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SPATIALLY EXPLICIT HYDROLOGIC MODELING OF LAND USE CHANGE[1]

Glenn E. Moglen and R. Edward Beighley[2]

ABSTRACT: Using a Geographic Information System (GIS), a method is presented to develop a spatially explicit time series of land use in an urbanizing watershed. The method is prefaced on the existence of independent observations of land use at different times and data that describes the spatial-temporal land use transition characteristics of the watershed between these two points in time. A method is then presented to generalize the TR-55 graphical method, a common lumped hydrologic model for estimating peak discharge, for use in a spatially explicit scheme. This scheme predicts peak discharge throughout a watershed, rather than at a single selected watershed outlet. Coupling these two methods allows the engineer to model both the temporal and spatial evolution of peak discharge for the watershed. An illustrative watershed in a suburban area of Washington, DC is selected to demonstrate the methods. The model results from these analyses are presented graphically to highlight the complex features in peak discharge behavior that exist both spatially, as a function of position within the watershed drainage network, and temporally, as the watershed undergoes urbanization. These features are not commonly noted in most hydrologic analyses but are captured in these analyses because of the high spatial and temporal resolution of the methods presented. The physical implications of the modeled results are discussed in the context of the information content of a stream gauge located at the overall outlet of the illustrative watershed. This work shows that the common practice of transposition of gauge information to locations internal to the watershed would neglect internal variability in peak discharge behavior, and could potentially lead to the determination of inappropriate design discharges.
(KEY TERMS: aerial photography; digital terrain model; Geographic Information Systems; lumped models; spatial variability; streamflow; temporal effects; urbanization; watersheds.)

INTRODUCTION

The impacts and modeling of land use change on discharge behavior is well documented in the literature (e.g. Carter, 1961; James, 1965; Viessman, 1966; Leopold, 1968; Andersen, 1970). Classic lumped parameter models developed by the Natural Resources Conservation Service (SCS, 1984; SCS, 1986) and by the Army Corps of Engineers (USACE, 2001a) are representative of some of the most commonly applied tools for estimating the change in discharge behavior as a watershed undergoes urbanization. Although the data and computer hardware resources are becoming increasingly available to support efforts to perform fully-distributed hydrologic modeling, lumped models still are commonly used for design purposes throughout the United States. Today, with heightened interest in the need to model water quality, the tool of choice is a lumped parameter model (Donigan and Huber, 1991; Bicknell *et al.*, 1997; USGS, 2001a; USEPA, 2001a) that has its origins in a program developed over 30 years ago (Crawford and Linsley, 1966). It seems likely that these models will remain a part of the planning, management, and design process for years to come.

The automation of the hydrologic analysis process is becoming more commonplace. The growing presence of Geographic Information System (GIS) software, high quality spatially distributed data (e.g., digital elevation models – DEMs) available online through the internet (USGS, 2001b), and customized GIS-based software (e.g., Maidment and Olivera, 2001; U.S. Army Corps of Engineers, 2001b), have reduced much of the drudgery and streamlined the data analysis and development process of implementing the hydrologic models mentioned above. A strength of the GIS approach to hydrologic modeling is its ability to effectively handle spatially distributed data, perform tedious book-keeping tasks that have a

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[2]Respectively, Assistant Professor and Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Maryland, College Park, Maryland 20742 (E-Mail/Moglen: moglen@eng.umd.edu).

spatial component, and support an internal programming language that can be used to customize applications that internally or externally make use of longstanding hydrologic models.

The purpose of this paper is to present a general procedure that takes advantage of GIS technology while retaining the framework of a lumped parameter model. The GIS is first used to develop a detailed spatially and temporally varied description of land use (and thus land use change) as a watershed undergoes urbanization over a period of many years. The GIS is then used to facilitate the repetitive execution of the hydrologic model at a high level of spatial resolution. This method produces spatially explicit estimates of peak discharge at all channel locations within a watershed, not just at the watershed outlet. The simple basis for this method is the systematic application of the lumped parameter modeling rules to each pixel within the stream network of the watershed of interest. Further, these spatially explicit estimates of peak discharge also have a temporal component, since they capture the change in land use that takes place over a period of many years. Graphical and tabular depictions of the model output will be presented so as to emphasize the spatial and temporal characteristics of the results.

LAND USE CHANGE MODELING METHODS

Accurately capturing land use change requires access to data with both high spatial and temporal resolution. One must have access to information at some starting time, t_1, and some ending time, t_2. In between these two endpoints, it is necessary to be able to describe both the timing and location of any changes in land use. Managing such data in an effective way is greatly facilitated through the use of GIS-based techniques. This section describes a method that is likely to be broadly applicable throughout the United States.

The availability and quality of data that can be used to model land use change itself is a temporally changing quantity. Land use/land cover information is broadly available for locations in the U.S. in the form of the USGS GIRAS data set (Mitchell *et al.,* 1977) which tends to reflect land use of an approximately 1970s vintage. These data are now commonly distributed as part of the core dataset in the BASINS model (USEPA, 2001b). Other datasets may also exist on a more regionally varied level, for instance the MRLC dataset (Vogelmann *et al.,* 1998a; Vogelmann *et al.,* 1998b; USEPA, 2001c) that covers many states in the Eastern U.S. and dates to approximately the early 1990s. Other, more high quality, data sets will likely be available on an even more limited basis, perhaps varying by state, county, or municipality. Generally, the better quality data will reflect conditions from periods more recent than the GIRAS data mentioned earlier. Knowledge of land use from periods earlier than the 1970s will likely need to be gleaned from non-digital sources such as historical aerial photography or paper maps. The hydrologist endeavoring to develop a long-duration history of land use change will likely need to obtain multiple sources that convey land use at a given "snapshot" in time.

Modeling the transition between snapshots requires even more creativity. A crude approximation of land use change would be to simply assume some linear change in land use over time between snapshots. While such an assumption accounts for the temporal dimension of land use change, it does not address how to distribute such land use change in space. Capturing the spatial element of land use change is indeed critical to effective hydrologic modeling, particularly at the scale of small subbasins draining on the order of 1 km^2 because hydrologic behavior at this scale can be extremely sensitive to the development of even a single parcel of land.

An effective way to obtain information about land use change is to search out sources that record construction dates and sales dates for tracts of land or ideally individual parcels of land. An excellent source for these kinds of information is in the state or county records used to assess real estate tax information. Such data are, therefore, almost certain to exist, but obtaining and assembling such data over the extents of a watershed can be a daunting task. Further, such data may exist only in paper form, introducing the additional need to geo-reference and digitize this information. We now present a straightforward procedure for developing a series of GIS-based descriptions of land use corresponding to annual time steps between t_1 and t_2.

Step 1: Obtain a spatially-distributed description of land use at times t_1 and t_2. If t_1 corresponds to some time earlier than the 1970s this description is likely to take the form of an historical map or aerial photograph, rather than a digital data source.

Step 2: Obtain a source that details the spatial and temporal transition of land use between t_1 and t_2. As discussed earlier, tax maps are a good potential source for this information.

