ABSTRACT

This paper presents specific examples comparing catchment and overland flow pathway delineation using GIS grid based techniques and the traditional (manual) approach in urban sewer and stormwater catchments. With increasing availability of detailed ground topography and LiDAR datasets (Light-Imaging Detection and Ranging) accurate digital elevation models (DEM) of urban areas can be produced using GIS raster techniques. Features like roads, buildings and stream banks have great effect on catchment dynamics and overland pathways and as such must be accounted for in the model set-up. This is possible by means of high resolution DEM’s that relate to the catchments topography.

Catchment and overland pathway delineation is an essential and important step for both stormwater and sewer system modelling studies. Topography and network features, influence urban catchment delineations and flow path generation. Manual catchment and flow paths delineation is very time consuming. This paper presents two different methods of automated catchment and flow path generation. Conclusions on the viability of GIS-based automate approaches for catchment delineation and flow path delineation to support urban network modelling studies are also provided.

KEYWORDS

Catchment delineation, Overland flow paths, LiDAR, Grid’s, TIN’s

1 INTRODUCTION

The first step in undertaking any kind of urban hydrologic modelling whether it is associated with stormwater, sewer, or combined systems involves delineating catchments and overland flow paths. In the recent year’s advances in terrain data collection techniques, most notable Light Detection and Ranging (LiDAR), computing power, and geographical information systems (GIS) have allowed many opportunities for enhancing hydrological parameter estimation for urban systems.

Traditionally, drainage areas and overland flow paths have been delineated from topographic maps, where drainage divides and flow direction were located by analysing contour lines, or by visually inspecting ground slopes on site.

Drainage areas and flow path can now be delineated automatically using digital elevation models (DEM) of the land surface terrain. DEM’s can be developed from almost any terrain data, however the cost of collecting detailed terrain data using traditional survey techniques such as Total Station and GPS can be prohibitive depending on the level of detail required. The recent accumulation of detailed LiDAR data by local authorities in New Zealand facilitates the cost effective development of detailed and accurate DEMs. Detailed DEM’s allow hydrologist and engineers to utilise powerful spatial algorithms to get a better understanding of the complex drainage patters in the urban environment. It should be noted however that no matter how detailed the input data, DEM’s are only an approximate representation of land-surface and manual checking and editing of drainage boundaries and flow paths will be necessary, especially in areas with very flat terrain and/or many
constructed drainage crossings. Nevertheless the ability to perform spatial analysis for the development of lumped and distributed hydrologic parameters not only saves time and effort, but may also improve accuracy over traditional methods.

There are several tools available online for terrain processing. In this paper however we will only discuss the use of the ESRI ArcGIS (at least ArcView license – Editor license is recommended) and Spatial Analyst based tools ArcHydro. ArcHydro is a powerful GIS data schema and toolbox developed at the Centre for Research in Water Resources at the University of Texas at Austin. The toolbox is open source free ware and is available on the web. (http://www.ce.utexas.edu)

2 DATA REQUIREMENTS

The data required to perform the analysis discussed in this paper includes:

- Terrain data - raw LiDAR points or LiDAR produces contours. (Any terrain data can be used but for detailed modelling in urban catchments LiDAR is highly recommended.)
- Vector polyline file of the piped and/or steam network.
- Vector polygon file of parcel boundaries.
- Aerials can also be very helpful however are not necessary.

3 TERRAIN

The DEM is the basis of the entire analysis and care should be taken during preparation. Production of an incorrect DEM will almost certainly produce erroneous results. The ArcGIS Spatial Analyst extension includes a tool named Topo-to-Raster used to produce DEM’s from LiDAR point sets and contours. Topo-to-Raster is an interpolation method specifically designed for the creation of hydrologically correct digital elevation models (DEM’s). It is based on the ANUDEM program developed by Michael Hutchinson at the Australian National University (http://cres.anu.edu.au/outputs/anudem). ANUDEM has proven to be a very good tool to create DEM’s for hydrological use. The details of DEM preparation is beyond the scope of this paper and is not discussed.

3.1 TIN OR GRID?

Only terrains represented in raster form (grid) can be used in this type of analysis. Triangulated irregular network (TIN) can be useful and provide relatively accurate terrain models from point data sets like LiDAR; however TIN’s can produce erroneous results from contours especially in flat areas. It is also cumbersome to edit TIN data so that water will flow downhill and therefore they are not used in hydrological analysis. As discussed above Topo-to-Raster (ANUDEM) is an excellent tool for hydrological DEM’s when you have dense point distribution (as in LiDAR data sets) or LiDAR developed contour information. Because raster based DEM’s are required for hydrological processing TIN’s will not be discussed further. However it should be noted that TIN’s can be useful for large areas as at the time of this print Topo-to-Raster had a limitation of approximately 2 gigabytes or 6500 x 6500 cells (approximately 4250 ha with a 1m grid spacing). In these cases TIN’s can be created and converted to raster format for use in hydrological processing. There have been discussions at ESRI to upgrade the capabilities of Topo-to-Raster in subsequent versions, and the latest ANUDEM can produce grids of virtually unlimited size.

