GIS and Urban Hydrology:

Flood Hazard Mapping With GIS

By: Errin Kemper, E.I.T
Todd Wagner, P.E.

City of Springfield, Missouri
Department of Public Works
Storm Water Services Division

Abstract:

The federal Emergency Management Agency publishes Flood Hazard Maps with designations up to a drainage area of one square mile. However, for small urban watersheds subject to intense rainfall and flash flooding, additional flood hazard mapping with greater detail is needed.
In Springfield, Missouri, flood hazard mapping along major waterways to a drainage area of 40 acres is being completed. These maps provide a tool useful for identifying flood hazards and establishing priorities for future capitol improvement projects. A watershed assessment approach is being taken toward each drainage basin and includes information such as soil data, topographic data, existing and future land use, and flood hazard mapping of the City's 250 sinkholes. These watershed assessments are being completed using automated GIS techniques.

Introduction

Storm water engineers and planners have always sought after better tools that would provide the ability to master plan capital improvement programs and reduce flood hazards.

The City of Springfield, Storm Water Services Division has used GIS to create a hydrologic model to estimate storm water runoff at different points throughout the watershed. The development of this information is part of a watershed assessment approach to comprehensive storm water management. This unique approach has led to the creation of a series of maps pertaining to soil data, land use, and flood hazard boundaries up to a 40-acre drainage that give a hydrologic synopsis of the entire watershed. These maps also provide valuable information to city storm water engineers and can be used as a starting point from which to create master plans on a watershed basis.

One of the drainage basins used as a pilot for the watershed assessment project was the North Branch of Jordan Creek. This watershed is approximately 4 miles long, 2298 acres, and contains a variety of land uses; from heavy manufacturing to residential. The Jordan Creek – North Branch watershed is used as an example throughout most of the following discussions. However, a series of flood hazard maps were created for the Inman Creek watershed that is approximately 5miles long and 2465 acres. The Inman Creek map is used as an example for the section on flood hazard mapping.

Performing a Watershed Assessment

Watershed Soil Properties

One of the most important parameters affecting the rainfall-runoff relationship is soil infiltration. The amount of runoff produced by a watershed is primarily controlled by both the ability of the soil to "soak up" precipitation and the amount and type of vegetative cover found on the surface of the soil. A runoff curve number (CN) can be obtained for a given soil type by first looking at its hydrologic soil group and then making assumptions about the type of vegetative cover present throughout the watershed and its antecedent moisture condition. Soils are grouped into four categories, A through D, based on their ability to "soak up" precipitation. In an urban setting such as the City of Springfield, it was assumed that the majority of watershed area not covered by an impervious area was covered with grass. The tree canopy was not accounted for due to the possibility that a storm might occur in the winter months. These assumptions lead to the following curve numbers for each hydrologic soil group that are applied throughout the watershed:

Hydrologic Soil Group	Curve Number
A	49
B	69
C	79
D	84

A shapefile containing soil data for the entire county was used for the analysis. This data layer contained information such as soil type and hydrologic soil group. By combining this layer with a layer containing the watershed boundary, Figure 1 was produced.

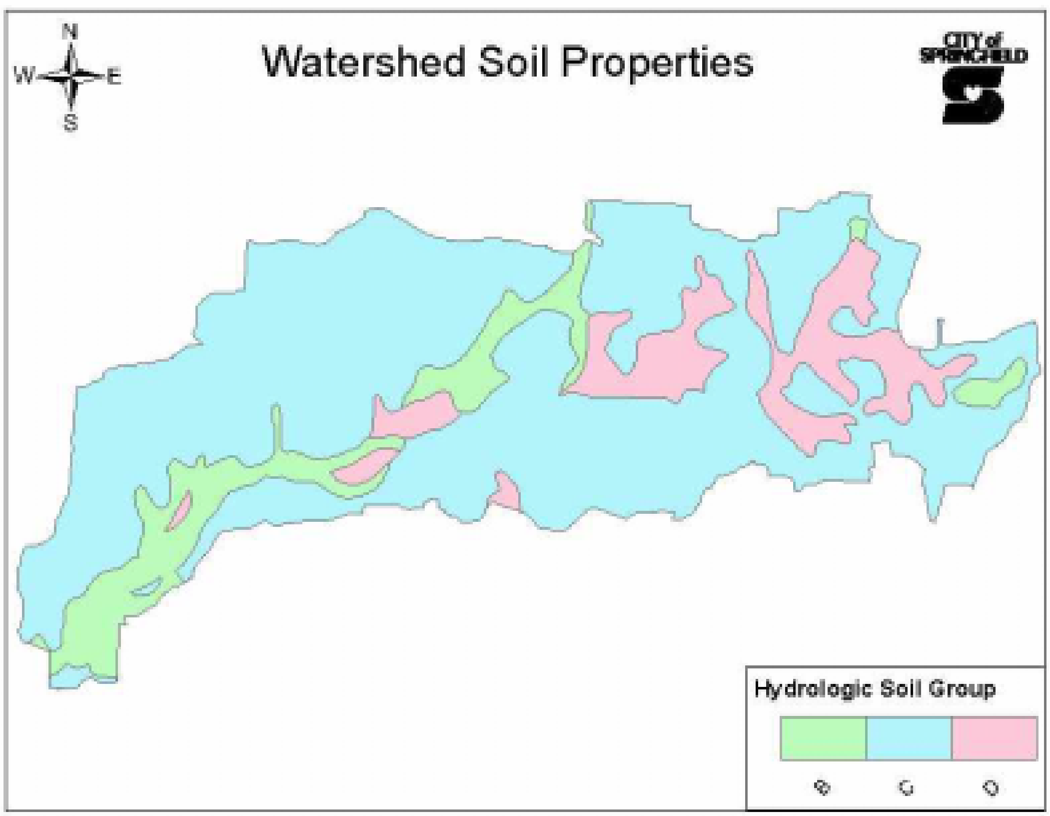


Figure 1

Mapping Current Land Use

Another important parameter affecting the rainfall-runoff relationship is land use. As more homes and business are constructed within a watershed, there is generally an increase in both the volume and peak flow of storm water runoff. These increases are due to both an increase in the amount of impervious area, as well as an increase in the efficiency of the conveyance structures that convey the water.

