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Calculation of time of concentration for hydrologic design and analysis using geographic information system vector objects

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ABSTRACT

Synthetic unit hydrographs are commonly used to estimate runoff from rainfall events in a hydrologic analysis. A key parameter required as part of any hydrologic analysis using a synthetic unit hydrograph is time of concentration or lag time. Generally, equations used to compute time of concentration or lag time are empirically derived from basin parameters such as area, slope, and a specific flow path length. A more realistic method for determination of flow path travel time is to divide the flow path according to different hydraulic conditions such as sheet flow, shallow concentrated flow and open channel flow as specified in the NRCS method using TR55. Such equations are all based on flow length and the slope of the flow path, two parameters that are easily calculated from GIS vector objects. A method is presented that uses GIS vector objects with equations assigned for the calculation of time of concentration or lag time for use in hydrologic analysis and design.

Key words | time of concentration, lag time, hydrology, flow path

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INTRODUCTION

Many hydrologic analyses use unit hydrograph synthesis to predict rainfall runoff from a watershed. Since measured stream flow/rainfall data for a particular point of analysis is rarely available, a fundamental part of the development of a runoff hydrograph is the use of a synthetic unit hydrograph such as the SCS (USDA, 1985) or Clark (1945) unit hydrographs. Both of these unit hydrograph methods (as well as most others) require the estimation of a time of concentration or lag time.

With the advent of GIS and the ability to process spatial data, including digital elevation models (DEMs) and triangulated irregular networks (TINs), the ability of estimating travel times from watershed geometric data has been realized. These methods, which use empirical equations, generally require the use of lumped basin values such as basin area, average slope and length. These empirical equations do not allow computations to be made using the actual flow paths, and resulting computations within a GIS from such methods become a black box to engineers. Further, they do not allow for visual or manual verification of the accuracy of the flow path and the variables used in the equation.

Hydraulically based flow equations (i.e. Manning's equation) have been developed to more accurately represent travel times, but the parameters for these equations are more difficult to estimate than in the 'black box' type of processing that is typical of GIS systems, especially when a model becomes complex with several interior sub-basins. However, while it is difficult to automate all calculations of travel time within a GIS, something that is not necessarily a desired approach, many of the parameters required could easily be extracted from geographic data. The assistance of a GIS can greatly improve the speed and accuracy with which these parameters can be estimated and travel times computed. Two such parameters common to all of these equations are length and slope.

A new approach for computing more representative travel times is to assign these equations as attributes to lines stored in a GIS and then allow for a visual choice of a representative flow path. Techniques for automating paths of steepest descent (Nelson *et al*. 1994; Martz & Garbrecht 1992) can be used to determine flow paths from points on digital terrain models in order to assist the development of lines used to define the time of concentration or lag time equations. The database attributes of such flow path lines can then be used to store the necessary parameters for a selected equation. Attributes such as length, slope and roughness can then be measured directly from the flow path lines, or extracted from other geographic layers such as a digital terrain model or land use map.

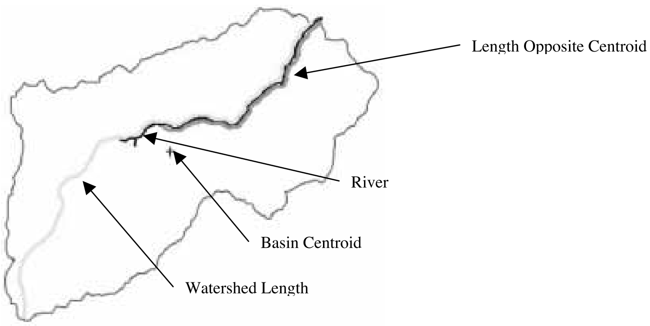


Figure 1 | Parameters for computing lag time and time of concentration from basin data.

TRAVEL TIME EQUATIONS

Travel time equations are used to estimate the time of travel at a particular point within a watershed (generally the furthest point) to the watershed outlet. Travel time is dependent on many parameters including length and slope of the flow path, ground surface roughness (land use classification), rainfall intensity and conveyance medium. These parameters can be difficult and time consuming to estimate. Because of the difficulty in defining complete flow paths and determining the necessary parameters; empirical equations have been developed from basin average parameters to simplify the estimation of travel time. As a result of hydrologic model development, two different classifications of travel times have emerged and become commonplace. They are time of concentration and lag time. Since equations for the computation of lag times are sometimes used for determining a time of concentration (or vice versa), the SCS has developed a relationship between the two:

$$T_{\mathrm{LAG}} = 0.6T_C \tag{1}$$

where T_{LAG} is the lag time and T_{C} is the time of concentration.

