

# A GIS Approach to Watershed Modeling in Maricopa County, Arizona

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**Abstract:** Most conventional rainfall-runoff modeling methods are tedious and time-consuming. The Watershed Modeling System (WMS) is a comprehensive computer software application for watershed characterization and rainfall-runoff modeling in a graphical user interface environment. Through several GIS operations and tight integration with GIS databases, WMS enables hydrologists and water resource engineers to perform rainfall-runoff modeling more efficiently than conventional modeling methods. In this paper, methods of computing hydrologic parameters for the Flood Control District of Maricopa County are discussed, and demonstrated by applying them to the Gavilan Peak Watershed. This watershed is located in the vicinity of the community of New River in northern Maricopa County, Arizona.

## Introduction

Hydrologic modeling is one of the many natural applications of Geographic Information Systems (GIS). Using GIS software, digital elevation data can be used to define the drainage basin boundaries, create stream networks, and compute drainage basin data. Once computed, several important variables, such as area, slope, and runoff distances, important to hydrologic analysis, can be determined. With grid-based elevation data readily available, it is a relatively simple task to define the extents of drainage basins and compute sub-basin parameters. However, drainage basin delineation and basic parameter computation is only the first step in developing data for a lumped parameter model such as HEC-1. Further processing of land use, soil, and rainfall data are equally important to developing the model.

The HEC-1 model has been the standard for hydrologic analysis in Maricopa County for years. To use lumped parameter watershed modeling programs like HEC-1, the sub-basin data values at each grid cell in a GIS must be "lumped" into a few data values (such as a runoff coefficient and watershed response time) for the entire sub-basin.

Aggregation of GIS data to a format that is usable by a lumped parameter watershed model is a daunting task. A program called the Watershed Modeling System (WMS) has been developed that has the capability of automating watershed delineation and parameter calculation from digital elevation data, importing GIS data, extracting important watershed information from the GIS database, running hydrologic modeling programs, and viewing the results of those programs.

The focus of this research was to create hydrologic models using available GIS data and the standard Flood Control District of Maricopa County hydrograph computation procedures. The methods described here were implemented for use in the WMS so the entire model could be developed within a single application program.

## Overview

The purpose of this study was to create a more efficient method of creating HEC-1 models as described in the Drainage design manual for Maricopa County, Arizona (Sabol et al., 1995).

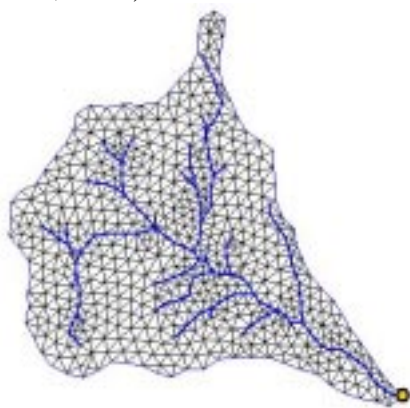
The WMS was chosen because it already has the capability to delineate watershed boundaries and develop standard HEC-1 models using TIN or grid-based digital elevation models. Once delineated, important geometric parameters can be computed and used to create input files for commonly used hydrologic models such as HEC-1, TR-20, TR-55, and others. Because important data used for hydrologic model development are often stored in a GIS, several import/export options have been developed to provide a mechanism for seamless data transfer. To specifically accommodate the Maricopa County data and hydrologic modeling methods, routines were added to the WMS to automatically compute Green and Ampt loss parameters, sub-basin times of concentration, and Maricopa county unit hydrographs generated from pre-defined S-graphs.

## Linking GIS Data to Hydrologic Data

The primary purpose of watershed modeling is to determine the drainage area that contributes flow to an outlet, or confluence point. Determining this area is known as drainage basin delineation. After the area of land is determined for a single watershed or several sub-basins, hydrologic information can be determined and a hydrologic model used to compute the flow characteristics at that outlet point. While many raster (grid) based GIS' support watershed delineation from grids, watershed models in WMS can be developed using one of three different data sources—TINs, grids, or map-based vector data. An overview of how this is done is outlined in the following sections.

### ***TIN-Based Watershed Models***

TIN (*Triangulated Irregular Network*) based watershed models (Figure 1) consist of a set of vertex points, connected by triangles, that represent scattered X, Y, and Z locations. These vertex locations can be randomly dispersed throughout the watershed, and their triangulation represents a piece-wise linear surface that honors each of the vertices (Jones et al, 1990).

