Monday10

Integrated modelling of sewers, rivers and overland flows

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Introduction

The paper presents the outputs from an "Integrated Catchment and Urban Modelling" study of a highly urbanised area in Yorkshire, UK undertaken by Halcrow for the Environment Agency. The paper demonstrates how separate 1-D hydrodynamic models of the river and sewer/culvert surface water network can be dynamically linked with a 2-D hydrodynamic model of the overland (surface) flow. The purpose of the work being to assess the impacts of river flows on the sewer/culvert network as well as determination of the overland flood propagation resulting from surcharging of the surface water network.

The paper also shows that the application of these techniques, which are still in their infancy, needs to be carried out with care since software is often being applied to problems for which they were not originally developed. With reference to initial benchmarked results it is shown, for the overland flow component, how inappropriate use of software may give a false degree of confidence in predictions that may well be seriously flawed and in error.

Background

Making Space for Water (July 2004), the Government strategy for flood and coastal erosion risk management, promotes the adoption of "whole catchment" and "more holistic" approaches to managing flood risks. It specifically stresses the need to take into account all sources of flooding and thence be consistent with, and contribute to the implementation of, the Water Framework Directive (WFD).

In response to MSfW, Defra is embarking on a programme of Integrated Urban Drainage (IUD) pilot studies through "integrated urban drainage pilot partnerships" which will trial and establish cost efficient and practical means of protecting citizens in urban areas from the distressing impacts of flooding, regardless of its source. Resolving urban flooding problems presents a significant challenge because the frequency and severity of flooding is increasing at the same time as pressures on urban development are growing. All this is happening under regulatory and institutional arrangements which can be confused, not aligned and even counter productive.

It is also desirable to consider urban water quality management within the context of Integrated Urban Drainage Planning. Urban runoff, as well as constituting a flood risk, also presents a water quality risk as it contains hydrocarbon, bacteriological and heavy metal pollutants. When mixed with foul sewage it can also pollute receiving watercourses. Well established planning methodologies (e.g. Urban Pollution Management) exist for the integrated management of urban water quality and these will become more important as the Water Framework Directive seeks to improve the quality of most urban water bodies.

Therefore effective flood management needs to be combined with water quality management. Similar intuitional barriers exist in water quality planning as in flood management. For example, the control of sewerage undertaker's intermittent point source discharges (CSOs) is handled quite separately from that of their continuous discharges (WwTWs).

Taking an appropriately joined-up approach has the potential to provide integrated catchment benefits for urban areas. It will not only provide a better understanding of catchment processes but it will enable the management of flood risk by all stakeholders, specifically local authorities, water companies, the Highways Agency and the Environment Agency. It will also lead to improved water quality and water resources management.

Integrated catchment modelling (ICM) is a key process in the planning and design of a more integrated urban drainage system. If better integration is to be realised in practice, it must first be proven to be effective in reliable and robust simulation models. It is on the basis of results from these models that regulators will agree to innovative integration proposals and engineers will be able to design them. Integrating the modelling of sewer network, overland flow and river components of the urban drainage system is a significant challenge in itself, only made possible by recent improvements in computer processing power and software. Choosing the most appropriate method and tool/software for each component is another challenge if not only to avoid prejudice or bias.

Modelling methods and toolkit

For almost all types of flooding projects someone somewhere has developed a modelling method and tool that can provide us with an answer to our questions. However, this may only be part of the answer, since the tools used have historically considered only part of the "problem". This is due to the way problems have been solved i.e. in isolation. The barriers which have led to this isolation include legislative drivers, knowledge management, investment in and approach to research, technical capability, data availability, computing power and of course financial and time constraints. This is supported by the findings of Defra's Integrated Urban Drainage scoping study (Defra 2006).