The first step in producing a land use map was to create a shapefile dividing different land uses based upon land use homogeneity. Aerial photos of the entire city were used within GIS to digitize polygons that represented homogeneous land uses such as fields, residential areas, parking lots, and commercial areas. Each of these polygons was assigned an impervious percentage based on sample areas measured from the aerial photograph.

The second step was combining this shapefile with another shapefile depicting all of the city streets and right-of-way, which were assumed to be 90% impervious. The end product is an overall map showing concentrations of impervious areas, including streets, throughout the city (fig 2).

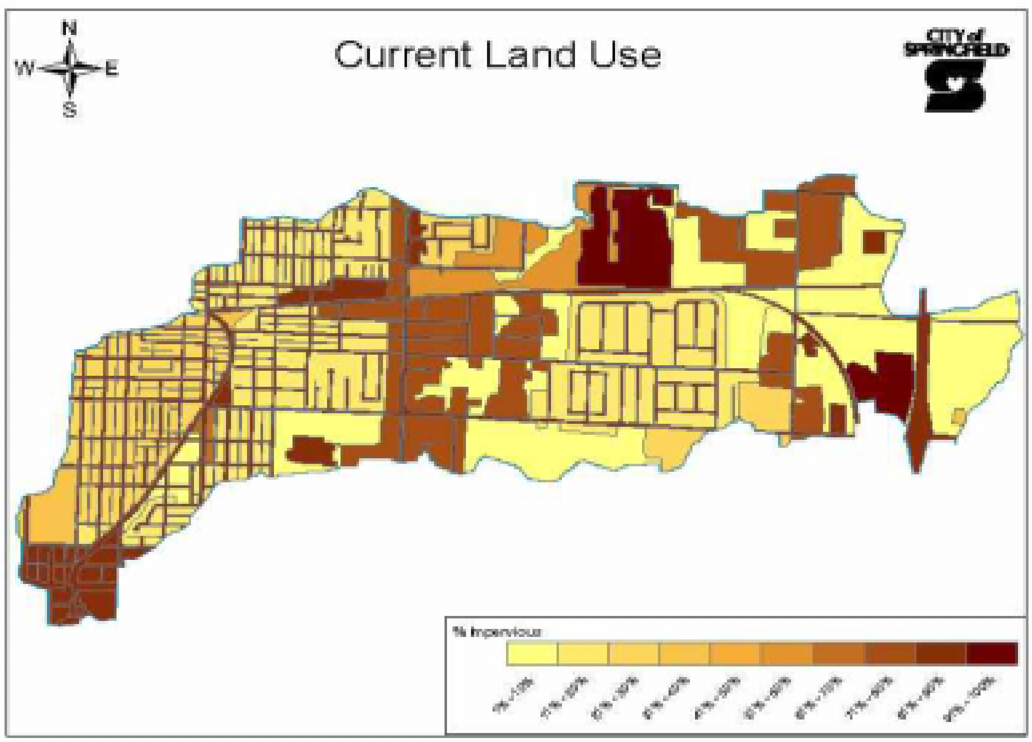


Figure 2

Projecting Future Land Use

Estimations of future land use within a watershed are necessary for long-term master planning and public improvement programs. By predicting future watershed conditions, decisions can be made regarding the placement of future storm water improvements in order to get the most long-term value. Also, by predicting increases in runoff due to watershed development, City engineers can provide a level of protection that will be maintained even after development of the upstream watershed has taken place.

The projected land use map produced by the City of Springfield was created by estimating impervious areas based zoning information. For each type of zoning, an overall impervious percentage was estimated based on national averages. This information was combined with data from the current land use map to produce a map showing ultimate development conditions in the watershed (fig 3).

