Adjusting measured peak discharges from an urbanizing watershed to reflect a stationary land use signal

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[1] A procedure to adjust gauged streamflow data from watersheds urbanized during or after their gauging period is presented. The procedure adjusts streamflow to be representative of a fixed land use condition, which may reflect current or future development conditions. Our intent is to determine what an event resulting in a peak discharge in, for example, 1950 (i.e., before urbanization) would produce on the current urban watershed. While past approaches assumed uniform spatial and temporal changes in urbanization, this study focuses on the use of geographic information systems (GIS) based methodologies for precisely locating in space and time where land use change has occurred. This information is incorporated into a hydrologic model to simulate the change in discharge as a result of changing land use conditions. In this paper, we use historical aerial photographs, GIS linked tax-map data, and recent land use/land cover data to recreate the spatial development history of eight gauged watersheds in the Baltimore-Washington, D. C., metropolitan area. Using our procedure to determine discharge series representative of the current urban watersheds, we found that the increase of the adjusted 2-year discharge ranged from 16 to 70 percent compared with the measured annual maximum discharge series. For the 100-year discharge the adjusted values ranged from 0 to 47 percent greater than the measured values. Additionally, relationships between the increase in flood flows and four measures of urbanization (increase in urban land, decrease in forested land, increase in high-density development, and the spatial development pattern) are investigated for predicting the increase in flood flows for ungauged watersheds. Watersheds with the largest increases in flood flows typically had more extensive development in the areas far removed from the outlet. In contrast, watersheds with development located nearer to the outlet typically had the smallest increases in peak discharge. *INDEX TERMS:* 1803 Hydrology: Anthropogenic effects; 1821 Hydrology: Floods; 1854 Hydrology: Precipitation (3354); 1860 Hydrology: Runoff and streamflow; *KEYWORDS:* adjustment, annual maximum discharge, flood frequency analysis, geographic information systems, trends, streamflow gauge

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1. Introduction

[2] Measured streamflow data are vital in the context of hydraulic structure design and stream restoration plans where flood frequency information is used to provide design guidance. The U.S. Geological Survey (USGS) operates and maintains an extensive network of gauges to record streamflow at thousands of points throughout the United States. Gauges are added and removed annually, with some gauges on larger rivers having periods of record exceeding 100 years. However, as the period of record of a gauge increases, there are many factors that can cause the measured discharge series to no longer represent the current watershed conditions. Excluding climate variability, some of the more dominant factors affecting the magnitude and variability of streamflow are channel modifications, land use changes, and upstream diversions and regulations. Channel modifications change the ability of the channel to convey flow by increasing or decreasing channel capacity. Land use change is any activity that affects the runoff generation and infiltration properties of the land surface. Upstream diversions and regulations alter the flow regime by diverting flow to other resources and regulating the control of various hydraulic structures. The combination of decreasing channel losses and residential and/or commercial development are commonly defined as urbanization.

[3] Urbanization or land use change can lead to changes in the response of a watershed to precipitation. This response is captured by USGS streamflow gauges, which record daily averaged and instantaneous annual maximum discharges. Typically, urbanization increases impervious

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area, which increases peak flood discharges by increasing the storm runoff volume and decreasing the time of concentration. This increase in peak discharge over time tends to produce a shift in the discharge signal, which can be significant depending on the percentage of the watershed altered. In cases where the discharge signal is nonstationary as a result of urbanization, the discharge series is not representative of the current watershed conditions because the discharges were recorded over a range of land use conditions. Likewise, in cases where urbanization occurs after the gauging period, the discharge series measured prior to the urbanization is not representative of the current watershed conditions even though the measured discharge signal may be stationary. Thus the continued use of these data may not be appropriate in design applications.

[4] This paper presents an approach for adjusting measured annual maximum discharges, which can have a stationary or nonstationary signal, to be representative of specified fixed land use conditions (i.e., current or future conditions). Using both spatially and temporally distributed land use data, peak discharges recorded before or during the urbanization process can be adjusted to be representative of a fixed land use condition. This adjustment is analogous to a present worth or future cost analysis in economics. This work addresses the question, What would an event resulting in a peak discharge in, for example, 1950 produce on the current urbanized watershed?

2. Background

[5] In the literature, there are few methods presented for removing the urbanization signal from measured discharge data. *McCuen* [1998] presents an index flood adjustment procedure, where the index variable (percent imperviousness, degree of channelization, or climate change) represents the cause of the nonstationarity in the discharge signal. This method requires a model that relates the index variable to changes in discharge and exceedence probability. Then given a desired level of the index variable and return period, the measured flow value can be adjusted by

$$Q_a(t) = (f_2/f_1)Q_p(t), \tag{1}$$

where $Q_a(t)$ is the adjusted peak discharge, $Q_p(t)$ is the measured peak discharge, and f_1 is the peak adjustment factor based on the exceedence probability of $Q_p(t)$ and the level of the index variable at time t. The peak adjustment factor f_2 is based on the exceedence probability of $Q_p(t)$ and the level of the index variable associated with the adjusted flood series.

