Coupled 1D - 2D Modelling in Urban Areas

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1. INTRODUCTION

This User Note provides guidance on hydraulic modelling in urban areas using the latest versions of software which have the capability to model overland flows in 2 dimensions (2D). This User Note compliments the more established procedures for 1 dimensional (1D) modelling of sewerage networks which are set out in the WaPUG Code of Practice for Hydraulic Modelling of Sewer Systems. In most instances Modellers will want to combine 1D modelling of the sub-surface (sewer) system with 2D modelling of the surface system and with one or more coupling arrangements to link the 1D and the 2D domains; hence the terminology 1D-2D modelling.

In common with the WaPUG Integrated Urban Drainage Modelling Guide (WaPUG 2009)(1) the following terminology is used:-

- **Minor System** – this is the underground sewerage or drainage network of manholes, gullies, pipelines etc. Culverted watercourses also fall within this category. These systems are generally capable of conveying the flows during moderate storm conditions with all flow kept below ground;
- **Overland Major System** – this is the streets and other flow pathways along the surface whose primary purpose is generally not to convey flow. These systems come into operation in more extreme storm conditions. From a modelling perspective functional flood plains alongside rivers also fall within this category;
- **Major System** – this category includes watercourses and rivers (generally with flows kept within the banks) but in some instances can also include canals. These systems generally have a far greater conveyance capacity than the other systems.

Most 2D modelling software incorporates sophisticated visualisation of above ground flows. If model results are to be used in presentations, particularly to the general public, it should be borne in mind that, unlike the (unseen) performance of the below ground (Minor System) network, the general public will have a lot of knowledge about what actually happens. The modeller should fully appreciate this depth of public knowledge right at the start of a 1D-2D study as it can be used to help determine the extent of the 2D model and the data requirements. This issue is so important that it is recommended that experienced modellers/engineers should lead any 1D-2D modelling studies and have sufficient involvement to ensure accurate models are produced.

1D-2D models will be a key component of Integrated Urban Drainage, an area currently in its infancy that will increase in importance over the next few years, particularly following the Pitt Review(3,4) of the 2007 floods. Modelling with 2D software allows inflows to the ground surface to be brought together in one application and for overland flow paths to be determined by the software. The modeller is then able to determine the route of least impact (most safe) overland route for flows to be diverted to a natural ponding area – this is the principal behind ‘Designing for Exceedance(5)’. It should therefore be noted that where solutions to flooding involve increasing or redirecting overland flows, the Modeller should be cognizant of any consequent risks to human safety (Designer responsibilities under CDM). For this reason senior staff should be engaged to ensure appropriate decisions are taken.

2. DEFINING THE PURPOSE

The drivers for undertaking 1D-2D modelling should be carefully understood at project inception. In many cases where overland flow contributes to flooding problems, but the proposed solutions to the flooding are "conventional" (constraining it within the Minor System networks rather than managing the overland flow), then 1D-2D modelling is not always justified. One exception to this is "Designing for Exceedance" - where there is a need to understand overland flow mechanisms during rainfall events which exceed the target design standard for the proposed scheme.

2D modelling is considerably more expensive to undertake than 1D modelling because of the additional data which is required, the improved accuracy required, the need to use more experienced staff and because of the need to pay close attention to detail which involves more fieldwork and more intensive modelling work. For this reason fully integrated detailed 1D-2D modelling is likely to be used sparingly and in most cases 1D-2D modelling will not be applied across whole catchments or drainage areas but will be concentrated in specific areas. The exception to this is where pluvial (also referred as 'surface water') runoff modelling is undertaken which involves the rainfall creating runoff directly off the simulation mesh. In these cases the whole catchment should be modelled. However, the modeller can still use different size triangles with larger triangles in less important areas.

1D-2D modelling can have the following drivers:

- Understanding the mechanism of observed flooding – is overland flow a contributory factor?
  1D-2D modelling has proved useful where properties affected by flooding are remote from the predicted flooding. By including overland flow routing a link between system incapacity at one location and observed flooding at another can often be established. Also, 1D-2D modelling has frequently been used to demonstrate that flooding which had been attributed solely to incapacity in the public sewer network was in fact due to overland flow from other sources;
- To model all of the potential flooding mechanisms (from sewers, fluvial, pluvial, groundwater etc) in an integrated manner;
- To quantify numbers of properties at risk of flooding and to determine the hazards which the flooding present;
- Scheme Design – Where a scheme solution involves managing and attenuating overland flow, rather than solving flooding conventionally, it is important to have a detailed understanding of the overland flow routing, quantity and velocity;
- Designing for exceedance - To understand overland flow and resultant flooding risk in the event of storms that exceed the stated target standard for proposed "conventional" solutions. This enables the mode of failure to be simulated and any consequences identified;
- Integrated Urban Drainage – where a 1D-2D model is required to be integrated with other models such as river models. In some instances 1D river models cannot provide the necessary level of detail in urban areas and it can be better to use a 1D-2D model to better represent the urban areas with flows into and out of urban watercourses;
- To simulate pluvial runoff which could include the effects of runoff from fields etc flowing overland into urban areas.

The WaPUG Code of Practice[(2)] has defined 3 different types of model; Type I is a coarse skeletal model, Type II for DAP's and Type III for detailed design. A single model could potentially have all 3 types within it with Type I in the outlying areas, Type II in the bulk of the urban area and Type III where there are flooding issues to be resolved. This concept fits nicely with 1D-2D modelling where it can be included selectively and to differing levels of detail. The drivers for the study will determine the type and detail of the 2D part of the model. It is generally considered that Type I^{2D} will be of limited benefit and most 2D modelling studies will use Type II^{2D} or Type III^{2D} models.

3. SOFTWARE SELECTION

There are a number of software programs in use for modelling urban drainage systems and there are many others at various stages of development. This User Note is not specific to any particular program and as far as possible the principles described in this User Note are generic to all programs. However, it should be recognised that there are fundamental differences in the way in which the different programs work and as a consequence some of the aspects described in this User Note will not apply to all programs. The most important difference in respect of 2D modelling is the manner in which the simulation meshes or grids are created.

Programs can use an irregular triangular mesh is created (e.g. Infoworks™) or a regular square grid. In urban areas where it is important that flow routes around buildings and even along narrow alleyways are modelled, the irregular triangular mesh has significant advantages. In many cases programs which do not use an irregular triangular mesh cannot model flows along such important flood pathways. This is a very important consideration when selecting which modelling program to use because the adequacy of the simulation results can be seriously compromised if certain flood pathways cannot be modelled. Software selection should also consider whether the coupling between the 1D and 2D domains is undertaken seamlessly within the same program or whether add-on programs are needed.