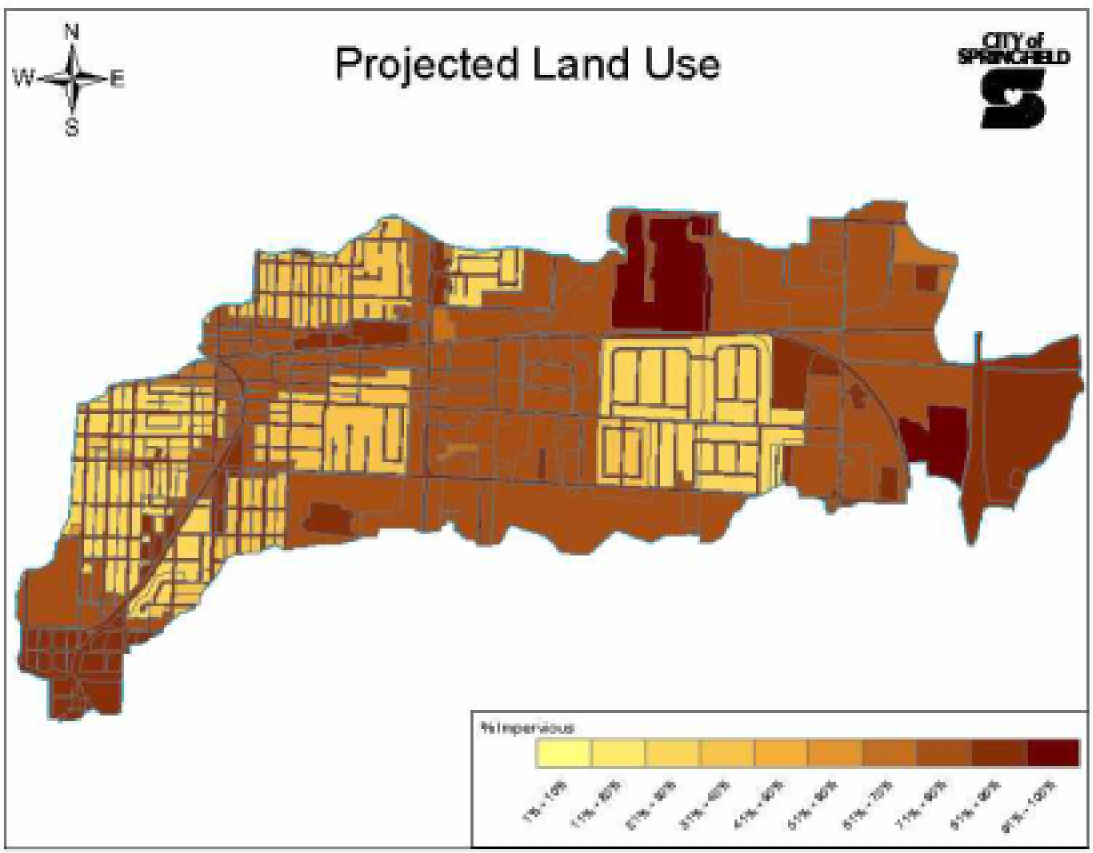


Figure 3

Creating a HEC-1 model of the Watershed

"Every model should be as simple as possible, but no simpler"-Ockham's razor

One of the most powerful applications of GIS, in regards to hydrology, is the ability to analyze watershed parameters in order to predict surface water runoff. Runoff models such as the U.S. Army Corp of Engineer's HEC-1 establish runoff hydrographs and peak flow rates to assist in the design of drainage improvements, and the delineation of flood hazard areas. GIS technology has enhanced the City's ability to create a "lumped parameter" hydrologic model of the watershed in order to predict the runoff resulting from a given rainfall situation. The basic unit of a lumped parameter model is usually taken to be a sub basin of the total watershed being considered. The sub basins used in this study are shown in the figure labeled "watershed sub basins". Each sub basin is taken as a hydrologic response unit, so that all attributes must be averaged or consolidated into unit-level parameters. (DeVantier (1993))

Many different types of watershed parameters affect the way runoff occurs. Some of these parameters, such as land slope, are a product of one type of GIS data set. Other parameters are a combination of various data types such as hydrologic soil grouping and land use. GIS gives us the ability to integrate different data layers in order to develop very descriptive parameters.

The key to effective watershed characterization involves determining the physical properties that control the runoff-response characteristics of a particular sub basin. Therefore, we must combine information such as land use, soil type, watershed slope, and channel geometry in order to obtain accurate indicators of how the watershed reacts during a storm event.

Effective watershed characterization is vital to the accuracy of any rainfall-response model. Watershed parameters for large numbers of sub basins are not easily obtained using traditional methods, simply because of the large amounts of data needed over an entire watershed. However, the use of a GIS system allows engineers to accurately lump the physical attributes of one sub basin together in order to produce an accurate hydrological model.

The following steps were taken in order to develop a HEC-1 rainfall-runoff model for the Jordan Creek watershed in Springfield Missouri.

Delineating Watershed Sub Basins

There are several techniques available that will delineate a watershed into sub basins based on a digital elevation model (DEM). These methods work relatively well in drainage areas where the slope of the landscape is primarily responsible for the path taken by runoff. However, very often in a highly urbanized setting control structures, such as culverts and detention basins, will control the boundaries of various sub basins. Therefore, all of the sub basins used in this analysis were delineated "by hand" using the 2-foot digital contour data and aerial photographs available on GIS (fig 4). It was determined that the minimum drainage area required to initiate a first order channel in this watershed was approximately 40 ac. Therefore, the area of most delineated sub basins remained close to this value.

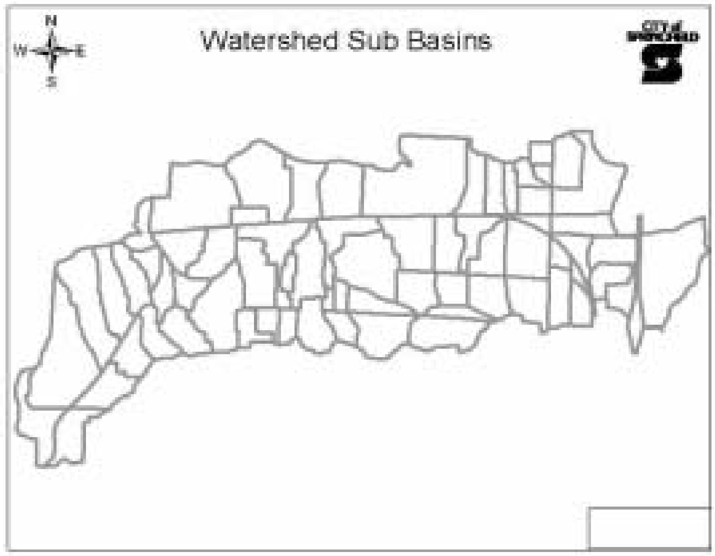


Figure 4

Field Reconnaissance of Control Structures

Strom water system mapping for much of the City of Springfield is currently available on the GIS database (fig 5). However, detailed information pertaining to many of the control structures such as culverts and detention basins were not available. In order to produce accurate rating curves used in the HEC-1 model, it was necessary to measure many of these structures in the field.

