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Using DTM's to determine locations Of permeable runoff into Sewerage Networks

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1. Introduction

In recent years the availability of accurate Digital Terrain Data has improved and it is now reasonably priced. This has meant that the network modeller can use the data as a tool to help develop accurate models. Digital Terrain Data can be obtained by many methods, from ground surveys to airborne LiDAR.

Over the last few years there have been many papers and discussion on overland flow routing, and Digital Terrain Models (DTM's) are a vital part of any method of predicting overland flow routing. In this paper I will concentrate on the use of DTM's to determine locations of permeable runoff into the sewerage network.

2. What is Digital Terrain Data

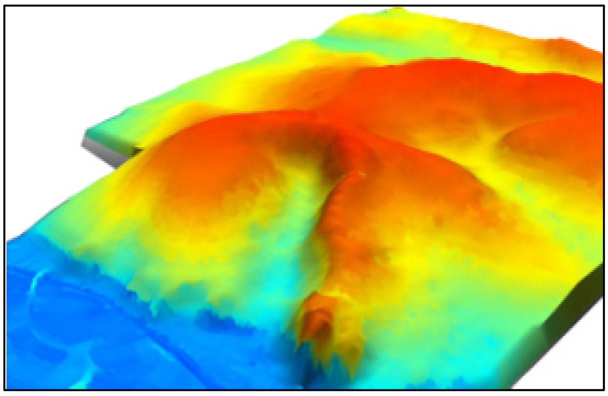


Figure 1: 3D terrain model, Courtesy of Infoterra Global

It is important to first understand what is meant by Digital Terrain Data. Digital Terrain Data has many names and can come in various formats. Principally Digital Terrain Data is a list of elevations at known locations stored in a digital format which can be imported into a computer. Once the elevation data is imported into a GIS package such as MapInfo Professional or ARCView then it is possible to create 3D models of the terrain as shown in Figure 1.

As well as producing 3D models of the terrain it is possible to use the digital terrain data to create accurate contours (see figure 2) at various intervals (depending on the vertical accuracy of the data) such as 1m or ½m intervals using software packages such as MapInfo Vertical Mapper. Such contours are very useful when try to understand flooding mechanisms and flood routing.

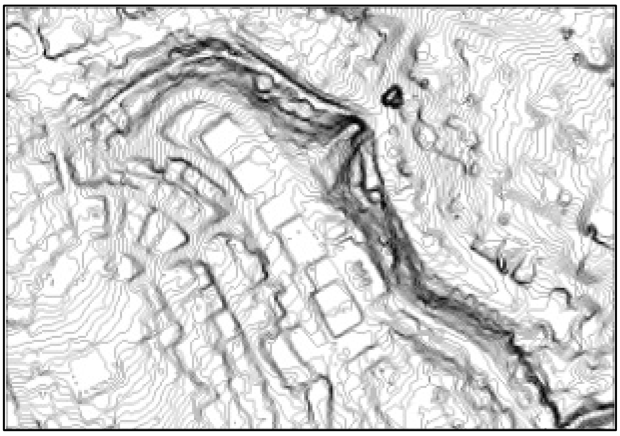


Figure 2: Contours generated at ½ m intervals, Courtesy of Infoterra Global

From Digital Terrain Data there are typically two main models produced namely a Digital Elevation Model (DEM) and a Digital Terrain Model (DTM). The DEM contains data on the heights of buildings, trees, etc whereas the DTM contains data from the ground (sometimes referred to as bare earth). DEM's are also referred to as DSM's (Digital Surface Models) in some places. Both models are useful but it is normally the DTM's which are used, however if flood routing is been undertaken then attention should also be paid to the DEM's and to in-catchment checks to ensure that no obstacles would cause the flows to be diverted in a different direction than would be expected from the bare earth topography.

DTM's and DEM's can be produced in two formats, either GRID or TIN (Triangular Irregular Network). A GRID format is where the data is collected at a fixed distance apart in all directions, for example at 1m intervials. The DTM/DEM is then modelled by looking at all the 8 nearest points and calculating the slope in each direction. A TIN format is where the collected data is at regular or irregular spacing and the DTM/DEM is generated by looking at the surrounding points.

3. Digital Terrain Data Collection Techniques

Digital Terrain Data can be obtained by many methods. The main methods are summarised below.

