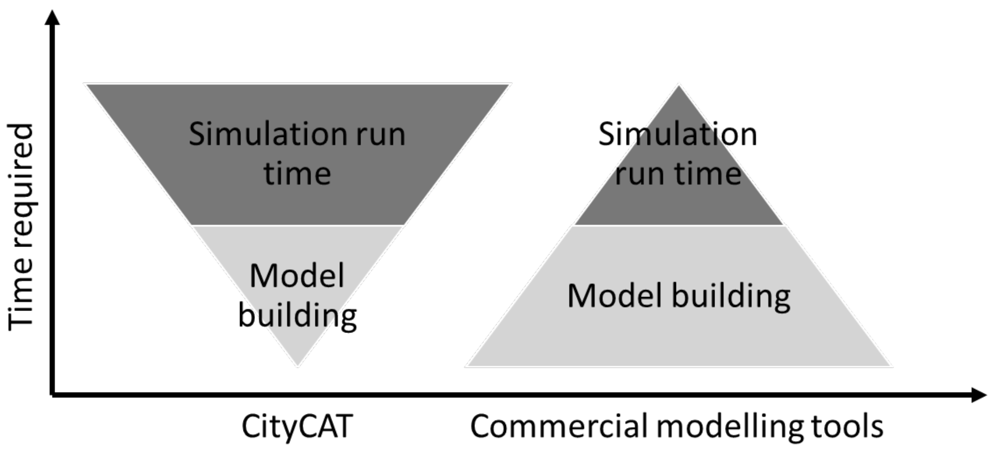


Figure 6.2 Generic time required for model building and simulation of models. Most model building processes in CityCAT are done automatically reducing the time required for the modelling whereas commercial 1D/2D modelling tools involve multiple manual steps and parametrisations (e.g. sub-catchment delineation and 2D mesh refinement). The run times of commercial modelling tools on the other hand are faster compared to CityCAT.

As shown in Figure 6.2 commercial modelling tools generally require more time to build a model compared to CityCAT. This is because they often involve multiple processes which have to be done manually. Particularly labour intensive in this context are: (1) discretisation and parametrisation of sub-catchments, (2) defining flood volumes for manholes, (3) refinement of 2D TIN mesh and (4) assigning head/discharge curves to sub-surface network nodes. According to Gibson et al. (2016), the mesh refinement process for an InfoWorks ICM model may take several months in case of a large and detailed modelling domain. Furthermore, the model building and simulation of models is generally completed inside the same software package such as InfoWorks ICM. This means that software end-users are dependent on a single software supplier limiting the use of alternative solutions.

The open software architecture in CityCAT on the other hand allows users to optimise the flood modelling and analysis process by choosing alternative solutions for the model building, model simulation and model analysis (Figure 6.3). The model building process benefits from different automated tools based on freely available open-source tools including: (1) application of open-source GIS to convert sub-surface network data from GIS data or other flood models and to automatically delineate catchments, (2) specifically developed parsers for extracting buildings and permeable surface areas from GML (Geography Markup Language) or shapefile data, (3) synthetic method to generate missing storm drain networks and (4) automated building of computational grid in CityCAT.

CityCAT as an open architecture modelling software also means that it does not require any specific post-processing tools. Instead the model results in CityCAT are provided in the standard file formats csv and txt. This allows users to apply freely available open-source tools as presented in Chapter 5 to conduct further analysis and to visualise the model results.

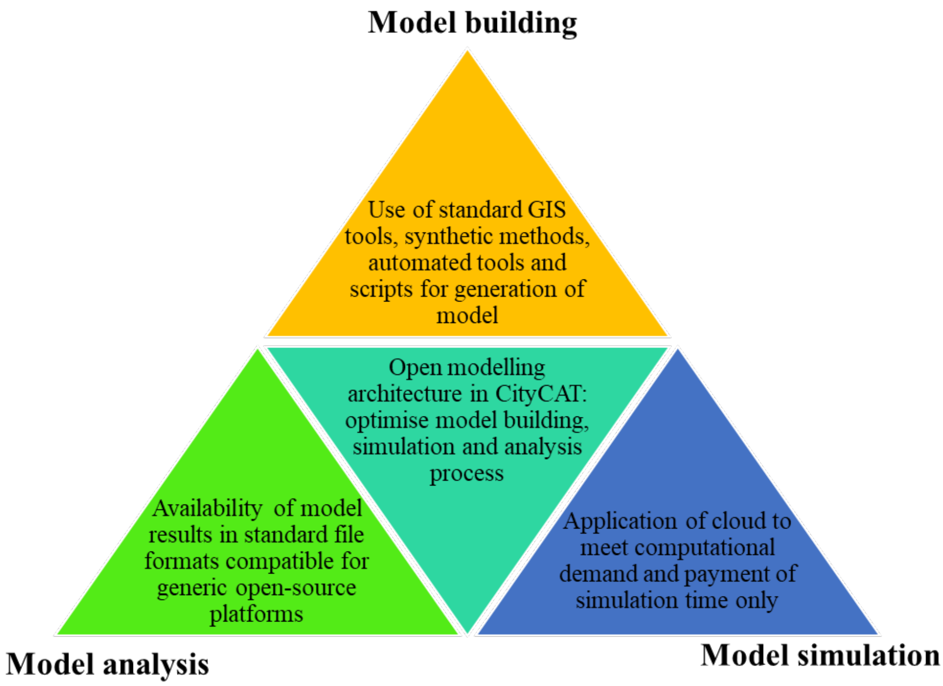


Figure 6.3 Open software architecture of CityCAT enables users to choose from alternative solution optimising the flood modelling and analysis process.

