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Urban Flood Modelling and Mapping 2D or Not 2D

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Abstract: Once limited to coastal hydraulics, two-dimensional (2D) modelling of free-surface flows is today used for a broad range of investigations, from the ocean to the floodplain. Growth in computer hardware technology is driving this expansion and software is evolving to meet the scientific and engineering challenges. The use of 2D hydraulic software to characterise flooding in rural and broad floodplain environments is becoming commonplace, the benefits of which are considerable. But do the same benefits apply to urban flood environments? In this paper we present the relative benefits and limitations of 2D vs 1D flood modelling techniques in the urban environment. We examine the increasingly common question; 2D or not 2D?

Keywords: Flood Modelling, Flood Mapping, 2D modelling, urban flooding, MIKE11, TUFLOW.

1 INTRODUCTION

Fully two-dimensional (2D) solution schemes have been widely used for modelling river and coastal hydraulics and, more recently, have become a practical option for floodplain modelling. The application of 2D schemes in the urban flood environment is now an option for floodplain managers due to improvements in computer hardware. The benefits of a 2D approach in the rural floodplain are considerable, but do the same benefits apply on the urban scene?

This paper compares 1D and 2D flood modelling techniques in the urban environment. The benefits and limitations of undertaking 2D modelling on this scale are identified. As well, a range of techniques used by modellers to overcome many of the difficulties encountered when applying 1D and 2D methods to the urban environment is discussed.

A case study is presented. The study was undertaken to assess mitigation options for an urban catchment in Geelong with a history of flooding problems. Both DHI's MIKE11 (1D) and WBM's TUFLOW (2D) hydraulic modelling packages were used in the assessment. The case study reveals a range of implications for both 1D and 2D modelling techniques and their future application.

2 URBAN FLOODPLAIN MODELLING

Floodplain modelling and mapping in the urban environment is typified by characteristic difficulties that make it considerably more challenging than rural floodplain studies. These include:

- Increased level of topographic detail (eg road crests and gutters, raised house pads);
- The complexity in the terrain (which includes houses, fences, garden beds);
- Complex underground networks of pipes; and
- The many efforts engineers have entertained to alleviate flooding problems (original and augmented pipe systems, pumps, levees, retarding basins and offline storages, etc).

Accordingly, modellers require extremely high resolution software to adequately represent the area under consideration. Quality, high resolution terrain information is required to define the drainage characteristics and provide the basis for the floodplain mapping. In addition, detailed information regarding the drainage system components and their design characteristics is also required.

All this information is required at a very detailed level to ensure as accurate as possible representation of the urban floodplain. Nevertheless, the principles and objectives of flood modelling and mapping in the urban setting remain the same as those of larger scale rural flood studies.

2.1 Traditional 1D Approach

The traditional 1D approach to floodplain modelling and mapping in the rural environment has been embraced by urban floodplain managers and, following some modifications and assumptions, has been successfully applied in numerous flood assessments in the urban environment. In addressing the primary difficulties outlined above, modellers have employed a range of techniques to simplify the complexity of the urban floodplain within the chosen modelling and mapping software. In many cases these assumptions/simplifications are well justified and do not diminish the validity of the derived results.

In a simple linear urban floodplain (see Figure 1), one may choose to separate the underground and overland flow components and treat them separately. In such a situation, the aim is to calculate the capacity of the underground system and remove this component from the total flow, leaving the excess as the overland flow component. The estimate of the underground component of the flow could be derived using simple hand calculations of pipe capacity or via a more sophisticated technique. Once the underground component has been established, that proportion of the flow is subtracted from hydrological model results and “thrown away”. The resultant flows (ie with the underground flow component removed) are applied to a hydraulic model representing the surface drainage characteristics of the area to be mapped. The hydraulic modelling results are then transferred to a GIS or other spatial modelling system to be mapped.

Figure 1 – A Simple Linear Urban Floodplain

Figure 2 – A Simple Linear Urban Floodplain Including Retarding Basin

In urban floodplain systems where there is little interaction between the overland and underground flows, this technique provides an effective methodology that generates valid results while minimising the complexity of the system.

