GIS Tools for Proactive Urban Watershed Management

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Abstract

The City of Greensboro, North Carolina, USA is developing and implementing a proactive Municipal Stormwater and Watershed Management Program that includes unique Geographic Information System (GIS) database and application tools for a high level of GIS integration for urban stormwater management. For example, customized GIS technology allows the City to prioritize stormwater infrastructure and drainage system maintenance, assist with implementation and tracking of the municipal NPDES stormwater discharge permit, track water quality data and improvements, enhance the local floodplain management program, and facilitate multi-objective, watershed-based modeling and urban stormwater management master planning. Advanced technology coupled with dedicated staff and stakeholder involvement, clearly defined goals, and a watershed-based focus are allowing the City to develop optimal plans for urban stormwater management, watershed protection, and watershed restoration.

This paper provides an overview of the City's Stormwater Management Program with a focus on an integration of interactive hydrologic, hydraulic, and water quality models with a robust GIS database to create a tool that provides a sound technical basis for informed watershed-based management and restoration decisions by local officials. A foundational aspect of the City's program includes ongoing stakeholder and community input as staff attempt to balance science and engineering with local values related to natural resources and urban watershed management. Once legal requirements are satisfied for designated water resources, community values provide an ultimate measure of success for local stormwater and watershed management programs.

The current work is referred to as the "Dynamic Watershed Management" (DWM) project and represents initial steps at the local level towards development of a holistic and sustainable urban

watershed management program. Due to the flexibility of the GIS tools and databases, the DWM program could be expanded in the future to include comprehensive urban water resources management such as water supply system optimization, sanitary sewer system inventory and modeling, and advanced water quality modeling to support Total Maximum Daily Load (TMDL) programs, pollutant load allocations, discharge limits, and pollutant trading programs for local watersheds. The GIS-based applications and modeling tools are therefore helping the City of Greensboro effectively meet today's stormwater management requirements while also preparing for the comprehensive watershed-based management challenges and opportunities of the future.

Introduction

Federal National Pollutant Discharge Elimination System (NPDES) Stormwater Regulations have mandated that urbanized municipalities develop and implement stormwater management programs to ensure that pollutants in stormwater runoff from urban non-point sources are controlled to the maximum extent practicable. As non-point pollution sources have been shown to contribute significantly to the degradation of receiving water quality, improved stormwater management programs at the local level should play an important role in protecting our nation's surface water resources. The City of Greensboro, North Carolina is developing and implementing a comprehensive and proactive urban stormwater and watershed management program to address issues in a holistic manner for optimal management of surface runoff and water resources into the 21st century.

Greensboro, with a current population of approximately 205,000, is located in Guilford County in North Carolina's Piedmont physiographic region. It is situated in the headwaters of the Cape Fear River Basin, with no major rivers flowing through or near the city. The North Buffalo Creek and South Buffalo Creek originate in and flow through the central part of Greensboro, and drain approximately two-thirds of the 109 square mile area of the city. Three reservoirs, Lake Higgins, Lake Brandt, and Lake Townsend, on the Reedy Fork Creek, which flows through the northern part of the city, are the existing primary sources of drinking water supply for Greensboro. A planned water supply reservoir, Randleman Lake, which will be located south of Greensboro along the Deep River, will provide Greensboro, High Point, and other area communities with a future additional source of drinking water. Figure 1 shows the major watersheds and sub-watersheds in Greensboro, along with the existing water supply lakes and a vicinity map showing the general location of Greensboro in the Cape Fear River Basin.