In contrast to the model building process, commercial modelling software packages generally have lower simulation run times compared to CityCAT. In particular semi-distributed modelling tools which rely on: (1) the sub-catchment/manhole approach, (2) limited simulation of 2D areas for simulating sewer flooding and (3) the Preissmann scheme to simulate pipe flow. The detailed, fully coupled modelling approach of CityCAT which explicitly simulates manholes and inlets is computationally much more demanding.

To meet the computational demand, CityCAT can be deployed on the cloud (Glenis *et al.*, 2013; Glenis, Kutija and Kilsby, 2018). In fact the cloud has two particular benefits for flood model simulations: (1) the scalability of the Virtual Machine (VM) and (2) the pay as you go payment scheme. A VM basically mimics a computer platform on the cloud which can be configured to host a software. The Microsoft Azure cloud platform for instance offers VM's with different configurations ranging from 1 core with 0.75 GB RAM to 64 cores with 432 GB RAM (Microsoft Azure, 2017).

From a financial aspect the application of the cloud benefits twofold. First, the scalability of the computational resource and the payment in form of a pay-as-you-go scheme with offers the flexibility to balance demand and costs. And second, on the cloud only the consumed time has to be paid. Commercial modelling license subscriptions are often fixed rates. The annual maintenance costs for InfoWorks ICM for instance can be up to £6,844/year[2] with an initial one-time license payment of £45,624[2] (Macdonald, 2013). The annual maintenance fee of £6,844 has to be payed regardless of the time spent on using the software and regardless of the purpose of application i.e. model building or model simulation. An open architecture modelling software like CityCAT on the other hand allows users to conduct all pre- and post-processing of data in open-source software locally on a laptop or PC while the cloud is exclusively used for the actual model simulation. The Microsoft Azure cloud VM A10 with 8 cores and 56 GB RAM (more powerful than standard PC's or laptop's) for instance has a price rate of £0.874/hour (Microsoft Azure, 2017). For the price of a single InfoWorks ICM license of £6,930 per year, the VM A10 could be used 7,929 hours or 330 days for model simulations only. Since hydraulic modellers also have to invest time for data gathering, model building, analysis of simulation results and writing reports (see also Table 6.2), one VM may suffice multiple users.

6.4 Costs of building and using a CityCAT model

This section provides an estimation of costs for building and running a CityCAT model based on a case study. Two different model set-ups are compared using a surveyed and synthetically generated network of storm drain inlets respectively.

6.4.1 Model building

The catchment has an area of 2.1 km^2 and the computational grid has a horizontal resolution of $\Delta x = \Delta y = 2$ m. The pipe network with a length of 10.9 km and 294 manholes were converted from an InfoWorks CS model and required approximately two days to fill missing data.

A field survey was conducted to record the locations of storm drain inlets. In total approximately 15 km of road were surveyed with a total of 634[3] storm drain inlets recorded. The surveying of the 634 inlets took about two days. Four days, including preparation time, computing and post-processing of the surveyed data. The surveying costs can be described as a function of the area or distance and the number of inlets. Hence, the larger the domain and the more inlets to record the longer the survey time. Although several other factors influence

[2] £6,844 and £45,624 were converted from $9,000 and $60,000 respectively in Macdonald (2013) with exchange rate of 0.7604 from 18/09/2018 (https://www.bankofengland.co.uk).

[3] Not all of the 634 inlets surveyed were used in the modelling presented in chapter 4 because the surveying area covered more than simulated catchment.

the actual survey time (e.g. terrain, topography, experience, equipment and weather conditions) the relationship can be approximated as linear shown in Figure 6.3.

In comparison, the generation of a synthetic network for the same area following the method presented in chapter 4, took approximately five hours. This includes the simulation of the 2D CityCAT model (one hour) and the data pre- and post-processing (four hours) and. The data used for the 2D simulation are subsequently applied in the 1D/2D simulation. Hence they do not add further costs.

Crucially, compared to a surveyed network of inlets the time required for generating a synthetic network increases at a lower rate with the catchment area or number of inlets (Figure 6.4). First, because the model building and simulation time for a 2D CityCAT model does not increase linearly with the size of the catchment. And second, the post-processing of the 2D model results and the actual delineation process following the method in Chapter 4 only increases marginally as the domain size increases.

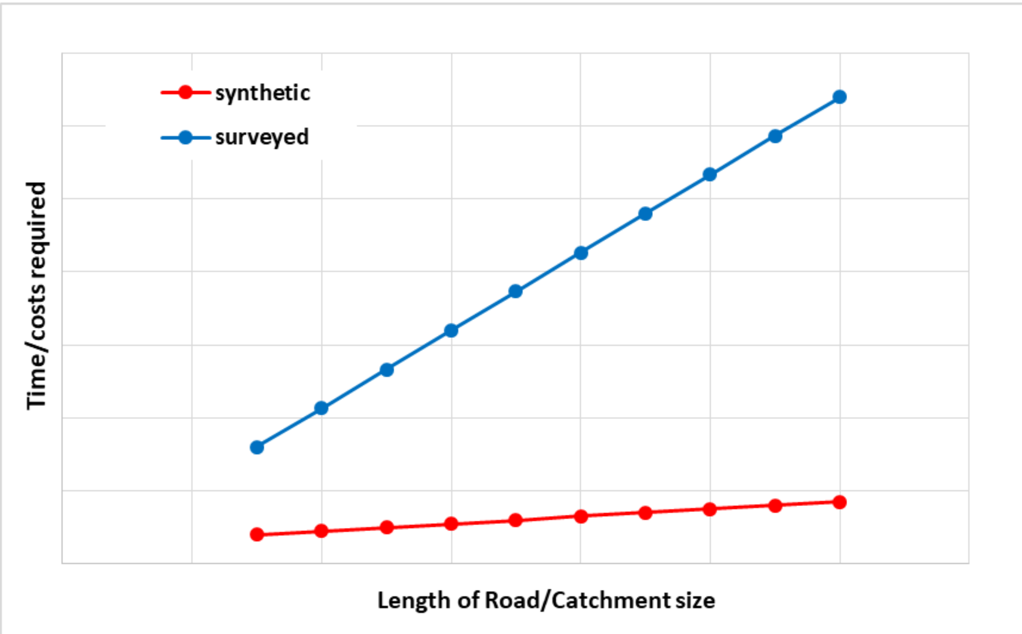


Figure 6.4 Schematic representation of the relationship between catchment size and time required to generate a surveyed network of storm drain inlets (blue line) and a synthetic one (red).