However, difficulties arise when the interaction between overland and underground flows is more complex. For example, if the floodplain were as in Figure 2 including a retarding basin that collects and stores a large proportion of the underground flow, the modeller may be required to feed some or all of the underground flow component back into the hydraulic model. This type of situation can be easily resolved by including additional hydraulic boundary conditions to represent the underground pipe network discharging into the retarding basin. Nevertheless, this requires a certain amount of interpretation on the part of the modeller.

Unfortunately, not all floodplains are arranged as a simple linear network of channels and storages. Indeed, most are considerably more complicated, and in areas where there is a history of flooding and numerous attempts to resolve drainage issues, one is often faced with quasi-2D networks of pipes of various sizes, grades, inverts etc. It is no longer a simple matter to calculate the capacity of the underground pipe network, and the modeller may choose to represent the underground network in purpose built software to calculate its capacity and apply these findings to the overland flow modelling software.

These approaches have been traditionally adopted because of the relatively low level of sophistication in the hydraulic models chosen for the modelling of overland flow. Steady state or backwater models (eg. HEC-RAS) have limited capacity to incorporate an underground component of the flow, and this is also true of a range of unsteady flow models. This has lead modellers to develop techniques along the lines of those outlined above to *re-define the problem within the limitations of the chosen modelling software*. Indeed, this is often thought of as the primary role of the modeller.

2.2 Current 1D Approach

Advances in software have provided modellers with tools to undertake complex 1D modelling problems by integrating overland and underground networks in the one hydraulic model. Because the overland and underground flow components are modelled simultaneously and dynamically linked, any and all interactions between the overland and underground can be represented. This immediately offers the modeller tremendous flexibility as there no longer exists a need to separate the flow components. The system can be modelled as one.

The application of these advanced hydraulic models in the urban setting has been highly successful. Streets that carry flood flows naturally form 1D networks in the modelling domain and these are supplemented with complex underground pipe networks.

2.3 Limitations of 1D Modelling

While advances in the capabilities of 1D models have occurred, there remain a number of key limitations that are inherent in a 1D approach. These limitations are not a fault of 1D modelling approach, but merely a by-product of the assumptions required for a cross sectionally averaged solution scheme. Key limitation are discussed below:

Predifinition of Flow Path – A 1D model is arranged typically with branches or channels representing the flow paths and cross sections defining the conveyance characteristics of the branch. Storage may be defined separately or interpolated from adjacent cross sections. However, the flood flow path for a 100 year event may be quite different to that of a 10 year due to the increased flows and volumes of the larger event. Moreover, as floodwaters rise during a single flood event, the flow paths may change in length and/or slope and new flow paths may be created.

In a 1D model, the modeller must ensure that all possible flowpaths are accurately represented. If a flow path is omitted or inappropriately defined, the resulting flood water levels may be incorrect because too much water has been forced down this channel instead of spilling into that channel. For example, the length of the flow path for a meandering creek would be significantly longer (and of shallower grade) than for the adjacent floodplain, and the characteristics of the creek and floodplain may be quite different. In such cases, parallel branches are often created, one for the creek and the other for the floodplain, with appropriate interactions.

However, this can still lead to flowpath definition problems. The parallel branches in a 1D model will interact over, say, a weir representing a levee bank at the side of the creek. Typically, the floodplain branch is broad and may slope away from the river to a remnant riverbed. Water transferring from the creek to the floodplain pours into the deepest part of the floodplain branch, which may be well removed from the creek.

Transverse Water Slope – In a 1D model, momentum is conserved in 1 direction; along the branch. By definition, there is no opportunity to account for momentum conservation at bends in the river, as a 1D model is only interested in the cross sectionally averaged conveyance characteristics of the section. Additional “form losses” are typically applied to account for head losses at the bend, but the water surface across the section is assumed constant. This can lead to problems when the transverse water slope is relatively large, and water levels on the outside of the bend are significantly higher than those on the inside. In such cases, whether or not waters overtop the outside of the bend, or the time at which this occurs during the flood event, can be significantly misrepresented.

