WaPUG Autumn Conference 2009

Investigations into 1D-1D and 1D-2D Urban Flood Modelling

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Synopsis

UKWIR commissioned demonstration projects in 2007 to trial the use of modelling procedures/programs which were developed at Imperial College and University of Exeter as part of an FRMRC project. Three case studies were to be selected and modelled conventionally and also utilising the research developments.

The first case study used conventional 1D Infoworks modelling and added to this 1D overland modelling with direct coupling between the 'minor' (sub-surface) system and the 'major' (surface) pathways. The 1D overland pathways and storage ponds and their geometry were determined by Imperial College from an interrogation of the Digital Terrain Model. These were imported into Infoworks to achieve a fully coupled 1D-1D model. Simulations were run for real storms when flooding had occurred and also for design storms. A good correlation was achieved between observed and simulated flood extents. This modelling was done by Richard Allitt Associates.

The second case study followed a similar pattern but also used some high resolution Lidar survey data acquired from a vehicle. At about this time the Infoworks 2D module was released and this was used for part of the study area. This modelling was done by Torbay Council.

For the third case study the Project Steering Group decided to come back to the location of the first case study and to trial 1D-2D modelling. Modelling was undertaken by Richard Allitt Associates using the Infoworks 2D program and by the University of Exeter using the SIPSON/UIM programs which they have been developing. In both programs the whole sewer network was modelled in 1D and the whole of the surface area within the catchment was modelled in 2D. Different coupling arrangements between the 1D and 2D domains were modelled. In addition pluvial modelling with and without buildings and with and without sewers was undertaken. The same storms were repeated as used in the first case study. The results between the 1D-1D modelling and the 1D-2D modelling could therefore be directly compared and the similarities and differences were highlighted.

From this research the benefits of 1D-1D modelling compared with 1D-2D modelling were identified. The researchers would like to share their experiences of this modelling and to present their thoughts on how catchments could be modelled in the future to maximise the benefits of these complementary modelling techniques.

Introduction

UKWIR commissioned demonstration projects as their contribution to the aims of Work Package 6 of the Flood Risk Management Research Consortium (FRMRC). This provided real life applications of the modelling techniques developed by FRMRC and provided user feedback for the transition from research tool to end product. The initial aim was to apply the 1D surface modelling approach developed in FRMRC using the outputs of the new 1D surface model builder within InfoWorks as a representative modelling platform. But as the research progressed and its scope was widened to investigate important aspects of 2D surface modelling, the scope of the UKWIR project was also widened to demonstrate their relevance and to show that the research tools were compatible with industry standard software. Project sites on the Isle of Wight and at Torbay were selected based on availability of relevant data and catchment characteristics, including documentation of flood incidents, to maximise the probability of achieving the aims and objectives of the project.

Development of 1D Overland Modelling by Imperial College

Within the FRMRC project the Urban Water Research Group (UWRG) completed development of the new module for enhancing modelling of overland flow and pluvial flooding in urban areas. The module called AOFD (Automatic Overland Flow Delineation) uses a high resolution DTM (Digital Terrain Model) for creation of the network of ponds and preferential pathways that connect them as well as for identifying their characteristics.

Modelling urban flood flows requires that the water movement over the catchment surface is modelled by solving the appropriate mass, and momentum (or energy) conservation equations, leading to physically based overland flow modelling Radojković and Maksimović (1987)[1]. The initial version of the module was based on the development of Prodanovic (1999)[2] and Djordjević (2001)[3] and its most recent version is presented in Maksimović et al (2009)[4]. On the urban surface, modelling mimics the dynamics of the processes that naturally occur in temporary surface retention (ponds) and of the flow across the urban catchment along preferential pathways. The ponds and pathways are mutually connected and multiple connections may exist with inlets to the underground sewer network. This is the essence of the dual drainage concept. During flood events these two networks interact, when the sewer network is surcharged water can flow in both directions. The methodology of creating preferential pathways between ponds and their mutual connectivity are presented in Fig 1. In order to apply LIDAR obtained DTM for this purpose, it is necessary to prepare it by performing several enhancement operations in order to deal with flat areas and pit cells (Leitao (2009))[5].

The connectivity algorithm used to describe the overland flow complexities was firstly developed by Prodanović in the AUDACIOUS project (2005). A rolling ball technique is used to identify surface and overflow pathways between ponds. Starting at the natural exit point of the ponds, the analysis determines pathways by preferential flow directions based on terrain slope, taking into account the presence of buildings and other urban features represented in the DTM. The pathways delineation concept is shown in Fig 1. The entire process is done automatically within the AOFD module and the pathways identified form a complete surface network by linking ponds (nodes) throughout the DTM. There is a possibility that two or more pathways come close which are parallel or coincident to each other. In reality these pathways merge into a single pathway which is replicated in the program with a new set of computational nodes (called "surface junction") created at all the merging points.

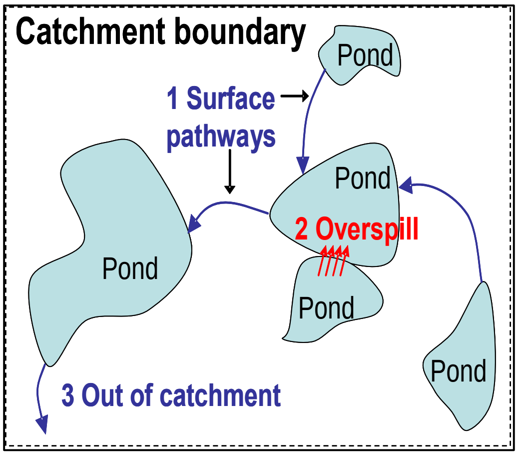


Fig 1 : Concept of pathway delineation

Modelling of the flow in surface pathways requires the geometry of the channel to be known. The process of determining these is presented in Fig 2. The algorithm for this uses the previously identified pathways and draws equi-distant cross-sections along each pathway length (Fig 2b). It then uses the surrounding DTM to estimate the flow areas of each cross section (Fig 2c) and finally, the algorithm allows users to select the form of the output which may be either an arbitrary (user defined) set of points or pre defined (trapezoidal) cross-section (Fig 2d).