3.1 Sewer Records

This source of DTM data is frequently overlooked but all modellers have access to some basic digital terrain data, in the form of sewer records with X & Y coordinates for each manhole together with the elevation in terms of the cover level. Using a spreadsheet program such as Excel, a table can be created of ground levels and coordinates from manhole records. This can then be imported into InfoWorks as a txt file to form a triangular irregular network (TIN), which can then be visualised in 3D.

This source of terrain data can be useful but it is limited to the fact that there is only elevation data at manholes and therefore a true representation of the whole terrain is not possible. One good use of this digital elevation data is as a check on the quality of the ground level data. An example of a DTM created from sewer records can be seen in Figure 3.

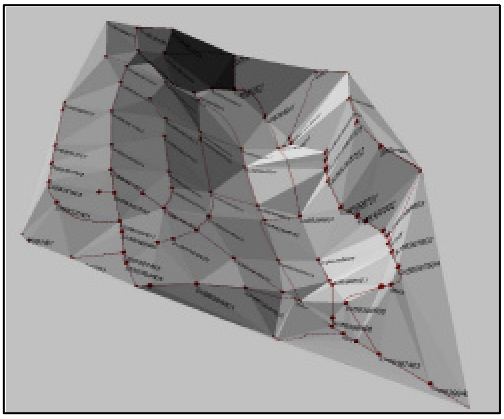


Figure 3: DTM created from Sewer Records.

3.2 Ground Surveys

Ground surveys are the oldest method of obtaining elevation data; it is still amongst the most accurate method due to the ability to focus the survey on the area of interest, e.g. river channels. With the recent developments in digital theodolites and total GPS stations, it is now possible to quickly collect accurate elevation data, (in the order of ± 1cm). The data from ground surveys is similar to sewer records in that elevations are contained within a table along with coordinates. With a ground survey it is possible to survey points on particular features or at any distance apart, from every 10 metres to every metre making them more accurate than just relying on sewer records.

Ground surveys can be very time consuming and therefore relatively expensive for catchments other than small ones. For larger catchments it is usually more economical to undertake remote sensing surveys as described below.

3.3 Photogrammetry

This method of obtaining elevation data is one of many airborne techniques and is perhaps the oldest of these methods. Photogrammetry uses stereo photographic images of the terrain so that the relative elevations can be measured and related to a ground control. This technique can be used to collect data over a large area, but the processing of the data can be a lengthy process as it requires both automated measurements and some manual measurements. Digital elevation data is available from the Ordnance Survey under the name of Land-Form PROFILE and is supplied either as contours or as a DTM. The DTM is interpolated from the contours, which have been produced from photogrammetry. The vertical accuracy of the contours is ± 1.0m and the vertical accuracy of the DTM is ± 2.5m. This data typically costs approximately £100 for a 5km grid square.

3.4 Synthetic Aperture Radar (SAR)

This is another of the airborne techniques available today. Like Photogrammetry this technique uses 2 images of the same area captured at slightly different geometries to calculate the elevation of the terrain relative to a control point. Instead of a camera capturing photographic images radar is used to capture the image. The radar is side looking and as a result the vertical accuracy of the data within built up areas is only about ± 1.0m depending on the altitude of the aircraft and is usually either on a 5m grid (data points every 5m) or a 10 m grid.

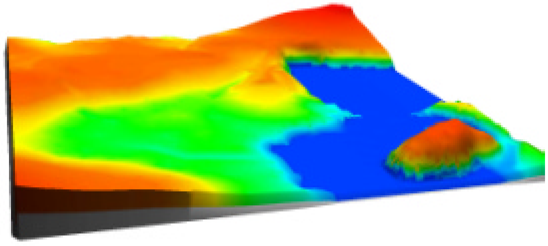


Figure 4. DTM created from Data obtained by SAR

A DEM (DSM) and a DTM for anywhere in England and Wales and some parts of Southern Scotland is currently available through www.getmapping.com. This data was collected using the SAR technique during 2002. It is planned to extend the coverage in Scotland. This data costs from around £45 for data on a 10m grid covering a 500m x 500m square up to about £4,000 for a more accurate 5m grid covering a 10km x 10km square. The vertical accuracy of this data is ± 1m , (± 0.7m in the south east of England). An example of this data can be seen in Figure 4.