6.4.2 Model simulation

The 2D simulation for the delineation of a synthetic network of storm drain inlets – was done on a laptop with 2 cores and 8 GB RAM. The simulation time was approximately 60 minutes. Applying a VM with similar specification formed of 2 cores and 8 GB RAM (D2-v3 on the

Azure cloud) comes at a cost of £0.156/hr (Microsoft Azure, 2017). Hence, running a single 2D simulation for this particular case study area on the cloud costs £0.156 in total.

Simulating the final 1D/2D CityCAT model for the case study was done on a University server with the configurations of 4 cores and 28 RAM. For the simulation of a 60 minutes rainfall event with a 50 year return period the run time was approximately 39 hours. The VM A6 with the same specification as the server has a cost of £0.492/hour (Microsoft Azure, 2017). Hence running the WM A6 for 39 hours results in a total simulation costs of £19.2.

Table 6.2 presents a summary of the time and costs required for building and running the two models introduced. Although the catchment of the investigated case study are is relatively small, the model based on the surveyed inlet network is 2.4 times more expensive compared to the synthetically generated network model. Combining the observations from Figure 6.3 and the results from Table 6.2 suggests an increasing financial benefit of synthetically generated networks of storm drain inlets as the length of roads to be surveyed increases. The choice between a surveyed and synthetic network of storm drain inlets however should not be primarily a question of money but of the purpose of the analysis and modelling conducted.

Table 6.2 Summary of time and costs required for building and running a CityCAT model based on synthetic and surveyed networks of storm drain inlets. Costs are calculate with: [a]hydraulic modeller salary of £16/hour and cloud rates of: [b]£0.156/hour and [c]£0.492/hour. Time and costs for collection other data are not included.

	CityCAT model using synthetic network of storm drain inlets		***CityCAT model using surveyed network of storm drain inlets***	
Item	*Time (hrs)*	*Costs (£)*	*Time (hrs)*	*Costs (£)*
Converting InfoWorks CS model data (includes completion of missing data) [a]	16	256	16	256
Data preparation (catchment delineation, rainfall data, extracting buildings and permeable surface areas) [a]	2	32	2	32
Generating synthetic network of storm drain inlets [a]	2	32	N.A.	N.A
2D simulation for synthetic network generation [b]	1	0.156	N.A.	N.A
Surveying inlets [a]	N.A.	N.A	32	512
1D/2D simulation [c]	39	19.2	39	19.2
Total	***60.0***	***339.4***	***89.0***	***819.2***

6.5 Requirements

Having identified the major practical and financial benefits to be expected from an additional application of CityCAT, this section outlines the key requirements for a successful implementation.

6.5.1 Data

From a practical perspective, data quality and quantity related issues are amongst the biggest challenges for conducting flood modelling analysis. The specific problem of missing storm drain inlets in detailed fully coupled 1D/2D models has been highlighted in Chapters 3 and 4. Terrain and topography data on the other hand have become less of an issue in recent years, as at least in the UK, high resolution LiDAR (DEFRA, 2018) and OS MasterMap (Ordnance Survey, 2018) data are generally available for most urban areas. Alternatively, Open Street Map topography data can be used (Open Street Map, 2018).

Working on the development of the method to generate synthetic storm drain inlets (Chapter 4) and the simulation of CityCAT models presented in section 6.4 this thesis revealed that other sub-surface network data about pipes and manholes were sometimes also missing. In the past, information about the network was stored analogue in form of maps and has to be carefully digitised for use in hydrodynamic models. Analogue maps however may have gone missing over the years. Also, change in network ownership might have interfered with a continuous data collection and storage. Furthermore, surveying and collecting information about in situ sub-surface assets such as pipes is more complex and requires more resources compared to above-ground features such as inlets.

As shown in Chapter 2, the data required for generating and running a hydrodynamic model is to a large extent determined by the specific modelling approach and software used. Common modelling methodologies such as the sub-catchment/manhole approach allow users to work around missing data by altering model parameters or by merging data. Although this may allow to run a hydraulic simulation, the overall data quality and quantity of the network does not meet the requirements of fully coupled flood models.

On a short term basis but crucially with a continuous effort, the issue of missing data an enhanced data collection and data management ought to be addressed. This also concerns measured flow data for the important aspect of model validation. Alternatively, to the collection of data from the field, synthetic sub-surface networks could help fill the gap. This would require new methods such as the one presented in Chapter 2 for synthetic storm drain inlets.

6.5.2 Computational resource

As mentioned earlier, the simulation of detailed flood models in CityCAT requires powerful computational resources. The actual simulation time depends on multiple factors including the size of the model domain, resolution of the terrain model, number of inlets, manholes, and the occurrence of pressurised pipe flow, the intensity of the rainfall event simulated and the complexity of topography and terrain. While smaller domains and less complex 1D/2D CityCAT models can be run on a single Laptop or PC, large scale catchments require alternative solutions.

