GIS APPLICATIONS IN URBAN DRAINAGE MASTER PLANNING

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ABSTRACT: In recent years, GIS applications in water resources management have become widespread and diverse in the Province of Ontario, Canada. Application areas include urban infrastructure master planning for storm and sanitary drainage systems, water distribution, watershed planning, and regional groundwater protection. This development has occurred despite the challenge faced by users that base data (e.g., DEM's) is not as readily available as in other jurisdictions in North America. Recent applications include aspects of i) *data management* - reviewing and editing of catchment and infrastructure data for hydraulic simulation models such as XP-SWMM and EPANET, ii) *analysis* - using custom applications developed for water balance analysis, or using core GIS functions such as geoprocessing, surface modelling and hydrologic analysis of major drainage systems within ESRI's Spatial Analyst extension, and iii) *presentation* – sharing study findings with clients, colleagues and the public using thematic mapping and 3-dimensional models. These aspects are presented in a case study "City of Stratford, City-Wide Storm System Master Plan", currently being completed on behalf of the City. The study reveals GIS to be as an indispensable, multi-purpose tool for infrastructure master planning that enables sophisticated desktop analyses, efficient simulation model pre- and post-processing, and effective data management and communication, all through the use of intrinsic functionality and readily available on-line utilities.

INTRODUCTION

Since the mid-1990's, the prevalence and diversity of GIS applications in water resources management in Ontario has increased considerably, such that the use of GIS technology for data management, analysis, and presentation has evolved from a specialty service to an established, core service offered by many engineering consultants, municipalities and public agencies. This evolution may be attributed to the availability of continually advanced desktop software tools and an increasing amount of spatial data being established and maintained to support infrastructure planning and other municipal and resource management applications.

The City of Stratford, Ontario, located 150 km (94 mi.) west of Toronto, initiated the development of an infrastructure asset database in the early 1990's and continues to develop digital mapping to support the maintenance and management of municipal services. In continuing these efforts, the City initiated the City-Wide Storm System Master Plan (the Study) in 2002 to evaluate the impact of current and future development on the existing storm drainage system. The Study Area, illustrated on Figure 1, encompasses 27 sq.km (11 sq.mi) of land within the City's boundaries, as well as external lands that drain into the City's drainage systems. Given Provincial regulatory requirements for Environmental Assessment, public and agency consultation was a key Study activity, requiring the presentation of findings and recommendations at Open House's and City Council meetings throughout the study. An aggressive schedule was imposed in light of recent basement flooding that had heightened the need to identify any possible system improvements and assuage public concerns.

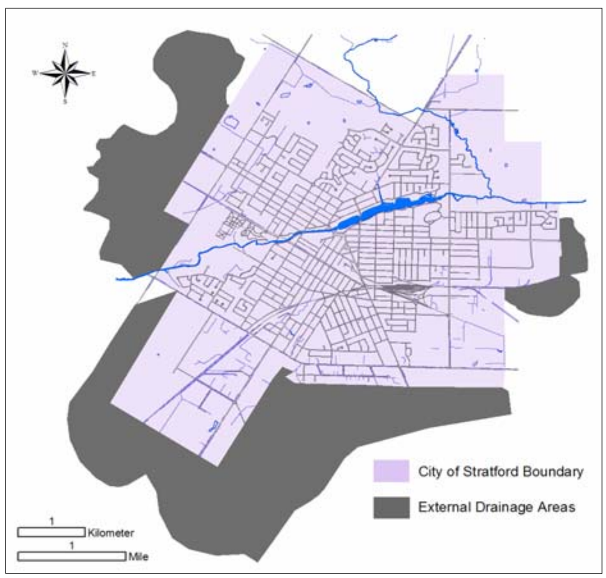

Figure 1 - Master Drainage Plan Study Area

The use of GIS, while not a requirement of the Study, was proposed as the ideal tool to not only efficiently address

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immediate Study requirements, but also to provide additional long-term benefits to the City - examples of this include i) the development of pre- and post-model GIS layers of infrastructure features that can be later used to advance asset management initiatives and to increase accessibility to consolidated hydraulic model results, and ii) the development of a Digital Elevation Model (DEM) for major drainage analysis that can be used for numerous visualization and analysis applications.

The following sections describe how GIS was used throughout the Study including data collection, management, and analysis activities conducted as part of the minor drainage system model development, surface analysis conducted as part of the major drainage system assessment, and the presentation of both data and analysis to communicate Study findings.

MINOR DRAINAGE SYSTEM MODEL DEVELOPMENT

The City storm sewer system is comprised of over 157 km (98 mi) of pipe, of which 48 km (30 mi) is 600 mm (24 in) in diameter or greater, and was assessed as part of the Study. Total station surveys for just under 20% of the system were completed prior to the Study, by the City, and these results were made available in AutoCAD plan and profile drawings. Digitized plans of the overall storm sewer network schematic and trunk sewer boundaries were available in a geo-referenced GIS format - despite having limited attributes and horizontal accuracy, these provided valuable guidance on catchment areas and system configuration. In addition, the network schematic incorporated a manhole numbering nomenclature developed as part of previous asset management activities, and this standard was adopted to provide the primary index for system features.