Complex 2D Flow Patterns – Quasi 2D systems can be satisfactorily modelled using networked 1D models, however, in complex 2D flow situations the predefinition of the flow path and the inherent difficulties associated with cross sectionally averaged flow and velocity severely limit the application of 1D models. This is a particular problem in areas of flow separation of confluence, where 1D models typically transfer a water level to each of the branches involved and limited information regarding flow velocity or momentum is provided.

Broad Floodplain Sheet Flow – If the floodplain branch is broad and flat, a 1D model will evenly distribute the water over the width of the cross section because a 1D model assumes that the water level is constant across a cross section. The effect of the flow resistance characteristics (eg Manning's n) on this very shallow sheet flow will be quite different to the real world situation where fingers of floodwaters propagate across the floodplain.

In an urban setting, the floodplain may include residential properties, which are represented using a relatively high resistance coefficient to account for the presence of houses, gardens, fences etc. However, the areas between the houses, along paths etc. will have a relatively low resistance coefficient and some interpretation of this will be required to simplify the situation to one dimension.

Safety Risk Calculations – Often the floodplain manager is interested in safety/risk considerations where the need to identify deep and/or fast flowing water is required to provide input into the assessment of, say, evacuation routes. The cross sectionally averaged flow and velocity from a 1D model is used in the calculation of such risk, often parameterised as the maximum of the depth and velocity × depth at a particular location. The cross sectionally averaged velocity, calculated as the flow divided by the cross sectional area, will underestimate velocities midstream and over estimate velocities at the edge of the flow. It is the responsibility of the modeller and cartographer to adjudicate the distribution of flood velocities across the cross section.

Floodplain Mapping – Mapping of the flood extent and depth derived from 1D modelling requires extensive interpretation by the modeller and cartographer. The spatial location of the results may not be geographically referenced but simply identified as a chainage along a branch. This requires considerable interpretation by the cartographer within the chosen GIS environment to geo-reference the results prior to the production of flood maps.

The geo-referenced flood modelling results will be in the form of water levels at a point along the branch or keyed to lines representing the cross sections in the model. The cross section represents a flood contour, often assumed transverse to the flow direction. The cartographer and modeller must work together to interpret these cross sections/flood contours with reference to the underlying digital terrain model, land use characteristics, vegetation type etc. The flood surface is generated by interpolating between adjacent cross sections.

All these steps require intensive collaboration between the flood modeller and the cartographer, and a significant amount of interpretation based on a variety of inputs and the experience/expertise of the flood modeller. To a certain extent, the flood mapping becomes a subjective exercise. Nevetheless, floodplain mapping within the GIS environment is a powerful tool for the floodplain manager (See Walden et al 1999 for further discussion)

2.4 Two Dimensional Approach

Many of the limitations of the 1D approach are eliminated when a 2D modelling approach is adopted. Flow paths are no longer predefined, there is conservation of momentum in both the x and y directions, complex flow patterns are resolved, the model more realistically represents sheet flow, flow velocity and water depth are calculated throughout the modelling domain to input to safety/risk assessments and it is a relatively easy process to geo-reference the model results data such that little "interpretation" is required.

All this comes at a cost. For high resolution modelling, the accurate representation of the topography requires the model spatial resolution to be quite high, and as resolution increases, so do run times. Such limitations on the computational efficiency of the model are becoming less prohibitive as computer technology provides us with high speed computing power. Nevertheless, many of the 2D modelling schemes have limitations in there application due to:

- Computational efficiency or length of run time;
- The need for detailed spatial topographic information (ie DTM);
- Poor or non-existent representation of hydraulic structures;
- Stability at high Courant numbers; and
- Lack of robust wetting and drying schemes.

Modellers have developed ways around these problems, utilising similar techniques as described above for the traditional 1D approach. The key issue in application to urban flood modelling is adequate representation of complex underground pipe networks. In resolving this issue, one approach has been the use of nesting whereby a representation of the pipe network is created and in some way linked to the 2D model. The nesting is considered static or dynamic depending on the way in which information travels between the overland and underground components.