On a medium to long term scale the development and operation of a cloud based CityCAT platform is therefore desirable. The schematic diagram in Figure 6.4 shows the principal structure and operational elements of a potential CityCAT platform on the cloud. The participating stakeholders provide data to generate CityCAT models. Missing data such as storm drain inlet locations or sub-surface network data are generated synthetically. To limit the use of cloud time those steps can be done on a local PC or laptop using open source GIS software for instance. The actual model simulation is conducted on the cloud. Upon completion of a simulation, the model results can be downloaded for further analysis using the flood exposure tool for instance. Modelling on the cloud offers the additional benefit as the involved users and stakeholders have a single access point to the model results helping in the communication and exchange of information and data.

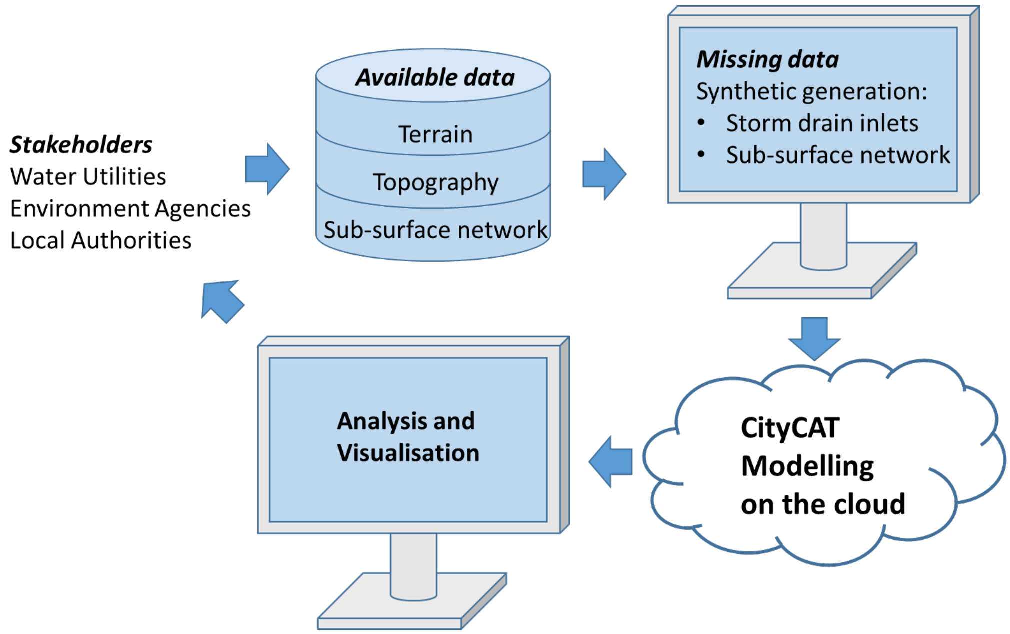


Figure 6.5. Concept of cloud based CityCAT platform: The different stakeholders involved in urban flood modelling provide the data they have available to generate a CityCAT model. Missing data will be generated synthetically. The actual hydrodynamic modelling is conducted on the cloud. The model results can be downloaded or accessed from the cloud for further analysis and visualisation.

6.6 Conclusions

The aim of this management chapter was to highlight practical and financial implications of a potential industrial application of CityCAT and the deliverables of the thesis including: (1) the methodology to generate synthetic networks of storm drain inlets, (2) the mapping scripts and (3) the flood exposure analysis tool. An options appraisal was conducted which identified an additional application of those new technologies to current modelling tools as the most practicable way forward.

Effective modelling of urban floods in CityCAT due to fully distributed and fully coupled models is particularly beneficial for practical applications requiring a city-wide assessment of: (1) pluvial and sewer flooding, (2) detailed modelling of surface water runoff pathways (3) detailed modelling of drainage performance of storm drain inlets and (4) flood hazard and flood risk. Specific examples for potential future applications in this context are SWMP and ICS.

As an open architecture software CityCAT allows for an optimisation of the model building, model simulation and model analysis phase. This makes end-users less dependable on a single software supplier. The model building process in CityCAT benefits from a series of automated functions: (1) catchment delineation in open-source GIS, (2) specifically developed parser to extract buildings and permeable surface data from GML or shapefile data, (3) synthetic generation of storm drain inlet networks in open-source GIS and (4) generation of the computational grid inside CityCAT. All CityCAT model results are produced in the standard file formats csv and txt making them compatible for various post-processing tools – including the ones developed in this thesis.

Another benefit of CityCAT as an open architecture software is the availability of a stand-alone modelling engine and its capacity to be deployed on the cloud for the sole purpose of model simulation. Pre- and post-processing of model data on the other hand is done locally on a laptop using open-source tools. In combination with the pay-as-you-go scheme of cloud services the time and hence costs for model simulation can be reduced to a minimum. In contrast, commercial software licenses often have fixed annual subscriptions rates regardless of how much the software is actually used.

Applying cloud computing is likely to become an inevitable part of future flood modelling as the demand for high performance computing is constantly growing (Glenis *et al.*, 2013). Already today commercial flood modelling software suppliers have started to explore and offer cloud versions of their flood models (Jacobs, 2018). With CityCAT, end-user have the rare chance of embracing technological advancement on all levels of the flood modelling and analysis process: (a) modelling approach, (b) model building, (c) model simulation and (d) model analysis.

Chapter 7 Retrospective, conclusions and outlook

7.1 Introduction

Recent developments in the field of urban flood modelling have produced fully coupled 1D/2D hydrodynamic modelling tools like CityCAT – City Catchment Analysis Tool (Glenis, Kutija and Kilsby, 2018) offering effective and efficient simulation of the holistic problem of urban flooding in a more realistic way. Implications of past modelling methodologies on the current modelling environment and data management however limits the application of new developments. Delivering practical solutions for end-users to address those limitations the aim of this thesis is to explore new technologies for the simulation and analysis of urban floods including:

- CityCAT (Glenis, Kutija and Kilsby, 2018), a newly developed fully coupled flood model was applied for conducting high resolution flood simulations.