The City had selected the XP-SWMM modelling package for hydrologic and hydraulic analysis of its sanitary and storm sewer systems. The model was deemed to be appropriate considering the complex system hydraulics. XP-SWMM uses a node-link data model to represent the drainage system, whereby links represent conveyance elements such as sewer pipes, channel reaches or culvert and nodes represent manholes/catchments, junctions, outfalls or other physical transition points along the links. With the exception of irregular geometry features, the majority of node-link data may be readily imported into XP-SWMM using database import utilities (XP-GIS).

A data management approach was developed in which consolidated point and polyline shapefiles would be developed to compile existing and future sewer survey data, and which would be used as the basis for importing hydraulic node-link data into XP-SWMM. These files would be supplemented with additional hydraulic features (e.g., polylines for natural channel reaches, points for sewer and channel junctions) and hydraulic modelling attributes. As such, the consolidated model input layers would represent more than the typical hydraulic features in the City's infrastructure database. Additional special features would be added only directly into XP-SWMM.

XP-SWMM Hydrology Model Development

The XP-SWMM Hydrology Module is generally equivalent to the EPA SWMM Runoff block, generating nodal inflow hydrographs to the Hydraulic Module based on typical catchment parameters affecting runoff volumes (area, imperviousness or land cover, depression storage), and those affecting runoff rates (slope, width, roughness or time of concentration). The EPA SWMM Runoff hydrology method using the non-linear reservoir runoff routing method and the SCS hydrograph method were used for urbanized catchments and rural/open use catchments, respectively.

Recently obtained 15 cm (6 in.) resolution black and white orthophotos of the Study Area, and previous AutoCAD base mapping of topographic features were available from the City and were used as the basis for many derived hydrology shapefiles, GRIDs, and TIN surfaces as described below. The vector base mapping included 0.5 m (1.6 ft) interval elevation contours and spot elevations (0.1 m (4 in.) accuracy).

Catchment Impervious Percentage

In addition to being a primary simulation model parameter, the percentage impervious of catchments was recognized as a key factor affecting traditional design runoff coefficients. Designers of the City storm sewer had in the past relied on the rational method calculations using accepted design values for runoff coefficients. A review of these standards was requested by the City to address the suitability of these values in light of current development conditions.

An exploratory review of the vector base mapping and orthophoto in ESRI's ArcGIS suggested that the orthophoto could be reclassified to distinguish impervious and impervious surfaces simply by radiance. While paved roadway, sidewalk and driveway surfaces were consistently bright and could be readily distinguished from vegetated surfaces (lawns, boulevards, parkland), impervious rooftop areas could not, given the variability in shingle colour and shading which was greatly influenced by the varied orientation and pitch of residential rooftops. Recognizing the hydrologic significance of rooftop areas, and to address this deficiency, rooftop areas were essentially 'hard wired' into the initially reclassified impervious raster GRID.

A series of downloaded Avenue scripts were employed in ArcView 3.3 to convert the available building outline polylines to an equivalent GRID by first closing the building polylines (snapping), and then converting closed polylines to polygons. Polygons were converted to a GRID in Spatial Analyst (ArcGIS 8.3) and integrated with the initial impervious GRID using the Raster Calculator. As final impervious and pervious GRID cells were assigned values of 1 and 0 respectively, the mean statistic for minor system catchments 'zones' provided the average impervious value for the simulation. Results for the southern portion of the City (Figure 2), show both the detailed 15 cm GRID classification (insert upper left) and the composite catchment values. The analysis was found to be accurate in most instances, discerning even the variability in residential catchments due to property lot depth. Manual corrections were found to be required only in areas with a high proportion of open fields where impervious coverage had been overestimated.