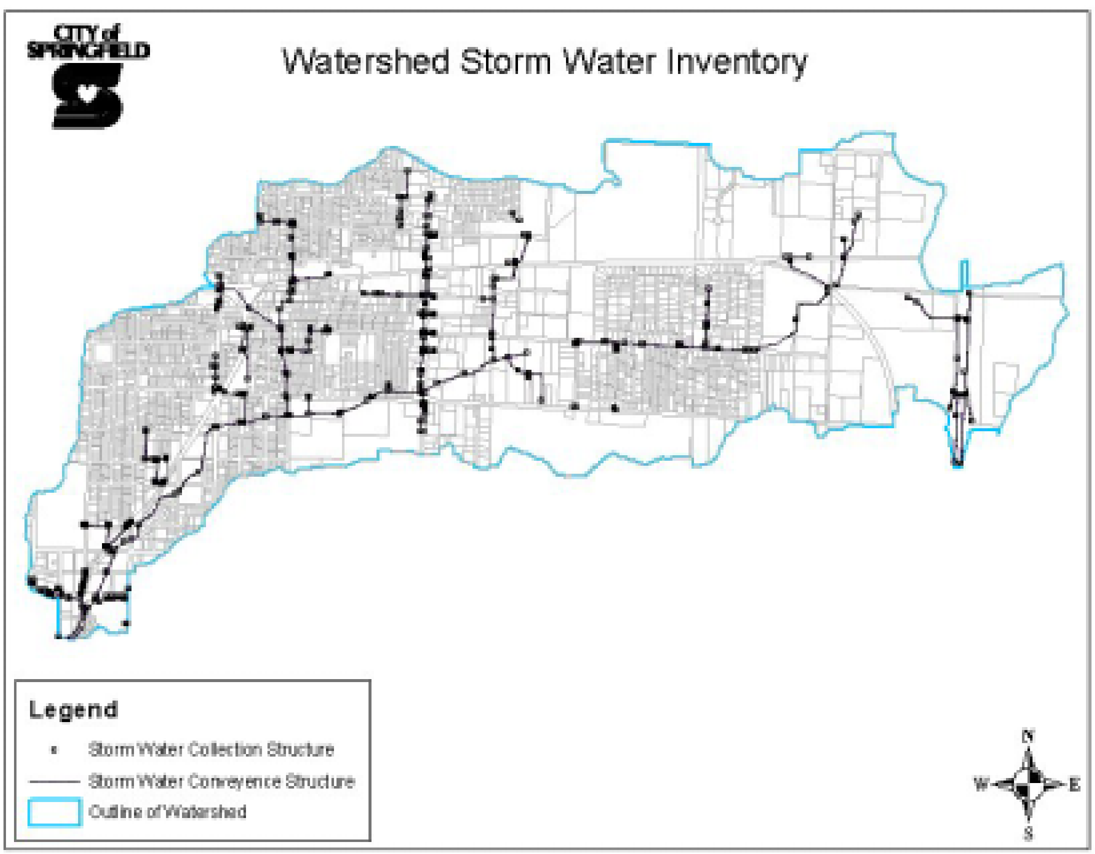
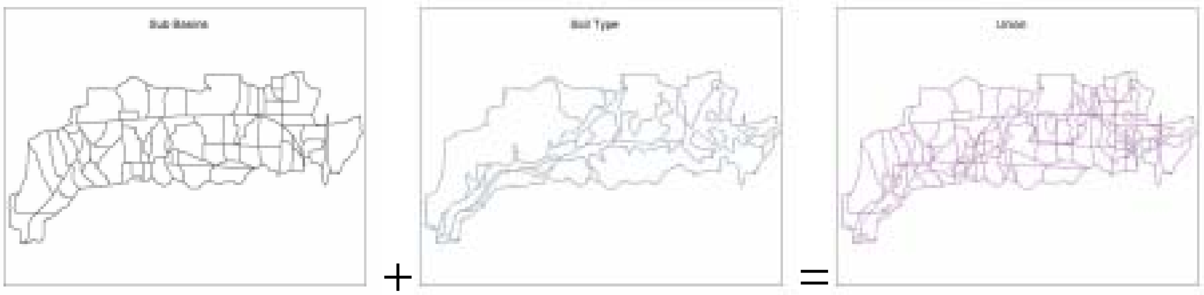


Figure 5

Incorporating land use and soil property GIS layers

As was discussed earlier, one of the primary functions of a GIS for hydrological modeling is to "lump" parameters such as runoff curve number, slope, and land use for each sub basin used in the model. This is done by combining the data layer for each attribute (runoff curve number, ultimate and current percent impervious) with the sub basin layer. Once each layer is combined with the sub basin layer, a number of unique polygons are formed within each sub basin. The following figures give an illustration of how a weighted curve number is calculated for each sub basin:



Since each of these unique polygons make up a percentage of the parent sub basin, a weighted (based on area) curve number is found for each polygon. Next, the weighted values for each polygon within the parent sub basin are added together. The sum of all weighted curve numbers within a sub basin is equal to the effective curve number for the entire sub basin (fig 6).