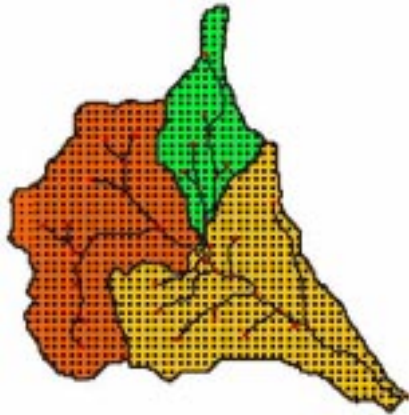


**Figure 1: A TIN-Based Watershed Model**

TINs for basin delineation can be created from digitized contour maps, randomly surveyed elevation points, or from existing gridded elevation data sources such as the USGS DEMs using an adaptive tessellation method as described by Nelson, Jones, and Berrett (1999). Watershed boundaries are delineated from TINs by identifying "outlet" locations, then tracing flow paths along the path of steepest descent and combining together triangles whose flow paths pass through a common outlet point (Nelson et al, 1994). The advantages of using a TIN based model for watershed delineation is that they generally require less memory than grids, and linear features such as streams, ridges, and roads can be accurately represented using triangle edges.

### ***Grid-Based Watershed Models***

Grid-based watershed modeling methods use a rectangular elevation grid as a background for creating a watershed model. In the grid-based method, the direction of flow is computed for each elevation cell in the grid using methods such as those developed by Puecker (1975) and refined by Garbrecht and Martz (1995) among others.



**Figure 2: A Grid-Based Watershed Model**

Like flow paths on a TIN, the flow directions are then used to determine which grid cells contribute flow to specified outlet points to delineate watershed and sub-basin boundaries (Figure 2).

Grid-based watershed modeling provides the following advantages:

- Grids have a simpler data structure than TINs.
- An abundance of grid-based data is available.
- A grid-based model is reproducible.

### ***Map-Based Watershed Models***

Map, or vector GIS-based watershed models, are based on data types in a vector-based GIS. Points or nodes can be used to represent outlet points, arcs (polylines) can be used to represent streams, and enclosed polygons can be used to represent watershed and sub-basin drainage boundaries (Figure 3).



**Figure 3: A Map-Based Watershed Model**

Map-based watershed modeling is extremely useful. It has all the qualities of TIN-based modeling (it is adaptive, linear features can be represented, and a small amount of memory is required). In addition, drainage boundaries and streams in GIS format can be directly used to define a map-based model. However, in the map-based method, automated sub-basin delineation is not available since elevation data do not exist.

### ***Computing Hydrologic Data in the WMS***

After defining watershed and sub-basin boundaries, important parameters for hydrologic model development, such as area, slope, and runoff distance must be determined. The WMS provides tools to compute some hydrologic data using the geometric properties of each sub-basin. Other hydrologic parameters required for Maricopa County can be computed by importing and using existing GIS land use and soil type data layers.

#### **Compute the Sub-basin Data**

Each sub-basin's area, maximum flow distance, slope along the maximum flow distance, and other geometric parameters can be automatically computed after a watershed model has been created (slopes and runoff distances cannot be computed if a map-based delineation is being used). Hydrologic models directly use many of these parameters, and others are important in calculating supplementary data such as the time of concentration or lag time. For Maricopa County, procedures for automating computations of the following HEC-1 parameters have been incorporated in the WMS and were tested as part of the Gavilan Peak model: basin times of concentration and/or lag times, Green & Ampt infiltration parameters, and unit hydrographs.

#### **Computing Time of Concentration and Lag Time**

Maricopa County uses the Clark unit hydrograph method extensively. This method requires the time of concentration for each sub-basin. In addition, Maricopa County requires the Lag Time for each sub-basin in their S-graph method (Sabol et al., 1995). The time of concentration is given by the following equation:

$$T_c = 11.4L^{0.50} K_b^{0.52} S^{-0.31} i^{-0.38}$$

Where:

$T_c$  = time of concentration (hours).

$L$  = length of the flow path for  $T_c$  (miles).  
 $K_b$  = representative watershed resistance coefficient.  
 $S$  = watercourse slope in feet/mile.  
 $i$  = the average rainfall excess intensity, during the time  $T_c$ , in inches/hour.