Lag time equations

Lag time is defined as the time from the centroid of rainfall excess to the time of peak runoff for a watershed (Wanielista *et al*. 1997). Methods that use lag time include the SCS synthetic unit hydrograph, among others (Cabeza & Shoopman 1996). Many of the empirical equations used to estimate lag time from geographic data are of the form shown in Equation (2):

$$T_{\mathrm{LAG}} = C_{\mathrm{t}} \frac{(LL_{\mathrm{ca}})^m}{\sqrt{S}} \tag{2}$$

where C_{t} accounts for the difference in watershed slope and storage (generally determined from experimental data for different classes of watersheds), L is the length of the watershed along the main channel from the point of reference to the upstream boundary of the watershed, L_{ca} is the distance along the main channel from the point of reference to a point opposite the centroid, S is the slope and m is the lag exponent. Figure 1 identifies these parameters for an actual flow path.

A primary limitation of this class of equations is that runoff parameters are ‘lumped’ into a single equation to generalize the flow path and runoff of the entire basin. Most of the variability is represented by the coefficient and exponent. The actual flow path will traverse areas that are of different slopes, land uses, and other hydraulic conditions. While this might be accurate for homogenous basins, more heterogeneous basins will require the area to be divided or use a different set of equations.

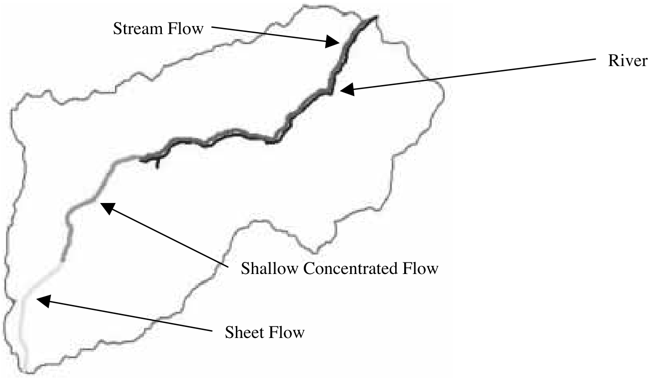


Figure 2 | Parameters for computing lag time and time of concentration from feature lines.

Time of concentration equations

One definition for time of concentration is the longest travel time it takes a particle of water to reach a discharge point in a watershed (Wanielista *et al.* 1997). While some methods of computing time of concentration are developed from single, lumped parameter empirical equations, such as Equation (2), others divide the flow path up into different hydraulic flow conditions and then sum the travel time from the separate segments of flow. One set of equations commonly used in the United States are the TR55 equations used to estimate time of concentration in a TR55 analysis (USDA 1986).

The TR55 equation group is divided into three classes of flow, including sheet flow, shallow concentrated flow and channel flow, as seen in Figure 2.

Sheet flow is used to describe flow at the headwater of streams. Typical recommendations include that this segment of flow be less than 300 feet:

$$T_t = \frac{0.007(nL)^{0.8}}{(P_2)^{0.5}S^{0.4}} \tag{3}$$

where T_t is the travel time in hours, n is Manning's roughness coefficient, L is the flow path length in feet, P_2 is the 2-year, 24-hour rainfall in inches and S is the slope of the hydraulic grade line (ground slope) in ft/ft.

After the initial sheet flow, an equation describing shallow concentrated flow is used until the flow path can be represented as open channel flow:

$$T_t = \frac{L}{3600V} \tag{4}$$

where T_t is the travel time in hours, L is the flow length in feet and V is the average velocity in ft/s. Velocity for shallow concentrated flow is computed from the following equation:

$$V = c\sqrt{S} \tag{5}$$

where c is a constant, dependent on whether there is pavement, and S is the average slope.