Static Nesting – In the case of static nesting the flow component within the underground network is calculated (perhaps using a 1D pipe network model) and removed from the total flow component. The remaining flow is used to drive the 2D model. Boundary conditions, in the form of flows or water levels, may be introduced to represent significant pipe inflows or outflows (eg under roads, into and out of retarding basins).

Many 2D models do not have the capability to model pipes or culverts under road embankments. A technique often adopted to simulate such flow is to create a head vs flow boundary condition at the pipe inlet location and draw out of the 2D model the appropriate flow component. Some models allow the opportunity to return this flow component elsewhere in the model. When such a feature is not available, the modeller must undertake a first pass of the simulation, identify the flow component exiting the model via the pipe, generate a boundary condition reflecting this component as an inflow elsewhere and resubmit the model for execution. This is a time consuming process, and due to the amount of user intervention, is open to the generation of errors.

Dynamic Nesting – Dynamically nested models are executed simultaneously. Typically the solution scheme will undertake a sweep of the surface 2D model during the first phase or pass of an iteration and supply information to the underground network model. The underground network model undertakes a first pass iteration and feeds information back to the surface 2D model. That is, flow and water level information is transferred to and from the both model components.

Static nesting has been the traditional approach to 2D modelling situations that include underground pipe flow components. It does not require any specialised software and offers the modeller opportunities to take information from one package to another.

Both finite element and finite difference 2D schemes have been applied successfully in large scale and rural flood modelling applications (see Syme et al 1998 for a thorough discussion). However, there remain difficulties in the application of 2D schemes in an urban setting due to limitations in the representation of the underground network that is dynamically nested within the 2D modelling domain.

2.5 Latest 2D Approaches - TUFLOW

TUFLOW (Two-dimensional Unsteady FLOW) is the product of a research and development project jointly funded by WBM Pty Ltd and the University of Queensland. The objective of the project was to develop a 2D modelling system with dynamic links to a 1D system. The primary motivation was the application of 2D modelling in large estuarine environments, with the 2D component representing the area near the entrance and the 1D components representing the long estuarine arms. The development project was completed in 1990.

Recognising the deficiencies in existing 2D modelling software, particularly the problems associated with adequate representation of structures, in 1997 WBM initiated further development of TUFLOW to specifically meet these challenges. The resulting software is extremely powerful and can be used to represent complex networks of underground drainage systems dynamically nested within a 2D model. The underground drainage system is schematised as a network of 1D elements in the model, with connections to and from the overland system at appropriate locations. The system is fully geo-referenced and much of the model preparation is undertaken with the MapInfo GIS environment.

3 CASE STUDY – RIPPLESIDE MAIN DRAIN

3.1 Background

The catchment of Rippleside is the largest urban drainage system in the Shire of Greater Geelong (approximately 750 Ha). The catchment is characterised by almost complete urbanisation with few open space or floodway areas. The existing drainage infrastructure is typically very old, much of it in place and unchanged since subdivision and development 30-60 years ago. The catchment has a history of drainage and flooding problems, mostly related to subdivisional drainage design practices of the period. This is typified by high levels of urbanisation, limited retention of natural drainage characteristics, undersized pipe drainage infrastructure and the lack of dedicated conveyance and/or storage capacity above ground.

The City of Greater Geelong commissioned WBM to undertake a study to model and map existing flooding characteristics and to evaluate a range of flood mitigation strategies. Figure 3 illustrates the catchment and study area.

3.2 Methodology

The study was undertaken initially with a 1D methodology using MIKE11 as the hydraulic model. Figure 4 shows the 1D model layout of branches and cross sections. The complex nature of flooding in parts of the catchment and the limitations inherent in 1D modelling approach led to a decision to prepare a 2D model of the drainage system using TUFLOW. The 2D model was developed with a horizontal resolution of 5m (ie cell size is 5m) and provides detailed coverage of the flood mapping area.