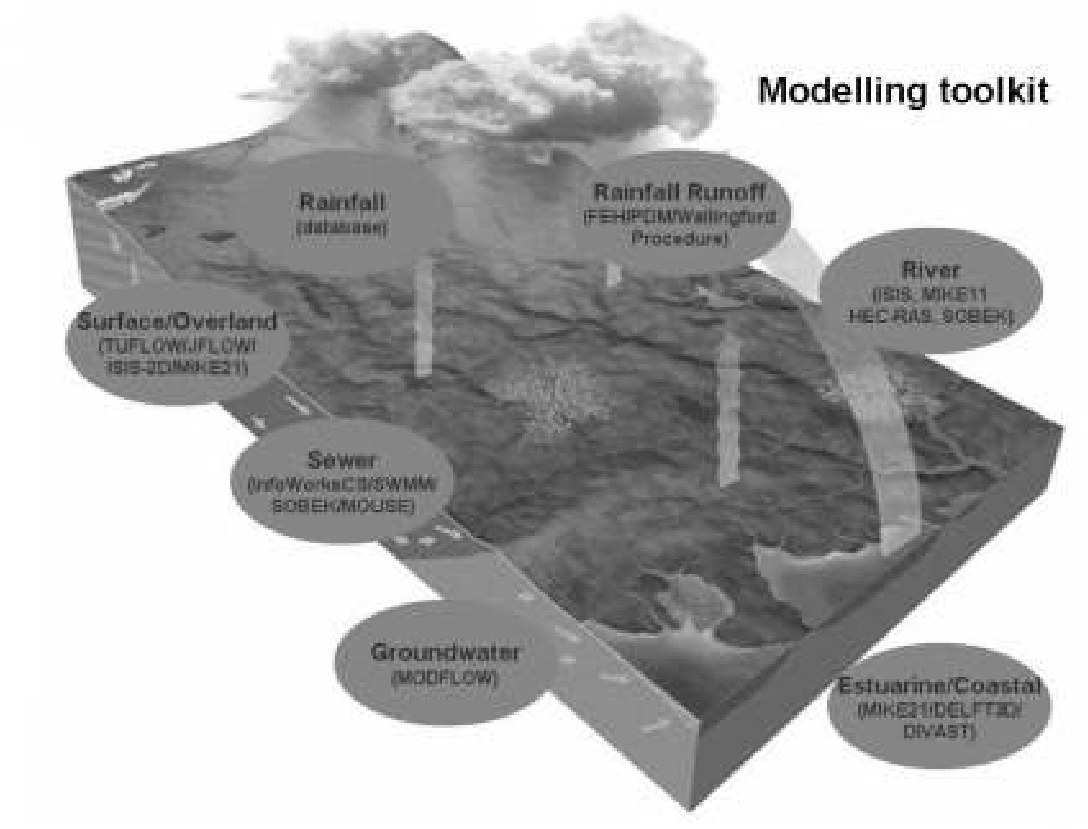

Figure 1: Typical modelling toolkit

Figure 1 illustrates the typical segmentation of the toolkit; rainfall analysis and rainfall predictions, the estimation of flows in sewers, rivers, and groundwater, flows overland (surface) and in estuarine and coastal waters. For each of these there are many examples of where urban flooding has been a component. However, the aforementioned barriers have frequently resulted in simplified approaches to understanding the problem of urban flooding and thence limited the development of more holistic and robust solutions. For example, when assessing the interaction of river and sewer flooding (see Figure 2), the rainfall analysis provides a suitable inflow (flow time boundary) to the respective river model. The impact of the sewer model on the river, however, is considered as an independent (static) process i.e. a flow time boundary needs to be extracted from the sewer model and applied separately to the river model. Similarly, the impact of the river model on the sewer model has to be considered by applying a predefined water level time boundary to the sewer model. Although this approach provides a method of assessing integrated flooding problems it can be a labour intensive process as current modelling tools are not user friendly in this context. Furthermore, this does not provide interdependences in the hydrodynamics which ultimately leads to poorly designed solutions.

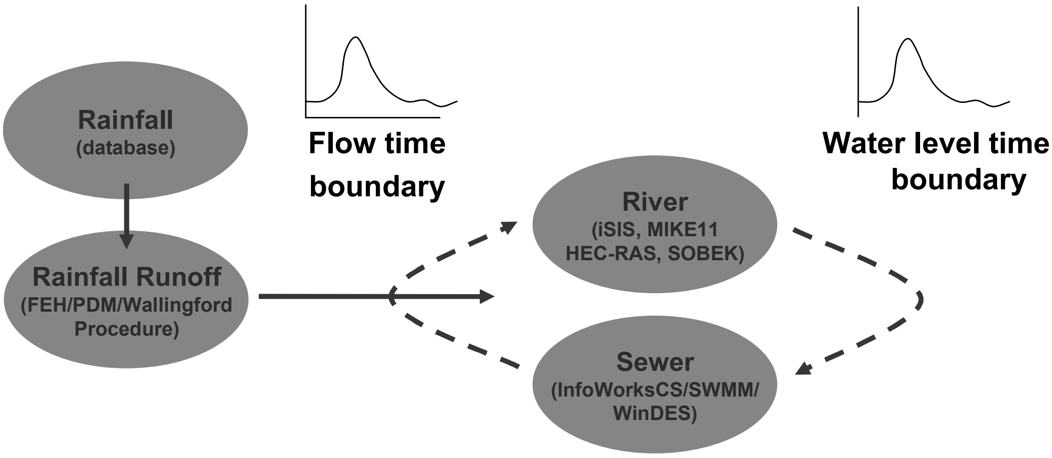

Figure 2: Static linking of models

In the case of ISIS and InfoworksCS the labour intensive procedures of static linking can be streamlined with the use of a Halcrow developed ISIS-IWCS utility which allows the user to open an IWCS Master Database, select a specific simulation and export the time-series results for a selected node resulting in a hydrograph (Q-T) boundary. This utility is illustrated in Figure 3.