Step 3: Convert all information to a digital format. Two elements are crucial here. First, land use categories used at both t_1 and t_2 should be based on a consistent classification scheme. The classification hierarchy provided by Anderson *et al.* (1976) covers a

broad range of potential land uses with a good degree of refinement within categories. Second, the transition source should be in the form of a spatially attributed table where the table contains one or more fields that indicate the timing of the land use change event.

Step 4: Develop a GIS-based algorithm that simulates on an annual time step (or higher if the data support it), land use at times between t_1 and t_2. The basic premise of this algorithm is that the land use is initialized at conditions present at time t_1. Then, for some t^* between t_1 and t_2 documented in the land use transition source, the land use at location, x, will be updated to the land use at time t_2. Locations, x, where there has been no land use change, will not have an entry in the transition source data. There exists the possibility that at some locations multiple land use changes may take place between t_1 and t_2. For instance, initially forested land might first be converted to agricultural land and then ultimately to residential land. If such occurrences are common, the transition source data will need additional entries to reflect these changes, and the GIS algorithm would be more complicated as well. Regardless, the fundamental concept remains the same. One needs to know the land use at two points in time and the date at which conversion takes place.

Illustration on a Sample Watershed

We provide the following example to illustrate this procedure. The Watts Branch watershed (location map shown in Figure 1) is located in the Maryland Piedmont about 15 kilometers northwest of Washington, D.C. It has a drainage area of 9.6 km^2 (3.7 mi^2) and, as of 1997, its land use distribution was approximately 57 percent urban land uses, 11 percent forest, and 32 percent agriculture. The watershed also has almost 32 percent impervious cover. This is in

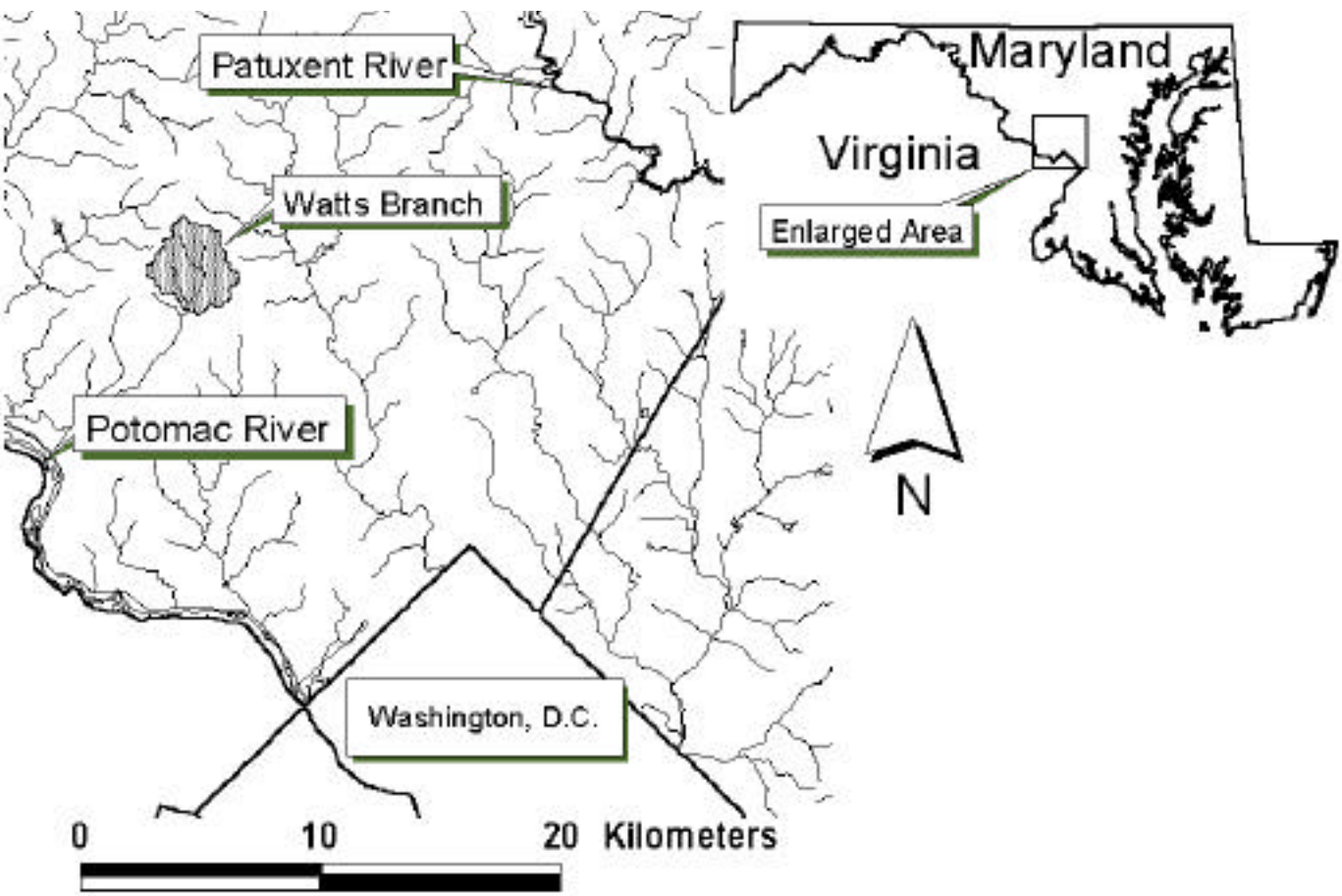

Figure 1. Geographic Location of the Watts Branch Watershed.

contrast to conditions in 1951 when the land use distribution was 10 percent urban, 23 percent forest, and 67 percent agriculture, with approximately 3 percent impervious cover. Figure 2 presents the temporal evolution of land uses within the watershed between 1951 and 1997. As is the case in many of the watersheds in the Baltimore-Washington, D.C. region, most of the urban development in this watershed has occurred since World War II, with a particularly strong pulse of development during the 1960s and 1970s. A U.S. Geological Survey stream gauge (01645200) is located at the outlet of this watershed. The period of record for this gauge is indicated in Figure 2 to span from 1958 to 1987, coinciding well with the period of active urbanization.

The data obtained from our "Step 1" are mapped in Figure 3 with t_1 being 1951 and t_2 being 1997. Land use at t_1 was determined from 1:62,500 scale aerial photography obtained from the Maryland Geological Survey. Land use at t_2 was obtained directly in a GIS format from the Maryland Department of Planning (MDP) as part of their generalized land use and land cover data set that this agency publishes on an approximately three-year cycle.

Tax map data to support "Step 2" were also obtained from the Maryland Department of Planning as part of their "Property View" data set (MDP, 2001). These data provide parcel level information throughout the state for a wide range of attributes. Pertinent to our study, these attributes include parcel area, year of development, and current land use. The authors benefited greatly from the ready availability to such a well-organized GIS database. Had the data only existed in paper, our efforts on this particular step would have needed to be much greater.