3.5 Light Detection And Ranging (LiDAR)

LiDAR is another of the airborne techniques and is probably the most appropriate of all the techniques for use by network modellers. LiDAR is a highly accurate method of collecting elevation data over large areas. The principal of this technique is that an aircraft fitted with a laser scanner passes over the catchment, as illustrated in Figure 5. As the aircraft passes over the catchment the laser scanner scans the terrain below. One of the advantages with this data collection method is that as the aircraft pass a point several sets of data can be collected. The laser is emitted as a series of pulses from the aircraft and is bounced back from the terrain to the aircraft. The first signal returned is off the first surface struck which might be a tree canopy or the roof of a building. It is this first pulse returned which is used to create the Digital Elevation Model (DEM). The emitted laser signal will also pass down through the canopy of the trees etc and be returned by the ground (also referred to as 'bare earth'), this is known as the last pulse. It is the information gained from this last pulse which is used to create the Digital Terrain Model (DTM). Another advantage of this technique is that it can be carried out either during the day or at night.

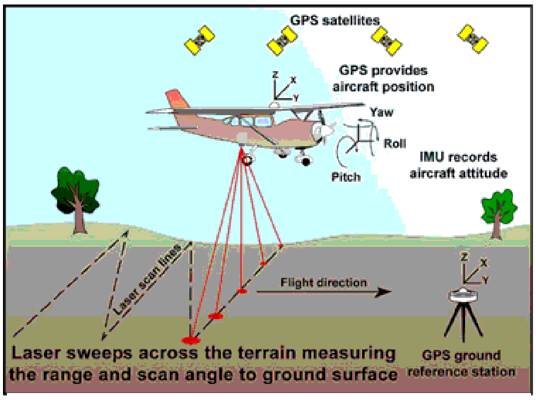


Figure 5. Components of a LiDAR Survey, Courtesy of the Bureau of Economic Geology, Texas

The vertical accuracy of data collected by the LiDAR technique is related to the altitude of the aircraft, for example if the aircraft passes over the catchment at a height of 900 m then data is collected on a 1m grid giving a vertical accuracy of ± 15cm (150 mm). Whereas if the aircraft passes over the catchment at 2,000 m then the data is collected on a 1.7m grid with a vertical accuracy of ± 25 cm (250 mm). Modern LiDAR equipment can collect vast amounts of data rapidly, for example the equipment used by Infoterra Global can collect 33,000 individually heighted data points every second. With this much data collected it is possible to create very accurate DTM's.

If there is a requirement for very accurate elevation data (± 15 cm) it is worthwhile checking with the various companies such as Infoterra Global that offer LiDAR data to see if they have already flown the area of interest. Many of the major cities in the UK have recently been flown to produce 1m grid datasets. If the area of interest has not already been flown, a specialist company can be commissioned to fly the catchment and provide both a DEM and a DTM. The cost of capturing LiDAR data is not as high as people perceive, the majority of the cost is tied up in getting the aircraft airborne. For example a 14Km^2 catchment would cost around about £10,000 to obtain a DTM and a DEM produced at 1m grid resolution (vertical accuracy of ± 15 cm).

LiDAR collection is not limited to the use of fixed winged aircraft, it is possible to use helicopters. An example of this is a technique referred to as FLI-MAP; Figure 6 shows the set up of FLI-MAP. This technique allows the collection of data to occur at a lower altitude; increasing the accuracy, it is also ideally suited for flying linear features such as railway cuttings or flood defences. For the network modeller FLI-MAP might be very useful for covering the relatively small area upstream of flooding locations.

The Environment Agency also holds a stock of LiDAR data for a number of limited areas of the country, but this is at either 5m or 10m grids. These are generally in coastal regions or along river valleys.

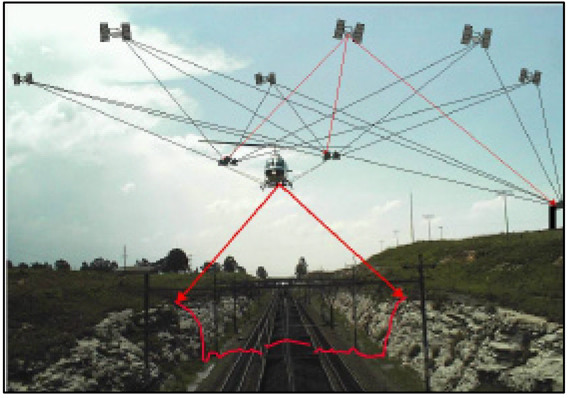


Figure 6. Example of FLI-MAP in action. Courtesy of Furgo-Inpark B.V.