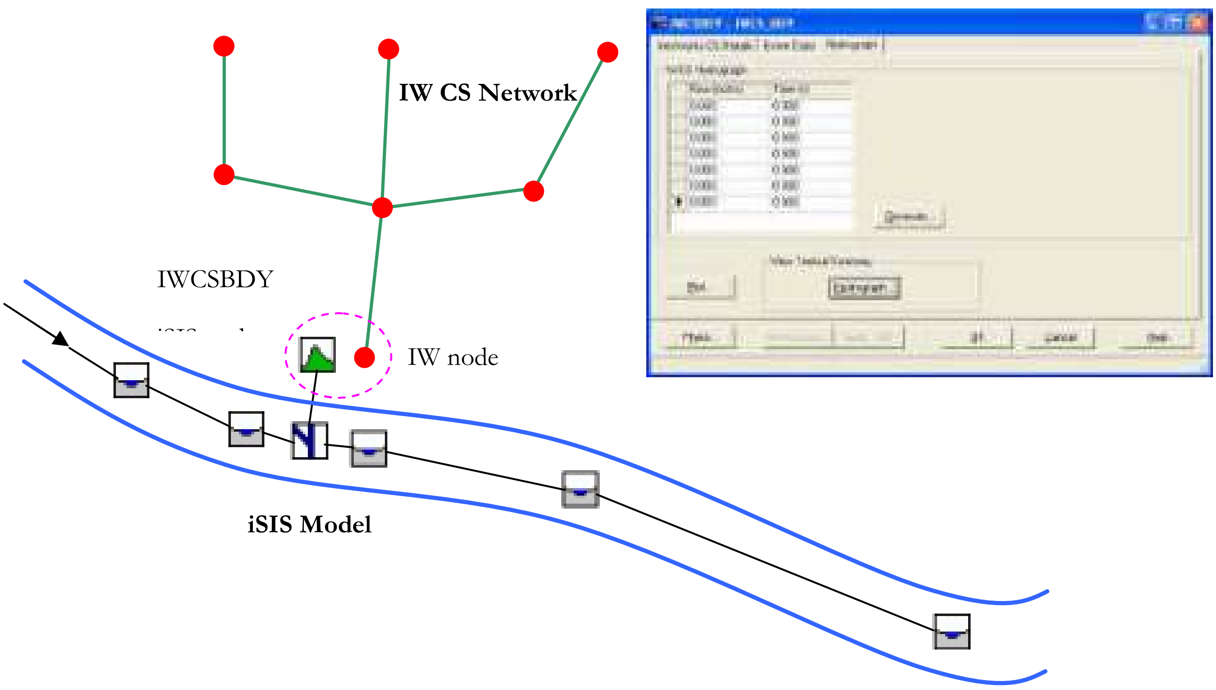

Figure 3: Static linking between ISIS and InforworksCS

The development histories of the software packages (i.e. academic research, software houses, and bespoke projects) have led to a rich and diverse heritage to the modelling tools. There are various types of ownership of the models and accessibility to the underlying software code (i.e. open sources, public domain and licensed) and there are also very different technical capabilities, strengths, weaknesses and performance of the software tools, as tested in the Environment Agency's Benchmarking Studies (Crowder 1997 and Crowder 2004 for 1D river modelling software).

Over the past decade computing power and data availability has significantly increased which has prompted many of the software houses to link their own models. However, a drawback of this has been that the modeller (and client) is generally limited to using software from just one software house thus stopping the "mix and match" approach which could otherwise lead to more appropriate investigations or unlock investment from previous modelling studies. However, this is changing, as discussed later.

Defra's scoping study for Integrated Urban Draiange for their proposed Pilot studies identified that "flood modelling tools are not yet fully available in a user friendly form" and that the "proposed pilot studies will hopefully stimulate their development", however, the leading software houses are likely to argue otherwise. The scoping study also identified that current industry standard modelling tools are "not sufficiently far advanced as to fully identify and replicate surface flood pathways, though there are some interesting developments in universities, consultants and software houses". The software houses will probably argue that there have been significant advances in recent years and that there are tools available which will enable a step change in understanding urban flooding (Syme 2004). For example, the Environment Agency study which developed integrated 1D river and 2D urban overland flooding along the Thames (Wicks 2005) and their flood mapping study that considered integrated sewer and overland flooding (Crowder 2006).