4 TERRAIN PREPROCESSING

Development of a hydrologically-correct DEM and its derivatives, primarily the flow direction and flow accumulation grids often requires some iteration through drainage path computations. To accurately representing the movement of water through the watershed, the hydrologically corrected DEM must have the proper accuracy and resolution to capture the details of overland flow. Problems often arise when the drainage area has little to no relief and resolution is not fine enough or proper care is not taken in terrain pre-processing. The following steps were used to obtain a hydrologically-corrected DEM that was used to delineate catchments and flow paths for an urban catchment in North Shore City, New Zealand.
4.1 FILLING SINKS

Filling sinks fills all sinks in a grid. A sink is a cell with an undefined drainage direction; no cells surrounding it are lower. If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. Filling the sinks modifies the elevation value to eliminate these problems. As seen in Figure 4-1 below when the stream is piped under the road the DEM was filled behind the road in order to maintain a positive flow slope. This is helpful for minor fill areas however large fill areas like the example below may need to be eliminated by reconditioning the DEM to maintain correct flow direction; DEM reconditioning is discussed further in Section 4.5. Fill grid is also very helpful in predicting potential ponding areas, however, one must be cautious because ponding areas are sometimes misrepresented by incorrect topography. The detailed methodology of filling sinks is discussed in S.K. Jenson and J. O. Domingue paper (http://edna.usgs.gov/Edna/pubs/extractingtopographicstructure1.pdf).

Figure 4-1 Example of areas where sinks were filled during initial filling process

4.2 FLOW DIRECTION

The flow direction grid was then derived from the fill grid and the premise that water flows downhill, and in so doing will follow the path of steepest descent. In a DEM grid structure, there exist at most eight cells adjacent to each individual grid cell. Accordingly water in a given cell can flow to one of its eight adjacent cells according to the slope along the direction of steepest decent. The resulting flow direction grid is encoded 1 for east, 2 for south east 4 for south, and so on, to 128 for northeast as shown in Figure 4-2 below. As seen in Figure 4-2b the flow direction can be incorrect due to the filling. Filling must be derived correctly or erroneous results will persist in the flow direction grid. This will be discussed further in DEM reconditioning section below. The flow direction grid is the core grid used in catchment and overland flow delineation.
Incorrect filling can results in incorrect flow direction due to terrain imperfection.
4.3 FLOW ACCUMULATION
Flow accumulation grid was then calculated from the flow direction grid. The flow accumulation records the number of cells that drain into an individual cell in the grid. The flow accumulation grid is essentially the drainage area to a specific cell measured in grid units. The flow accumulation grid is the core grid used in stream delineation.

4.4 STREAM DEFINITION
With the flow accumulation grid, streams were defined using a drainage threshold area of 3 hectares. The threshold area is the area (number of cells) that must be accumulated before cells will be labelled as a stream path. This results in a raster grid of 1’s and 0’s where 1 signifies a stream path. From this grid a polyline vector file can be derived with the stream network for the defined threshold.

\[\text{Figure 4-3 Stream definition grid}\]

4.5 DEM RECONDITIONING
Once the stream definition is completed it is very important to carefully examine the derived streams and ensure that streams are in the correct location. A common place where the stream delineation most often failed was at roads and in flat areas. These errors can cause many problems in the catchment and flow path delineation and were corrected by reconditioning the DEM. The decision to recondition the DEM needs to be made with DEM use in mind. In urban modelling a reconditioned DEM is required for catchment delineation however for overland flow path generation an unconditioned DEM will have its advantages. As seen in Figure 4-4 the stream delineation in the unconditioned DEM accurately portrays what would happen when the culvert overtops, this type of analysis is very useful in overland flow determination, however can produce incorrect results in catchment delineation. The unconditioned DEM’s were found to better identify overland flows paths at roadways and stream blockages. Below are a few examples of incorrect stream delineation.
Figure 4-4 Incorrect stream delineation on with an unconditioned DEM
Reconditioning the DEM modifies the DEM by imposing liner features (corrected streams) onto it (sometimes referred to as burning and fencing). It was implemented using the AGREE method developed at Centre for Research in Water Resources at the University of Texas at Austin. Full reference to the procedure is provided at http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html. The algorithm requires a raw DEM (or filled DEM) and vector polyline (corrected streams produced in Section 4.4 above).

What AgreeDEM (or DEM reconditioning) does is push the raw DEM along the stream to create a distinct profile along the streams which otherwise does not exist in raw DEM. This was mainly utilised when the stream is piped under roadways or where there was inaccurate or missing elevation data along the streams due to heavy bush cover.