4. Using DTM's to Determine Locations of Permeable Runoff

4.1. Technique

The technique which we have used successfully on a number of projects utilises a proprietary program called "Streambuilder" which reads the DTM directly and automates much of the work. However, the technique can be undertaken manually using a slight variation to the technique.

The first step is to plot the locations of flooding incidents and ascertain what the conditions were when flooding occurred and whether there were any service defects (eg blockages) which accounted for the incident. If there are a cluster of flooding locations and there was a tendency for flooding to occur in winter or with prolonged rainfall there is a good chance this was (at least in part) due to runoff from permeable surfaces.

Having plotted the flooding locations to be examined in more detail the next step is to identify the 'bare earth' topography which forms a catchment upstream of these points. This can be done automatically using 'Streambuilder' or if the manual technique is used the catchment area can be determined from contour information. Contours at close intervals of 1m, 500mm (or even less) can be produced using such programs as 'MapInfo Vertical Mapper'. The next step is to then load mapping or DEM data to assess whether any of these catchments might be extended by roads, railways or other features intercepting the 'bare earth topography' and potentially transferring flows into the catchment from adjoining areas.

Once the catchments have been identified an examination of mapping or better still aerial photography will reveal how much of the catchment comprises impermeable surfaces and how much comprises permeable surfaces such as gardens, playing fields, agriculture, public open spaces or areas left to grow wild. If the impermeable surfaces form the bulk of the catchment it is likely that conventional modelling techniques will produce satisfactory results. However, if the permeable surfaces form the bulk of the catchment it is likely that permeable or slow response runoff could be a significant factor contributing to the flooding problem. It is in these circumstances that the next stages of this technique are required.

The next step is to identify all the different surface types (also referred to as the "Land Cover") within the catchment. Clearly the paved and roof areas are easy to identify but the remaining areas could be a wide variety of different land cover. Each different land cover type needs to be indexed to the standard types included in the Soil Conservation Service (SCS) Runoff Method which is included within Infoworks. There are 4 soil groups (A, B, C, D) for different hydrological soil conditions and 83 different land cover categories listed in the Infoworks Help pages (but there are many more available from external references). However, it is best to keep the number of different land cover types to 9 or less. The reason for restricting it to 9 or less is because Infoworks will only allow 12 different surface areas within a particular subcatchment and 3 of them are required for the paved, roof and residual areas (uncoded areas) (this must always be the last column used). The easiest way to categorise the different land cover types is either with a description (eg short grass) or by the Curve Number (the curve number can be looked up in the Infoworks Help).

The next step is to decide what land cover type is going to be allocated into each of the surface area columns within the contributing area data (e.g. you might decide to put short grass into column 4 – again remember that at this stage columns 1,2 & 12 are required for the paved, roof and residual areas). Having decided which land cover will go into which column the individual surfaces need to be prepared as polygons. In Mapinfo each individual surface should have system type in one column of the attribute data (headed 'System') and the destination column (3 to 11) in the other column in the attribute data (headed 'Surface') e.g. areas of short grass would be coded 'Combined' and '4' in our example. Having created and coded all the areas, the next stage is to do the Area Take Off in the latest approved method (see Infoworks Help if in doubt). It is important to remember in the land use tab to allocate each surface type with a runoff surface. If for example you use surfaces 1 to 9, 1 is roads, 2 is roofs, 3 is lawns etc, you need to allocate each surface upto 9 with a runoff surface, even if you have no roads contributing.

The contributing area data will therefore have paved areas in Column 1, roof areas in Column 2, areas appropriate to the different land covers in columns 3 to 11 (e.g. short grass in column 4) and then in Column 12 is whatever is left over.

The next stage is to set the correct Surface Types and Land Use Indexes within Infoworks. For the individual surface types (land covers) the runoff model is set to 'SCS' and the appropriate data value for the "Storage Depth" S – this is calculated from the Curve Number for the land cover. The Initial Losses also need to be included and these are calculated from the Storage Depth 'S'. The desired 'Routing Factor' also needs to be inserted depending on how long the runoff is to be delayed. For the Land Use Indexes the appropriate columns (1-12) are set to match the required surface types.