If the user-defined arbitrary shape is selected, the algorithm will determine the average elevation of the entire pathway at each offset distance from the centreline (Fig 2c). If the trapezoidal shape is selected, the algorithm will compute the average flow areas at different depths along the length of each pathway (so called “stage-flow area” curve) and then the geometry of a trapezoidal shape is calculated to satisfy the stage-flow area curve. The calculation is done by recognising that the relation between area (A) and depth (H) of trapezoidal shape is quadratic (second-order polynomial). The width (B) and the 1/slope (m) are the major unknowns to be calculated. A least square polynomial regression was used to find the unknowns.

Sub-catchment delineation is also used to identify the contributing areas for each computational unit in the sewer network and these can either be “link-based” or “node-based”. Those areas that do not contribute runoff to any of the pipes are called “unsewered areas”. These are either because they are local depressions outside the sewered area or secondly the DTM data may be of poor quality. It has been previously identified that in extreme conditions, overland flow from adjacent permeable areas contributes to the runoff in sewered areas. In such cases, input hydrographs for those local depressions located in unsewered areas should also be included in the model as an unsewered pond and it becomes necessary to delineate the sub-catchment for the those ponds. The algorithm identifies unsewered ponds and their contributing areas. It begins by overlaying all ponds identified previously with sewered areas. Following this, the ponds are separated into those that drain to sewers and those that are in undrained areas. Then the sub-catchments of undrained ponds are delineated. This procedure is necessary to prevent double sub-catchment delineation counting the contributing area within the sewered areas.

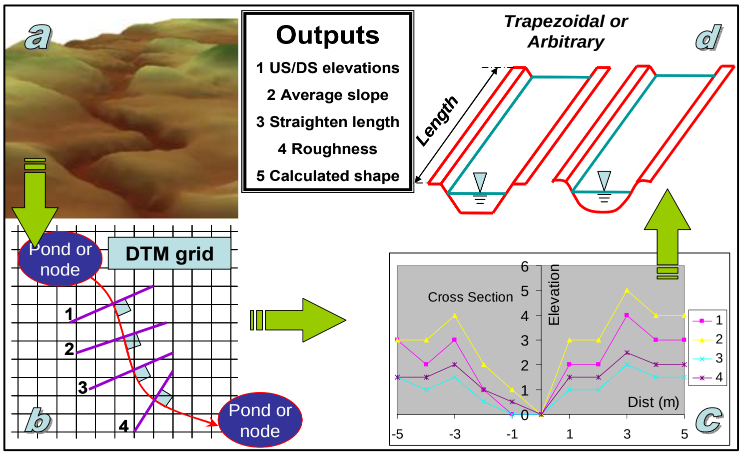


Fig 2 : Estimation of pathway geometry

The AOFD module is conceptualised so that it enables advanced modelling of the surface runoff and pluvial flooding and it can be “merged” with or enhance the most frequently used commercial models such as InfoWorks and MOUSE, public domain models such as SWMM as well as with the SIPSON system (Djordjevic et al (2005))[6] primarily used in research.

The AOFD module was used in the 3 case studies presented in the paper as well as in several other studies. An example of the processed system prepared for modelling is given in Fig 3.

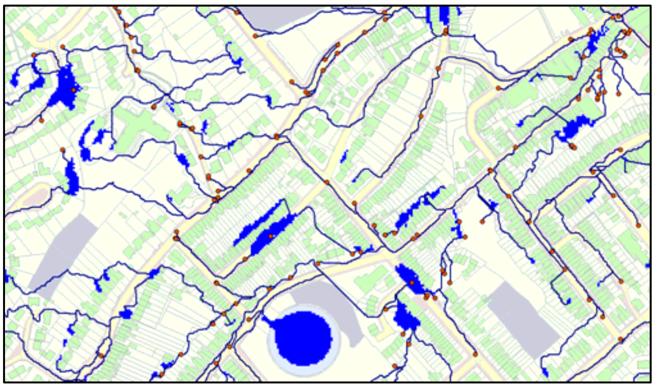


Fig 3 : Surface pond pathways (blue) delineated and superimposed over the storm drainage network nodes (red)

1st Case Study; 1D-1D Modelling

The first case study selected is an urban catchment on the Isle of Wight. This catchment was well known to the modelling team at Richard Allitt Associates Ltd and a fully verified Type II (as defined in the WaPUG Code of Practice) model supplied by Southern Water Services was available as the basis of the study. The model had recently been re-verified with a new flow survey in 2007.

The catchment is served principally by a combined sewer network and has a mixture of steep slopes, gentler slopes and some areas which are very flat. There were 4 particular locations where there were flooding problems with overland flows playing a significant part in the flooding mechanism. In drainage terms parts of the catchment are very steep and the study area is almost entirely a dense urban area with primarily terraced residential properties. For this study the program developers at Imperial College used their AOFD program. The locations and references of the modelled nodes in the Infoworks model were provided to the developers together with locations of all the road gulleys in the catchment.

There were a total of 4 different versions of the model used in this study. These versions of the model are:-

- The 'Base Model' is the verified model with no overland flow routing.
- The 'Simplified Model' is a derivative of the Base Model but with the addition of simple open rectangular 1D overland flow channels linking between manholes. The 1D overland channels were at a constant grade, were routed according to field observations, were set to link between manhole cover levels and were simple open rectangular channels 5 metres wide by 150mm deep.
- The 'Enhanced Model' was similar to the Simplified Model but with the 1D overland flow routes identified by the AOFD software using the Digital Terrain Model (DTM) of the catchment. The software also defined any storage nodes (ponds) in the catchment surface but any of these which were not on an overland flow route from a manhole were pruned out of the model. The cross sections of the overland flow links were confined to open trapezoidal channels.
- The 'Integrated Model' not only contained all the manholes in the study area but also all of the road gulleys. 1D overland flow links were derived by the AOFD software with the links either originating at manholes or at road gulleys. As with the Enhanced Model any identified storage nodes which were not on an overland flow route originating at a manhole or road gulley were pruned from the model. Similarly all links which did not originate at a manhole, road gulley or intermediate storage node were pruned from the model. The contributing areas for this model were re-defined such that the actual areas of roads, footways, drives and roofs (where they discharge onto the highway) were allocated to the overland link between road gulleys. The remaining roof areas (principally the rear roofs) were included in the contributing areas allocated to the manholes.

