CATCHMENT AND OVERLAND FLOW PATHWAY DELINEATION USING LIDAR AND GIS GRID BASED APPROACH IN URBAN STORMWATER AND SEWER NETWORK MODELS

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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 REQUIERMENTS

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.

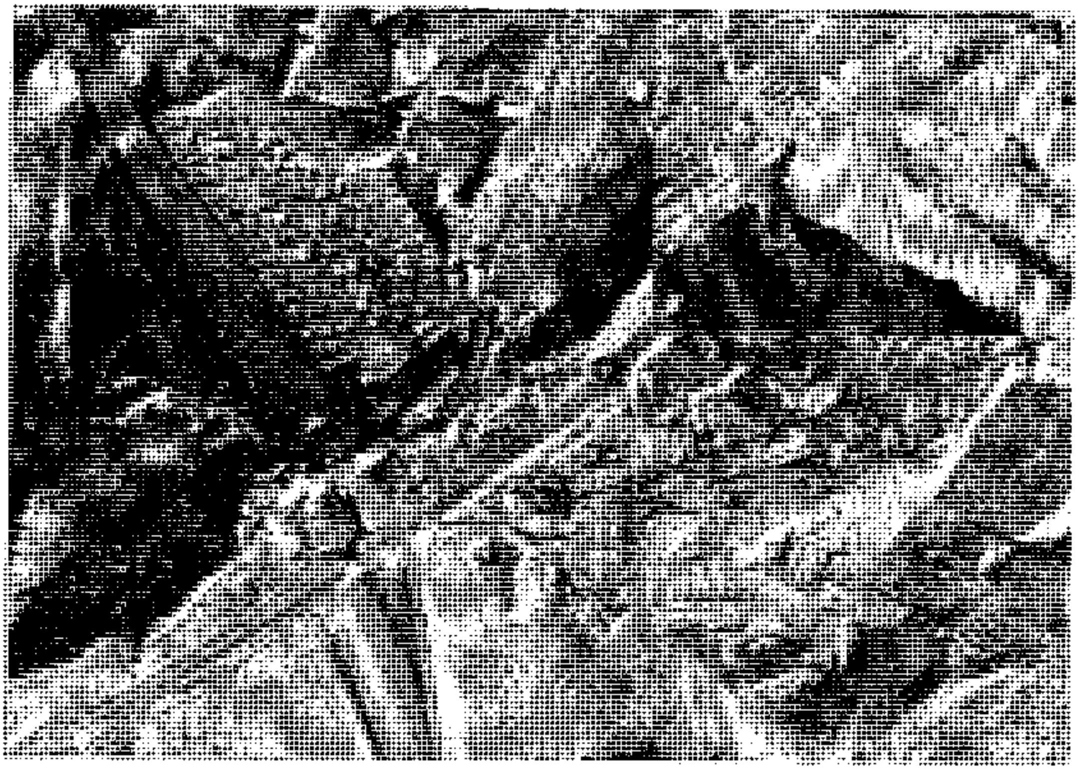
4 TERRAIN PREPROCESSING

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 Zeeland.

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. Filing 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.

Figure 4-2 Example of two flow directions grids using the in the eight-direction pour point model

Figure 4-2a Correct Flow Direction Grid

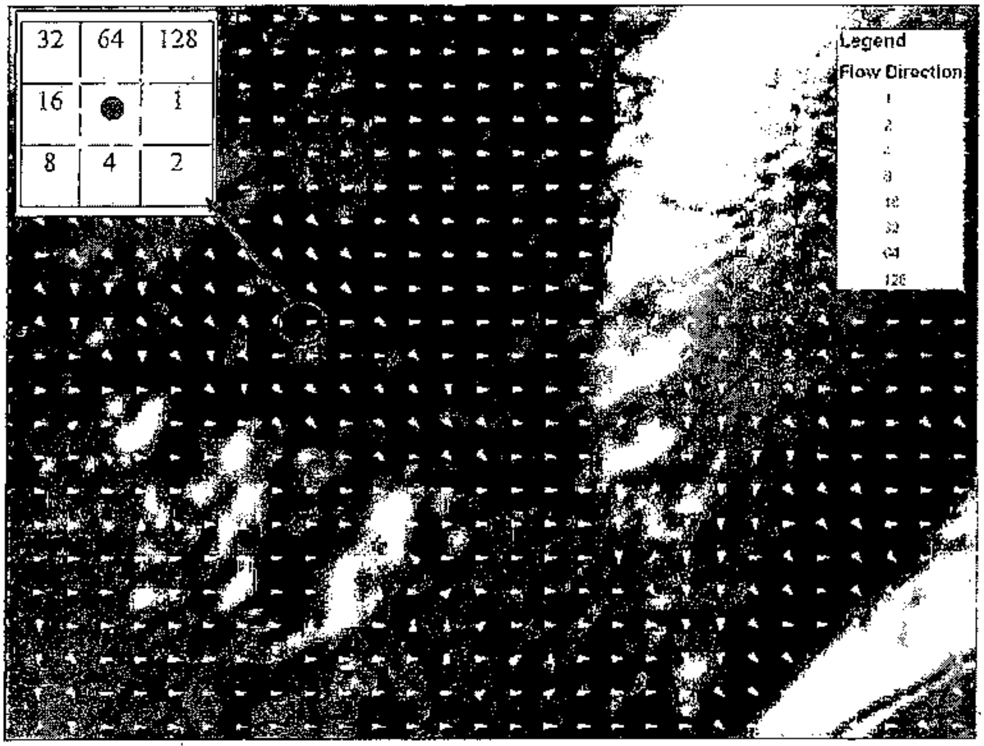
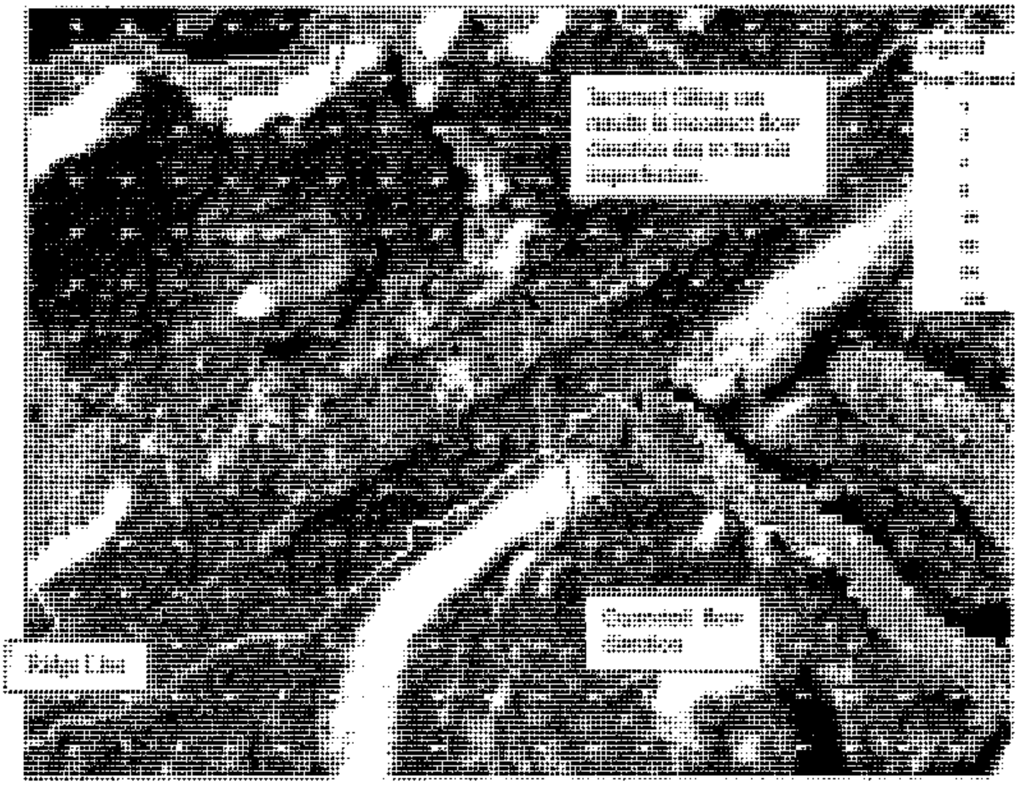