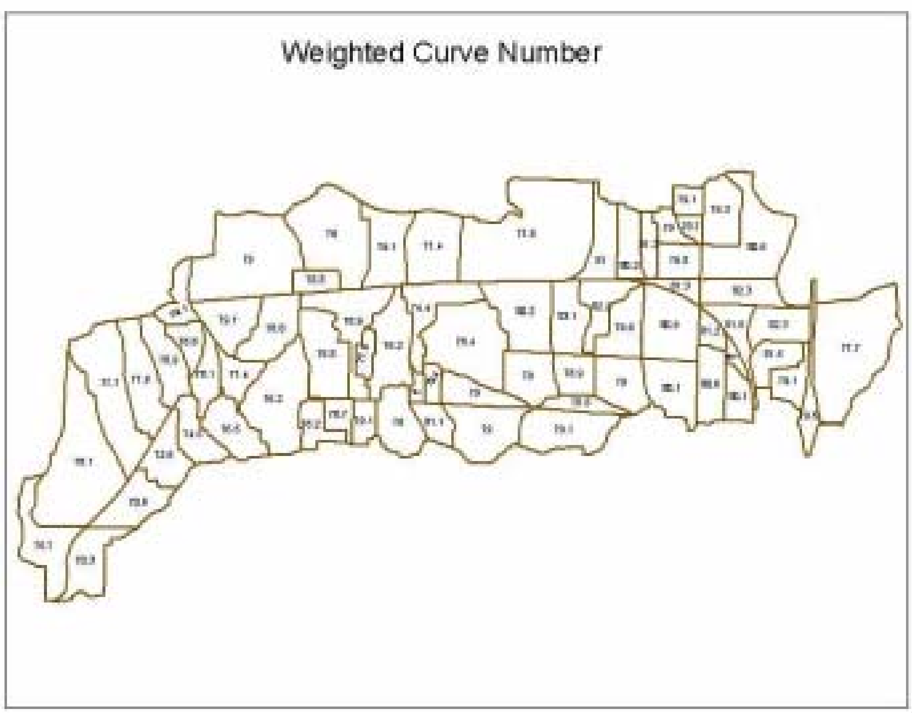


Figure 6

This method can be repeated with different data layers to produce weighted values of curve number, current percent impervious, and ultimate percent impervious for each sub basin. These values can quickly be entered into a hydrologic model. This method also removes the variability that gets introduced when these watershed characteristics are estimated using human judgment.

The results of one study showed that the prediction error of equations obtained from GIS parameters has 38 percent less error than equations obtained from lump sum parameters not derived with a GIS. (Civco (1995))

Extrapolating flow path information from ArcGIS

Once the infiltration and basin connectivity parameters have been calculated for each sub basin, attributes of the watershed that are required by HEC-1 such as overland flow length, channel geometry, channel roughness, channel length and channel slope must be obtained. This is done by examining each sub basin independently in the GIS. Flow lengths can be measured from the aerial photo and slopes can be measured using the City’s 2-foot digital contour data. An estimate of channel and overland roughness can be made based on field observations and current knowledge of the watershed.

Calibration

Calibration is the last step in creating a hydrologic model. Two methods of calibrating a HEC-1 model include 1) Checking modeled flow rates against recorded flow rates for a particular rainfall event, and 2) Comparing modeled elevations in detention areas against recorded elevations for a particular storm event. The various physical parameters of the model should be adjusted until simulated runoff values match observed runoff values.

Interactive map of flow data

Using peak flow rates obtained from the hydrologic model, an interactive flow map was created. This map works with tables in a GIS geodatabase to provide an instantaneous look at flow rates at various points within a watershed. This is an exceptionally useful tool for engineers and storm water planners who want an instant look at what is happening in the watershed.

A number of different frequency/duration simulations are performed using the HEC-1 hydrologic model and the results are exported as a frequency/duration matrix into an Excel spreadsheet. In this spreadsheet, calculated flow rates are sorted according to how the flow rate is labeled in the HEC-1 model. This data is then sent to a geodatabase table where it can be accessed through the GIS.

Using GIS, a multipoint shape file is created that contains points at locations in the watershed where flow rates have been calculated. Each of these points contains a label attribute matching it to its corresponding point in the HEC-1 model as well as the corresponding point in the geodatabase. The data in the multipoint file can then be linked to the data in the geodatabase. This allows the user to access a wide array of flow data (multiple frequency/duration combinations) from the GIS interface, simply by clicking on the point of interest (fig 7).

