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AUSTRALIAN RAINFALL AND RUNOFF
REVISION PROJECT 15: TWO DIMENSIONAL SIMULATIONS IN URBAN AREAS-
REPRESENTATION OF BUILDINGS IN 2D NUMERICAL FLOOD MODELS

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Project Project 15: Two Dimensional Simulations In Urban Areas-Representation of Buildings in 2D Numerical Flood Models	**AR&R Report Number**
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FOREWORD

AR&R Revision Process

Since its first publication in 1958, Australian Rainfall and Runoff (AR&R) has remained one of the most influential and widely used guidelines published by Engineers Australia (EA). The current edition, published in 1987, retained the same level of national and international acclaim as its predecessors.

With nationwide applicability, balancing the varied climates of Australia, the information and the approaches presented in Australian Rainfall and Runoff are essential for policy decisions and projects involving:

- infrastructure such as roads, rail, airports, bridges, dams, stormwater and sewer systems;
- town planning;
- mining;
- developing flood management plans for urban and rural communities;
- flood warnings and flood emergency management;
- operation of regulated river systems; and
- prediction of extreme flood levels.

However, many of the practices recommended in the 1987 edition of AR&R now are becoming outdated, and no longer represent the accepted views of professionals, both in terms of technique and approach to water management. This fact, coupled with greater understanding of climate and climatic influences makes the securing of current and complete rainfall and streamflow data and expansion of focus from flood events to the full spectrum of flows and rainfall events, crucial to maintaining an adequate knowledge of the processes that govern Australian rainfall and streamflow in the broadest sense, allowing better management, policy and planning decisions to be made.

One of the major responsibilities of the National Committee on Water Engineering of Engineers Australia is the periodic revision of AR&R. A recent and significant development has been that the revision of AR&R has been identified as a priority in the Council of Australian Governments endorsed National Adaptation Framework for Climate Change.

The update will be completed in three stages. Twenty one revision projects have been identified and will be undertaken with the aim of filling knowledge gaps. Of these 21 projects, ten projects commenced in Stage 1 and an additional 9 projects commenced in Stage 2. The remaining two projects will commence in Stage 3. The outcomes of the projects will assist the AR&R Editorial Team with the compiling and writing of chapters in the revised AR&R.

Steering and Technical Committees have been established to assist the AR&R Editorial Team in guiding the projects to achieve desired outcomes. Funding for Stages 1 and 2 of the ARR revision projects has been provided by the Federal Department of Climate Change and Energy Efficiency. Funding for Stages 2 and 3 of Project 1 (Development of Intensity-Frequency-Duration information across Australia) has been provided by the Bureau of Meteorology.

Project 15: Two Dimensional Simulations in Urban Areas

At the time that the 1987 Edition of Australian Rainfall and Runoff was prepared, the use and implementation of two-dimensional (2D) models for assessment of flooding in riverine and urban systems was not common and required significant computing power and modelling expertise. Since 1987, the situation has changed considerably with technological advances enabling the implementation of 2D models for flooding assessments. There is little guidance, however, about the practical application of 2D models in the 1987 edition of AR&R.

The aim is to develop guidelines for the use of 2D modelling systems in urban environments. It is intended that this project will provide guidance on a number of issues including:

- Model conceptualisation and representation of hydrological and hydraulic processes;
- Influence of the conceptualisation on the input data;
- Parameter estimation and its uncertainty; and
- Predictive uncertainty.

Stage 2 has addressed issues identified in Stage 1 as requiring further testing and/or more detailed assessment.

M K Babister

James Ball

Mark Babister
Chair Technical Committee for
ARR Research Projects

Assoc Prof James Ball
ARR Editor

AR&R REVISION PROJECTS

The 21 AR&R revision projects are listed below :

ARR Project No.	Project Title	Starting Stage
1	Development of intensity-frequency-duration information across Australia	1
2	Spatial patterns of rainfall	2
3	Temporal pattern of rainfall	2
4	Continuous rainfall sequences at a point	1
5	Regional flood methods	1
6	Loss models for catchment simulation	2
7	Baseflow for catchment simulation	1
8	Use of continuous simulation for design flow determination	2
9	Urban drainage system hydraulics	1
10	Appropriate safety criteria for people	1
11	Blockage of hydraulic structures	1
12	Selection of an approach	2
13	Rational Method developments	1
14	Large to extreme floods in urban areas	3
15	**Two-dimensional (2D) modelling in urban areas.**	**1**
16	Storm patterns for use in design events	2
17	Channel loss models	2
18	Interaction of coastal processes and severe weather events	1
19	Selection of climate change boundary conditions	3
20	Risk assessment and design life	2
21	IT Delivery and Communication Strategies	2

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EXECUTIVE SUMMARY

Flood events in Newcastle in June 2007 and more recently in Queensland and Victoria in 2011 have highlighted the importance of having robust planning guidelines and building stability criteria for floodplains. These floods have also highlighted a requirement for accurate representation of flood hazard behaviour to support land use planning and flood evacuation planning documentation.

Currently, the application of two-dimensional (2D) hydrodynamic (numerical) models has become a de-facto standard for baseline flood information for planning and management of Australian floodplains, especially in urban areas. Investigations addressing flood behaviour definition have typically followed a scope devised and refined over many years by government agencies to meet statutory requirements. However, the development, application and calibration of numerical models within this overall study scope have been open to considerable interpretation.

Individual agencies and the specialist consultants servicing these agencies have developed various techniques and methods to address overland flooding using 2D numerical models. However, in many instances, these methods are quite different and produce significantly different outcomes in terms of the generated flood behaviour characteristics.

One such aspect of 2D numerical model application for urban floodplains has been the method by which buildings and similar obstacles to flow are represented. Numerous methods have been devised to represent the influence of buildings on flood flow behaviour, including (Syme, 2008):

- Increased model roughness for building footprints;
- Blocking out model elements for building footprints;
- Modelling building exterior walls partially or in full;
- Using an energy loss coefficient over the building footprints; and
- Modelling buildings as ‘porous’ elements.

The model testing conducted as part of this project has successfully investigated the stated project objectives which were:

1. To develop a base data set of reliable flood behaviour information (flow levels and depth, flow distributions and flow velocities) for an urban floodplain; and

2. To test various methods for representing buildings in 2D numerical models with the aim of determining a preferred method(s).

A literature review confirmed that this project is unique in its approach to developing a physical model of an actual urban floodplain to use as the basis of a comparison with numerical methods. The literature review also confirmed that the modelling community internationally recognizes that the influence of buildings and other obstacles to flow passage in urban floodplains is an important issue in the context of urban floodplain management. The influence of buildings and other obstacles to flow and their representation in numerical floodplain models was also identified in literature as contemporary issue that requires further research and investigation.

A physical model of a section of the upper Cottage Creek floodplain at Merewether Heights in Newcastle, NSW (see Figure 1) was constructed at the Water Research Laboratory (WRL), validated against historical flood information and successfully used to expand the quantitative description of urban flood flow behaviour for the site in terms of flow velocities, flow directions and flow discharge distributions.

A series of measurements of the physical model were then compared against similarly calibrated numerical models. Numerical models were developed using TUFLOW and MIKE FLOOD on the basis of their common use in the Australian market and the availability of these packages to WRL.

Detailed analysis of the developed models including comparison of the models with observed data and data measured in the physical model has concluded that correctly discretised, 2D numerical models are able to adequately represent observed flow behaviour on urban floodplains as long as a suitable method of representing buildings is applied.

Analysis of numerical model results showed that the model spatial resolution is important for estimation of flood flow velocities, flow directions, flow discharge distributions and flood hazard definition. Hazard definition of flood flows is an important aspect of floodplain planning and flood emergency management and this investigation has concluded that numerical model resolutions should be carefully chosen in order to adequately represent flow hazard conditions. While model resolutions of up to 10 m were shown to be adequate for representing peak flood levels, model resolutions of 2 m or less were required to represent the complex flow patterns in and around buildings on the floodplain.

The results of the physical model assessment have shown that while buildings stand, they have a considerable influence on flood flow structures in urban environments, significantly deflecting flows irrespective of whether the building is flooded inside or remains water tight. Anecdotal evidence from videos of the recent Queensland Floods of January 2011 also showed buildings significantly deflecting flows when completely inundated and filled with flood water. It follows that this aspect of urban flow behaviour representation is also important for reproduction of flood behaviour in numerical models. The current investigation has shown that the method used to represent buildings in a numerical model is fundamental to matching prototype flow patterns, and the chosen method must realistically deflect flows. In the project test case, several methods proposed in literature for representing the influence of buildings on flood flows were found to be deficient for that purpose.

Numerical model trials showed that on the basis of the available data sets, the best performing method when representing buildings in a numerical model was to either remove the computational points under the building footprint completely from the solution or to increase the elevation of the building footprint to be above the maximum expected flood height. Other methods, while able to reproduce peak flood levels, were not able to satisfactorily reproduce flow distributions and flow directions around buildings on the floodplain.

Analysis of flood volumes on the floodplain has shown that in a floodplain with flows passing through the floodplain, achieving peak levels due to peak flow rate rather than due to peak storage volume, the influence of the flow volume stored inside buildings is not significant. This has also been shown to be the case by analysis of model results in both the physical and numerical models tested in this project.

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1. Introduction

Flood events in Newcastle in June 2007 and more recently in Queensland and Victoria in 2011 have highlighted the importance of having robust planning guidelines and building stability criteria for floodplains. These floods have also highlighted a requirement for accurate representation of flood hazard behaviour to support land use planning and flood evacuation planning documentation.

Currently, the application of two-dimensional (2D) hydrodynamic (numerical) models has become a de-facto standard for the definition of flood assessment for Australian floodplains, especially in urban areas. Investigations addressing flood behaviour definition have typically followed a scope devised and refined over many years by government agencies to meet statutory requirements. However, the development, application and calibration of numerical models within this overall study scope have been open to considerable interpretation.

Individual agencies and the specialist consultants servicing these agencies have developed various techniques and methods to address overland flooding using 2D numerical models. However, in many instances, these methods are quite different and can produce significantly different outcomes in terms of the generated flood behaviour characteristics.

One such aspect of 2D numerical model application for urban floodplains has been the method by which buildings and similar obstacles to flow are represented. Numerous methods have been devised to represent the influence of buildings on flood flow behaviour.. These methods fall into two broad categories as they either account for the effect of buildings by physically them including in the model topography, or accounting for the influence of the building on flow by introducing additional head loss in the model computational grid points within each building footprint.

The merits of these various methodologies have been the topic of vigorous industry debate. However, no conclusions as to which method(s) is most appropriate have been drawn.

In response, this investigation has two key objectives:

1. To develop a base data set of reliable flood behaviour information (flow levels and depth, flow distributions and flow velocities) for an urban floodplain; and

2. To test various methods for representing buildings in 2D numerical models with the aim of determining a preferred method(s).

2. Literature Review

A review of published literature was completed and found that there are, in general, three methods commonly employed for validation of numerical floodplain models:

1. Validation to measured field data.
   This is probably the most common method employed for model validation and in the case of flood models this usually consists of high water marks measured post a flood event and in some cases an inundation extent.
2. Validation to physical model data.
   This is somewhat rare, and though it is not a "real" data set, the validation process may be considered superior in some aspects since boundary conditions, and time series of water levels, velocities and flow distributions are typically available.
3. Validation against a base case numerical model simulation.
   Where there is no data available, or a fictitious scenario is being modelled, a set of sensitivity cases is often employed to test a models response to various model parameter changes.

In the literature review presented here, Section 2.1 outlines the methods that are on the record as being used to represent buildings in 2D numerical models. In Section 2.2, available physical model data sets for validation of 2D urban numerical flood models are reviewed, along with sensitivity testing of numerical models that was performed on the representation of buildings using these data sets. Section 2.3 presents a selection of comprehensive field data sets that have been identified. Following this, Section 2.4 summarises the relevant urban numerical modelling validation assessments as published. The choice of available software tools for testing the representation of buildings in 2D numerical models is briefly discussed in Section 2.5.

2.1. Methods for Representing Buildings in 2D Numerical Models

The application of 2D hydraulic models to rural floodplains is relatively well understood. However, the relative merits of different approaches of 2D hydraulic models to urban areas remains less understood (Hunter *et al*. 2008). Numerical modelling in urban areas requires the representation of buildings in the model, which affect flow through (1) blocking of flow, (2) resistance to the floodwater, (3) inundation by floodwater, (4) potential loss of floodplain volume, (5) changes in infiltration rates and pathways, and (6) destruction of buildings during extreme events (Brown *et al*. 2007). Modelling of buildings as a consequence will result in complex flow paths (Hunter *et al*. 2008; Syme, 2008).

In an attempt to adequately represent the above processes, several different techniques have been applied to represent buildings in 2D numerical models (Syme, 2008):

- Increasing the roughness or friction (Manning's *n*), or, using an energy loss coefficient;
- Removing elements from the mesh grid, resulting in a mesh boundary;
- Increasing the elevation of buildings, resulting in steep slopes in the model topography;
- Representing buildings as external walls;

- Partially blocking out buildings; and
- Modifying the shallow water equations to include a porosity term for urban areas.

At face value, each method has its relative merits. Increasing roughness is suggested to be best suited to coarse model meshes where groups of cells are used to represent the bulk effect on flow of building groups (as opposed to individual buildings). This method allows for storage effects within buildings and also allows for variation of the parameter (Syme, 2008) to enable calibration to field data. Using a higher roughness to represent buildings has its challenges. It is difficult to know what value of roughness should be applied before modelling, and since the friction factor holds a strong relationship to velocity, calibration to a single event can be achieved, but validation across a range of events using a single roughness configuration is more problematic. (Alcudro, 2004). Further, the bed friction used may be non-stationary with mesh resolution (Fewtrell *et al*. 2008; Yu and Lane, 2006) resulting in a calibration that is fixed to the initially adopted model resolution. Adjustment of the model resolution might require a complete model recalibration if a roughness based solution is applied.

In order to avoid the above problems, and with the advent of faster computing power and higher resolution models, “blocking out” buildings through removing elements from the computational grid at building footprints, or increasing bed elevation has become common practice. Both these methods result in a flow pattern that visually appears valid with flow simulated to be obstructed by the buildings (Syme, 2008). Where buildings may be overtopped it is more suitable to elevate the bed of the model to ensure the building is correctly represented (Syme, 2008), however, when the building is not overtopped it can be suggested that the height of the building is not relevant as the water is never able to flow above the maximum height of the building (Brown *et al*. 2007). It should be noted however that using abrupt bottom elevations changes violates the shallow water equation assumption that the bed slope is small enough that the sine and tangent of the slope are equal to the angle. However, as the flow is around the building, this assumption is effectively not violated (Alcrudo, 2004). Representation through increased bed elevations can destabilise the numerical solutions in some instances and so blocking out buildings is often preferred (Alcrudo, 2004). The weakness of these two methods is that they do not account for any storage effects of the flood volume (Syme, 2008) and are limited by the mesh resolution required to replicate the urban features.

Representing buildings in the model domain using only the external walls of the building footprint, or partially blocking out buildings attempts to replicate the key benefits of the above methods. Buildings are represented individually in the mesh and the storage that results from water entering a building during a flood event is also accounted for (Syme, 2008).

The last method listed, of modifying the shallow water equations is not covered in this study as it requires modification of the shallow water equations which are the basis of most commercially used software in 2D urban modelling. For examples and further discussion refer to Sanders *et al*. (2008) and Alcrudo (2004).

There is currently no obviously superior method for building representation identified in the available literature, and as far as the authors are aware, no guidelines exist which recommend the preferred representation of buildings in a 2D numerical model.

Two issues that are noted in the literature as important when modelling buildings are:

- the ability of the method to include the flood storage within the building; and,
- the ability of the method to accommodate variability in model grid resolution.

Further investigation of these issues is included in the current investigation. A number of studies have created useable validation data sets for representation of urban areas in numerical models. These studies are now discussed.

2.2. Physical Model Data Sets

In order to address the stated objectives of this investigation, a flood behaviour data set with the following attributes is required:

- High accuracy, high resolution topography;
- Water surface level/depth data;
- Flow velocity data;
- Flow distribution data;
- Building footprint information;
- Building construction information;
- Anecdotal discussion of flood affectation of the buildings;

There are a number of physical model studies which have sourced or created data sets for validating urban numerical flood models. Many of these data sets have been used to test various representations of buildings in 2D numerical models. The data sets, and the results of sensitivity tests using these data sets are presented here.

2.2.1. The CADAM Project

The EU Concerted Action on Dam Break Modelling (CADAM) created a physical model base case for verification of numerical modelling code for modelling a dam-break. The physical model was a 1:100 scale reproduction of the Italian alpine Toce Valley (Soares-Frazão and Testa, 1999). The model reproduced a 5 km reach of the Toce River in the Northern Alps of Italy. The physical model reproduced buildings, a reservoir, a dam and two bridges. Water levels were measured at 28 locations with two different hydrographs modelled. The physical model topography and boundary condition data was first released to the various modelling parties before the physical model results were released to allow “blind” model validation. Following this, the modellers performed sensitivity testing of their models based on the physical model results. In general, the water levels were found to be in good agreement (Soares-Frazão and Testa, 1999). Different bed friction values and elevation were tested for the representation of buildings, with variable results. No final conclusions on the most appropriate representation of buildings in the 2D numerical models were made (Haider and Paquier, 1999). Note however, a subsequent Computational Fluid Dynamics (CFD) model, validated using the physical model data described above, showed that representation of buildings by a description using their topography was more successful than using a representation of increased friction (Haider *et al.*, 2003).

2.2.2. The IMPACT Project

Another major initiative, using the facilities described above, was the Investigation of extreMe flood Processes And unCerTainty (IMPACT, 2004) project. Three data sets were developed for the purposes of validating of numerical models for flow in urban areas.

The first data set was the result of a laboratory experiment for a dam-break flow over a sill (in profile, a triangular bed slope). A time series of water level was recorded at three locations and free surface profiles were also made available for various times throughout the simulation (Soares-Frazão and Zech, 2007).

The second dataset modelled the effects of a dam-break on a single building in the Civil and Environmental Engineering Department of the Universite catholique de Louvain (UCL) in Belgium (Soares-Frazão *et al*. 2003). The water level and velocity were measured at six points. The surface velocity field was also obtained at four different time steps using digital imaging techniques (Soares-Frazão and Zech, 2007). This data set has been used for numerical model verification (Capart, 2003), as well as sensitivity testing on building representation using solid walls, higher bed elevations and higher friction (Mulet, 2003). This model has been recently used in an extensive benchmarking study comparing commonly used numerical modelling codes (Néelz and Pender, 2010)

The third was a physical model of a flash flood through a fictitious urban district (Testa *et al*. 2007). The Toce River valley model used in the CADAM Project was modified for this purpose. Using the existing topography, twenty 15 cm square buildings constructed of concrete were placed in the physical model. Two different topographies were tested, one with masonry walls placed on either side of the model town and one without. Two building layouts were tested, one with the buildings aligned in rows, and one with the building rows staggered. For each experiment the water level was measured at ten locations, with three different hydrographs simulated. This data set has since been extensively used for verification and comparison of numerical modelling codes (e.g. Abderrezak *et al*. 2009; Sanders *et al*. 2008; Murillo *et al*. 2003; Alcrudo, 2004).

As part of the IMPACT Project several different techniques were used to represent buildings in numerical models including:

- Using increased friction;
- Using abrupt bottom elevations; and
- High resolution grids with buildings included individually in the model topography represented by solid walls which effectively exclude the buildings from the modelled computational mesh. .

Using abrupt changes in modelled bed elevations typically under-predicted the water levels in the fictitious city as less water was flowing through the system due to the resultant storage (Alcrudo, 2004). As the buildings were concrete cubes in the physical model it is expected that blocking the buildings out would be the most accurate technique, though in an actual flood event it is expected the buildings will often behave as porous media in full or in part. Separate sensitivity testing showed that there was little to no difference in model results when using solid walls or elevated bottom bed elevations, and indeed increasing the friction for this case was valid (Murillo *et al*. 2003).

2.2.3. Other Studies

The CADAM and IMPACT projects have been discussed in detail, however, some additional physical model studies are listed here. A physical model representing flooding of the city centre of Kyoto in Japan due to an overflow from the Kamo River (Ishigaki *et al*. 2003) has been used to validate numerous numerical models (e.g. Mignot *et al*. 2006; Thang *et al*. 2004). The physical model included about 200 impervious blocks representing the buildings which were included in the model according to the map of the city. Calibration using data from this model study consisted of water level data only. Another fictitious city consisting of twelve solid buildings was used to perform verification of an urban flood model flow velocity as well as hydrodynamic forces (Shige-eda and Akiyama, 2003).

2.3. Observed Data

The data sets presented above are comprehensive, however, for the purposes of the current study, they are lacking: (1) a comprehensive real-world flood data set with measured flow velocities and flow distributions; (2) a constructed physical model calibrated to and representative of a real-world flood event; and, (3) a physical model constructed so that the porous nature of buildings during floods is represented. Regardless of these shortcomings, there are numerous observed data sets available, examples of which are presented here.

As part of the IMPACT project, numerical models were tested against a base case of flooding after the Tous Dam Break (Alcrudo and Mulet, 2007) which occurred in 1982. The available data for this study included a Digital Terrain Model (DTM) of the study area and a list of the buildings and their coordinates. The numerical models were validated against 21 high water marks, and an envelope of the shore line along the river reach. Sensitivity testing on the representation of buildings was performed on the methods presented above but the results demonstrated that no one method was superior to another, as the results are not independent to the mesh size, the type of flood, and the location of the city relative to the primary flow path (Mulet and Alcrudo, 2004). The ability to match high water marks appeared to be more difficult than matching laboratory results from the physical model. This data was also used for validation by Abderrezzak *et al*. (2009).

At the time of writing, a comprehensive data set was available from the Carlisle 2005 flood event in the UK (Neal *et al*. 2009). Level measurements sampled at 15 minute intervals were available from six gauges, three of which had discharge measurements. In addition 263 point measurements of the maximum water surface elevation were available and the extents of the flood based on wrack marks were also measured. This represents a comprehensive data set given the number of high water marks, the number of level measurements and discharges measurements available. A DTM of the study site was also available.

An extensive data set was gained from a dam-break incident that occurred in 1963 in Baldwin

Hills, Los Angeles, California (Gallegos *et al*. 2009). This data set included a 1.5 m resolution DTM, flood extent data and stream flow data at a single gauging station. Apel *et al*. (2009) describes a similar data set for a flood in Eilenburg, Saxony, Germany in 2002 for which upstream conditions were given by a measured hydrograph, with a maximum flood extent and 380 high water marks being recorded. These data sets are extensive and could be well used for calibration and verification of numerical models.

Other studies of verification to actual data sets include:

- LiDAR data of the flood plain surface and remotely sensed inundation extent for the River Ouse, Yorkshire UK November 2000 (Yu and Lane, 2006);
- DEM and cross-sections of the site of the 1998 flood of Nîmes, with a number of flood marks are available for verification (Abderrezzak *et al*. 2009); and
- A number of high water level marks in a flood event in Hanoi, 2001 (Thang *et al*. 2004).

Whilst any of the above listed data sets is in principle suitable for a model validation, none of the noted data sets covered the seven attributes desired from a flood behaviour data set as listed in Section 2.2. This being the case, the chosen methodology to progress this investigation was to expand a known historical flood data set using a calibrated physical model. The adopted data set was recorded following the June 2007 “Pasha Bulker” storm in Newcastle (Haines *et al*. 2008). For this event, more than 1500 peak water level marks were available. This study site was also favoured as it was well known to the study team, was readily accessible, and suitable topographical data and numerous anecdotal descriptions of the flooding were available. These data attributes provided confidence that an accurate physical model representation of the site could be constructed.

2.4. Numerical Model Studies

There are a number of studies which have focussed on the modelling of buildings in 2D numerical models, without the added credence of verification to recorded data. These relevant studies are summarised in this section. Most such studies have focussed on the mesh resolution effects and represented buildings representation.

Brown *et al*. (2007) used the Delft Flooding System (Delft-FLS) to undertake such a study. In this case, the a default model building height was adopted to effectively remove the buildings from the model computational grid. For this particular case study the influence of the building orientation was found to be negligible (Brown, 2004). It was found that there was a limiting grid resolution for an accurate representation of the building area with a grid resolution of 10m noted as the upper limit before significant divergence of model results. A comparison of solid buildings (effectively removing building footprints from the grid) and hollow buildings (which allowed uptake of the volume within the building footprint) was also tested and it was found that the change in the inundation extent was small at approximately 2% with a corresponding difference in flooded volume of approximately 3%.

It has been observed that significant improvement in the predicted depth is gained from an increased mesh resolution (Mulet, 2003). Fewtrell *et al*. (2008) used increased bed elevation to model buildings and subsequently performed extensive sensitivity tests on spatial resolution. The highest resolution model of 2 m grid size was used as a benchmark to compare coarser model predictions. The original 2 m resolution digital surface model was aggregated to 4, 8 and 16 m grids. It was found that a binary measure of flood extent decreased substantially with decreasing model resolution, suggesting poor process or topographic representation within the coarser models. It was found however, that up to an 8 m grid the maximum water depths were well predicted and this corresponds to the critical length scale which is a function of the building length and separation. Note that this work, though extensive, fails to suggest what grid resolution is necessary to represent flow fields correctly which is one of the current study aims.

The coarser the resolution, the poorer the ability to control the inundation process, as these parameters not only affect the speed, but also the direction and resolution of wetting. Therefore, it is suggested that high-resolution data needs to be coupled to a more sophisticated representation of the inundation process in order to obtain effective predictions of flood inundation extent (Yu and Lane, 2006).

2.5. Modelling Software Choice and Benchmarking

A choice of software for the current investigation is required. Numerical models can be broadly graded into three classes (Néelz and Pender, 2009). Finite difference models are currently the most popular among consultants due to their compatibility with high resolution digital terrain models created from LiDAR. Finite element models are less commonly used as although they benefit from a rigorous mathematical foundation (Alcrudo, 2004), they are more cumbersome in runtimes and model creation. Finite volume methods are increasing in popularity due to their theoretically perfect mass and momentum conservation, and the majority of the above referenced studies employed finite volume techniques. For this study, the finite difference TUFLOW (2009) and MIKE FLOOD (DHI, 2009) packages were used as, at the time of writing, they were among the most widely used software packages in Australia for 2D numerical modelling of flood issues.

Benchmarking studies of modelling codes have been undertaken previously (Leopardi *et al.* 2002; Hunter *et al.* 2008; Néelz and Pender, 2010), however none of these examine different representation of buildings within a model mesh, but rather, assume a representation and compare the models based on water levels and flooding extents. The studies listed above are briefly reviewed.