The length of flow path and watercourse slope can be computed from elevation data by determining the flow path from an upstream point in each sub-basin. Values of  $K_b$  and  $i$  must be defined to compute  $T_c$ . However, methods for incorporating tables and automating computation using standard Maricopa County procedures are currently under investigation.

The lag time is given by the following equation:

$$Lag = C \left( \frac{LL_{ca}}{S^p} \right)^m$$

Where:

$Lag$  = basin lag (hours).  
 $L$  = length of the longest watercourse (miles).  
 $L_{ca}$  = length along the watercourse to a point opposite the centroid (miles).  
 $S$  = watercourse slope (feet/mile).  
 $C$  = coefficient.  
 $m, p$  = exponents.

The watercourse lengths and slopes can automatically be computed from the geometry of a watershed model. Coefficients for Maricopa County are defined in Sabol et al. (1995) and have been incorporated in WMS so that lag time computations for sub-basins can be automated.

### Computing Green-Ampt Loss Parameters

One method of determining the amount of precipitation that infiltrates into the soil during a precipitation event was developed by W. H. Green and G. A. Ampt in 1911 (Sabol et al., 1995). The basic equation for the Green and Ampt model is given by the following equation:

$$f < i, f = K_s \left( 1 + \frac{\psi\theta}{F} \right)$$

$$f \geq i, f = i$$

Where:

$f$  = Infiltration rate (L/T).  
 $i$  = Rainfall intensity (L/T).  
 $K_s$  = Hydraulic conductivity, wetted zone, steady-state rate (L/T).  
 $\psi$  = Average capillary suction in the wetted zone (L).  
 $\theta$  = Soil moisture deficit (dimensionless), equal to the effective soil porosity times the difference in final and initial volumetric soil saturations.

$F$  = Depth of rainfall that has infiltrated into the soil since the beginning of rainfall ( $L$ ).

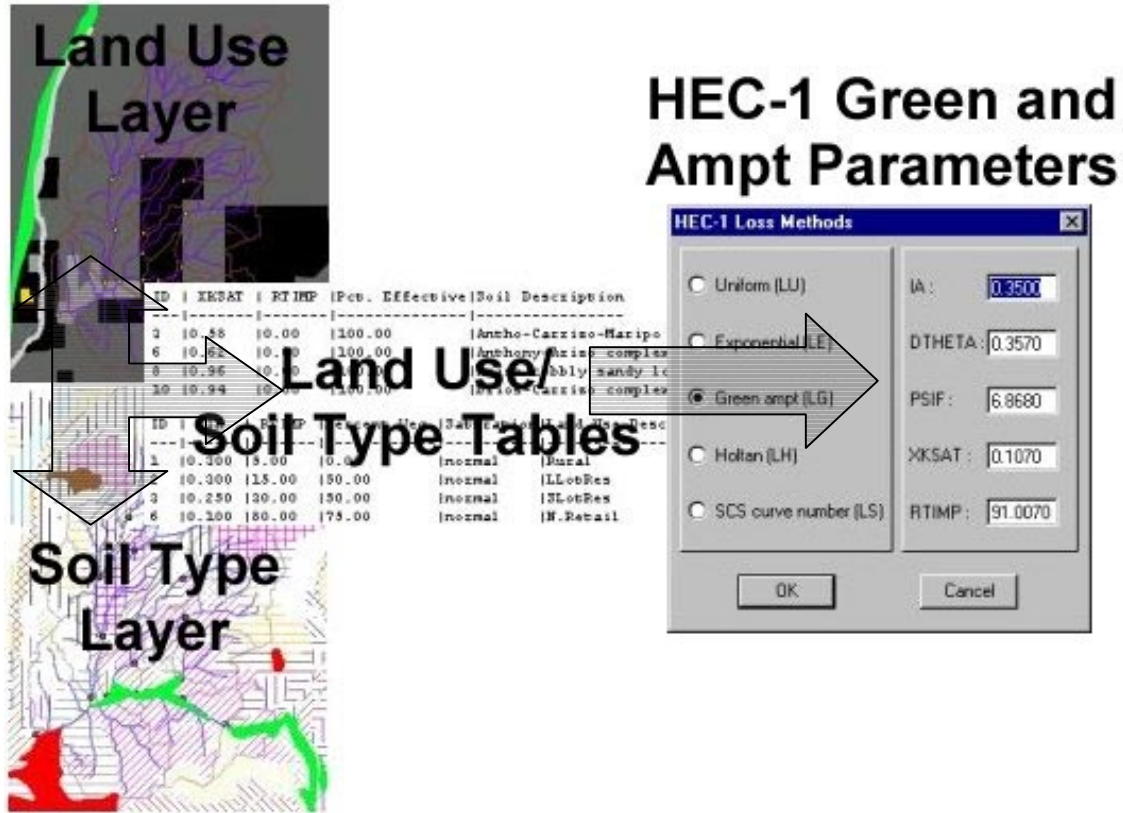
The Green and Ampt method is one of the available rainfall loss methods that have been incorporated into HEC-1. The Green and Ampt model is an accurate, physically based model for determining infiltration, and has been adopted by the Flood Control District of Maricopa County as the method of choice when creating rainfall-runoff models. However, the input parameters for the Green and Ampt model are difficult to determine because of either the lack of existing data or the cost in performing the tests required to determine them.