Figure 4-2b Incorrect Flow Direction Grid



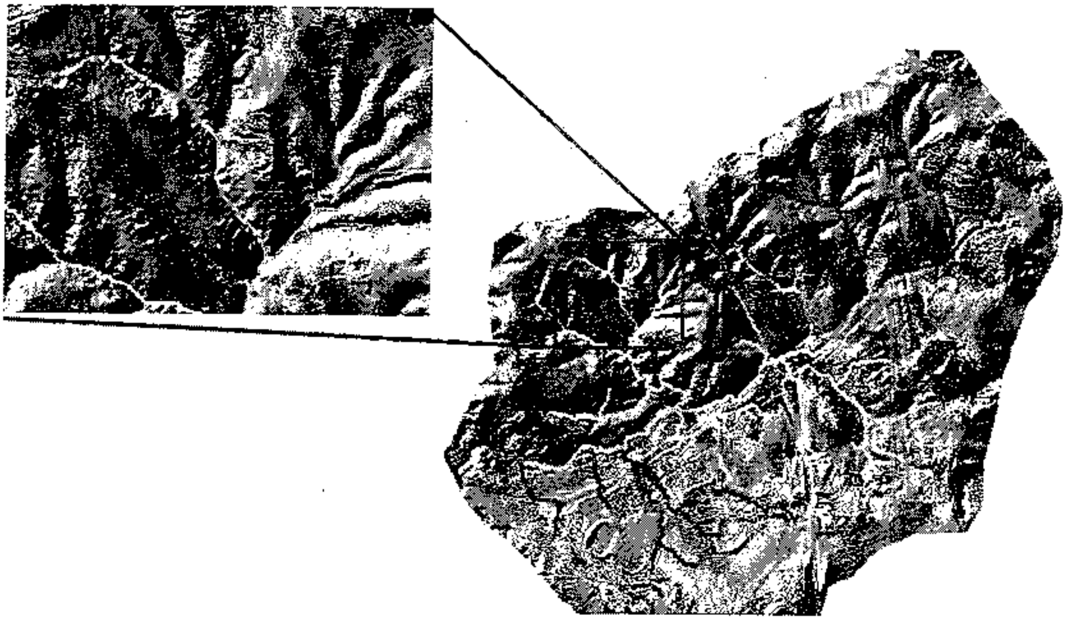
4.3 FLOW ACCUMULATION

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.