When the different versions of the model had been completed they were run with a matrix of different storms including two historical storms. The results were compared to assess whether any of the models provided a better or worse representation of the flooding mechanism and extents.

There were some instances found in this case study where the pathways initially identified were not in accordance with known routing. One of these instances was at a location of terraced houses with narrow alleyways where the exit route for the flooding was through an alleyway between houses; this was not identified in the initial assessment because the DTM did not show the alleyway. This problem was overcome by manual intervention – this illustrates what can be done if there is adequate catchment knowledge. The second instance was where a retaining wall which is omitted from the DTM allowed flows to exit one flooding area at a lower elevation than the known route. These instances raised question about whether the modelling software should be able to compensate for this or whether the DTM should be adjusted to be more representative.

One aspect which was found during the modelling work was the difficulty of presenting the results in a manner in which they are easily understood. The actual numerical values of flooding depths, volumes, flows or velocities could be extracted in the conventional manner either as gridded results or as graphs. However, in the geoplan view it was difficult to appreciate where flooding had occurred and very difficult to appreciate flooding volumes.

As a consequence of this it was decided to assess whether the 'flood compartment' feature within the Infoworks program could be used. The 'Flood Compartments' require a DTM to be able to operate and they can provide a representation of the flooding. It is important that the 'flood compartments' results are not confused with 2D modelling results as the outputs can look similar though in practice they are very different. The 'flood compartments' use the double cone shaped flood storage zone above the manhole and the maximum water level within the double cone is illustrated as a constant water level across the whole of the flood compartment. The 'flood compartments' can therefore tend to over represent the flooding unless the 'double cone' flood cone is made very flat.

For the study area 'flood compartments' were created across the whole study area by defining them as Thiessen polygons around each manhole. The flood compartments were then manually adjusted to give a better representation of the areas which flood. The final results were reasonably encouraging. However, there were particular difficulties found with the representation of flooding in flatter areas which were modelled as 'storage nodes' as these showed no representation of any flooding until the water level had exceeded the top level of the storage node. This was studied carefully and it was found that computationally the correct water levels were simulated; it was simply a case that the geoplan representation was not clear.

The objectives for this case study were twofold. Firstly to apply and evaluate the new 1D surface flow AOFD module developed by the FRMRC to support the better management of urban flooding; and secondly working with the FRMRC model developers, to identify any required improvements prior to the models being applied in further demonstration catchments.

In both of these respects this case study was successful. The AOFD software was proven to be a relatively quick means of adding overland pathways to existing sewer models and once the teething troubles with data structure were resolved the data could be quickly imported into Infoworks. On the basis of these conclusions it was recommended that the study should progress to the other case study areas.

Infoworks 2D Modelling

Towards the end of the 1st Case Study modelling work the 2D module for Infoworks CS was released by Wallingford Software. This significantly changed the focus of the remainder of the study as potentially the requirements for accurate overland flow modelling could be met in a different way. At this point in the project some stakeholders formed an at first glance understandable impression that the 1D surface modelling approach had become irrelevant because of the release of InfoWorks 2D. This impression was formed on the basis that the two approaches are competing, rather than complementary.

It was clear from preliminary trials that the Infoworks 2D module is a powerful tool for use in urban drainage modelling. The Project Steering Group therefore considered that it would be worthwhile undertaking a direct comparison between the 1D overland modelling with 2D overland flow modelling. As a result of this the scope of the 2nd Case Study in Torquay was widened to undertake a direct comparison for part of the study area.

2nd Case Study; 1D-1D Modelling and 1D-2D Modelling

Torquay is a coastal town in Devon, with approximately 65,000 residents. The town centre is at the base of a steeply sided valley adjacent to the sea front. Historically a river, known as the River Fleet, took all the surface water flows to the sea. As the town developed the River Fleet was used to convey sewage flows and was gradually culverted eventually forming part of the public sewer network. The town centre has had a long history of flooding which is well documented (see Fig 4).

Fig 4 : Flooding in Torquay

The scope of the Torquay study was to apply the 1D AOFD software to the Torquay catchment in order to evaluate the use of the software and its accuracy. Torquay was one of the 15 (Defra) Integrated Urban Drainage national pilot studies areas and was chosen for this study due to its large urban area which contains distinct coastal interactions. South West Water's fully verified 1D Infoworks (sewer) model, which was built in 1994 as a Walrus model was used in the study.

In order to compare the results of the 1D-1D and the 1D-2D modelling approaches five versions of the hydraulic model were built during the study. The first 3 versions were 1D-1D models and were of the same structure as those in the 1st Case Study namely:

- The 'Base Model'.
- The 'Enhanced Model' (see Fig 5).
- The 'Integrated Model' (with road gulleys).

The final two models were 1D-2D versions:-

- The 'Infoworks 2D Base Model' – This model consisted of the "Base Model" with a 2D zone in the study area.
- The 'Infoworks 2D Integrated Model' - This model consisted of the "Integrated Model" with a 2D zone in the study area. This model included all the road gulleys.

When the different versions of the model had been completed they were simulated with a matrix of different storm events including the historical storm of 24th October 1999 and design storm events ranging from 1 in 5 year to 1 in 100 year return periods. The results were compared to assess whether any of the models provided a better or worse representation of the flooding mechanism and extents.