Because Maricopa County uses this method, soil type and land use data have been gathered into a GIS so that Green and Ampt parameters can be determined for any watershed affecting the region. A method for computing the Green and Ampt parameters for each sub-basin is outlined in the Maricopa County Drainage Design Manual (Sabol et al., 1995) and has been incorporated in the WMS.

The following data are required to compute Green and Ampt parameters:

- A land use polygon layer with land use IDs assigned to each polygon.
- A soil type polygon layer with soil IDs assigned to each polygon.
- A table relating each land use ID to initial abstraction (IA), land percent impervious (RTIMPI), percent vegetation (Percent Veg.), and a saturation value.
- A table relating each soil ID to hydraulic conductivity (XKSAT), soil percent impervious (RTIMPs), and percent effective (Pct. Effective).

Figure 4 illustrates how these data are combined/overlaid to compute the Green and Ampt parameters.



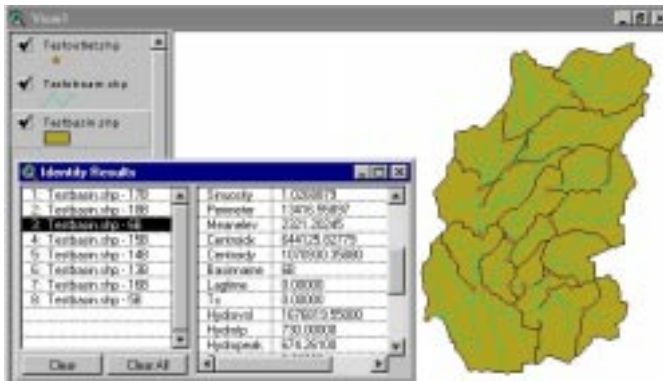
**Figure 4: Computing Green and Ampt Parameters**

### Computing Maricopa County Unit Hydrographs

Most lumped parameter models are based on unit hydrographs, either synthetic or derived. A unit hydrograph represents the volume of runoff from a watershed for a unit depth (1-inch) over the entire watershed. Multiplying ordinates of the unit hydrograph by the total rainfall for a storm will yield the actual storm hydrograph. Maricopa County has developed a series of S-graphs for different regions of the county so that a unit hydrograph corresponding to the appropriate storm duration can be generated for use in HEC-1 models. The county has been divided into four sections, each using a different S-Graph (Phoenix valley, Phoenix mountain, desert rangeland, and agricultural). Unit hydrographs for watershed models in these regions are computed in WMS by specifying the appropriate region and then using lag time as computed from the equations above.

### Exporting Computed Hydrologic Data to a GIS

Once a watershed model and all its hydrologic data has been defined, the model can be run in HEC-1. After running HEC-1, computed hydrographs and peak flow data can be viewed. All the resulting data can then be exported to a GIS using the ArcView<sup>®</sup> shapefile format (Figure 5). This allows hydrologic information to be overlaid with other county data layers to further aid in making county development decisions.