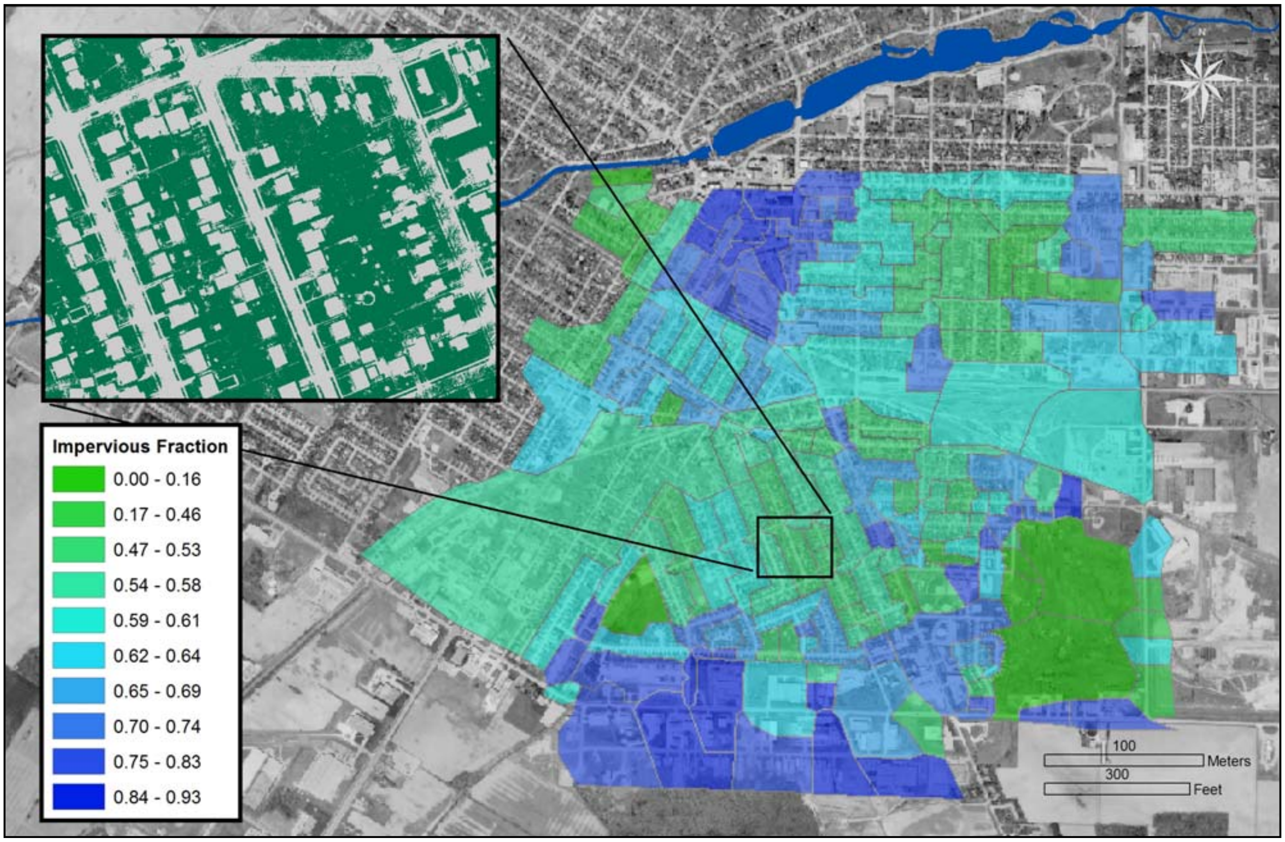

Figure 2 – Weighted Catchment Impervious Fraction and Orthophoto Raster Impervious Classification (inset)

Catchment Slope

Urban catchment slopes were known to vary considerably based on a catchment's proximity to the Avon River valley, which bisects the Study Area. To determine representative parameter values, a mean zonal statistic approach was pursued similar to the impervious classification method above.

The AutoCAD elevation contours and spot elevations were used as the basis for creating the DEM GRID. A series of on-line Avenue scripts and Spatial Analyst functions were used to create a DEM for the study area, from which a slope value GRID was calculated for the zonal analysis. The AutoCAD elevation layers were first converted to shapefiles using Avenue scripts and were converted from their original NAD27 to the current NAD83 datum using ArcGIS. Avenue extensions for polyline generalization (weeding) and polyline to vertex-point conversion were applied to the contours and resulting vertices were then added to the spot elevation points. This composite point shapefile was used to create an elevation surface through kriging analysis in Spatial Analyst. The resulting DEM GRID is shown in Figure 3 and average catchment slopes are shown in Figure 4.

Minor System Catchment Areas and Widths

The minor system catchment boundaries for moderate intensity design events are determined largely by the storm sewer layout and lot patterns, but are also influenced by ground surface elevations, especially in open areas. To consider all of