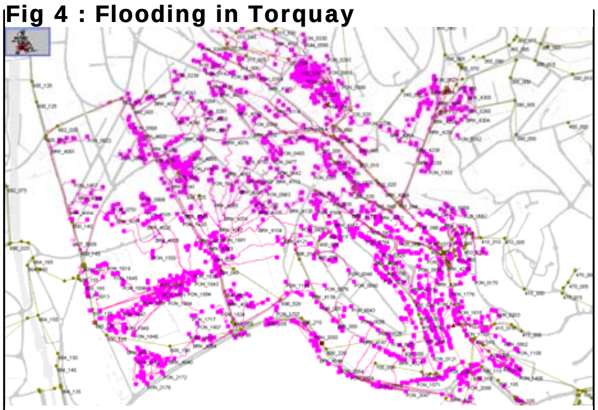


Fig 5 : Enhanced model of Torquay

The output from the study included tabulated results comparing the different approaches. Depths of flooding were compared with the CCTV footage for the historic storm event. When considering total flows the models did not show any clear differences however, the 1D-2D model predicted more flow in the above ground system (see Fig 6). When comparing the results against the CCTV footage, the volume and depth of flow predicted by the 1D-2D model more accurately represented the historic flooding than the AOFD module.

The study was a success and the AOFD software was proven to be a relatively quick means of adding overland pathways to existing sewer models. Torquay proved to be an excellent study area due to the detailed historic flooding records and the availability of a verified hydraulic model. The CCTV footage of the historic flooding was invaluable as a means of verifying the predicted overland network performance and flooding. A major benefit of the Infoworks 2D software is the graphical viewing of results which is easier to view than the results produced using the AOFD software.

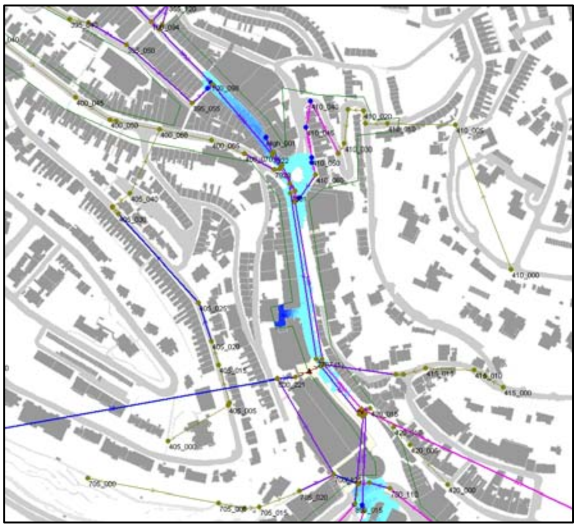


Fig 6 : 1D-2D model results

Development of 2D Overland Modelling by University of Exeter

SIPSON/UIM (acronym: Simulation of Interaction between Pipe flow and Surface Overland flow in Networks/Urban Inundation Model) is a coupled 1D-2D sub-surface/surface model. The hydrological components of this model were not employed in this study; hence they are not discussed here. The hydraulic component of SIPSON simultaneously solves system of network node continuity equations, equations of flow in links (full-dynamic St. Venant equations, weir/orifice equations, pump curves) and the relations between flow variables at the nodes and at the ends of the links. The numerical procedure utilizes the Friazinov algorithm for solving finite difference problems on directed graphs based on temporary elimination of unknowns at internal computational cross-sections, in which surcharged flow and supercritical flow are handled using the standard open slot approach and Havnø's approximations, respectively. The St. Venant equations are solved by the Preissmann four-point method and the conjugate gradient method is implemented as the node matrix solver. Essentially, the pipe flow component of SIPSON can be considered as the "Infoworks-type" model. More details are given in Djordjević et al. (2004)[7] and Saul (2007)[8].

UIM is a 2D non-inertia model derived from the St. Venant equations in which the inertial terms are neglected by assuming that the acceleration terms of water flow on the land surface are relatively small compared to gravity and friction terms. The numerical procedure utilizes the alternating-direction explicit (ADE) finite-difference numerical scheme on a regular grid. The stability of the scheme is ensured by checking the Courant condition in every time step and choosing the computational time step accordingly and – on very steep grid cells – by limiting the flow velocity from one cell to another by the available volume of water. Hence, UIM is not a shock-fitting model. More details are given in Chen et al. (2007)[9]. The parallel processing feature has been implemented in UIM which enables the model execution on a powerful grid-computing environment. Another way of speeding up the simulation in a regular grid with UIM is by so called *multi-layer* approach (Evans et al., 2009)[10], in which a coarse resolution model (with grid cell size of 10-20m) is coupled with the usage of building information data mined from the fine-grid (1m) data set. This approach enables simulation of the propagation of surface water over a coarse grid within an urban environment with an accuracy close to that of a fine grid model and with the ability to preserve small scale surface features such as narrow alleyways.

The linking between the two models i.e. the explicit exchange of flow rates between the two models is calculated at every time step based on the relationships between the hydraulic head in an underground network node and the water level at the overlapping surface model grid cell. The time step used in the SIPSON is generally larger than the ones used for the UIM, hence the simultaneous simulation by the two models is done by running UIM from within SIPSON (several UIM time steps within one SIPSON time step). In this study, the grid cells containing manholes were considered as the locations where the interactions occurred and the time step used in the SIPSON model is selected as the time step at which the 1D and 2D models are linked. The ground levels acquired from sewer network dataset usually differ to an extent from the values extracted from the DEM dataset, because the datasets reflect different features of the system. The ground level used in sewer model reflects the point value on the top of a manhole, whereas, the grid elevation in the overland flow model stands for the average level of the topography within a grid. This often results in significant differences between two datasets and particularly when the manhole is located at a local peak or depression within the surface grid. Three types of linkages that apply different discharge equations were used in SIPSON/UIM applications in this study, namely: weir, submerged weir and orifice equations. The bidirectional interacting discharge is calculated according to the water level difference between sewer network node and surface grid cell.