[6] In addition to the above technique, there are statistical methods that use relationships between the measured discharge series and periods of known watershed conditions [*Salas*, 1993]. These adjustments can remove trends in the mean or variance of a discharge series. The basic approach is to determine the mean $\overline{Q}_p(t)$, or variance $S^2(t)$, corresponding to known watershed conditions at time t, which can represent predevelopment, period of urbanization, or postdevelopment. Then the measured discharges, $Q_p(t)$, can be adjusted for changes in either the mean or variance using equation (2):

$$Q_a(t) = \left[\frac{Q_p(t) - \overline{Q}_p(t)}{S(t)}\right] S_a + \overline{Q}_a, \tag{2}$$

where $Q_a(t)$ is the adjusted peak discharge, $\overline{Q}_p(t)$ and $S(t)$ are the trend in the mean and standard deviation of peak discharge at time t (predevelopment or urbanization period), and $\overline{Q}_a$ and S_a are the mean and standard deviation for the postdevelopment period.

[7] The inadequacy of the above methods is that they do not account for the physical processes affecting runoff generation or the knowledge of spatially and temporally distributed land use change. While the index flood adjustment method incorporates return period effects, it assumes a spatially uniform development pattern throughout the watershed and cannot accommodate the varying development patterns commonly associated with urban sprawl. Additionally, the statistical methods, while capable of removing trends in the mean and variance, cannot account for spatial development patterns or event magnitude. Given the need to consider both spatial and temporal nonuniformities in urbanization structure, the goal of this research is to develop an approach that makes use of information that elucidates the actual patterns of development in both space and time.

3. Adjustment Procedure

[8] We propose an approach that unites geographic information systems (GIS) based methods with a hydrologic modeling component. The basic concept behind the GIS adjustment procedure has three components. First, determine the spatial and temporal distribution of land use throughout the gauging period and for the current or future watershed conditions. Next, determine a calibrated precipitation series corresponding to the measured discharge series. This precipitation time series is inferred using the measured annual maximum discharges and the land use conditions in place at the time of each discharge to determine the magnitude of precipitation from a fixed distribution design storm such that the simulated discharge equals the observed discharge. Finally, use the calibrated precipitation series and a single fixed land use condition to simulate the adjusted discharge series. The adjusted time series is then reflective of the discharges that would have been observed in the annual maximum record had the specified land use been in place throughout the gauging period.

4. Case Study

[9] We provide the following case study to illustrate our adjustment procedure. Focusing on the Baltimore-Washington, D. C., metropolitan area, all USGS gauged watersheds (shown in Figure 1) meeting the following criteria were selected: greater than 10 percent urbanization during and/or after gauging, greater than 25 years of record, no hydraulic constraints, and drainage areas ranging from 10 to 150 km^2. The eight gauges that satisfied the above conditions are listed in Table 1. Table 2 provides land use conditions for the watersheds at the onset of gauging and in year 2000. For the eight gauged watersheds, the increase in urbanization ranged from 24 to 66 percent.

4.1. Streamflow and Precipitation Data

[10] This case study builds upon a recent assessment of nonstationarity in annual maximum discharge signals from

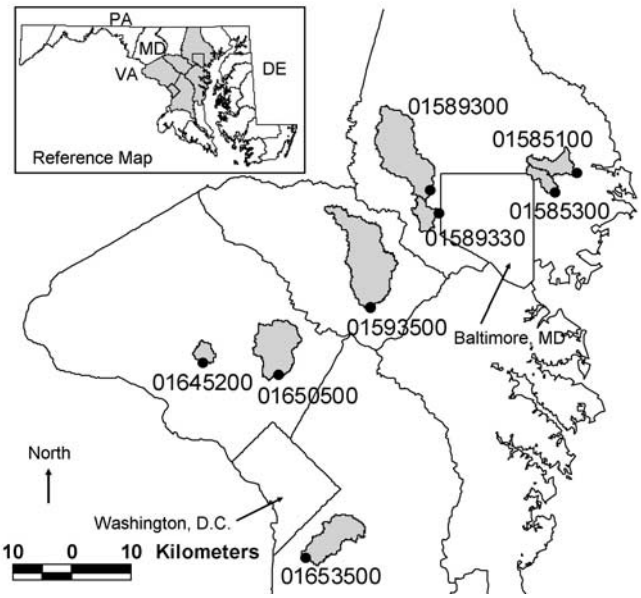

Figure 1. Case study watersheds (shaded regions) with U.S. Geological Survey streamflow gauge locations (circles designated by numbers) for the Baltimore-Washington, D. C., metropolitan area.

urbanized USGS gauges in the Baltimore-Washington, D. C., region by *Beighley and Moglen* [2002]. In their assessment, three time series (the measured annual maximum discharge series, $Q_p(t)$; the corresponding precipitation series, $P(t)$; and the annual maximum discharge/precipitation ratio, $R(t)$) were tested for the presence or absence of a significant trend, where a significant trend indicates the time series' signal is nonstationary. The point of this study was to show the benefit of testing the $R(t)$ series rather than the $Q_p(t)$ series for trend detection because the $R(t)$ series is less sensitive to climatic variability.