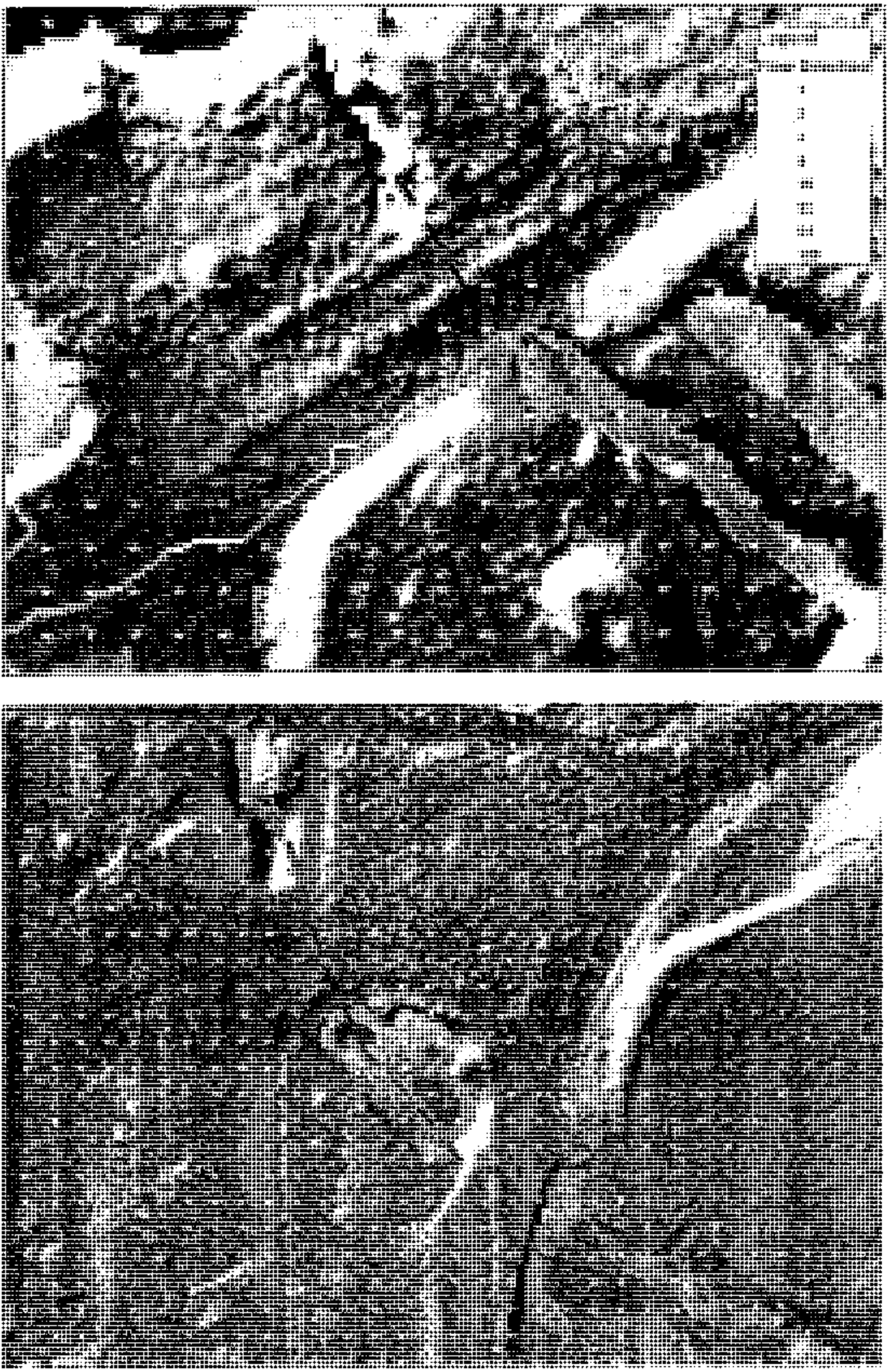
Figure 4-3 Stream definition grid



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

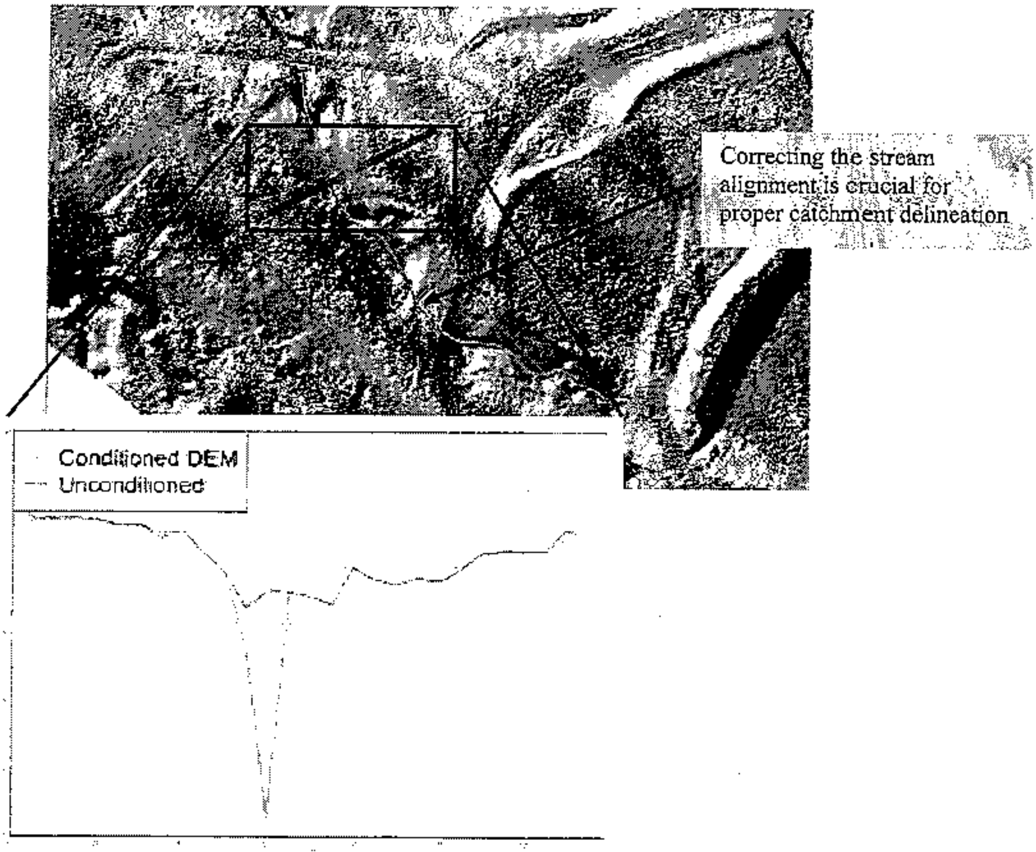


Reconditioning the DEM modifies the DEM by imposing liner features (corrected streams) onto it (sometimes referred to as burning and fencing). It was implemented using the AGREE method developed at Centre for Research in Water Resources at the University of Texas at Austin. Full reference to the procedure 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



Correcting the stream alignment is crucial for proper catchment delineation

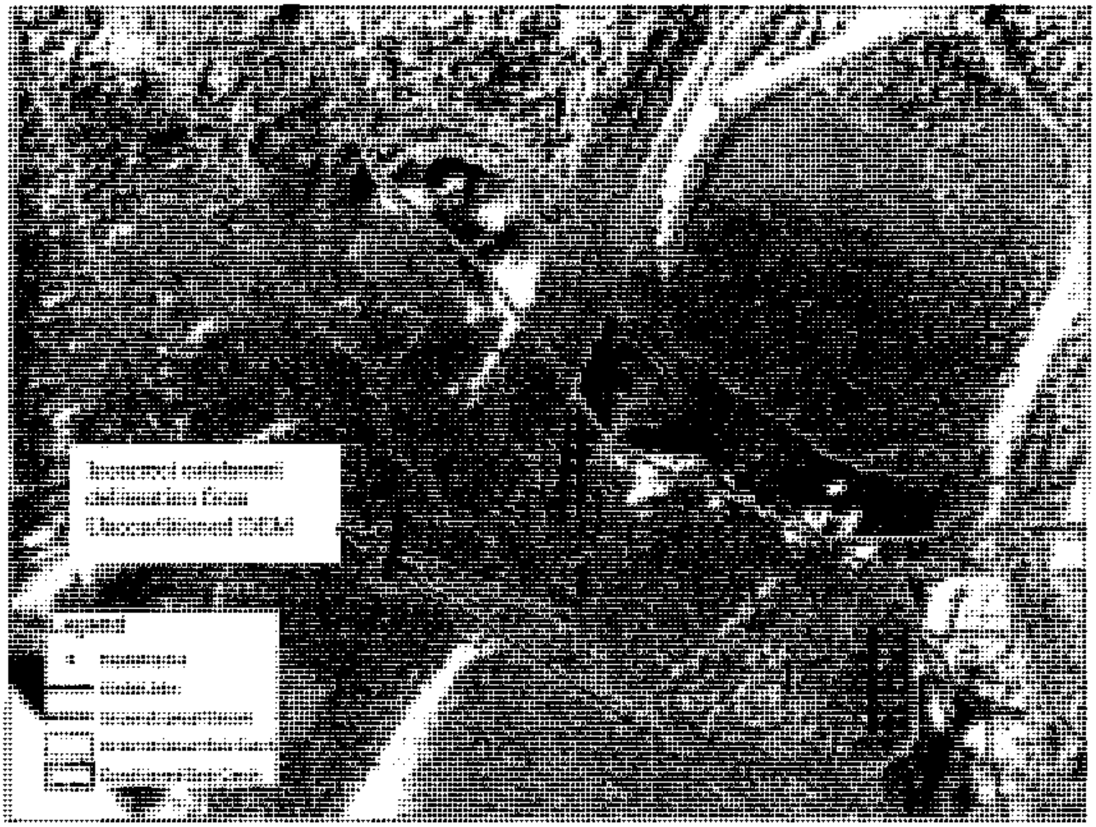
5 AUTOMATED CATCHEMNT DELINIATION METHODS

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.