4. COLLECTING DATA

To ensure an accurate model is created it is important that the above ground detail is correct. Much data is freely available or is contained within datasets normally made available for conventional modelling. Data can also be specifically obtained for the study. The purpose of the model will define its extent and also the data requirements.

Mapping.

Ordnance Survey data showing above ground features preferably in Mastermap™ format is critical to understand what surface features exist and how these can influence above ground flow routing. This gives a good understanding from the office of the areas where site inspections and closer attention to detail are required. Mastermap™ data is particularly useful because buildings and highways are represented as closed polygons – this is required when creating the 2D simulation mesh.

Know the problem.

If a 1D-2D model is to be constructed, it follows that the problem being investigated has high impact. It is paramount that the modeller/engineer fully understands the catchment in great detail. This type of study cannot be completed without detailed site visits so that the problem and mechanism can be fully understood. There is no better way to appreciate the flood mechanism than to visit the site during storm conditions and observe and record the effects. However, given the infrequent nature of severe flooding it is very unlikely that a planned site visit will coincide with a severe storm. It is therefore invaluable to obtain copies of any photographs and videos of flooding incidents.

Photographs and Videos

Photographs and videos of flooding incidents either taken by the media, by clean-up crews arriving at an incident or by householders affected by the flooding can sometimes be the only source of reliable data showing the flooding or overland flows occurring. These sometimes provide the only available data with which to validate or test the model for similar or more extreme storms.

Lidar data.

1D-2D modelling cannot be undertaken without a good quality terrain model. There are various sources of ground level data ranging from OS contour data to highly accurate digital terrain data captured by aerial survey. The fact that a 1D-2D model is required dictates that an enhanced survey is needed over and above the data freely available. Lidar (Light Detection and Ranging) data sourced by aerial survey is by far the most accurate and efficient method of sourcing terrain data for the 3 dimensional ground model. As the greatest proportion of the cost of a LIDAR survey is getting the plane airborne it makes sense to survey to a high tolerance. An adequate tolerance for 1D-2D modelling would be a guaranteed vertical accuracy of between ±50mm and ±150mm. This normally can only be achieved with LiDAR surveys acquiring data on a 0.25m, 0.5m or 1m grid. A number of 'Truthing Surveys' should be undertaken within the catchment by the contractor to calibrate and validate the data. Data acquired on a 2m grid which is typical for rural areas is not sufficiently accurate for urban areas.

For even greater accuracy, where needed, there are LIDAR survey techniques that use road vehicles to capture data. This is particularly useful when understanding the part that kerbs play in channelling flow. The disadvantage of this technique is that it cannot be used to survey areas "behind" buildings and other obstacles such as parked cars.

Topographic/GPS surveys.

Despite the advance in remote survey techniques there is always a place for traditional topographical surveys. Even if "drive by" LIDAR surveys have been undertaken there will be places where data was not captured, for example where parked cars prevent the kerb line from being detected. Also there can be anomalies in the data that require investigation and more detailed levelling. However, topographical surveys ought to now be seen as an auditing tool or a gap filling technique rather than the primary data collection method.

Gullies

In any model and particularly integrated urban 1D-2D models the highway drainage provision is a very important factor and is often a dataset hard to come by. It is extremely important to understand:

- whether there is a highway drainage system,
- how effective the gullies are (spacing, area drained per gulley, type, size, direction of grill),
- what condition the gullies were in at the time of the storm (blocked with leaves in autumn, blocked by plant growth in spring/summer),
- what the cleaning regime is,
- how gullies are connected to the receiving piped system, soakaways or ditch,

Gullies can perform in two ways. In normal conditions they will take flow off the highway and discharge it into the connected drainage network thereby relieving overland flow either directly from storm runoff or excess flow from other piped networks. However, in events in excess of the highway drainage system design (normally a lower design standard than public sewerage networks) they will act as relief points allowing flow to exit the 'minor' system and to contribute to overland flows from other sources thereby increasing the severity of the problem. Details of the type and condition of the gullies should be obtained by surveys.

Kerbs and Dropped Kerbs

A typical kerb height of 125mm is adequate in steeper catchments to keep overland flows within the highway and it is therefore important to have sufficient information to be able to model kerbs as walls or breaklines (see below) where they are needed. Perhaps more importantly it is necessary to know where the full kerb height is not provided (e.g. pedestrian or vehicle crossings) because these points can frequently be where overland flows depart from the highway and enter properties. A detailed "walk around" survey should be undertaken to identify and record all kerblines and dropped kerbs within the relevant area. It is usually a cost effective practice to undertake some initial simulation runs without details like kerbs in order to understand better the areas to be investigated in detail.

Walls, Fences and Hedges

During the detailed 'walk around' surveys the positions, heights and nature of all walls, fences and hedges should be recorded and appropriate photographs should be taken. These features can be particularly important in determining the routes which overland flows will take. It is frequently the case that boundary walls can re-direct overland flows significantly. It is important to recognise that in most cases walls and fences will not have been captured by the Lidar survey as they are too narrow when compared to the grid spacing of the survey.

Retaining Walls

The way in which the software creates the 2D simulation mesh can be profoundly influenced by abrupt changes in levels within the catchment. Very steep slopes and particularly the sharp changes in slope can to a degree be accommodated by the software without severe implications but would be improved by adding breaklines at these sharp changes in slope. However, with retaining walls where there is an abrupt change in level over a very small horizontal distance there can be severe implications. In some cases the absence of a retaining wall from a model can result in an incorrect drainage route being identified with the retained height contributing to the severity of the false route. Details of all retaining walls within the relevant part of the catchment should be obtained and recorded during the detailed 'walk around' survey.

5. DIGITAL TERRAIN DATA

The availability of accurate Digital Terrain data is of key importance for this type of study as the data is used to generate the 2D simulation grid. As previously stated the vertical accuracy needs to be in the range ±50mm to ±150mm. Digital terrain data comes in two forms; Digital Terrain Models (DTM) [also known as bare earth models] and Digital Elevation Models (DEM). DTM's show the ground level data with buildings and vegetation removed and this data is used to determine the fall of the land and therefore the natural overland flow route. DEM's include buildings and vegetation and can be useful for identifying hedges and other important vegetation features. DTM's usually have bridge decks removed whilst DEM's retain them. Where a flow path is beneath a bridge the DTM should be used whilst if there is a flow path over the bridge (eg a road bridge over a railway) the DEM can give better results. Generally 1D-2D modelling will use the DTM data.

In some instances the Lidar survey can have a small number of missing data points (referred to as 'pits') which if left have a value of either zero or -9999m. These can have a significant effect if not attended to because they can create within the simulation polygon a large hole which takes a considerable volume of water to fill. Most programs which can manipulate Lidar data have a routine for locating and filling these 'pits'. Care should however be taken when running such routines that they do not also fill all the low points within the DTM which can be real hollows or areas of ponding.