Six two-dimensional flood models were benchmarked including DIVAST, DIVAST-TVD, TUFLOW, JFLOW, TRENT and LISFLOOD-FP (Hunter *et al.* 2008). In all models buildings were represented as increased bed elevations. It was found that all models yielded plausible results, and were in general similar. In fact differences between models were in the order of the vertical error in the LiDAR data which was used to construct the bed elevation topography. Further, minor differences between models could be subsumed with parameter optimisation (changing the roughness). It was interesting that the modelling showed that individual models performed better at different sites, and there was not a single, all-encompassing model. The same was found of ANUGA, FloodFlow, Infoworks 2D, ISIS2D, MIKE FLOOD, SOBEK, TUFLOW and TUFLOW FV (Néelz and Pender, 2010).

This implies that point based model calibration and validation is only a limited test of model performance (Hunter *et al*. 2008). This is because calibration of hydraulic models against point data using spatially lumped parameters is unlikely to result in spatially uniform changes in predicted flow quantities. It would be preferable that calibration included both time series of water depths and velocities at single points, and replication of spatially correct flow paths and fields. However, this is unfortunately not practical due to the difficulty in obtaining such data.

3. Research Program

Based on the above review, the most rigorous method of verifying a numerical 2D urban flood model would be through replication of spatially correct flow distributions and velocities with a pre-requisite match of flood surface levels and inundation extent.

The total set of pre-requisite data, as specified in Section 2.2, is as follows:

- High accuracy, high resolution topography;
- Water level data;
- Flow velocity data;
- Flow distribution data;
- Building footprint information;
- Building construction information;
- Anecdotal discussion of flood affectation of the buildings.

Since available data sets only partially meet the stated requirements of this investigation, the adopted approach for this study was to supplement available recorded data for a known historical flood with additional data measured in a scale physical model.

The primary tasks of this research were to:

1. Expand an available measured data set of an historical flood to best meet the stated data set requirements.

   The historical data set was expanded by means of a scale physical model, suitably validated against available flood peak water levels in a flooded urban area. Flow velocities and flow distributions were measured in the physical model using standard laboratory techniques.
2. Compare numerical models of the subject floodplain developed in TUFLOW and MIKE FLOOD validated against the measured data set to;
   1. Test the accuracy of the model outputs at various model grid resolutions; and
   2. Test the accuracy of the model outputs using various methods to represent buildings.
3. Prepare a set of recommendations for applying numerical models in urban flood zones.

4. Test Site – Merewether NSW

Newcastle has a long history of flooding both due to flash flooding in urban catchments and on the Hunter River floodplain. In particular, extreme rainfall in the Cottage Creek catchment has resulted in flooding of Newcastle's eastern suburbs and CBD on numerous occasions. Most recently, the city famously flooded in June 2007 in what has become known as the "Pasha Bulker" storm.

A précis of the storm is provided in Haines *et al*, (2008):

> *"The long weekend of June 2007 will be recorded in history as one of the worst natural disasters affecting Australia, and the Hunter / Central Coast region in particular. An East Coast Low (ECL) weather system developed off the coast of Newcastle as a result of a pre-existing low pressure trough, a high pressure system strengthening over the southern Tasman Sea delivering further humid air, an extremely cold pool of air in the upper atmosphere attached to a north westerly jet-stream across northern NSW, and above average sea surface temperatures directly off Newcastle. The result was extreme rainfall and gale force winds which pounded the coastline between Newcastle and the northern Sydney suburbs for more than 24 hours. The strong winds generated large ocean swell (up to 17 metres offshore), which resulted in the grounding of the bulk ore carrier the Pasha Bulker on Nobby's Beach. The storm of the long weekend has thus been affectionately termed the 'Pasha Bulker Storm', similar to the 'Sygna Storm' some 33 years previous wherein the coal carrier Sygna was grounded on Stockton Beach during similar high seas. Most suburbs of Newcastle and surrounding areas received record levels of rainfall, in excess of the predicted 1% AEP rainfall. The intensity of the rain combined with the topography of the local catchments resulted in flash flooding throughout Newcastle to an extent that had not previously occurred in living memory. Streets turned into rivers as cars became overwhelmed and stranded in the floodwaters. Efforts turned to rescue and recovery, as thousands of homes became inundated, some by over a metre of water."*

In the period immediately post the "Pasha Bulker" storm, Newcastle City Council proactively engaged with the community to identify and survey more than more than 1500 peak water level marks (Haines *et al.* 2008). These marks indicated the depth and extent of inundation of flooding through the city. Peak flood level marks also provided an indication of flood surface slope across the floodplain. This information, along with the many anecdotal descriptions of flooding across the city provided by residents enabled an overview of flooding behaviour for the event to be established.

The test site chosen for the physical model experiment was the overland flow path in the vicinity of Morgan Street, Merewether. The site is located just below the catchment divide at Merewether Heights (see Figure 1).

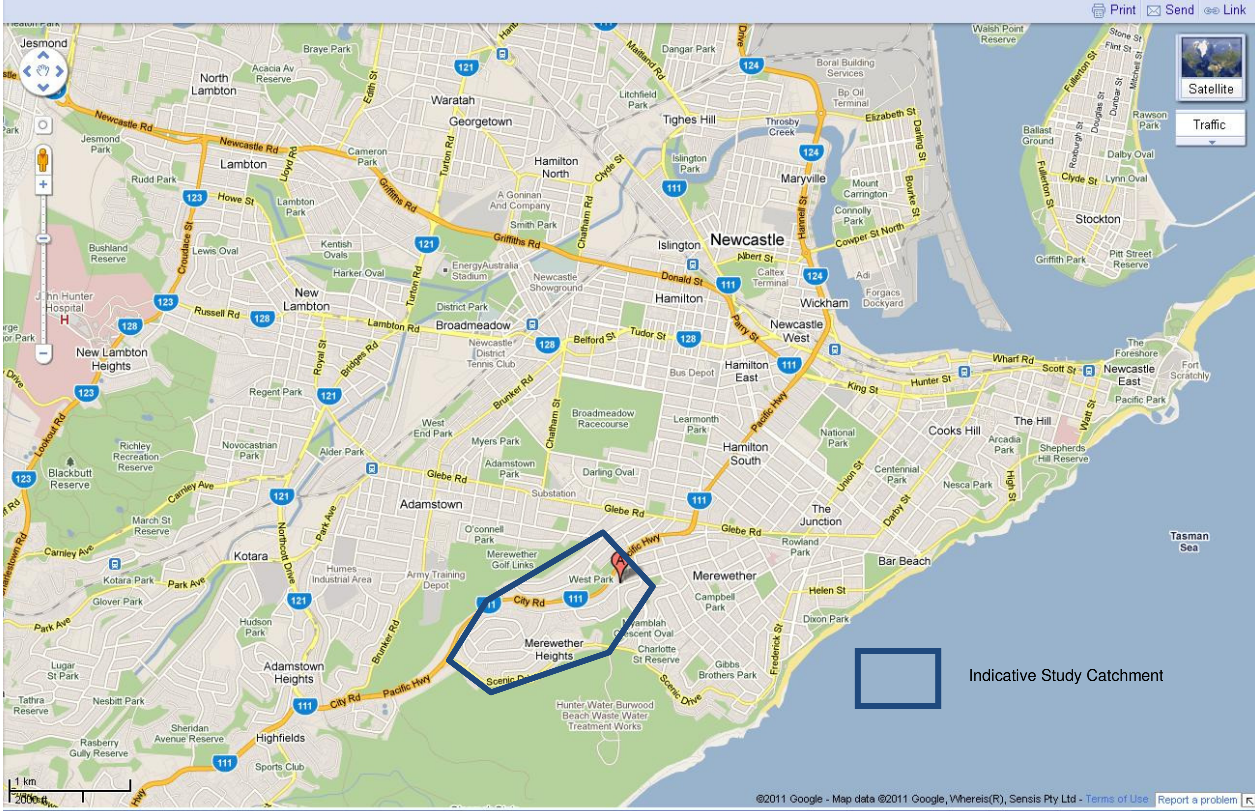


Figure 1: Test Site: Catchment Locality Plan

Flooding in the suburb of Merewether was particularly severe during the “Pasha Bulker” Storm of 2007. Haines *et al.* (2008) reports:

> “*Flow travelled at speed from the steep upper catchment of Merewether Heights northwards down Morgan, Arthur and Little Edward (Little Arthur) Streets, into Selwyn and Wilton Streets and Glebe Road; and down Mitchell and Merewether Streets and into Lingard and Frederick Streets. One house at 166 Morgan Street, which is located within the natural overland flow path, was severely damaged by the flow, with some of the lower level of the house torn away. Significant velocities and flow were also evident immediately downstream at a house on the corner of Little Edward (Little Arthur) and Selwyn St where fences and bricks were dislodged by flood waters.*”

While no photographic evidence of the actual floodwaters is available at the test site for the June 2007 event, photographs taken from 166 Morgan Street, Merewether in the March 1984 flood are available as presented in Figure 2. Flooding as a result of the March 1984 storm was not as severe as the June 2007 event.

Figure 2: 166 Morgan St Merewether – March 1984 Storm

The Merewether site is attractive and suitable as a test site for this research. The severity of the flooding hazard during the June 2007 storm, the influence of buildings as obstructions to flow, the dendritic and somewhat constrained nature of the overflow path and availability of key data sets provides a location and data set which fits a wide range of criteria for a successful physical and numerical modelling exercise to meet the stated project objectives.

4.1. Available Data: ‘Pasha Bulker’ Storm

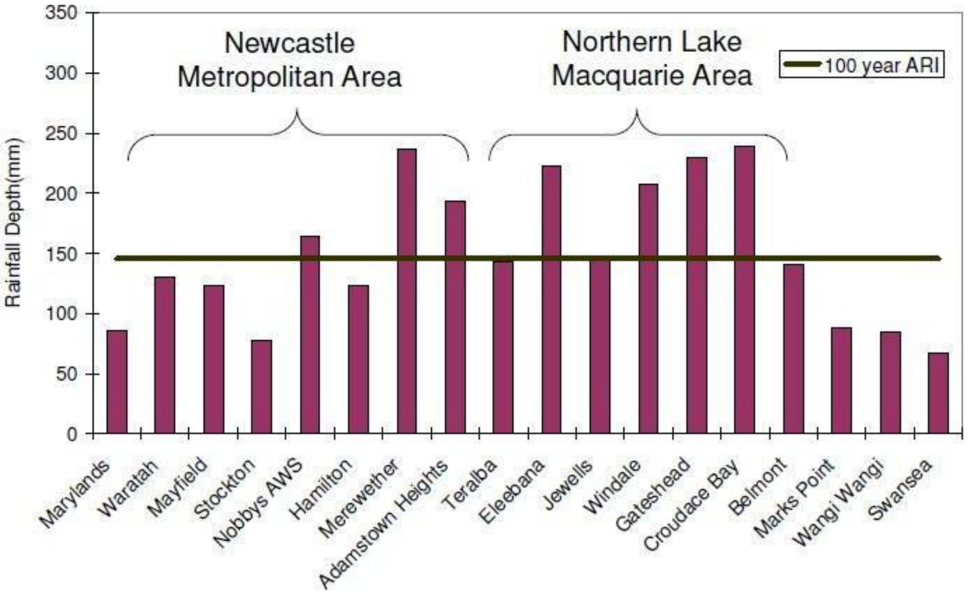
As previously noted, the Merewether site had a range of data suitable to meet the project requirements. The range of available data has a comparable coverage and accuracy limits representative of data standards typically available for a flood study in NSW.

4.1.1. Topography

Newcastle City Council provided a Digital Elevation Model (DEM) that had been developed using photogrammetry. The aerial photography used to develop the topography was flown by QASCO Pty Ltd in 2000. The stated vertical accuracy of the DEM is ±0.2 m.

4.1.2. Rainfall

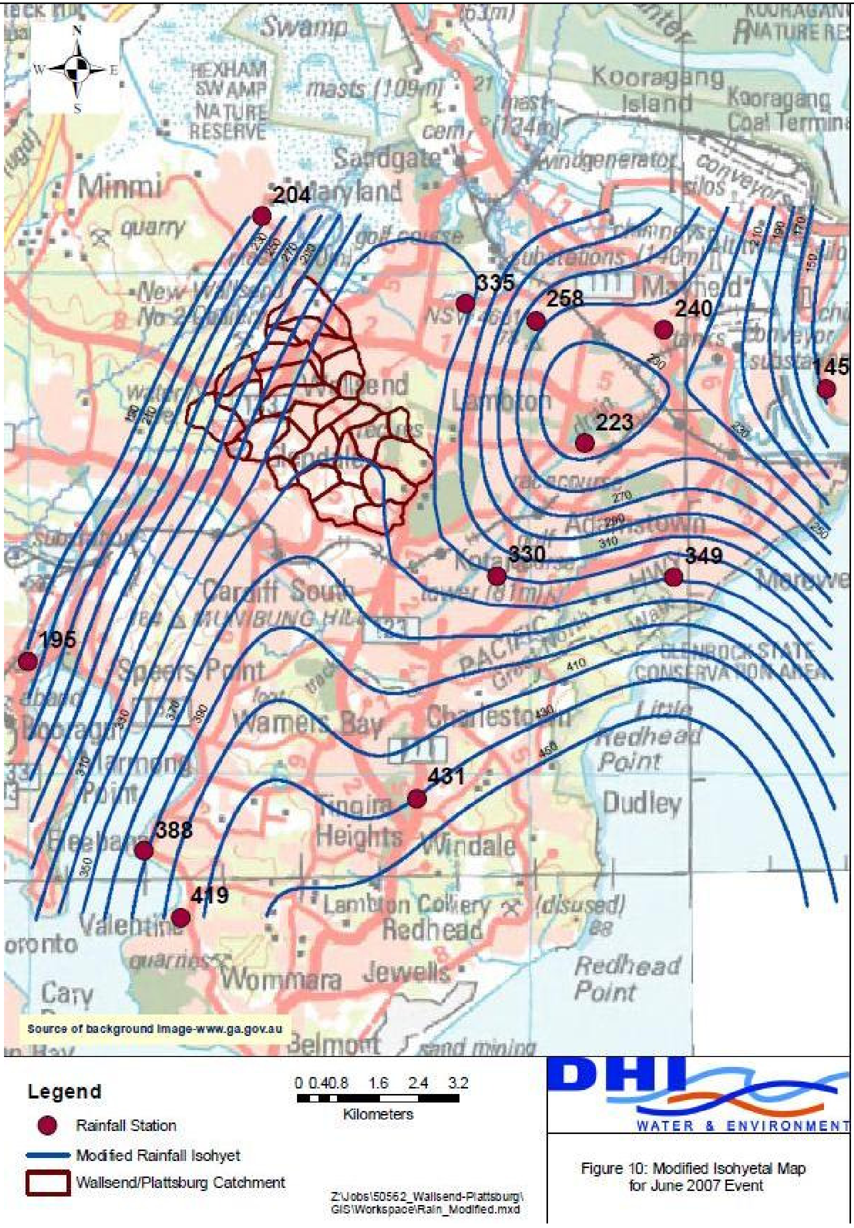
The report by Haines *et al*. (2008) describing the “Pasha Bulker” storm of June 2007 has collated and analysed rainfall data recorded for the event. This analysis reported that rainfalls over the Newcastle area were significantly greater than the 1:100 AEP design rainfall on the currently adopted Newcastle Intensity-Frequency-Duration curve as determined by the Australian Bureau of Meteorology (see Figure 3). This was especially so at the Merewether rainfall pluviometer where 6-hour rainfall depth was approximately 240 mm compared to the 1:100 AEP 6-hour rainfall depth of 150 mm.



*Reproduced from Haines *et al.* (2008)

Figure 3: Comparison of 6-Hour Rainfall Depths to 1:100 AEP ARR (1987) Storm

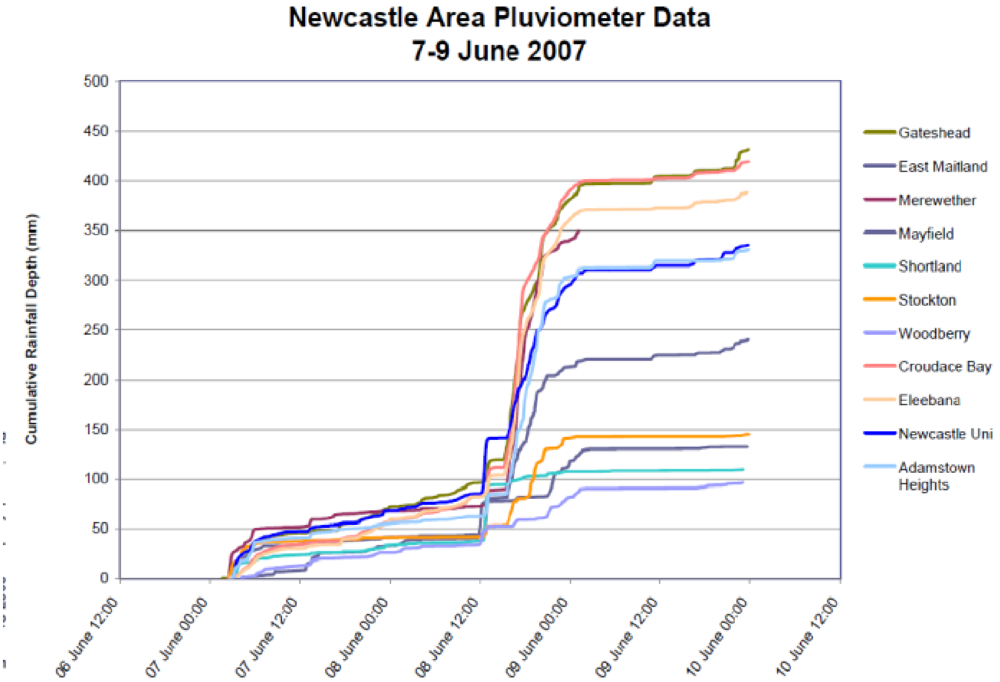
DHI (2008) further analysed the June 2007 storm data producing isohyets of rainfall over the Newcastle catchments. The isohyets from this report, reproduced as Figure 4, show a considerable gradient in recorded rainfall depths from the south-east towards the north-west over the Newcastle suburbs, with the highest rainfalls recorded in the northern areas of the Lake Macquarie local government area.



*Reproduced from DHI (2008)

Figure 4: Storm Rainfall Isohyets: June 2007

The processed 5 minute pluviograph data for the storm was available and is presented in Figure 5. The pluviograph data demonstrate the high intensity of the rainfall experienced in the flood event with the bulk of the rainfall volume falling in a period no more than six hours on the 8th of June 2007.



*Reproduced from DHI (2008)

Figure 5: Storm Pluviograph Trace: June 2007

4.1.3. Recorded Flood Level Data

Newcastle City Council and its consultants were diligent in collecting more than 1500 individual flood level marks immediately following the flood event in June 2007. The location of recorded flood marks relative to the project site in Merewether is presented in Figure 6.

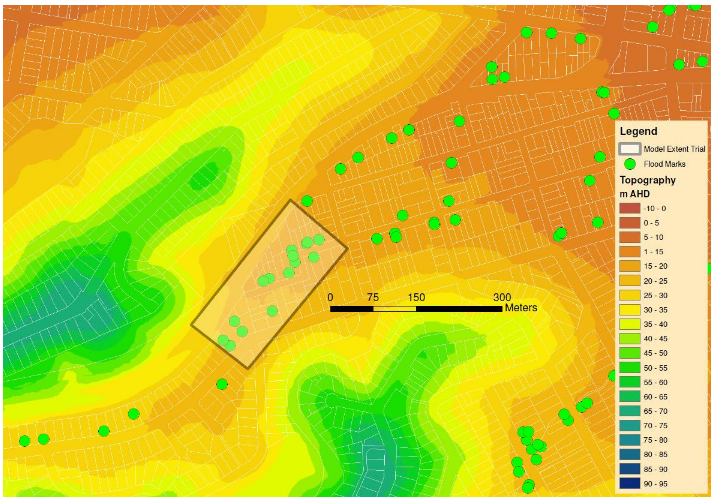


Figure 6: Local Area Flood Marks: June 2007

Council's flood level data base records various information associated with each flood mark, including a surveyed peak water level where this is available. Flood marks with surveyed peak water levels within the project site suitable for model calibration are presented in Table 1.

Table 1: Recorded Flood Marks, June 2007

Flood ID	Level (m AHD)	Address	Description
MWR_0031	19.985	10 Little Edward St, Merewether	1.23m up from concrete slab 5.3m from back fence on wire fence
MWR_0032	18.382	75 Selwyn St, Merewether	180mm up from concrete veranda adjacent to front door
MWR_0033	18.658	80A Wilton St, Merewether	300mm up from back pavers next to back gauze door
MWR_0042	23.364	183 Morgan St, Merewether	at ground on pebble 7.16 m from b/path
MWR_0043	23.14	174 Morgan St, Merewether	at ground level, top of drive at base of garage door
MWR_0044	23.014	170 Morgan St, Merewether	up 320mm from concrete350mm up from concrete step

4.2. Catchment Runoff Estimates

The urban floodplain that is the subject of this project lies high in the Cottage Creek catchment, close to the catchment divide. The catchment is bounded by the Pacific Highway to the north and Scenic Drive to the south and west (see Figure 8).

The total sub-catchment area contributing flow to the project floodplain is 84 Ha. Being high in the catchment, the contributing catchment slopes are steep. Figure 7 shows that the catchment is more or less bowl shaped, with the highest point in the south-west at 100 m AHD falling to the project area floodplain at 23 m AHD. The red colours in Figure 7 indicate higher ground with graduating through yellows to green colours showing lower levels. The catchment is zoned residential and, by inspection of the site and available aerial photography as shown in Figure 8, is fully developed.

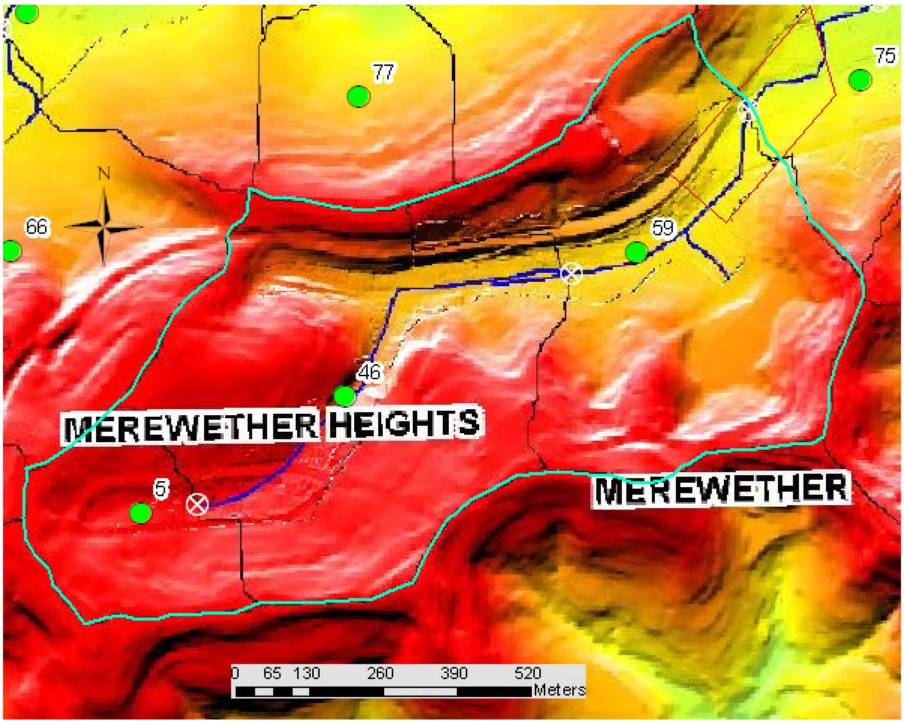


Figure 7: Local Catchment Area Topography

Two methods have been investigated to estimate the rainfall runoff entering the project floodplain as described in Sections 4.2.1 and 4.2.2, respectively.

Figure 8: Aerial Photo Showing Local Catchment Area

4.2.1. Flow Estimate 1: WBNM Hydrological Model

A WBMN model (Boyd *et al.* 2007) was developed as part of the Throsby, Cottage and CBD Flood Study by Syme and Ryan (2008) and made available for the project by Newcastle Council. The model had been validated as part of the flood study to previous historical floods. The WBNM model sub-catchment layout for the project sub-catchment is presented in Figure 7. The annotated green circles indicate the WBMN sub catchment centroids with the black polygons showing the WBMN model sub catchment extents. There are three (3) model subcatchments contributing flow from upstream to the subject floodplain site, these being sub catchments 5, 46 and 59.

The WBNM model configuration file representative of existing catchment conditions from the flood study was adopted for this project. The model configuration was configured with June 2007 rainfall from the Merewether Street pluviometer gauge (Reference Number: 310000R8) maintained by Hunter Water Corporation. The recorded rainfall was processed on a 5 minute increment and the WBNM model simulated for the storm using a 5 minute model time step. Accumulated rainfall runoff estimated by the model at WBNM model node 59 provided the flow hydrograph presented as Figure 9. The peak flow rate in the hydrograph is 19.7 m^3/s. This compares to the 1:100 AEP 2 hour storm flow rate of 17.9 m^3/s and the 1:200 AEP storm flow rate of 20.2 m^3/s.