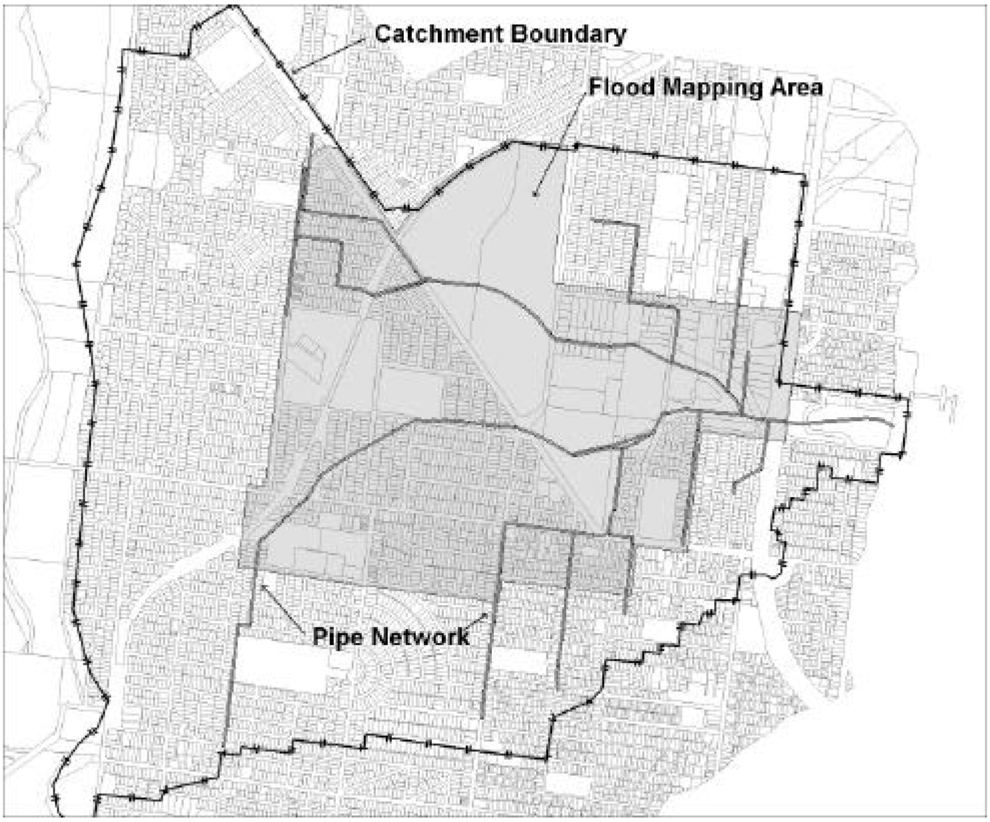

Figure 3 – Rippleside Catchment

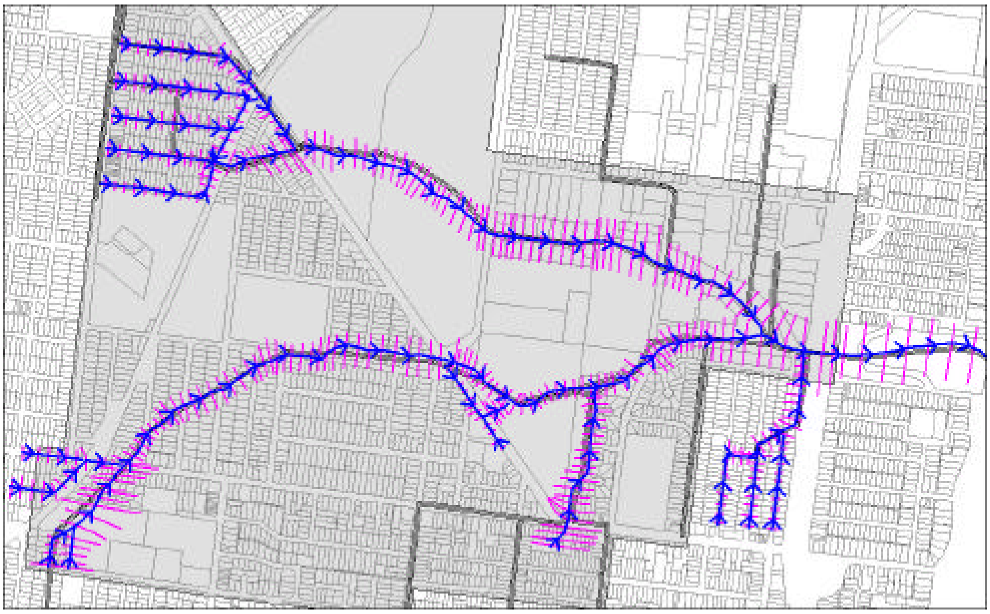

Figure 4 – 1D Model Setup

Key elements of the underground drainage infrastructure for the study area were replicated in each model. This was primarily associated with pipes of diameter 600mm and above, but also included some pipes of smaller diameter in key locations. Rainfall runoff hydrographs were calculated using RORB and applied at similar locations in each model.

The models were developed concurrently and the results for identical design flood events compared. These are presented and discussed in the next section.

3.3 Results

3.3.1 Comparison of Underground Drainage Components

As a first step in comparing the 1D and 2D models, the comparison of flow characteristics in the underground network was critical to establish consistency in both the below ground and overland flow characteristics. Figure 5 shows a typical hydrograph for pipes in the study