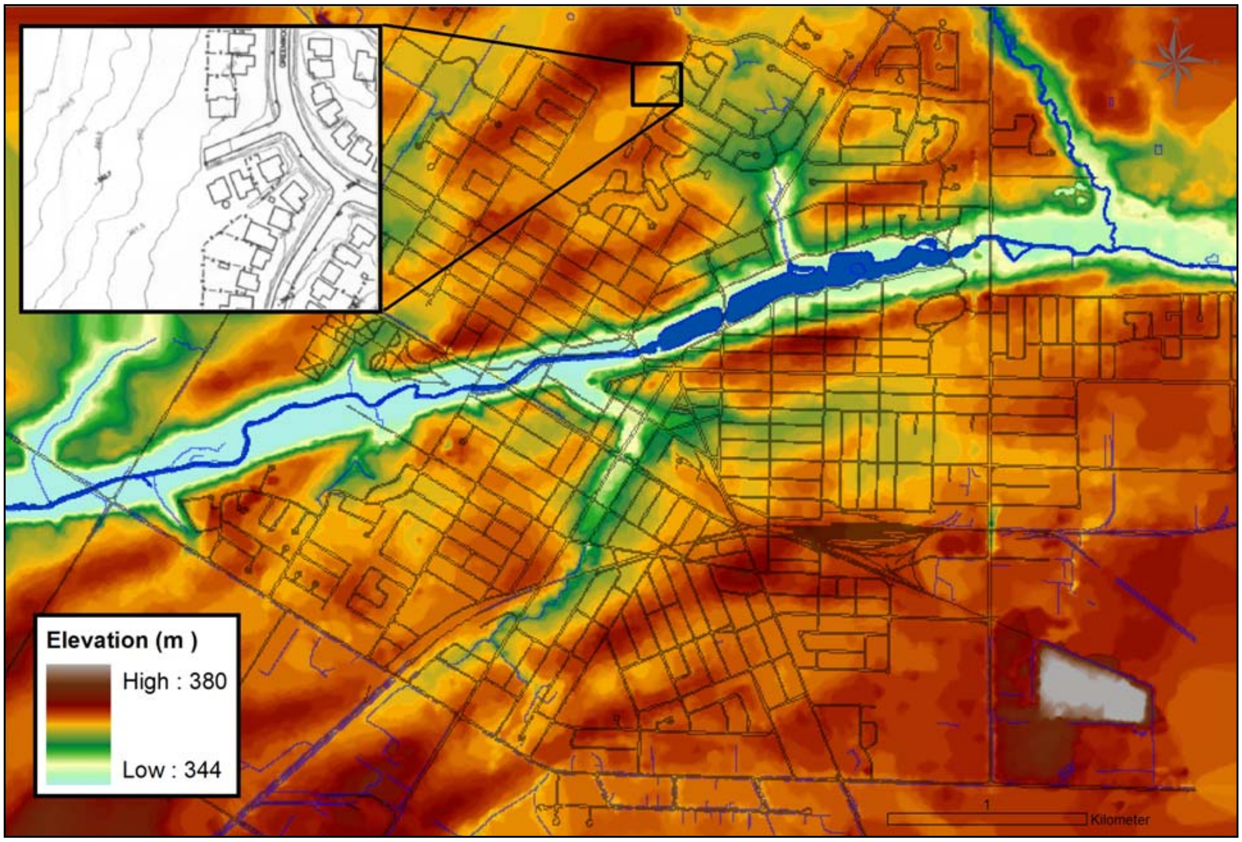

Figure 3 - Derived Digital Elevation Model and Source Vector Base Mapping (inset)

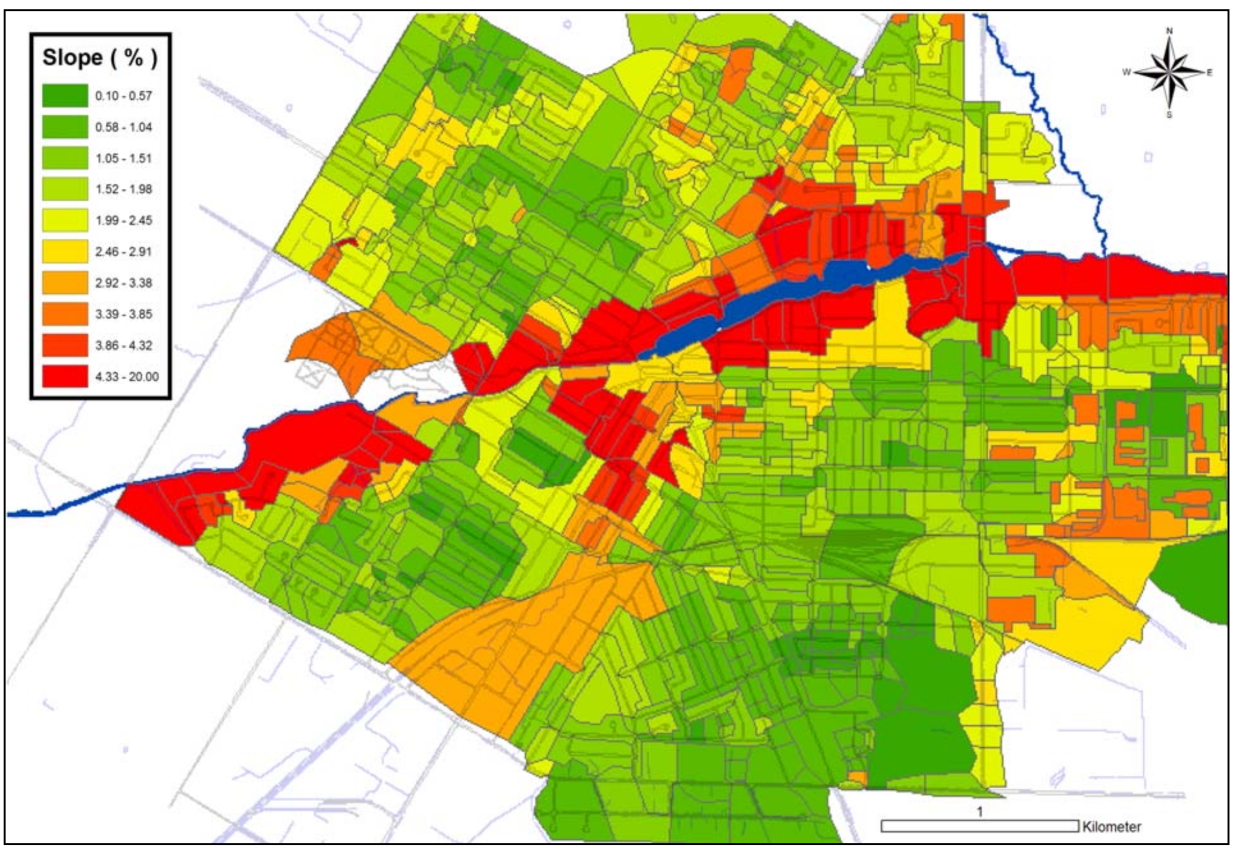

Figure 4 - Minor System Average Catchment Slopes (urban areas)

these factors, 'heads-up' digitizing of most polygon boundaries were completed in ArcMap using a multitude of reference layers including the sewer network schematic, building, fence line and property base layers, the orthophoto, and a transparent DEM GRID. In areas with extensive industrial-commercial-institutional (ICI) uses, building complexes with large flat rooftop areas were also digitized, as known site stormwater management controls were modelled discretely in XP-SWMM. Catchment areas were calculated in ArcMap using VB scripts obtained on-line through ESRI. Initial catchment widths were estimated based on catchment areas and were subsequently adjusted considering model flow calibration to monitoring results obtained through the course of the Study.