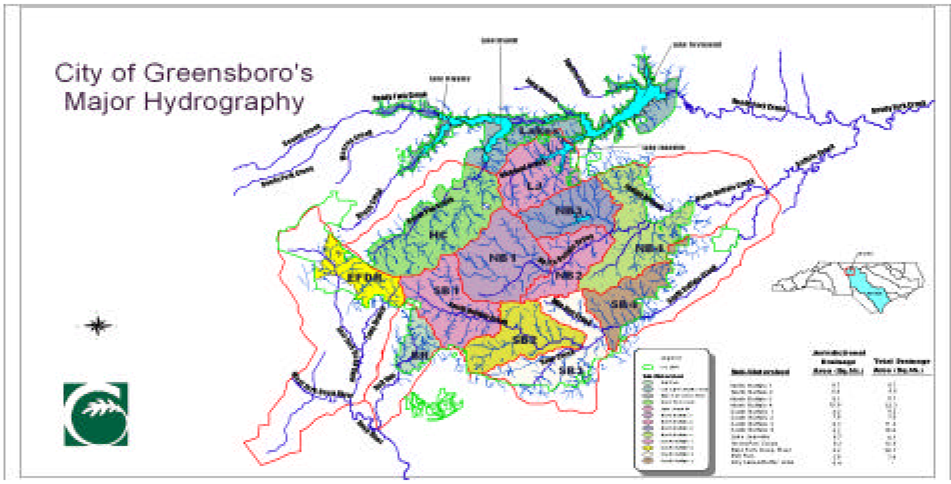

Figure 1. Major watersheds and sub-watersheds in the City of Greensboro.

Overview of Greensboro's Stormwater Management Program

The Federal NPDES Phase 1 and Phase 2 Stormwater Regulations mandate that municipalities take a comprehensive approach towards stormwater management issues within their jurisdiction and develop new programs that will prevent or minimize impacts to water quality from non-point pollution sources, such as urbanized areas. Local governments within the State of North Carolina are also required to implement watershed protection programs for designated drinking water supply watersheds, as noted above. These two regulatory mandates, along with local interest in developing an optimum stormwater management program, have served as initiatives for Greensboro to begin developing improved programs for both stormwater and watershed management. The City's developing Stormwater Management Program includes the following key components:

- Implementation of a Stormwater Utility to serve as the dedicated funding mechanism for the new and improved stormwater management programs..

- Development and implementation of a comprehensive GIS database of stormwater infrastructure along with a proactive stormwater infrastructure maintenance program.
- Development of a "Dynamic Stormwater and Watershed Management System," which includes interactive linkages between the GIS database and major hydrologic, hydraulic, and water quality / pollutant loading models.
- Implementation of an extensive public education and awareness program because improved watershed management begins with individual citizens and businesses, i.e.; stopping the pollution at its source is always the best approach
- Implementation of a watershed-based water quality monitoring program, including wet weather land use-based monitoring, ambient and wet weather stream monitoring, structural Best Management Practice (BMP) assessment monitoring, and biological / habitat assessment and monitoring. The City is also working with the United States Geological Survey to establish a citywide network of continuous monitoring rainfall and streamflow gaging stations to provide data for the watershed modeling and management program.
- Innovative restoration projects for local degraded streams including enhancement or creation of adjacent riparian wetland areas.
- Development of a comprehensive and watershed-based stormwater management ordinance.

With this brief overview of Greensboro's Stormwater Management Program, the remainder of the article will focus on the City's GIS applications development strategy, including the unique Dynamic Stormwater and Watershed Management (termed "DWM") System under development by the City.

GIS Applications Development Strategy

The Greensboro approach to GIS applications is to focus on making the utilization of GIS central to the key tasks within the Stormwater Management Program. The approach has been to highlight the most critical operational tasks, and create GIS applications as tools to help solve those tasks.

As noted earlier, the City's Stormwater Management Program is funded by a Stormwater Utility, which is levied based on the acreage of impervious area for non-residential properties and a flat fee for residential customers. This funding is used for operation and maintenance of drainage structures, proactive planning, and for monitoring of receiving streams and lakes within the City.

It was noted at an early stage of the project that all these tasks could be automated fully or partially using GIS technology and it was known that tools had been developed by other organizations that partially assisted with some of this automation for specific data structures and computing environments. The challenge was to provide these tools to fit the existing data structures, computing environments and workflow that existed within the group.

The first application to be developed was for calculating impervious areas and the consequent utility fee, which provides the funding for the local program. This application was originally developed in 1993 and re-engineered in 1998 when ARC/INFO by ESRI was adopted as the citywide GIS platform.