The last remaining step before running the model is to decide what to assume as the catchment wetness (Dry, Average or Wet), which needs to be included in the rainfall data (the catchment wetness will automatically adjust the 'S' value upwards or downwards as necessary). The catchment wetness is defined as the antecedent moisture class (AMC), and is divided into three class, AMC_I, AMC_{II}, AMC_{III} (Dry, Average or Wet)

The model can now be run with whatever range of rainfall events is required.

In many cases following this procedure has created substantial additional runoff during the wetter winter periods with little or no change in simulated flows in the drier summer months.

Once this technique has been used to identify the permeable surfaces that contribute runoff it is important to check the verification. A historic verification should be carried out to check that the model predicts the correct amount of flooding at the correct locations for the correct return periods. Once this historical verification has been carried out successfully there is greater confidence that the runoff has been modelled correctly and that the model is "Fit For Purpose".

4.2. Case Study No 1

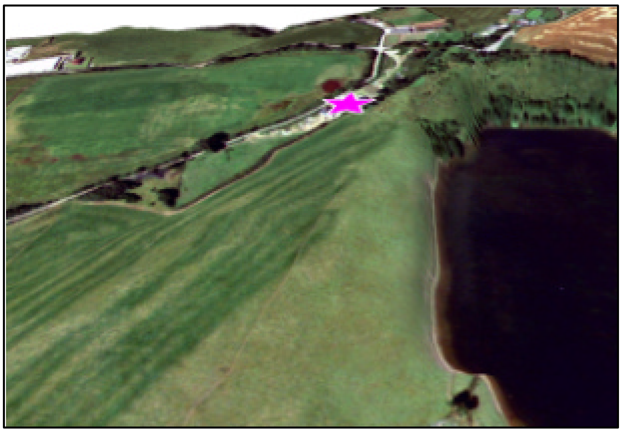


Figure 7. Aerial View of Catchment

4.2.1 Background

Flooding occurs at a property that is situated near a recently filled quarry. The flood water is believed to be from runoff from the raised ground in the area of the quarry. The runoff flows across the land onto the road, and then enters the property via the driveway. The first part of the technique detailed in this paper was used to determine the upstream catchment that could contribute the runoff flows that cause the flooding.

4.2.2 Defining the Upstream Catchment.

For this study a DTM was purchased which was created from data collected by the SAR technique. The DTM was based on a 5m grid with a vertical accuracy of ± 1m. The DTM was loaded into MapInfo and the flooding location was plotted on top of the DTM. Streambuilder was then used to determine the drainage basin based on the DTM and the potential flow routes from the catchment. Figure 7 shows the location of the flooding marked (with a pink star) on the aerial photograph, which has been draped over the DTM. Figure 8 shows a close up of the flooding location. Once Streambuilder had calculated the drainage basin and the possible flow routes, these were overlaid on to the aerial photograph to see where they were in relation to the known flood routes. It was known from the resident of the property that flood water entered his property by flowing off the road and down his drive way, leading to the front door. Any flood water that did not enter the property would find its way around the building and continue across the land until it came to the edge of the property boundary where it turned and flowed south-westwards along the alignment of an old railway embankment (now removed). The predicted flow routes around the property can be seen in Figure 8. The next stage of the work on this project is currently underway and will be to model the runoff flows.

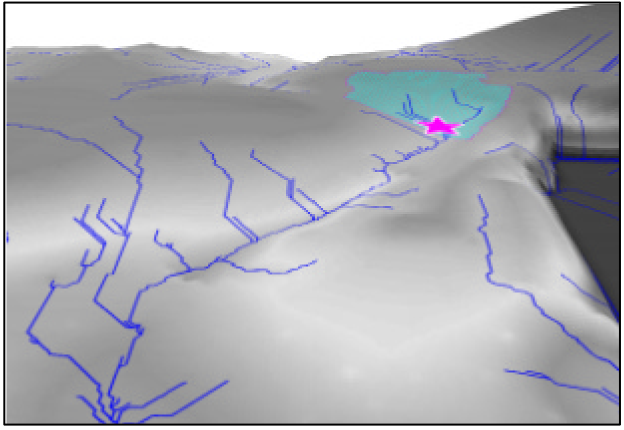


Figure 8. Streambuilder Flood Routes and catchment.