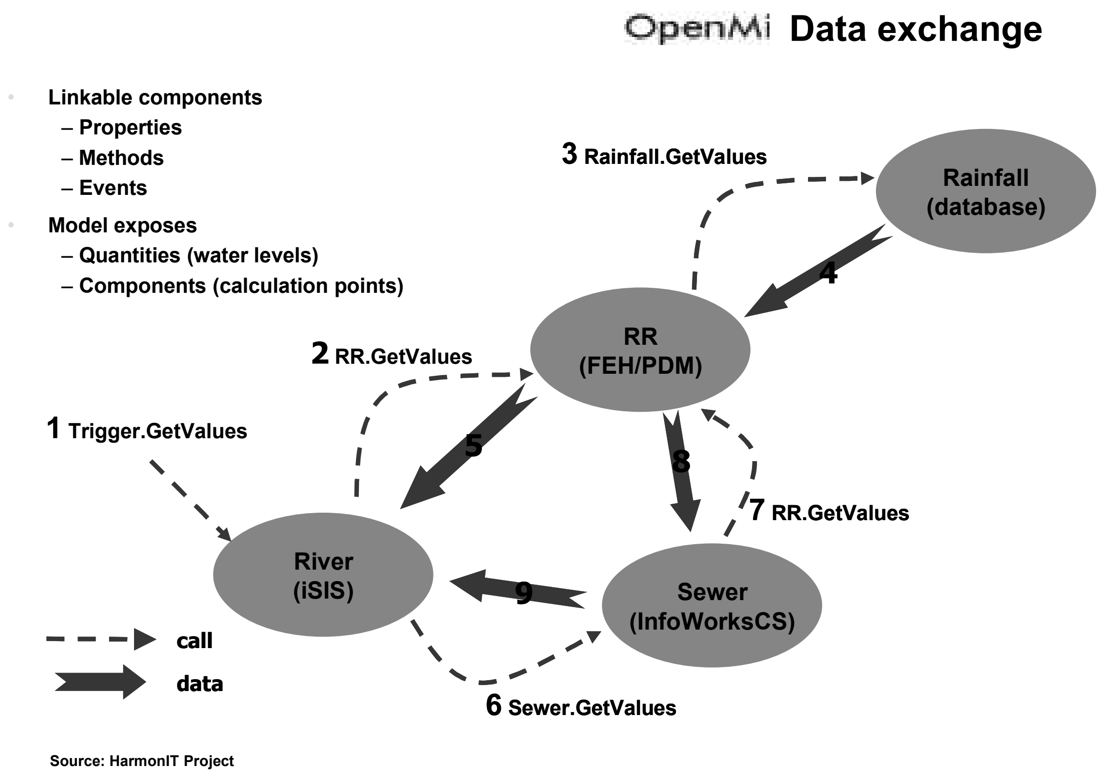

Figure 4: Concept of OpenMI data exchange

Linking models has many technical and commercial issues. For example, technical issues include different model processes, spatial resolutions, temporal resolution, terminologies (i.e. units and programming languages) and ultimately physical modelling concepts. With respect to commercial issues, the software houses (developers) are often in competition, source code is generally not freely available and there is of course the matter of modeller's freedom (preferred choice of software), client needs and the most appropriate modelling approach. A way in which this will be addressed in the future will come from harmonising modelling integration. A recent EC 5th Framework R&D study HarmonIT (HarmonIT) has set out a framework for this and has specifically developed new data exchange standards for developers to adopt called OpenMI. The concept of this, as illustrated in Figure 4, has been tested and is currently being adopted by software houses (Fortune, 2006). In particular, the OpenMI standard is likely to pave the way for significant flexibility in modelling, model capabilities and re-use of previously developed models.

The European Commissions LIFE-Environment programme has recently supported the Natural Environment Research Council project "Bringing the OpenMI-Life" for which the purpose is to transform the Open-MI framework from a research output to a sustainably operational product. The project will build the capacity to use the OpenMI framework and will demonstrate it in real life situations.

Integrated Catchment and Urban Modelling - Flanshaw Flood Mapping

It is known from anecdotal evidence that a number of properties within the small (area 0.81km^2) but largely urban catchment experience surface flooding via overland flow from Flanshaw Beck and from manholes surcharging. As part of the Environment Agency's Strategic Flood Risk Mapping programme the Environment Agency required a better understanding of these flooding mechanisms and improved information on flood risk to properties and roads within the catchment.

A combined 1D/2D hydrodynamic model was selected (Crowder, 2006 & Halcrow 2005) as the most appropriate method of simulating the routing of fluvial flow through the catchment. This approach facilitated the modelling of floodplain flow through the urbanised portion of the catchment and was considered to be more accurate than a purely 1D hydrodynamic model as flow routes on the floodplain are modelled. Consequently, the uncertainty in results, particularly in terms of flood extent output, has been reduced by selecting a combined 1D/2D model over a purely 1D model.

Model Construction

ESTRY was used to model the 1D sewer and open channel component of the model and TUFLOW was used to model the 2D overland flow component of the model, i.e. the floodplain. Figure 5 shows a schematic of the 1D elements of the model, including model node labels. All floodplain regions within the model extent, shown in Figure 6, were modelled in TUFLOW using a regular 2D grid of 2.0 m by 2.0 m. This cell size was chosen in preference to 4.0 m (or larger) in order to adequately represent the small gaps/alleys between buildings (Wicks 2005) and walls at a number of locations in the lower Flanshaw catchment.