In "Step 3" our only necessary task was to convert the 1951 aerial photograph to a digital format. This photograph was digitally scanned, geo-referenced, and then digitized into three broad categories of urban, agricultural, and forested land use. As

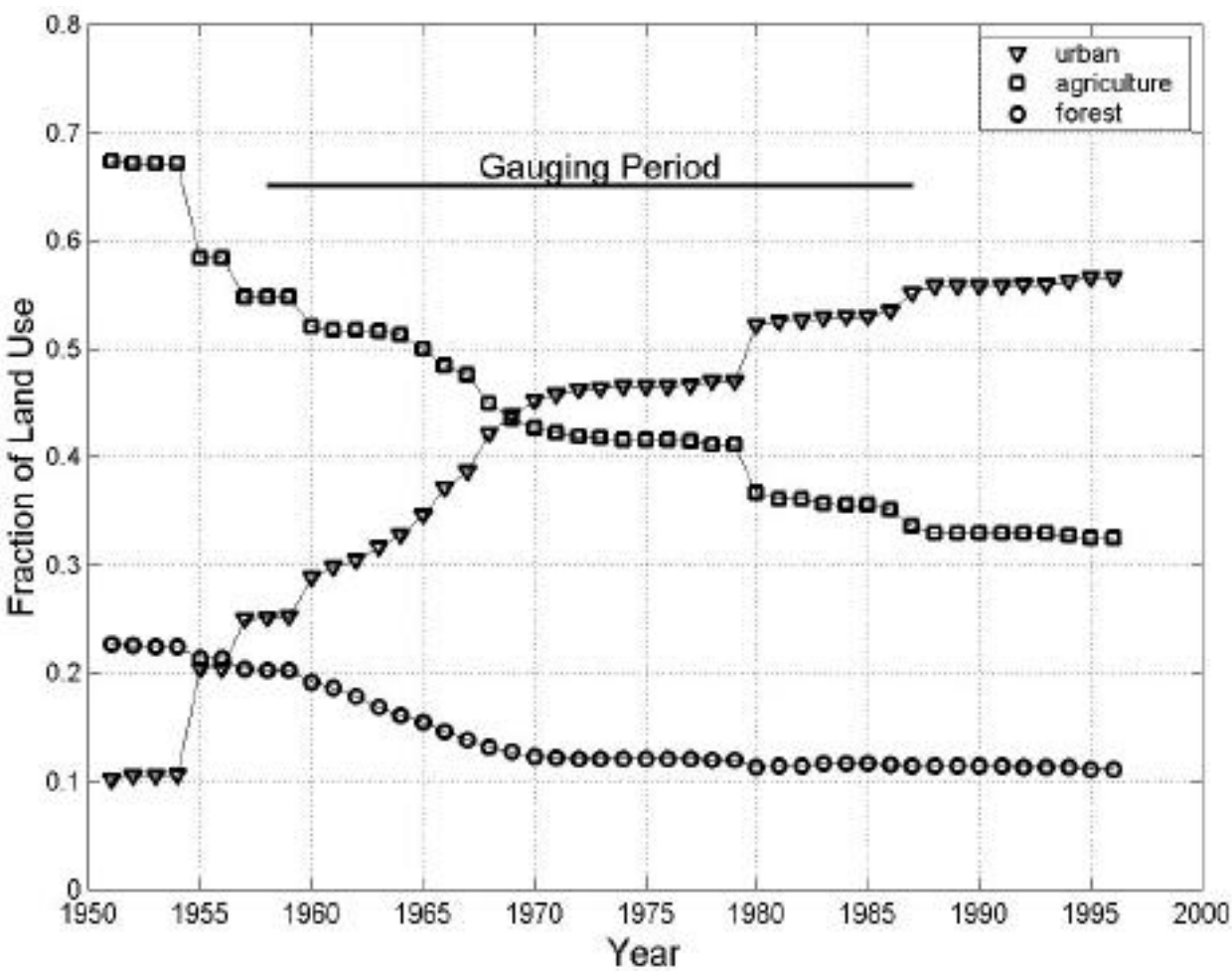

Figure 2. Temporal Change in Land Use Distribution for the Watts Branch Watershed.

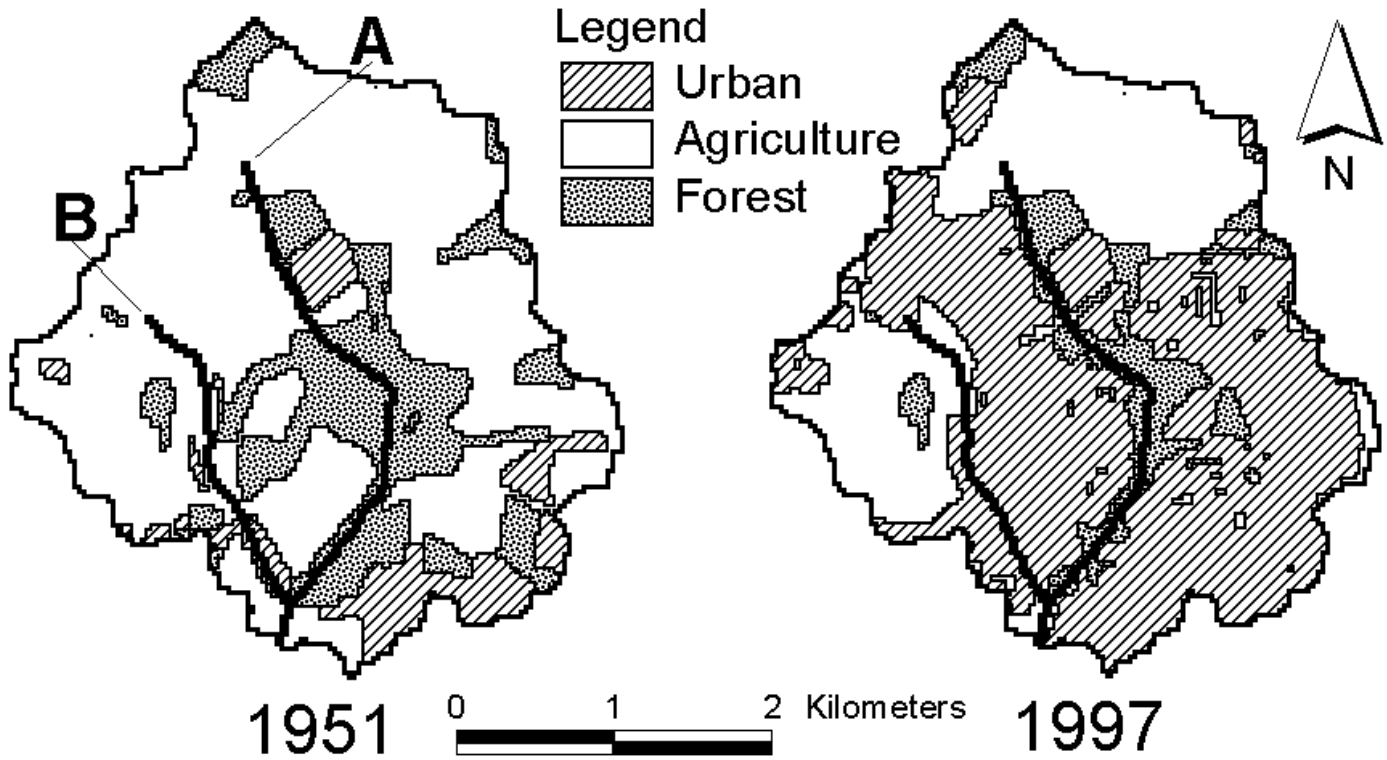

Figure 3. Land Use Distribution in 1951 and 1997. Stream traces A and B are shown for reference.

obtained from the MDP, the 1997 land use data was categorized using a scheme that differed only slightly from the one created by Anderson *et al.* (1976). For consistency, the 1951 data were categorized using this same categorical scheme.