In 1996, a pilot application was developed which included infrastructure view/query tools, stormwater modeling using simplified tools and a monitoring database for information collection and analysis. These applications were not heavily used at the time because the infrastructure inventory data collection program, which was the data source, was in its infancy. This exercise provided useful insight into what lay ahead, both in terms of the potential benefits and also the complexity and the lack of available integrated products to address stormwater and watershed management problems.

In 1998, the view/query application for the infrastructure inventory was re-engineered and a complementary work management application was added. This was to address the routine and proactive maintenance requirements of the stormwater management program, one of its primary functions, and utilize the data provided by the on-going infrastructure inventory effort. These applications were provided in an integrated form, but because of the limitations of the GIS, the transition from view/query to maintenance was not fully transparent. The goal for this stage of the development effort was to provide a very high level of integration between modules, which was facilitated by the Microsoft COM architecture. However, to accomplish this integration, it was necessary to make some compromise in the ease-of use of the user-interface.

In 1999, work commenced on the most ambitious phase of the project to date, to automate the Stormwater Modeling and Master Planning process. This development is the main focus for this article and is discussed in more detail below. This component (the “DWM System”) is still under development and should be complete by the end of 2000. The application incorporates interfaces to HEC-HMS, HEC-RAS and XP-SWMM for closed conduit modeling, water quality modeling, and various planning tools to assist in the master planning process. The goal was to integrate these solutions in a single integrated tool to facilitate the master planning process by engineers and water quality professionals.

A further application currently being developed to aid master planning is the display and assessment of water quality monitoring data. This application will build a database for the on-going chemical and biological-monitoring program, which includes chemical monitoring of streams and lakes and biological monitoring of bugs, fish and stream habitats. The databases will facilitate the rapid calculation of indices for local streams based on methodologies determined by various academic and state agencies. These indices will allow citizens to monitor the water quality in their local streams and lakes and the trends in this data. The results will feed into a live Internet application and will generate thematic maps showing the chemical indices and symbology to display the biological indices at the monitoring sites. In addition, a summary of results will be displayed for each of the watersheds within the City.

Technical Components of DWM System

The Dynamic Stormwater and Watershed Management System, or DWM, is the City's GIS-based modeling tool that will be used to facilitate effective stormwater and watershed management decision making. The term "dynamic" is intended to reflect the capability of the system to accommodate the changing nature of many natural and manmade systems within urban watersheds, including land areas, streams and floodplains. Importantly, the DWM System is being designed to be easily updated as conditions in the dynamic urban watershed change. With the DWM System and its integrated modeling modules, the City can efficiently evaluate the impacts of alternative land use and other watershed management decisions on stormwater runoff quality and quantity, receiving stream system stability, floodplain and floodway elevations and boundaries, as well as determine optimum site specific and/or regional measures to mitigate negative impacts of stormwater runoff and non-point source pollution.

The programming environment used for the DWM System will consist of Visual Basic, SQL, ArcView and ESRI Map Objects. The DWM Modeling Modules, which include Watershed Hydrologic Modeling Module (HEC-HMS), Floodplain Hydraulic Modeling Module (HEC-RAS), and the Water Quality Modeling Module, will be developed using primarily Avenue in an ArcView environment. In addition to ArcView, the modeling modules will require ArcView's Spatial and 3-D Analyst extensions. The DWM System is modular in design for flexibility and expandability and includes the following:

- Stormwater Infrastructure and Conveyance System Inventory Module
- Interactive Hydrologic, Hydraulic, and Water Quality Modeling Modules
- Watershed Planning and Modeling Tools
- Master Plan Manager Module

Stormwater Infrastructure and Conveyance System Inventory Module: The scope of Greensboro's Stormwater Infrastructure Inventory included going beyond development of a drainage infrastructure database to encompass the overall connectivity of the storm sewer system with various natural and manmade open channels, ponds, and lakes. The overall connectivity of the drainage system is important for stormwater modeling applications, as well as other proactive applications such as tracking and removing illicit connections to the drainage system and emergency spill response activities.

The major stormwater system features within the Greensboro database include: various types of drainage inlets, manholes or junction boxes, storm sewer pipes, drainage swales, natural and manmade open channels, energy dissipators, culverts, bridges, and waterbodies such as ponds and lakes. The stormwater inventory database is also linked to the City's bridge inspection database, a stormwater pond and BMP database, and water quality monitoring information required by the NPDES permit and for the developing watershed management program.