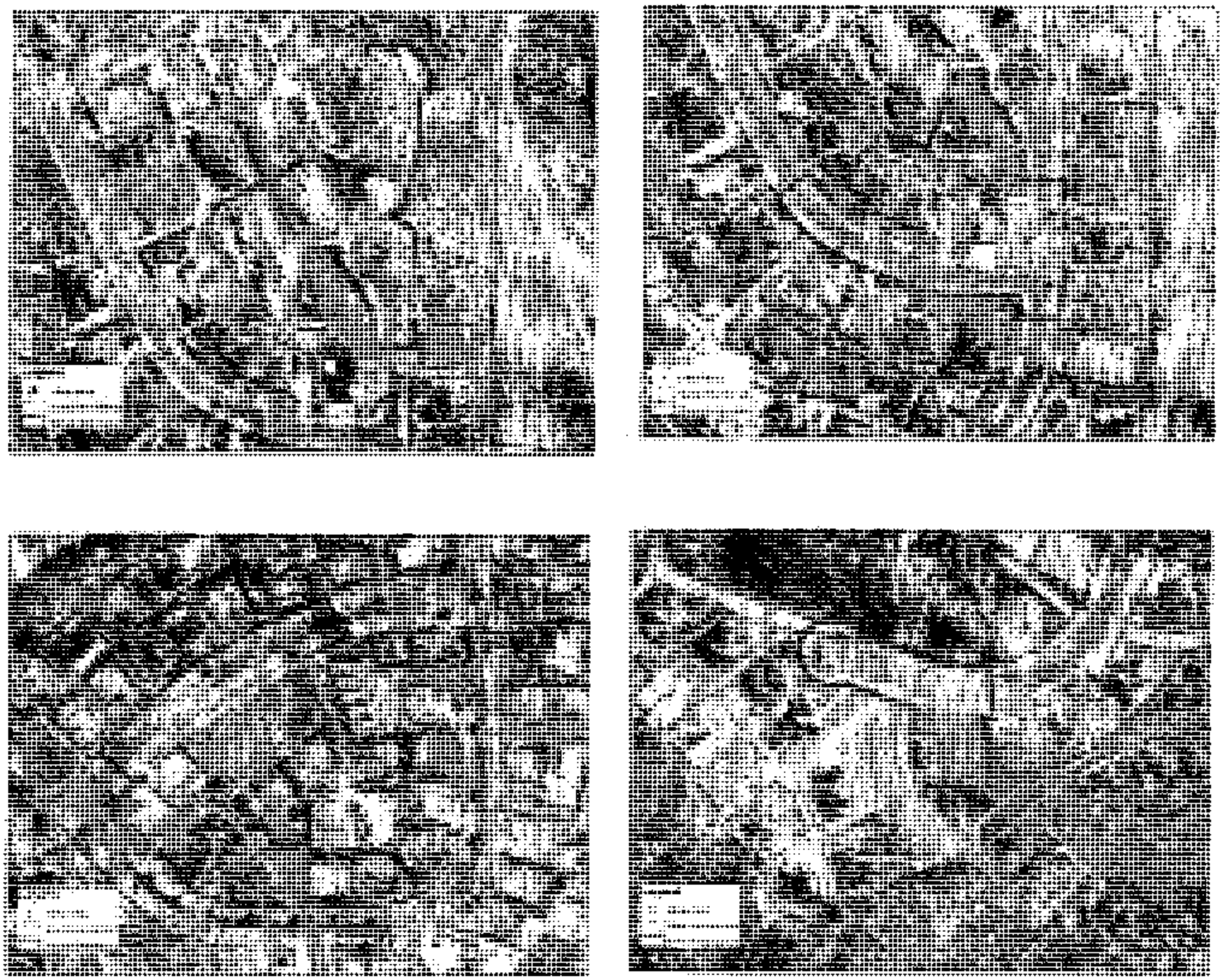
We have used the watershed method in several urban catchments and it has proven to be a very useful tool for automating catchment delineation in stormwater and combined systems. We have attempted to use this technique in sewer systems with less luck. This is due to the fact that the watershed method 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 then 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 TECHINUQUES

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 then the previous manual delineation.

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



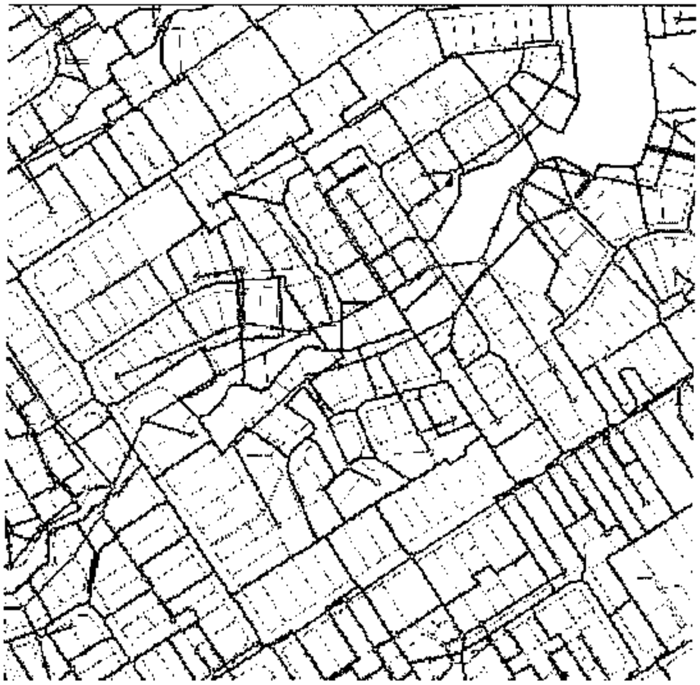
5.3 THE THIESSEN POLYGON PROXIMITY METHOD

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 there 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 lager 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 (MULITTIPLE 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

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DELINEATING DRAINAGE NETWORKS IN URBAN AREAS

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ABSTRACT

Urbanization alters the natural water cycle. One of urbanization's most significant effects is increasing impervious surface cover which reduces infiltration, increases runoff volume and rate, and decreases evapotranspiration. Effective management of urban stormwater runoff and water quality issues can only be accomplished once drainage area and flow networks are accurately identified. Typically, geospatial evaluation of hydrologic impacts begins with identification of water flow and watershed boundaries, applying assessment techniques based on those designed for natural landscapes. However, urban hydrology differs from that of natural environments and thus urban watersheds require innovative evaluation techniques.

This study identifies information gaps that originate from applications of standard geospatial techniques in urban hydrology. Delineation of a highly urbanized watershed in Fairfax County, Virginia was first accomplished using standard techniques. Next, using lidar data, the watershed was again delineated and both results compared. By overlaying both delineations on aerial photos and adding impervious surface and storm network layers, we identified regions redirecting the natural flow of water from the stream channel, then removed these regions from the watershed area. The results revealed a decrease in the watershed area by almost 17%, the natural watershed boundary was significantly altered, creating a much longer perimeter, and sink areas revealed.

These results support the hypothesis that delineations of urban watersheds differ from those in natural settings. Anthropocentric alterations to land cover and laudscape create a complex hydrology. The greatest complications are impervious surfaces and storm networks which redirect water flow.

KEY WORDS: urban, drainage networks, Lidar, GIS, Fairfax County, Virginia

INTRODUCTION

One of the most significant land use changes is conversion of rural to urban land — losses of agricultural and forested lands, coupled with increasing impervious surface cover (Deelstra and Girardet 2000; Pickett et al. 2001). Decreasing vegetative cover and increasing impervious surface cover have direct effects on natural temperature regulation (DeBusk et al. 2010; Geiger et al. 2003; Slonecker et al. 2001), alters the hydrologic cycle (DeBusk et al. 2010; Slonecker et al. 2001; Welker et al. 2010) and destroys habitats (Burton Jr. and Pitt 2002). The most significant effect of increasing urbanization is the creation of large areas of impervious surface cover which alters the natural water cycle. Alteration of the hydrologic cycle represents the most significant water quality issue present today (Civco et al. 2002; DeBusk et al. 2010; Slonecker et al. 2001).

The landscape change due to reduced vegetative cover and increased impervious surfaces has resulted in less infiltration, higher runoff volume and rate, declining groundwater tables, and decreased evapotranspiration (DeBusk et al. 2010; Welker et al. 2010). Stormwater runoff from impervious surfaces in urban regions creates water quality problems, including higher water temperatures and elevated levels of contaminants in surface waters (Davis et al. 2010; Slonecker et al. 2001; Welker et al. 2010). Stormwater runoff not only effects the water quality within a specific urban region but also vitiates downstream waterbodies (Bhaduri and Minner 2001). Water bodies experience changes from stormwater runoff with less than 10% impervious surface cover within its watershed (Center for Watershed Protection 2003). A better understanding of hydrologic impacts of urbanization is required as current best management practices implemented to address urban stormwater runoff are proving to be insufficient (Burton Jr. and Pitt 2002). Effective management of urban stormwater runoff and water quality issues can only be accomplished once drainage areas and flow networks in urban settings are better identified (Burton Jr. and Pitt 2002; McPherson and Schneider 1974).