area for each model. These hydrographs compare favourably and are consistent with hand calculations of theoretical peak flow in the pipes (in this case 5.4 m^3/s).

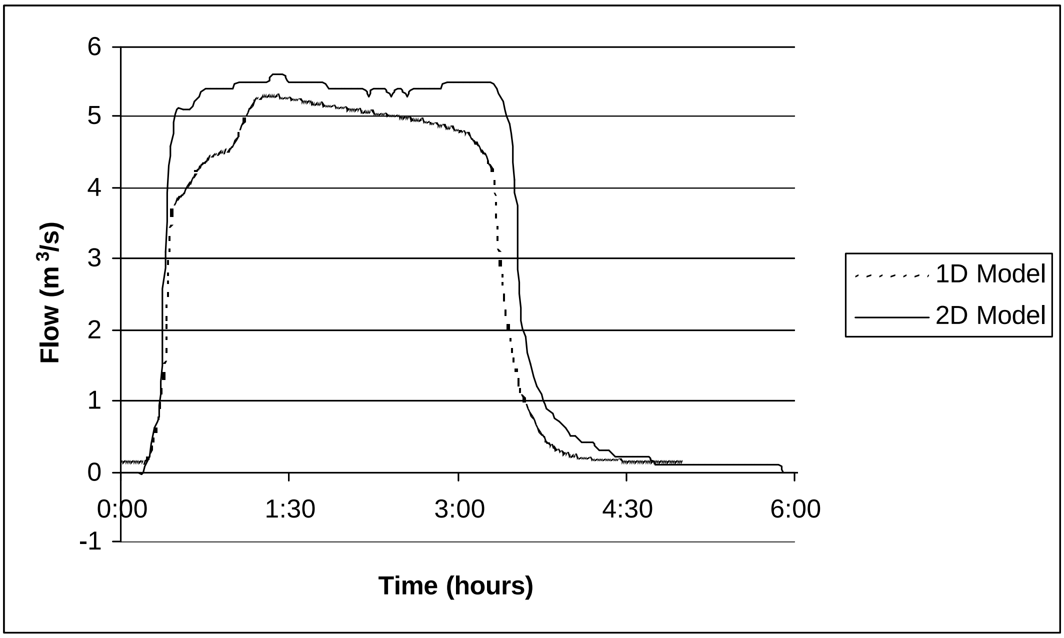

Figure 5 – Comparison of Underground Flow Components

These results offer the modeller confidence that the underground drainage component is accurately represented and that the overland flow components are similar between the two models.

3.3.2 Comparison of Flood Extent – Linear Flow Paths

Figures 6 and 7 show flood extents as calculated from the results of each of the modelling approaches. In Figure 6, where the flow path is well defined, the flood extents are very similar. The flood extents are almost identical. Peak flood levels in the 1D model are slightly lower than those of the 2D model (~0.1m). In the area presented in Figure 6, the additional computational detail of the 2D model provides little additional information to the modeller and floodplain manager.