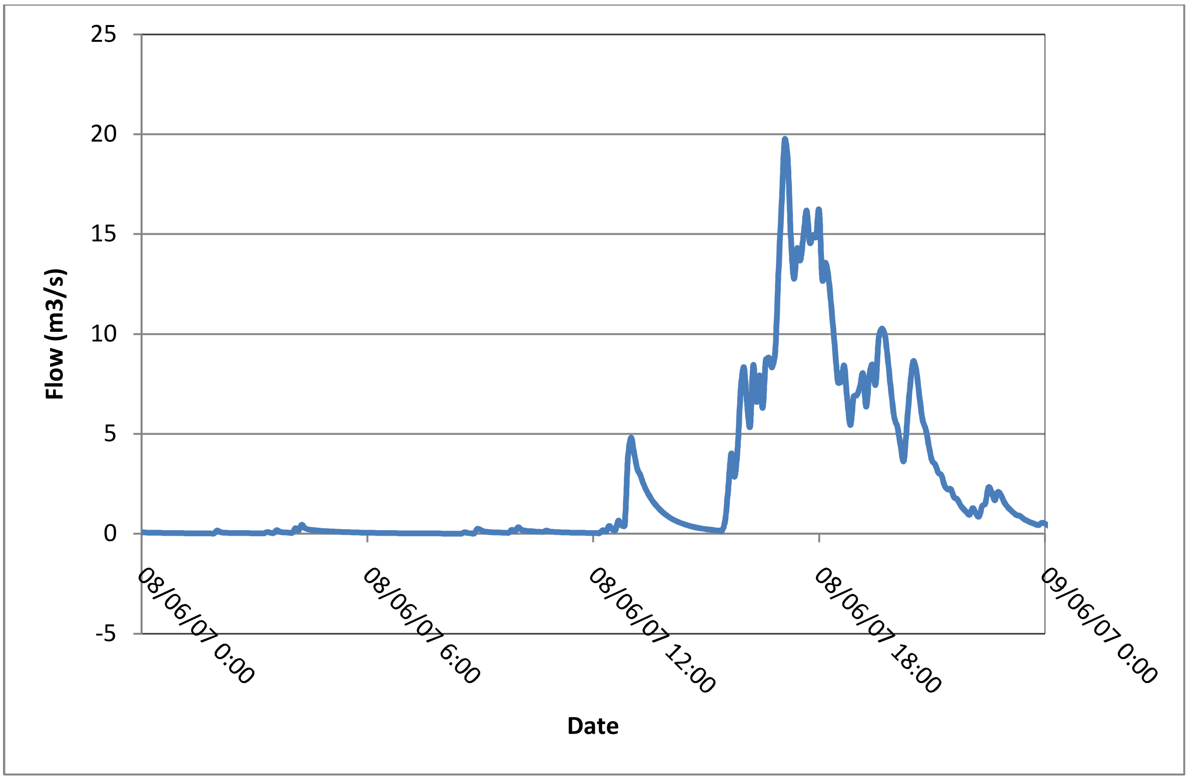


Figure 9: WBNM Generated Runoff Hydrograph, June 2007

4.2.2. Flow Estimate 2: Flood Slope

Anecdotally, catchment runoff during the June 2007 storm flowed off the catchment from the south-west and accumulated to flow in a north-easterly direction down Morgan Street, Merewether. Flow running down Morgan Street was constrained by higher ground in properties either side of the road so that flow was essentially contained within the road reserve on the road surface and the adjacent foot paths. Flows were constrained to the road reserve in this way until at 166 Morgan Street, the rising road topography forced flows off the road reserve and into the residential properties between Morgan Street and Alice Street.

The peak flow rate from the June 2007 storm could be estimated by applying Manning's formula to the flood slopes interpreted from the peak flood levels recorded along Morgan Street. Peak flood levels in the vicinity of the project floodplain are shown on Figure 10.

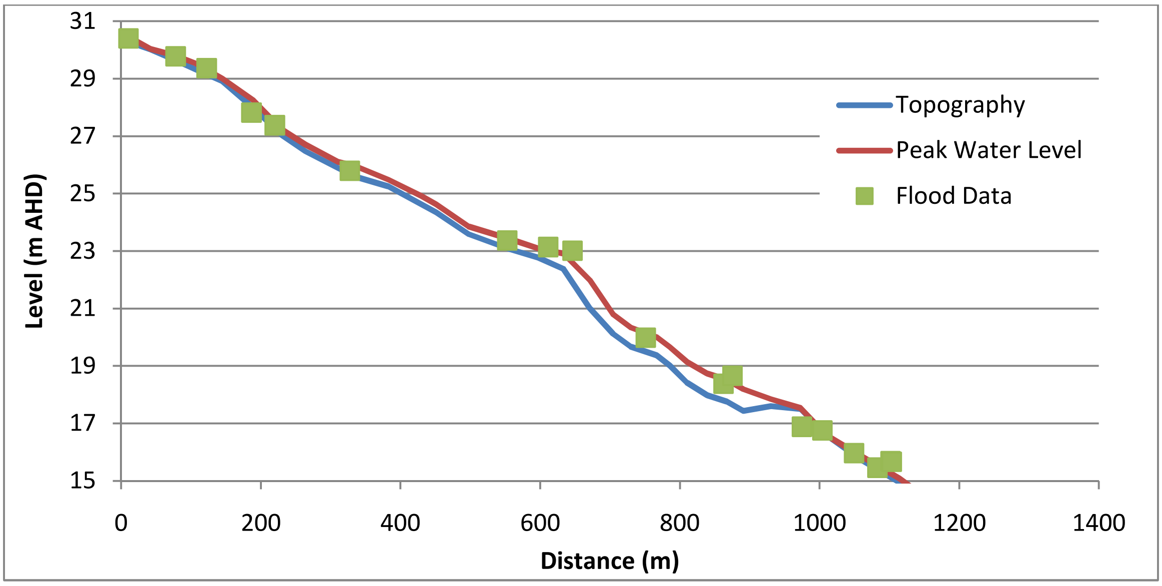


Figure 10: June 2007 Peak Flood Levels compared to the Local Topography

Peak flood flow estimates were calculated at two locations on the flow path presented in Figure 9. Cross section details perpendicular to the assumed flow path were extracted from the available topography at chainage 113 m and 553 m, respectively. Flood slopes of approximately 1 % were apparent at both of these cross sections. A Manning's "n" of 0.015 was adopted for the flow analysis (ARR, 1997). The results of the flow estimation at these locations are presented in Table 2. Sensitivity testing was undertaken using a Manning's "n" of 0.020.

Table 2: Flood Flow Estimates – Flood Slope Method

Cross Section Chainage (m)	Flood Mark Elevation (m AHD)	Flow Depth (m)	Flow (m^3/s)	Froude Number
n = 0.015				
123	29.370	0.3	15	2.7
553	23.364	0.3	25	3.3
n = 0.020				
123	29.370	0.3	12	2.0
553	23.364	0.3	19	2.5

The estimated flow rates of 15 m^3/s and 25 m^3/s are remarkably similar to the flow estimate of 19.7 m^3/s determined using the WBNM model. On the basis of these calculations, a flow of 19.7 m^3/s was adopted for the physical model design.

5. Physical Modelling

The model domain adopted in both the physical and numerical models was selected following careful consideration of a range of constraints and parameters. A suitable model scale for the physical model able to adequately reproduce the flow behaviour of the prototype floodplain was primary amongst the wide range of constraints and parameters considered.

In the first instance, a coarse scale numerical model of the floodplain flow path was constructed as a pilot model to assist with the physical model design by providing a first pass estimate of the flow conditions likely to be encountered in the project. The pilot model was relatively simple to configure since Newcastle City Council had provided a DEM and design catchment flow estimates (e.g. 1:100 AEP flows) from the catchment flood study completed in 2008 (Syme and Ryan, 2008).

Key considerations for the physical model design included:

- Physical aspects of the model topography including:
    - Total fall of the terrain over the domain;
    - Likely width of the floodplain;
- Adequate flow depths for measurement with available instrumentation;
- Ensuring the physical model flows are turbulent;
- Minimising viscous scale effects;
- Adequate scaling of drag forces between buildings;
- Adequate scaling of bed roughness;
- Adequate flow delivery available at the laboratory;
- Distance required to establish uniform flow at the upstream end of the model; and
- Method to remove flow from the model without causing downstream boundary effects.

The physical model scaling was determined using Froude similitude with assessment of Reynolds numbers used to ensure that flows in the physical model would be in the turbulent range.

The adopted model domain is presented in plan-view in Figure 11. The model extends from approximately chainage 550 - 900 m on the profile presented as Figure 10. These figures illustrate the model domain relative to the recorded flood marks from the June 2007 flood. There are six flood marks available for calibration in the model domain.

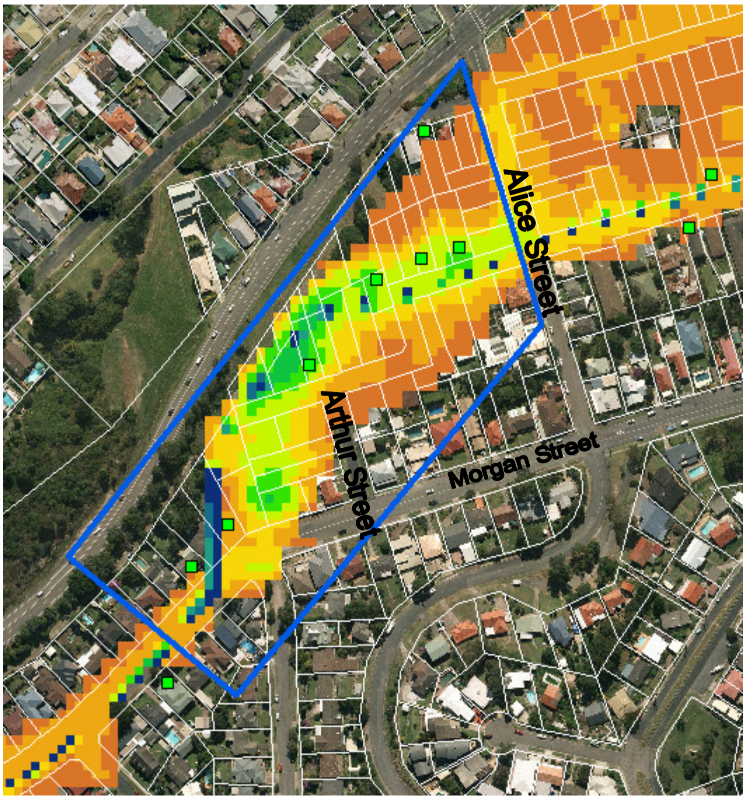


Figure 11: Pilot Numerical Model Showing Adopted Physical Model Domain and Flood Marks Available for Calibration

Non-dimensional analysis is the technique of organising parameters into dimensionless forms, which provide the basis for similarity between models and prototypes. The physical model for this project was scaled on the basis of Froude Number scaling, with Reynold's Numbers checked to ensure that the model would operate in the turbulent range.

In due consideration of all listed constraints, the adopted model scale for the physical model was:

- 30:1 horizontal (L_{HR}), and
- 9:1 vertical (L_{VR}).

A distorted scale model was adopted primarily to ensure that flow depths were adequate for accurate measurements with the available instrumentation and that the physical model roughness could be adjusted through a reasonable range to calibrate the model.

The following relationships provide a summary of scaling factors for model parameters.

Table 3: Physical Model Parameters

Parameter	Symbol	Calculated as	Units	Dimensions
Horizontal length ratio	L_{HR}			
Vertical length ratio	L_{VR}			
Model velocity	V_m		m/s	L/T
Prototype velocity	V_p		m/s	L/T
Froude Number	F	$\frac{V}{\sqrt{g.d}}$		
Velocity ratio	V_R	$\sqrt{L_{VR}}$		
Flow	Q	V.A	m^3/s	L^3/T
Flow ratio	Q_R	$V_R.L_{HR}.L_{VR}$		
Time ratio	T_R	$\frac{L_{HR}}{V_R} = \frac{L_{HR}}{\sqrt{L_{VR}}}$		

Substituting adopted horizontal and vertical scale factors it follows that:

Flow scale $= Q_R = V_R.L_{HR}.L_{VR} = \sqrt{L_{VR}}.L_{HR}.L_{VR} = L_{VR}^{1.5}.L_{HR} = 30 * 9^{1.5} = 810$

Time scale $= T_R = \frac{L_{HR}}{\sqrt{L_{VR}}} = 30 / \sqrt{9} = 10$

In an undistorted model, Manning's "n" is proportional to $(L_R)^{1/6}$. For a scale of 9:1, the roughness coefficient ratio would be 1.44:1 and for a 30:1 scale, the roughness coefficient ratio would be 1.76:1, that is smoother than the prototype. In a distorted scale model, the hydraulic radius and velocity scales are based on the depth scale, however, the slope scale is no longer unity and becomes $(L_{HR} / L_{VR})^{1/2}$ which in this case becomes 0.55 giving an overall roughness coefficient scale of 0.79:1, that is the model roughness is greater than the prototype. In simpler terms, if the slope in the model is distorted by a ratio of 3.3:1 then the hydrostatic driving forces are also changed by a ratio of 3.3:1. This change in hydrostatic forcing theoretically needs to be balanced by increased friction. This is partially important for sub-critical flow regimes, but not quite as important for super-critical flow regimes with regular critical controls.

The roughness coefficient scale ratio has some implications for the comparison of the physical model to both the prototype case and the numerical models of the test site. Further discussion of this aspect of the investigation is provided in Section 6.4 where the physical model and numerical model results are compared and discussed.

A check of physical model Reynolds numbers in the indicated that they ranged from 6.5×10^4 to 9.3×10^4 and therefore were in the turbulent range. Further, for good representation of aeration to be achieved in the model so that hydraulic jumps scale with a reasonable correlation from the model to prototype, Reynolds numbers should be 8.0×10^4 (Kobus and Koschitzky, 1991). Analysis of the model results indicates that this is generally the case.

The adopted model domain demonstrates the following characteristics:

- A 40 m length at prototype scale for development of flow conditions at the upstream end of the model relative to the first flood mark inside the model domain;
- A model length of 370m at prototype scale finishing at Alice Street. The flow at this location was determined to be more or less perpendicular to the model domain boundary from the pilot numerical model results. Note that the distance between the downstream model boundary and the furthest downstream flood mark is 30 m; and
- A model width of 150 m at its widest perpendicular transect.

The final physical model was constructed to be 12.5 m long 5 m wide and included 59 buildings.

5.1. Steady-State Model Assumption

An analysis was completed to investigate whether the physical model could be run as a steady state model. Manipulating inflows to a physical model, while possible, adds another level of complexity to the model operation. Running the model as a steady state model at the flow peak negates the need for programmable flow controller for model inflows and allows for numerous measurements at the peak floodplain conditions to be made without having to repeatedly re-run the model.

The requirement for a variable inflow control to represent the flood hydrograph is necessary if the flow volume on the floodplain is influencing/controlling flood behaviour in terms of the flood depths and flow distributions. If the floodplain holds a large volume relative to the volume of flow in the flood hydrograph, then a steady-state assumption could be violated as the peak of the hydrograph may not be of a sufficient duration to satisfy this volume, resulting in an overestimation of flood inundation. Using the pilot model results, analysis showed that the inundation area is approximately 25,000 m^2 with an approximate average flood depth of 0.5 m. This is a volume of 12,500 m^3, which, filling at a rate of 20 (19.7) m^3/s would take 10.5 minutes to fill. This is a comparatively short period given that the period of peak rainfall intensity for the June 2007 storm was approximately 2 hours. On the basis of the hydrograph developed using the WBMN presented in Figure 9 the floodplain was filled 21 times over during the June 2007 event with the peak inundation volume replaced in approximately 15 minutes (prototype) at the peak of the flood. On the basis of this assessment, the amount of storage on the floodplain was not considered to be a factor in determining peak flood levels and as such the physical model was run in steady state.

5.2. Model Construction

The physical model was constructed in Laboratory 2 at the Water Research Laboratory's facility at Manly Vale, Sydney, NSW. The model was constructed to scale by first producing a digital, distorted scale topography. The scaled digital topography was then used to produce templates representing the model topography at 600 mm (model) intervals. The templates were laser cut by a sub-contractor to ensure vertical accuracy to +/- 1 mm. The location of the templates is presented in Figure 12.

Figure 12: Model Templates and Building Footprint Alignment

A perimeter wall was constructed and the templates aligned using surveying techniques (See Figure 13). Road base was used to fill between the templates. Areas of rapidly varying terrain between the 600 mm spaced templates were surveyed independently and levelled in using steel pins. The model surface was capped in sand/cement mix and finished by hand (see Figure 14).

Figure 13: Template Installation

Kerb and guttering was applied as a secondary detail. Kerbs are approximately 20mm high in the model. As it was expected that residential driveways could also influence the flow patterns in the model, these were also surveyed for location and included in the finished model surface.

Buildings were constructed to scale based on building footprints determined from aerial photography and from site inspection as described below.

Figure 14: Finished model with Buildings Installed

5.2.1. Physical Model: Representation of Buildings

Each building within the model area was included in the physical model. Buildings were constructed to scale using plywood. Each building was constructed to scale to match the building footprint of the external walls. The buildings were located in the model using surveying techniques. Each building was then cut to match the local topography with the end result being that the building walls matched the model surface to within 1 or 2 mm. The 1 – 2 mm gap at the base of the building walls was large enough for water to enter the buildings, but not large enough to allow water to flow freely through the buildings. As a result, the water level achieved inside the buildings during model simulation was approximately equal to the hydraulic head of the flow outside the buildings.

Eight out of the 59 buildings in the model area are constructed on stumps in the prototype. These buildings have a façade on the street facing wall which is typically bricked to ground level and therefore inhibiting flow under the house from the front, but allowing flow under the house from the remaining 3 sides of the building. These buildings have been included with solid outside walls on the building footprint in the present physical model. The influence on flow behaviour by buildings on stumps may be tested in the physical model at a future date.

5.3. Model Validation

The physical model was validated by comparing the recorded peak flood levels from the June 2007 flood with the flow surface level in the physical model. The available peak flood levels in the physical model domain are listed in Table 4.

Table 4: Physical Model: Comparison of Modelled and Recorded Peak Flood Levels

Point ID	**Recorded Flood Elevation (m AHD)**	**Physical Model Water Level (m AHD prototype)**
MWR_0042	23.36	23.27
MWR_0043	23.14	23.05
MWR_0044	23.01	22.92
MWR_0031	19.98	19.89
MWR_0032	18.38	18.29

The recorded peak flood levels from June 2007 were generally located on residential properties. These levels were located in the model and the heights levelled on the appropriate buildings using surveying techniques. Flow surface levels achieved in the physical model were within 90 mm at prototype scale. While there was some variation of the flow levels along building walls, both up and down, it should be noted that all flow surface levels in the physical model were generally lower than the equivalent recorded flood marks. An example of the match of water levels in the model is presented in Figure 15 where the black pen marking represents the peak flood level recorded for the June 2007 event.

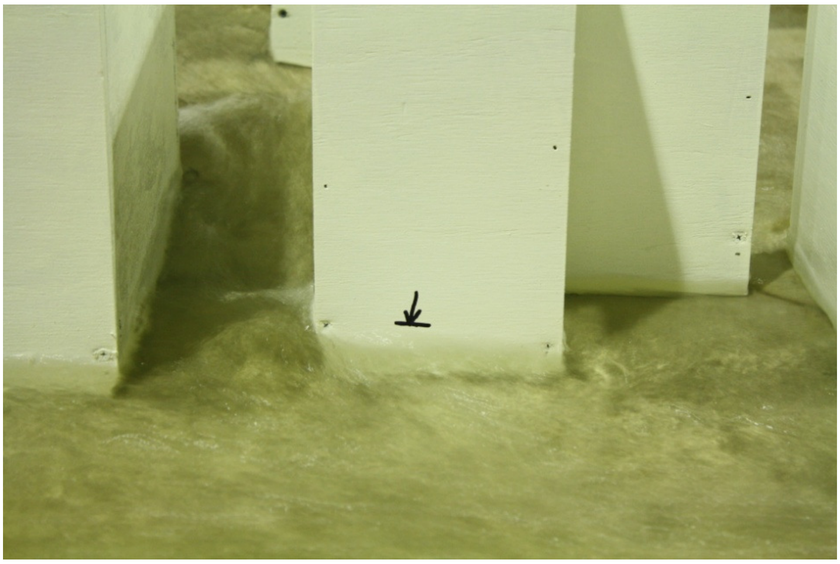


Figure 15: Physical Model: Typical Match to Recorded Peak Flood Levels

It must be noted that even though the model was steady state, variations in water levels were observed as pressures and transient flows varied. This would also be expected in the prototype.

The match of peak water levels in the model to within 90 mm (prototype) of the recorded levels was within an acceptable range for a flood study and the calibration was considered good. Brief investigations showed that water levels in the model could be raised by increasing the model roughness. However, with a good calibration already achieved and in consideration of both internal (WRL) and external funding constraints, further model calibration was not considered necessary.

Sensitivity testing of the models is discussed further in Section 6.4.

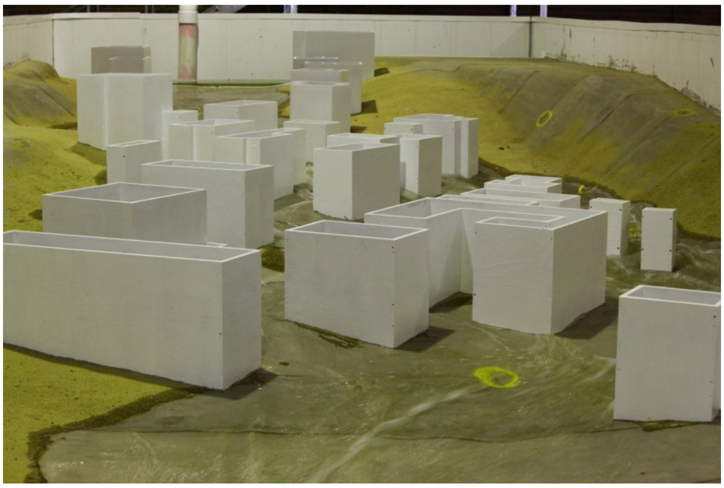


Figure 16: Physical Model Flood Extent - Oblique

Additional photos of the operational model showing flood inundation extents are presented in Figures 16 and 17. Anecdotally, the flow behaviour observed in the physical model generally matches the descriptions available from eye witnesses to the flooding. The authors anticipate continued debate as to whether the method applied to represent houses in the physical model was representative of prototype houses. Video footage of recent flood events in Queensland has demonstrated that irrespective of the amount of flow volume inside the building, if the building remains standing the flow field around the house will be deflected by the house. The amount of deflection could be quantified by further detailed measurement and analysis of flows around the houses and flow around houses of different construction e.g. slab on ground versus on piers. While this could be investigated using the existing model it was considered outside the scope of the present project. It is the author’s opinion that the currently applied method for including buildings in the physical model is representative of slab on ground construction which is prevalent in the Merewether floodplain.

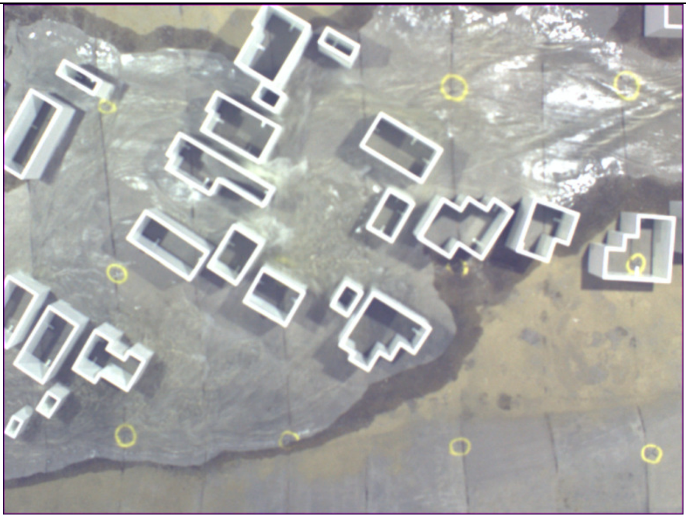


Figure 17: Physical Model Flood Extent - Overhead View

In the process of building and testing the physical model, numerous comparisons were made of the flow extent, water surface profile and flow depths, speeds and directions. While the bed roughness no doubt contributes to the modelled flow behaviour, in the author's opinion the observed prototype depths and water surface profile could not be reproduced in the model by increasing the bed roughness alone. While it warrants further detailed investigation, it is the author's opinion, that in an urban environment such as the subject site at Merewether, the influence of the buildings on flood flow by form loss due to flow contraction, expansion and re-direction has a larger and more dominant influence on flow behaviour and flood routing than that of "pure" bed friction. This conclusion is fortified by the observed result that by including the buildings in the model as flow obstacles, the peak flow depths and flood surface profile measured in the prototype flood could be adequately reproduced in the model. Unfortunately, further detailed analysis of this aspect of the model with respect to the quantification of the various contributions to head loss and flow routing by bed friction and building form loss is beyond the current study scope.

5.3.1. Fences and Other Floodplain Obstacles

A brief literature search on the subject of the influence of fences on urban flood flows showed that there is very limited knowledge documented on the subject. However, there is general agreement amongst flood professionals approached by the authors that fences will have some influence on flood flows both locally and potentially further afield. There is also an acknowledgement that in many instances, the influence on flows is either fully or partially negated by failure of the fence structure during the flood event.

There is certainly evidence of fence failure in the Merewether Heights floodplain event of June 2007. An inspection of the site observed numerous fences on the overland flow path which showed obvious signs of repair. On the site inspection on 10 August 2010, it was noted that many of the fences on the flood flow path had been recently repaired, presumably following the June 2007 flood. For example, the rear fence at 168 Morgan Street Merewether, where the premises were demolished post the flood, has a new rear fence as shown in Figure 18.

Figure 18: 168 Morgan Street Post House Demolition

The degree to which the fence collects debris during the flood event may also impact the local flow behaviour.

Analysis of recorded peak flood levels and model results from the June 2007 flood in Merewether showed that for a large flood i.e. circa 1:100 Annual Exceedance Probability (AEP) at that site, the assumption that all fences failed with the residual influence of fences on flows accounted for in the adopted macro-scale roughness coefficient was an adequate approximation and as such was adopted for this study.

It is acknowledged that the influence of fences on urban flood flows may be significant where the fence does not fail under the prevailing flood conditions. The flood conditions required for failure of fences of various construction types are largely unknown and warrant further investigation, which was considered beyond the scope of this study.

5.4. Flow Velocities and Flow Distributions

The physical model was then used to expand the available flow behaviour data set by measuring flow velocities and integrated flow discharges. Flow velocities were measured in the physical model using a hand held Streamflo Velocity Meter (Type 403) manufactured by Nixon Instrumentation Limited. This device was considered fit for purpose as it was designed to measure small velocities in shallow water depths.

A total of five velocity transects were measured in the physical model. The location of these transects is presented in Figure 19. Each transect is labelled by the closest property to its start and end point and is listed in Table 5.

Table 5: Summary of Velocity Transects

Transect Number	Description
1	175 Morgan St. – 172 Morgan St.
2	166 Morgan St. – 1 Arthur St.
3	11 Little Edward St. – 1 Arthur St.
4	4-6 Little Edward St. – 2 Little Edward St.
5	82 Wilton St. – 80 Selwyn St.