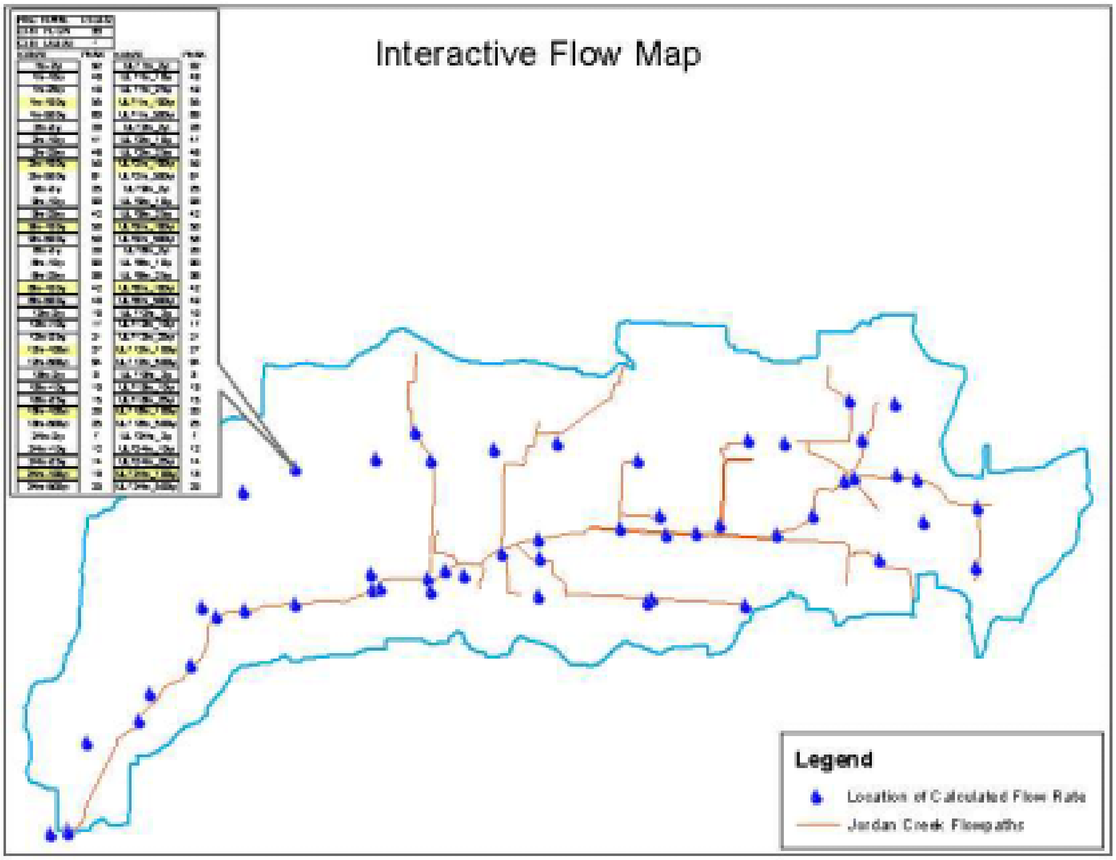


Figure 7

Defining Flood Hazard Areas

Small Scale Flood Hazard Areas

Small-scale Flood Hazard Area maps are a primary product of the Watershed Assessment approach. These are updated floodplain maps that include areas not usually included in FEMA's regulatory floodplains. Used in combination with the interactive flow map, peak flow rates and flood hazard boundaries can be observed simultaneously for watercourses with a contributing drainage area greater than 40 acres.

Once peak flow rates are estimated, the channel geometry corresponding to each watercourse or channel must be modeled in HEC-RAS. Geometric data needed for this model was obtained by either traditional level survey methods, existing public improvement plans, or through the use of an automated software package such as HEC-GeoRAS. Once a water surface elevation has been established for each river reach, a floodplain is delineated by hand using the City's 2-foot digital contour data.

The flood hazard map goes beyond the 1-square mile drainage area limit typically seen on FEMA Flood Insurance Rate Maps and allows cities to regulate development in areas prone to flooding that may not be located in a FEMA floodplain (fig 8). These maps also provide on overview of flooding problems and can prove to be invaluable for master planning public improvement projects throughout the watershed.