Figure 7 illustrates the results through a residential area, where numerous minor flow paths exists but are represented in the 1D model as a single branch (as is the case near peak flood level). In this case the 1D model shows water levels higher than those of the 2D model as floodwaters are “forced” to flow along the one path.

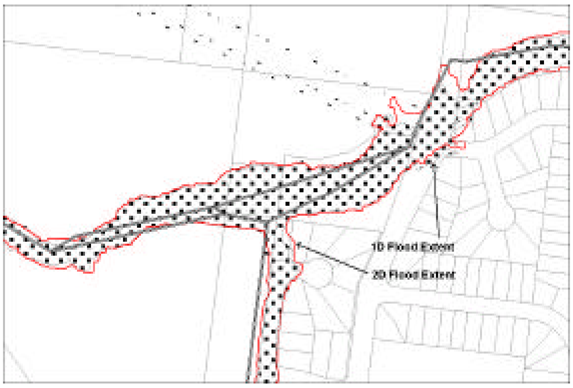

Figure 6 – Comparison of 1D and 2D Model Results – Well Defined Flowpath

Figure 7 – Comparison of 1D and 2D Model Results – Poorly Defined Flowpath

3.3.3 Comparison of Flood Extent – Complex Flow Paths

Figure 8 illustrates a situation of complex two dimensional flow that clearly demonstrates the deficiencies in the 1D approach. The 2D flow path is considerably more complex than that derived from inspection of the underlying terrain and defined in the 1D model.

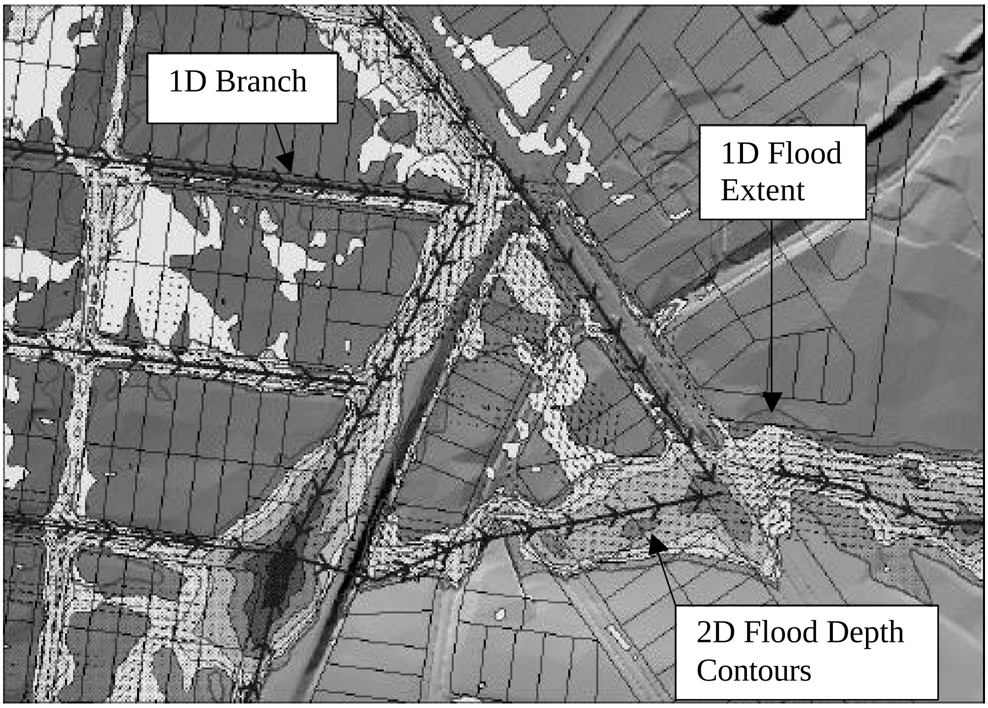

Figure 8 – 1D/2D Comparison in Complex Flow Areas

3.3.4 Flood Velocity

Figure 9 also shows velocity vectors from the 2D model and illustrates the significant increase in detail for the velocity profile. 1D models cannot provide this level of detail directly for linear sections of drain and in areas of simple junctions or separations of flow paths, the distribution of velocity across the floodplain is almost impossible to establish.