"Step 4" involves the development of an algorithm to create a spatial time series of land use between 1951 and 1997, in this case. All of our work was performed within an ArcView GIS system, taking advantage of its built-in scripting language. Figure 4 illustrates the key concept relevant to this step. Shown in this figure is a small section of a residential subdivision that underwent development in the mid-1960s. The shaded areas show those parcels that are considered to be developed. To further illustrate the concept we show two consecutive years: 1965 and 1966, with the year of development associated with each parcel indicated. The GIS algorithm simply determines which areas are developed in a given year and then spatially assigns the land use at t_1 for all undeveloped areas, and the land use at time t_2 for all developed areas. The process is repeated for all years between t_1 and t_2. The output of this algorithm are a series of land use maps, hereafter denoted by $LU(x,t)$ that describe the spatial variation in land use on an annual time step. These $LU(x,t)$ data were the source for the temporal change in land use distribution over the interim years between t_1 and t_2 reported in Figure 2.

HYDROLOGIC MODELING METHODS

The hydrologic modeling presented in this study is novel for two reasons. First, it makes use of the very high temporal resolution of land use information determined in the previous section; and second, it takes advantage of the capacity of the GIS to repetitively determine the variation in lumped characteristics of the watershed at all points along the stream network within a watershed. This is in contrast to the more common calculation of hydrologic change at only the watershed outlet at two discrete points in time, such as our modeling endpoints, t_1 and t_2.

Spatial Lumping

We begin by first illustrating a subtle, but very important notion which we will refer to as "spatial

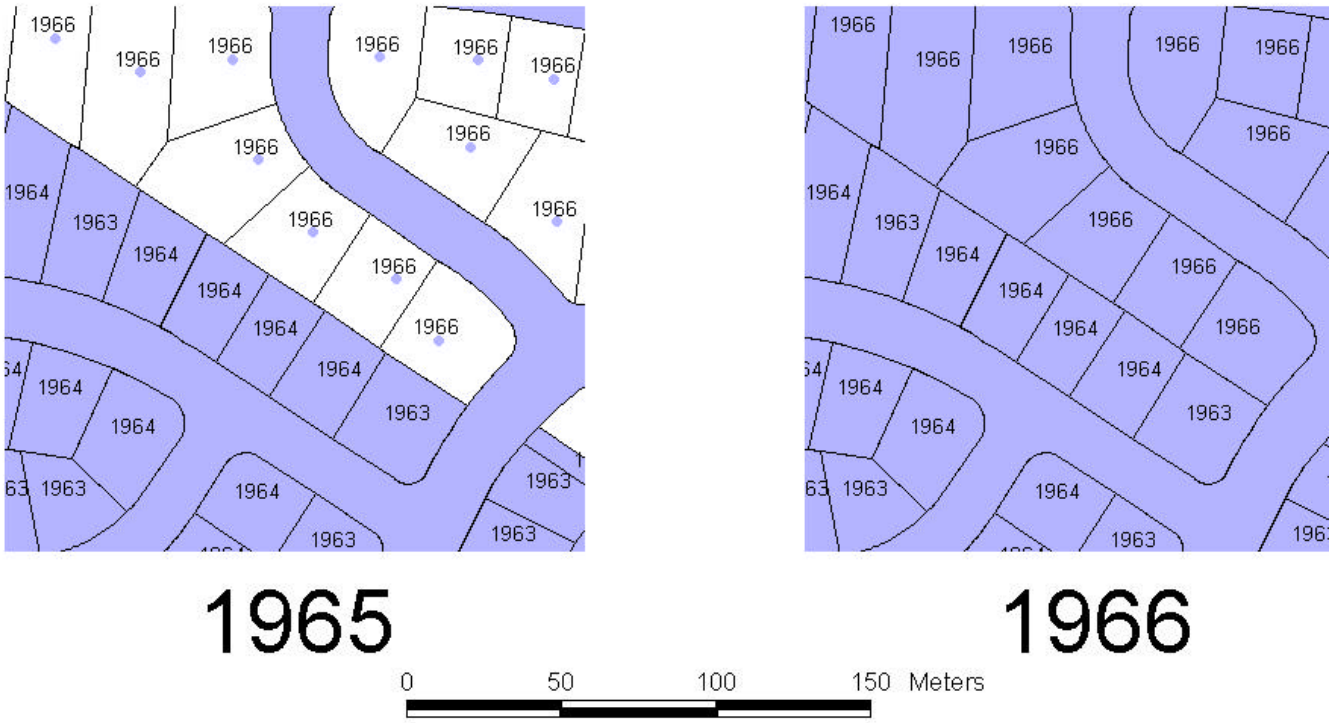

Figure 4. Illustration of Modeling of land Use Transition for Years 1965 to 1966. Shaded areas are considered to be transitioned to land use at time, t_2.

lumping." Figure 5 illustrates two different sets of three pixels located along the stream network in our illustrative watershed. The pixels from "Set A" have been chosen judiciously for their location at the confluence of the two biggest streams in the southern portion of the watershed. Table 1 reports five quantities: drainage direction, cumulative area, local curve number, cumulative curve number, and the spatially lumped curve number. The drainage direction is determined using a common "D8" algorithm that assigns a flow direction to each pixel based on the steepest slope between this pixel and its eight immediate neighbors. Drainage direction is presented in this table to help the reader visualize how the flow is aggregating. Cumulative area is a GIS-determined quantity that corresponds to the number of pixels draining to the pixel in question. Multiplying this number by the surface area of a single pixel yields the drainage area of the watershed draining to that unique pixel. The local curve number is a function of the land use and hydrologic soil type observed at each location within the watershed. In contrast, the cumulative curve number is analogous to cumulative area except each pixel has a different weight, given by the local value of the curve number at that location. The spatially lumped curve number is simply the quotient of the cumulative curve number and the cumulative area.