- Surveying techniques were used to collect field data of storm drain inlet networks for validation purposes.

- Cloud computing was utilised to demonstrate the practical and financial benefits for running flood model simulations.

- A new methodology was developed for generating synthetic networks of storm drain inlets.

- Open-source coding platforms Python and Jupyter were applied to develop stand-alone and modelling-platform independent mapping and analysis tools.

In this final chapter, the major findings of the thesis are presented. Subsequently, they are discussed in the context of a potential step-change in the approach and perception of integrated urban flood modelling for the water industry as a whole.

7.2 Conclusions against objectives

This section presents the major findings of the thesis related to the objectives which were defined in the introduction chapter.

Objective 1: Highlight the major drivers for integrated urban flood modelling

Outcome: First, recent legislation such as the EU Floods Directive (Directive 2007/60/EC) or Flood Risk Management (Scotland) Act 2009 seek a more integrated approach encouraging stakeholders to collaborate rather than working side-by-side. As a result, specific duties and responsibilities were assigned for the individual stakeholders in the context of FRM.

And second, environmental changes like climate change and urban growth have also driven the need for new modelling tools. With a growing urban population, more people are potentially exposed to the hazard of floods. Intensifying storm events (see for instance Chan et al. 2018) as well as increasing impermeable surface areas (see for instance Skougaard Kaspersen et al. 2017) affect the hydrological regime of cities by generating more quantities of surface runoff. In response to those emerging challenges blue-green features and SUDS have to be assessed in integrated flood models before their implementation.

Conclusion: Legislative and environmental changes are main drivers seeking solutions to simulate the urban drainage system more holistically in fully coupled flood models demanding advanced flood modelling concepts and technologies of the 21st century.

Objective 2: Review the current urban flood modelling approaches adopted by the industry

Outcome: A common methodology adopted by water utilities and their consultants to simulate sewer flooding is the semi-distributed sub-catchment/manhole approach in combination with coupled 1D/2D models. Digitising and parameterising the catchment into multiple sub-catchments is not only time consuming it also prevents modelling of rainfall-induced surface runoff and the bi-directional flow through storm drain inlets. Using this methodology pluvial flooding cannot be modelled. Simulating the exceedance flow from surcharging manholes as 2D overland flow is usually limited to pre-defined areas as the TIN mesh grid generation and refinement can be time consuming.

Modelling pluvial flooding, 2D surface flood models are required. Large scale, 2D pluvial flood models generally do not simulate the sub-surface drainage domain. To mimic the drainage effect of the sub-surface domain, rainfall reduction factors are commonly applied (Environment Agency, 2013b). As demonstrated in this thesis however, the drainage performance of the sub-surface domain can vary considerably across space and time.

Conclusion: The current state-of-the-arte modelling methodologies have intrinsic limitations for the purpose of conducting high resolution fully coupled 1D/2D flood model simulations and analysis for large domains.

Objective 3: Assess the recent research outcomes and developments in the field of integrated urban flood modelling

Outcome: Research in the field of urban flood modelling has recently focused on a more realistic coupling of the surface and sub-surface domain relying on inlets instead of manholes. Early attempts combined nodes which merged the information from multiple single inlets. This approach however has its deficiencies if the single inlets are located at considerably different elevations and distances related to the later combined node.

Instead of recognising the actual storm drain inlet locations, manhole locations are often applied instead. Simulations conduced in this thesis demonstrated that the drainage performance of inlets is particularly sensitive to the inlet elevation. Considering the lateral road curvature and the application of weir equations, the location of manholes may therefore considerably affect the simulated drainage flow rates. In some cases head/discharge curves are applied to calculate the flow entering/leaving a storm drain inlet. This method however does not take into account approaching velocities which affects the drainage performance of inlets particularly at high velocities.

Conclusion: Recent research has acknowledged the important role of storm drain inlets to link the surface and sub-surface domain. However, the availability of practical modelling platforms for simulating large storm drain inlet networks for entire cities in high resolution fully coupled 1D/2D models is limited.

Objective 4: Evaluate the specific attributes which make CityCAT a useful software in addressing some of the key challenges in urban flood modelling

Outcome: The fully distributed and fully coupled 1D/2D modelling approach of CityCAT simulates large catchments (>10 km^2) at high resolutions of 1 m. Permeable surfaces and building can be automatically extracted from generic shapefile data sets (e.g. MasterMap data or Open Source data). CityCAT can apply spatial and temporal varying rainfall enabling the simulation of storm events based on radar or rain gauge data.

CityCAT simulates drainage for permeable surfaces. Building footprint cells are removed from the computational grid reducing the number of computational cells and therefore the simulation run times. The water volumes of the building footprint cells however remain in the system. Furthermore, a storage coefficient can be applied to building roofs allowing for a simulation of green roofs.

The surface domain in CityCAT is fully coupled with the sub-surface domain solving the relevant equations simultaneously. Both manholes and storm drain inlets are applied to couple the two domains allowing for a bi-directional flow. This allows for a realistic simulation of the flow paths across the surface and sub-surface domain. The simulation of pipe flow in CityCAT is based on new mathematical methods and does not rely on a Preissmann slot.

The modelling engine of CityCAT is available as a stand-alone version and can be deployed on the cloud. This enables the software to access strong computational resources which was a major limiting factor for the application of fully distributed and fully coupled flood models in the past.