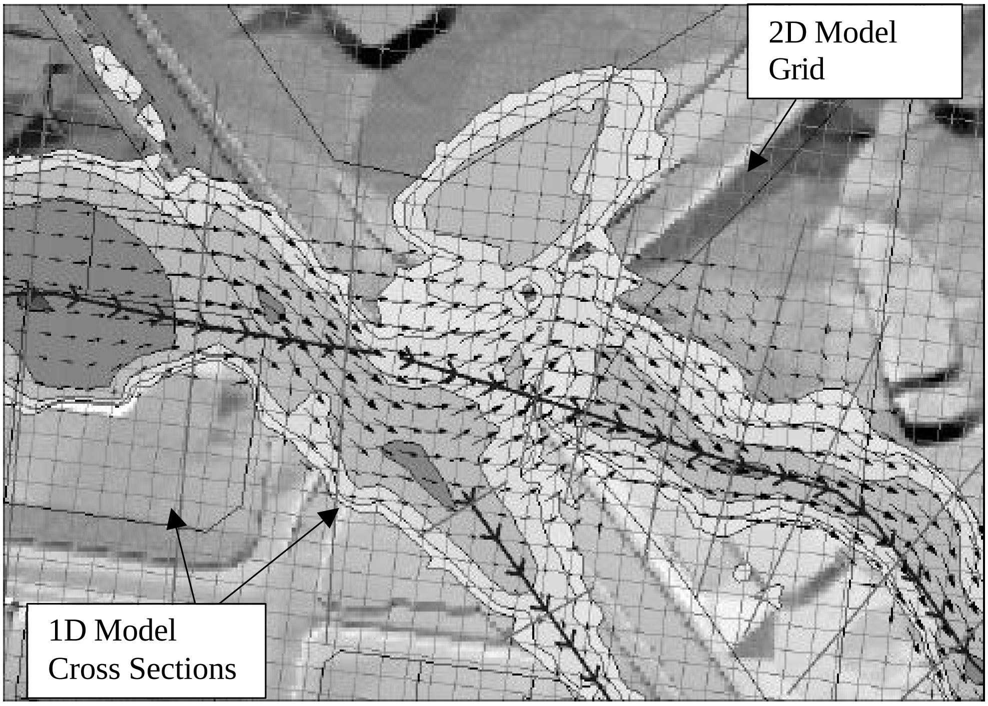

Figure 9 – Detail of Velocity Achieved by 2D Model

4 FLOOD MODELLING IN AN URBAN ENVIRONMENT – 2D OR NOT 2D

The case study clearly demonstrates a number of advantages in utilising advanced 2D modelling methods within urban environments. These include:

- Increased detail and accuracy of model definition is increased due to fewer assumptions required in setting up (eg. do not predefine flow paths)
- The accurate simulation of 1D situations with good correlation with Mike11 results in 1D areas both above and below ground;
- Outstanding representation of the flood regime in complex flow areas;
- Better representation of sheet flow;
- Increased confidence in flooding results due to lower interpretation required during flood mapping.

The latest advances in 2D modelling is towards inclusion of a facility to model pipe networks and this means they are very applicable to urban floodplain modelling and mapping. The data requirements for detailed flood mapping in 1D or 2D are very similar and with the aid of GIS, the geographically referenced 2D model may be easier to set up than 1D since much of the information is already available in a geo-referenced format.

2D or not 2D – In the end the choice of modelling approach will be dominated not by cost, but by the applicability of the model to the terrain and the resultant information required. In simple hydraulic cases where the cross sectional distribution of velocity is not required, a 1D model may be more than adequate. Where the floodplain manager needs to assess flooding in complex areas with multiple flowpaths, then a 2D approach may be more appropriate.

Software like TUFLOW makes floodplain mapping using 2D models no less difficult than 1D and, in many cases, much more cost effective due to less interpretation required, either in defining flow paths or mapping of the results. In addition, 1D and 2D approaches have similar input data requirements, which means their non-modelling related costs are comparable. 2D or not 2D – the choice is up to you.

5 ACKNOWLEDGEMENTS

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