Once the reconditioned DEM was produced the process, from Section 4.1, was repeated until an acceptable stream definition grid is achieved. It was also very useful to keep the unconditioned filled and flow direction grid for overland flow path delineation. This will be discussed further in Section 6 below.

Figure 4-5 Using AgreeDEM to produce the correct flow path

5 AUTOMATED CATCHEMNT DELINIATION METHODS

The discussions thus far have focused on terrain processing methods that have been used for many years in watershed analysis. These tools and methods have proved very useful in large watershed analysis. The remainder of this paper highlights, through specific examples, how these tools can be manipulated and utilised for detailed urban catchment modelling.

5.1 WATERSHED METHOD

The watershed method utilises the flow direction and flow accumulation grid to automatically delineate catchment boundaries. Using the watershed method to develop urban catchments is slightly different then the
other documented methods because most other documented methods are designed for catchment delineation in large open watersheds using streams as the drainage network. For urban catchments a polyline vector file of the complete urban conveyance network with all pipes (modelled and un-modelled) and open watercourses was used to delineate catchments. It is essential that open watercourses are spatially correct and are obtained from the reconditioned DEM analysis. The network features including open watercourses were converted to a single raster grid with an integer grid code representing a feature ID. Merging non modelled and short links was used to reduce the clean up process because every link with a unique feature ID receives a unique catchment boundary. Figure 5-1 shows how the reconditioned DEM must be used to delineate catchments or incorrect delineation can occur.

Figure 5-1 Depiction of the importance of the reconditioned DEM for catchment delineation

The results of the catchment delineation are stored in a catchment grid, with values of each cell representing the feature ID it drains to. The catchment grid can then be converted to a polygon vector file and linked back to inlet nodes via the pipe ID. Catchments were then slightly adjusted and erroneous polygons merged in an attempt to “clean” the catchment file. As with most automated tools there is a fine balance between pre-processing (i.e. DEM reconditioning, stream delineation, and network link merging) and post-processing “cleaning” that must be met.

We have used the watershed method in several urban catchments and it has proven to be a very useful tool for automating catchment delineation in stormwater and combined systems. We have attempted to use this technique in sewer systems with less luck. This is due to the fact that the watershed method is very dependent on the flow direction and ultimately the flow accumulation grid. Often sewer pipes are not placed in low lying areas of the catchment, in an attempt to avoid infiltration, this results in unpredictable flow accumulation along these pipes and difficult catchment delineation. The Thiessen polygon method has been utilised much more effectively for separate sewershed catchment delineation and is discussed below.

Using the network links rather than the node points has proven to be more suitable method for catchment delineation in urban areas because it inherently allows more cells to accumulate flow. This is especially important in the case where links are along roads with very small drainage areas or on hillsides.
5.2 COMPARISON WITH MANUAL TECHNIQUES

It is well documented that the watershed method works particularly well in non-urban areas where open watercourses are the primary form of conveyance. We have attempted to use this method in an urban setting where a pipe network is the major conveyance system with satisfactory results. Figure 5-2 shows comparison of a few catchments delineated manually, in a separate exercise, and the watershed method. As seen in Figure 5-2 the results from the watershed method are in most cases more accurate than the previous manual delineation.

Figure 5-2 Comparison of catchments delineated with the manual method and the watershed method.

5.3 THE THIESSEN POLYGON PROXIMITY METHOD

Thiessen (Voronoi) polygons define individual areas of influence around a set of points or polygons. Thiessen polygons are polygons whose boundaries define the area that is closest to each point relative to all other points. This method is the best attempt to mimic the manual techniques used to delineate catchments in sewer catchments. The method uses a double sweep Thiessen proximity calculation to dissolve parcel boundaries and road reserves based on their proximity to the sewer network. All links in the sewer network can be used to get a “proximity” catchment for each link in the network or a generalised network can be used for larger scale models.

In the first sweep all parcel boundaries are joined in the nearest link and then dissolved based on the link id. In a second sweep road reserves are divided and dissolved into each catchment boundary by performing a second proximity analysis on the dissolved parcel boundaries. This will result in a topologically correct polygon vector file that was associated with each identified network link. The catchments are based on the parcel boundaries
and road reserve proximity to the associated link not topography. Land use and census grids can then be used to determine population and land use. The Thiessen polygon method has proven to be the most effective and accurate approach to delineate catchments in sewer sewershed modelling. Figure 5-3 shows an example of detailed sewer catchments delineated with the Thiessen polygon method in an urban catchment in Pukekohe, New Zealand.

As with the watershed method we have found that the use of the links, rather then nodes, produces the best results in the proximity analysis.