Example attributes for structures and features within the stormwater inventory database include: a unique tag or identification number, reference to a standard drawing for the feature (if applicable), elevation data from the survey, physical dimensions and measurements, number of incoming flow elements (generally the number of incoming pipes) to the feature, physical condition observations, observations of any obstructions to flow, a check for potential illicit connections, public or private system ownership data, date of information collection, date of future inspection, any unusual flow observations such as odor, watershed data, NPDES storm sewer outfall information, and a field for any specific comments. Digital photographs were also obtained for most drainage structures such as culverts, bridges, larger open channel segments, non-standard infrastructure elements, or features that required near term maintenance (Bryant et al., May 1998).

When completed, the stormwater inventory module will contain over 4.5 million attributes of data surveyed using GPS technologies to 3.5 cm accuracy on the size, location and condition of pipes, culverts, bridges, and open channels.

Figure 2 shows a typical area of the storm system inventory incorporated into the GIS module, with a digital orthophoto in the background.

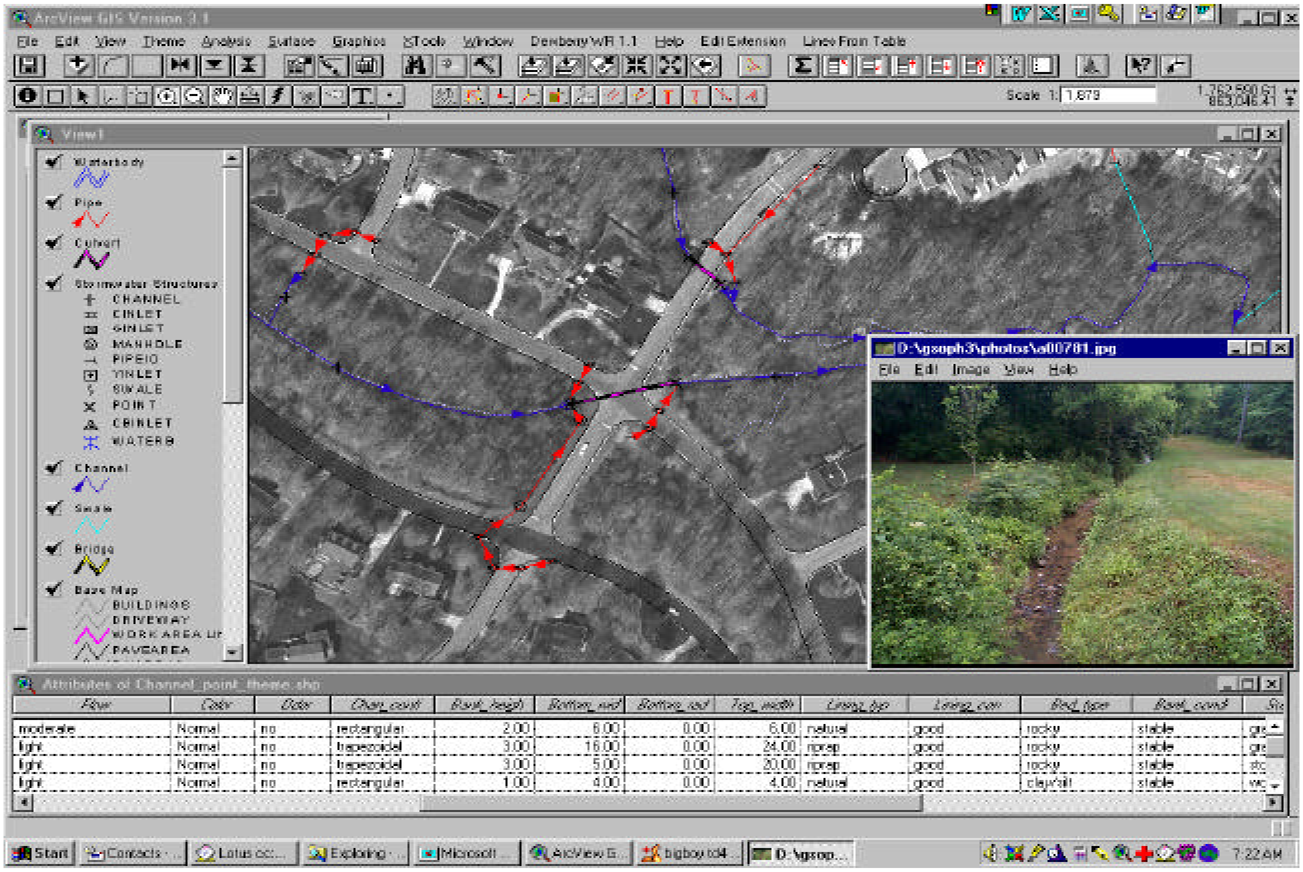

Figure 2. Stormwater system inventory module.

Interactive Hydrologic, Hydraulic, and Water Quality Modeling Modules: The interactive modeling module will create the hydrologic, hydraulic, and water quality models from the City's inventory and watershed databases. The watershed databases include such GIS layers as existing land use, future zoned land uses, locations of industrial and municipal facilities, soil classifications and hydrologic soil groups, aerial photography layers such as orthophotos and planimetrics, a digital terrain model and topographic contours, and related watershed data layers.

While the GIS applications and relational databases are customized software to meet the needs of Greensboro, the DWM integrates widely-used and accepted computer models such as the U.S. Army Corps of Engineers' HEC-HMS and HEC-RAS hydrologic and hydraulic models, the EPA SWMM hydrologic, hydraulic, and water quality model, and a non-point source pollutant load estimation model based on procedures developed by Schueler (1987).

Figure 3 shows an example of watersheds imported into the DWM system for hydrologic analysis.