The software used by the Lidar survey companies is becoming more sophisticated and the accuracy of the filtering procedures to convert DEM's to DTM's has improved significantly in recent years. However, there can be instances where errors do occur. Modellers should familiarise themselves with the catchment and should examine the DTM in detail to identify any possible anomalies or errors. If any errors are found the Modeller can make the necessary adjustments to the DTM though most Modellers will not have access to suitable software; in these circumstances the matter should be referred back to the Lidar contractor.

6. CREATING THE 2D SIMULATION MESH

There is a common misconception that the 2D simulation mesh and the Digital Terrain Model (DTM) are one and the same. This is not the case. The 2D simulation mesh can be best thought of as a 'sample' of the DTM because not all the features in the DTM will automatically appear in the 2D simulation mesh; for example kerblines captured in the DTM (perhaps using mobile laser scanning techniques) will not automatically appear in the 2D simulation mesh. The 2D simulation mesh is best thought of as a series of horizontal triangles with the level of the triangle being the average of the spot levels (interpolated off the DTM) at each vertex. It is therefore highly probable that features such as kerblines etc will not be included as vertexes in the mesh. However, if the Modeller specifically wants to incorporate features such as kerblines in the 2D simulation mesh then 'breaklines' or 'porous walls' along the kerblines can be specifically included for the purpose. Expertise in creating 2D simulation meshes will become one of the essential skills which a Modeller will need to master.

2D simulation polygons are the areas within a model where the overland flows will be simulated. The 2D simulation polygon will have a mesh of triangles or a regular grid created from the DTM and specific features selected by the Modeller. Within the 2D simulation polygon there can be one or more 'mesh polygons' which have a higher degree of resolution in the mesh.

It is unusual for 2D simulation polygons to be created for the whole of a modelled catchment (unless pluvial runoff is modelled) as this would unnecessarily complicate the model and lengthen model run times. The extent of the 2D simulation polygon should be identified from flooding records, observations on site, anecdotal records or by carefully studying an accurate Digital Terrain Model. The 2D simulation polygon should include the following:

- Headwaters of the areas affected by flooding
- Flooding areas
- Overland Flow paths that convey flow away from flooded areas

It is also possible to identify the areas where 1D-2D modelling is required by means of an iterative process starting with a model with the normal flood cones and progressively adding 2D Simulation Polygons or extending them. Alternatively one of the techniques for determining pluvial flood pathways can be used as an indication of the extent of 2D modelling required. In an urban area where flows reach a 2D Simulation Polygon boundary it is usually worthwhile extending the 2D simulation polygon so that the full impacts are simulated.

Within each 2D Simulation Polygon (a model can have more than one simulation polygon) it is possible to have any number of 'Mesh Polygons' which should not overlap one another and can have differing mesh sizes. It is usual for Mesh Polygons to have a smaller mesh size than the host 2D Simulation Polygon though it can be found sometimes that simply making the mesh smaller in the main 2D Simulation Polygon provides adequate results without any loss of simulation time.

There are two important aspects when considering what mesh size to use. The first is the 'Maximum Mesh size' which is the maximum size of any triangle in the mesh. The second is the 'Minimum Virtual Element Area'. The mesh within a 2D simulation polygon consists of many triangles of which some can be very small. Once the mesh is passed to the simulation engine, small triangles are aggregated together to form irregular shaped elements which have the minimum area. This has the advantage of increasing the processing efficiency. As a rule of thumb the maximum triangle size should be 4 times the Minimum Virtual Element Area. The lowest practical value for the Minimum Virtual Element Size is $1m^2$. Therefore the smallest practical value for the 'Maximum Mesh size' is $4m^2$.

It is important to understand the relationship between mesh sizes and the steepness of the catchment being modelled. In many ways it is best to have the largest possible mesh size as this speeds up the simulations but using large mesh sizes can lead to anomalies occurring. The individual triangles forming the mesh are a horizontal plane with the elevation of the plane derived by averaging the level at each vertex (this is why an accurate DTM is so important). Therefore on steeply sloping terrain the resultant mesh can become a series of large steps with a significant vertical difference between neighbouring mesh triangles. Also by using large mesh sizes it is possible that some important differences in topography do not get translated into the mesh because it is only the ground level at the 3 vertices of each triangle which are used to establish the elevation of that triangle.

In order to avoid triangles being created which partially overlap a relatively flat area (eg a road) at the top or bottom of a steep slope and partially overlap a steep slope (which results in a triangle with an elevation partway between) it is always advisable to have a 'breakline' at the top and bottom of all steep slopes, irrespective of mesh size. Breaklines are discussed in more detail later in this User Note.

Some experimentation has been undertaken and in the context of an urban area it was found that triangle areas of between $10m^2$ and $100m^2$ were generally satisfactory. With areas larger than $100m^2$ it was found that some problems occurred. There are no hard and fast rules about what triangle size to use and to an extent the Modeller will need to do some experimentation or follow an iterative process until a suitable triangle size is reached. It should always be remembered that a larger triangle size can be used across a large area with smaller triangles within a series of 'mesh polygons' at particular points of interest.

7. MODIFYING THE DIGITAL TERRAIN DATA

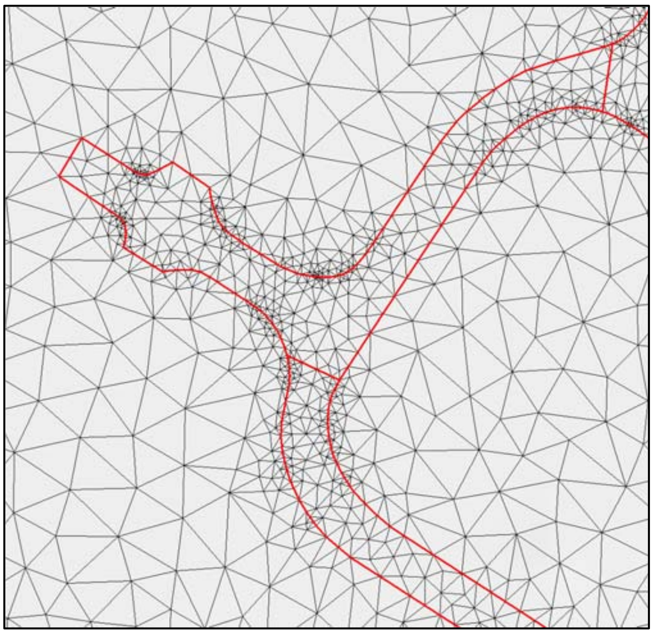
The Digital Terrain data as the DTM or DEM can be modified within most 1D-2D modelling programs. This can be done by means of defining the area to be raised or lowered as an ordinary polygon. There is then a facility to create a new DTM or DEM with the required area raised or lowered. It is important to realise that modifying the DTM or DEM in this way is before the mesh is created and will not necessarily alter the 2D simulation mesh in the way which the Modeller intended. If the Modeller wants to modify the simulation mesh to create features such as kerblines or walls it is better to use the option described below for use after the mesh has been created.