Finally, once the flow path reaches a channel, curb and gutter, or other hydraulic condition where travel time can be estimated using open channel flow equations, Manning's equation is used to develop the velocity used by Equation (4):

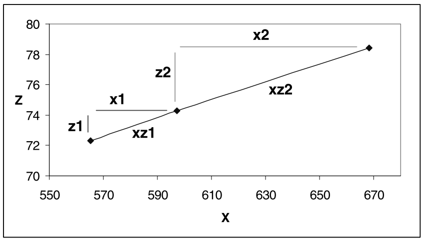
$$V = \frac{k}{n}R^{2/3}S^{1/2} \tag{6}$$

where V is the velocity, k is a units factor (1 for SI and 1.49 for English), n is Manning's roughness, R is the hydraulic radius and S is the slope.

The actual flow path used to compute time of concentration can theoretically be broken up into any number of flow path segments, each with its own equation (such as the TR55 equations listed above) in order to estimate the overall travel time.

USING GIS VECTOR DATA LINES

GIS vector data are a combination of geographic entities (points, lines and polygons) and their associated database attributes. They can be thought of as CAD data combined with a database. Because travel time equations are defined from linear flow paths, a line object is the natural choice to represent the flow path. The attributes or database for



Segment	Length
x1	31.90
x2	71.20
z1	1.94
z2	4.13
xz1	31.96
xz2	71.32

Figure 3 | Calculating slope from three-dimensional lines.

such lines are the associated parameters required as input to any one of the equations (the actual attributes of a given line will depend on the type of flow equation assigned to it). The common parameters in these equations include slope and length as well as some measure of surface roughness over which the flow path moves. Since a given line may be comprised of several segments, the slope is derived by averaging all line-segment slopes found by taking the difference in z (elevation) of the two vertices and dividing that by the length of that single segment. The length can be either the 3D distance or the projected 2D distance, as the equation requires. Although the differences in the computed distances are small, they may have application depending on the intended equation. Either is easily calculated using a GIS. If the slope from the line in Figure 3 used the 3D distance, the slope would be

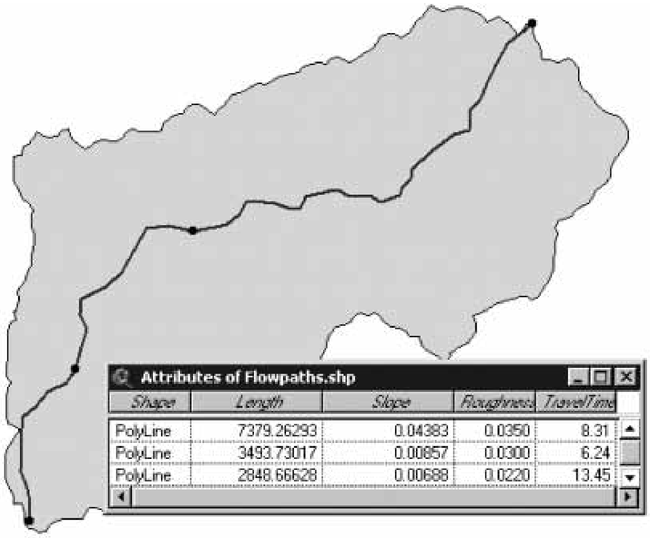
$$6.07/(31.96+71.32)=0.0588.$$

Using the 2D distance, the slope would be

$$6.07/(31.90+71.20)=0.0589.$$

The line object is used to store travel time equation parameters, but also serves as a visual representation of the flow path, allowing the engineer to double check that the flow path is representative and accurate.

Line segments, together with the key parameters such as length, slope, roughness, etc., can be maintained in a GIS database as depicted in Figure 4. The parameters used by the different possible equations for computing lag time or time of concentration are stored as database attributes of the line segments. A computer application or script can then be developed to solve the time of travel computation based on the stored attributes and a travel time for the line segment stored as an additional attribute.



Shape	Length	Slope	Roughness	TravelTime
PolyLine	7379.26293	0.04383	0.0350	8.31
PolyLine	3493.73017	0.00857	0.0300	6.24
PolyLine	2848.66628	0.00688	0.0220	13.45

Figure 4 | Flowpath line definition and attributes in ArcView® GIS.