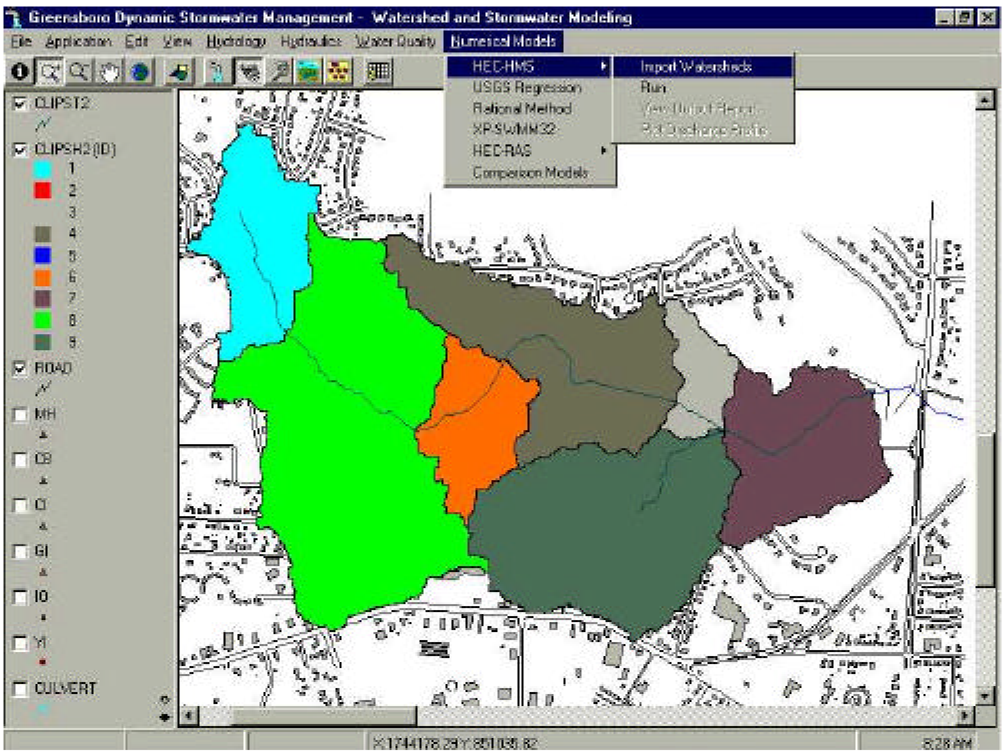

Figure 3. Watersheds imported into DWM System for analysis

The Watershed Hydrology Module of the Dynamic Watershed Management (DWM) system will be used to simulate runoff hydrographs and determine peak flows for a selected subwatershed(s). The Watershed Hydrologic Modeling Module will be used to compute design flows for use in the Hydraulic Modeling Module (HEC-RAS). Hydrologic modeling will be performed using NRCS methodologies (NRCS Unit Hydrograph and Runoff Curve Number Loss Rate) within the US Army Corps of Engineers HEC-HMS computer program (Replacement to HEC-1). HEC-HMS (referred to as HMS) will be used to simulate hydrographs for relatively large sub-watersheds that include significant open-channel flow and/or ponds. Level-pool routing procedures in HMS will be used for routing flows through lakes and ponds. The source code for the Watershed Hydrologic Modeling Module will be flexible to allow for upgrades to HEC-HMS. The HMS Module is designed to interface different GIS data layers with the HMS hydrologic model. The HMS Module will serve as a preprocessor for HMS input data. Different GIS data layers will be manipulated to derive new GIS data layers and compute several hydrologic parameters such as drainage areas, area-weighted Curve Numbers, and lag-time.

The GIS-based modeling environment will automatically create and format the HMS basin file. In addition, an HMS map file that depicts the sub-watershed boundaries and streams in state plane coordinates will be created. The HMS precipitation files will be developed outside the GIS environment and stored on disk for access within the DWM system. Internal quality control checks will be performed to ensure that parameters and data are within a reasonable range. Options regarding the type of output results will be included in the input file. Automated routines will be developed within the DWM system for checking model input. These routines will ensure that input data and parameters are within reasonable ranges. The DWM system will send a warning message to the user if parameter checks show possible problems with the input data.