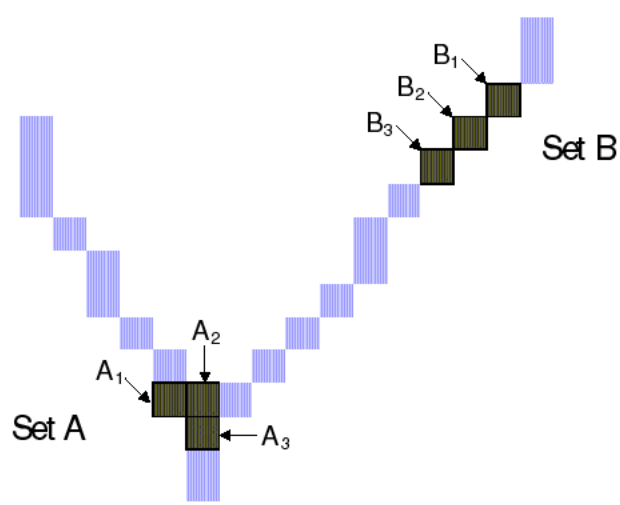

Figure 5. Illustration for Spatial Lumping Procedure.

Table 1 further shows the mixing or averaging that takes place at the confluence modeled by the "Set A" pixels. The spatially lumped curve numbers at the downstream end of the east and west tributary streams are 78.6 and 85.0, respectively. The resulting spatially lumped curve number just downstream of this confluence is 80.5, which is essentially the average of the two tributary values, weighted by the relative cumulative areas associated with these tributaries. These large, discrete jumps in both cumulative area and spatially lumped curve number are in contrast to the pixels in "Set B" which are located along a section of stream that does not have any significant inflow from side tributaries. The result is relatively small incremental increases in both cumulative area and cumulative curve number and a stable value of average curve number. The reader should keep in mind that the GIS is performing this accounting process at all pixels along the stream network for a number of hydrologically relevant parameters discussed later in this section. We introduce the notation here of an overbar [e.g., $\overline{CN}(x,t)$, the spatially lumped curve number at location, x, and year, t] to indicate that a quantity has been spatially lumped using GIS techniques. Such techniques result in spatial coverages that reflect the lumped value of the given quantity at each point within the channel network. This is equivalent to recognizing that each channel pixel is essentially the outlet of the unique watershed upstream of it.

Hydrologic Model Selection

For this study we have chosen the NRCS TR-55 graphical method (SCS, 1986) hydrologic model. Although the modeling details are specific to TR-55, the basic approach remains the same for any lumped parameter hydrologic model. The decision to use TR-55 was based on the scale of our illustrative watershed and the capability of this model to readily capture the effect of land use change on peak discharge. Further, it was a relatively straightforward undertaking to codify this model completely within the GIS environment. Using the spatially lumped coverages approach outlined above, TR-55 will be applied at all locations along the stream network within the study watershed. The modeling effort presented herein will provide estimates of peak discharge throughout the watershed, not just at the outlet. This will allow us to see how peak discharge varies, not only temporally as a function of the land use condition being examined, but also spatially as a function of location within the watershed.

Hydrologic Model Framework

Our next objective is to develop a time series of the NRCS curve number, $CN(x,t)$, and imperviousness, $I(x,t)$, corresponding to the land use, $LU(x,t)$, developed earlier. For any given year, t^*, the $CN(x,t^*)$ is determined by performing a spatial "table lookup" operation between the $LU(x,t^*)$ and the hydrologic soils coverage, $G(x)$. We employed the commonly used NRCS compilation (SCS, 1984; SCS, 1985; SCS, 1986) assuming average antecedent moisture conditions and fair hydrologic conditions throughout. In a similar manner, a time series of spatially varied imperviousness was developed using a set of average imperviousness values organized by land use category and obtained from the Maryland Department of Planning (Weller, personal communication).

The channel network was defined to be all locations (pixels) draining an area in excess of 0.25 km^2. This source area was determined to roughly approximate

TABLE 1. Values Corresponding to the Pixels Highlighted in Figure 4. Curve number values correspond to 1997 land use conditions.

Stream Pixel	Drainage Direction	Cumulative Area (pixels) $\overline{A}(x)$	Local Curve Number $CN(x,t)$	Cumulative Curve Number	Spatially Lumped Curve Number $\overline{CN}(x,t)$
A_1	Southeast	2,968	91	252,298	85.0
A_2	South	7,230	91	568,609	78.6
A_3	South	10,203	91	821,137	80.5
B_1	Southwest	6,776	79	530,444	78.3
B_2	Southwest	6,792	79	531,944	78.3
B_3	Southwest	6,978	100	546,203	78.3

the mean source area associated with stream sources indicated in the 1:100,000 scale National Hydrography Dataset (USGS, 2001c). Using the GIS, it is a relatively straightforward task to generate estimates of the quantities relevant to the hydrologic model for each identified stream pixel. These quantities include drainage area, $\overline{A}(x)$, the length of the longest flow path, $\overline{L}(x)$, average slope, $\overline{S}(x)$, average curve number, $\overline{CN}(x,t)$, and average imperviousness, $\overline{I}(x,t)$. We include the functional dependencies of these quantities to emphasize that this method uniquely determines each entity distributed in space (and time, where indicated). We remind the reader that the overbar notation is used here to indicate that each of these quantities has been spatially lumped using the GIS techniques discussed earlier. All GIS data were resolved to a resolution of 100 feet, approximating the 30 meter DEM data used to derive all of the topographically-driven hydrologic quantities. This resolution is finer than the scale of land use variation within the study watershed and is therefore adequate for the work presented here.

Application of the TR-55 model was done following directly from the procedures outlined by the NRCS (SCS, 1986). First the distribution of the NRCS storage, $\overline{S_t}(x,t)$, is determined

$$\overline{S_t}(x,t) = 2.54\left(\frac{1000}{\overline{CN}(x,t)} - 10\right) \tag{1}$$

where $\overline{S_t}(x,t)$ is in units of centimeters. Next the initial abstraction, $\overline{I_a}(x,t)$, was taken to be 20 percent of the storage as is commonly assumed:

$$\overline{I_a}(x,t) = 0.2\overline{S_t}(x,t) \tag{2}$$

The distribution of runoff was determined using

$$\overline{Q}(x,t) = \frac{\left[P - \overline{I_a}(x,t)\right]^2}{P + \overline{S_t}(x,t) - \overline{I_a}(x,t)} \tag{3}$$

where $\overline{Q}(x,t)$ is the runoff depth in centimeters, and P is the 24 hour precipitation depth in centimeters for the storm event being modeled. The time of concentration was determined using the SCS Lag Equation (SCS, 1973)

$$\overline{t_c}(x,t) = \frac{0.136\,\overline{L}(x)^{0.8}\left[\left(1000/\overline{CN}(x,t)\right) - 9\right]^{0.7}}{\overline{S}(x)^{0.5}} \tag{4}$$

where $\overline{t_c}(x,t)$ is the lag time (used synonymously with time of concentration in this work) in units of minutes. Imperviousness tends to speed up the response of the watershed to runoff. This effect is captured by SCS (1986) as a function of both imperviousness and curve number