4.2.3 Conclusions

With the use of the DTM and Streambuilder it was possible to show that there was an overland flood route from the infilled quarry onto the road and then into the affected property via the landowners drive way. This is a good example of where the use of a digital terrain data has helped to define the contributing areas and to then calculate the permeable runoff which contributes to the flooding.

4.3. Case Study No 2

4.3.1 Background

Flooding occurs at properties in the bottom of a valley. The mechanism of flooding was unclear and conventional modelling did not simulate the known flooding. The catchment upstream of this location is a mixture of residential, open space, bowling greens and tennis courts.

There was an accurate DTM available for the area, which had been captured by LiDAR on a 1m grid (vertical accuracy ± 150 mm). Figure 9

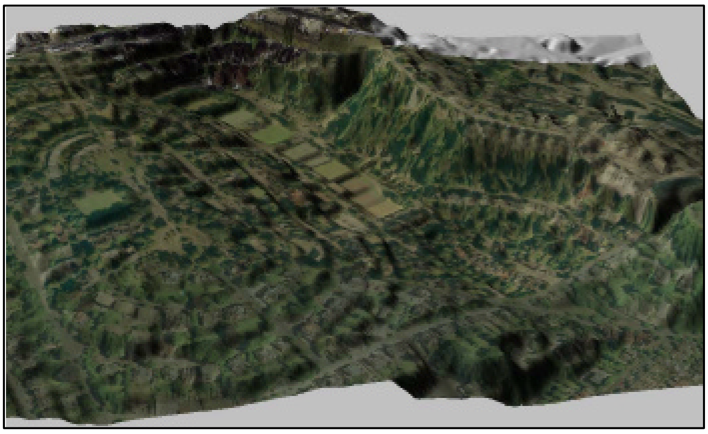


Figure 9. Aerial View of catchment from Southwest

shows the DTM (5 x vertical exaggeration) with an aerial photograph draped over it showing the valley. The Tennis courts and bowling green can clearly be seen in the bottom of the valley. It is clear that there are some large permeable areas within the valley that could contribute large runoff volumes during storms and for a period afterwards.

4.3.2 Defining the Upstream Catchment

"Streambuilder" was used with the DTM to determine the upstream catchment for the known flooding location. It would also have been possible to generate contours from the DTM and use these to determine the catchment. Figure 10 shows the upstream catchment and the flooding location (Pink Star). It is clear from this that the whole of the valley forms the upstream catchment.

Once this upstream catchment had been defined it was clear to see that the permeable areas could have a significant impact on the flooding downstream.

4.3.3 Modelling the Runoff.

Conventional modelling using fixed runoff for the Impermeable areas and New UK Runoff for the small permeable areas in the model was used initially. The subcatchments were defined following the 10m rule so that they included all impermeable areas but only small permeable areas. This method did not simulate the known flooding at the downstream properties. The valley has a significant proportion of permeable area, (most of which was not included in the initial model). It was decided that the subcatchments should be redefined following property boundaries and the permeable area added to the model. As can be seen in Figure 9 the valley falls from north to south with the sides being much steeper. As a result of this it was important to accurately define the subcatchments to include the most likely route for the runoff from the permeable areas.

The DTM was used to create contours at ½ m intervals for the whole of the valley area. The subcatchments were redefined using the contours as a guide to the direction of the runoff. The subcatchments where possible followed property boundaries so that all of the permeable area in the catchment was included in the model. Using both the DTM and the contours allowed us to appreciate the topography of the valley and to accurately define the subcatchments. Using the DTM in a 3D view allowed us to view the catchment and study potential runoff routes from different angles as if we were standing on the ground in the catchment.

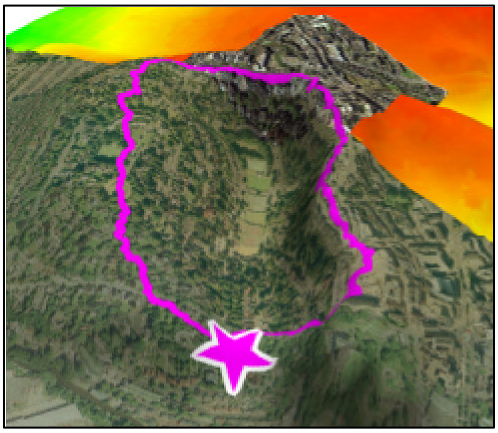


Figure 10. Upstream Catchment determined using Streambuilder and Flooding Location.