[11] For the case study watersheds, Table 3 shows the results of Kendall's tau trend tests on the $Q_p(t)$ and $R(t)$ series by listing the probabilities at which the computed test statistics would indicate a significant trend (i.e., critical probabilities) for a given time series. Table 3 shows that the critical probabilities in the $R(t)$ series are lower than those from the $Q_p(t)$ series, which highlights the difficultly in detecting trends in the $Q_p(t)$ series alone. While the $Q_p(t)$ series trend tests result in only three and four significant trends at 1 and 5 percent levels of significance, respectively, the $R(t)$ series trend tests result in six significant trends at both 1 and 5 percent levels of significance, indicating that peak discharge per unit rainfall is increasing over time. The two gauges without significant trends at 1 or 5 percent, 01650500 and 01653500, experienced substantial urbanization after their gauging period, where 01650500 was inactive from 1984 to 1997 and reactivated in 1998 and 01653500 stopped recording in 1978. While their measured ratios are stationary, the current watershed conditions are more urban compared with the conditions when gauging first commenced (Table 2), and the measured peak discharges are not representative of the current conditions. In all eight watersheds, using the measured discharges to develop flood frequency information for design purposes could ultimately result in underdesigned structures or engineered cross sections.

4.2. Land Use Data

[12] At the center of this adjustment procedure are spatially and temporally distributed land use data, which make it possible to simulate the land use conditions associated with each measured annual maximum discharge. To recreate the spatially distributed land use for each discharge event, three sources of land use data were used: GIS-linked tax maps (i.e., parcels data), generalized land use/land cover data, and historical aerial photographs. *Beighley and Moglen* [2002] and *Moglen and Beighley* [2002] provide details for combining the three sources of land use. As an illustration of the overall process, Figure 2 shows how the parcels data provide temporal resolution between historical and current land use sources to recreate the development history to date for one of the case study watersheds: Watts Branch, USGS 01645200. The benefit of using these various data sources is that both the spatial and temporal distribution of land use, $LU(x, t)$, is known at every location x and year t.

[13] While the spatial and temporal land use distribution is valuable, other time series such as the percentage of impervious area $I(x, t)$ and runoff curve number $CN(x, t)$ are required for the modeling process. Using the combination of the hydrologic soil types, $G(x)$, and the spatial and temporal distribution of land use, $LU(x, t)$, the GIS is used to generate the temporally varying curve number series. This process uses a reference table [*Soil Conservation Service* (*SCS*), 1985] that associates a curve number with a given land use and soil type. Where applicable, the hydrologic condition was assumed to be good. The GIS coverage for hydrologic soil types was obtained from the National Resources Conservation Service (NRCS) State Soil Geographic (STATSGO) Data Base [*SCS*, 1994]. Similarly, the spatial and temporal percent imperviousness $I(x, t)$ is determined by assigning fixed levels of imperviousness as a function of residential housing density or other categories of urban land use following NRCS guidelines [*SCS*, 1986].

4.3. Hydrologic Modeling

[14] While numerous hydrologic models are available, lumped parameter models are the most common for hydrologic design applications in the United States. For this research, the U.S. Army Corps of Engineers HEC-HMS model [*U.S. Army Corps of Engineers* (*USACE*), 2000a] was selected. HEC-HMS is a lumped parameter hydrologic

Table 1. U.S. Geological Survey Stream Gauge Information

USGS Gauge	Area, km^2	Record, Years	Gauging Period	
			Start	End
1585100	19.7	38	2/1/1959	active[a]
1585300	11.6	29	12/1/1958	active[a]
1589300	84.2	34	2/1/1957	active[a]
1589330	14.3	29	10/1/1959	active[a]
1593500	98.4	67	4/1/1932	active
1645200	9.6	30	10/1/1957	9/30/1987
1650500	54.6	61	10/1/1923	active[a]
1653500	43.3	30	8/1/1948	9/30/1978

[a]Gauge temporally inactive during gauging period.