$$\overline{f}(x,t) = 1 - 2\left[\overline{I}(x,t)\left(\beta_0 + \beta_1\overline{CN}(x,t) + \beta_2\overline{CN}^2(x,t) + \beta_3\overline{CN}^3(x,t)\right)\right] \tag{5}$$

where the polynomial coefficients are: β_0 = -6.789 x 10^{-3}, β_1 = 3.35 x 10^{-4}, β_2 = -4.298 x 10^{-7}, β_3 = -2.185 x 10^{-8}. The adjusted time of concentration is then determined as the product of Equations (4) and (5)

$$\overline{t_{c,a}}(x,t) = \overline{f}(x,t)\overline{t_c}(x,t) \tag{6}$$

The unit peak discharge, $\overline{q_u}(x,t)$, is a function of both the adjusted time of concentration and the ratio, $\overline{I_a}(x,t)$ / $P(t)$. We model the unit peak discharge as a spatially lumped quantity based on the NRCS equation (SCS, 1986)

$$\log_{10}\left\{\overline{q_u}(x,t)\right\} = C_0 + C_1\log_{10}\left\{\overline{t_{c,a}}(x,t)\right\} + C_2\left[\log_{10}\left\{\overline{t_{c,a}}(x,t)\right\}\right]^2 \tag{7}$$

where C_0, C_1, and C_2 are table values provided by the NRCS for varying values of $\overline{I_a}(x,t)$ / $P(t)$. An assumed Type II storm distribution was used which is appropriate for the region encompassing the study watershed. Finally, the peak discharge is determined as the product of drainage area, $\overline{A}(x)$, and Equations (3) and (7)

$$\overline{Q_p}(x,t) = \overline{q_u}(x,t)\overline{A}(x)\overline{Q}(x,t) \tag{8}$$

where $\overline{Q_p}(x,t)$ is in units of m^3/s.

APPLICATION OF METHODS

Validating the Model

We first present a comparison between the observed flood frequency record of the USGS gauge located at the overall outlet and the modeled two-yr peak discharge at this same location. We performed a

flood frequency analysis of the stream gauge data gathered during the gauging period of 1958 through 1987. Using Bulletin 17B methods (IACWD, 1982), the two-year peak discharge was estimated to be 17.8 m^3/s (628 ft^3/s) with a 95 percent confidence interval of 14.0 m^3/s (496 ft^3/s) to 22.4 m^3/s (790 ft^3/s). The TR-55 model outlined in Equations (1) through (8) was applied to the study watershed for a uniformly distributed precipitation depth of 7.75 cm (3.05 inches). For land use varying between 1958 and 1987 conditions, we obtained peak discharge estimates ranging from 17.3 m^3/s (610 ft^3/s) in 1958 to 24.2 m^3/s (854 ft^3/s) in 1987, with a mean two-year peak discharge of 20.8 m^3/s (733 ft^3/s).

Observed and modeled peak discharges both clearly contain a fair degree of uncertainty. Although the modeled peak discharges are slightly elevated relative to the observed two-year peak, the width of the 95 percent confidence interval on the observed data and the range of modeled discharges that result from nonstationarity in the land use over this period indicate considerable uncertainty in both the observed and modeled two-year discharges. Further, it is common engineering practice to apply the n-year precipitation event and assume that the resulting modeled discharge is an estimate of the n-year peak discharge. The actual precipitation depth associated with the two-year event may vary considerably depending on actual antecedent conditions, the spatial and temporal distribution of rainfall, and seasonality, just to name a few complicating factors. Given this uncertainty in both the observed and the modeled discharges, we consider the observed data and modeled peak discharges to compare favorably.

Space-Time Examination of Model Results

Figure 6 presents the space-time variation of the two-year peak discharge along the stream trace labeled "A" in Figure 3. For a given year, moving from

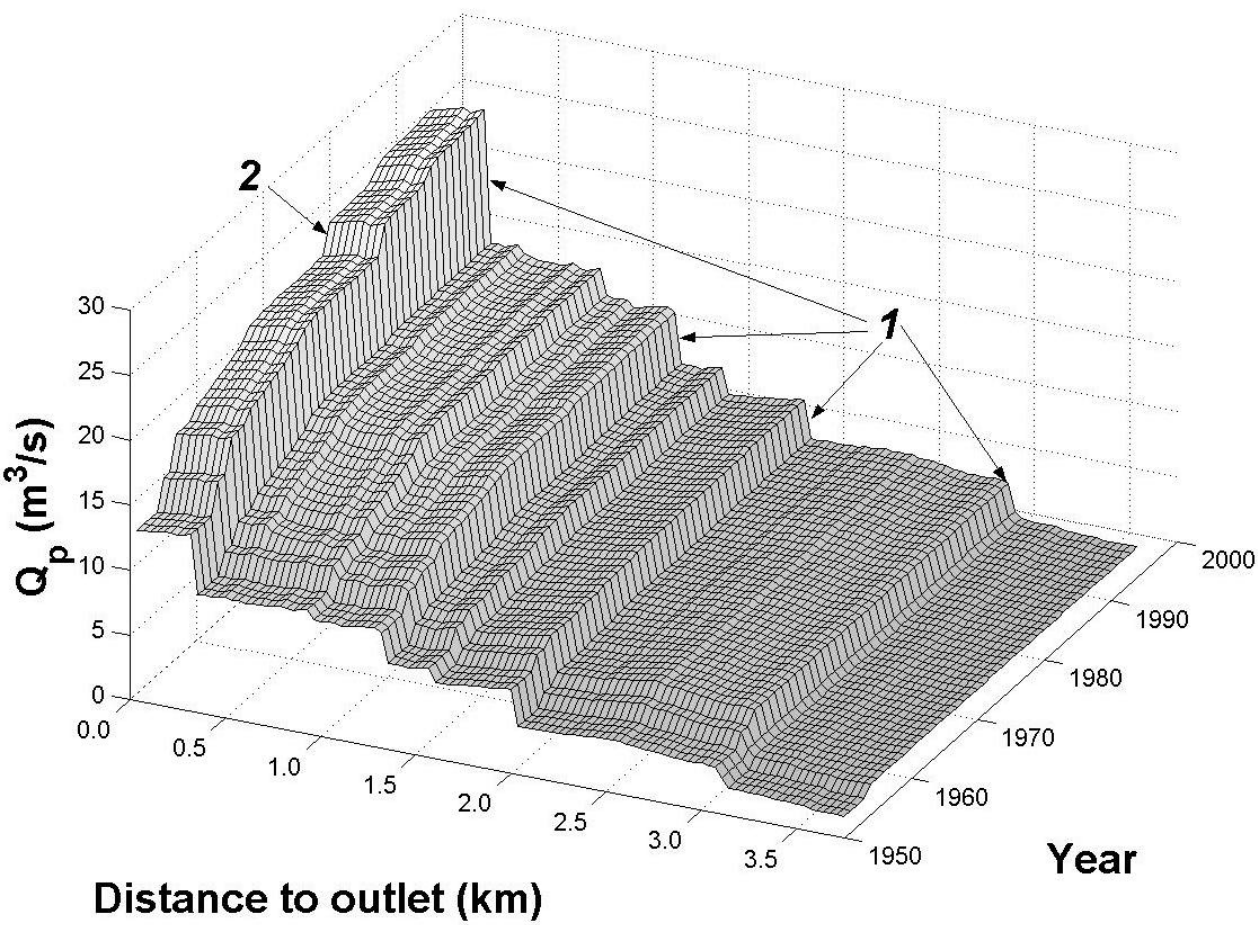

Figure 6. The Space-Time Evolution of the Modeled Two-Year Peak Discharge Along Stream Trace A.

right to left across the figure corresponds to traveling downstream along the stream trace and noting the two-year peak discharge at each point in that year. Likewise, for a given location along the stream trace (fixed "Distance to Outlet") moving from front to back across the figure corresponds to noting the temporal change in the two-year peak discharge from 1951 to 1997.