The Floodplain Hydraulics Modeling Module of the Dynamic Watershed Modeling (DWM) system will provide a semi-automated link to HEC-RAS to perform backwater analyses for open channel reaches. The Floodplain Hydraulics Modeling Module will accept peak discharges from the Watershed Hydrologic Modeling Module (HEC-HMS) through the use of HEC-RAS's DSS (Data Storage System) import procedures. The user will also have the ability to modify the location of changes in peak discharges within the standard HEC-RAS Graphical User Interface (GUI).

The Floodplain Hydraulics Modeling Module is designed to serve as both a pre- and post-processor for the HEC-RAS computer model. Different GIS data layers and their associated attributes will be pre-processed and formatted for input into the HEC-RAS model. HEC-RAS output such as water-surface elevations and floodway encroachments will be post-processed to produce new GIS data layers depicting the floodplain and floodway boundaries. The basis for cross sections and bridge and culvert information required by HEC-RAS will be taken from the infrastructure inventory database. Hydraulic modeling and floodplain mapping procedures will be supplemented with additional cross sections extracted from the digital terrain surface within the DWM system.

Steady state, one dimensional hydraulic modeling will be performed using the US Army Corps of Engineers HEC-RAS program (version 2.2). The source code for the Floodplain Hydraulic Module will be flexible to allow for upgrades to HEC-RAS. The DWM system will have the overall flexibility to incorporate other models in the future (such as UNET).

The purpose of the Water Quality Module is to provide planning level tools suitable for the assessment of water quality issues at a watershed scale. This Module is intended to support other more detailed applications such as an evaluation of citywide stormwater pollution prevention plans or support for future determination of Total Maximum Daily Loads (TMDLs), as these functions are developed. Water quality assessments completed in the module will be based primarily on an annual pollutant loading approach. Statistical procedures will be formulated to introduce seasonal variations into the annual loading estimates.

The basic tool for the Water Quality Module is the "Simple Method" proposed by Tom Schueler to compute annual pollutant loadings from various land uses. Basic pollutants to be included in the Module are total suspended solids, total phosphorous, total Kjeldahl nitrogen, nitrates & nitrites, COD, BOD5, lead, copper, zinc, and cadmium.