Once the subcatchments had been redefined and a new area take off carried out the simulations were rerun using a different land use file. The runoff from the Roads and Roofs were left unchanged at 75% and 80% respectively. The runoff from the permeable areas was again modelled using the New UK Runoff, but the routing factor was increased from 4 to 20, to allow for the fact that some of the rainfall would permeate into the soil and would be slower at entering the sewerage network. The simulations carried out using this method again still did not simulate the know flooding, the peak flows were similar to the peak flows from the initial conventional modelling method. The volumes were slightly higher due to the curve of the peak being broader and the presence of a tail to the hydrograph.

The runoff from a catchment like this is fairly complex due to the fact that there are many different types of permeable area each with different runoff characteristics. The next stage was to try and model the runoff from each of the different permeable surfaces more accurately using the SCS runoff model. The Soil Conservation Service Model (SCS) is a rural catchment model, but it can be used effectively on a rural subcatchment draining to an urban catchment. The SCS runoff model can be applied individually to different surfaces allowing the different runoff characteristics to be modelled, it is also possible to mix the SCS model with the fixed model.

Within the catchment we identified 8 different surface types which all needed to be modelled. These surfaces were, Roads, Roofs, Closely Mown Grass (fairly flat, e.g. Lawns), Infrequently Mown Grass on a medium gradient slope, Unmown Grass on a steep slope, Astro Turf Tennis Court, Tarmac Tennis Court and

Grass Tennis Court/Bowling Green. The Roads and Roofs were again modelled with the fixed runoff model (75% and 80% respectively) while the remaining 6 surfaces were modelled with the SCS model. The following table shows the different parameters used for the 6 surfaces.

Surface	Curve Number	Initial Losses (m)	Storage Depth (m)	Routing factor
Grass (fairly flat, e.g. Lawns)	39	0.03972800	0.39728000	50
Grass on a medium gradient slope	49	0.02643673	0.26436734	35
Grass on a steep slope	68	0.01195294	0.11952941	20
Astro Turf Tennis Court	65	0.01367692	0.13676900	100
Tarmac Tennis Court	98	0.00051836	0.00518360	4
Grass Tennis Court/Bowling Green	39	0.03972800	0.39728000	10

Also included in the model is a 9th surface in column 9 (for the residual areas) with 55% fixed runoff, this is for any area that has not been allocated.

The SCS model uses the following equation to relate the rainfall falling on a surface to the runoff from the surface:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

Where I_a is the initial losses (mm)
P is the total rainfall (mm)
Q is the total runoff (mm)
S is the storage parameter (mm)

The SCS Model uses curve numbers to identify different surface types. The curve numbers are made up from both the land use and the soil type. For this catchment the soil was type A all over, Figure 11 shows the permeable areas and how they were defined.

Once the Curve Number was defined for each surface type it was used to calculate both S (Storage) and I_a (Initial Losses). S was calculated from the curve number using the following equation:

$$S = \frac{25400}{CN} - 254$$

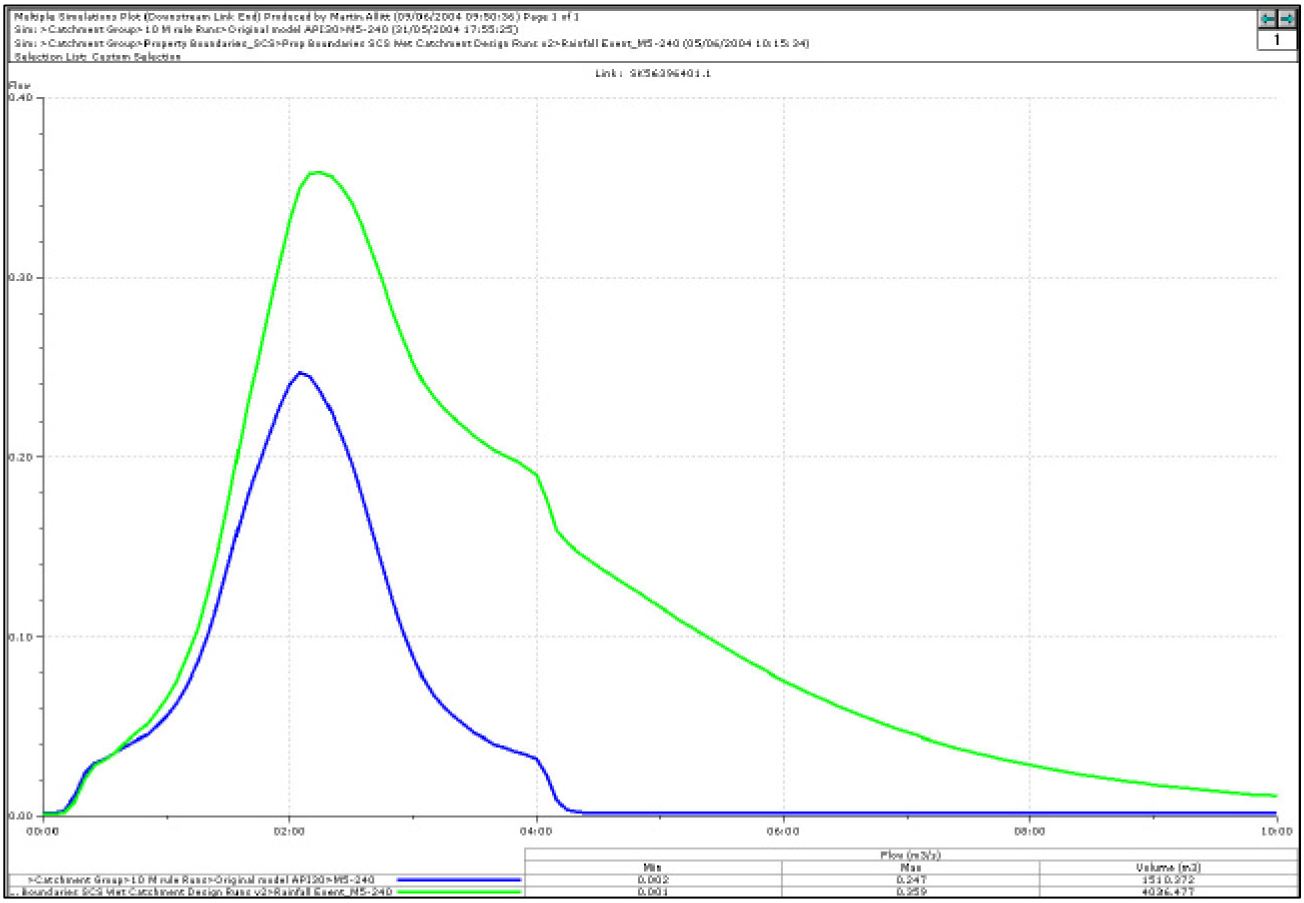
The initial losses were calculated using the following equation:

$$I_a = 0.1S$$

The values used in the model for S and I_a for each of the 6 permeable areas types can be seen in the table above.

Figure 11. Permeable Area allocation.

Simulations were carried out using the SCS method for both an average wetness catchment (AMC_{II}) and a wet catchment (AMC_{III}). The results from the AMC_{III} model and the conventional model can be seen in Figure 12 In Figure 12 the blue line was the flow hydrograph if conventional modelling was used and the green line is the flow hydrograph that was generated at the flooding location from the model using the SCS method with a wet catchment. It is clear to see that the peak flow increased from 247l/s to 359l/s. The volume of flow also increased significantly. When the SCS method was used with a wet catchment the known flooding was simulated and a good match to the historic information was achieved.



	Flow (m3/s)		
	Min	Max	Volume (m3)
>Catchment Group>10 M rule Runs>Original model API30>M5-240	0.002	0.247	1510.272
...Boundaries SCS Wet Catchment Design Runs v2>Rainfall Event_M5-240	0.001	0.359	4026.477

Figure 12. Flow Hydrographs for Conventional and SCS Method.

4.3.4 Conclusions.

The application of this technique has identified extensive permeable areas which have contributed to the flooding which occurs at the bottom of the valley. The use of the SCS method to model runoff from the multitude of different pervious surfaces has enabled a model to be created which gives a good representation of the flooding mechanism which only occurs with prolonged rainfall or in saturated conditions.

5. References

1 United States Department of Agriculture, Soil Conservation Service Runoff Method

2 InfoWorks Help

3 www.Infoterra-global.com

4 www.getmapping.com

5 Hale J, *"Urban Flood Routing…..The Next Step"*, (2003)

6 Misha SK et al, *"Soil Conservation Service Number (SCS-CN) Methodology"*, (2003)