Several items in Figure 6 are worthy of special note. First, this figure conveys the general trend for peak discharge to increase in both the downstream direction and as the years (and urbanization level) go by. Both trends are expected, but the graphical depiction of these trends would not be possible without the high spatial and temporal resolution of our methods. Second, the large step-like features identified as "1" in this figure correspond to locations where the traced flow path meets a confluence with other significant tributary inputs. This was suggested earlier in Table 1 with the large increase in cumulative area from pixels A_1 and A_2 to pixel A_3 immediately downstream of them. Finally, the feature identified as "2" in Figure 6 corresponds to a large jump in peak discharge downstream of the last significant confluence along stream trace A. Notice that there is no suggestion of such an increase in peak discharge upstream of this last confluence. This indicates that some significant pulse of development took place in the adjacent subwatershed that joins with stream trace A at this confluence. Consulting Figure 2 confirms a large aggregate jump in urbanization levels between 1979 and 1980 as observed at the overall watershed outlet.

Let us now take a closer look at the information that is conveyed for 1997 conditions in Figure 6. To repeat, this perspective corresponds to that of an observer traveling downstream along a stream trace. It provides useful insight into the magnitude and variation of peak discharges spatially distributed throughout the watershed. This perspective emphasizes that peak discharges do not increase in a simple, predictable way, but rather that there are points of discontinuous increases in peak discharge that correspond to the confluence of the traced flow path with other significant streams. Further, it is important to realize that the spatial distribution of land use is not uniform within the watershed, but that it varies in a patchwork fashion, especially when aggregated along the unique drainage structure of the watershed.

Figure 7 illustrates two stream traces that provide this perspective. In Figure 7a, the progression of peak discharges corresponding to the two-year storm for 1997 land use conditions is shown along stream traces A and B identified earlier in Figure 3. In both cases, we trace downstream and record the change in peak discharge as we approach the outlet. This results in the discharges indicated in Figure 7a. The confluence of the two flow paths, located about 0.3 km upstream of the overall watershed outlet, is indicated by a circle. This is the same confluence previously identified as the "Set A" pixels in Figure 5 and Table 1. The modeled two-year discharge for 1997 conditions at the watershed outlet (25.2 m^3/s or 891 ft^3/s) can be seen at the extreme left edge of this graph.

Figure 7b provides a comparison of the two-year peak discharges corresponding to 1951 and 1997 land use conditions. Shown are the same two traces as in 7a, but plotted as the ratio of the 1997 peak discharge to the 1951 peak discharge. Any ratio greater than one indicates an increase in peak discharge along the indicated stream trace over time. Flow path B clearly exhibits the greater increase in discharge between these two points in time. Referring back to Figure 3, we find the degree of urbanization in the vicinity of this stream to be more extensive than nearby the neighboring flow path A. The subwatershed drained by flow path B has lost almost all of its forest cover and much of its agricultural cover to urbanized land uses. By comparison, the subwatershed drained by flow path A has retained most of its original forest cover and has undergone a much more modest amount of urbanization, mostly at the expense of lost agricultural land. Since the curve numbers associated with agricultural land and residential land are similar, the increase in peak discharge is less than what is experienced in flow path B.

An important conclusion to draw from this analysis of these two traces is that the impact on peak discharge from spatially varied urbanization cannot be captured by point measurements taken at the watershed outlet. Considering only the watershed outlet, Figure 7b shows that the effect of urbanization is to approximately double the two-year peak discharge over the period from 1951 to 1997. This, however, does not mean that peak discharges doubled everywhere within the watershed. Trace A shows the ratio to vary between about 1.2 and 2, while Trace B shows the ratio to vary between 1.8 and 2.9. From a stream gauging viewpoint, the USGS gauge located at the overall watershed outlet records information that has been averaged or integrated in much the same way as our spatial lumping procedure described earlier. The doubling of the two-year peak discharge at the gauge location suggested by our modeling is quite significant. While such information is quite valuable, it does not convey the knowledge of internal variability that is shown in Figure 7. Without the methods and analyses presented here, the analyst would not appreciate that within the watershed there were some reaches where the two-year discharge essentially tripled (e.g. along stream trace B) while other reaches experienced much more moderate increases (e.g. along stream trace A) over the modeled period of urbanization.