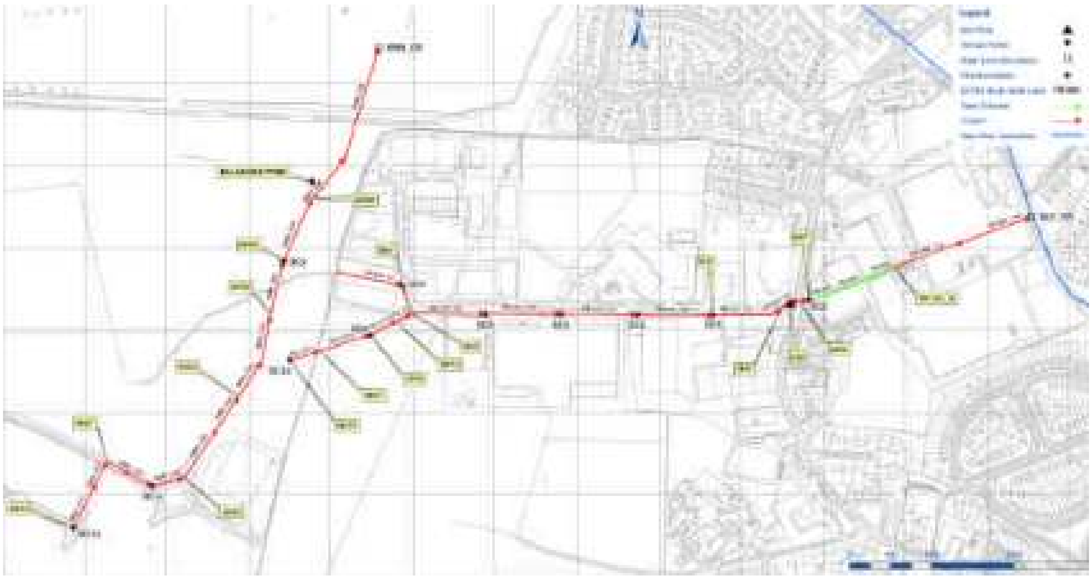

Figure 4: 1D model domain

Features within the floodplain that act as barriers to overland flow, such as buildings and walls, were represented by setting the associated grid cells inactive for buildings and using elevation lines to define ridge crests for walls, where appropriate. Smaller features, such as kerbs, were not fully represented due to the limitations of the LiDAR resolution. In most cases however, the ground elevation of the pavement/threshold is adequately represented. Through the use of laser scanning techniques representation of kerbs could be easily incorporated to the model.