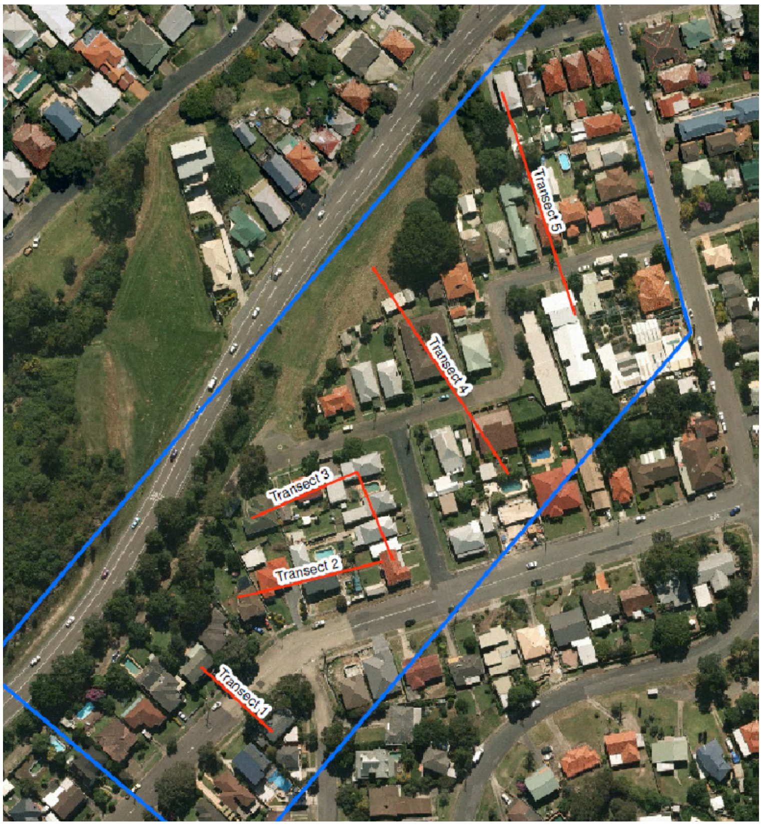


Figure 19: Overview of Flow Measurement Transects

As there were areas of quite shallow flows depths in the physical model, the flow velocity was generally measured at a single depth near the base of the flow column. However, where the flow was constricted between buildings, deeper flow depths allowed measurement at approximately the midpoint of the flow depth. Each transect was chosen to maximise measurement of velocities perpendicular to the transect and therefore allow integration of the flow discharge across the transect. For this reason, the transect from 11 Little Edward St to 1 Arthur Street (Transect 3) includes a right angle, as the flow between the buildings was in fact perpendicular to the transect direction. Although every effort was made to maintain velocity measurements perpendicular to the transect direction this was not always possible due to the rapidly varying flow directions in some parts of the model. In order to make the flow velocities directly comparable to the numerical model results, every attempt was made to measure them in the direction of flow, regardless of the transect direction. An example of the measured flow velocities is presented in Figure 20. Complete flow measurements for all sections are provided in Appendix A. The corresponding flow depth at each location was also recorded. Each point measurement has been assigned a unique identity number as presented in Appendix A.

Figure 20: Velocity Measurements: Transect 1

Flow velocities and depths at each location were integrated to provide a discharge estimate for each transect. The results of the calculated flow in each of the transects is summarised in the Table 6. Note that all transect flows presented in Table 6 have been scaled from model to prototype units and normalised to the inflow of 19.7 m^3/s. Where flow is separated by buildings, the flow is presented as the flow between those buildings in order to show the flow distribution.

Table 6: Physical Model: Summary of Measured Discharges

TRANSECT 1	Flow (m3/s)	Percentage	Scaled (m3/s)
175 Morgan - 172 Morgan	19.36	100%	19.70
TOTAL	19.36	100%	19.70
TRANSECT 2			
166 Morgan - 168 Morgan	6.48	29%	5.74
166 Morgan - 1 Arthur Garage	15.75	71%	13.96
TOTAL	22.23	100%	19.70
TRANSECT 3			
11 Little Edward - 9 Little Edward Garage	1.65	8%	1.49
9 Little Edward Garage - 9 Little Edward	8.57	39%	7.75
9 Little Edward - 5 Arthur Garage	3.54	16%	3.20
5 Arthur Garage - 5 Arthur	0.52	2%	0.47
5 Arthur - 3A Arthur	1.08	5%	0.98
3A Arthur - 3 Arthur	3.60	17%	3.25
3 Arthur - 1 Arthur Garage	2.82	13%	2.55
TOTAL	21.79	100%	19.70
TRANSECT 4			
4-6 Little Edward Garage - Edge of model	15.92	57%	11.18
4-6 Little Edward Garage - 4 -6 Little Edward	7.93	28%	5.57
4-6 Little Edward - 3 Little Edward	3.96	14%	2.78
3 Little Edwards - Edge of Model	0.25	1%	0.18
TOTAL	28.07	100%	19.70
TRANSECT 5			
82 Wilton - 82 Wilton Garage	0.40	2%	0.34
82 Wilton Garage - 77 Selwyn	2.00	9%	1.70
77 Selwyn - 80 Selwyn	20.72	90%	17.66
TOTAL	23.12	100%	19.70

Transect 1 was primarily used to verify the model inflow, as well as to validate the discharge integration methodology. A 2 % error in the flow at Transect 1 indicated that the methodology as applied is valid. The integrated discharge at each of the remaining transects has been overestimated compared to the inflow as a result of measuring peak velocities in the direction of flow, which is not entirely accurate given that the flow direction was not always perpendicular to the transect. This is supported by the fact that Transect 1 and Transect 3 were the most accurate and these both exhibit the most perpendicular flow to the transect direction. For Transect 1 this is because the flow is channelled down Morgan Street, and in Transect 3 the flow is channelled between the buildings. Assuming the errors for measurement are uniform across each transect measurement the flow was normalised so that the total flow was equal to the applied model inflow flow of 19.7 m^3/s. The tabulated results are presented graphically in Figure 21.

Figure 21: Physical Model: Measured Flows (m^3/s)

Qualitative assessment of the inflow directions around buildings was also observed. Typically, it was observed that buildings represented in the physical model had a significant influence on both flow direction and flow levels, with buildings having flow build up at the upstream side of the residence and change direction to flow around the building. Flows through gaps between buildings were typically observed to accelerate through these spaces with an associated reduction in water surface level. This correlated well with video footage of flow around buildings in the recent Queensland floods of January 2011 and anecdotal evidence provided by residents in Newcastle recalling observations of the June 2007 flood. Figure 22 demonstrates the observed influence of buildings on the flow.

Figure 22: Physical Model: Observed Influence of Buildings on Flow Direction and Level

On the basis of experience gained calibrating the physical model, it was noted that accurate representation of the model topography and buildings was of greater importance and had a greater influence on the modelled flow behaviour paths than the influence of the model roughness (Note: Model roughness was not presently adjusted since flow behaviour representation was considered fit for purpose).

5.1. Assessment of the Importance of Flooded Volume in Buildings

A recurring theme noted in the project literature review is that the volume of flow temporarily stored inside flooded buildings during a flood has an influence on the observed flood flow behaviour in terms of peak water levels and flow velocities on the floodplain. The implication is that the volume of flow stored inside the buildings is a significant proportion of the flow hydrograph passing through the floodplain.

The relative proportions of hydrograph volume and flow volume temporarily stored in flood affected buildings have been compared using results observed in the physical model. The flow hydrograph at the Morgan Street site as predicted by the WBNM model is represented in Figure 23. The volume of the hydrograph in the period indicated by the red arrows represents the flow volume during the flood causing peak of the storm. The flow volume calculated as moving through the floodplain through the indicated period is 124,015 m^3. There are 59 buildings on the section of floodplain included in the physical model. Observations of flooded water level within the flood affected buildings (see Figure 24) show that flood depths *inside* the buildings are no more than 0.5 m deep. If all buildings are assumed flooded to 0.5 m depth, then the total volume of flow inside the buildings is 2,790 m^3 or approximately 2% of the total volume in the highlighted section of the hydrograph.

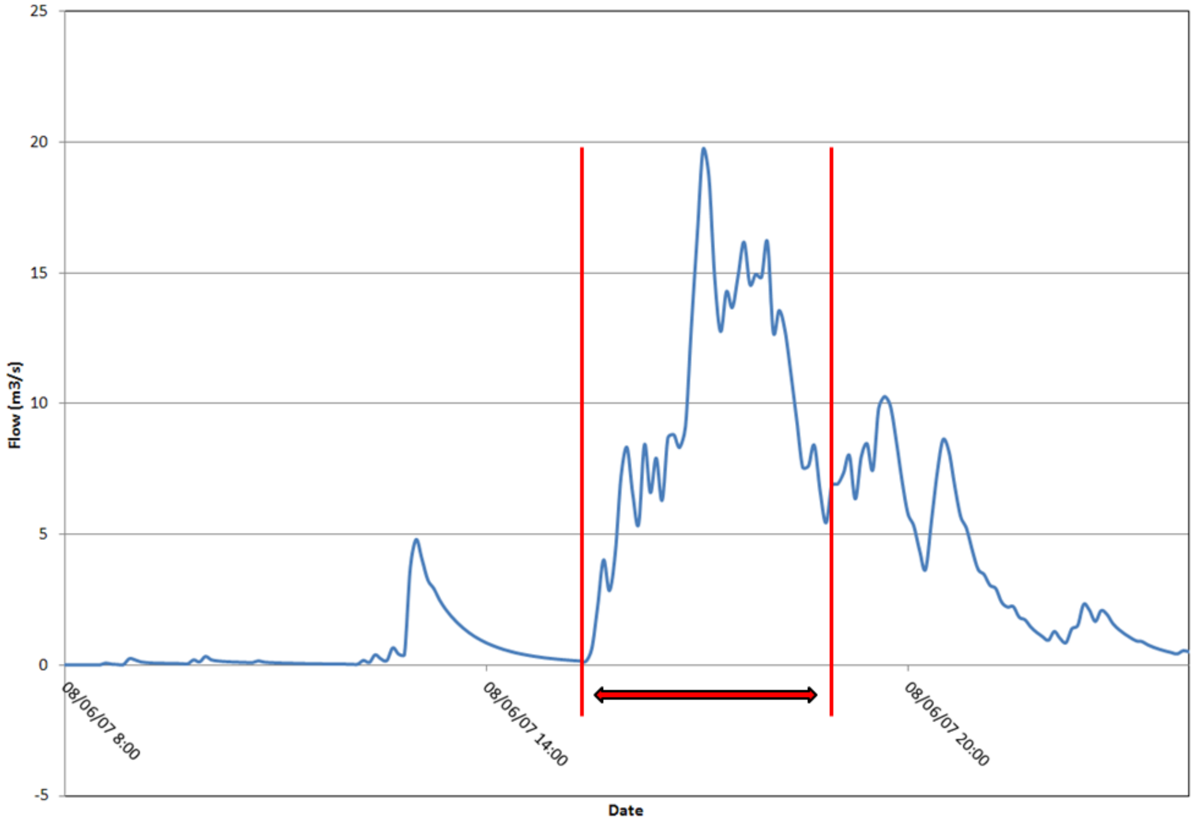


Figure 23: June 2007: Flow Volume Calculation

Figure 24: Physical Model: Flow Volume inside Buildings

A comparison of flow behaviour around a building was performed by comparing flow conditions nearby a building in the physical model with flow allowed inside and a building which was sealed to exclude flow from entering the building. No difference in flow behaviour could be observed or measured. On the basis of the calculated volume ratios and the absence of an observable difference in flow behaviour, it was concluded that the inclusion of the flow volume potentially inside a building during flood would have an insignificant influence on flood behaviour outside the buildings. This conclusion supports the findings of Brown *et al*. (2007) who also concluded that the volume of flow stored inside buildings on an inundated floodplain was insignificant.

6. Numerical Modelling

6.1. Scope

The scope of the numerical modelling exercise was determined on the basis that the following two questions needed to be addressed:

1. Is there a preferred method(s) to represent buildings in a 2D Numerical Model?
2. Do the buildings need to be 'physically' represented in the model topography?

Numerical modelling was undertaken using two commercially available software packages, TUFLOW (2009) and MIKE FLOOD (DHI, 2009). These were chosen on the basis of the literature review and in consideration of WRL's access to the software. Future application of alternative software packages is envisaged.

6.2. Model Development and Validation

The TUFLOW and MIKE FLOOD models were developed using identical data sets. The topography adopted for the numerical models was identical to that used as the basis of the physical model. The model topography was adjusted at the upstream and downstream boundaries to enable flows to enter and leave the model domain without flooding and drying of the model grid on the boundary, a common source of model instabilities. The models were run using the flow hydrograph presented in Figure 9 with a constant downstream water level of 17.8 m AHD. Model roughness was set using a roughness map developed on the basis of values typically adopted in urban flood studies. Adopted Manning's 'n' roughness values were applied as listed in Table 7.

Table 7: Numerical Models: Adopted Manning's 'n' Roughness Values

Surface	Manning's 'n'
Roads	0.020
Other areas	0.040

These roughness values were adopted following a calibration process, which involved adjusting model roughness parameters until a reasonable fit with recorded peak flood levels was achieved. The calibration adopted a model topography on a 1 m grid resolution with building footprints excluded from the model calculation. A comparison of the modelled and recorded peak water levels is provided in Table 8.

The 1 m grid was adopted as a base case as it represented the prototype grid spacing that enabled at least two computational grid points in between all buildings in the model grid.

The results show a reasonable match of modelled and recorded values has been achieved. Remarkably, the MIKE FLOOD and TUFLOW model results are within centimetres of each other. This was also found to be the case at coarser grid resolutions.

Table 8: Numerical Model: Comparison of Modelled and Recorded Peak Water Levels

Point ID	Recorded Flood Elevation	MIKE FLOOD Peak Water Level (m AHD)	Difference (m)	TUFLOW Peak Water Level (m AHD)	Difference (m)
MWR_0042	23.36	23.57	0.21	23.56	0.20
MWR_0043	23.14	23.10	-0.04	23.11	-0.03
MWR_0044	23.01	22.79	-0.22	22.77	-0.24
MWR_0031	19.98	20.09	0.11	20.08	0.10
MWR_0032	18.38	18.34	-0.04	18.36	-0.02
MWR_0033	18.65	18.67	0.02	18.59	-0.06

6.3. Overview of Floodplain Flow Conditions

Observations of initial simulations of the physical model at the simulated June 2007 historical scale flows indicated that flow on a large proportion of the modelled floodplain was supercritical. Flows were observed to be generally supercritical on open areas and were seen to form hydraulic jumps at the front of obstacles to flow (buildings) as shown in Figure 25. Flow in the hydraulic jumps was re-directed sideways by the buildings before accelerating again downslope to supercritical.

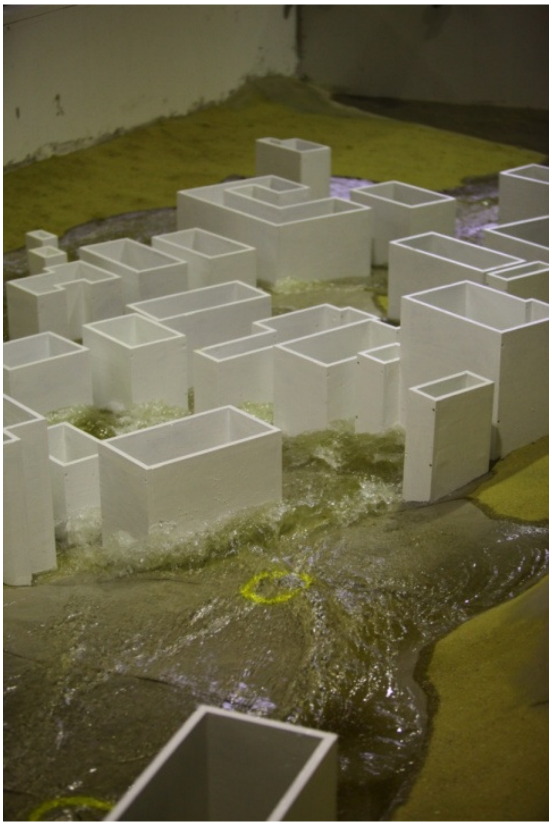


Figure 25: Physical Model: Observed Super-critical Flow

Pilot numerical modelling for the same June 2007 scale flood conditions was assessed to determine whether the numerical models also indicated that flow in the test floodplain was predominantly supercritical. The model results presented in Figure 26 from the MIKE FLOOD model show that to be the case for a ‘natural’ floodplain i.e. the existing floodplain without buildings in place. Flood flows are shown to be supercritical for most of the floodplain except for locations where the flow is being influenced by rapid changes in the topography.

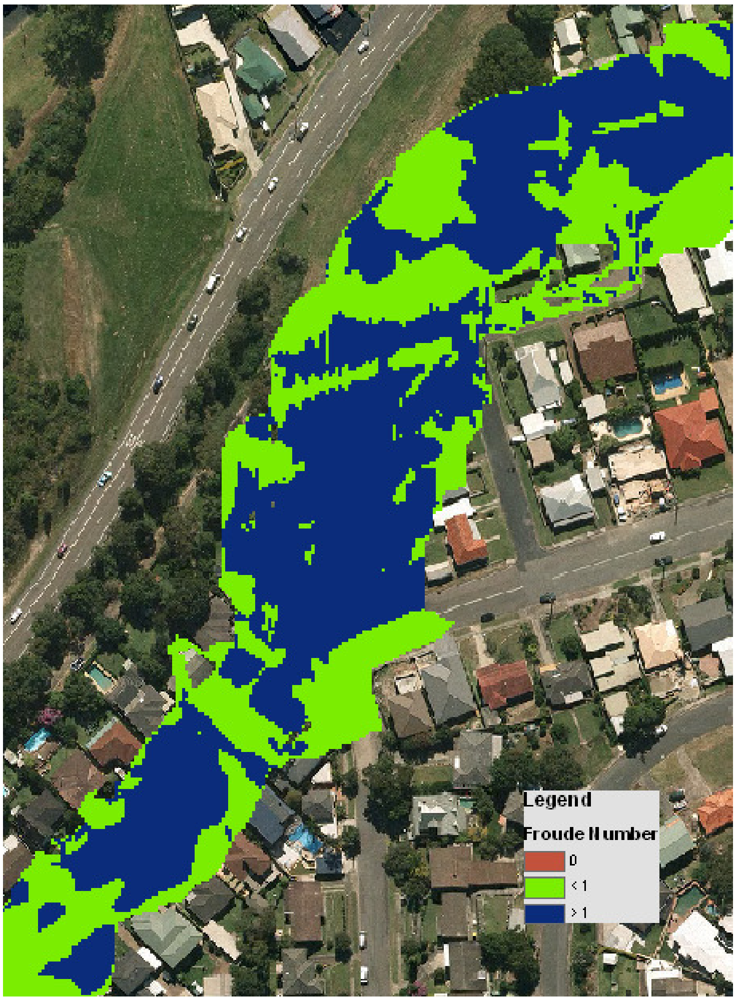


Figure 26: Numerical Model: Froude Number Analysis for the Merewether floodplain without Buildings

Supercritical flow conditions are a stern test of both physical and numerical models. While the software code for both MIKE FLOOD and TUFLOW solves the shallow water equations, which are generally for representation of subcritical flow conditions, the codes have been adapted to provide approximate solutions for supercritical flows.

In MIKE FLOOD these code adaptions involve selective ‘upwinding’ of the influence of convective momentum terms locally in the solution scheme with increasing Froude Number. The rationale behind this approach is that the introduction of numerical dissipation at high Froude Numbers can be tuned to be roughly analogous to the physical dissipation caused by increased levels of turbulence. This approach has been demonstrated to adequately reproduce supercritical flow phenomena for standard test cases, with approximate results only in transition zones from supercritical to subcritical flow and vice versa.

In TUFLOW the code adaptions include a test to determine whether the flow in each grid square is upstream or downstream controlled and a check for Froude Number. Where flow is found to be upstream controlled and supercritical, TUFLOW automatically switches to an upstream controlled friction flow solution (see TUFLOW, (2009) for more details). Similarly to MIKE FLOOD, this approach has been demonstrated to adequately reproduce supercritical flow phenomena for standard test cases, with approximate results only in transition zones from supercritical to subcritical flow and vice versa.

The selected test site is not unique in this regard, with supercritical flow expected to occur in many urban floodplains around Australia.

6.4. Comparison of Physical and Numerical Models

Both the physical and numerical models have been developed and validated on the basis that they are representative of the prototype floodplain. It is recognised that both models have inherent assumptions and limitations in their formulation and parameterisation which limit their accuracy when compared directly to the prototype.

While the peak water levels determined using the physical and numerical models were generally within a range typically acceptable for model calibration at calibration locations, there were some marked differences in flow velocity and depth distributions for the models as validated. Figures 27 and 28 demonstrate the differences recorded at Transect 1, which is representative of a straight section of road reserve with reasonably constant cross sectional shape.

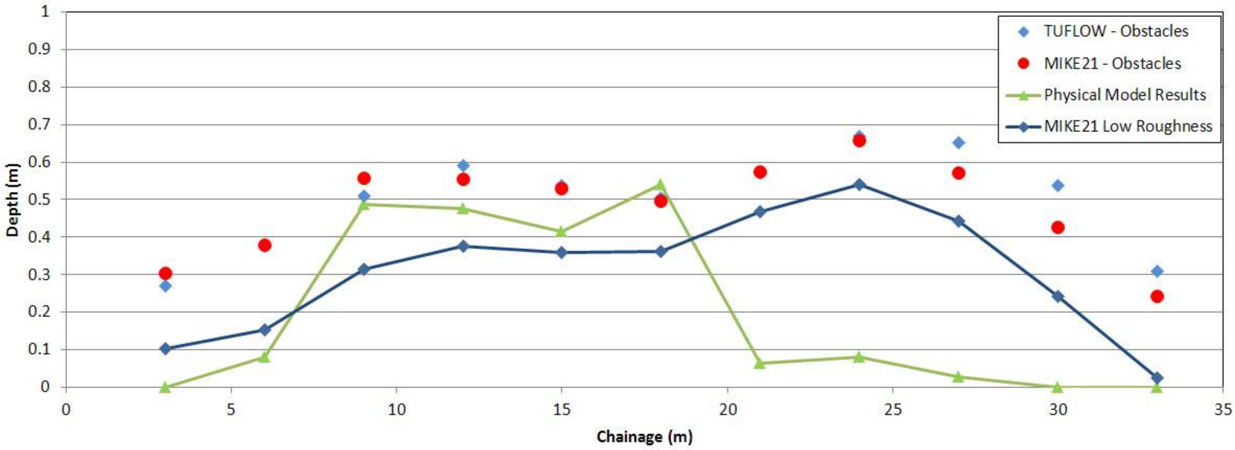


Figure 27: Comparison of Physical and Numerical Model Levels at Transect 1

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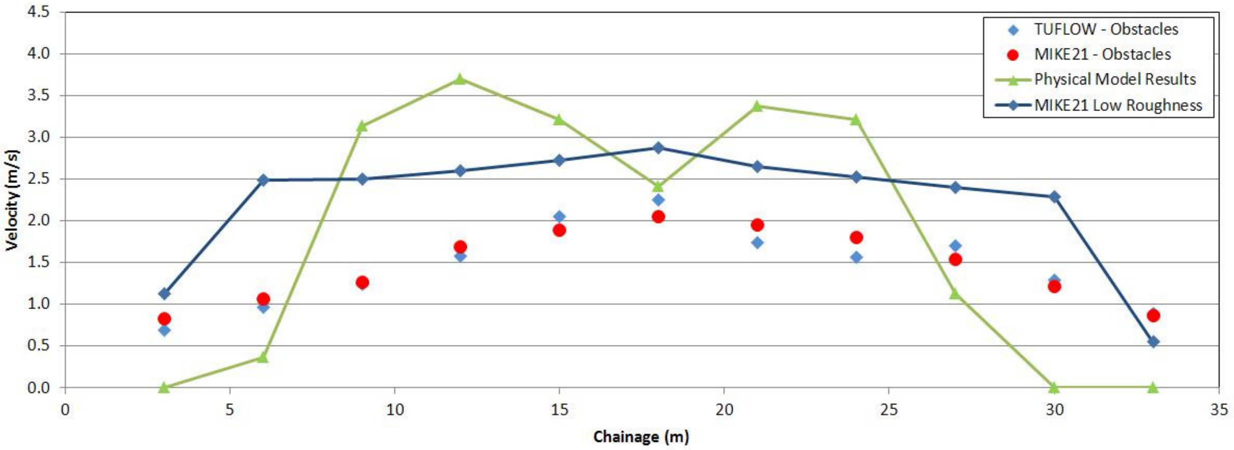

Figure 28: Comparison of Physical and Numerical Model Velocities at Transect 1

Figures 27 and 28 show that there is a general trend for the numerical models to ‘smooth’ out the flow representation, with the physical model exhibiting faster, deeper flows at the centre of the transect. Integration of flow depths and flow velocities for discharge volume demonstrates that both models are conserving mass, nonetheless with quite variable ranges of flow velocity and depth distribution.

A comparison of all measured model depths and velocities at all locations is provided in Appendix B. The results in Appendix B show that there is a general trend for the physical model velocities to be higher and more concentrated in the centre of flow paths compared to the numerical model. Observations of the physical model running at a steady flow rate show that there is a tendency for the physical model flows to oscillate with higher order 3D wavelets super-imposed on the ‘averaged’ flow. The numerical models have a tendency to provide a ‘smoother’ solution to the flow behaviour presumably as a result of the approximation to ‘real’ flow conditions. This is imposed by the assumptions inherent in the 2D shallow water wave approximations used in these models and the associated numerical diffusion and dampening inherent in the algorithms used to solve the process equations.

Peer review of the draft project results further noted that the physical model as constructed had a bed friction coefficient that was, at a Manning’s “n” value of approximately 0.015 (model), significantly lower than the Manning’s “n” coefficients adopted for the numerical model which ranged from 0.020 for roads and 0.040 for other areas (prototype). By way of further comparison, sensitivity testing of the numerical model to lower values of roughness coefficient was undertaken by assigning a Manning’s “n” value of 0.012 in the numerical model on the basis of the physical model scale ratios as described in Section 5. The results for the numerical model sensitivity test (shown in blue in Figures 27 and 28) for lower roughness demonstrated that on a straight, relatively uniform section of the modelled flow path at Transect 1, the lower roughness value resulted in an expected change of lower model depth and increased model velocity. However, the changed bed roughness did not influence the numerically modelled velocities to the extent that they matched the peak velocities in the physical model. Nor did the reduced roughness change the observed numerical model result of a “smoother” more distributed lateral flow distribution compared to the physical model’s more concentrated flows. Further, model sensitivity testing to eddy viscosity coefficient showed no demonstrable change in the lateral flow profile in the numerical models. The observation remains that the numerical models generally under predict the concentration and jetting of flows, particularly as the flows accelerate locally e.g. through spaces between buildings.