BMPs will be evaluated using techniques compatible with the loading model given by the "Simple Method." Removal efficiencies will be selected for various BMP types including wet ponds, dry ponds, extended detention, constructed wetlands, grass swales, filter strips, infiltration trenches, and bioretention facilities. The Module will be developed such that these removal efficiencies can be implemented in a number of user-defined BMP scenarios to examine their combined pollution-reduction effectiveness. The Module will also allow the user to revise BMP types and associated pollutant removal efficiencies, as new information becomes available.

Linkages will be developed between the water-quality output and the GIS to present output in tabular format, and to show loadings by sub-basin in a graphical format. Color schemes will be used to display the effectiveness of implementing various BMP scenarios. Users will be able to export the results of water-quality assessments for further analysis in spreadsheets or other software packages.

Watershed Planning and Modeling Tools: The Floodplain Management Tool within the DWM allows the user (City and stakeholders such as a developer, an engineer, or water quality professional) to interactively evaluate the impacts of development or encroachments on flood elevations throughout the watershed or to evaluate alternative flood hazard mitigation measures. Within the HEC-RAS Module, the user will be able to access the results from the hydraulic model and automatically map the floodplain boundaries for the modeled reach. The floodplain management tools will require a floodplain polygon (i.e., area of inundation) and water-surface TIN (triangulated irregular network) (i.e., flood elevations) for each recurrence interval to be investigated. Combined with digital elevation certificates for all structures located in the 100-year floodplain and tied to georeferenced address fields, the risk assessment may be performed on a structure-by-structure basis.

The buildings GIS data layer will be linked with the results from the hydraulic modeling (i.e. floodplain boundary polygons) so that flood prone structures can be identified. Tools will be provided to determine the lowest adjacent grade from a ground surface TIN for any number of structures. The user will identify the floodplain polygon associated with a given recurrence interval and the DWM will automatically determine the number of structures impacted and the maximum depth of flooding at each structure. The DWM can also be used to determine the availability of elevation certifications for individual structures. If an elevation certificate is available, the software will automatically override the approximate structure elevations obtained from the digital terrain model (DTM) with actual surveyed first floor elevations from the GPS elevation certificates. If no elevation certificates are available for the buildings, the maximum depth of flooding will be based on the difference between the computed flood elevation and the lowest adjacent grade obtained from the ground surface TIN. It is envisioned that the tools to determine maximum depth of flooding and lowest adjacent grade for the structures will be accessed through an ArcView environment.

Proactive flood hazard mitigation planning will be evaluated within the HEC-RAS modeling module on a watershed basis. By combining structure-by-structure risk assessment with automated modeling capabilities, the benefits and costs of proposed mitigation measures can be quickly evaluated. The flood mitigation measures to be evaluated include structural flood control measures, bridge and culvert crossing improvements, stream restoration, relocation, acquisition and floodproofing of individual or groups of structures (Bryant and Beadenkopf, May 1999).

Figure 4 shows an example of 100-year and 500-year floodplains developed within the DWM System and how floodprone structures are determined.