Table 2. Land Use Conditions at the Onset of Gauging and in Year 2000, Where Land Uses and Impervious Values Represent the Percentage of Watershed Area and Runoff CN Values Represent Spatially Averaged Values for the Entire Watershed

USGS Gauge	Year	Residential, %	Commercial/ Industrial, %	Agriculture, %	Forest, %	Impervious, %	Runoff CN
1585100	1959	28.3	10.4	25.9	35.5	16.5	76.8
	2000	56.4	21.2	7.2	15.2	36.2	81.3
	ΔLU_i	28.1	10.8	−18.6	−20.3	19.8	4.4
1585300	1958	40.7	12.3	18.8	28.2	20.2	77.0
	2000	56.7	20.5	3.3	19.4	32.6	79.5
	ΔLU_i	16.0	8.2	−15.5	−8.8	12.3	2.5
1589300	1957	19.0	8.6	40.2	32.0	12.5	72.3
	2000	51.6	15.3	9.5	23.4	30.0	75.2
	ΔLU_i	32.6	6.7	−30.7	−8.6	17.5	2.9
1589330	1959	23.3	21.1	36.4	19.2	23.8	79.3
	2000	51.6	39.3	1.1	8.0	48.6	83.5
	ΔLU_i	28.4	18.2	−35.3	−11.2	24.8	4.2
1593500	1932	1.1	0.4	72.4	26.1	0.6	71.0
	2000	53.0	12.7	15.0	19.2	24.2	74.5
	ΔLU_i	51.9	12.4	−57.5	−6.9	23.6	3.5
1645200	1957	6.4	9.6	63.0	21.0	9.2	72.1
	2000	40.0	33.0	16.6	10.4	42.2	79.1
	ΔLU_i	33.6	23.5	−46.5	−10.6	32.9	6.9
1650500	1923	0.6	0.2	71.9	27.3	0.3	69.5
	2000	63.3	3.9	7.5	25.3	18.3	70.1
	ΔLU_i	62.6	3.8	−64.4	−2.0	18.0	0.6
1653500	1948	20.7	13.4	21.1	44.7	18.0	78.0
	2000	52.7	22.0	1.9	23.2	35.0	81.5
	ΔLU_i	32.0	8.6	−19.1	−21.5	17.0	3.5

model capable of incorporating spatially varied land use by subdividing the watershed such that only subareas with homogeneous land use exist. The decision to use the HEC-HMS model was based on several capabilities of the model: (1) the ability to use subdivisions and accommodate a wide range of drainage areas; (2) the model's support of the NRCS runoff curve number modeling methodologies; (3) the availability of existing GIS interfaces to reduce the drudgery of input data development [e.g., *Olivera*, 2001; *Moglen and Kosicki*, 2000; *USACE*, 2000b]; and (4) the widespread use of the model in hydrologic design throughout the United States. The following describes the modeling methodologies and assumptions used in the adjustment procedure.

[15] While the HEC-HMS model has numerous modeling options, the main components focus on determining runoff hydrographs from subareas and routing those hydrographs through channels to the overall watershed outlet. For this research, the NRCS runoff curve number loss model and dimensionless unit hydrograph methods [*SCS*, 1985] were used to determine subarea runoff hydrographs, which were then routed to the watershed outlet using Muskingum-Cunge [*Cunge*, 1969] channel routing. The NRCS methodologies were used because of the ease with which these methods could be applied to model the effect of changes in

Table 3. Probability (Percent) at Which a Given Time Series (Measured Annual Maximum Discharge $Q_p(t)$; Adjusted Discharge $Q_a(t)$; Measured Discharge-Precipitation Ratio $R(t)$; and Adjusted Discharge-Precipitation Ratio $R_a(t)$) Would Indicate a Statistically Significant Trend Based on the Kendall Tau Trend Test, With Significant Trends for a 1 Percent Level Significance in Parentheses

USGS Gauge	$Q_p(t)$	$Q_a(t)$	$R(t)$	$R_a(t)$
1585100	(0.5)	11.9	(0.0)	12.6
1585300	1.5	16.3	(0.0)	12.9
1589300	18.1	24.2	15.7	23.9
1589330	21.6	40.1	8.2	48.6
1593500	9.3	40.1	(0.4)	41.5
1645200	(0.2)	2.1	(0.0)	2.0
1650500	13.1	26.2	(1.0)	25.8
1653500	(0.5)	2.7	(0.0)	2.0

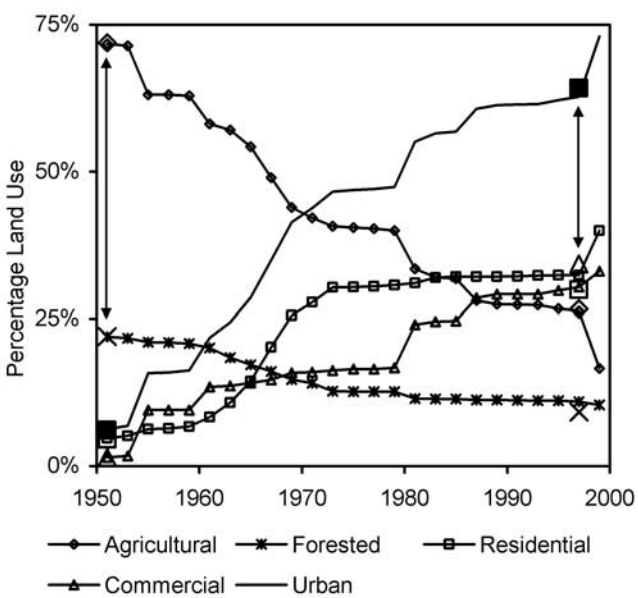

Figure 2. Temporally distributed land use data for the Watts Branch watershed (USGS 01645200), where the urban series (i.e., residential plus commercial land uses) illustrates the urbanization that took place during and after the gauging period.