Analysis of the numerical model results for the Merewether floodplain with the buildings represented as obstacles provided further insight into the ‘smoothing’ of the numerical model results. Figure 29 shows a map of Froude number for peak flow conditions on the Merewether floodplain with buildings in place.

Figure 29: Numerical Model: Froude Number Analysis for the Merewether floodplain with Buildings

The numerical results show that the flow conditions in the models for this case are predominantly sub-critical over the model domain. This is not the case in the physical model, which demonstrates super-critical flow conditions predominating in most locations in the model domain. In the physical model, flows transition from super-critical to sub-critical to super-critical regularly as the flows pass down the floodplain. These transitions occur as the flows are obstructed by, and back up in front of, the buildings to form hydraulic jumps before the flow accelerates away between the buildings and back to the underlying super-critical energy state forced by the steep slopes of the natural topography (as demonstrated in Figure 26). The approximate solutions for super-critical flow conditions applied in the numerical models (as described in Section 6.3 are unable to respond to these rapid transitions and remain predominantly in a sub-critical state, which is the foundation of the process equations for these models.

The focus of the study is the influence of buildings on floodplain flows, and the physical model represents this aspect of the flow behaviour to a level that is fit for purpose to support the pragmatic focus of this investigation. The remainder of this report focuses on assessing the ability of 2D numerical models to reproduce the observed flow behaviour of the physical model.

6.5. Assessment of Numerical Model Grid Resolution

The influence of grid resolution on model results was tested by simulating models at four additional grid resolutions, using a 1 m grid as a base case, with buildings excluded from the model results. The additional grid resolutions tested were:

- 0.5 m;
- 2 m;
- 5 m; and
- 10 m.

The model topography was determined by resampling the base model topography at the various grid resolutions. In all simulations, the model roughness and other parameters were held constant. Results from each of the various model grid resolutions are presented below in Table 9.

Table 9: Numerical Model: Summary of the Influence of Grid Resolution on Peak Levels

Point ID	**Recorded Flood Elevation (m AHD)**	**1 m grid (m AHD)**	**0.5 m grid (m AHD)**	**2 m grid (m AHD)**	**5 m grid (m AHD)**	**10 m grid (m AHD)**
MWR_0042	23.36	23.57	23.43	23.58	23.36	23.61
MWR_0043	23.14	23.10	22.91	23.11	23.14	23.13
MWR_0044	23.01	22.79	22.69	22.77	23.01	22.85
MWR_0031	19.98	20.09	19.85	20.09	19.98	20.30
MWR_0032	18.38	18.34	18.12	18.20	18.38	18.67
MWR_0033	18.65	18.67	18.47	18.67	18.65	19.46

The model results show that similar peak water levels are maintained for the 1 m and 2 m grids. Some drift in peak water levels is noted outside the range of typically acceptable model calibration for the 5 m grid model with levels in the 10 m drifting by generally unacceptable increments. The 0.5 m model grid resolutions have also changes by a significant amount at some locations to the point where further consideration of model calibration parameters might need to be considered. Model peak flood depths and velocities for the various grid sizes are presented in Figures 30 to 34.

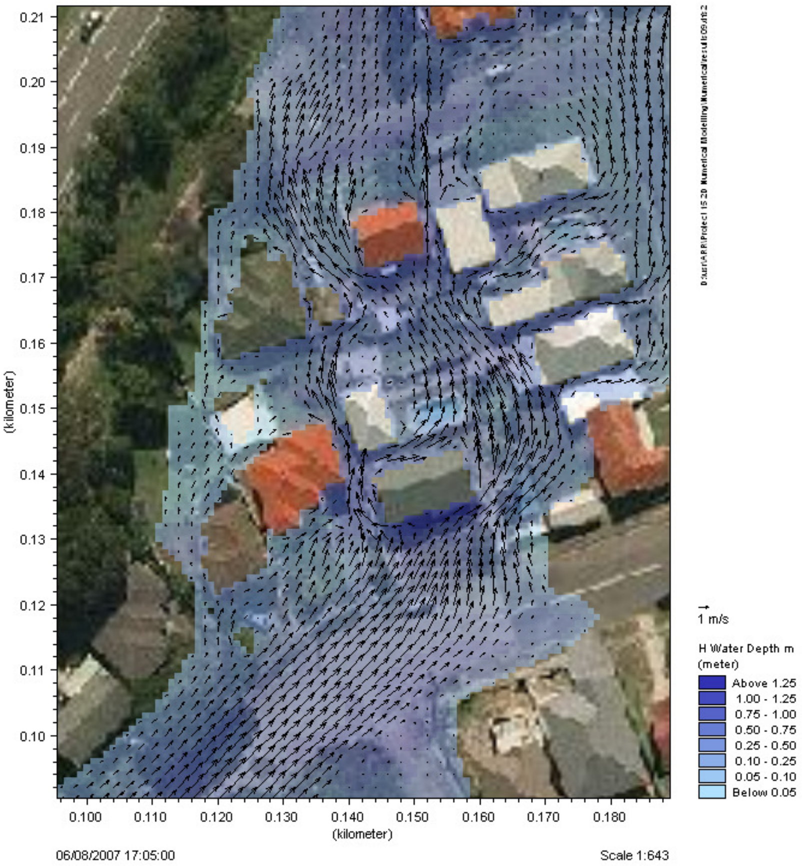

Figure 30: Numerical Model Depths and Velocities: 1 m grid buildings excluded from grid

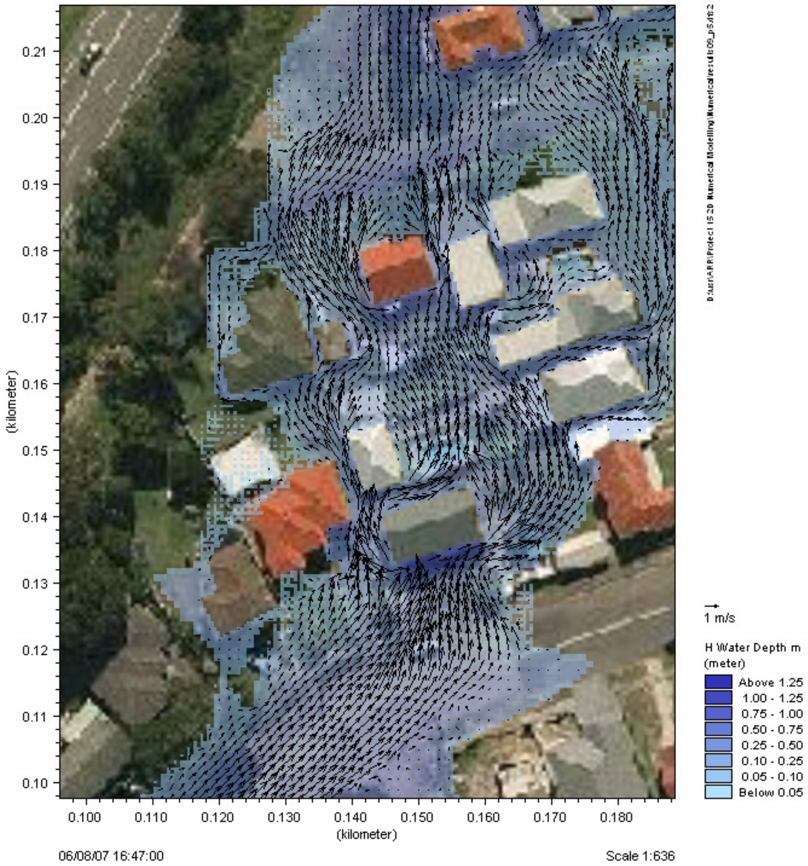

Figure 31: Numerical Model Depths and Velocities: 0.5 m grid buildings excluded from grid

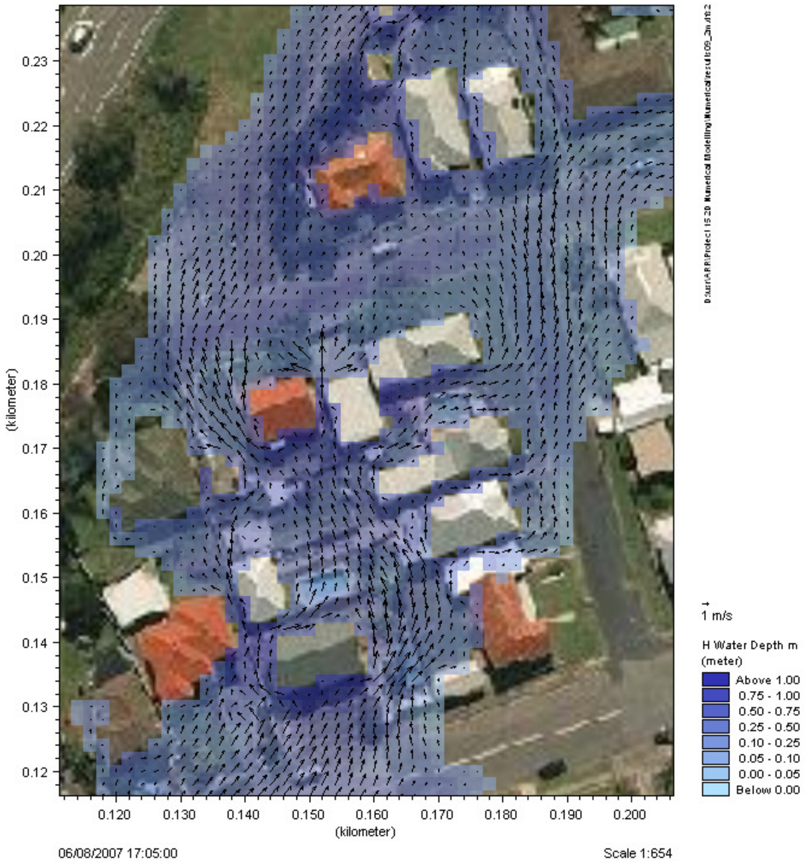

Figure 32: Numerical Model Depths and Velocities: 2 m grid buildings excluded from grid

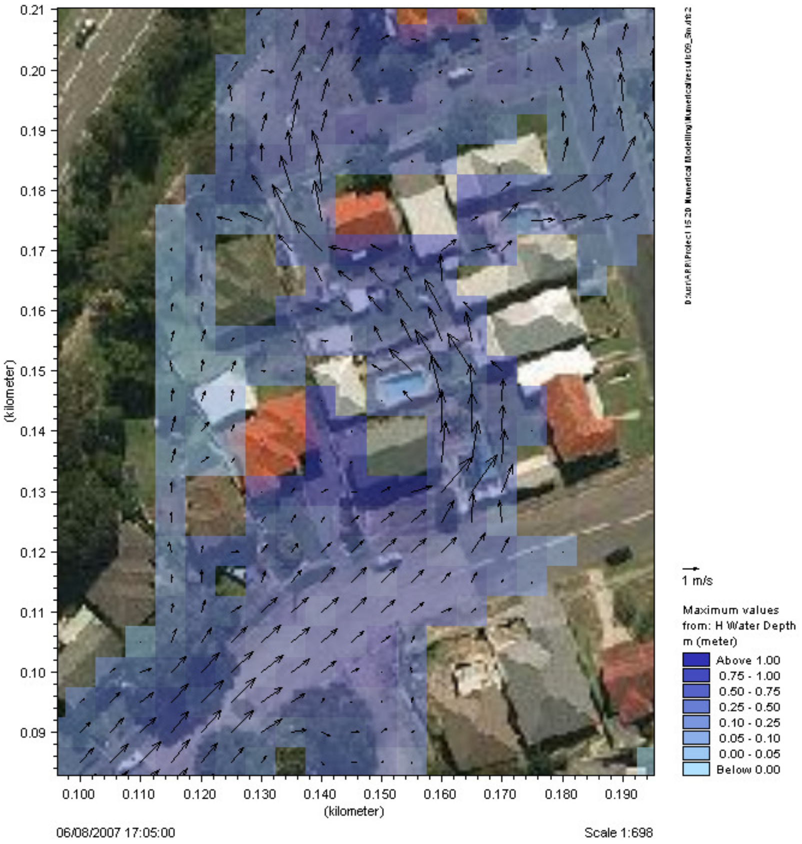

Figure 33: Numerical Model Depths and Velocities: 5 m grid buildings excluded from grid

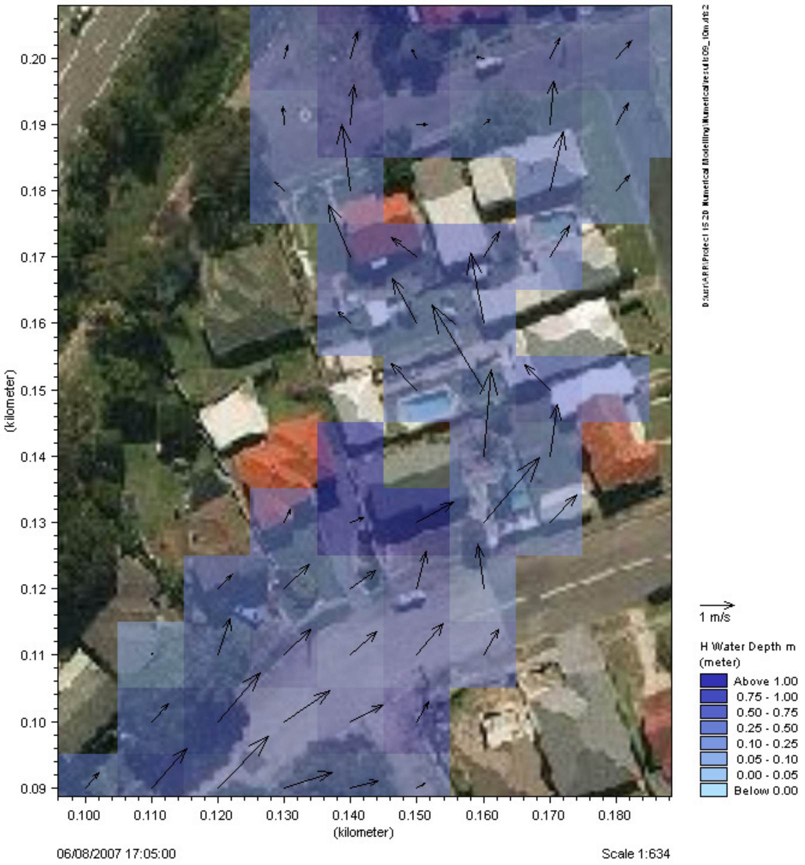

Figure 34: Numerical Model Depths and Velocities: 10 m grid buildings excluded from grid

These figures show that the flow directions and velocities are reproduced consistently between the 0.5 m and 1 m grids. Flows at the 0.5 m, 1 m and 2 m grids generally match flow directions observed in the physical model. Some minor changes are observable in the 2 m grid. Flow directions and flow path representation is noticeably different at the 5 m grid size and at the10 m grid resolution, numerous flow paths are either not represented or the flow direction and magnitude has markedly changed from the finer grid sizes. Flow velocity measurements at all grid resolutions are presented in detail and compared to the physical model in Appendix B. Analysis of the model results shows that measurements taken in the centre of a flow path are generally under-represented by the numerical models, while flow velocities at the extremes of flow paths are generally over estimated by the numerical models.

6.5.1. Hazard

The provisional flood hazard (the product of velocity and depth) for each grid resolution has also been compared. Figures 35 to 39 show that generally, as grid size increases, the magnitude and resolution of flood hazard in flow paths decreases. This is true for all increases in grid size including the change from a 1 m grid to a 2 m grid resolution where the peak flood depth and flow directions are generally in agreement.

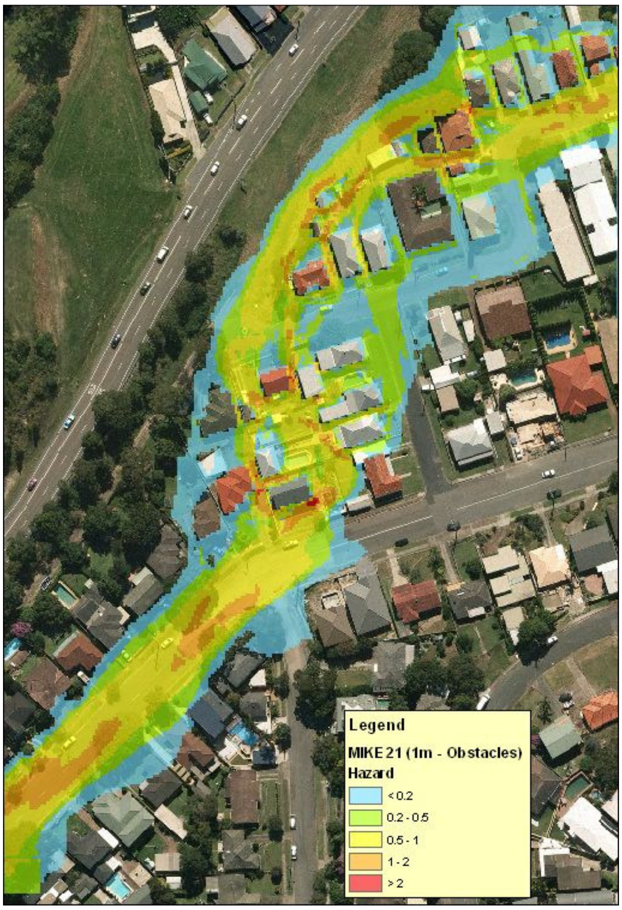

Figure 35: Numerical Model Flood Hazard: 1 m grid buildings excluded from grid

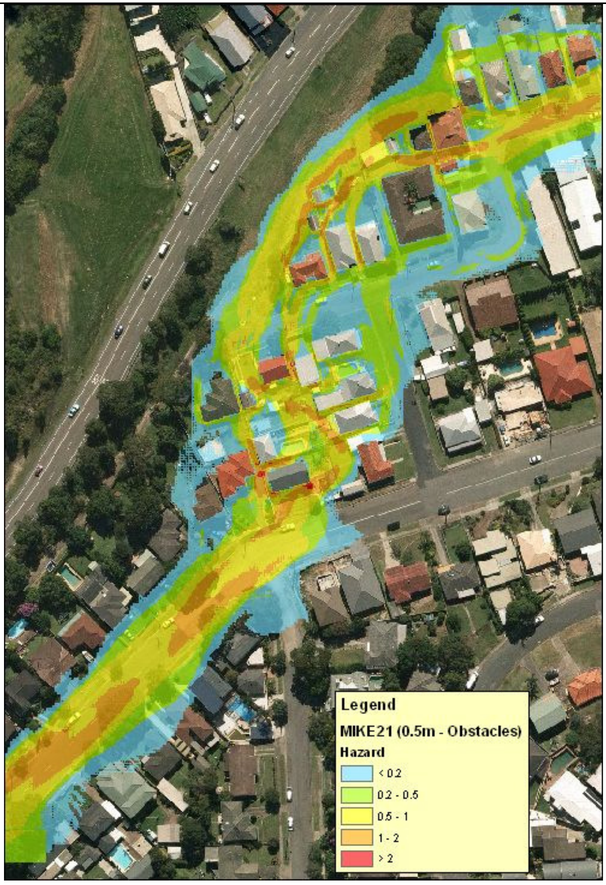

Figure 36: Numerical Model Flood Hazard: 0.5 m grid buildings excluded from grid

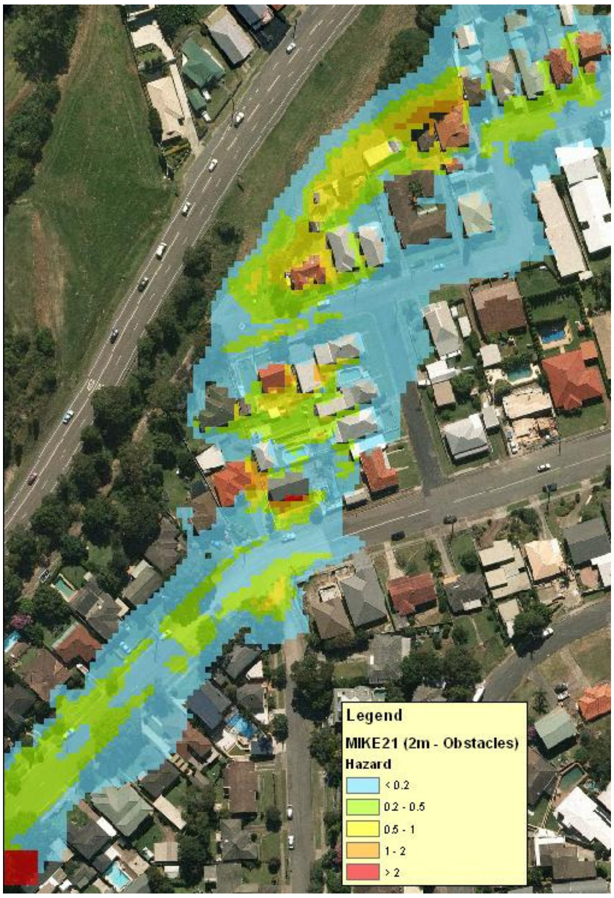

Figure 37: Numerical Model Flood Hazard: 2 m grid buildings excluded from grid

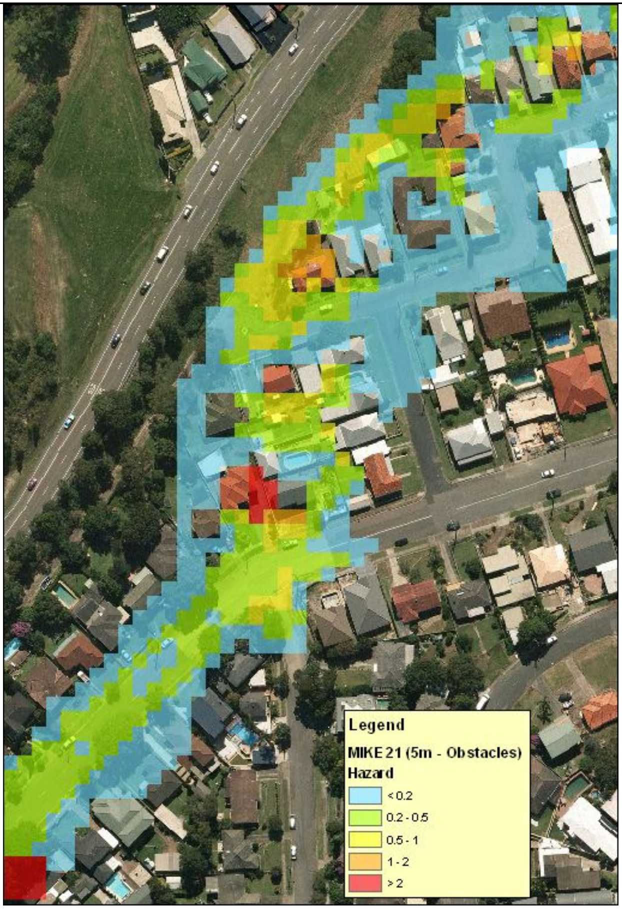

Figure 38: Numerical Model Flood Hazard: 5 m grid buildings excluded from grid

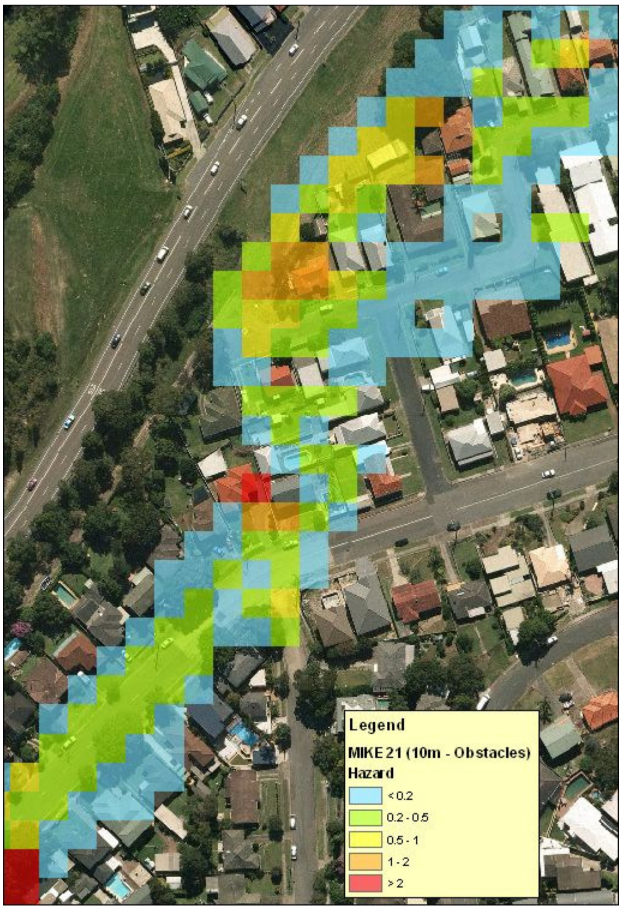

Figure 39: Numerical Model Flood Hazard: 10 m grid buildings excluded from grid

A concerning aspect of the hazard comparison is that the 5 m and 10 m grid results generally under-predict hazard with lower hazards in areas where the 0.5 m and 1 m grid models present higher hazards. The implication of this is that flood studies completed with grid resolutions with 2D models on 5 m grids and greater may be under-estimating flood hazards both around buildings and along/over evacuation routes and that model results on coarser grid resolutions may not present 'warning signals' for dangerous flow conditions. Further investigation to determine whether there are methods/rules of thumb that can be applied to interpret dangerous hazard conditions from coarser grid model results is warranted.

6.6. Comparison of Building Representation Methods

Over the years, numerous methods for representing a building in a numerical model have been developed. These methods have been developed for various reasons, many of them to suit corporate mapping and GIS systems rather than on the basis of correctly representing flood flow behaviour.

The various methods of representing a building in a numerical model have been described in Syme (2008). These are:

a) Buildings removed from the grid;
b) Buildings as increased roughness;
c) Buildings as upstream walls only;
d) Buildings as downstream walls only;
e) Porous buildings; and
f) Form loss representation.

6.6.1. Buildings Removed from the Grid

Buildings can be represented within the model grid by adjusting the model topography. In this case the buildings are assumed to be impermeable with no flow volume able to enter the building footprint. Computational grid points can either be completely removed from the computational grid under the building footprint or the grid points in the topography under the building footprint can be raised so that they are above the highest anticipated flood level.