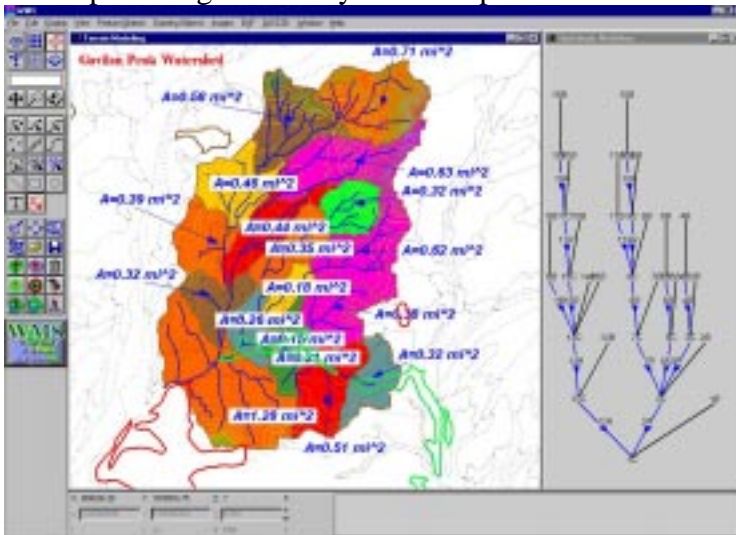


**Figure 5: Sub-basin data Exported to the ArcView® GIS**

Watershed boundaries derived from TINs, DEMs, or map-based vector data can also be converted to ArcView shapefiles.

### Case Study: The Gavilan Peak Watershed

In order to test the Maricopa County hydrologic modeling procedures as implemented in WMS, a watershed model with 17 sub-basins was successfully delineated for the Gavilan Peak Watershed in the vicinity of the community of New River in northern Maricopa County, Arizona. Hydrologic parameters were defined using the methods outlined, the HEC-1 model was run, and the resulting hydrographs were compared with hydrographs developed using the county's current practices. The final model is shown in Figure 6.



**Figure 6: The Gavilan Peak Watershed Model**

Using current county practices, basic GIS operations were used to determine some values, such as the percentage of each kind of land use in a sub-basin. After these parameters were determined, time of concentration and Green Ampt parameters were calculated using a calculator or simple, stand-alone computer programs.

One of the primary purposes of this study was to compare results of key parameters computed by WMS with the same parameters computed using current practices. Table 1 compares and shows that there is excellent agreement between the Green and Ampt parameters computed in the WMS with current practices for a single sub-basin:

**Table 1: Comparison Between WMS and Hand-Computed Green Ampt Parameters**

<i>HEC-1 Parameter</i>	<i>WMS Value</i>	<i>Hand-Computed Value</i>
IA	8.18 mm	8.17 mm
DTHETA	0.304	0.303
PSIF	167.13 mm	167.64 mm
XKSAT	3.33 mm/hr	3.42 mm/hr
RTIMP	30.39 %	30.34 %

Because WMS has tools for automatically computing Green Ampt parameters, Time of Concentration, and other modeling parameters all in a single application, it can be used to model watersheds more efficiently and timely than with traditional methods.

## **Conclusion**

Conventional rainfall-runoff modeling methods can be tedious and time-consuming. Using GIS data, hydrologists and water resource engineers can perform rainfall-runoff modeling in a fraction of the time required by conventional modeling methods. Both hydrologic and geometric watershed parameters can be computed using GIS-based methods.

These GIS methods in WMS were effectively used to compute geometric and hydrologic watershed data for a watershed in Maricopa County, Arizona. After HEC-1 data were defined, the HEC-1 model was run and the results were viewed in a GIS. Some features were customized in the WMS to facilitate the transfer and computation of watershed data between a GIS and HEC-1.

The following summarizes the advantages of using GIS and the WMS over the current Maricopa County hydrologic method:

- USGS 7.5' quadrangles, aerial photographs, and streams in digital format can be imported to automatically delineate a watershed and compute the geometric parameters for each sub-basin.
- Soil maps and land use maps in GIS format can be used to calculate the Green-Ampt rainfall loss parameters for each sub-basin.
- The Maricopa County S-graph unit hydrograph is automatically computed for each sub-basin.
- Development of time of concentration and lag time for each basin can be determined from computed watershed parameters and/or flowpaths in GIS vector data format.
- An HEC-1 input file is automatically generated by the WMS.
- HEC-1 can be started, and the results visualized in the WMS.
- The sub-basin boundaries, streams, and concentration points, along with all relevant data including peak flows, times to peak, and runoff volumes, can be exported in GIS format.
- Time can be saved over previous computation methods.

## Appendix I. Reference

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