land use on hydrologic response. Muskingum-Cunge channel routing was selected also for its ease of application and its sensitivity to changes in cross-sectional geometry in both the channel and floodplain. For details regarding HEC-HMS methodologies, see *USACE* [2000a]. The spatial calculations for storage, initial abstractions, and lag time required for the HEC-HMS model are described by *Moglen and Beighley* [2002], where parameter values are determined from a GIS-derived drainage network and spatial/temporally distributed land use data.

[16] Given our lack of high spatial and temporal resolution precipitation data, which is required to accurately simulate storm hydrographs [*Beven*, 2001], our research focused on the use of design storms. The NRCS 24-hour type II design rainfall distribution was selected given the location of the study watersheds [*SCS*, 1986; *Levy and McCuen*, 1999] and the lack of detailed hourly precipitation data. With regard to the spatial distribution, precipitation is assumed uniformly distributed over the entire watershed. An additional discussion on the use of a design storm for simulating the measured discharges is presented later in the adjustment procedure assessment.

[17] Muskingum-Cunge channel routing was used because it allows for both the channel and floodplain to be simulated by using an eight-point cross section. Since surveyed cross-sectional data were not available, cross-sectional geometry was determined from the combination of digital elevation model (DEM) data and regional channel geometry relationships developed by *Brown* [1999]. Our use of *Brown*'s [1999] relationships is illustrative; however, if more appropriate spatial/temporal cross-sectional data are available, they should be used. First, the representative cross-sectional location for a reach was assumed to be the point along the reach with a drainage area equal to the geometric mean of the drainage areas at the upstream and downstream ends of the reach:

$$A_r = 10^{[\log(A_u)+\log(A_d)]/2}, \tag{3}$$

where A_r is the representative drainage area; A_u is the drainage area at the most upstream point along the reach; and A_d is the drainage area at the most downstream point along the reach. At the location along the reach where the drainage area is A_r, three elevations were determined from the DEM: (1) 90 m to the right of the stream pixel looking upstream; (2) the stream pixel; and (3) 90 m to the left of the stream pixel.

[18] Next a detailed channel was determined based on channel geometry relationships from *Leopold and Maddock* [1953] and *Brown* [1999]. *Leopold and Maddock*'s [1953] hydraulic geometry relationships for width and depth can be combined into a single relationship of the form

$$w = \alpha d^u, \tag{4}$$

where w (m) is the channel width at depth d (m) and u and α are shape coefficients. *Brown* [1999] provides relationships for the Maryland Piedmont region that relate u and α to drainage area and land use:

$$u = -0.23LU_r^{0.14} + 0.69 \tag{5}$$

$$\alpha = 3.28^u\left(7.78A_r^{0.18} - 0.69LU_a^{0.34} - 0.13LU_f^{0.52} - 3.12\right), \tag{6}$$

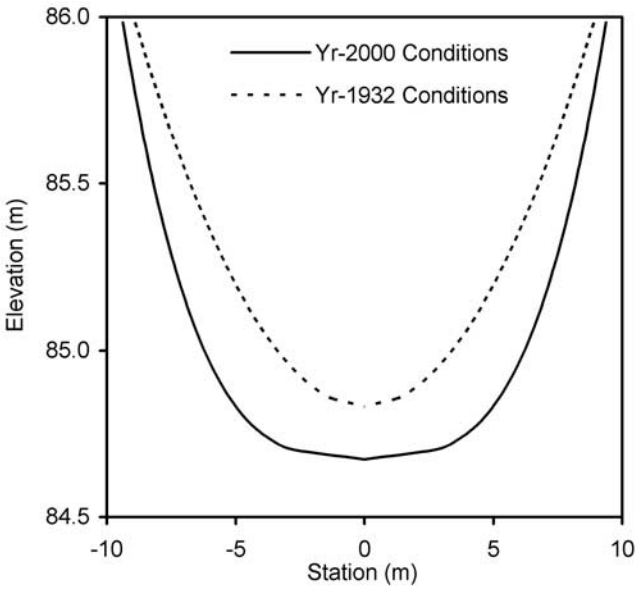

Figure 3. Inferred channel geometry for Little Patuxent watershed (USGS 01593500) at the onset of gauging (1932) and year 2000 land use conditions.