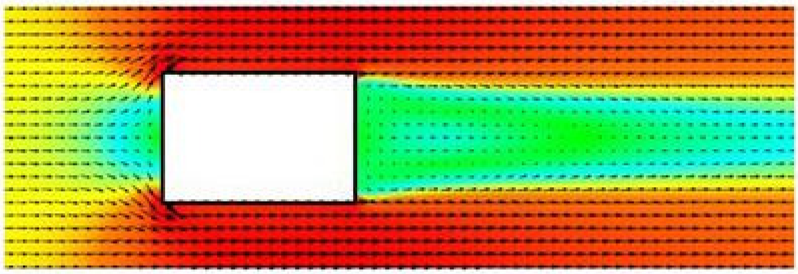

Figure 40: Building Removed from Grid (Syme, 2008). (Red shades indicate higher flow speeds. Arrows indicate velocity direction and magnitude)

6.6.2. Buildings as Increased Roughness

In this case, a higher roughness is applied to the computational grid under the building footprint. Ideally, the applied roughness value to represent buildings should be calibrated from case to case. The value of roughness coefficient required to reproduce observed flood levels may vary from floodplain to floodplain and with grid resolution. Syme, 2008 has applied a Manning's roughness value of 0.3. A value of 0.3 was also found to provide a reasonable match of peak flood levels in the Morgan Street test case used in this project.

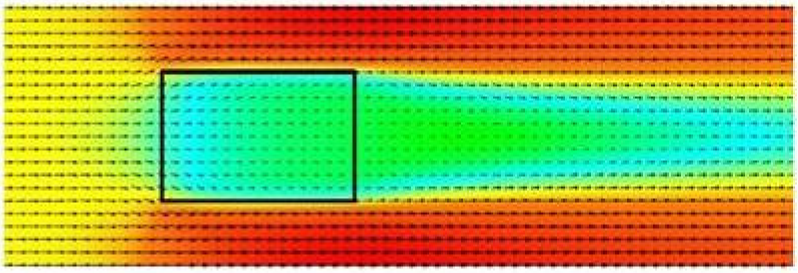

Figure 41: Building as Increased Roughness (Syme, 2008). (Red shades indicate higher flow speeds. Arrows indicate velocity direction and magnitude)

6.6.3. Buildings as Upstream Walls Only

Numerous flood studies in NSW have been completed with buildings represented with 'upstream' walls only. In this case, the building footprint is represented by one or more of the outer walls of the building perimeter. This causes the flow to be deflected by the building, but also allows flow to enter the building footprint, thereby allowing flood levels inside the building to be represented. This method requires manual interpretation of which walls represent the 'upstream', a process that can be time consuming. In some cases, where flows are complex or can reverse direction, it is somewhat problematic as to which direction is upstream. Figure 42 shows a portion of the project floodplain where flow directions can change several times in the space of 100 m. While this method might be applicable on smaller floodplains, applying the building walls to several thousand properties would require a significant and patient effort.

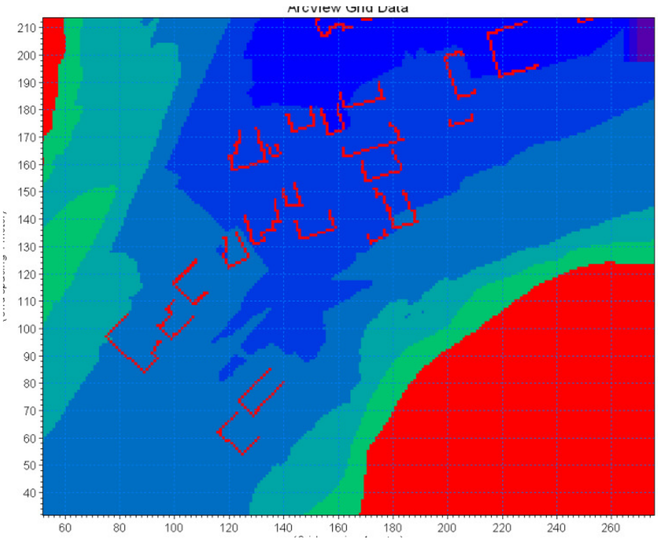

Figure 42: Building as Upstream Walls (Colour scale represents topography. Red indicates

cells removed from computational grid)

6.6.4. Buildings as Downstream Walls Only

An alternative method is to simulate representation of downstream walls. This method has a tendency to 'catch' flows initially before they are deflected around the building once it fills with water. Similar issues arise with the definition of 'downstream' in complex flow paths. Figure 43 shows a section of the project floodplain with downstream walls defined.

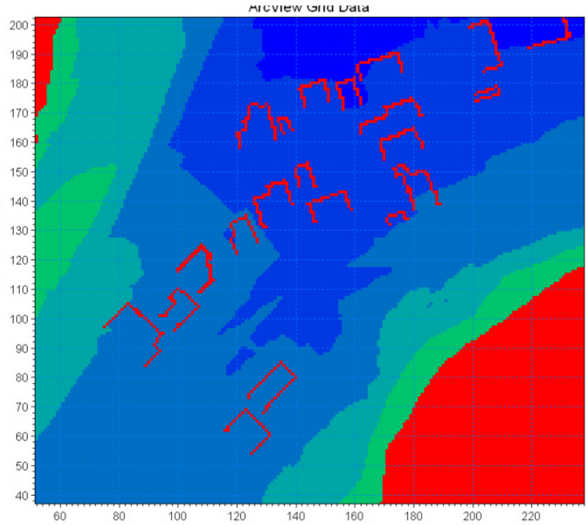

Figure 43: Building as Downstream Walls Only. Colour scale represents topography. Red indicates cells removed from computational grid)

6.6.5. Porous Buildings (TUFLOW)

The preceding methods for representing buildings are generic and therefore can be applied in any 2D hydrodynamic modelling software system. The TUFLOW software system (2010) also allows for buildings to be represented using two further methods. The first is to apply a porosity value to each element covered by the building footprint. The result of applying a porosity factor is to reduce the flow conveyance and flow storage volume at each element. The porosity value applied to each building would ideally become a calibration parameter.

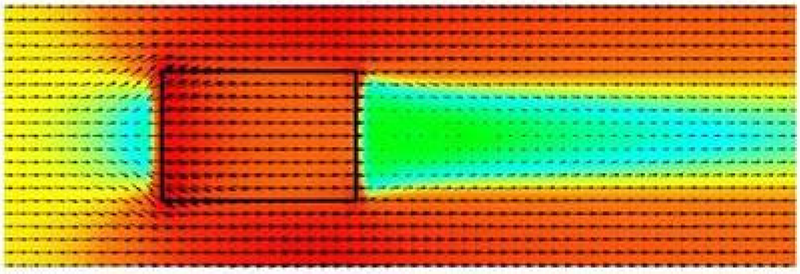

Figure 44: Building as Porous Elements (Syme, 2008). Red shades indicate higher flow speeds. Arrows indicate velocity direction and magnitude)

The authors are not aware of any investigation that recommends porosity values for buildings based on measured data sets. A porosity coefficient of 0.9 was adopted for this study based on the value used in Syme (2008).

6.6.6. Form Loss Building Representation (TUFLOW)

In a similar manner to increasing the roughness coefficient, TUFLOW allows buildings to be represented as a form loss factor. In this method, an additional 'head loss' factor is applied to each computational grid cell within a building footprint. The form loss factor is applied to the velocity head in each grid point as per the equation below:

$$\text{Form Loss} = C\frac{v^2}{2g}$$

where v = flow velocity
g = gravity
C = head loss coefficient

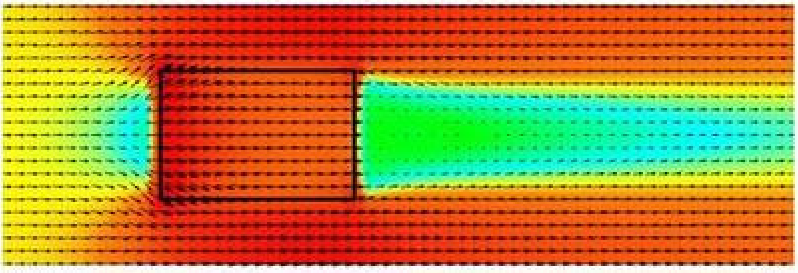

Figure 45: Building as Form Loss Elements (Syme 2008). Red shades indicate higher flow speeds. Arrows indicate velocity direction and magnitude)

Ideally, the form loss coefficient would be used as a calibration coefficient. The authors are not aware of any investigation that recommends form loss coefficient values for buildings based on measured data sets. The form loss coefficient is applied per metre length of the flow obstruction. A form loss coefficient of 0.1 was adopted for this project following review of the project model by TUFLOW's authors (Pers. comms Philip Ryan 18/03/2011).

These various methods were tested on a 1m grid resolution with all other parameters left constant to determine the impact on flow behaviour for each method.

6.6.7. Flood Level and Velocity

A summary of peak flood levels at the calibration locations for the range of building representation methods tested is presented in Table 10. A comparison of levels shows that the various methods are generally consistent for peak level at the sampled locations.

Table 10: Comparison of Building Representation Methods – Peak Water Levels

Point ID	Recorded Flood Elevation	Buildings as Obstacles	High Roughness	Upstream Walls only	Downstream Walls only	Form Loss Buildings	Porous Buildings
MWR_0042	23.36	23.57	23.57	23.56	23.57	23.56	23.56
MWR_0043	23.14	23.10	23.10	23.10	23.10	23.11	23.09
MWR_0044	23.01	22.79	22.77	22.79	22.81	22.72	22.77
MWR_0031	19.98	20.09	19.91	20.07	20.08	19.71	19.96
MWR_0032	18.38	18.34	18.28	18.33	18.37	18.30	18.38
MWR_0033	18.65	18.67	18.69	18.70	18.68	18.66	18.75

Figures 46 to 51 present maps of flow depth overlaid with flow velocity vectors. Figure 46 presents the case of buildings excluded from the model. The model results show an obvious deflection of flows by each building within the floodplain flow path. This flow behaviour shows a strong correlation to the flow deflections, directions and resulting flow structures observed in the physical model. While comparison of the flow structures (flow direction changes, decelerations/accelerations, eddies etc.) are somewhat subjective, it is the author's observation that this method of representing buildings in the numerical model is the best match with the flow behaviour observed in the physical model.

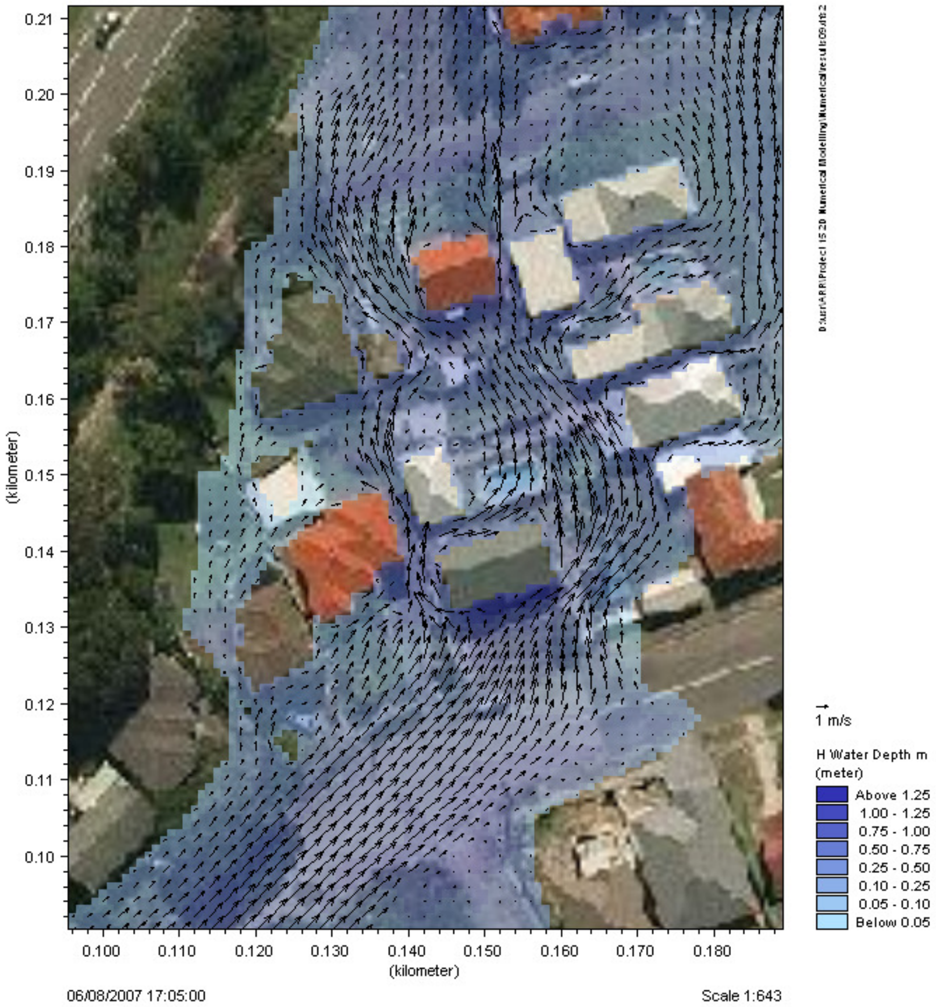

Figure 46: Numerical Model Depths and Velocities: 1 m grid buildings excluded from grid

An analysis comparing particle tracking techniques in the numerical model with Particle Image/Tracking Velocimetry (PTV/PIV) techniques in the physical model would be a valuable exercise in this regard. Unfortunately these methods are beyond the current project budget.

Figure 47 shows that representation of buildings using higher roughness results in a set of flow depths and directions near buildings that are somewhat different than the case with buildings excluded from the grid (and hence the physical model results). The model result with buildings represented as high roughness does not realistically represent the flow depths and directions adjacent to buildings as per the physical model. Flows basically pass through the buildings unimpeded in the numerical model, a phenomenon that is not anticipated at prototype scale. The lack of re-direction of flows by the buildings using this method is likely to over-estimate flow velocities inside the buildings and under-estimate flow velocities and directions outside the buildings.

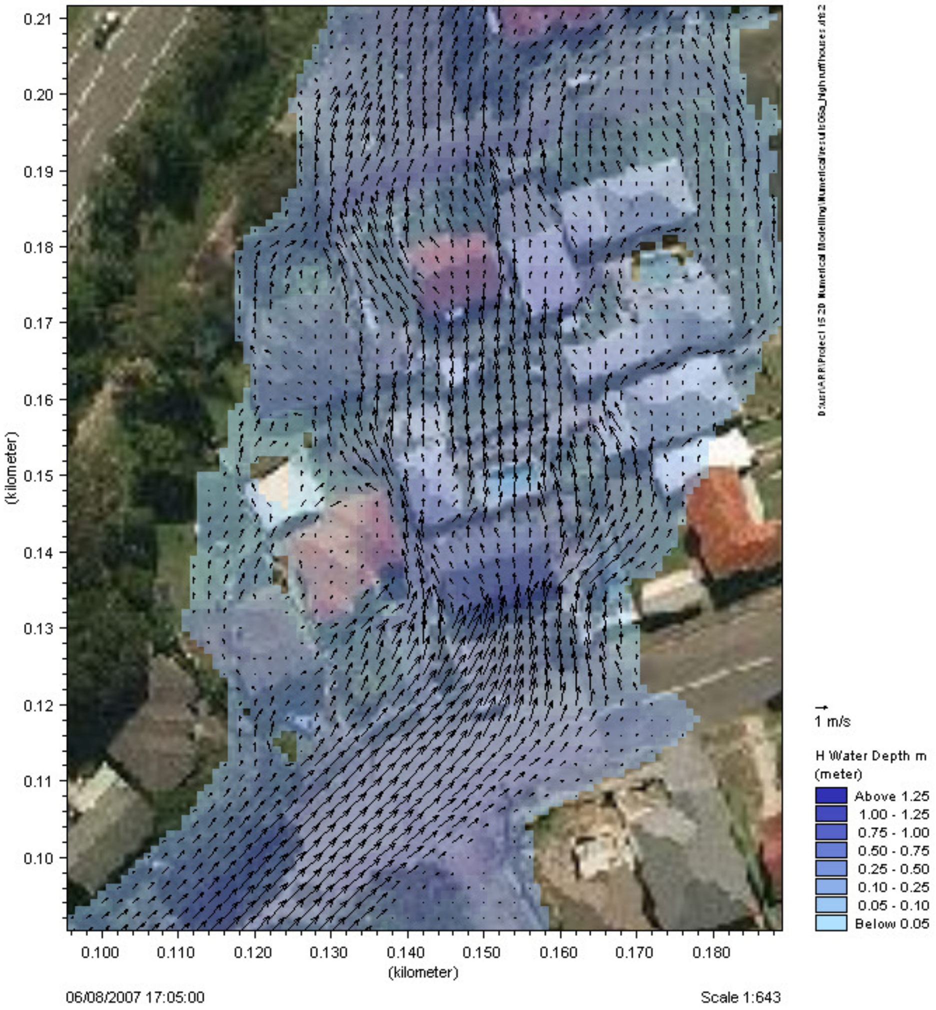

Figure 47: Numerical Model Depths and Velocities: 1 m grid buildings as high roughness

In the case with buildings represented by the upstream walls of the building footprint only (see Figure 48), the flow depths are similar to the case of the buildings removed from the computational grid and the flow velocity fields are similar in that the flow is deflected by the building walls upstream of each building. However, the absence of a downstream wall leads to unrealistic, eddying flow patterns on the downstream side of some buildings. The eddy structures are not observed in the physical model and are considered unlikely to occur at the prototype scale.

In a flow field where flow directions are changing either due to the topography or the presence of buildings themselves, it is quite problematic as to what the 'upstream' side of a building is, making it difficult to imagine an automated method of configuring the model set-up for this case when there are numerous buildings on the floodplain to address.

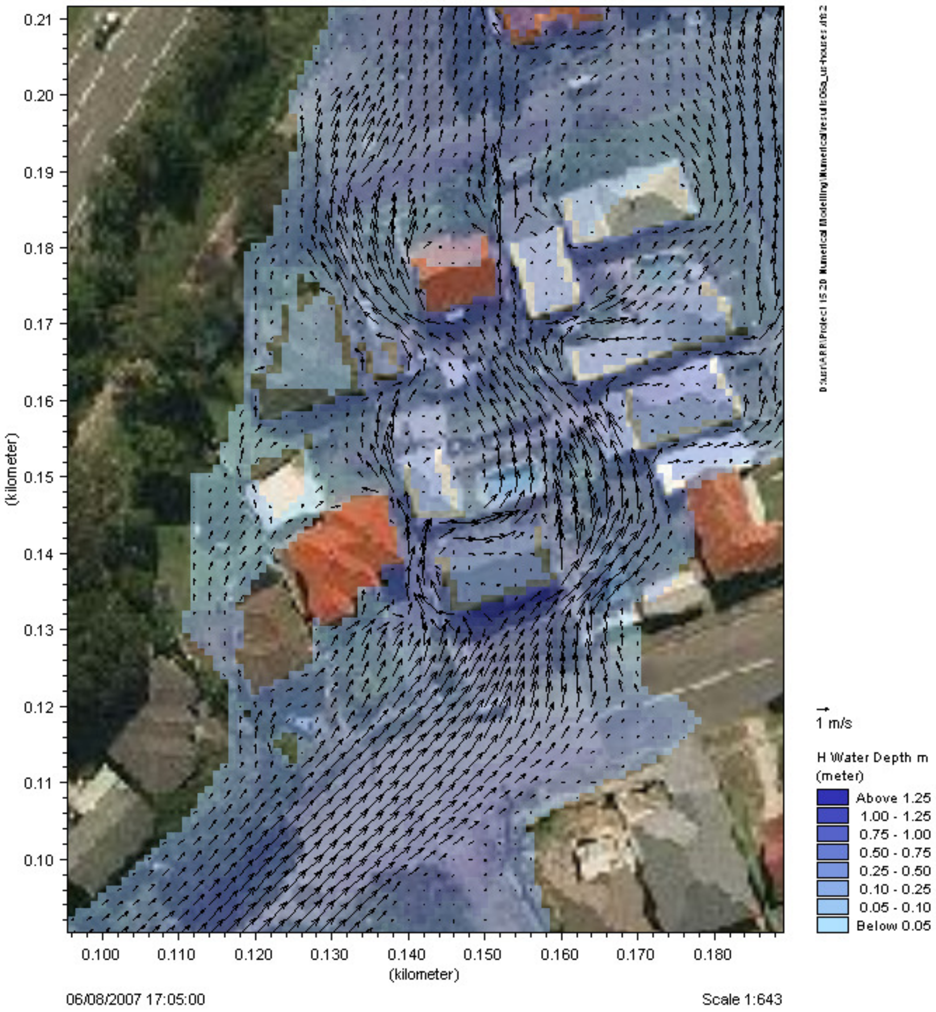

Figure 48: Numerical Model Depths and Velocities: 1 m grid buildings with upstream walls only

Similarly, the case where buildings are represented by the downstream perimeter wall only (see Figure 49) provides for a reasonable match of water levels and flow paths generally, but with some unrealistic eddying of flows within buildings. The building representation using downstream walls has the effect of 'catching' the flow in the building footprints, thereby showing all buildings flooded inside, but at the expense of the flow velocity distributions in some areas compared to the physical model. As with the case of using upstream walls only, the downstream wall only method is somewhat problematic when configuring the model. Considerable interpretation is required to decide which walls are the 'downstream' walls making automated model configuration a difficult proposition.

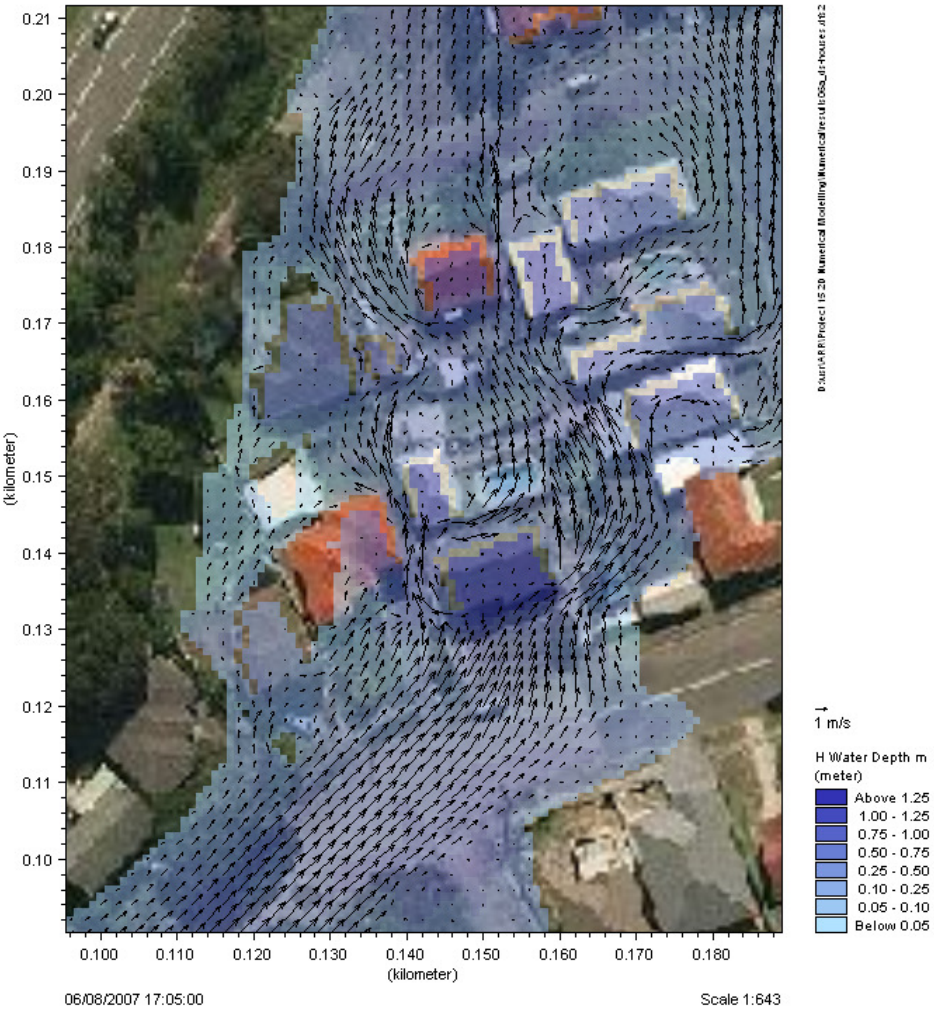

Figure 49: Numerical Model Depths and Velocities: 1 m grid buildings with downstream walls only

Modelling the buildings as ‘porous’ elements (See Figure 50) has been shown to have an interesting result on flow depths and levels in the model results in and nearby the buildings in the test case. The net result appears to have resulted in flows being accelerated through the reduced area for each grid square inside each building footprint. The accelerated flows have resulted in both higher velocities and flood depths in the buildings than outside the buildings, which in turn appears to have influenced the flow directions and magnitudes nearby the buildings. The results are not intuitive in some areas, with water flowing out of the buildings at strange angles in some instances and the flow directions do not generally reproduce the physical model results. The flood depths are considerably higher inside the buildings in some instances than the flood depths immediately outside the same buildings. On the basis of the presented results, this method should be used with caution.