Conclusion: CityCAT is a newly developed fully coupled 1D/2D flood model which explicitly simulates storm drain inlets, buildings and infiltration. As an open architecture software, CityCAT models can be built in open-source tools using automated functions. While the actual simulation is carried out on the cloud accessing powerful computational resources, the availability of model results in common file formats makes them easily interchangeable for post-processing applications.

Objective 5: Identify the challenges and limitations which prevent a full application of new modelling tools such as CityCAT and other developments

Outcome: The full application of new modelling tools such as CityCAT is limited by the implications of past and present modelling approaches on the current modelling environment. They are relatable to:

- *Data quality and quantity*
  Compared to CityCAT, simplified modelling methodologies do not rely on storm drain inlet data to couple the surface and sub-surface domain. Hence, from an applications perspective there was no incentive for the modelling sector to collect detailed records of storm drain inlets in the past. Research for this thesis also found

that pipe data or entire pipe sections are occasionally missing. Certain modelling approaches allow to work around the problem of missing pipe data by simplifying the model through the adaptation of specific model parameters or by aggregating information. The work-around techniques are often specific to a certain modelling methodology or software. Network information obtained from simplified hydraulic models may therefore not meet the necessary data quantity and quality requirements of fully coupled models.

- *Flood model analysis tools*
  Commercial flood modelling packages often rely on software-specific post-processing tools to analyse and visualise simulation results. This means that users may experience compatibility issues as they are bound by a single software supplier for the model building, model simulation and model analysis.

- *Perception of integrated flood modelling*
  Despite the legal incentives aiming for an integrated approach towards FRM, shared responsibilities amongst stakeholders is still contributing to a certain silo-thinking. The spatial boundaries in models are often aligned with institutional boundaries and reflect the duties and responsibilities of the individual stakeholder. Therefore no individual authority at this stage is in 'need' of the capacity and capability of fully coupled 1D/2D urban flood models.

Conclusion: Flood model end-users are often dependent on single flood modelling software platforms. This affects the entire modelling environment of a company which limits the capacity of adopting alternative software tools. The thesis identified the particular need for high resolution data about the sub-surface drainage system and storm drain inlet networks in particular. Furthermore, advanced analysis tools to post-process flood model results are required which can operate independently from the modelling platform.

Objective 6: Develop a method to generate synthetic storm drain inlet locations for the purpose of hydrodynamic modelling and evaluate the performance against field surveyed storm drain inlets

Outcome: The developed methodology does not replicate an existing network but generates a synthetic one based on design criteria. For this purpose road geometry data as well as results from a 2D flood model simulation are used. Initially inlets are placed at an equal distance along a reference line which is delineated from the road geometry layer. Based on the 2D model results, surface water accumulation areas are identified to locate additional inlets with the purpose of mimicking in-sag inlet locations. The final location of inlets is adjusted using terrain data.

Comparing the drainage performance of a synthetically generated network of storm drain inlets with a surveyed one shows satisfactory results. The difference of the surface water depth grids between simulations using a surveyed and synthetically generated network of inlets range between 0.0 and 0.1 m. The synthetically generated networks of storm drain inlets can be used in fully coupled 1D/2D flood models and constantly updated with the availability of surveyed storm drain inlet locations.

Conclusion: The developed methodology enables users to generate synthetic networks of storm drain inlets and closes the gap of missing data which would prevent the application of detailed fully coupled 1D/2D flood models. Compared against results from a surveyed network of storm drain inlets the simulated drainage performances show satisfactory results.

Objective 7: Develop generic and stand-alone tools for analysing and visualising fully coupled 1D/2D flood model simulation results

Outcome: A series of generic, modelling-platform independent, open-source Python scripts were written to visualise and analyse hydrodynamic model results. The tools do not require any GIS platform and directly access the raw model results. The source code of all scripts is easily accessible and can therefore be adapted to accommodate specific user needs.

The first set of scripts were developed to visualise the large volumes of data produced by fully coupled 1D/2D flood modelling tools. The different functions allow to visualise the surface flow depth and vector fields, the drainage performance of storm drain inlets as well as the pressure inside manholes. Furthermore, the difference between scenarios can be calculated to illustrate the impact of change.

Secondly, a flood exposure analysis tool was developed to assess the internal flooding likelihood of buildings following industry standards. The tool has the capacity to process high resolution flood model results and exact building geometries. Hence no information is lost through data aggregation or simplification. The tool is embedded in a Jupyter notebook with a user-interface.

Conclusion: The generic, open-source analysis and visualisation tools have the capacity of processing large quantities of data independently from the modelling platform reducing the reliance on a single software supplier. As open-source tools they can be adapted for specific user needs.

Objective 8: Highlight the benefits and practical implications of a potential industrial application of new developments

Outcome: A strategic-level options appraisal identified an additional application of the new technologies as the most practicable step forward. It ensure that the investment and knowledge related to current modelling strategies is not compromised while CityCAT and the thesis deliverables are applied in specific project and case studies of SWMP and ICS.

The efficient method of generating synthetic networks of storm drain inlets is particularly beneficial for larger catchments which would otherwise require considerable surveying costs. The model building in CityCAT is further supported by automated scripts and tools.

The open architecture software of CityCAT offers a stand-alone modelling engine which can be deployed on the cloud for only the model simulation. In combination with the pay-as-you-go payment option on the cloud this allows users to reduce the costs of running flood simulation. The generic analysis and mapping functions are open-source and not limited to a single flood modelling platform.

Conclusion: The methodology developed to generate synthetic networks of storm drain inlets and automated functions allow for an efficient model building in CityCAT. The stand-alone modelling engine of CityCAT has the capacity to efficiently take advantage of the scalable computational resources and payment scheme of cloud computing. The developed mapping and analysis tools enable users to work independently from the modelling platform.