IMPLEMENTATION IN THE WATERSHED MODELLING SYSTEM

The Watershed Modelling System (WMS) is a comprehensive tool developed to organize spatial and hydrologic data for use in hydrologic programs such as HEC-1 and TR20. WMS has the ability to delineate basins using digital images, vector GIS data, TINs and grids. WMS also supports the importing, exporting and creation of GIS vector data such as are required to compute and store travel time equation data.

GIS line objects are used in WMS to represent streams, or ridges, and are used in the creation of polygons. The concept described previously of computing travel time for lag time or time of concentration has been implemented in WMS by creating a travel time data layer comprised of line segments which can be assigned equations and their associated parameters. Since WMS also handles watershed delineation and modelling from digital terrain models and triangulated irregular networks (TINs), flow paths derived from paths of steepest descent

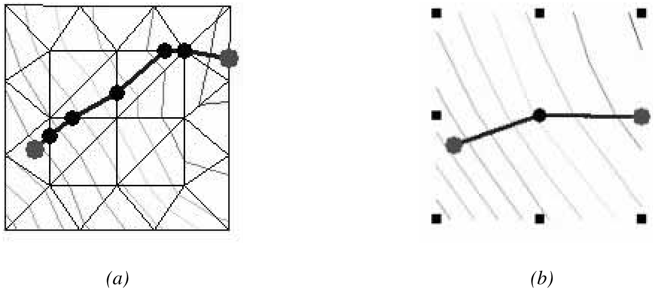


Figure 5 | Calculating flow path feature lines from (a) a TIN or (b) a DEM.

can automatically be generated for each sub-basin. Lengths and slopes can then be determined from these derived flow path segments. Creation of a travel time line typically follows these four steps:

1. Create the flow path in the xy plane.
2. Determine the elevations at the flow path line nodes and vertices.
3. Assign a travel time equation.
4. Enter other supporting equation parameters.

Create the flow path in the *xy* plane

Elevation data are imported into WMS in the form of TIN data or DEM (gridded elevation) data. A flow path line can be generated from either source of elevation data. After a source or beginning point is identified, following the path of steepest descent across the digital terrain model generates the flow path. The algorithm that creates the flow path follows a path to the nearest sub-basin outlet, creating vertices in the flow path line at triangle intersections when using a TIN, or at the centre of grid cells when using a DEM, as shown in Figure 5.

In WMS streams can be defined as a series of triangle edges (Nelson *et al.* 1994) or a collection of DEM cells with a relatively large upstream contributing area (Martz & Garbrecht 1992). If a travel time flow enters one of these defined streams, the flow path line is broken into two separate travel time lines by placing a node at the location where flow enters the stream. The flow path then continues down the stream to the nearest outlet as shown in Figure 6. This is done in anticipation of assigning separate flow equations to the lines representing flow that is in and out of the stream. If a digital terrain model is not available then the travel time lines can be created by digitization from a background map.

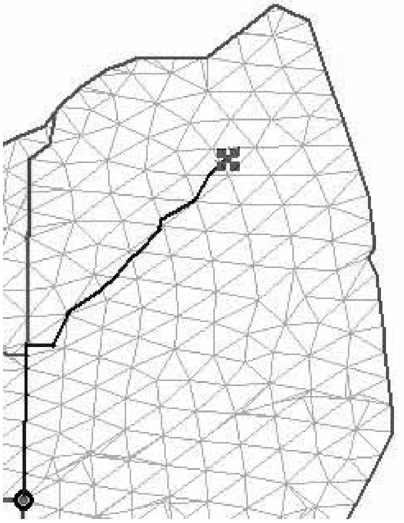


Figure 6 | Creating a travel time line from a point on a TIN.

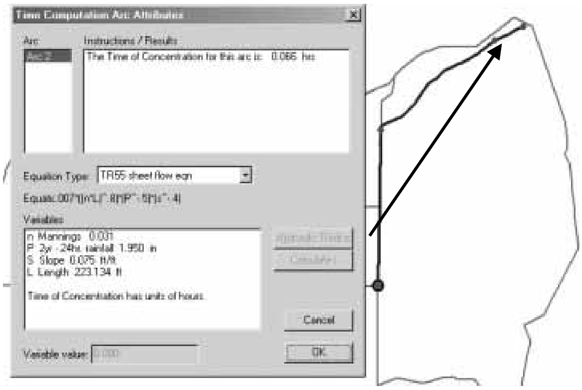
Determine the elevations at the flow path line nodes and vertices

Elevations assigned to the flow path lines are assigned at the end nodes. As described above, slope is calculated from the difference in elevation at the nodes and divided by the projected (*xy* or plan view) length of the flow path line.