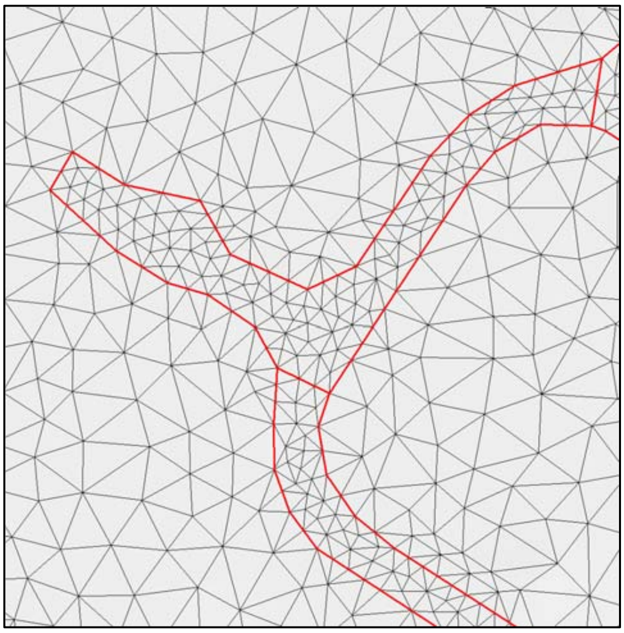
8. MODIFYING THE SIMULATION MESH

There is also a facility within some software programs to modify the simulation mesh after the mesh has been created but the area should be defined beforehand as a 'mesh polygon'. The area to be modified can be specified to be raised or lowered by a certain amount or set to a specific level. These adjustments are made to the levels of the triangles after they have been created and this enables a vertical step to be created along the boundary of such areas to represent kerblines or other features. This is an alternative to using 'walls' to create kerblines within the model and has the advantage of avoiding the problems with water getting trapped behind the wall (for example on the footway rather than on the highway).

9. SIMPLIFYING POLYGONS

When polygons are imported into the program they can either be retained in their original state or they can be simplified in order to speed up the simulation. The simplification process is done by specifying the minimum distance between points forming the polygon which changes curves made with a large number of points into a faceted curve with fewer points. The differences which this can make are highly significant and in some cases can result in a tenfold reduction in the number of triangles forming the simulation mesh. The diagrams below illustrate this point. The diagram on the left is the simulation mesh without any simplification of the mesh polygons whilst the diagram on the right is the simulation mesh after the mesh polygons have been simplified to a minimum of 5 metres between points. The reduction in the number of triangles can easily be seen. The result in the diagram to the right is probably sufficiently accurate for most purposes but if need be additional points can be put back in.





10. RAINFALL AND RUNOFF

Runoff in relation to 1D-2D modelling can be undertaken in two ways. Firstly, 1D-2D can be used with any of the normal runoff methods and there are no particular requirements in respect of rainfall or runoff. The 2D modelling aspects simply route any flooding from manholes across the surface until other manholes with spare capacity are encountered or the flows reach a watercourse or storage area. In most instances there will already be a model of the catchment under investigation and the use of 1D-2D modelling does not require any different runoff method from that already used. The normal range of rainfall-runoff models can still be used. 1D-2D modelling can however require a higher level of detail in terms of node density modelled, contributing areas definition and whether private sewers or laterals need to be modelled.

Secondly, the 2D modelling can be used to collect and route the runoff. This is described as 'pluvial runoff' in the following section. The currently available hydrological rainfall-runoff models are limited and are only able to simulate the runoff from a single surface type though developments are underway to develop multi-surface runoff models.

In standard (ie non 2D) modelling detailed definition of contributing areas is not generally vitally important as incorrect apportionment of flows will generally cancel each other out after flows enter the Minor System network. It is common with 1D modelling that contributing areas are only defined for a limited proportion of the nodes (varies between 1 in 2 and 1 in 10). In contrast, when carrying out 2D modelling, it is important to define contributing areas within the 2D simulation polygon accurately, generally at a lower ratio and in more detail than in "standard" Minor System models so that runoff is correctly apportioned. It is recommended that the contributing area definition is carefully reviewed and if necessary renewed (together with the area take off) for the 2D model area using the LIDAR data as a guide to better define the contributing area boundaries.

When Modellers want to combine pluvial runoff with conventional 1D runoff there are procedures available in some programs to achieve this; these are discussed in the section below.

11. PLUVIAL RUNOFF

2D modelling programs are now capable of modelling pluvial runoff which is the runoff which occurs from natural surfaces such as fields, recreation grounds and other areas which are normally excluded from urban modelling studies.

Pluvial runoff can be simulated within the model by runoff directly from the 2D simulation mesh with 100% runoff. In order for the runoff to correlate with rainfall return periods used in conventional urban modelling it is therefore necessary to modify the rainfall profile used to take account of initial losses and normal runoff percentages. It is possible to use more than one rainfall profile by means of defining the region over which each rainfall profile should be applied but these cannot overlap or be one area within another area.

It is also possible to set the parameters so that there is only pluvial runoff from those parts of the 2D simulation mesh where there are no (1D) sub-catchment or contributing areas. Different rainfall profiles can be applied to the rural areas and the urban areas but the use of more than one profile for each is difficult to achieve. This can be particularly useful when simulating direct runoff into urban streams so that overland runoff can be modelled directly into the streams whilst the runoff from the impermeable surfaces via road gullies and sewers can be explicitly modelled in the conventional manner.

Making full use of facilities to model pluvial runoff at the same time as modelling impermeable surfaces runoff will present many new challenges to Modellers and with experience can displace current conventional modelling practices. In time and with further advances in modelling programs it is possible that factors such as initial loss allowances and percentage runoff values (perhaps as a function of soil type and surface cover) can be applied to the 2D simulation mesh such that the same rainfall profile can be used throughout.

12. MODELLING ASPECTS

When overland flow occurs in a catchment, the roads within the catchment will often become the primary drainage pathways. Roads will generally drain to a series of road gullies usually located in the road channels alongside the kerbs. Road gullies are not designed to take all the flow and with more extreme storms can only drain or intercept a small proportion of the flow. In some cases where a very detailed 2D model is required it can be the case that the objective of the 2D modelling is to simulate the flows as they travel over the surface and the interface (also referred to as the "coupling") between the 1D and the 2D domains.