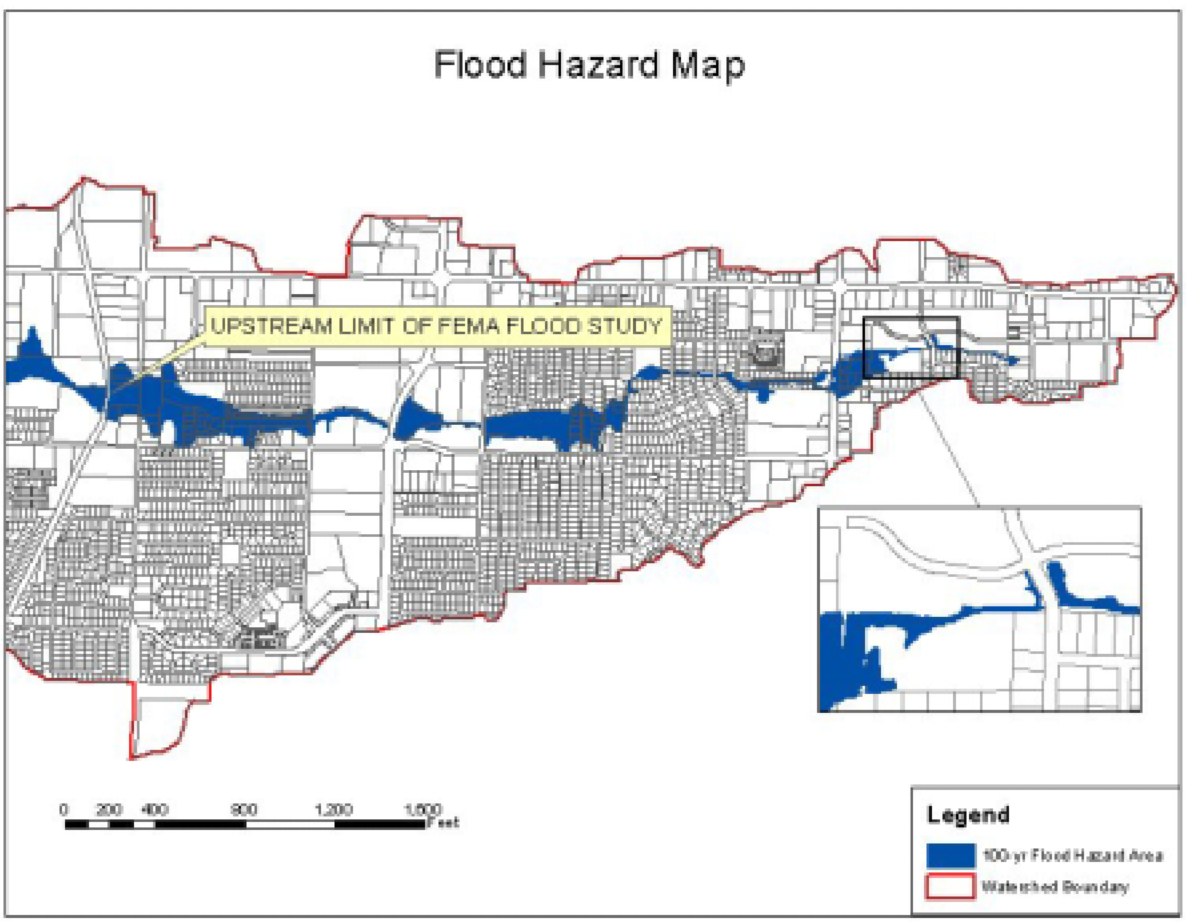


Figure 8

Sinkhole Flood Hazard Areas

Due to the karst topography common in southwest Missouri, many flooding issues tend to be related to one of 250 sinkholes within the City. As part of the watershed assessment process, nearly all sinkholes within the City have now been re-mapped using 2-foot digital contour information (fig 9). Each sinkhole and its drainage area were independently studied and a 100-year flood elevation was calculated and delineated for both current and ultimate development conditions. The GIS allows users to access information about each sinkhole, such as the 100-year water surface elevation, by simply clicking on a sinkhole of interest. These sinkhole flood areas provide yet another tool for City officials to manage projects and regulate development within a watershed.

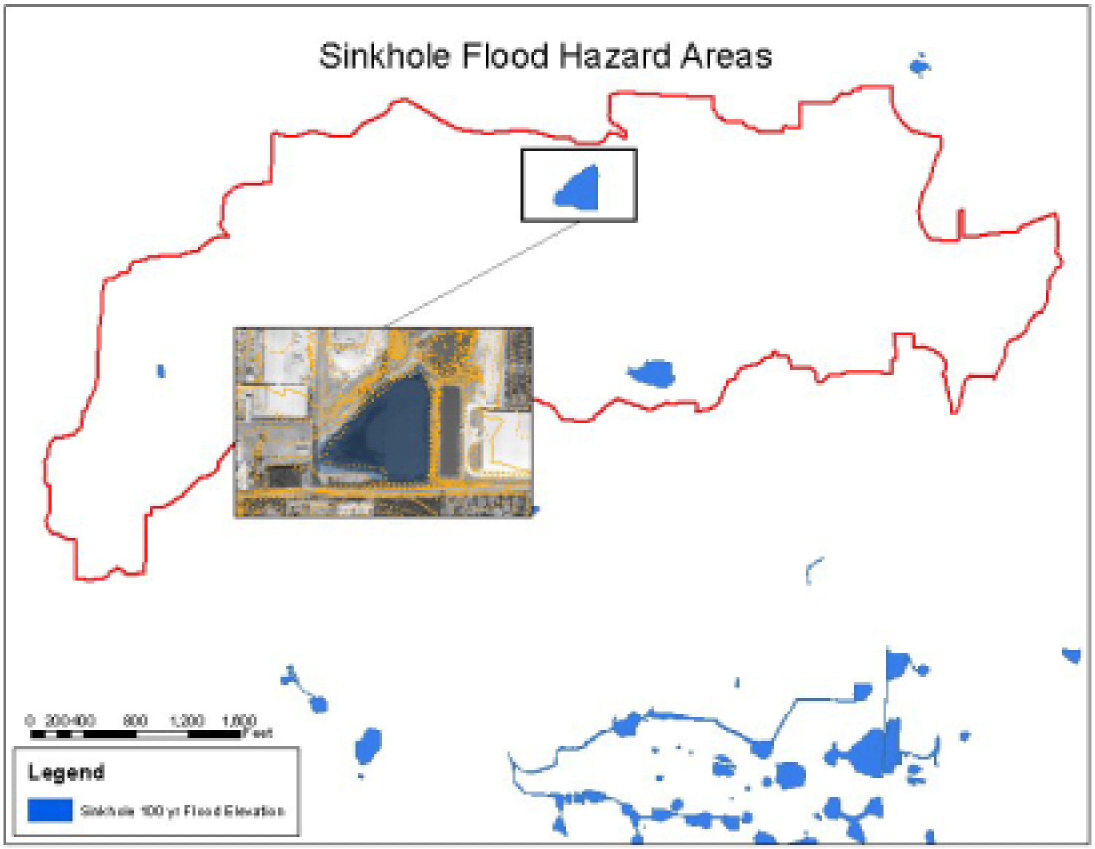


Figure 9

Stream Protection Buffers

With an increasing focus in recent years regarding the importance of stream stability and water quality, the City of Springfield is seeking to preserve the natural state of our waterways. The implementation of stream protection buffers encourage all new developments to maintain a specified buffer distance from all drainage ways that have a contributing drainage area greater than 40 acres. The buffer width is directly proportional to the amount of upstream contributing area. The advantages gained with the stream buffer system are that a series of stream buffers can be constructed in a relatively short amount of time when compared to traditional hydraulic modeling techniques. However, a stream buffer distance must be chosen that will not only protect property and stream corridors but must also allow properties reasonable space for development.