The most notable difference between Infoworks 2D and SIPSON/UIM is in the meshing arrangements – Infoworks 2D is based on an unstructured mesh (TIN) which may follow surface features, whereas UIM uses regular grid (1m grid size was adopted in this study). The other main difference between simulation engines is in the treatment of supercritical flows – UIM (as a non-inertia model with the above described way of ensuring stability through the velocity limitation method) gives somewhat numerically diffused results on a very steep terrain.

3rd Case Study; 1D-2D modelling with different programs and different coupling arrangements

The 3rd Case Study was a re-visit to the same catchment as the 1st Case Study and to trial the use of 2D surface flow modelling in conjunction with 1D sewer modelling using the Infoworks CS program and the SIPSON/UIM program.

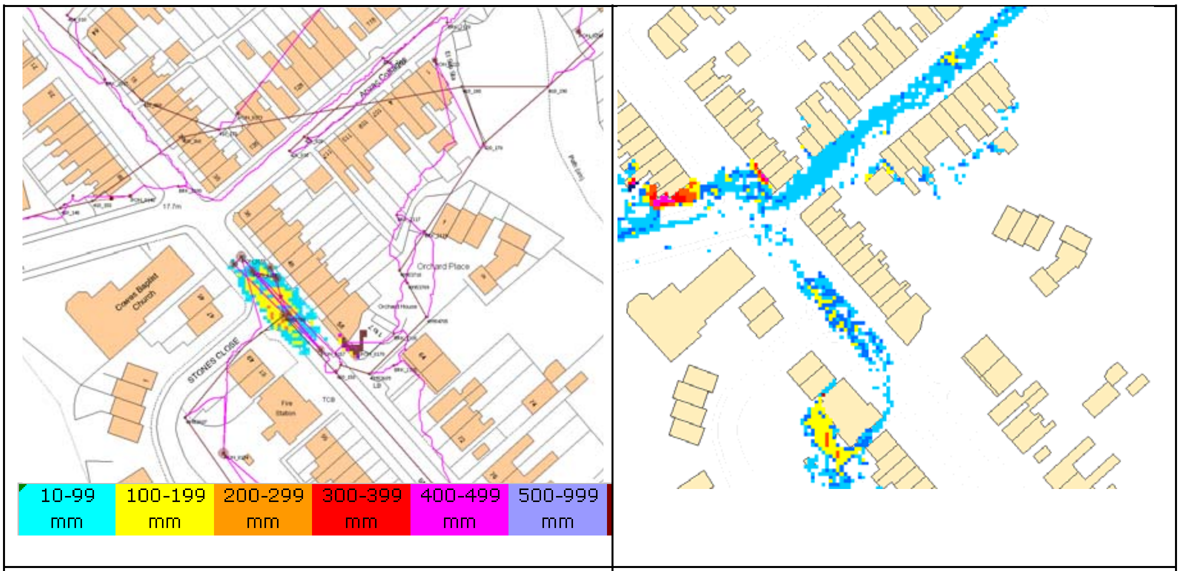
For the Infoworks modelling the previous ‘Integrated Model’ was modified such that all the 1D overland flow paths and storage nodes (ponds) were removed and a 2D simulation mesh was created to cover the full extent of the catchment. Two versions of this model were used. The first version utilised weir couplings at the manholes and road gulleys to connect the 2D overland system with the 1D underground system. The second version utilised head-discharge relationships at the manholes and the road gulleys to connect the 2D and 1D domains.

The sewer system data was exported from Infoworks to create a series of database files which were directly imported to create the SIPSON/UIM model. Runoff hydrographs for each of the contributing areas for each of the simulated storms were exported from Infoworks as csv files and these were directly imported into the SIPSON/UIM model. A similar procedure was followed for the wastewater flows in the system.

All the models were run with an identical matrix of storms including one historical storm. The results were compared to identify any differences between the models and to assess whether any of the models provided a better or worse representation of the flooding mechanism and extents.

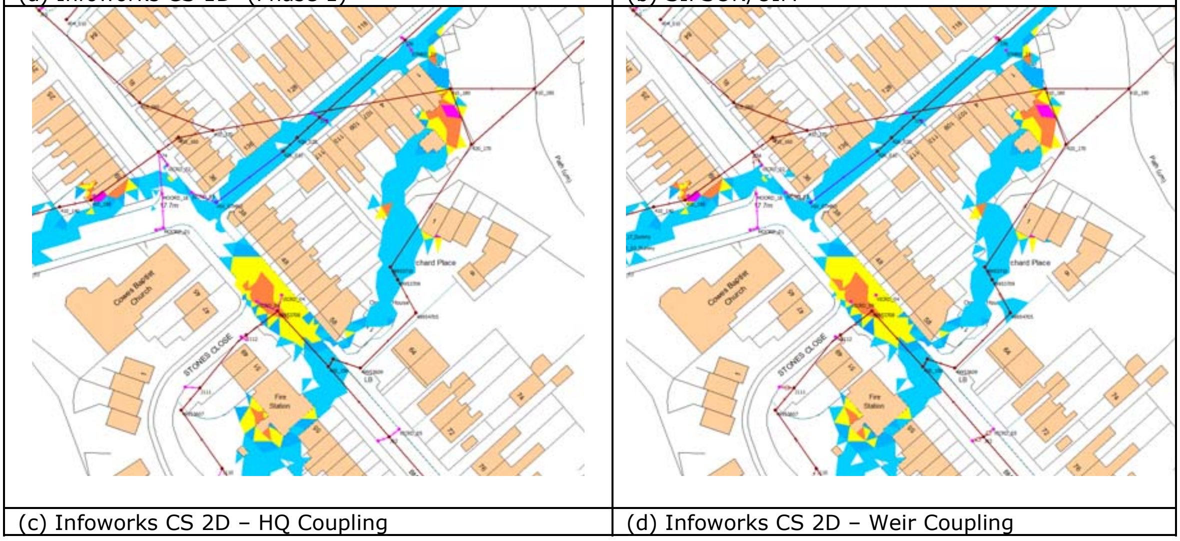
In addition to the 1D-2D modelling both the Infoworks and the SIPSON/UIM models were used to model the pluvial runoff from the catchment. This is with the runoff created directly off the surface topography and both models modelled these runoff flows as being 100% with no allowances for infiltration, initial losses or depression storage. Both models were run with 3 conditions; (i) with no sewers or buildings, (ii) with buildings but no sewers and (iii) with sewers and buildings.