*Figure 5-3 Example of detailed catchment delineation using the double sweep Thiessen Polygon Method*

**6  OVERLAND FLOWPATH GENERATION**

An overland flow path is an above-ground component of any drainage system. Overland flows occur when the underground network reaches its capacity and cannot cope with more inflow usually as a result of heavy rainfall. The excess run-off then travels overland, following low-lying, natural drainage paths. Historically overland flow path generation was very time consuming process especially in stormwater and combined models where nearly all manholes overflow during the larger design events and the overland flow paths must be determined. Automatic generation of these overland flow paths significantly speeds this process up and produces a much more accurate depiction of overland flow. Overland flow is also very useful in sewer models to assess the environmental effect of uncontrolled overflows. Automated flow path generation quickly answers the question; where will the overflow from this node point end up?

**6.1 RAW DEM OR RE-CONDITIONED DEM**

It is important to understand what overland flow paths you are trying to delineate so that the correct DEM can be chosen. In stormwater models you are mostly interested in what happens to water when the system is surcharged including culverts and open water course. We used the unconditioned DEM for this analysis because it will better predict that overflows over roads with blocked or under capacity culverts and streams. On the other hand the re-conditioned DEM was best suited to understand the receiving environment of uncontrolled sewer overflows. The raw DEM would not be ideal in this case as it fill streams and erroneously causes flow paths to divert around stream blockages and or road embankments. Figure 4-4 and above depicts how overland flow paths can be incorrectly delineated when the reconditioned DEM is not utilised.
6.2 CONTRIBUTING AREA METHOD
The stream definition step discussed in Section 4.4 above was used to delineate streams that have a contributing area of 3 hectares. The grid was then converted to a polyline vector and used as general overland flow paths. The same care must be taken when considering if DEM conditioning will be required. Using the stream definition processing was an easy way to understand the general flow paths of the catchment. However the contributing area method cannot predict overflows from any given point within the catchment. The next two methods described on demand overland flow path delineation.

6.3 FLOW PATH TRACING METHOD
Another simple way to determine overland flow path from any user specified point is the flow path tracing tool available in ArcHydro. This tool essentially follows the flow direction grid to the boundary of the DEM with a graphic line. The graphic line can then be converted to a polyline vector file. This is a very useful tool to find a flow path from any user specified point within the catchment and was also used to delineate the longest flow path for time of concentration calculations. The limitation of this tool is that only one point at a time can be delineated and that the delineation is in graphic format.

6.4 COST DISTANCE METHOD (MULTITUPLE POINT DELINEATION)
The shortest path tool available in the ArcGIS extension Spatial Analyst was used to determine multiple overland flow path delineation. The tool works in exactly the same way as the flow path tracing tool, but it can determine the shortest path from multiple overflow points to the boundary of the DEM. This tool, although developed for evaluating potential road alignments and or shortest distance travel planning, can be used with accuracy to determine overland flow paths from multiple user defined paths. The tool requires a point vector file and the flow direction grid (discussed in Section 4.2 above). It should be noted again that the correct DEM should be considered or the appropriate path will not be determined. The tool produces a topologically correct overland flow path network from every point in the point vector file. One drawback of this tool is that because it is grid based the flow path will not start at exactly the defined point. It can also produce many flow paths near each other which need to be amalgamated. Both of these issues can fairly easily be overcome with ArcGIS topology tools.

*Figure 6-1 multiple point delineation*
7 CONCLUSIONS

Accuracy of catchment delineation and overland flow path estimation plays a crucial role in the development and calibration of hydrologic and hydraulic models of urban catchments. Traditionally delineating catchments and flow paths was very time consuming. This paper presents two different GIS based automatic catchment and flow path delineation methods. We have also verified the success of the automated methods with manual delineation.

In general the watershed method was found to be the best approach in urban stormwater catchments and the Thiessen polygons method in sewer catchments. The cost distance method proved to be the most efficient overland flow delineation tool. With increasing availability of detailed ground topography in LiDAR datasets DEM’s can be produced using GIS raster techniques. Features like roads, buildings and stream banks have great effect on catchment dynamics and overland pathways and as such must be accounted for in the DEM set-up. Reconditioning the DEM to account for roads is required for catchment delineation.

A successful GIS based automatic catchment delineation is dependent on the following factors: the extent and accessibility of the data sources, the accuracy of the GIS base data, and the type of system being modelled. Manual “cleaning” of the automated techniques must be anticipated to obtain usable results. The level of cleaning is directly related to care taken with input parameters and the required accuracy for the project. The automated techniques discussed if used correctly can significantly expedite the model build process.

ACKNOWLEDGEMENTS

AWT would like to acknowledge North Shore City council for the use of there GIS and terrain data used for most of the terrain processing discussed in this paper. We would also like to acknowledge Felix Pertziger at URS for his help over the past few years and vast knowledge of GIS grid based solutions.

REFERENCES