In all 2D modelling it is important to consider what representation of the actual flow pathways is required in the model. Generally in steeper parts of catchments the overland surface flows tend to be shallower and faster with flows easily constrained or diverted by small (micro scale) surface features such as kerbs etc. In flatter areas of catchments the overland flows tend to be slower and deeper and are less influenced by small scale features but other features such as garden walls and fences become important. The Modeller will need to ensure that the necessary features are included in the appropriate level for the different parts of the catchment. If in doubt the Modeller should always model any features which can divert, attenuate or impound flows; especially those created during extreme storms.

The following sections provide some aspects which Modellers should consider including in their models.

Road Gullies

It is not always essential but in areas with more complex flow routes and with more complex interaction (1D-2D coupling) between the road gullies and the sewer system it has been found to be worthwhile modelling each road gulley as a node. The physical area which drains to each road gulley, including any driveways and footpaths, can be modelled specifically as can any permeable area (e.g. fields or gardens) which drain onto the road. The capacity of the road gulley grating and pipework then becomes important in determining how much of the flow along the kerbline is intercepted by the road gulley (and hence into the sewer) and how much continues past the gulley.

Infoworks System Type

If the individual road gullies are modelled it is recommended that they are modelled as the 'overland' system type. All connecting conduits, orifices etc and all contributing areas can also then use the 'overland' system type – this allows them to be readily differentiated within the model.

Flood Types

There are 4 different flood types which can be used; (a) lost, (b) sealed, (c) stored and (d) 2D. If the modeller wants to simulate 2D overland flows and specifically wants to model flows in or out (ie 1D-2D coupling) of that particular node (manhole or gulley) then the 2D flood type should be used. There are two ways in which water can be brought onto the mesh or taken off the mesh; the first is via the coupling with the 1D domain at the nodes which have the 2D flood type and secondly by means of pluvial runoff. Within a 2D simulation polygon it can be appropriate to use the 'sealed' flood type but the 'lost' and 'stored' flood types should not be used as they would be contrary to the process which the modeller is trying to simulate because flows will either be lost or will be stored in flood cones rather than routed across the surface.

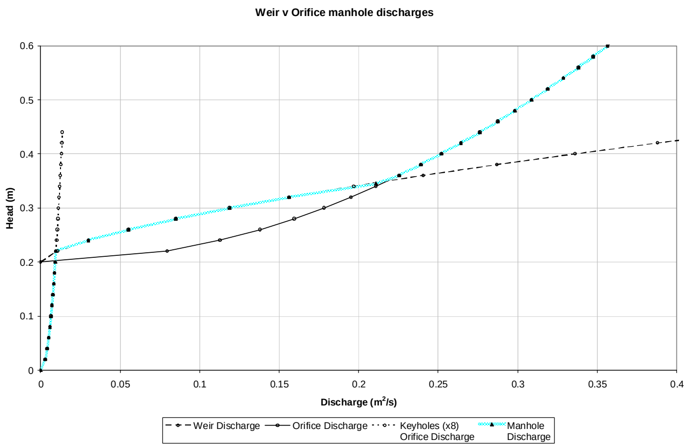
1D – 2D Coupling

The modelling of the interaction on the ‘Minor System’ and the ‘Overland System’ is known as the coupling between the 1D and 2D domains. The road gullies and manholes are the coupling points and there are two main ways in which these can be modelled:-

- The first method and perhaps the easiest to implement is to use a ‘Weir’ coupling which assumes that the perimeter of the manhole shaft or the road gulley acts as a weir. The length of the weir is not specifically input but is calculated within the program from the shaft area of the modelled node. It is important that very large shaft areas are avoided as these can lead to instabilities and run failure. Generally shaft areas of $1m^2$ or $2m^2$ appear to work best. The weir coefficient is input by the Modeller but the default value of 0.5 is usually adequate. If the Modeller wants to increase or decrease the flows into or out of nodes the shaft size and/or the discharge coefficient can be varied. Care needs to be taken to only use the appropriate data fields when the shaft areas of nodes have been increased to provide compensation for unmodelled storage otherwise the weir length can be unintentionally increased. If the Modeller wants a limiting discharge the Modeller has to apply any controls in the pipework between the road gulley and the sewer or manhole which it connects to. The simplest approach is to use a 100mm or 150mm dia orifice with a limiting discharge but this limiting value does not apply in both directions (to both flow either entering or leaving the sewer). If it is necessary to have a limiting discharge in both directions it is necessary to model back to back orifices in opposite directions. For standard road gullies a simple rule-of-thumb approach can be used for the limiting discharge with 10 l/s in steeper catchments and 5 l/s in flatter catchments though a modeller can choose different values if appropriate or where the road gullies are unusually small or are heavily silted.
- The second method is more complex and there are two important papers[6,7] on this matter. This method uses a Head-Discharge relationship for the modelled node. Derivation of the Head-Discharge relationship can be time consuming and depends upon factors related to the longitudinal and transverse gradients of the road, the geometry of the gulley grating and the degree of maintenance.

Flows into manholes

Manhole covers can work in such a way that they allow flow out onto the ground (flooding) when the system surcharges and the manhole cover lifts (as illustrated in the photograph below), but if the cover seats back into its frame (or is not lifted during a storm), ponded/overland flow cannot (except in small quantities) enter the sewers through the (seated) manhole cover. This phenomenon can be modelled using the Head-Discharge functionality and it is also possible within this to allow for the weight of the manhole cover before it is lifted allowing more water to escape. The graph below illustrates how a Head-Discharge relationship can be built up for a manhole starting with the keyholes and gaps between the cover and frame acting as a series of small orifices; as the head increases the cover starts to be lifted as we start to get a weir effect around the perimeter of the manhole opening, as the head increases further the cover is lifted out of the frame and the manhole opening then starts to act as an orifice.



Outfalls

There are 2 different types of outfall which can be used. A node modelled as an 'Outfall' (even if it is within a 2D simulation polygon) will act as an outfall from the model and flows out of the outfall will be lost from the model. Within the 2D simulation polygon there is an alternative which is a '2D Outfall'; this allows a sewer or conduit to discharge flows onto the mesh. This coupling between the 1D and 2D elements is bidirectional and the model requires the ground level of the outfall to be the same as the invert level of the discharging conduit.

Twin systems within one mesh triangle

There can be instances where there are two nodes (e.g. on separate foul & SW systems) within the same triangle in the mesh and the software validation routing can flag this up with a warning. In these situations the Modeller needs to carefully consider whether there could be flooding from both nodes or whether one of them can safely be changed to a 'sealed' flood type. This can be particularly important if transfer between foul and SW systems is an issue. The Modeller can also apply different head-discharge characteristics to the foul and SW manholes so that for example both manholes can release flood water but only SW manholes can drain flood water off the surface.