The Infoworks modelling was undertaken by Richard Allitt Associates Ltd and the SIPSON/UIM modelling was undertaken by staff at the University of Exeter.



(a) Infoworks CS 1D (Phase 1)

(b) SIPSON/UIM



(c) Infoworks CS 2D – HQ Coupling

(d) Infoworks CS 2D – Weir Coupling

Fig 7 : Comparison of simulated maximum flood depths for one road in 1st and 3rd case study

The most striking difference between Fig 7 (a) and Fig 7 (b), (c) or (d) is the absence of flooding along the road leading off towards the north-east. This is however a false impression because in the 1D modelling there were 1D open channels modelled along these roads and flows along these channels are not illustrated in this image. Once the fact that flow depths along the 1D pathways are not shown is appreciated it is clear that there are very good similarities between all 4 images. There is very little difference between the two Infoworks 2D images but the SIPSON/UIM results do not show a flow path around the southern end of the group of houses on the eastern side of the main flooding location. The SIPSON/UIM model simulates a shallower flooding depth in Victoria Road whilst the other simulations have deeper flooding which accords better with the reported flooding. This is likely to be due to smaller flow rates in the sewer branch along the incoming road from the west.

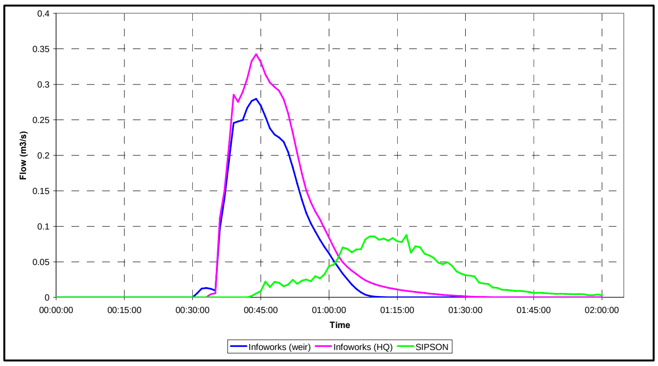


Fig 8 : Comparison of overland flows with Infoworks and SIPSON

Fig 8 shows some hydrographs for a 1 in 50 year storm showing the overland flows along one street. These flows are those draining from the ‘pond’ formed in the road shown in Fig 7. There is a notable difference between the two Infoworks models with the HQ coupling showing higher flows and for longer; this is because the HQ model has more flows from the upper catchment flowing overland than occurs with the weir coupling model, whilst the SIPSON/UIM hydrograph is much lower and diffused compared with the other two. The latter is due to the fact that the flow at this point is mainly the result of the runoff from an upstream road and there is little discharge from the ponding flooding because the surcharge at this location is much less in the SIPSON/UIM modelling. At the same time there is more water ponded in the upstream garden areas due to the manhole surcharge and draining away gradually, therefore, the peak is lower and its appearance is later than in the Infoworks results.

The objectives for this case study were twofold. Firstly to apply and evaluate the Infoworks 2D module in a known catchment which had already been modelled using a 1D-1D approach; and secondly to use the same catchment to evaluate and further develop the SIPSON/UIM model. The Infoworks modelling was expanded to consider and evaluate two different approaches to coupling the sub-surface (1D) system and the surface (2D) pathways. These were to use a simple weir coupling arrangement and a more sophisticated head-discharge coupling arrangement.

This study again emphasised that within urban areas the definition of overland flow routes needs to be considered at both the ‘macro’ scale and also at the ‘micro’ scale. The vertical accuracy of the Digital Terrain Model is of paramount importance in this regard.

The simulation results from this study were compared with the results from the 1st Case Study when a 1D-1D approach was taken. A comparison of these results has highlighted the difficulties of representing the results of the 1D-1D simulations. The comparison of the results between the Infoworks 2D modelling and the SIPSON/UIM modelling has demonstrated some differences but has also confirmed the similarities achieved.

This 3rd Case Study has clearly demonstrated that the Infoworks 2D module enables complex catchments to be modelled with comparative ease and achieving plausible results which correspond with reports of known flooding problems. The modelling has also demonstrated a strong correlation with the flooding records from an actual rainfall event which caused flooding. All of the reported flooding locations were replicated by the model. The SIPSON/UIM model has also been used to successfully model the catchment and this model has also been shown to satisfactorily replicate the known flooding.

This study has reinforced the need for sufficient time and resources to be devoted to catchment familiarisation and undertaking sufficient field observations so that all the necessary small scale surface features which can divert or constrain flows can be incorporated into the model.

Ongoing Research

Phase 2 of FRMRC has been underway for some time and both 1D and 2D surface modelling have a role to play in the work being carried out in Super Work Package 3, urban flood risk management. The more efficient use of resources in the 1D approach makes it valuable in rapid simulations associated with real time predictive flow modelling using radar based nowcasting of rainfall and sewer flow and depth measurement to determine the settings for flow controls. The 2D surface modelling technique will be applied to the modelling of interactions at inlets (gulleys) for which the basic understanding is being developed using laboratory modelling, CFD analysis and street scale testing. By combining these approaches it is hoped to provide the means of satisfying the needs of both local authorities and sewerage undertakers in their joint responsibilities for surface water management.

Types of Urban Flooding

There are two distinct types of urban flooding. The first is in areas with steeper topography where the flooding is usually shallow, with a relatively wide path (e.g. a road width) and with high velocities. The routing of this type of flooding can be influenced by small features in the urban landscape (e.g. kerbs). This type of flooding can be termed “conveyance flooding”. The second type is when the topography flattens or where buildings have been constructed across valleys; in these cases the floodwater accumulates in ponds and significant depths of flooding can result. This type of flooding can be termed “ponding flooding”

The accuracy to which the overland flow pathways are identified is particularly important. In fluvial flooding situations in non-urban areas a relatively coarse assessment is usually adequate but when the urban situation is considered the routing needs to be identified on a far smaller scale; perhaps even a micro-scale. This is especially the case when flow conditions are shallow, wide and fast because small features can divert flows along different routes. In other cases small garden walls, perhaps built by householders, are sufficient to safeguard individual properties or divert flows. It is therefore essential that the modelling procedures are sufficiently accurate and detailed to identify these small features.