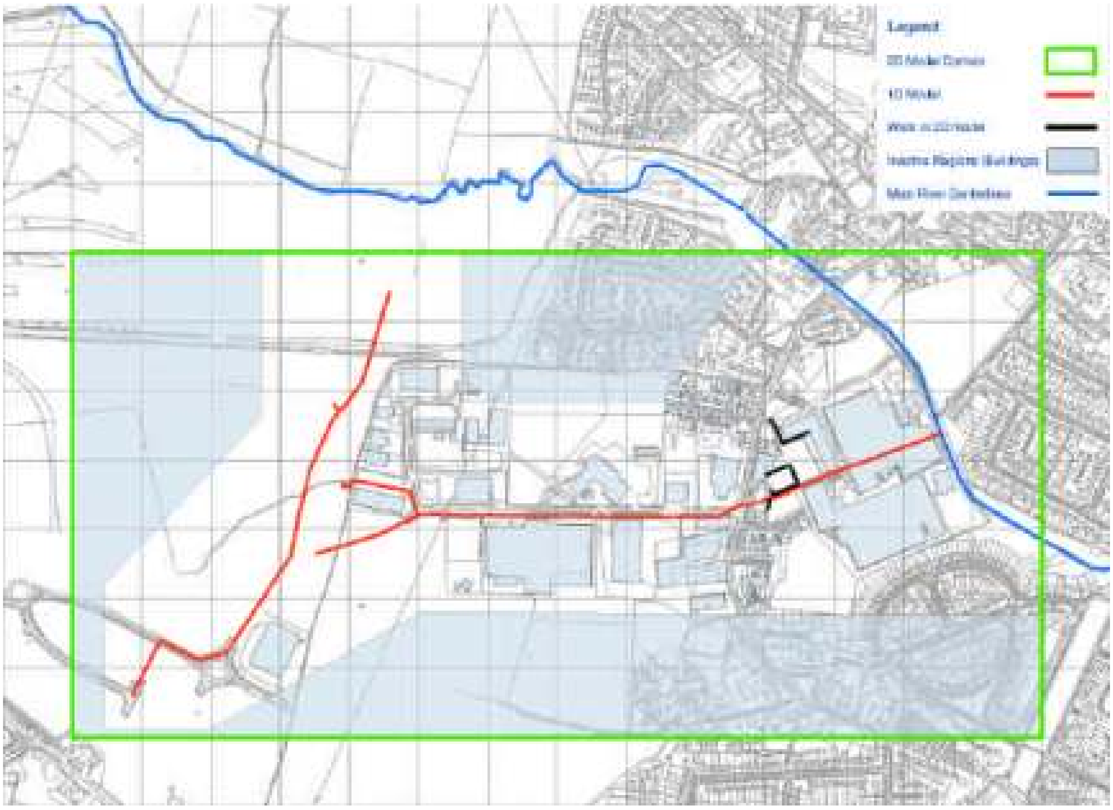

Figure 6: 2D model domain

In addition to the 2D model configuration described above, where buildings are modelled as solid boundaries, an alternate configuration was developed to investigate the effect of removing all buildings from the catchment.

In order to model flow from the 1D component to the 2D component and vice versa, it is necessary to link the two components. Further details of this are described in Crowder 2006 and reported in Halcrow 2005.

Upstream flood flow estimates were obtained (Halcrow 2005) from a simplified rainfall-runoff method, as the FEH rainfall-runoff and statistical method are not suitable for flow peak estimation for small urbanised catchments. The flood flow estimates were incorporated into the hydrodynamic model as point-source flow-time boundaries that connect to the 1D components of the model, as shown in the model schematic (Figure 5). The positioning of the inflows was determined by the hydrological sub-catchments. In general, the inflows were applied towards the upstream end of the sub-catchments in order to represent a worst case scenario. In reality, storm water is likely to enter the pipe networks through a combination of gullies, filter drains and manholes. However, since individual gullies and filter drains were not included in the model, inflows were directly connected to the pipe network. In most cases, such connections are at the same location as manholes.

Downstream stage-time boundary conditions representing the water level in Alverthorpe Beck during the corresponding flood event (Halcrow 2004) were applied to (1) the downstream end of the 1D component of the model and (2) the location of Alverthorpe Beck in the 2D component of the model. The stage-time boundaries were configured to peak at the same time as those on Flanshaw Beck, to be representative of a worst case scenario.

For the 1D model a Manning's *n* roughness coefficient of 0.050 was selected for the short section of open channel towards the downstream end of the catchment. This relatively high value reflects the significant debris and vegetation in the open channel observed during site inspection and is based on reference to published values (Chow, 1959).

A Manning's *n* roughness coefficient of 0.020 was selected for all culverted channels and manholes, this being based on the higher value for closed channels (Chow, 1959) since the culvert material and condition is not known. As this higher roughness coefficient limits culvert flow capacity, model results will be indicative of the worst case scenario.

For the 2D model the Manning's *n* roughness coefficients used are given in Table 1. The majority of floodplain flow is confined to the industrial development through the middle of the downstream half of the catchment. Consequently, the majority of the active floodplain has been given a roughness of 0.025; this being considered representative of the predominantly smooth hard surfaces such as roads, paths and car parks.

Manning's n	Land Use
0.020	Industrial and commercial (roads, paths, car parks, some grass)
0.030	Residential (roads, alleys, gardens)
0.035	Playing fields and parks (soil, grass, isolated vegetation)
0.035	Brownfield land under development (soil, grass, isolated vegetation)

Table 1: Estimated Manning's n roughness of 2D domain (floodplain)

A sensitivity analysis was undertaken which confirmed that the Manning's *n* values for both channel and floodplain were appropriate for this study (discussed later). The flood extent, level and flow results are relatively insensitive to Manning's *n*.

Model Run Parameters

The selection of the timestep is critically important for the success of a model. The run time is directly proportional to the number of timesteps required to complete a model simulation, while the computations may become unstable or inaccurate if the timestep is greater than a limiting value. This is obtained from the Courant stability criterion which for the 2D model suggested a timestep of approximately 2.0s, however, as the Flanshaw Beck catchment is steep with high Froude numbers and supercritical flow, a timestep of 1.0s was used. The minimum timestep required for the 1D scheme was calculated at approximately 12.5s.

For the 1.0% probability flood event, the model took 0.65 hours (39 minutes) to run a 5.5 hour model simulation on a Pentium 4 2.8 GHz desktop computer. Diagnostic information output during each model simulation indicated that model simulations were stable and convergent.

Model Outputs

There was no formal calibration data available for the area hence it was only possible to conduct a qualitative calibration of the model. From knowledge of the catchment and data gathered from walkover surveys, model results in terms of water levels and flood extents appeared to be consistent with what could be reasonably expected. Additionally, the model results appeared to be consistent with anecdotal evidence of flooding, including residents photographs.