where A_r (km^2) is drainage area at the cross-sectional location, LU_x (percent) represents land use, and x refers to a agricultural, f forested, or r residential land use classifications. To differentiate between in-channel and overbank characteristics, *Brown* [1999] also provides a relationship for the top-of-bank depth, D_{tb} (m):

$$D_{tb} = 0.38A_r^{0.13} + 0.50LU_r^{0.06}. \tag{7}$$

[19] Finally, using equations (4)–(7), channel shapes were imposed on the centers of the stream pixels because the channels in the study watershed have top of bank widths less than the 30-m resolution of the DEM. The top-of-bank elevation was assumed to correspond to the DEM elevation of the stream pixel with the actual channel incised below this elevation. To illustrate this process, Figure 3 shows the inferred channel geometry for the most downstream reach simulated in the Little Patuxent Watershed (USGS 01593500) at the onset of gauging in 1932 and for year 2000 land use conditions. Comparing the two channels shows that equations (4)–(7) predict channel incision and widening with increasing urbanization, which is consistent with actual observations in all of our study watersheds.

[20] To simulate the difference between in-channel and overbank flow, Manning's n coefficients were assumed to be 0.1 and 0.035 for the floodplain and channel, respectively, for all years and all watersheds. These values were selected to represent the range of floodplain and channel coefficients [*Chow*, 1959] that were likely during the gauging periods. Because Manning's n is difficult to estimate, limited data are available on historical and current values, and there is a lack of rigorous relationships between land use and Manning's n, a sensitivity analysis on the effects of Manning's n in the adjustment procedure was performed and will be discussed in a later section.

4.4. Adjustment Procedure

[21] Using the GIS to track both spatial and temporal development characteristics, the adjustment procedure

incorporates the spatial aspects of the urbanization process through the use of explicit hydrologic modeling. The GIS adjustment has five main components: (1) develop spatially distributed land use on an annual temporal resolution for the gauged period of record and the watershed conditions which the adjusted discharges will represent, $LU(x, t)$; (2) determine hydrologic modeling parameters from the spatial and temporal land use data, $CN(x, t)$ and $I(x, t)$; (3) set up a hydrologic model for the gauged watershed by subdividing the watershed, determining spatially averaged modeling variables for each subarea and year and establishing representative cross sections for the reaches connecting the subareas to the watershed outlet; (4) determine the magnitude of the precipitation events responsible for each annual maximum discharge, $P(t)$; and (5) use the inferred precipitation series, $P(t)$, and the target land use conditions to simulate the adjusted annual maximum discharge series, $Q_a(t)$.

[22] Once all the required preprocessing is completed (i.e., steps 1–3), the adjustment procedure consists of two steps: determining precipitation for the measured discharges, and simulating the adjusted discharges with that precipitation. The gauged precipitation data were not used because of the lack of gauges within or very near the study watersheds, the variability between the available gauges, and the occurrence of occasional zero or negligible gauge rainfall depths on days of the observed annual maximum discharge event. Given that the precipitation events being simulated resulted in annual maximum discharges, it is likely that the precipitation in the watersheds was significant. We concluded that the negligible rain gauge values were the result of spatial variations in precipitation. Thus the gauged precipitation data were not used to simulate the measured discharges. Instead, precipitation was used as a calibration parameter within the model.

[23] The difficulty of using precipitation gauge measurements (i.e., point measurements) to infer precipitation both spatially and temporally over a catchment for simulating storm hydrographs has been highlighted by numerous researchers [e.g., *Beven*, 2001; *Engelmann et al.*, 2002; *Urbonas et al.*, 1992]. *Beven* [2001] refers to the use of constant rainfall multipliers to adjust measured rainfall data to calibrate storm hydrographs but cautions this approach because the variability between events will likely require different multipliers. *Engelmann et al.* [2002] present a precipitation adjustment method that uses hourly rainfall data from one gauge to define the temporal rainfall distribution over the entire watershed while using numerous daily gauges to assign area weighted rainfall magnitudes. *Urbonas et al.* [1992] discuss the importance of rainfall gauge density. They show that as the gauge density increases, the accuracies of peak flow estimates improves. While these authors offer potential solutions to overcome the problems associated with using point rainfall measurements to simulate storm hydrographs, the use of the NRCS 24-hour type II design storm to determine a representative precipitation series corresponding to the annual maximum discharges was selected. This approach is supported by *Levy and McCuen* [1999], which indicates that the NRCS 24-hour type II design storm is appropriate for prediction of discharges comparable to annual maximum discharges in Maryland.