XP-SWMM Hydraulic Model Development

The XP-SWMM hydraulic module, generally equivalent to the EPA SWMM Extran block, completes the complex hydraulic routing of generated hydrographs through the drainage system. This module predicts hydraulic grade line elevations (HGL's) under various design flow conditions that are used to assess overall system performance and flooding potential. Extensive surveying of the closed conduit and open channel drainage features was required to obtain basic hydraulic characteristics including cross section dimensions, inverts, and material. Radical changes in cross section between single manholes were sometimes found, necessitating confined space entry to large trunk arch sewers that were aligned under private properties, and that had been modified over the past 80 years.

Closed-Conduit Systems

As indicated previously, consolidated point and polyline shapefiles were developed to compile survey data and were used as the basic hydraulic node-link data for importing into XP-SWMM. To promote efficiency and accuracy, many point-node file features were created using total station database files that included the manhole ID, coordinates in UTM NAD83 and manhole ground elevations. Database files were used to create X-Y events in ArcMap that were exported to point shapefiles and then compiled. Polyline-link features were then created in ArcMap using point features and as-built drawings to establish feature limits, and using survey records to populate most attribute fields describing upstream and downstream manhole ID's, inverts, size, shape and roughness. Node invert elevations, required in XP-SWMM, were set using table summarize functions and table joins in ArcMap, that quickly determined the minimum sewer elevation at each manhole/node.

Open Channel Systems

Surveying of open channel drainage features was competed to establish inverts at culvert and bridge structures and channel reaches. The node-link data for open channel features and open channel cross section locations were created using 'heads-up' digitizing in ArcMap using watercourse, roadway, building and contour base layers, and the orthophoto as reference layers. X-Y pairs defining each open channel cross section were extracted from the contour layer in ArcMap using a VB script obtained on-line. Channel and overbank lengths were calculated in ArcMap and roughness values were estimated based on vegetation types apparent in each reach using the orthophoto.

XP-SWMM Model Import / Export

The XP-GIS module can be used to facilitate importing of basic XP-SWMM data from external database sources. Using OLE and ODBC technology, this module is used to associate model parameters with corresponding external database fields, e.g., fields in the shapefile attribute tables for node and link features described above. Model features can be either created or updated through importing, or external data can be updated through exporting. The majority of basic hydraulic node and link data was imported in this manner. Exceptional features including i) the irregular geometry of arch-shaped sewers, ii) channel cross section and reach data, iii) culvert and roadway geometry and inlet hydraulic conditions, and iv) stormwater management control outlets, were added directly into the XP-SWMM model using the model's GUI. It is noted that where warranted, cross section data could alternatively be imported in HEC-2 format.

Additional feature data including virtual or 'dummy' features were added directly into XP-SWMM. Such features included hydraulic conveyance links between sewer outfalls and the centreline of their receiving watercourses, and most hydraulic storage nodes representing the detention storage characteristics of ponds, rooftops, or natural storage areas at channel inlets to the sewer system. Ultimately, the XP-SWMM model hydraulic nodes represent a diverse range of features of varying physical scale including manholes, pipe and channel junctions and transitions, culvert inlets and outlets, large rooftops, constructed stormwater detention ponds, and natural surface storage features.

Once nodes had been created for the Hydraulic module, hydrologic parameters associated with these inflow points were imported to the Hydrology module. Catchment polygons already containing area, percentage impervious, slope and width values were updated to include their destination manhole/node ID's so that the XP-GIS module could be used for importing this data to its corresponding XP-SWMM node.

Extensive simulation results may be viewed or exported from within XP-SWMM. Common results used in the characterization of minor drainage systems include the ratio of link design flow to capacity and the associated maximum HGL elevations at bounding nodes. Customized summary tables of these results were exported for model links and joined to the input link attribute table in ArcMap. Example results for the 5-year design event are illustrated in Figure 5, and are now more readily available for review, without requiring access to the original simulation models. This figure illustrates the average depth of the design water level below the ground surface, and is used to characterize the risk of roadway flooding and basement flooding.