Without formal calibration, confidence in the accuracy of the flows derived from the hydrological analysis and the subsequent hydrological modelling results is subjective. To address this, a detailed sensitivity analysis (Halcrow 2005) was undertaken.

The results in Figure 7 show that flood extent in the Flanshaw Beck catchment is generally not sensitive to return period. This is because the catchment is steep, causing high flow velocities and low flow depths along Flanshaw Way and Flanshaw Lane. This prevents attenuation of the overland floodwater for the majority of the catchment. However, there is an appreciable difference in the flood extent where the two most upstream manholes begin to surcharge during the 0.1% probability flood event and at the lower part of the catchment where flows route around buildings. The analysis undertaken shows that there is a significant difference between the “buildings included” and “buildings removed” modelled flood extents. This is because a number of large properties lie within the natural flow path of the overland flooding for all flood events.

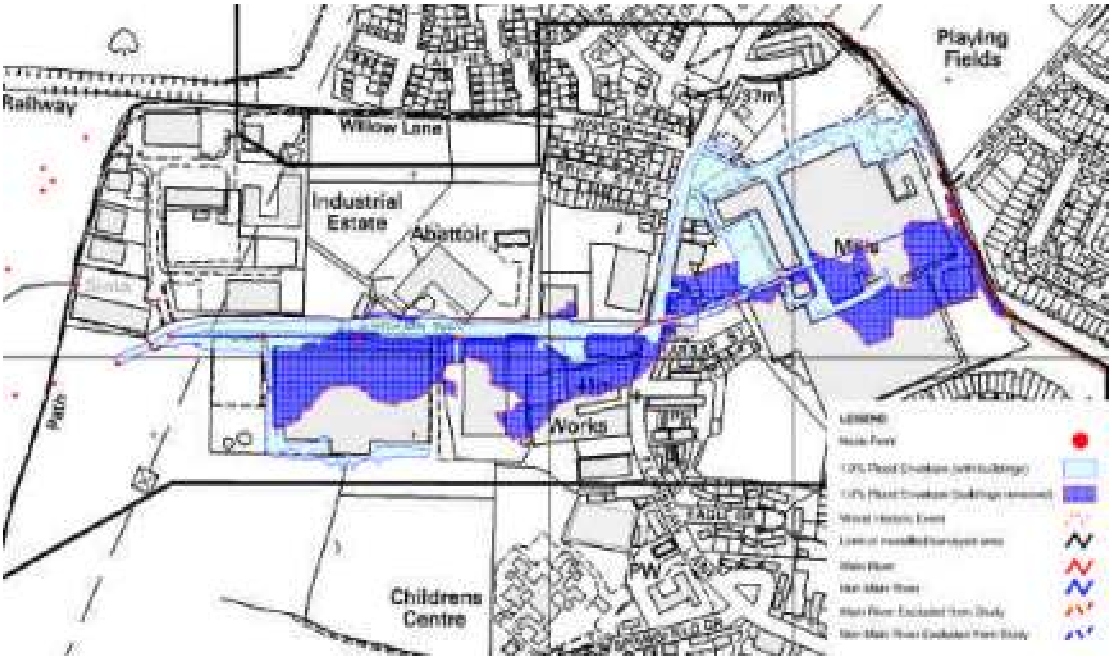

Figure 7: Flood extents

Benchmarking

Benchmarking can be undertaken in many different guises; however, in the opinion of the author the benchmarking of software should embrace some method of assessing the following (Crowder 2004):

- Numerical accuracy
- Capability
- Reproducibility
- Adaptability
- Form and function

The numerical accuracy of a software package can only be assessed if an analytical solution exists for the physical situation/configuration that is being modelled, which for real world modelling probably never exists. The capability and reproducibility of a software package can be assessed objectively by testing the most commonly required features of a software package. For the Environment Agency's benchmarking study (Crowder 2004), the capability of the software was tested by a series of "can do" tests, whereas the reproducibility was tested by a series of comparison tests i.e. numerical results compared with experimental or real world datasets. It is the later which has been tested here for the overland flow component.

An initial assessment of the performance and validity of TUFLOW (developed by WBM Pty Ltd Australia), MIKE 21 (Developed by DHI) and ISIS-2D (developed by Halcrow/Cardiff University) to a steep urban catchment has been made.

TUFLOW, MIKE 21 and ISIS-2D all employ what is termed an ADI (Alternating Direct Implicit) numerical scheme to solve the shallow water wave equations. However, within ISIS-2D there is an alternative TVD (total variation diminishing) explicit scheme which has also been tested. The TVD scheme is intended to overcome some of the numerical limitations of ADI schemes and provide a more accurate solution /representation of the 2D 'shock' (rapid changes in water surface profile with associated transcritical and supercritical flow) that can occur in urban flooding situations.