On-the-ground surveys in an urban area produce a watershed boundary that is dissimilar to those of a natural watershed because they can account for grading and slope changes from impervious surfaces. However, such surveys cannot account for inflows or outflows of water due to storm network systems. In addition, in large urban areas, field surveys can be quite complex, expensive, and disruptive to daily human activities.

With the advent of GIS, extensive research has been accomplished in modeling water flow (Rodriguez et al. 2008). Typically, geospatial evaluation of hydrologic impacts begins with identification of overland water flow and watershed boundary areas, and application of evaluative techniques based on similar techniques used in natural landscapes (Rodriguez et al. 2003; Sample et al. 2001). However, urban hydrologic characteristics are unique -- quite unlike those of natural environments (Debo and Reese 2003; Kaufman et al. 2001; Rodriguez et al. 2003; Sample et al. 2001). Anthropogenic changes from grading land, and building impervious surfaces, along with storm sewer systems can direct water flows from one catchment area to another (McPherson and Schneider 1974).

Despite recognition by many researchers that storm networks and impervious surfaces have altered water flows in urban areas, and the need to include these and aerial photographs with raster based-delineations (Debo and Reese 2003; Kaufman et al. 2001), few researchers alter standard geospatial methods to delineate an urban watershed. We did locate methods which included storm networks into catchment identification within four articles on evaluating stormwater flow, however, each of these limited their applications (Table 1). One other researcher does advocate using Arc Hydro tools in such analyses (Johnson 2009), but "Arc Hydro describes natural water systems, not constructed" (Maidment 2002, p 8).

Table 1. Research including storm network systems in their identification of urban watershed boundaries

Author Year	Method
Sample et al. 2001	Gathered vector based data from an on-the-ground analysis for a 43 acre neighborhood.
Rodriguez et al. 2003	Used a land-based survey to delineate three specific catchment areas (between 18 and 180 hectares) and then added storm sewers to analyze water flow.
Lhomme et al. 2004	Established a DEM delineated flow path, overlaid the storm drainage system and calculated the change in flow path
Amaguchi et al. 2012	Vector-based urban landscape delineation and divided study area into city blocks to evaluate water flow within each block. Also split water flow into above surface and below surface, eventually all flowing into the river channel.

Our study approach addressed gaps in use of geospatial techniques in urban hydrology. We used geospatial technologies, vector and raster analysis along with aerial photos. We propose using these additional techniques for a complete evaluation in urban settings. Our final results demonstrate why using standard geospatial techniques for watershed and water flow identification used in natural areas are insufficient in urban environments.

A case study for a small urban watershed in Fairfax County, Virginia illustrates the value of applying different methods to delineate the watershed and flow network, and forms the basis for comparative analysis. We included additional information, such as the storm drainage network, high-resolution aerial photos, and slopes and aspects of impervious surfaces to this analysis. Alterations of the watershed will be demonstrated and discussed. Finally, we will identify additional processes necessary to validate the inclusion of this additional information in adequately delineating an urban watershed and its flow network.

STUDY AREA

The Flatlick Branch of the Cub Run watershed in Fairfax County, Virginia is our study site. This stream and watershed are located in the extensively urbanized northern Virginia area, just outside of Washington, D.C. Specifically, the stream is in northwestern Fairfax County, very close to Washington Dulles International Airport (Figure 1). Land use in the watershed is generally single-family residential, with smaller areas of commercial land uses, a golf course, and dispersed forest patches.

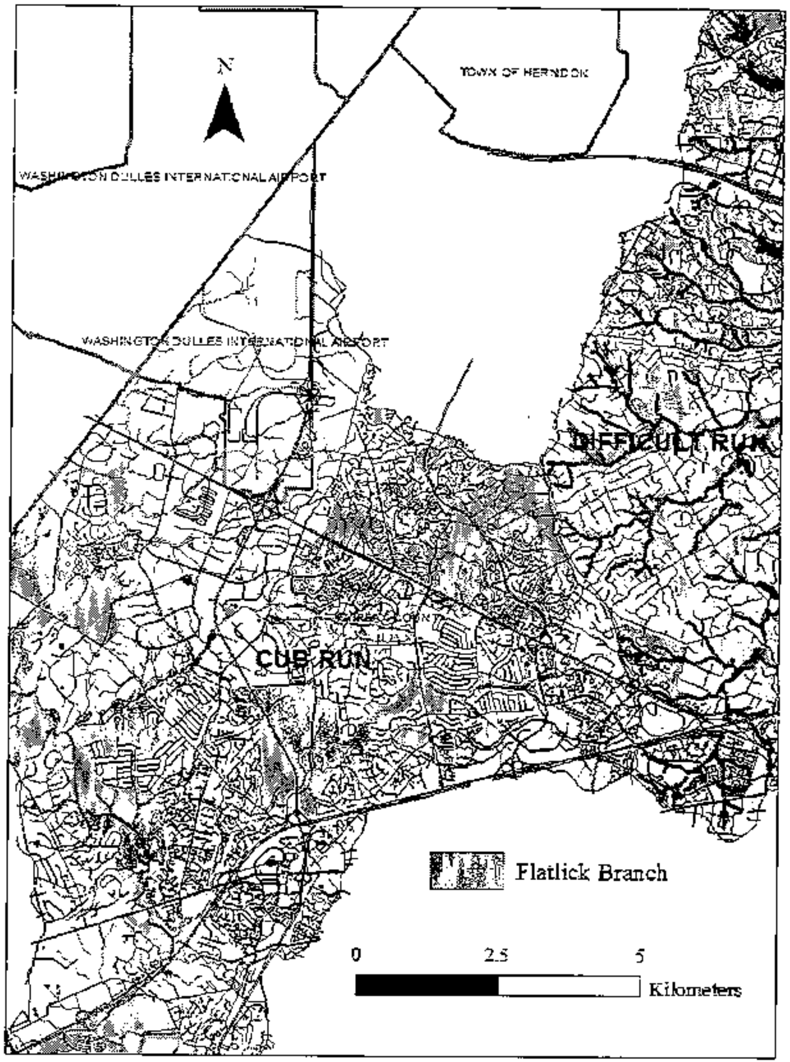


Figure 1. Location of Flatlick Branch of the Cub Run Stream, Fairfax County, VA

Extensive data is available for Fairfax County watersheds, as the U.S.G.S. has numerous streams gauged in this area for water quantity and quality assessments. The U.S.G.S. office in Richmond, Virginia provided the data used in this analysis:

- natural color aerial photos at ½ foot resolution, acquired in 2009;
- an elevation model generated from lidar with 1x1 meter resolution, acquired in 2009;
- Fairfax County field documented stream channels in a GIS shapefile, completed in 2008 (Figure 2);
- U.S.G.S watershed map, digitized after hand delineation from a topo map in a GIS shapefile (Figure 2);
- shapefile for the location of the U.S.G.S. Flatlick Branch stream gage, installed in 2007; and
- shapefiles for all known or surveyed stormwater pipes, drains (manholes and curbside), and retention ponds for Fairfax County, completed in 2005.