In order to produce a set of stream buffers, a digital elevation map (DEM) was constructed. Using the software Arc Hydro, a grid-based data set is produced that gives a value of upstream contributing area for every grid cell. All grid cells with a contributing area greater than 40-acres are then converted to a polyline shapefile. This shapefile is then "buffered" a certain distance based on the amount of upstream contributing area for each line segment. The finished produce can be viewed in GIS as shown in figure 10.

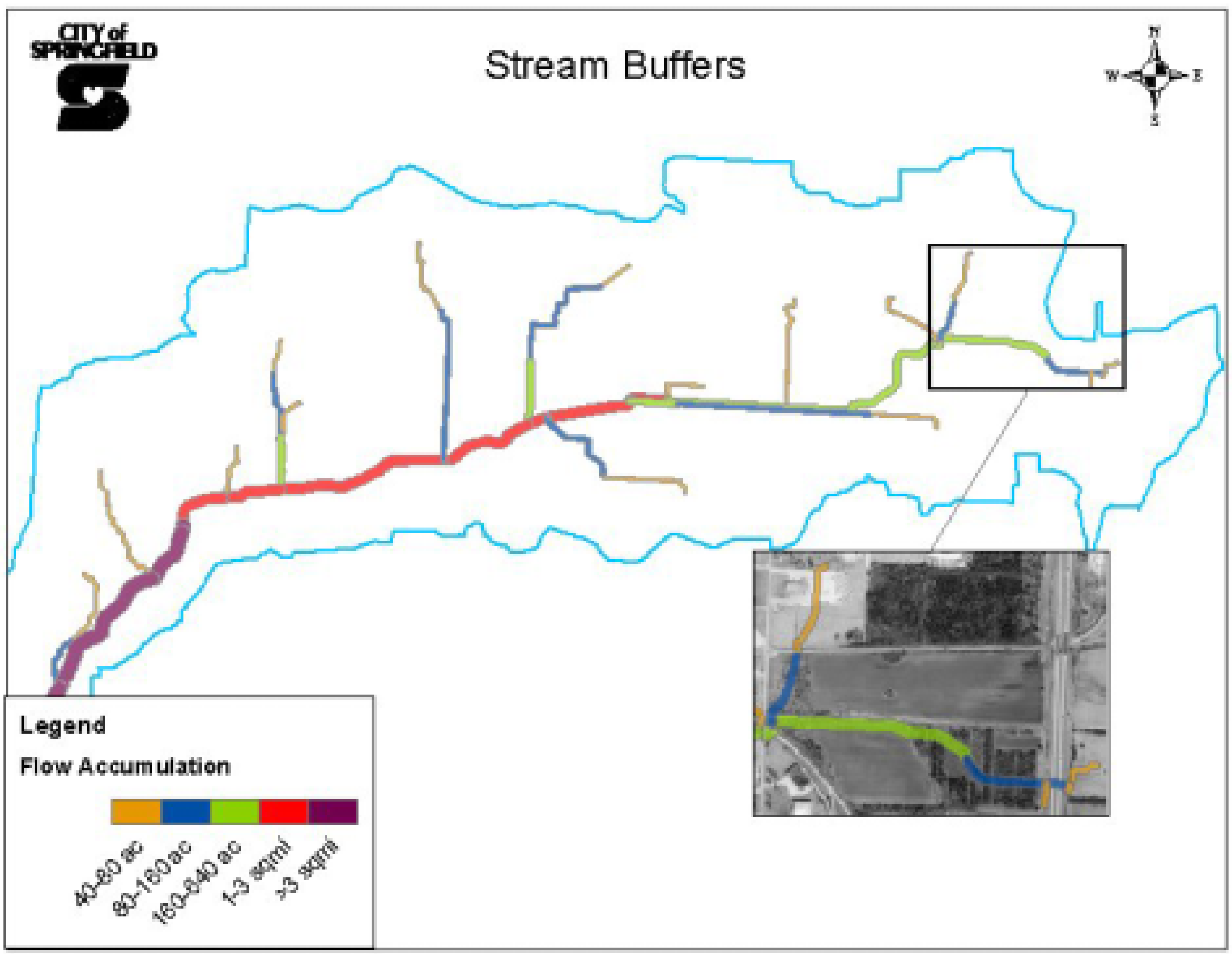


Figure 10

Conclusion

The watershed assessment process has provided the City of Springfield with some very useful and informative tools for managing watersheds. Results from each watershed study can be assembled into a series of paper maps that can then be bound into a book. These books can make information readily available to consultants and planners who are working on projects within the watershed. Future additions to the City's watershed assessment program include locations of storm water complaints and tracking of subsurface water movement.

A large-scale watershed assessment could never be managed without the use of ESRI's ArcView GIS. This GIS platform provides a vast number of specialized tools and data storage options that make for an unlimited number of watershed management possibilities.

Appendixes

References

DeVantier, Bruce A., Feldman, Arlen D. (1993). "Review of GIS Applications in Hydrologic Modeling." Journal of Water Resources Planning and Management, Vol. 119, No.2, March/April, Paper No. 3607, p. 246-259

Civco, Daniel L., Garcia, Andres R, Warner, Glenn S. (1995). "Key Steps to Effective Watershed Characterization." GIS World Inc. 155E. Boardwalk Drive, Suite 250, Fort Collins, CO 80525, p.62-67

Author Information

Errin Kemper, EIT

Errin is a graduate of the University of Missouri-Rolla and is currently working as a storm water analyst for the City of Springfield, Missouri.

Todd Wagner, PE

Todd is the Principal Storm Water Engineer for the City of Springfield's Storm Water Services Division. He has a B.S. and M.S. in Civil Engineering from the University of Missouri-Rolla.