Advantages of 1D-1D Modelling

Although the efficiency of any model primarily depends on its spatial resolution and the consequent temporal resolution, 1D-1D tools are *generally faster* than 1D-2D models. This is a considerable advantage, particularly when a large number of runs are required. However, the former should only be trusted where the nature of surface flow is essentially one-dimensional, i.e. where there is little uncertainly about drainage routes and where the flow outside larger ponds is mostly limited to the road width. This situation is sometimes referred to as "conveyance flooding" and is more likely to occur in areas with steeper topography and would result in relatively high flow velocities.

1D-1D approach is more suitable for *designing* the major system to convey the overland ("exceedance") flow in a controlled manner (Balmforth et al., 2006)[11]. In optioneering and solution development, overland links can easily be edited, removed or added in a 1D model and the design quickly assessed, whilst this is more complicated to do in 2D.

1D models have been around for much longer than 2D tools that are – at least in the UK – still an emerging technology. With a careful definition of surface/sub-surface links, a 1D-1D approach can be implemented using any standard sewer modelling package such as InfoWorks CS or SWMM. Also, the hydrological component of urban drainage models is in a way compatible with 1D network modelling and the models of existing systems have been calibrated assuming introduction of runoff/wastewater hydrographs at network nodes. On the other hand, merging of hydrological phases of runoff and 2D models is yet to be implemented.

Finally, if the results of urban flooding simulation are to be used as a basis for modelling of potential health impacts of flooding through simulation of pollution from combined sewer systems on urban surfaces, 1D-1D models are currently more likely to offer a more practical means for such an analysis.

Advantages of 1D-2D Modelling

2D models involve a lower degree of averaging of fundamental hydraulic equations than 1D models, therefore the former can be considered as a more realistic description of flow conditions. This is particularly the case when surface flows are not limited to well-defined routes along roads or surface channels and when flooding is mainly a "ponding" process with relatively slow water movement. 1D-2D modelling is also the best choice when it comes to extreme events when most of the urban surface is covered with excessive flood depths.

Obvious superiority of 2D models lies in the fact that flow routes are not pre-defined and instead water spreading on the surface is only driven by urban features and by physical laws. This also means that setting-up of 1D-2D models is simpler than setting up of 1D-1D models because the generation of a surface network is not required, even though sophisticated tools are now available for this.

The results of 2D simulation are easier to visualise because they (depths, flow velocities and hazard rating) can be directly shown on a map and further manipulated within a GIS framework easily, whereas 1D model results require post-processing, which eventually gives imperfect presentation of the results. Therefore 2D models are more convenient for production of hazard maps and for flood damage analysis. 2D modelling results are also generally easier to communicate to non-experts.

Combined 1D-1D and 1D-2D Models

Choice of modelling approach depends on the size of the area in the first place. If a relatively large area is to be taken into account in an integrated manner, then 1D-2D modelling for the entire area might be too computationally demanding. Therefore it seems appropriate to *combine* different approaches such that different parts of the catchment are simulated by combining elements of 1D, 1D-1D and 1D-2D techniques within a single model, as outlined in Fig 9 (Blanksby et al, 2007)[12]. The communication between the different sections of the model can be achieved with current software but requires particular attention and skilful modelling.

The question is how to *delineate* parts of the urban catchments that should ideally be modelled by one or the other approach. It is to be expected that the methodology for this will be developed and that the future releases of flood modelling packages will have GIS-based tools capable of suggesting choice of modelling approaches for different parts of urban systems. Factors that such a methodology will have to take into consideration are numerous and should include terrain elevations and slopes, existence and characteristics of preferential flow paths, land use etc. First step might be identification of areas that can be modelled by simpler models i.e. the areas that do not require interactive surface/sub-surface modelling. These would include highest spots on the catchment and perhaps areas where detailed information about flood depths is less relevant. Secondly, looking at areas that will be modelled by integrated sewer/surface models, those that are on relatively steep slopes and are unlikely to be influenced by water levels in lower zones i.e. those that may experience "conveyance" flooding should be handled by the 1D-1D approach. Further, the decision to opt for 1D-1D or 1D-2D approach may also be influenced by the importance of objects in a certain zone and by the required level of protection and potential damage, in other words computational cost should not be the reason for oversimplified treatment of power stations, hospitals and schools. Better understanding of different delineation methodologies will be achieved through comparing a range of strategies on case studies.