When a flow path is created without using a background digital terrain model to provide elevation data, the slope must be determined separately from a topographic map and then entered manually. The length is derived from the flow path line itself, but can be changed or edited manually (as can slopes derived from background digital terrain data).

Assign a travel time equation

An equation used to calculate the travel time along the flow path line is then assigned to each segment within the



The Time of Concentration for this arc is: 0.066 hrs

n Mannings 0.031
P 2yr - 24hr rainfall 1.950 in
S Slope 0.075 ft/ft
L Length 223.134 ft

Time of Concentration has units of hours.

Figure 7 | Editing travel time arc attributes.

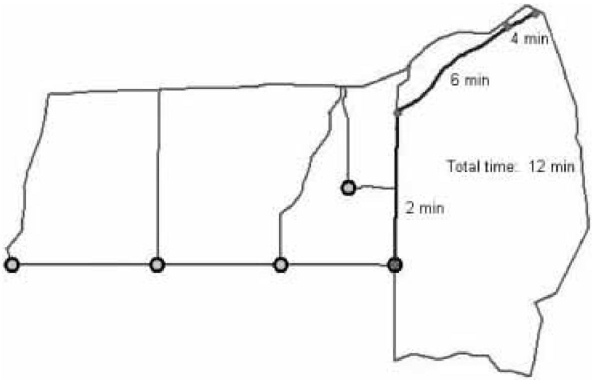


Figure 8 | Total travel time for a watershed basin by summing travel time arcs.

basin or watershed. WMS includes travel time equations developed by the FHWA (FHWA 1996), TR55 (USDA 1986) and Maricopa County (Sabol *et al*. 1991). However, any number of other equations can be used, or when none of the standard equations is applicable a user-defined equation can be developed. The user-defined equation allows any or all of the parameters included in the other equations to be grouped together in macro fashion. Within WMS, any of the variables computed from the digital terrain model, or available in the other equations, can be assigned as variables to the user-defined equation (i.e. slope, or Manning's roughness). Other variables must be entered as constants for each flow path line as a part of the equation.

Enter other supporting equation parameters

After the flow path line is defined and the equation assigned, the parameters associated with the selected equation must be defined. WMS will automatically enter the slope and length values that are computed from the line and digital terrain data. Figure 7 illustrates how these values can be manually changed if necessary. Other parameters such as a 2-year 24-hour rainfall depth must be entered separately, or computed from a GIS data layer containing this information. If a layer of land use polygons is available then automatic determination of Manning's roughness is possible by including a table that maps roughness values to the various land use types represented in the geographic layer.

Other tools can be used to define parameters within the individual equations. In WMS, for example, if an open channel equation requires the hydraulic radius, a hydraulic radius calculator can be used to estimate the appropriate value.

Calculating time of concentration for a watershed or sub-basin

After the equations and their parameters have been defined the travel times for each arc can be computed. Lag time and time of concentration are determined within a basin by summing the travel times calculated from the different arcs. In the case of the typical TR-55 equations a line representing sheet flow, another for shallow concentrated flow and a third for open channel flow are defined as shown in Figure 8. Since WMS can be used to determine basin boundaries and develop hydrologic models, each flow path line can be assigned to a basin by its geographic location.

CONCLUSION

A new approach has been presented for determining input to travel time equations using GIS objects, specifically lines, with assigned equations that can take advantage of the geometric properties of those lines and underlying digital elevation data. This method for determining equation parameters is efficient and further allows the engineer to visually confirm the validity of the flow path while minimizing the amount of data that needs to be manually defined for the equation. The travel time lines are then grouped together to obtain a single travel time value for a watershed basin that can then be used in a numerical model as an estimation of lag time or time of concentration to compute basin runoff using a synthetic unit hydrograph approach. The techniques have been implemented in the Watershed Modelling System (WMS).

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