Table 4. Summary Statistics for the (Percent Difference) Comparison Between Measured and Adjusted (to Year 2000 Land Use Conditions) Annual Maximum Discharge Series, Where a Positive Value Indicates the Adjusted Discharge is Larger; Adjusted 2-Year Return Period Discharges, Q_F; Simulated Discharges From the 2-Year Rainfall, Q_R; and the Difference, ΔQ, Between the Two 2-Year Floods

USGS Gauge	ΔMean, %	ΔMinimum, %	ΔMaximum, %	Q_F, m^3/s	Q_R, m^3/s	ΔQ, %
1585100	42.0	0.0	78.9	56.4	53.0	−6.1
1585300	22.6	0.0	68.2	44.2	45.8	3.7
1589300	14.3	0.0	24.1	39.9	40.4	1.1
1589330	32.0	12.6	80.4	44.7	78.8	76.4
1593500	79.8	26.0	212.8	30.2	27.4	−9.1
1645200	40.6	0.0	79.4	60.0	68.8	14.8
1650500	34.6	0.0	80.1	52.8	68.6	30.1
1653500	22.9	6.8	45.8	42.8	30.4	−28.9

[24] For each annual maximum event, the simulated precipitation $P(t)$ is determined using an iterative process that adjusts the depth of precipitation associated with a NRCS 24-hour type II design storm such that the simulated discharge $Q_s(t)$ equals the measured discharge $Q_p(t)$. Additionally, the hydrologic modeling is based on both spatially and temporally varying values of $CN(x, t)$ and $I(x, t)$. Finally, the adjusted peak discharge series $Q_a(t)$ is determined using the simulated precipitation series $P(t)$ and the desired fixed land use conditions. The fixed land use conditions are defined spatially by $CN(x, t_a)$ and $I(x, t_a)$, where t_a is the specific year that the adjusted annual maximum discharges $Q_a(t)$ will represent (i.e., current or future development scenario).

4.5. Results

[25] The adjustment procedure was applied to the measured annual maximum discharges from the eight study watersheds shown in Figure 1, where the adjusted discharges represent year 2000 land use conditions. Table 4 shows the comparison between the measured and adjusted discharges. In all cases, the adjusted discharges were greater than or equal to the measured values, with the mean increase for a given gauge ranging from 14 to 80 percent and the maximum increase for an individual event exceeding 200 percent. To highlight specific details of the adjustment procedure, the following discussion focuses on the Watts Branch Watershed (USGS 01645200). Figure 4 shows the comparison between the measured and adjusted annual maximum discharges for Watts Branch. Two points to note from Figure 4 are that the amount of adjustment decreases as (1) the level of urbanization at the time of the measured discharge approaches the current conditions and (2) the magnitude of the flood event increases. For example, moving from left to right along the time axis, the difference between the measured and adjusted discharge decreases as the the level of urbanization become more similar. However, because of the urbanization that occurred after the gauging period, the adjusted discharges near the end of the gauging period are still greater than the measured discharges. If no postgauging urbanization occurred, the adjusted discharge in 1987 would have equaled the measured discharge.

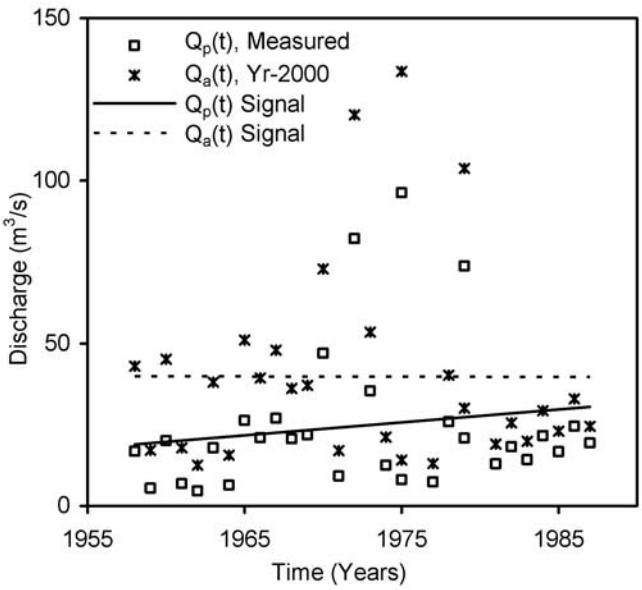

Figure 4. Measured, $Q_p(t)$, and adjusted to year 2000 land use conditions, $Q_a(t)$, annual maximum discharges, with their corresponding linear trends shown as lines, for the Watts Branch watershed (USGS 01645200).

[26] To show the effect of flood magnitude, two years, 1959 and 1960, having essentially identical land use conditions but significantly different flood magnitudes, 5.5 and 20.1 m^3/s, respectively, were compared. Looking at the amount of adjustment shows that the larger event increased by 125 percent to 45.2 m^3/s, while the smaller event increased by 213 percent to 17.2 m^3/s. Thus the larger event is not as affected by the difference in land use as the smaller event. This is to be expected because the magnitude of the larger storm is sufficient to more completely saturate the watershed, resulting in total runoff volume similar to that of a highly urbanized system.