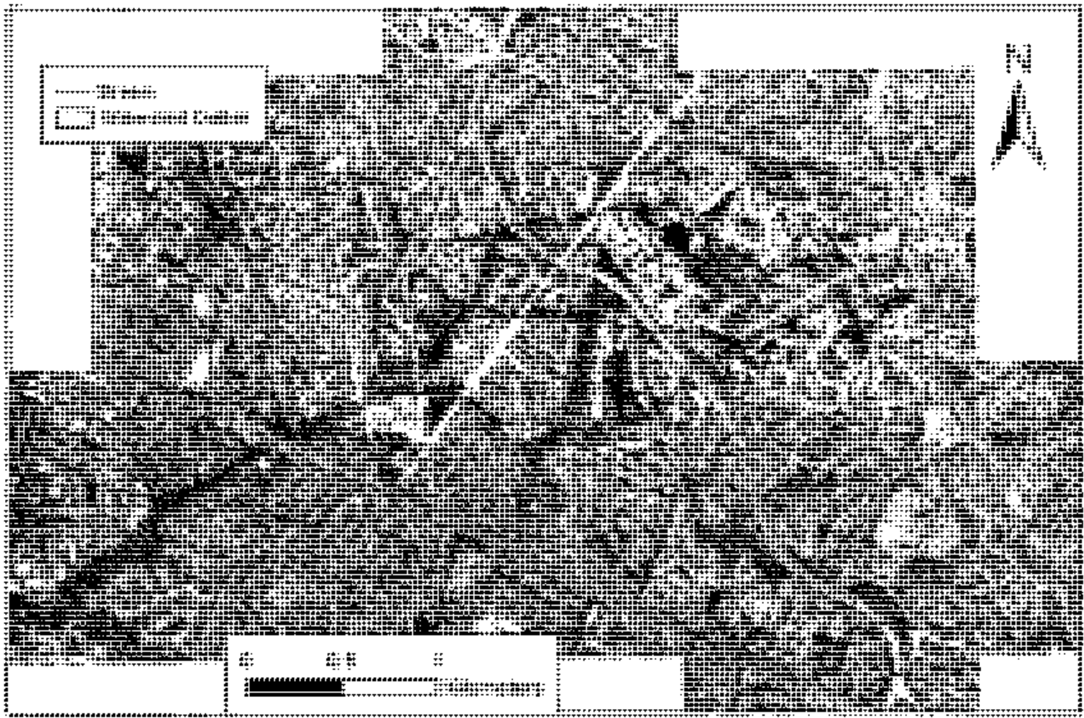


Figure [illegible]. The U.S.G.S. delineated watershed (red boundary) and field-documented stream channels (in blue) of the Flatlick Branch, overlaid on aerial photos.

METHODS

Our methods were simple and straight forward. We used the spatial analysis hydrology tools in GIS to delineate the watershed and flow accumulation network from the lidar elevation model using the U.S.G.S. station gage as the pourpoint. We wished to compare this to the U.S.G.S. watershed to determine which watershed model would be the best to use within our analysis.

According to the flow accumulation network, runoff from all the land area within the watershed should ultimately flow into the original pourpoint (the U.S.G.S. stream gage location). So for the next step of our analysis, we overlaid the storm network shapefiles on the watershed, contour lines generated from the lidar elevation model, stream channel shapefile, and surface flow network to evaluate how the storm networks would influence or impact water flow within the watershed area. We were specifically looking for three situations:

1) storm networks that do not connect to surface drainageways, thus are not part of the "naturally" delineated watershed and act as isolated catchment areas;
2) storm pipes that discharge outside the watershed (de facto decrease in drainage area); and
3) storm pipes that drain into the watershed (de facto addition to drainage area).

Additionally, we overlaid the storm networks on the aerial photos to confirm the three above situations.

For the final step of our analysis, we identified the land area that was drained by the above three situations, and thus either removed land area or added land area to the watershed delineation.

RESULTS

Figure 3 shows results of delineating the watershed from the lidar elevation model. Overlaying the U.S.G.S. watershed (green outline) on the lidar image reveals that the watershed shapes are very similar but also reveals the impact of roads and other impervious surfaces -- sharpening some of the edges of the lidar watershed. The area in hectares is very similar – 1089 for the U.S.G.S. and 1086.6 for the lidar elevation model. However, we felt that the lidar watershed was the most appropriate to use in the next two steps of our analysis, as it appears to include the influence of impervious surfaces in some areas of the watershed delineation.

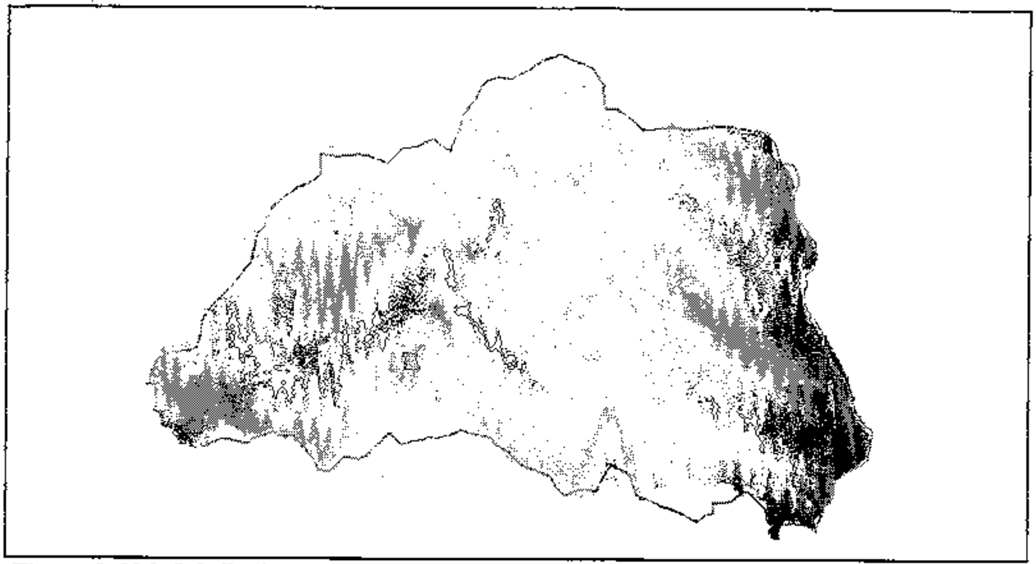


Figure 3. U.S.G.S. Delineated watershed (green outline) overlaid on the lidar elevation model

When overlaying the storm network shapefiles on the lidar elevation model, we indeed identified several areas that met each of the criteria of step two: 1) storm network facilities isolated from the stream network (Figure 4), including retention ponds either not located on water flow channels or connected only to each other by storm network pipes (Figure 5); 2) storm pipes that discharge outside the watershed; and 3) storm pipes that drain into the watershed area.

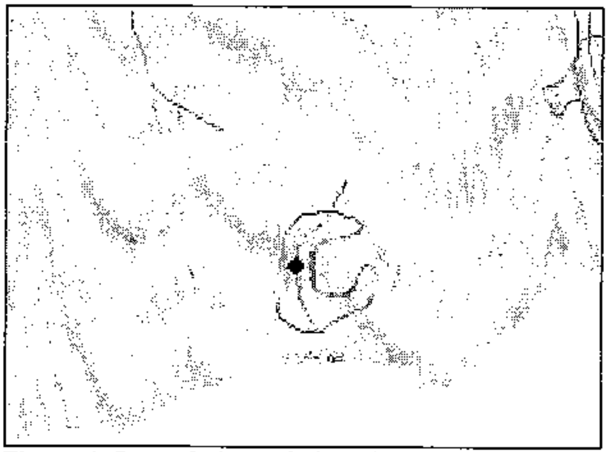


Figure 4. Storm drains and pipes designed to drain land area into a retention pond and not into the stream channel

Figure 5. Retention ponds connected to each other and not to the stream channel

We overlaid storm network files on the aerial photos and performed a visual examination to confirm our findings. We confirmed our discoveries, and in some instances identified storm networks designed to drain into a retention pond and not into the stream (Figure 6 – orange oval). In other cases, we discovered that the storm drain pipes actually connected two unconnected stream channels and then directed water flow into a buffer zone around the stream (Figure 6 – fuchsia rectangle). We also discovered that, for some locales where the storm pipes cross the watershed boundary, we could not determine the direction of the water flow (into or out of the watershed).