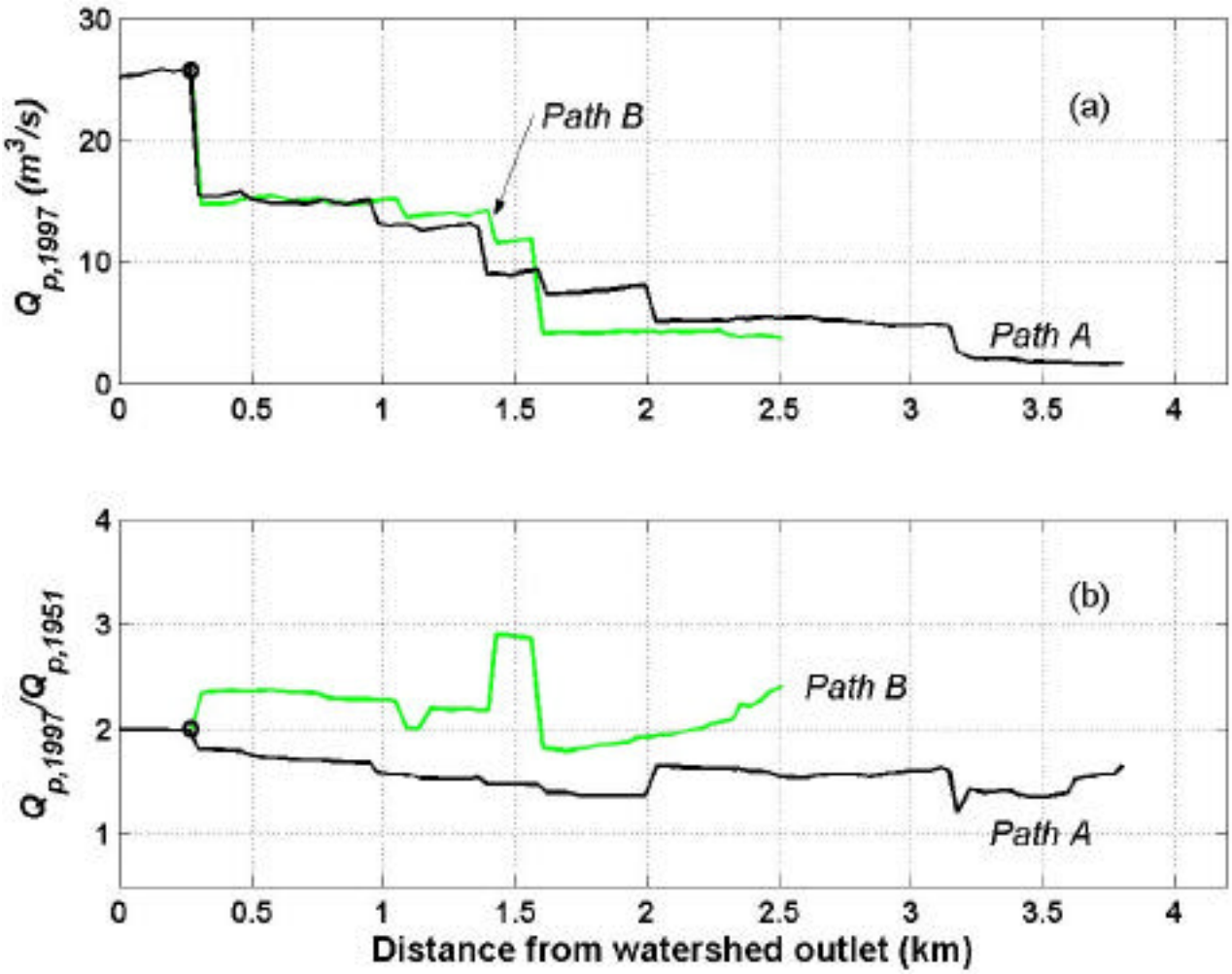

Figure 7. The Modeled Two-Year Peak Discharge Along the Two Selected Flow Paths Shown Previously in Figure 3. Figure (a) shows the two-year discharges corresponding to 1997 land use conditions while (b) shows the ratio of the 1997 two-year discharge to the 1951 two-year discharge.

The internal variability in peak discharge and change in peak discharge behavior relative to the gauged outlet is important to consider in the context of hydrologic design. It is common engineering practice to use transposition to infer peak discharges internal to a gauged watershed. Transposition methods range from a simple area-ratio approach to more sophisticated methods (e.g. Sauer, 1973; Hannum, 1976; Jordan, 1984). Regardless, these transposed peak discharges would be essentially scaled versions of the gauge information, and would tend to neglect the local variability captured in our modeling. Such neglect could potentially lead to transposed design discharges that are inappropriately large or small for a given location or reach. The result could be overdesigned or underdesigned engineered structures.

CONCLUSIONS

This paper presented a GIS-based method to generate a series of high spatial and temporal resolution land use coverages. This method depends on the availability of historical spatial information in the form of either paper maps or archival aerial photography to establish land use at the outset of the analysis. Similar data is required to define the endpoint of the analysis. The origin of these data is far more likely to be obtained in a digital format. Tax maps or other land transaction information are needed to effectively model the transition from original land use to final land use.

This paper also presented a method for integrating a lumped hydrologic model, the TR-55 graphical

method, directly into the GIS environment. An emphasis was placed on developing a method that exploits the capabilities of the GIS to determine spatially lumped quantities such that the method could be simultaneously applied to all stream pixels within a watershed, not just the overall watershed outlet. The result is a spatially explicit method that determines peak discharge throughout the watershed. When applied to the time varying land use developed earlier in the paper, it is possible to develop high spatial and temporal resolution estimates of peak discharge. The present study required considerable time and effort to develop data handling techniques and appropriate GIS-based algorithms. However, future studies of a similar nature could be carried out quickly and easily, requiring only that the land use and transition data described herein already exist.

Variability in land use change and the resulting peak discharge behavior throughout the watershed was shown to be considerable and was not necessarily reflected by the peak discharges viewed solely from the watershed outlet. Examination of the ratio of the 1997 to the 1951 two-year peak discharge along two flow path traces showed ratios ranging from a little more than one to almost three. Meanwhile, the ratio at the outlet was 2, indicating a doubling of the two-year peak discharge between 1951 and 1997 at this location. The traces emphasized that the change in peak discharge at any specific location within the watershed might be quite different than what was observed at the outlet, which tends to represent an integration or average of the internal variation. The implication is that one should be careful not to view measured changes at the watershed outlet as necessarily indicative of uniformly similar changes throughout the smaller subwatersheds nested within. If transposition of gauge data is employed, internal variation in peak discharges is essentially neglected and could potentially lead to inappropriate design discharges and ultimately overdesigned or underdesigned engineered structures.

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NOTATION

$\beta_0, \beta_1, \beta_2, \beta_3$	coefficients of equation for SCS time of concentration adjustment for imperviousness.
$\bar{A}(x)$	drainage area at location, x (km^2).
C_0, C_1, C_2	tabulated values provided by the SCS that depend on storm type and I_a/P ratio.
$CN(x,t)$	curve number at location, x, and year, t.
$\overline{CN}(x,t)$	spatially lumped curve number at location, x, and year, t.
$\bar{f}(x,t)$	SCS time of concentration adjustment function at location, x, and year, t.
$G(x)$	hydrologic soil group type at location, x.
$I(x,t)$	fractional imperviousness at location, x, and year, t.
$\bar{I}(x,t)$	spatially lumped fractional imperviousness at location, x, and year, t.
$\overline{I_a}(x,t)$	SCS initial abstraction at location, x, and year, t (cm).
$\bar{L}(x)$	flow path length from divide to location, x (m).
$LU(x,t)$	land use at location, x, and year, t.
P	precipitation depth (cm).
$\bar{Q}(x,t)$	SCS runoff depth at location, x, and year, t (cm).
$Q_p(t)$	the modeled discharge for land use conditions present in year, t (m^3/s).
$\overline{Q_p}(t,x)$	the modeled discharge for land use conditions in year, t, and at all locations, x (m^3/s).
$\overline{q_u}(x,t)$	SCS unit peak discharge at location, x, and during year, t (m^3/(s-km^2-cm).
$S(x)$	the slope at location, x (percent).
$\overline{S_t}(x,t)$	SCS storage at location, x, and year, t (cm).
t	time (years).
t^*	any specific year of interest.
$\overline{t_c}(x,t)$	SCS lag time estimate of time of concentration at location x, during year, t (min).
$\overline{t_{c,a}}(x,t)$	SCS adjusted (for imperviousness) time of concentration at location, x, during year, t (min).
x	location parameter, generally associated with a GIS-based pixel along the channel network.