7.3 A step-change in urban flood modelling?

Looking across other sectors of the water industry shows that the application of new technologies and developments is becoming reality. One example is the integrated source-to-tap approach (Rozos and Makropoulos, 2013) in water distribution management. Customer services embraces varies new technologies using mobile apps and social media to enhance the visibility and transparency of utility services and to engage with customers. Social media and crowdsourcing has also become a valuable source for collecting data (See *et al.*, 2016) and the validation of flood model results (Kutija *et al.*, 2014).

To further highlight the benefits of the explored technologies in this thesis, future work should focus on the collection of evidence through modelling of industry related case studies. Importantly for continuing work in this context is a validation of flood model results against observed flow data and measured drainage performance of storm drain inlets. This also concerns the validation of the flood exposure tool against observed flood damages.

As mentioned by Wiener 2004, p.483: *"Regulation may inhibit or stimulate change"*. Reflecting on the findings of the thesis it can be expected that legislation is pushing the development of flood models to even higher levels of integration requiring long term planning and solutions in the future. The DWMP (Richard, 2018; South West Water, 2018) framework is one recent legislative example demanding a more inclusive modelling approach for urban drainage.

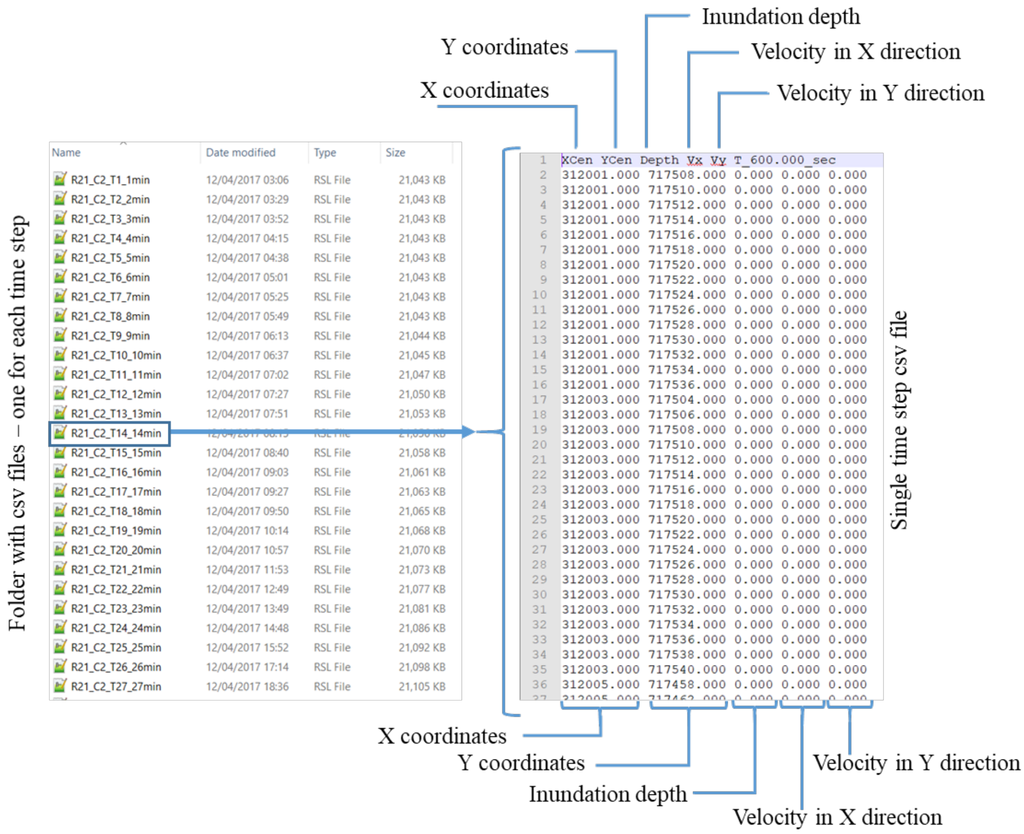
The increasing availability of data and cloud computing offers entirely new opportunities for future developments. One example is the concept of 'digital twins'. A digital twin is a virtual replication of real systems to monitor and simulate them supported by real time data (NWG, 2018). Linking flood models with water supply and demand models, customer service and operations could produce an interlinked modelling system to identify, communicate and resolve incidents more effectively and efficient. Digital twins could also monitor and simulate the impact of floods on the traffic network, power grid and the deployment of emergency services in case of a flood event.

To conclude, the thesis shows that the flood modelling sector is on the brink of a step-change as a result of increasing demand for new solutions and the availably of new concepts and technologies. It is therefore not so much a question if, but when and how, flood model end-users have to embrace new technology.