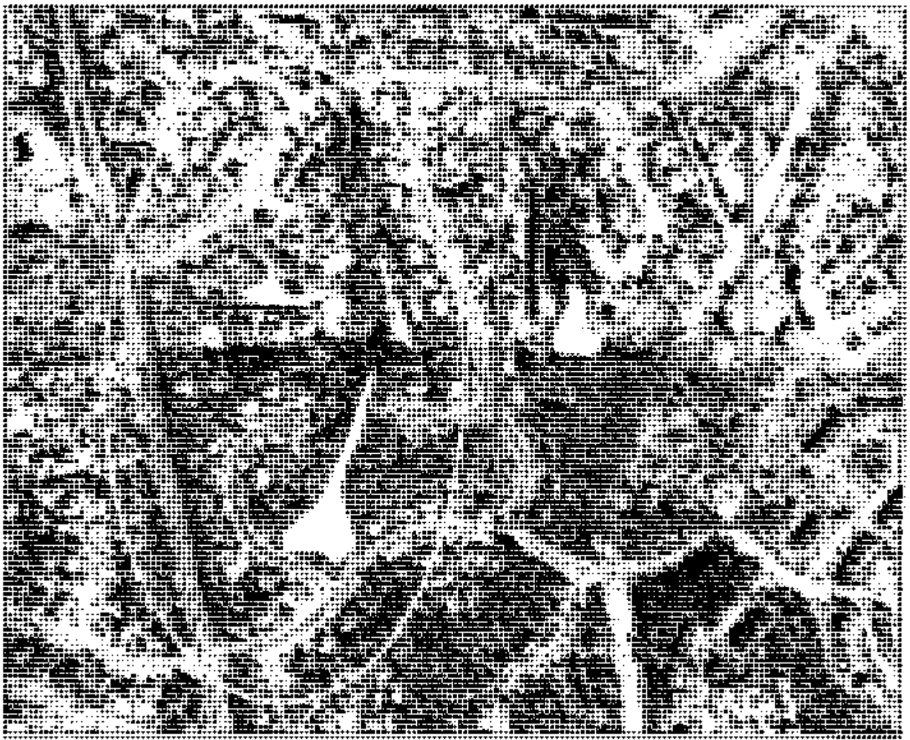
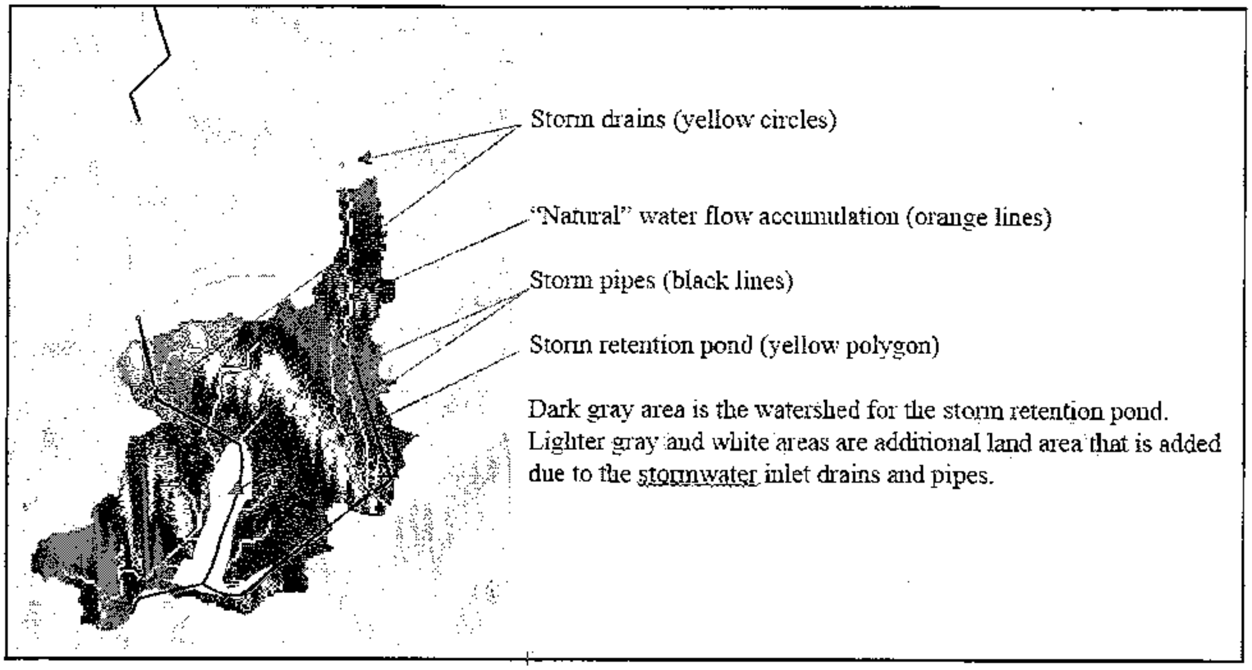


Figure 6. Isolated storm networks and retention ponds (orange area), a stream channel and storm pipes (yellow lines) that direct water flow into a storm retention pond. An area where storm drain pipes actually connected disconnected stream channels to the main stream channel (fuchsia rectangle).

After our overlay evaluations, we were left with 24 areas of water flow disconnected from the stream channel because of the storm network facilities. Some areas were clearly visible on the lidar elevation model as separate catchment areas (please refer back to Figure 4 - darker colors represent higher elevations, thus watershed divides). As such, we designated these isolated retention ponds as "sink" areas and used these locations as pourpoints. With the watershed delineation tool, we were able identify the land area drained by these storm network facilities and thus not included in the Flatlick Branch's "natural" watershed.

In several areas identified in the last two steps, impervious surfaces or drainage pipes brought additional water flow into the retention ponds -- in some cases with storm water inlets and in other areas by the grading of impervious surfaces. So after we identified the initial land area that drained into these retention ponds, we had to add the additional land areas served by the storm water inlets (for example Figure 7).

In Figure 7, the yellow polygon area is the storm network retention pond, the small yellow circles are the stormwater inlets (curbside drains and manholes), the black lines are the storm network pipes, and the orange lines represent the "natural" flow accumulation layer generated by GIS. The dark gray area is the watershed delineated for this retention pond. The stormwater inlets (yellow circles) were clearly installed at stormwater flow locations as they are placed directly on the flow accumulation. The storm network pipes tie directly into these drains to allow stormwater flow straight into the stormwater retention pond. Since we needed to pick up the additional land area covered by these flows, we used the stormwater inlets as additional pour points. The land areas in white and lighter gray represent the additional land area that drains into this retention pond.



Dark gray area is the watershed for the storm retention pond. Lighter gray and white areas are additional land area that is added due to the stormwater inlet drains and pipes.

Figure 7. Storm drain pipes adding additional land area to the retention pond's watershed

We conducted this delineation for all isolated storm network facilities within the watershed, each time checking our decision against the elevation model, contour lines, and aerial photos. The total area of these independent catchment areas (delineated for the storm network facilities isolated from the stream channel) is 162.4 hectares, and constitute locations to be subtracted from the Flatlick Branch watershed.