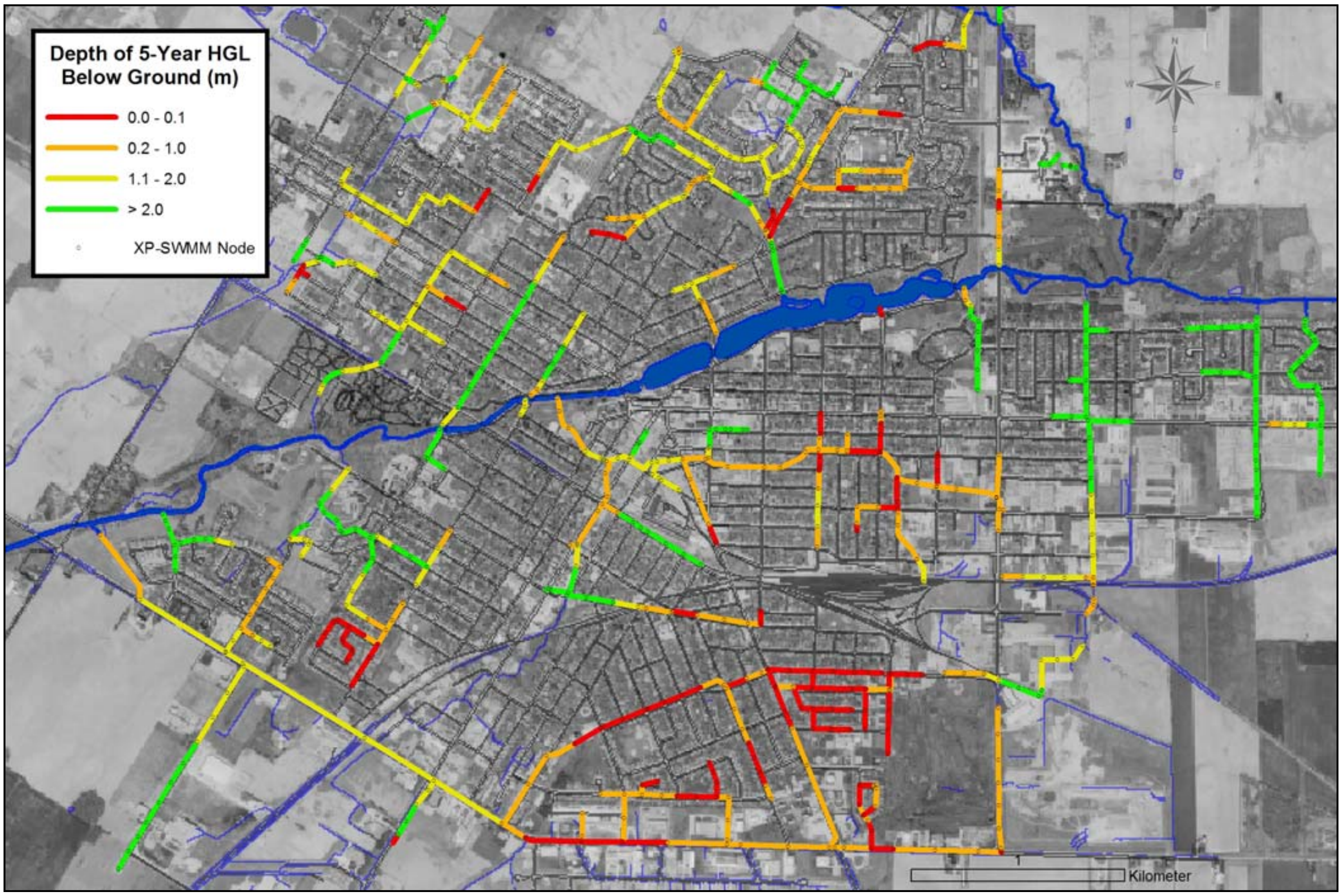

Figure 5 - Minor System Capacity Assessment Using Exported XP-SWMM Results

MAJOR DRAINAGE SYSTEM (SURFACE) ANALYSIS

The Spatial Analyst extension's core hydrologic analysis functions were used extensively as part of the major drainage system assessment. In particular, using the DEM developed for the study, these functions were used to identify 'sinks' or low points associated with potential ponding and flood risks and major drainage system flow paths (Figure 7). The spatial extent of sinks in each minor system catchment was used to assess where excessive capture of runoff into the minor system could occur during extreme events, as overland flow relief was limited.

Major system flow paths were determined using flow accumulation GRIDs, considering contributing areas of 2 ha (5 acres) or greater. Locations with inadequate flow paths, i.e., traversing private lots as opposed to being confined to channels or road right-of-ways, were identified by superimposing the major drainage flow path on the orthophoto and base mapping (see Figure 7 inset). Major drainage basins were compared with minor system catchments in ArcMap, and were found to diverge considerably in several areas, indicating the potential for spill between sewersheds during extreme events. In the southernmost portion of the City, 13.5 sq.km (5.2 sq.mi) of external drainage runoff could potentially spill to the City core, where major flow paths have been encroached upon by historical development. To assess flooding risks, the XP-SWMM model was revised to account for extensive surface ponding in low-lying areas associated with these external areas. The analysis revealed that ponding would provide significant flow attenuation during extreme events, even at the 100-year return period.