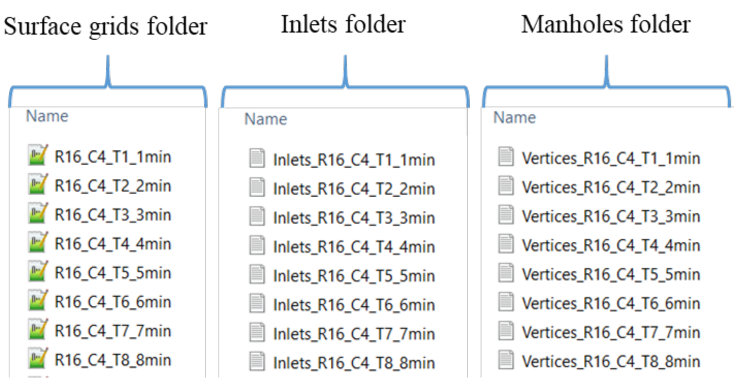
Appendices

Appendix A

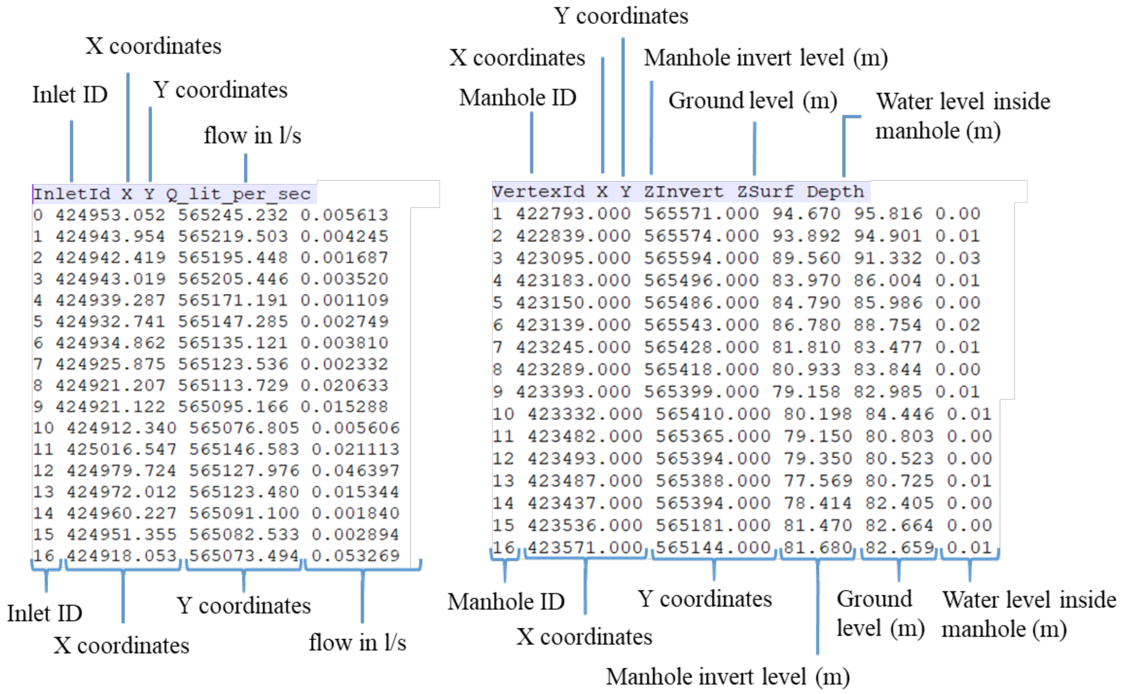
Folder and file structure required for applying the mapping functions:



Required folder structure to enable plotting of surface grids, inlets and manholes:



Required file format for plotting captured/surcharging flow (l/s) of inlets (left) and water level (m) inside manholes (right):



Appendix B

Options Appraisal

This option appraisal is part of the management chapter 6. The aim of the option appraisal is to assess the feasibility of the following three options in terms of a potential industrial application of CityCAT:

Option A. Do nothing option. Keep using the current modelling tool as the only modelling tool and not consider CityCAT at all.

Option B. Fully replace the current modelling tool with CityCAT for all modelling purposes. This would represent the most significant and fundamental change to the current way of conducting flood modelling.

Option C. Additional application of CityCAT. This represents a balanced option whereby CityCAT would be used on specific case studies or catchments expected to benefit most.

	Option A	**Option B**	**Option C**
Option	*'Do nothing option'. Keep using current tools without considering CityCAT at all.*	*Fully replace current modelling tool with CityCAT for all modelling purposes*	*Additional application of CityCAT on a case-by-case approach*
reasons for	• Established modelling software package with long history of industrial track record • Reliable software provider for technical support and regular software upgrades • Existing modelling strategies well tested • Large Investments committed to current modelling strategies in the past and for the future • Hydraulic modeller already trained and experienced in applying the software	• Fully coupled modelling of high resolution surface and sub-surface domain using inlets • Pluvial and sewer flooding assessed • Data from other models (e.g. InfoWorks ICM) can be converted into CityCAT format • The open software architecture of the CityCAT modelling engine can benefit from automated and open-source tools as well as cloud computing	• Fully coupled modelling of high resolution surface and sub-surface domain using inlets • Pluvial and sewer flooding assessed • Data from other models (e.g. InfoWorks ICM) can be converted into CityCAT format • The open software architecture of the CityCAT modelling engine can benefit from automated and open-source tools as well as cloud computing • Make use of the best of both worlds

	• No additional investment and modelling strategy for new modelling tool required		• Investments made and expertise gathered around current modelling tool is not lost • Initial application of CityCAT on a limited number of case studies to collect evidence and demonstrate benefits
reasons against	• Modelling methodologies have intrinsic limitations for the purpose of fully coupled 1D/2D flood modelling • Model approach (e.g. sub-catchments – manhole) do not reflect real urban drainage mechanisms of 1D/2D interactions • Sewer and pluvial flooding often simulated separately • Manual model building processes (e.g. 2D mesh creation and improvement) can be time intensive • Significant license costs may accrue • Relying on single software limits the flexibility to choose alternative options (compatibility issues)	• Additional extensive modelling strategy for CityCAT required • Additional investment and modelling strategy required for operating CityCAT • Additional expertise has to be acquired for running and operating CityCAT or using contractors • CityCAT has no track record of industrial application	• Additional investment and modelling strategy required for operating CityCAT • Additional expertise has to be acquired for running and operating CityCAT or using contractors • CityCAT has no track record of industrial application
risk to current business	• Low This option poses little risk as the current modelling tool are well tested and trusted.	• High Full replacement of current modelling tool with CityCAT represents major risk to the current way of conducting business as considerable investments and changes are required	• Medium By using CityCAT in a complementary way, the risk to the business can be kept at a reasonable level.

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