In addition, we identified 94 locations where stormwater inlets were connected to pipes crossing the watershed boundary (for an example see Figure 8). We carefully examined each location with the elevation model, contour lines, and aerial photos. Some of these areas clearly drained additional land area into the stream and some drained land into areas outside of the watershed.

Figure 8. Blue lines and polygons represent storm network pipes and facilities. Within the red outlines are examples of storm network areas that cross the lidar watershed delineated boundary

We determined that 32 stormwater inlets outside of the watershed boundary were connected to pipes that added stormwater flow into the watershed, thus adding land area. We also determined that 41 stormwater inlets inside the watershed boundary were connected to pipes that removed stormwater flow from the watershed, thereby removing land area from the drainage basin. The remaining locations of storm network pipes that crossed the watershed boundary had no impact as they were already removed from the watershed when we identified the individual catchment areas (see above paragraphs on isolated catchment areas). For each of these 73 inlets, the watershed delineation tool was used to identify the land areas drained by them. Again, with each delineation, we examined the elevation model, contour lines, and aerial photos to confirm the accuracy of our results. These areas were either added or subtracted from the lidar delineation as appropriate.

Figure 9 represents our final watershed overlaid with the boundary of the lidar delineation. The lidar watershed area was 1086.6 hectares. After adding and removing land area throughout this analysis, the area is 902.4 hectares, a difference of 16.9 percent. More important than total watershed land area, is the alteration of the watershed boundaries; boundaries determine the actual land area necessary for stormwater management and other best management practices related to urban water quality.

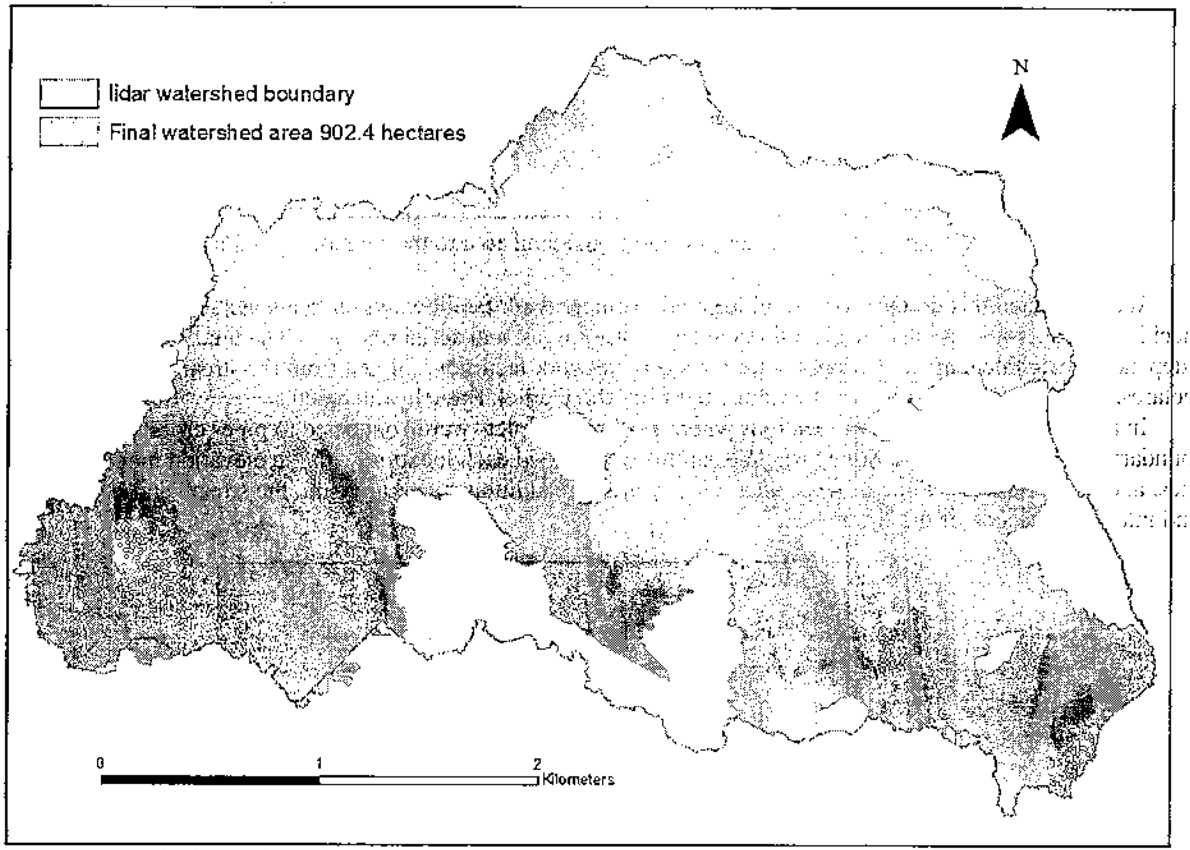


Figure 9. Watershed area (green) after removal of catchment areas delineated from storm network facilities, pipes, and inlets, and adding additional land areas contributing water flow from outside the original watershed boundary.

Some areas of the watershed still need field analysis. In several locations, the watershed boundary crossed over rooftops, both flat commercial buildings and angular roofs of residential buildings. Each building would need to be evaluated for their management of stormwater flow from the rooftops and the direction of this flow. In addition, it is not clear from the storm network shapefiles whether or not one specific area actually added or removed land area from the watershed (Figure 8 – the northwest-pointing U-shaped storm facilities, which represent a parking lot). We were unable to address this specific area within our remote geospatial analysis. We further note that additions and subtractions to the area of the watershed caused by mis-definition of watershed boundaries not only alters the size of catchment, but also, by adding and subtracting different land uses, can alter the hydrologic character of the watershed, further misrepresenting the its nature.

CONCLUSIONS

One meter resolution lidar delineation of a watershed only slightly changed the delineation based upon the U.S.G.S. manual interpretation using a topographic map. The difference in area was only 2.6 hectares. For those locales, with physical characteristic similar to the Cub Run watershed, that do not have lidar available, this result demonstrates very little difference between 10 x 10 meter and 1 x 1 meter resolution elevation models. Thus, lidar may not be a requirement for urban watershed delineation.

Actual boundary differences were more pronounced and may have more influence on the actual water flow in an urban area. The lidar delineated watershed appeared to provide a better account of impervious surfaces than did the U.S.G.S. model. The lidar resolution, at only 1 x 1 meter, was based on final returns of the lidar for the surface elevation. However, neither delineation accounted for additions or subtractions from the watershed resulting from storm network inlets (curbside drains and manholes), pipes, and retention facilities. After subtracting isolated networks from the watershed, the area decreased by almost 17%.

This GIS analysis has supported the original contention that using GIS to delineating watersheds in urban areas is not as simple as it is in natural settings, and that anthropocentric alterations to land cover and landscape create complex hydrologic geometries. The greatest complications are storm sewer networks and impervious surfaces, which are designed to redirect water flow. With the storm drain networks, lidar and high resolution aerial photography, GIS can include this data in delineating the watersheds. However, despite the ability to include the storm networks in GIS analysis, impervious surfaces interfere with use of the hydrology toolset and thus ground assessment may be necessary. Relationships between natural and built drainage systems also require further evaluation. Individual catchments identified are locations that would be amendable to greenspaces, such as urban agriculture, as these catchments can provide a source of water for plant life. In addition, these individual catchments, in the form of stormwater retention facilities, should assist in groundwater recharge in urban areas.

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