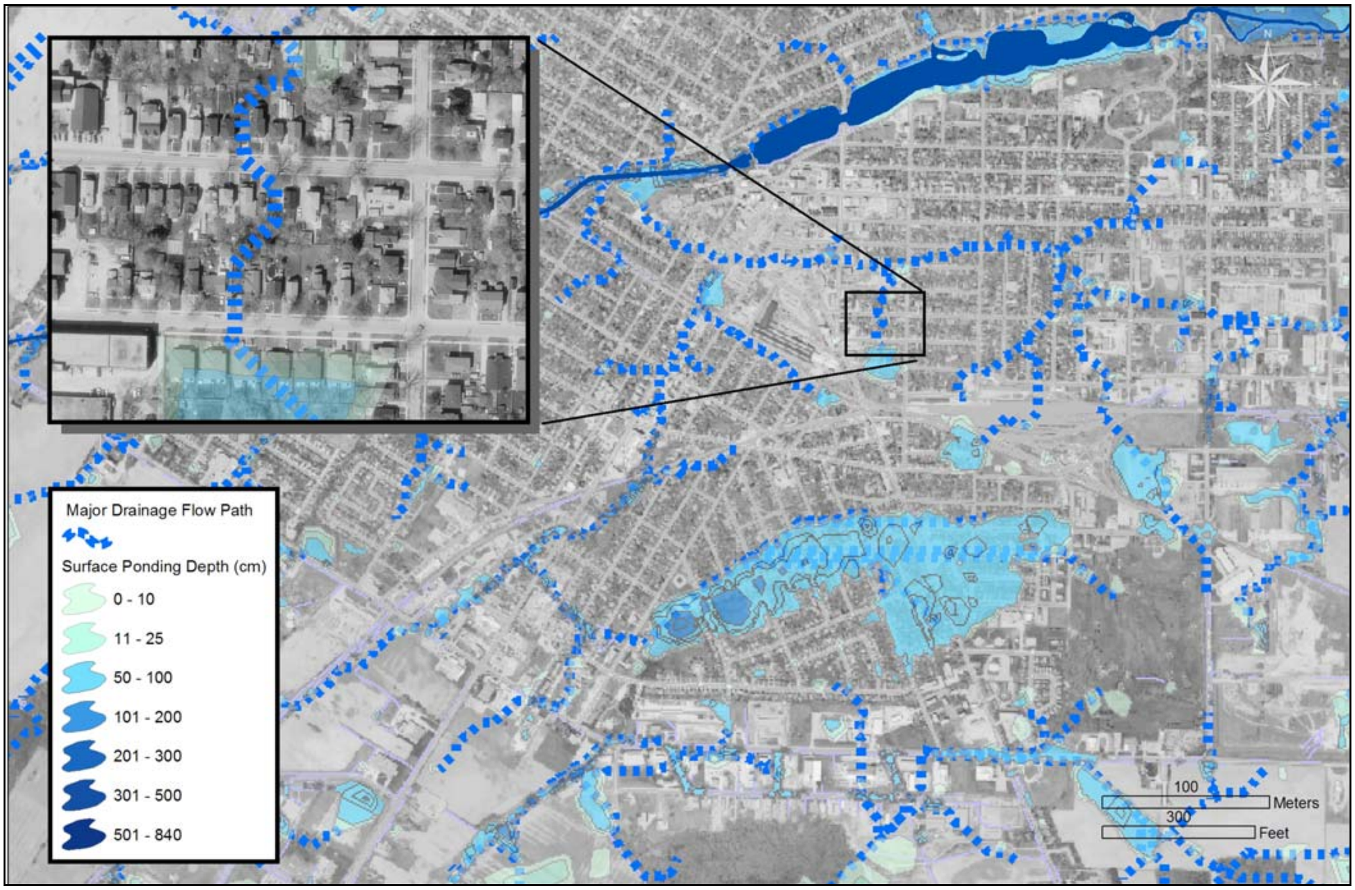

Figure 7 - Potential Surface Ponding / High Runoff Capture Areas and Major Drainage Flow Paths (inset: detail of mid-block overland flow route)

BASEMENT FLOODING RISK ASSESSMENT

The risk of basement flooding as a result of sewer surcharge varies throughout the City according to the servicing practices in place during the period of construction. Generally, areas developed since 1960 have a high proportion of separate private drain connections for sanitary and storm service discharges to the municipal servicing systems – these areas are most susceptible to basement flooding by storm sewers, due to the hydraulic connection between the storm sewer and foundation drains. Earlier development areas had been serviced by a single service connection to the sanitary sewer that effectively isolates foundation drains and basements from the storm sewer, reducing associated flood risks (Aside: it is acknowledged that, conversely, the risk of sanitary sewer related flooding is higher in older areas due to extraneous wet weather flow considerations). Figure 8 illustrates the distribution of private drain connections throughout the City based on a review of 1300 individual plumbing records, aggregated by street. Newer subdivisions within the City are shown have a high proportion of flood-susceptible separate connections while older, inner areas have more varied servicing and flood risk potential. The oldest City core areas were found to have mostly single connections resulting in low flooding risks. This was confirmed through flow monitoring results and historical flooding records.

Minor drainage systems were assessed based on a combination of characteristics including their runoff capture potential, minor system capacity, private drain connection types, and flooding history. To facilitate the assessment, minor system pipe capacities were summarized in ArcMap using geoprocessing functions that were used to aggregate and summarize results by catchment areas and trunk system. A multitude of system characteristics were also presented on consolidated mapping for comparative evaluations. Systems were ultimately ranked accordingly to basement and surface flooding potential during typical and extreme design events, and improvement strategies were prioritized on this basis.