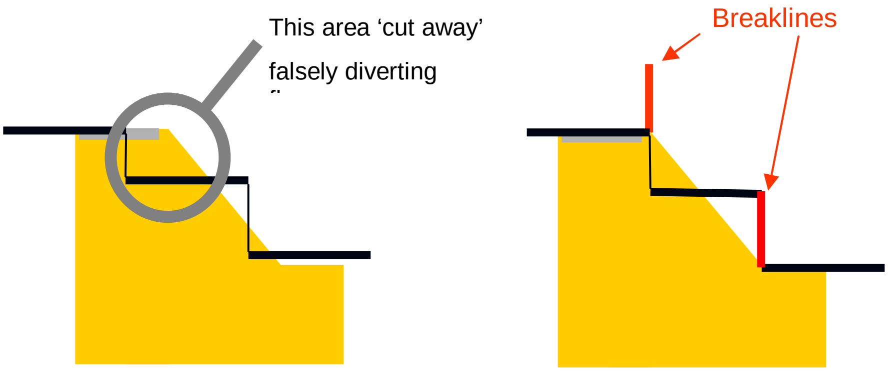
Buildings

In order to model the effects of buildings within the catchment it is necessary to construct the 2D simulation mesh so that the buildings are represented in such a way that there cannot be any flow through them and flows has to go around the buildings. This is done by using buildings to create 'voids' (infinitely high) in the mesh. The buildings used to create these voids should all be "closed" shapes. Building outlines obtained from O.S. MasterMap are closed but those obtained from O.S. Landline mapping are not and are only polylines (and thus need converting to closed polygons).

The Modeller will need to decide whether it is necessary or desirable to create voids for all the buildings; it is possible that garages and other outbuildings do not need to be cut out as voids as these can create unnecessary additional triangles in the mesh. It is worth noting that in some instances a small porch structure on a building can be safely removed without any adverse effects on simulations but with the benefit of considerably reducing the number and complexity of the mesh triangles which would need to be created around such protuberances. The simplest approach is to copy the buildings layer from MasterMap to create a "Buildings" layer and to store this in the dedicated "2D Features" folder. It is important that each building has a separate ID reference (if the data is extracted from OS MasterMap data it already has this). The buildings layer can then be displayed in Infoworks by loading it in the same way as any mapping. It is important that the boundaries for any ‘2D Simulation Polygons’ or ‘Mesh Polygons’ do not intersect any buildings.

Breaklines

Breaklines are a particularly important aspect in ensuring that the 2D simulation mesh is created how the Modeller wants. Breaklines are used to force the creation of the mesh triangles with two of the vertexes along the breakline. Breaklines have zero height and cannot be used to create features which will divert flow along particular flow paths. They are especially useful when creating meshes on steeply sloping terrain where there are either steep slopes or retaining walls; by positioning a breakline at the top and bottom of these slopes or retaining walls the resultant triangles either side of these are a reasonable representation of the actual surface. Failure to add breaklines at the top of steep slopes or retaining walls can result in a large ‘scoop’ being cut out of the upper level and this scoop could divert flows in an unrealistic direction. All of the breaklines to be used should be stored in a single GIS layer and displayed using the layer control.



<u>Without Breaklines</u> **<u>With Breaklines</u>**

Porous Walls and Collapsing Walls

Walls are particularly important features and are the only ones which can be directly added by the Modeller to add a feature which can divert or impound flows. Walls can be created in a GIS and then imported into the modelling program. Walls can have a specific height above the DTM or with a specific crest level. Walls can be set with a different porosity (to account for fences and hedges) and can also be set to collapse once there is pre-determined depth of water against one side of the wall. In most overland flow situations, especially in steeper areas, the flow depths are usually very shallow and fast flowing as illustrated in the photograph to the right. Kerblines are therefore particularly important in terms of flow routing because a standard 125mm high kerb face is often sufficient to keep any overland flows within the carriageway. Equally, any gaps in the kerblines at entrances, pedestrian crossings etc are important because

they can be the points at which the overland flows leave the carriageway and potentially enter properties.

As the topography flattens at the bottom of hills the flow depths deepen and the velocities reduce and in these circumstances kerblines become less important but other features such as garden walls, boundary walls and in some instances fences and hedges become more important as they have a greater role in flood defence.

All of the walls should have a unique ID reference and should be adequately documented. It is important to note that in some programs the attributes of walls are not included within any of the validation checks and therefore it is important that the data is carefully prepared and checked before it is used.

Roughness

In 2008 a paper(8) entitled "Benchmarking 2D Hydraulic Models for Urban Flooding" was published. One of the main conclusions in this paper was *'…it becomes critically important for any urban modelling study to examine the impact of a physically plausible range of friction parameters…'*.

At first reading this would mean that for every 2D modelling study the Modeller should make detailed and exhaustive assessments of the roughness values used in the model. However; in practice this is unlikely to be the case as the correct inclusion of walls, kerbs etc in the model will be far more important and will overshadow the effects of different roughness values. The Modeller cannot altogether ignore roughness and should ensure that appropriate values are used either as a single value across the whole model or specifically for different surfaces. Roughness polygons can be imported into the program so that different parts of the simulation mesh have different roughness values. In most cases using roughness values derived from standard publications will suffice but in some cases, especially with deeper flooding depths or in marginal areas it can be worthwhile undertaking a sensitivity analysis to explore the effects of different roughness values.

Channels and Watercourses

Watercourses and open channels can be modelled either in 1D or in 2D. If watercourses are modelled in 1D it is usually very difficult to model a satisfactory 1D-2D coupling and can lead to a duplication of the effects of the watercourse channel unless the Modeller is very careful. This is because the program will automatically model (to a limited extent) the channel within the 2D domain (this is because the DTM will include the channel) and at the same time the 1D will also convey flows. There is no simple way around this.

Another aspect to note is that most open watercourses have trees or other vegetation along both banks and accordingly the DTM can be the least accurate in these areas. The Modeller should carefully view the DTM data to ascertain whether the watercourse is adequately represented, if it is not, the DTM will need to be edited or manipulated.

The Modeller will need to consider on a case by case basis how important it is to model the watercourse accurately. If it is particularly important, the Modeller should consider coupling a 1D river model with the 1D-2D sewer model using linkages such as OpenMI to exchange data between the models. There are no fixed rules on how this can be achieved and one of the most difficult challenges is how to get out of bank flows from the river model onto the 2D simulation mesh of the sewer model.