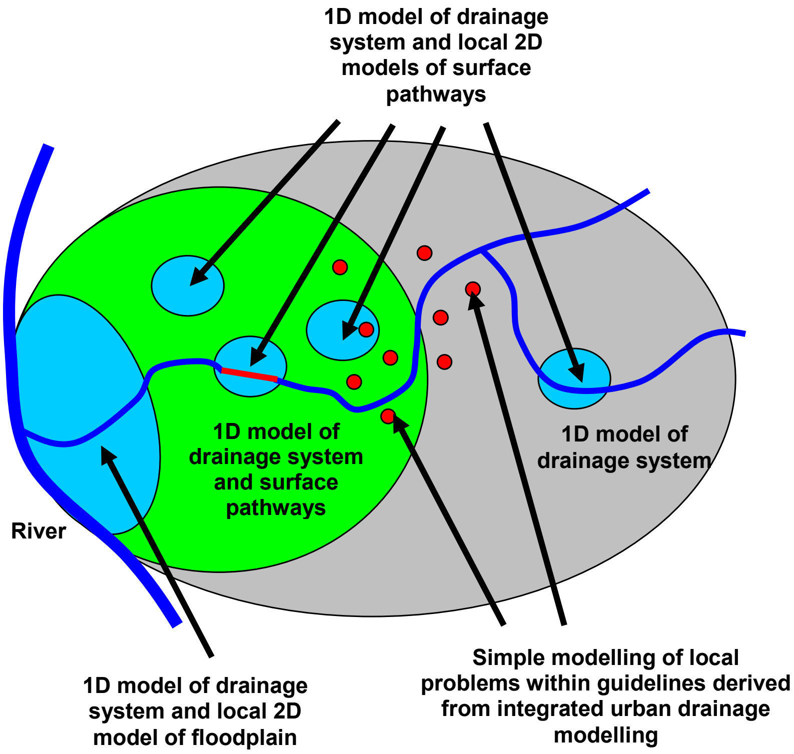


Fig 9 : Conceptualisation of Integrated Urban Drainage Model

Conclusions

In relation to the objectives this UKWIR project has been highly successful and has provided valuable for the transition of these programs from research tools into end products. The project was also successfully revised to enable comparisons to be made with the latest commercial 2D modelling developments. This latter aspect was not envisaged at the start but it has enabled important conclusions to be reached in respect of the use of 1D modelling, integrated 1D-1D modelling, integrated 1D-2D modelling and perhaps most importantly the integration of all 3 modelling techniques.

The conclusions reached from this project are:-

1) where the drainage system (irrespective of whether it is a 'minor' system or a 'major' system) has adequate capacity it should be modelled as simply as possible in 1D only;
2) all models which have an overland flow component require an accurate Digital Terrain Model (DTM) as a prerequisite for the quality and reliability of any models;
3) those parts of the catchment where overland flow pathways can easily be identified either simply by observations or by more means of programs such as the AOFD module and where the type of flooding is "conveyance" flooding should be modelled using 1D-1D modelling techniques;
4) 1D-1D modelling is more time consuming to set up than 1D-2D but is considerably faster computationally to run by factors of between 10 and 100;
5) numerical results are more easily extracted from 1D-1D models than 1D-2D models;
6) 1D-1D modelling techniques are more easily applied to optioneering and the design of solutions;
7) 1D-1D modelling techniques are more easily used in water quality modelling, especially in relation to sediment transportation and deposition;
8) results from 1D-2D modelling can be more easily presented to non technical audiences;

9) 1D-2D modelling is considerably more computationally demanding but should be used in those parts of the catchment where overland flow pathways can be multi-directional or cannot be easily defined and where the type of flooding is "ponding" flooding;

10) Modellers will need to carefully consider which modelling techniques to use for parts of the catchment taking due account of the trade off between the longer model build times for 1D-1D techniques versus the faster computational simulations, the audience which the results are to be presented to and future uses of the model for the design of solutions.

Overall, it is clear that 1D-2D modelling is not the panacea for all urban drainage modelling but rather it is one of a number of techniques which can be used alongside 1D modelling and 1D-1D modelling.

Acknowledgements

The authors would like to thank UKWIR for permission to publish this paper. FRMRC WP6 was led by Adrian Saul. The authors would also like to acknowledge the contribution of their collaborators: Hugh Foreman, Albert Chen, Surajate Boonya-aroonnet, Dušan Prodanović, Joao Leitão and Mike Wood. The opinions expressed in this report are those of the authors and do not necessarily represent the views of UKWIR nor of their respective organisations.

References

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[1] Radojkovic, M. and Maksimović, Č. (1987), "On Standardization of Computational Models for Overland Flow", (Proc. 4th ICUSD, Lausanne)

[2] Prodanovic, D. (1999) Improvement of the methods for the hydroinformatics application in urban runoff analysis, PhD Thesis, Faculty of Civli Engineering, University of Belgrade (In Serbian).

[3] Djordjević, S. (2001). A mathematical model of the interaction between surface and buried pipe flow in urban runoff and drainage. PhD Thesis, Faculty of Civil Engineering, University of Belgrade, Belgrade

[4] Maksimović, Č, Prodanović, D., Boonya-aroonnet, S., Leitão, J. P., Djordjević, S., and Allitt, R. (2009). Overland flow and pathway analysis for modelling of urban pluvial flooding. *Journal of Hydraulic Research*, 47(4):512-523

[5] Leitão, J. P. (2009). *Enhancement of Digital Elevation Models and Overland Flow Delineation Methods for Advanced Urban Flood Modelling*. PhD thesis, Imperial College London, London, UK

[6] Djordjević, S., Prodanović, D., Maksimović, C., Ivetić, M. and Savić, D., (2005). SIPSON - Simulation of interaction between pipe flow and surface overland flow in networks. Wat. Sci. & Tech., 52(5): 275-283

[7] Djordjević, S., Prodanovic, D., and Walters, G. A. (2004). "Simulation of transcritical flow in pipe/channel networks." *Journal of Hydraulic Engineering*, 130(12), 1167-1178.

[8] Saul A.J. (2007). *Integrated surface and sub-surface interactive flooding and inundation model*, http://www.floodrisk.org.uk/images/stories/Phase1/UR4%20signed%20off.pdf FRMRC Report UR4.

[9] Chen, A. S., Djordjević, S., Leandro, J., and Savić, D. "The urban inundation model with bidirectional flow interaction between 2D overland surface and 1D sewer networks." *NOVATECH 2007*, Lyon, France, 465-472.

[10] Evans, B., Chen, A., Djordjević, S. and Savić, D.A. (2009). "A Cellular Automata based approach to generalising Digital Terrain Models for 2D flood modelling", Int. Conference 8UDM & 2RWHM, Tokyo, CD-ROM.

[11] Balmforth, D et al. (2006) "Designing for Exceedance in Urban Drainage – good practice", CIRIA Report C635

[12] Blanskby, J. et al. (2007) Integrated urban drainage: setting the context for integrated urban drainage modelling in the United Kingdom, Special Aspects of Urban Flood Management, COST Session Aquaterra Conference 2007, Amsterdam, 103-118.