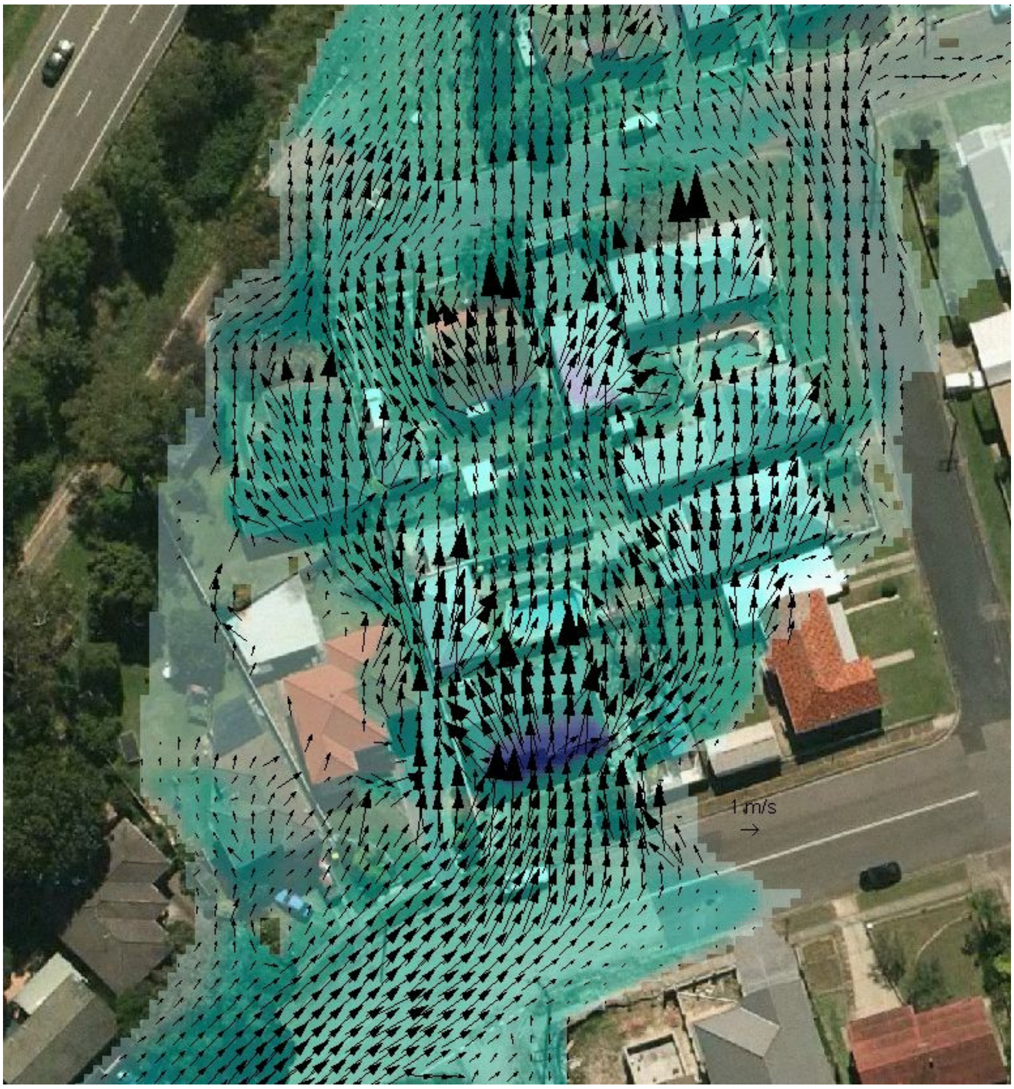

Figure 50: Numerical Model Depths and Velocities: 1 m grid buildings as porous

As with the previous case using porous elements, modelling the buildings using a form loss function as presented in Figure 51 has been shown to have similar impact on the flood levels and flow velocities near the buildings. The model results again appear to have resulted in flows being accelerated through the building for each grid square included under a building footprint. The accelerated flows have resulted in higher velocities and depths in the buildings, which in turn have influenced the flow directions and magnitudes nearby the buildings. The results are not intuitive in numerous areas, flowing out of the buildings at strange angles. On the basis of the presented results, this method should also be used with caution.

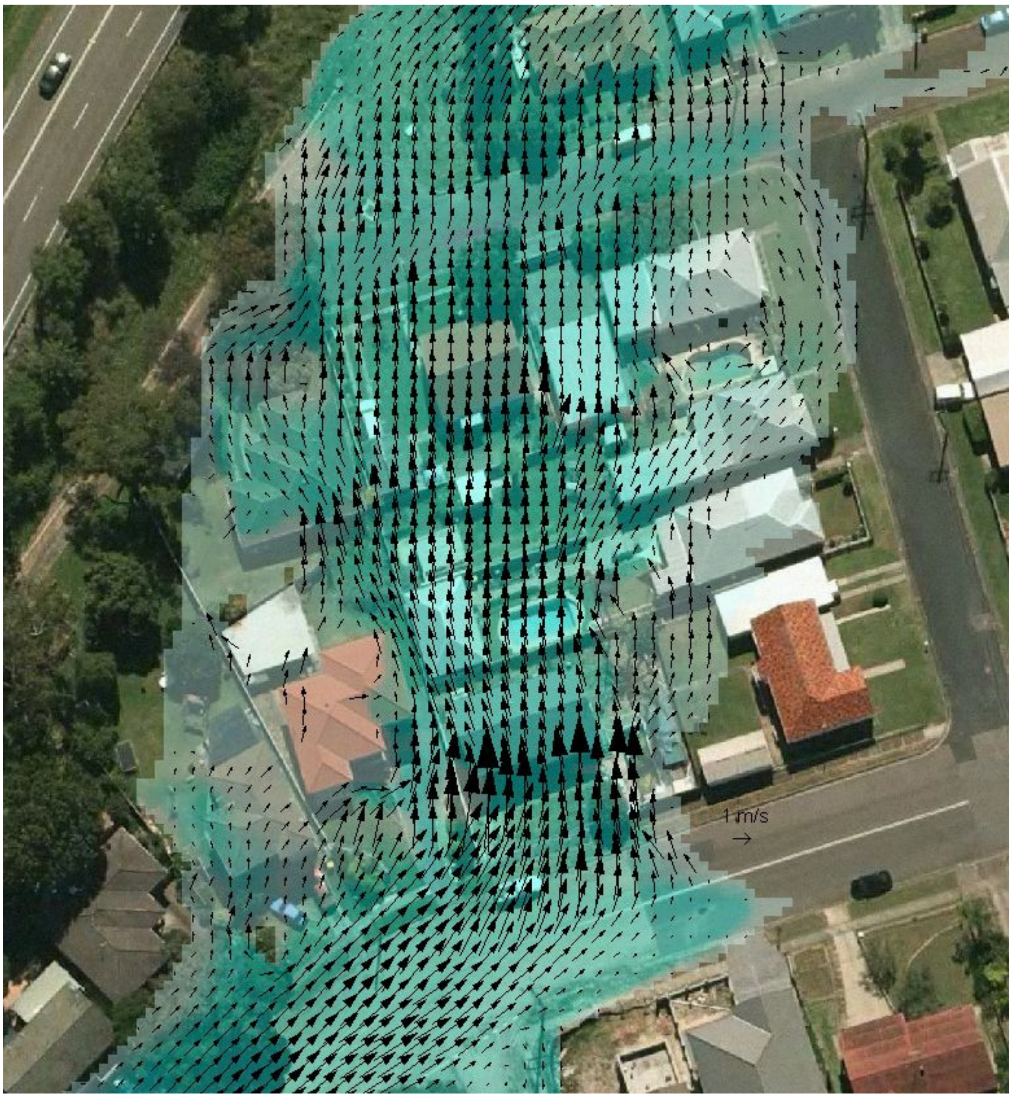

Figure 51: Numerical Model Depths and Velocities: 1 m grid buildings as form loss

6.6.8. Hazard

The model results for the various methods for representing a building have also been processed for preliminary flood hazard (product of velocity and depth). Figures 52 to 57 present these results graphically. The presented results show that the various methods produce variable results for hazard. In particular, the ‘high roughness’ method and the ‘downstream walls’ methods appear to underestimate hazard compared to the case where the buildings have been removed from the computational grid. The method where buildings have been represented using the upstream walls of each building outline is a closer match to the case where the buildings force the flow to be completely deflected. The methods where the buildings are represented as ‘porous’ and as form loss elements have variable hazard estimates which reflect the somewhat counter-intuitive flow velocity patterns. These methods show higher hazard within the building footprints in some cases, which may also be viewed as counter intuitive.

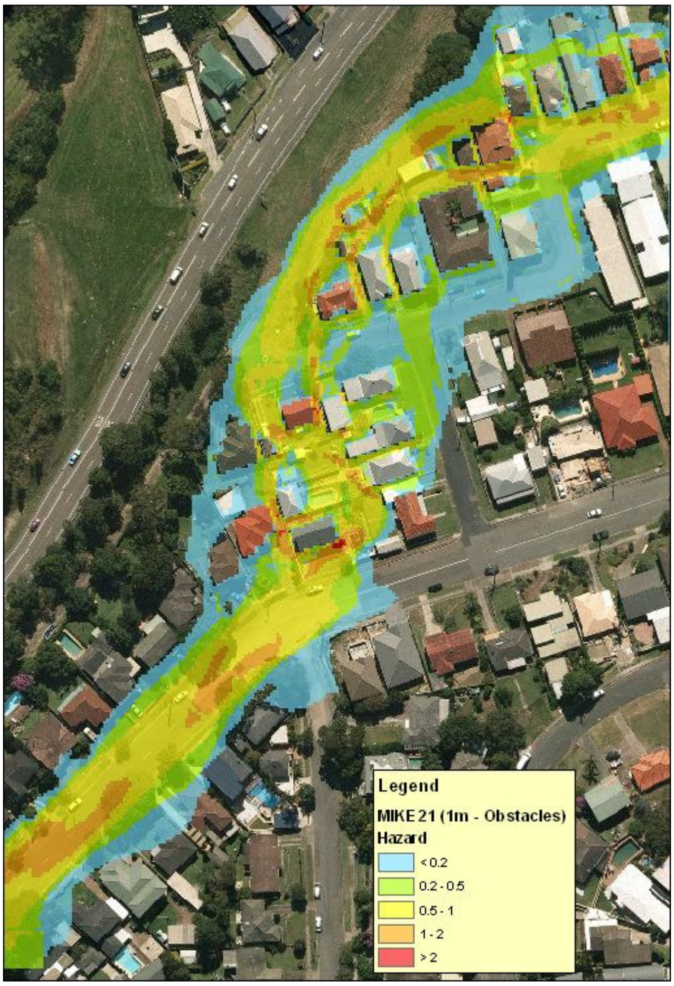

Figure 52: Numerical Model Hazard: 1 m grid buildings excluded from grid

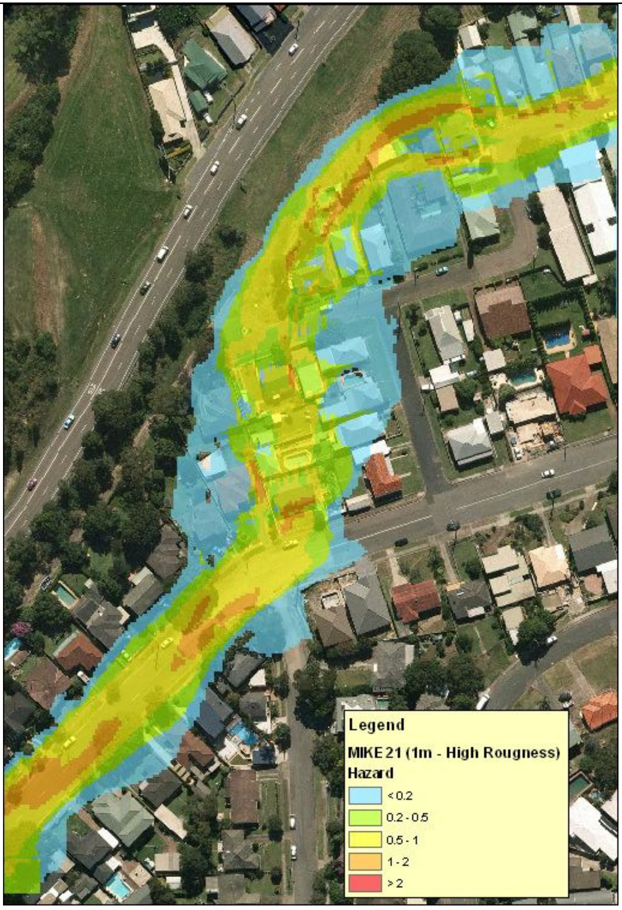

Figure 53: Numerical Model Hazard: 1 m grid buildings as high roughness

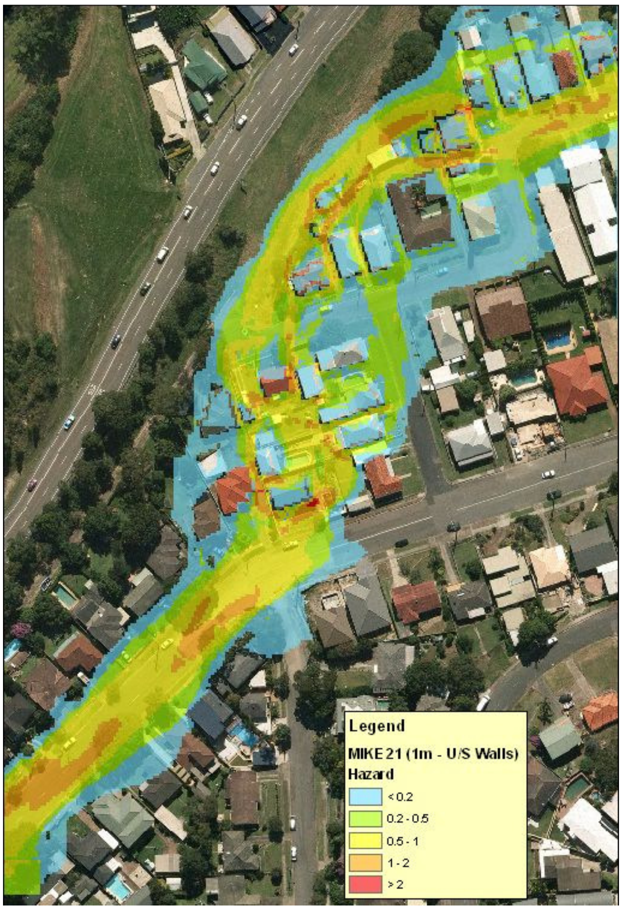

Figure 54: Numerical Model Hazard: 1 m grid buildings with upstream walls only

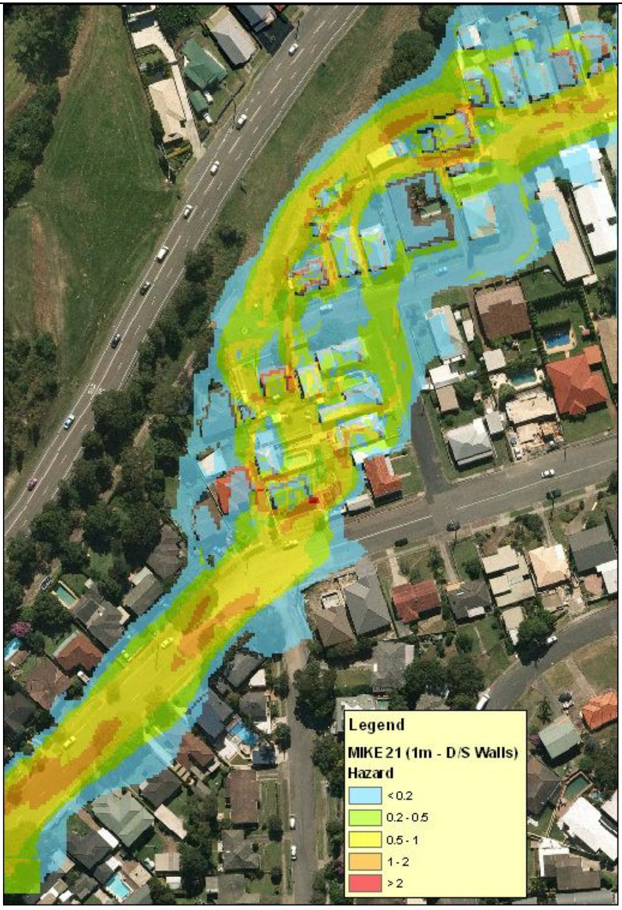

Figure 55: Numerical Model Hazard: 1 m grid buildings with downstream walls only

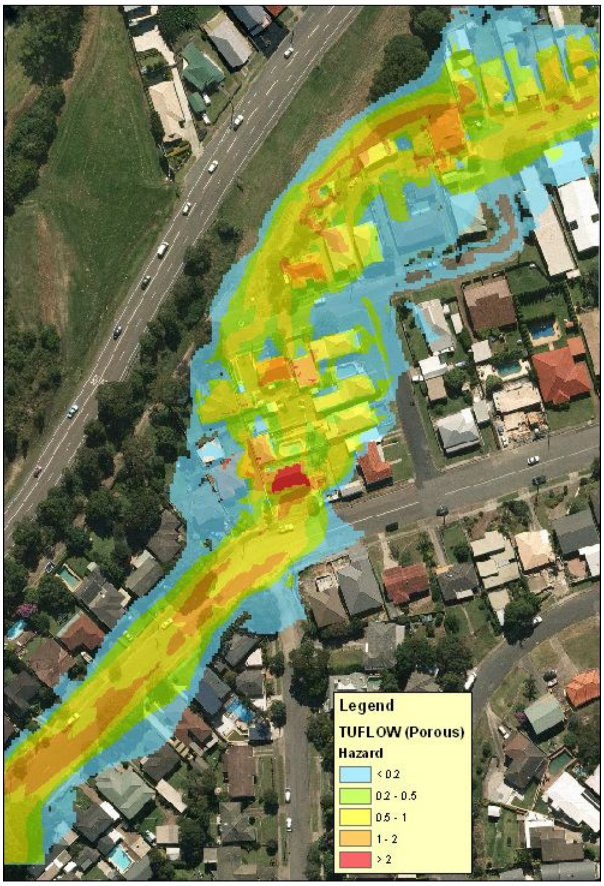

Figure 56: Numerical Model Hazard: 1 m grid buildings represented as porous

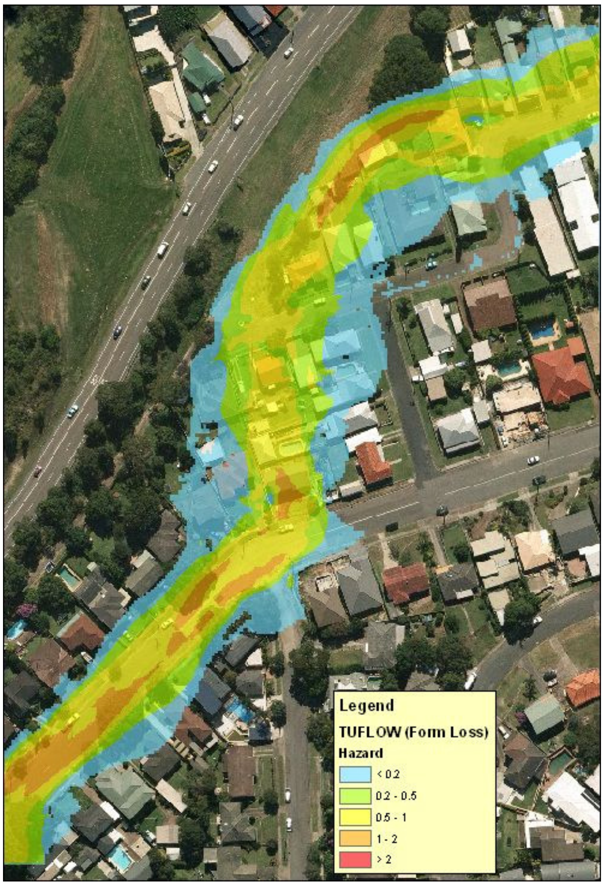

Figure 57: Numerical Model Hazard: 1 m grid buildings represented as form loss

7. Conclusions and Recommendations

The model testing conducted as part of this project has successfully investigated the stated project objectives of:

1. To develop a base data set of reliable flood behaviour information (flow levels and depth, flow distributions and flow velocities) for an urban floodplain; and
2. To test various methods for representing buildings in 2D numerical models with the aim of determining a preferred method(s).

A literature review confirmed that this project is unique in its approach to developing a physical model of an actual urban floodplain to use as the basis of a comparison with numerical methods. The literature review also confirmed that the modelling community internationally recognizes that the influence of buildings and other obstacles to flow passage in urban floodplains is an important issue in the context of urban floodplain management. The influence of buildings and other obstacles to flow and their representation in numerical floodplain models was also identified in literature as a contemporary issue that requires further research and investigation.

A physical model of the Merewether floodplain was constructed at the Water Research Laboratory (WRL), was validated against historical flood information, and was successfully used to expand the quantitative description of urban flood flow behaviour for the site in terms of flow velocities, flow directions and flow discharge distributions.

A series of measurements of the physical model were then compared against similarly calibrated numerical models. Numerical models were developed using TUFLOW and MIKE FLOOD on the basis of their common use in the Australian market and the availability of these packages to WRL.

Detailed analysis of the developed models including comparison of the models with observed data and data measured in the physical model has supported the conclusion that correctly discretised 2D numerical models are able to adequately represent observed flow behaviour on urban floodplains as long as a suitable method of representing buildings is applied.

Analysis of numerical model results showed that the model spatial resolution is important for estimation of flood flow velocities, flow directions, flow discharge distributions and flood hazard definition. Hazard definition of flood flows is an important aspect of floodplain planning and flood emergency management and this investigation has concluded that numerical model resolutions should be carefully chosen so as to adequately represent flow hazard conditions. While model resolutions of up to 10 m were shown to be adequate for representing peak flood levels, model resolutions of 2m or less were required to represent the complex flow patterns in and around buildings on the floodplain.

The results of the physical model assessment have shown that while buildings stand, they have a considerable influence on flood flow structures in urban environments, significantly deflecting flows irrespective of whether the building is flooded inside or remains water tight. Anecdotal evidence from videos of the recent Queensland Floods of January 2011 also shows buildings significantly deflecting flows when completely inundated and filled with flood water. It follows that this aspect of urban flow behaviour representation is important for faithful reproduction of flood behaviour in numerical models. The current investigation has shown that the method used to represent buildings in a numerical model is a key element required to match flow prototype flow patterns and the method must realistically deflect flows. In the project test case, some methods proposed in literature for representing the influence of buildings on flood flows were found to be deficient for that purpose.

Numerical model trials showed that on the basis of the available data sets, the best performing method when representing buildings in a numerical model was to either remove the computational points under the building footprint completely from the solution or to increase the elevation of the building footprint to be above the maximum expected flood height. Other methods, while able to reproduce peak flood levels, were not able to satisfactorily reproduce flow distributions and flow directions around buildings on the floodplain. It follows that flood hazard would only be satisfactorily reproduced using numerical model methods that deflected flows around building structures.

Comparison of the numerical model results with the physical model also found that the numerical models have a tendency to “smooth” the flow behaviour through a combination of the assumptions of the underlying process equations and numerical diffusion in the computer algorithms.

Analysis of flood volumes on the floodplain has shown that in a floodplain with flows passing through the floodplain, achieving peak levels due to peak flow rate rather than peak stored volume, the influence of the flow volume stored inside buildings is not significant to the presented flood levels in the prototype floodplain. This has also been shown to be the case by combined analysis of model results from the physical and numerical models tested in this project. This conclusion supports the findings of Brown *et al.* (2007) who also concluded that the volume of flow stored inside buildings on an inundated floodplain was insignificant.

7.1. Recommendations

The current study could be further advanced by the following investigations:

1. Additional numerical modelling with alternative software packages. The authors have been in contact with software vendors for the following software packages:
    - SOBEK;
    - TUFLOW FV; and
    - MIKE FLOOD FM.

   These vendors have agreed to apply these listed software systems to the test case. The current report can be updated with the results of additional software packages once they become available.
2. Further calibration of the subject physical model. As noted in the report, the physical model results would benefit from additional model calibration involving making the model

surface rougher. While it is not expected to change the current study conclusions, improving the quality of the physical model outputs would allow further detailed analysis of numerical methods.

3. Physical model representation of different building types. The current study focuses on slab on ground building construction. Different building types e.g. buildings on piers could also be tested to enable better parameterisation of these building types in numerical models.
4. Preliminary observations of the physical model found that flow accelerations between buildings could result in very high loadings on slab on ground buildings. Further analysis of this aspect of forces on buildings is warranted.
5. The outputs of the physical model and numerical models could be used to review current building standards for buildings in floodplains.
6. Correctly applied the numerical model could be used to analyse and assess more flood friendly sub-division designs resulting in reduced flood hazard and flood impacts.
7. Physical model measurement and analysis could be expanded by the use of continuous recording of flood levels and remote sensing of flood velocities using PIV techniques to produce maps of flow velocity to supplement the discrete point data set derived in this study.
8. This investigation has highlighted the importance of correctly representing flow obstacles and obstructions in the floodplain. The authors recommend a similar assessment of the influence of fences on urban flow paths.