If accurate modelling of the watercourse is less important but is nevertheless required it is possible to use the 2D simulation mesh to model an approximation of the watercourse channel. This can be done either with or without modification of the DTM. By creating the simulation mesh with the open channel it is possible to simulate flows within the channel though it should be recognised that the 2D modelling of the in-channel hydraulics is unlikely to be as accurate as 1D modelling of the open channel. With small or relatively short watercourses it is usually acceptable to model the flows in 2D but with longer, larger or more complex channels a different approach can be needed. If the Modeller chooses to modify the DTM, this can be done by creating a polygon to represent the extent and width of the channel and then arranging the program to lower the DTM within that polygon by the specified depth. This creates a new DTM with an open rectangular channel formed but with the invert mirroring the original DTM but lowered by the specified amount. The same effect can be achieved by means of using the mesh polygon to lower the 2D simulation mesh (after creation of the mesh) but this cannot be visualised.

If the Modeller does not wish to alter the DTM and considers that the DTM adequately represents the channel the use of 'breaklines' at the top and bottom of each bank with force the 2D simulation mesh to be created with a series of triangles along the channel invert and another series of triangles to represent each bank. Many O.S. maps have top and bottom of slopes lines delineated but care needs to be taken when using these to create the breaklines as these generally contain a very large number of points which in turn create a large number of triangles; the Modeller should consider simplifying this.

It is important to pay attention to the storage volumes within any open channels and in order to 'fill' or partially 'fill' these storage volumes prior to any simulations it might be worthwhile running a simulation specifically to fill these channels and then save the end of that simulation as a 'state file' for use at the start of the main simulation.

Balancing Ponds

Similarly, the modelling of Balancing Ponds can also be tricky and the Modeller needs to pay particular attention to ensuring that the mesh is created satisfactorily. It is important to note that pipes which discharge into a balancing pond or a watercourse cannot be modelled exactly as the actual pipes. This is because the only way in which flows can be brought onto or taken off the mesh is via nodes located within the mesh with a '2D' flood type or with '2D Outfall' nodes. It can be necessary to artificially steepen the last pipe (or add a short dummy pipe) into a balancing pond or open watercourse so that the pipe invert level is at the appropriate level with respect to the bed level of the balancing pond or watercourse.

Documentation of 2D Features

There are a number of important aspects to be considered when creating the 2D simulation mesh. These are the buildings which are to be used to create voids in the mesh, individual mesh polygons, breaklines and walls. It is recommended that all the data used to create the simulation mesh should be located in one place and stored so that the same mesh can be recreated accurately. A dedicated folder named "2D Features" is recommended and all data related to 2D modelling should be stored in this folder including the 2D simulation polygon. This enables the models using 2D features to be repeatable and auditable. It is also recommended that a formal method of recording and documenting all mesh polygons, breaklines and porous walls included in the model is used in order to assist with auditing, model reviews and repeatability aspects.

2D simulation polygons, the voids created by buildings and all porous walls are automatically included as part of the model but other features such as 'breaklines' are not. The buildings themselves and the breaklines can, if necessary, be brought into the model and stored as a permanent and integral part of the model.

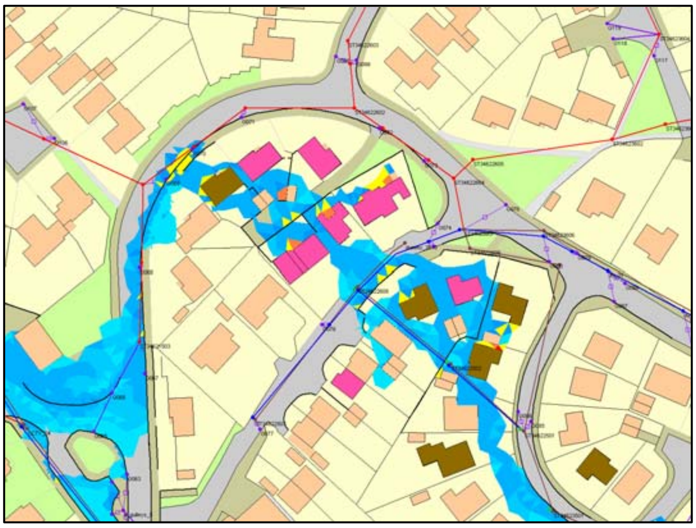
13. MODEL TESTING

As with all models it is essential that some testing is undertaken to ensure that the model is stable and does not lose or add volume during simulations. A series of trial runs with a mixture of single peak design storms and multi peak recorded storms should be simulated and the volume balances carefully scrutinised to ensure that the volume balance remains within acceptable limits.

One of the most important differences with running models with 1D-2D is the selection of the appropriate timestep. Experience has shown that these need to be considerably smaller than without the 2D simulations being used. Whereas typically a 60 second timestep is generally used for normal 1D runs it is necessary for this to be reduced to between 1 and 10 seconds when 1D-2D simulations are run. This reduces the likelihood of instabilities and also the transfer of flow between the 1D domain and the 2D domain is only calculated every major timestep. There are however no hard and fast rules because the mesh sizes, the extent of the 2D simulation polygon and the amount of water flowing over the surface are all factors. It is recommended that the modeller undertakes a few test runs with a short but severe storm (e.g. M100-60) to find the largest timestep which the model can handle.

14. MODEL VALIDATION

The starting point for modelling with 2D is a verified model of the Minor System. The storms used in this verification process are unlikely to have been sufficiently extreme to have caused any flooding. Therefore arguably the depth criteria normally applied to verification (+500mm to -100mm) should perhaps be tightened; that is a matter for the Modeller but clearly it would be desirable to simulate depths to with ±100mm. Having verified the model in the conventional manner the next step is to consider system performance during more extreme historic events.



If there is suitable tipping bucket or weather radar data available for actual historic storms which resulted in flooding it is possible to run the model with this rainfall and to compare the simulation results with video recordings, photographs and/or eye witness accounts of the actual flooding. By matching the simulated overland flow with that reported it is possible to increase confidence in the model. The illustration to the right shows a typical example of the simulation results from a real storm compared with the properties which reported flooding; the properties shaded pink reported internal flooding whilst those shaded brown reported external flooding during that event.

If there is not a satisfactory match additional site visits should be made to ensure that there are no walls or other factors which might explain the mismatch in behaviour. In public meetings or where it is necessary for affected householders to gain confidence it will be particularly important that the model is correct and will give satisfactory results to resolve the problem.

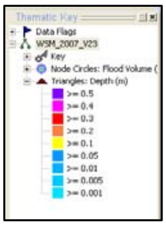
It is ideal if there are a number of storms for which this data is available. In the absence of any real rainfall data it is possible to use synthetic rainfall data of given return periods and to assess whether the simulated flooding and overland flows occur at about the right frequency.