For the steep urban catchment, comparing TUFLOW, MIKE21 and ISIS-2D, the same unfiltered LiDAR DTM at 4m grid resolution and 3hr inflow hydrograph was used (simulating the spill from a reservoir). A timestep of 0.5 sec was used for the ADI schemes whereas the ISIS-2D TVD was run using a timestep of 0.25 sec so as to satisfy numerical criteria of the scheme. Further details of this test are provided in Crowder 2006.

The results of benchmarking, as illustrated in Figure 8, show that each of the software packages (thence numerical schemes) exhibit similar characteristics and produce very similar flood extents. However, there are some notable differences with respect to timing and maximum water level and velocities attained (Crowder, 2006). Close to the source of the dam break all the software and hence schemes (ADI and TVD) show similar timing for the flood wave propagation. However with increasing distance from the source the ADI schemes propagate faster than the ISIS-2D TVD scheme. The flood risk area (extent) is very similar for each of the software packages (and schemes); however there are subtle differences in the results. These results are subject to ongoing analysis.

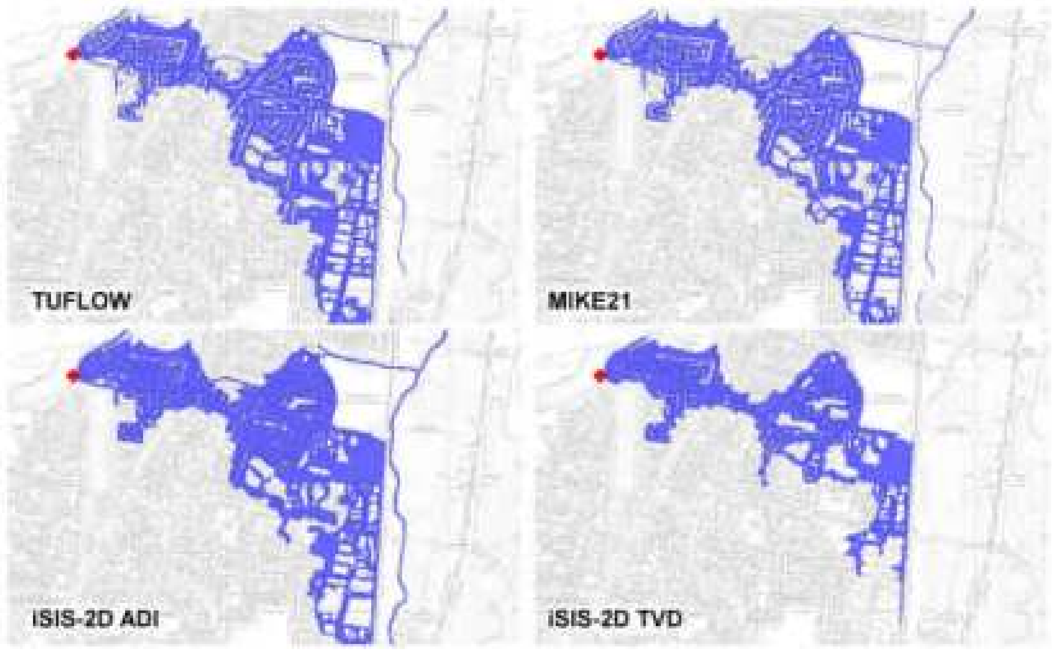

Figure 8: Benchmarking TUFLOW, MIKE21, ISIS-2D (steep urban catchment)

Conclusions and recommendations

From a modelling perspective there are tools already available that will enable the undertaking of Integrated Urban Flooding studies. However, there are technical limitations and shortcomings of the software packages which need to be considered carefully. Through continued R&D by the software houses most notably in making their software fully OpenMI compliant, the development of supporting tools for model building/development and analysis, and research by the likes of the Flood Risk Management Research Consortium we can expect to see significant advances in modelling capability over next few years.

For integrated catchment modelling to be realised in practice, it must first be proven to be effective in reliable and robust simulation models. A principal component of this which still needs to be addressed is the differences in the way flood hydrology is derived for river and urban flooding. This needs to be reconciled and more holistic and integrated approaches developed so as to enable constant and transparent approaches. This may be partly addressed by the adoption of continuous simulation methods rather than flood hydrograph methods.

The advent of integrated and larger modelling studies will exacerbate the problem of data management. It is imperative that solutions are developed as the use of inappropriate data or use of data in inappropriate ways will be costly in terms of poor solutions and additional and unnecessary work. It will also limit the potential value for re-use of data in subsequent studies i.e. for when flood management is combined with water quality management.

To address the inherent risks associated with undertaking such studies software benchmarking, modelling guidance and model management procedures are needed so as to drive consistent and quality controlled deliverables. Without this software will continue to be used inappropriately due to either prejudice for one software package over another, or lack of understanding the capability of a specific software package. This potentially has significant cost implications in terms of poorly designed solutions but more importantly it has life threatening consequences due to a false degree of confidence in predictions that may well be seriously in error.

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