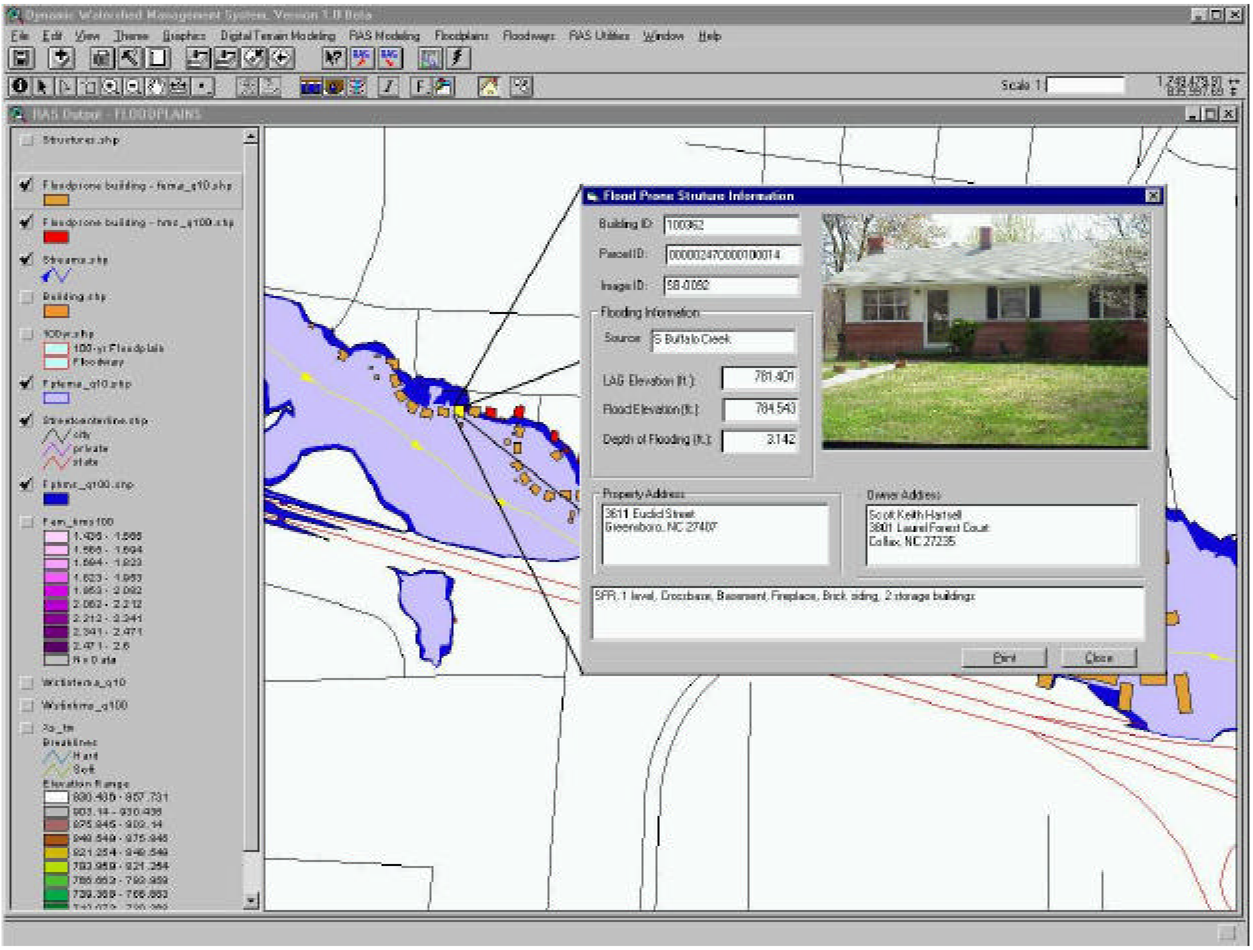

Figure 4. Floodplain mapping tools within DWM System.

Master Plan Manager Module: Users will be able to click on certain GIS features and get information on proposed mitigation projects. This module will include a GIS interface showing the locations, numbering-naming system, and approximate dimensions of selected projects of the Master Drainage Plans for completed watersheds within the city. A project database will contain photographs, sizing data, cost estimates, project summary, and any preliminary grading (scanned from worksheet) if available. The supporting projects database for this Module will be populated as the master plan is completed for various watersheds throughout the city. It is envisioned that the Master Planning Module will be developed in either MapObjects or ArcView.

Summary

This article provides a brief overview of the City of Greensboro's Stormwater Management Program and an introduction to the GIS-based "DWM System" under development that will aid local officials in effective stormwater and watershed management decision making. The authors hope that this summary will be useful as an example for local government officials, consulting engineers and scientists, watershed planners, public works officials, and others involved with challenging current and future urban stormwater and watershed management issues.

The Greensboro DWM System provides a strong linkage between data, watershed modeling results, and the technical basis for management decisions. The system and local monitoring program also allows progress to be tracked and improvements to be measured.

Examples of expected positive results from improved local stormwater management programs include protection and enhancement of water quality in receiving streams and lakes, reduced flooding or mitigation of drainage problems, proactive floodplain management measures, improved aquatic and riparian biota and habitat, and optimal maintenance management of stormwater infrastructure assets. The DWM System also provides a preliminary framework for comprehensive water resources and watershed management as the City moves into the 21st century.

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