As with all modelling it is important that formal records of the model building and all validation / verification are kept. This will be of great importance when subsequent Modellers wish to use the model, possibly for a different purpose. It is also important to have adequate documentation available for Peer Reviews and to support any discussions with any peers who are reviewing the model.

A formal record of all walls and breaklines used in creating the mesh or in running the model should be kept. The Modeller can choose to keep whatever formal records are considered appropriate but as a minimum the locations of these features should be recorded, especially in relation to any others or where they adjoin buildings. A detailed plan will often suffice, though it would be ideal for photographs and any other pertinent details to be recorded in a formal manner. One approach is to have a formal record of each wall or breakline on a separate A4 page with a plan, one or more photographs, the unique ID references and in the case of walls values for all the relevant variables.

15. RESULTS

There are a number of different ways in which the results from the 2D simulations can be extracted and displayed. The facilities available to replay simulations can, if used in a public meeting give a very powerful message about how the flooding is simulated. The Modeller will need to decide on the most appropriate settings to be used for reports and for presentations. There are a number of ways in which the results can be displayed.



This illustration shows how the flow depth in the individual triangles can be represented with different colours. In this case flood depths less than 1mm are hidden, from 2mm to 99mm there are different shades of cyan, 100mm to 199mm are shown in yellow, 200mm to 299mm are shown in orange, 300mm to 399mm in red, 400mm to 499mm in bright pink and greater than 500mm in purple.

The results can also be shown as a combination of depth of flow and velocity with flow direction arrows. This type of results presentation is particularly helpful in understanding the directions of flow which needs to correlate with the descriptions given by affected residents.

The combination of depth and velocity have been combined together to give a combined ‘Hazard’ score. The Defra publications ‘Flood Risks to People Methodology’ (FD2321/TR1[9]), ‘Framework and Guidance for Assessing and managing Flood Risk for New Developments’ (FD2320/TR2[10]) and ‘Supplementary Note on Flood hazard Ratings and Thresholds for Development Planning and Control Purpose (clarification of Table 13.1 of FD2320/TR2 and Figure 3.2 of FD2321/TR1)[11] set out the criteria and methodology for deriving the Hazard. One option for results presentation, which will be particularly useful to the emergency services is to map the ‘Hazard’ score directly.

When any results are shown at public meetings or are otherwise put into the public domain careful consideration should be given to how they might be mis-interpreted. Whenever results are used in this way there should always be an adequate explanation of what the results represent and there should be a disclaimer included.

16. MODELLING OPTIONS AND SOLUTIONS

Drainage systems are designed to retain flows below ground to a prescribed return period storm event and for those flows to be conveyed to a suitable outfall point (wastewater treatment works, watercourse or sea). It is common practice for new sewers to be designed to not flood for up to and including a 30 year return period storm of critical duration. In some sewerage undertakers areas this design criteria can extend to once in 50 year events. However, it is recognised that no matter what the design criteria is, a storm will occur at some point in time which is in excess of the design standard. When these conditions arise flooding will occur and at some locations this can create a physical hazard and a health and safety risk. It is becoming increasingly common for extreme conditions to be considered as part of the drainage design including identification of overland flow pathways and natural ponding areas. Where the extreme conditions are likely to create an unacceptable risk then these risks are often mitigated by the deliberate channelling of overland flow to areas where there are lesser consequences or where the risk is acceptable. This practice is commonly referred to as Designing for Exceedance[3] and is at the heart of Integrated Urban Drainage studies.

The general step by step approach is numbered below with further explanation following where necessary:

1. run exceedance event to generate flooding
2. use 1D-2D model to determine flood routes and ponding areas
3. if a known problem, verify the model against the flooding records
4. determine unacceptable risks
5. identify safe routes and lower risk ponding areas
6. add mitigating factors to scheme
7. ensure that mitigation structures are fully explained, documented and known to decision makers.

Step 1 – note the storm to be used will vary depending on the study area and limitations of the model. However, it is probable that a common national standard will be governed by the requirements of insurance companies rather than those with the responsibility for the drainage design. A 100 year return period event is frequently used by insurance companies and in fluvial flooding projects and this is probably as good a starting point as any in the absence of a specified frequency.

Steps 2, 3 and 4 - If the model is being used to test the system and there is no historical evidence of flooding then the overland flow paths and ponding areas should be noted and any unacceptable risks identified. Where a known problem is being investigated it is important that the Modeller pauses at this stage to ensure that the model accurately reflects the known flood paths gleaned at the data collection stage (Section 4) and where necessary, to add above ground detail to verify the above ground model.

Steps 5 and 6- The Modeller should then consider how to mitigate the effects of floodwaters on the risk areas. It is likely that in urban areas the solution will be to retain flow in highways as kerbing will form a man-made channel. In some areas to lay low level barriers (sleeping policeman) should be used to prevent flow from escaping from the defined channel e.g. at road junctions or driveways. Where this is not possible it is often appropriate to construct a channel to prevent flow from causing internal property flooding. An example of a safe area to pond can be open parkland or school playing fields. However, the legal aspect of this should be fully understood, discussed and resolved prior to implementation. This will be necessary on a case by case basis because in some circumstances a choice will need to be made to flood one persons land to protect another and the legal implications of this can be complex. Modellers could refer to CIRIA Report No C635[5], “Designing for exceedance in urban drainage – good practice” for further guidance.

Step 7 – once above ground barriers are constructed there is a risk that as time goes by the reasons for raising a kerb line or extending a wall fade from memory, particularly as they will only infrequently become active players in flood mitigation and flow control. To ensure that these defences are not removed over time it is important that the location and need for each is fully documented and provided to the local council and property owners, where appropriate.

17. THE FUTURE

The ability to model flows in 2 dimensions in urban areas is a major step forward in modelling in urban areas and in Integrated Urban Drainage Modelling. It is clearly a very powerful modelling tool with an easy to follow and dramatic results presentation. This can also be a potential problem because it can produce results very easily which are believable to the inexperienced Modeller but unless the results match closely with reported (and frequently recorded) flooding incidents any confidence in the model can be invalidated. It is particularly important that adequate detailed site inspections by experienced modellers are undertaken so that the important 2D features in the catchment, which are frequently at ‘micro’ scale, can be recognised, measured and recorded and then incorporated into the model.

Modelling with 1D-2D is far more subjective than many Modellers are familiar with and therefore a ‘Peer Review’ process should be encouraged and used as a mechanism to support Modellers. It is however, clear that in inexperienced hands there is considerable scope for incorrect modelling with associated undermining of the credibility of the modelling process. It is therefore recommended that the most experienced Modellers within the organisation are actively involved in 1D-2D modelling projects.

18. REFERENCES

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AMENDMENTS

Ver	**Description**	**Date**
1.	First Published	November 2009