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APPENDICES

APPENDIX A: Physical Model Measurements

Figure A1: Velocity Measurements: Transect 1

Velocity Measurements: Transect 2a

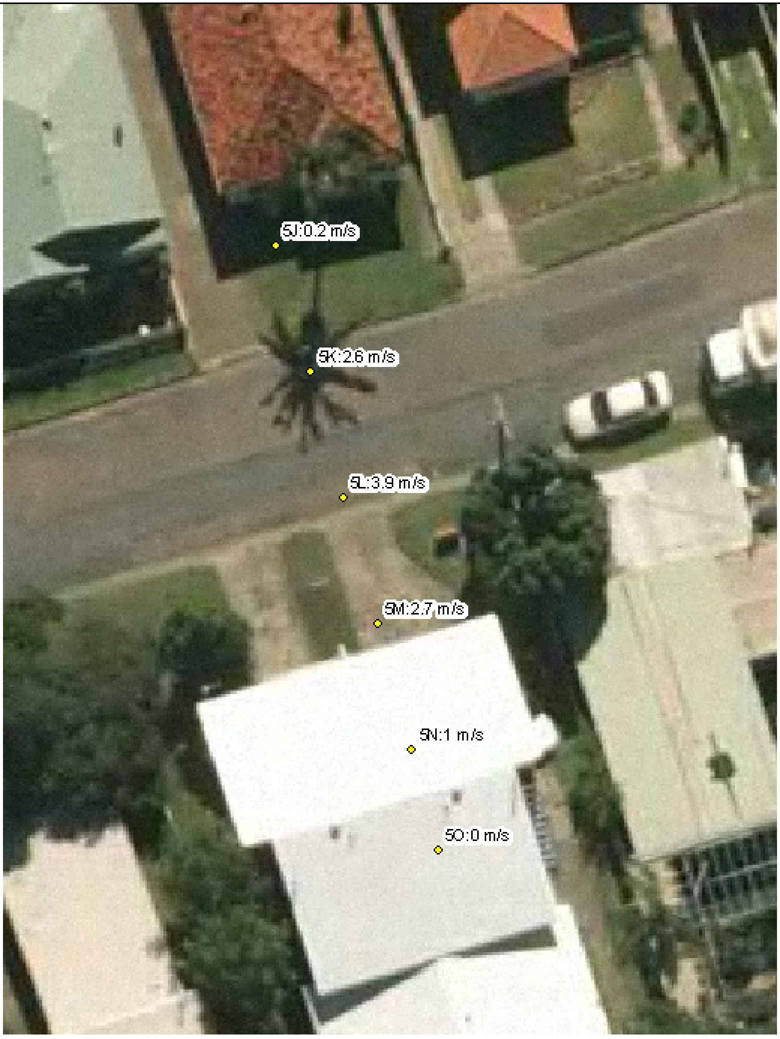
Velocity Measurements: Transect 2b

Velocity Measurements: Transect 3

Velocity Measurements: Transect 4a

Velocity Measurements: Transect 4b

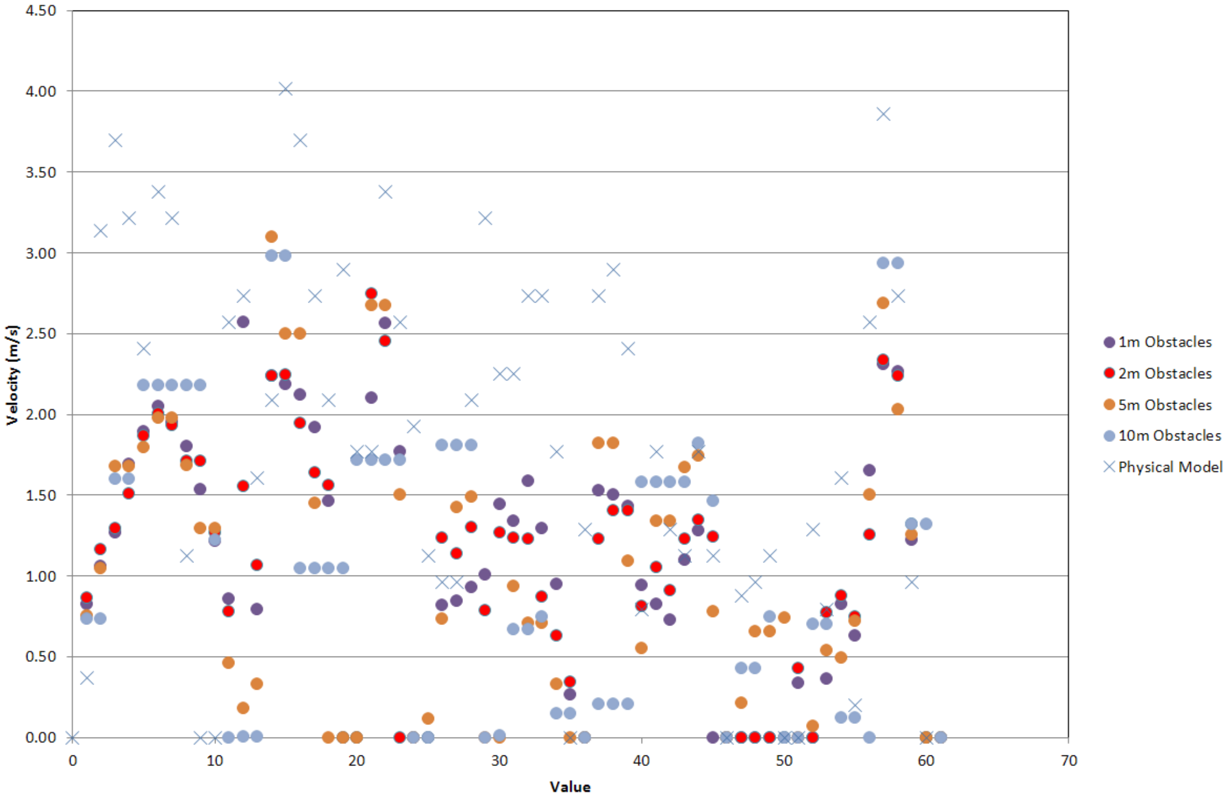
Velocity Measurements: Transect 5a

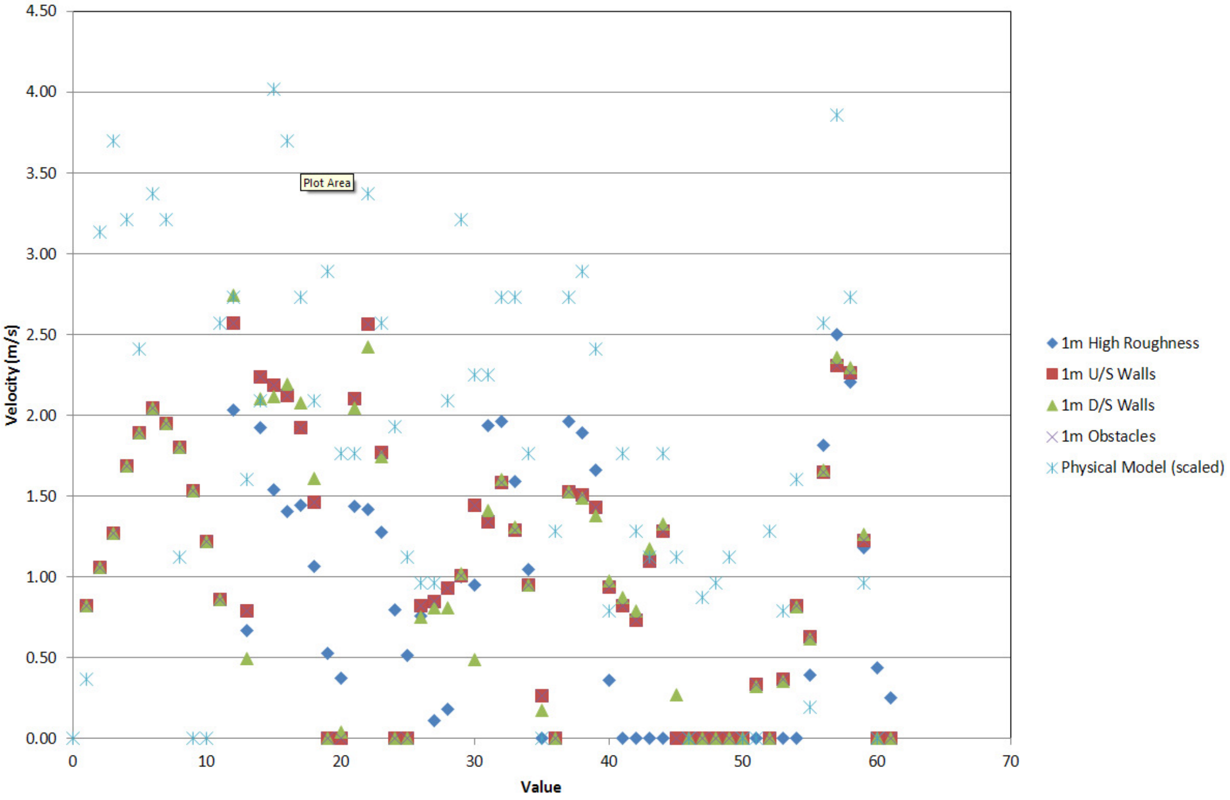


Velocity Measurements: Transect 5b

APPENDIX B: Additional Model Results

MIKE FLOOD Velocities



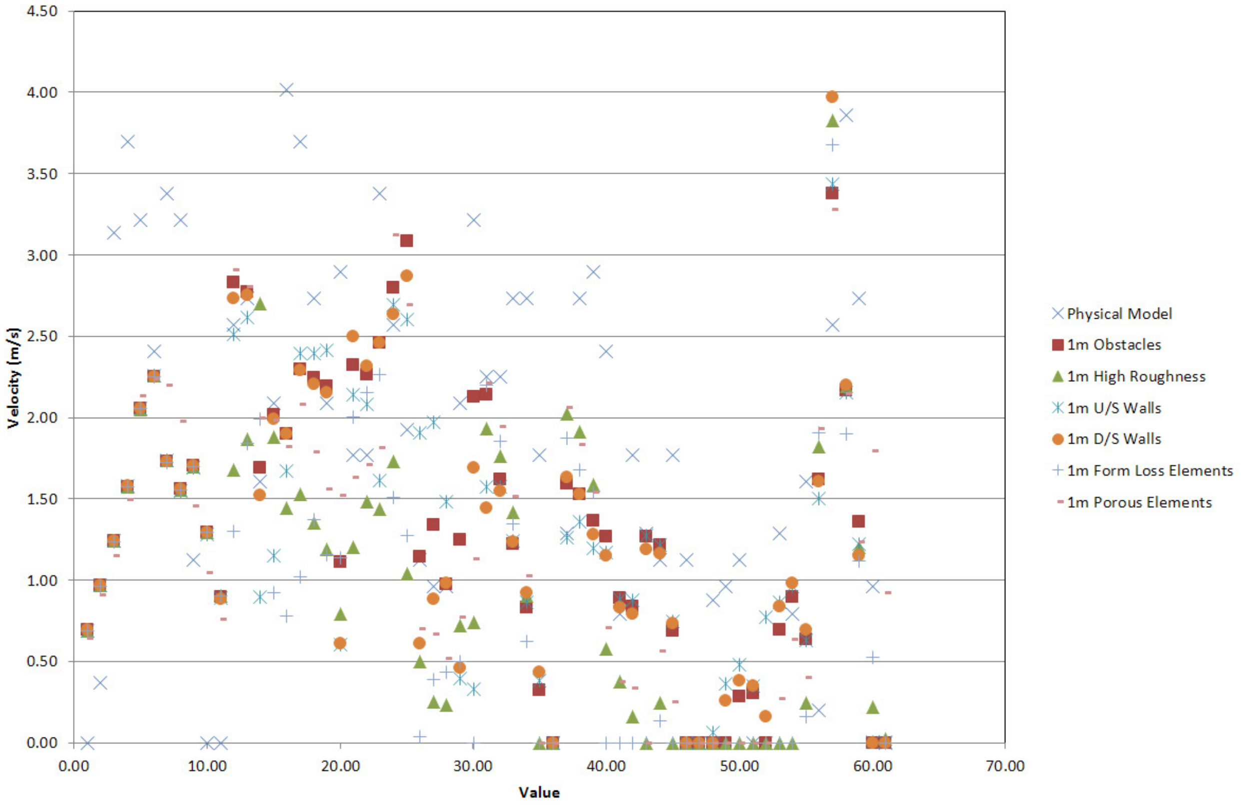


Summary of MIKE FLOOD Velocities

Plot ID	Location	ID NUM	Physical Model	1m High Roughness	1m U/S Walls	1m D/S Walls	1m Obstacles	2m Obstacles	5m Obstacles	10m Obstacles	10m High Roughness
0	175 Morgan -> 172 Morgan	1A	0.00	0.82	0.82	0.82	0.82	0.87	0.75	0.74	0.67
1	175 Morgan -> 172 Morgan	1B	0.37	1.06	1.06	1.06	1.06	1.16	1.04	0.74	0.67
2	175 Morgan -> 172 Morgan	1C	3.13	1.27	1.27	1.27	1.27	1.29	1.68	1.60	1.55
3	175 Morgan -> 172 Morgan	1D	3.70	1.69	1.69	1.69	1.69	1.51	1.68	1.60	1.55
4	175 Morgan -> 172 Morgan	1E	3.21	1.89	1.89	1.89	1.89	1.86	1.80	2.18	2.17
5	175 Morgan -> 172 Morgan	1F	2.41	2.05	2.05	2.05	2.05	2.00	1.98	2.18	2.17
6	175 Morgan -> 172 Morgan	1G	3.38	1.95	1.95	1.95	1.95	1.93	1.98	2.18	2.17
7	175 Morgan -> 172 Morgan	1H	3.21	1.80	1.80	1.80	1.80	1.71	1.69	2.18	2.17
8	175 Morgan -> 172 Morgan	1I	1.12	1.54	1.53	1.53	1.53	1.71	1.29	2.18	2.17
9	175 Morgan -> 172 Morgan	1J	0.00	1.22	1.22	1.22	1.22	1.27	1.29	1.22	1.19
10	175 Morgan -> 172 Morgan	1K	0.00	0.86	0.86	0.86	0.86	0.78	0.46	0.00	0.03
11	166 Morgan -> 168 Morgan	2A	2.57	2.03	2.57	2.74	2.57	1.56	0.18	0.00	1.33
12	166 Morgan -> 168 Morgan	2B	2.73	0.67	0.79	0.49	0.79	1.07	0.33	0.00	1.33
13	166 Morgan -> 1 Arthur Garage	2C	1.61	1.92	2.24	2.10	2.24	2.24	3.10	2.98	1.68
14	166 Morgan -> 1 Arthur Garage	2D	2.09	1.54	2.19	2.12	2.19	2.25	2.50	2.98	1.68
15	166 Morgan -> 1 Arthur Garage	2E	4.02	1.40	2.12	2.20	2.12	1.95	2.50	1.05	0.00
16	166 Morgan -> 1 Arthur Garage	2F	3.70	1.44	1.92	2.08	1.92	1.64	1.45	1.05	0.00
17	166 Morgan -> 1 Arthur Garage	2G	2.73	1.07	1.46	1.61	1.46	1.56	0.00	1.05	0.00
18	166 Morgan -> 1 Arthur Garage	2H	2.09	0.53	0.00	0.00	0.00	0.00	0.00	1.05	0.00
19	11 Little Edward -> 9 Little Edward Garage	3A	2.89	0.37	0.00	0.04	0.00	0.00	0.00	1.72	1.41
20	9 Little Edward Garage -> 9 Little Edward	3B	1.77	1.44	2.10	2.04	2.10	2.75	2.67	1.72	1.41
21	9 Little Edward Garage -> 9 Little Edward	3C	1.77	1.42	2.56	2.42	2.56	2.45	2.67	1.72	1.41
22	9 Little Edward Garage -> 9 Little Edward	3D	3.38	1.28	1.77	1.75	1.77	0.00	1.50	1.72	1.41
23	9 Little Edward -> 5 Arthur Garage	3E	2.57	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.98
24	5 Arthur Garage -> 5 Arthur	3F	1.93	0.51	0.00	0.00	0.00	0.00	0.11	0.00	0.73
25	5 Arthur -> 3A Arthur	3G	1.12	0.76	0.82	0.75	0.82	1.24	0.73	1.81	0.64
26	5 Arthur -> 3A Arthur	3H	0.96	0.11	0.85	0.81	0.85	1.14	1.43	1.81	0.64
27	5 Arthur -> 3A Arthur	3I	0.96	0.18	0.93	0.81	0.93	1.30	1.49	1.81	0.64
28	3A Arthur -> 3 Arthur	3J	2.09	1.00	1.01	1.02	1.01	0.79	0.00	0.00	0.15
29	3 Arthur -> 1 Arthur Garage	3K	3.21	0.95	1.44	0.49	1.44	1.27	0.00	0.01	0.00
30	4-6 Little Edward Garage -> Edge of model	4A	2.25	1.94	1.34	1.41	1.34	1.23	0.93	0.67	1.50
31	4-6 Little Edward Garage -> Edge of model	4B	2.25	1.96	1.58	1.60	1.58	1.23	0.71	0.67	1.50
32	4-6 Little Edward Garage -> Edge of model	4C	2.73	1.59	1.29	1.31	1.29	0.87	0.71	0.75	0.74
33	4-6 Little Edward Garage -> Edge of model	4D	2.73	1.05	0.95	0.95	0.95	0.63	0.33	0.15	0.00
34	4-6 Little Edward Garage -> Edge of model	4E	1.77	0.00	0.26	0.17	0.26	0.35	0.00	0.15	0.00
35	4-6 Little Edward Garage -> Edge of model	4F	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36	4-6 Little Edward Garage -> 4 -6 Little Edward	4G	1.28	1.96	1.53	1.53	1.53	1.23	1.82	0.21	1.21
37	4-6 Little Edward Garage -> 4 -6 Little Edward	4H	2.73	1.89	1.51	1.49	1.51	1.40	1.82	0.21	1.21
38	4-6 Little Edward Garage -> 4 -6 Little Edward	4I	2.89	1.66	1.43	1.38	1.43	1.40	1.09	0.21	1.21
39	4-6 Little Edward -> 3 Little Edward	4K	2.41	0.36	0.94	0.98	0.94	0.81	0.55	1.58	0.79
40	4-6 Little Edward -> 3 Little Edward	4L	0.79	0.00	0.83	0.88	0.83	1.05	1.34	1.58	0.79
41	4-6 Little Edward -> 3 Little Edward	4M	1.77	0.00	0.73	0.79	0.73	0.91	1.34	1.58	0.79
42	4-6 Little Edward -> 3 Little Edward	4N	1.28	0.00	1.10	1.18	1.10	1.23	1.67	1.58	0.79

Plot ID	Location	ID NUM	Physical Model	1m High Roughness	1m U/S Walls	1m D/S Walls	1m Obstacles	2m Obstacles	5m Obstacles	10m Obstacles	10m High Roughness
43	4-6 Little Edward -> 3 Little Edward	4O	1.12	0.00	1.28	1.33	1.28	1.35	1.74	1.82	0.60
44	4-6 Little Edward -> 3 Little Edward	4P	1.77	0.00	0.00	0.27	0.00	1.24	0.78	1.46	0.30
45	3 Little Edwards -> Edge of Model	4Q	1.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
46	82 Wilton -> 82 Wilton Garage	5A	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.43	0.00
47	82 Wilton -> 82 Wilton Garage	5B	0.88	0.00	0.00	0.00	0.00	0.00	0.65	0.43	0.00
48	82 Wilton -> 82 Wilton Garage	5C	0.96	0.00	0.00	0.00	0.00	0.00	0.65	0.75	0.00
49	82 Wilton -> 82 Wilton Garage	5D	1.12	0.00	0.00	0.00	0.00	0.00	0.74	0.00	0.00
50	82 Wilton -> 82 Wilton Garage	5E	0.00	0.00	0.33	0.32	0.33	0.43	0.00	0.00	0.00
51	82 Wilton Garage -> 77 Selwyn	5F	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.70	0.00
52	82 Wilton Garage -> 77 Selwyn	5G	1.28	0.00	0.36	0.36	0.36	0.78	0.54	0.70	0.00
53	82 Wilton Garage -> 77 Selwyn	5H	0.79	0.00	0.82	0.82	0.82	0.88	0.50	0.12	0.00
54	82 Wilton Garage -> 77 Selwyn	5I	1.61	0.39	0.63	0.62	0.63	0.74	0.72	0.12	0.00
55	77 Selwyn -> 80 Selwyn	5J	0.20	1.82	1.65	1.66	1.65	1.26	1.50	0.00	0.48
56	77 Selwyn -> 80 Selwyn	5K	2.57	2.50	2.31	2.36	2.31	2.34	2.69	2.94	3.05
57	77 Selwyn -> 80 Selwyn	5L	3.86	2.20	2.27	2.30	2.27	2.24	2.03	2.94	3.05
58	77 Selwyn -> 80 Selwyn	5M	2.73	1.18	1.22	1.26	1.22	1.32	1.26	1.32	1.11
59	77 Selwyn -> 80 Selwyn	5N	0.96	0.44	0.00	0.00	0.00	0.00	0.00	1.32	1.11
60	77 Selwyn -> 80 Selwyn	5O	0.00	0.26	0.00	0.00	0.00	0.00	0.00	0.00	0.09

TUFLOW Velocities



Summary of TUFLOW Velocities

Plot ID	ID_NUM	Location	Physical Model	1m Obstacles	1m High Roughness	1m U/S Walls	1m D/S Walls	1m Form Loss Elements	1m Porous Elements
0	1A	175 Morgan -> 172 Morgan	0.00	0.69	0.69	0.69	0.69	0.69	0.64
1	1B	175 Morgan -> 172 Morgan	0.37	0.97	0.97	0.97	0.97	0.96	0.91
2	1C	175 Morgan -> 172 Morgan	3.13	1.24	1.24	1.24	1.24	1.24	1.15
3	1D	175 Morgan -> 172 Morgan	3.70	1.58	1.58	1.58	1.58	1.58	1.50
4	1E	175 Morgan -> 172 Morgan	3.21	2.05	2.05	2.05	2.06	2.05	2.13
5	1F	175 Morgan -> 172 Morgan	2.41	2.25	2.26	2.26	2.25	2.25	2.24
6	1G	175 Morgan -> 172 Morgan	3.38	1.73	1.73	1.74	1.73	1.72	2.20
7	1H	175 Morgan -> 172 Morgan	3.21	1.56	1.55	1.55	1.56	1.56	1.98
8	1I	175 Morgan -> 172 Morgan	1.12	1.70	1.70	1.69	1.70	1.70	1.46
9	1J	175 Morgan -> 172 Morgan	0.00	1.29	1.29	1.28	1.29	1.29	1.04
10	1K	175 Morgan -> 172 Morgan	0.00	0.89	0.90	0.89	0.88	0.91	0.76
11	2A	166 Morgan -> 168 Morgan	2.57	2.83	1.68	2.51	2.73	1.30	2.91
12	2B	166 Morgan -> 168 Morgan	2.73	2.77	1.87	2.62	2.75	1.84	2.81
13	2C	166 Morgan -> 1 Arthur Garage	1.61	1.69	2.70	0.90	1.52	1.99	2.00
14	2D	166 Morgan -> 1 Arthur Garage	2.09	2.02	1.88	1.15	1.99	0.92	1.99
15	2E	166 Morgan -> 1 Arthur Garage	4.02	1.90	1.45	1.67	1.90	0.78	1.82
16	2F	166 Morgan -> 1 Arthur Garage	3.70	2.30	1.53	2.40	2.29	1.02	2.08
17	2G	166 Morgan -> 1 Arthur Garage	2.73	2.25	1.35	2.40	2.21	1.37	1.79
18	2H	166 Morgan -> 1 Arthur Garage	2.09	2.19	1.19	2.42	2.15	1.16	1.56
19	3A	11 Little Edward -> 9 Little Edward Garage	2.89	1.11	0.79	0.61	0.61	1.14	1.52
20	3B	9 Little Edward Garage -> 9 Little Edward	1.77	2.32	1.21	2.14	2.50	2.00	1.63

Plot ID	ID_NUM	Location	Physical Model	1m Obstacles	1m High Roughness	1m U/S Walls	1m D/S Walls	1m Form Loss Elements	1m Porous Elements
21	3C	9 Little Edward Garage -> 9 Little Edward	1.77	2.27	1.49	2.08	2.31	2.15	1.71
22	3D	9 Little Edward Garage -> 9 Little Edward	3.38	2.46	1.44	1.61	2.46	2.26	1.82
23	3E	9 Little Edward -> 5 Arthur Garage	2.57	2.80	1.73	2.69	2.64	1.51	3.12
24	3F	5 Arthur Garage -> 5 Arthur	1.93	3.09	1.04	2.61	2.87	1.27	2.70
25	3G	5 Arthur -> 3A Arthur	1.12	1.14	0.50	1.91	0.61	0.04	0.70
26	3H	5 Arthur -> 3A Arthur	0.96	1.34	0.26	1.97	0.88	0.39	0.67
27	3I	5 Arthur -> 3A Arthur	0.96	0.97	0.23	1.48	0.98	0.43	0.52
28	3J	3A Arthur -> 3 Arthur	2.09	1.25	0.72	0.40	0.46	0.50	0.77
29	3K	3 Arthur -> 1 Arthur Garage	3.21	2.13	0.74	0.33	1.69	0.00	1.13
30	4A	4-6 Little Edward Garage -> Edge of model	2.25	2.14	1.93	1.57	1.45	2.20	2.21
31	4B	4-6 Little Edward Garage -> Edge of model	2.25	1.62	1.76	1.57	1.55	1.85	1.95
32	4C	4-6 Little Edward Garage -> Edge of model	2.73	1.22	1.42	1.24	1.24	1.35	1.51
33	4D	4-6 Little Edward Garage -> Edge of model	2.73	0.83	0.90	0.86	0.92	0.62	1.03
34	4E	4-6 Little Edward Garage -> Edge of model	1.77	0.32	0.00	0.38	0.43	0.00	0.00
35	4F	4-6 Little Edward Garage -> Edge of model	0.00	0.00	0.00	0.00	0.00	0.00	0.00
36	4G	4-6 Little Edward Garage -> 4 -6 Little Edward	1.28	1.59	2.02	1.26	1.63	1.87	2.06
37	4H	4-6 Little Edward Garage -> 4 -6 Little Edward	2.73	1.53	1.92	1.36	1.53	1.68	1.84
38	4I	4-6 Little Edward Garage -> 4 -6 Little Edward	2.89	1.37	1.58	1.19	1.28	1.54	1.54
39	4K	4-6 Little Edward -> 3 Little Edward	2.41	1.27	0.58	1.17	1.15	0.00	0.70
40	4L	4-6 Little Edward -> 3 Little Edward	0.79	0.89	0.37	0.88	0.83	0.00	0.38
41	4M	4-6 Little Edward -> 3 Little Edward	1.77	0.84	0.16	0.88	0.79	0.00	0.34
42	4N	4-6 Little Edward -> 3 Little Edward	1.28	1.27	0.00	1.27	1.19	0.00	0.00
43	4O	4-6 Little Edward -> 3 Little Edward	1.12	1.22	0.25	1.22	1.16	0.14	0.56
44	4P	4-6 Little Edward -> 3 Little Edward	1.77	0.69	0.00	0.75	0.73	0.00	0.25
45	4Q	3 Little Edwards -> Edge of Model	1.12	0.00	0.00	0.00	0.00	0.00	0.00
46	5A	82 Wilton -> 82 Wilton Garage	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47	5B	82 Wilton -> 82 Wilton Garage	0.88	0.00	0.00	0.06	0.00	0.00	0.00
48	5C	82 Wilton -> 82 Wilton Garage	0.96	0.00	0.00	0.36	0.26	0.00	0.00
49	5D	82 Wilton -> 82 Wilton Garage	1.12	0.28	0.00	0.48	0.38	0.00	0.00
50	5E	82 Wilton -> 82 Wilton Garage	0.00	0.30	0.00	0.35	0.35	0.00	0.00
51	5F	82 Wilton Garage -> 77 Selwyn	0.00	0.00	0.00	0.78	0.16	0.00	0.00
52	5G	82 Wilton Garage -> 77 Selwyn	1.28	0.69	0.00	0.86	0.84	0.00	0.27
53	5H	82 Wilton Garage -> 77 Selwyn	0.79	0.90	0.00	0.97	0.98	0.00	0.64
54	5I	82 Wilton Garage -> 77 Selwyn	1.61	0.64	0.24	0.63	0.70	0.16	0.40
55	5J	77 Selwyn -> 80 Selwyn	0.20	1.62	1.82	1.50	1.61	1.91	1.93
56	5K	77 Selwyn -> 80 Selwyn	2.57	3.38	3.83	3.44	3.97	3.68	3.28
57	5L	77 Selwyn -> 80 Selwyn	3.86	2.17	2.19	2.15	2.20	1.90	2.15
58	5M	77 Selwyn -> 80 Selwyn	2.73	1.36	1.20	1.22	1.15	1.12	1.24
59	5N	77 Selwyn -> 80 Selwyn	0.96	0.00	0.22	0.00	0.00	0.53	1.79
60	5O	77 Selwyn -> 80 Selwyn	0.00	0.00	0.03	0.01	0.00	0.00	0.92