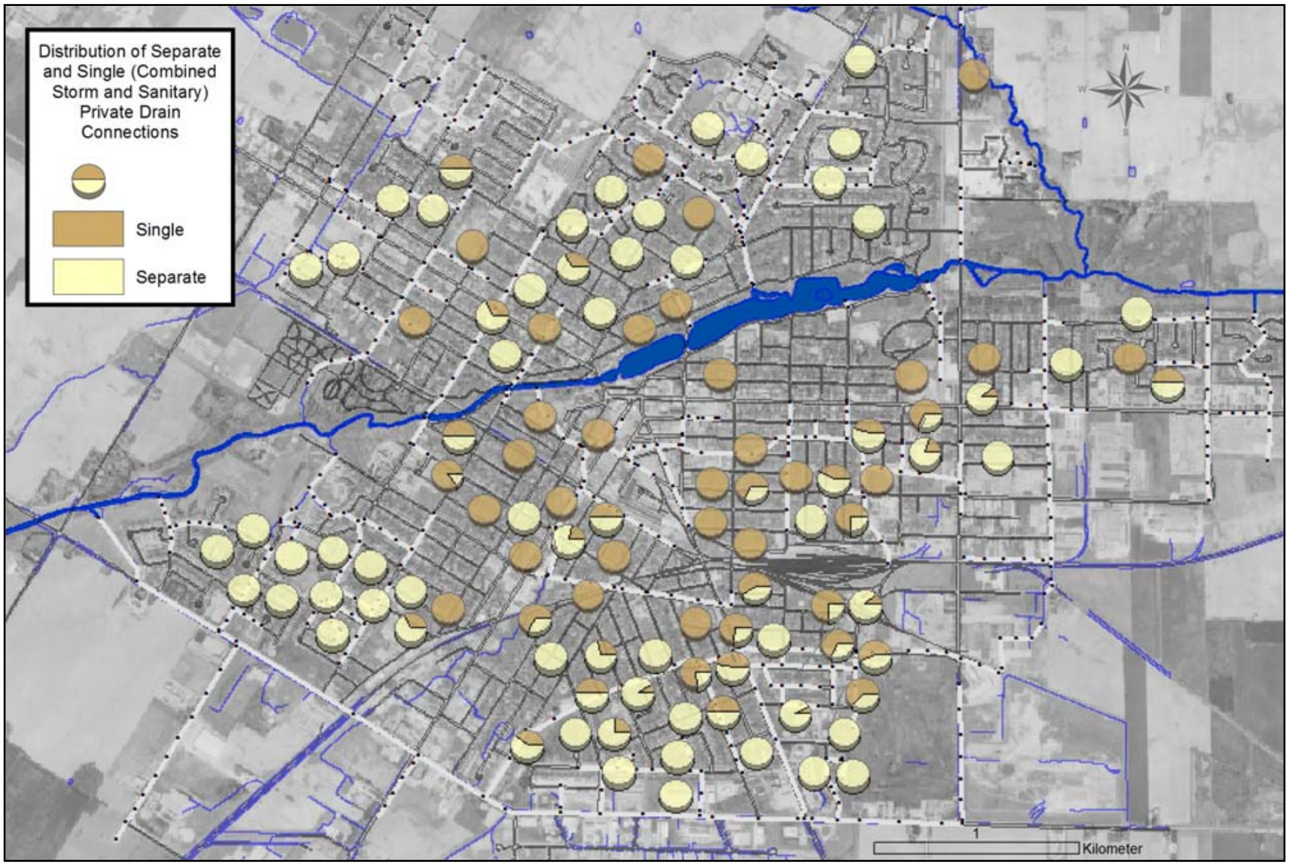

Figure 8 - Distribution of Private Drain Connections by Street

PRESENTATION / COMMUNICATION / DOCUMENTATION

Results of the XP-SWMM hydrologic and hydraulic analysis of the minor drainage system and the surface modelling of the major system were presented to the public, agencies and council using thematic mapping, three-dimensional model visualizations and animations. These displays and presentations were used to illustrate storm system capacities, major system drainage issues and potential environmental constraints associated with recommended improvement works.

Displays created to explain major drainage system concepts and analyses are shown in Figure 9. These visualizations, created using ESRI's 3D Analyst, highlight the results of much of the GIS analysis conducted as part of the study including i) the DEM generated from vector base mapping (shown here as a TIN), ii) extruded building polygons developed for imperviousness calculations, iii) 'green' pervious areas reclassified from the orthophoto and draped over the DEM, and iv) low points of potential ponding, and v) major drainage flow paths, both derived from the hydrologic surface analysis.

As provincial regulatory requirements for Environmental Assessment studies require detailed documentation of study findings, most of the graphical material presented here was ultimately included in study reports. Advancements in graphical capabilities of core GIS software, e.g., such as the enabling of transparencies for surfaces in ArcGIS, allowed study documentation to be created efficiently from analysis data, with no need for other graphical software.

CONCLUSIONS

Urban drainage master planning relies heavily on spatial-based data to establish the characteristics and performance of both major and minor drainage systems. This data includes the physical characteristics of the storm sewer and open channel drainage network, the physical characteristics of the runoff catchments, and the overall surface relief that defines the major drainage system boundaries, overland flow paths and potential hazard areas associated with flooding during extreme runoff events. As illustrated in the case study "City of Stratford, City-Wide Storm System Master Plan", GIS may be used a valuable tool for exploring, managing, creating, analyzing and presenting this data. Using built-in functionality of core software as well as specialized extensions and on-line resources, sophisticated desktop analyses, efficient simulation model

Figure 9 - 3D Illustration of Surface Model, Land Use and Major Drainage System Features

pre- and post-processing, and effective data management can ultimately be achieved even with limited initial data availability. With the exception of special hydraulic features, GIS was used to maintain the majority of hydraulic and hydraulic data required for the Study's XP-SWMM model development, and this GIS-based data was readily used to create and update model features using the XP-GIS import module. Basic modelling results were exported for model links and joined back to input attribute tables, making these results more readily available for review, without requiring access to the original simulation model. Based on the effectiveness of GIS technology as illustrated through this case study, the use of GIS applications can be expected to increase in the area of infrastructure master planning.