4.6. Sensitivity Analysis

[27] Hydraulic roughness is a critical component in estimating peak discharge because of its effect on timing (i.e., superposition of subarea generated hydrographs). However, estimating Manning's n is a difficult task even for a fixed time period. In our application, channel roughness is required for long periods of time under varying land use conditions. As noted previously, channel and floodplain Manning's n values were estimated as 0.035 and 0.1, respectively, for all years. To determine the potential effect of improper roughness estimates, three scenarios were simulated in the Gwynn Falls watershed (USGS 01589300) to encompass the possible range of Manning's n values. Scenario 1 employs a relatively large (rough) Manning's n = 0.05 for all years. Scenario 2 employs a relatively small (smooth) Manning's n = 0.02 for all years. Finally, scenario 3 begins with a rough Manning's n = 0.05 at the onset of gauging. However, under this scenario Manning's n diminishes linearly with increasing urbanization, reaching n = 0.02 in year 2000. This scenario of decreasing roughness is to depict the effect of channel armoring caused by urbanization owing to a lack of sediment supply from urbanized watershed surfaces. The Gwynn Falls watershed is used in this sensitivity analysis because its cumulative reach lengths were the longest among the systems we studied, making it especially sensitive to changes in the Manning's roughness. In all three scenarios as well as for the assumed conditions (i.e., n = 0.035), the peak discharge for water year 1959 had the greatest adjustment. The increases in peak discharges for scenarios 1, 2, and 3 were 64, 88, and 108 percent, respectively. For comparison, the roughness assumed for our case study resulted in a 79 percent increase.

[28] While the results are sensitive to Manning's n, it appears that the magnitude of the adjustment is only mildly sensitive to the assumption of a constant Manning's n for all years. The adjustment deviation for scenario 1 relative to our assumed conditions used elsewhere in this study is 64–79, or −13 percent. Similarly the adjustment deviations for scenarios 2 and 3 are 9 and 29 percent, respectively. These deviations from our standard results are relatively small compared with the overall adjustment of 79 percent due to hydrologic (rather than hydraulic) change. Further, these results are for year 1959, which experienced the largest adjustments, and for the watershed which had the greatest cumulative reach lengths among the systems we studied. When looking at adjustment deviations across all years, the mean adjustment deviation was −3.2 percent for scenario 1, 4.8 percent for scenario 2, and 14.2 percent for scenario 3, relative to the adjusted discharges for an assumed roughness of 0.035 in all years.

[29] Clearly the most sensitive of the scenarios we studied was scenario 3, in which hydraulic roughness decreased with increasing urbanization. Because information documenting roughness and land use relationships is limited and implementing such an approach is not in the scope of this work, the results discussed herein are limited to roughness being constant over time. However, we would like to motivate future research into the impacts of changes in channel roughness with urbanization. The results of such research would be readily incorporated into the adjustment procedure presented here.

4.7. Assessment

[30] The goal of our effort is not to calibrate a hydrologic model for a specific watershed and land use conditions, but rather to provide an approach for adjusting measured discharges from an urbanized gauged watershed. The application of the GIS adjustment approach must be accompanied with competent hydrologic modeling of the gauged watershed in question. Thus the intent of the hydrologic modeling assessment is to show that the simulated discharges used in this case study are reasonable, such that the adjustment approach itself can be evaluated for its applicability on any urbanized gauged watershed, where the hydrologist would be responsible for the hydrologic model calibration.

[31] The first step to assess the modeling used the 2-year, 24-hour precipitation, with a representative magnitude of 8.1 cm (3.2 inches) for the study region [*National Weather Service* (*NWS*), 1961] assuming average antecedent moisture conditions (AMC II) as defined by NRCS [*SCS*, 1984, 1986]. The simulated peak discharges resulting from the 2-year precipitation, AMC II, and the current (year 2000) land use conditions are shown in Table 4. The *Interagency Advisory Committee on Water Data* (*IACWD*) [1982] estimates for the 2-year return period discharges from the measured and GIS-adjusted flood frequency distributions,

where the adjusted discharges represent the current (year 2000) land use conditions, are also shown in Table 4. Comparing the year 2000 values shows that the simulated 2-year discharge agrees in general with the adjusted 2-year return period discharge, while both are larger than the 2-year return period flood from the measured discharge data. For five of eight gauges, the simulated 2-year flow is within ±15 percent of the GIS-adjusted 2-year return period discharge, with seven of eight within ±30 percent. Overall, the results from the GIS adjustment procedure are intuitively consistent with the change in watershed behavior expected of an urbanized watershed.

[32] The second assessment focuses on the intent of the GIS adjustment procedure, which is to remove the urbanization signal from the measured annual maximum discharge series such that the discharge signal is stationary and appropriate for continued use in various hydrologic and hydraulic design applications. To assess the intent of the adjustment procedure, the Kendall's tau trend test was used to determine if the adjusted discharge ratio signals are stationary. Table 3 lists the probabilities at which the adjusted to year 2000 conditions discharges, $Q_a(t)$, and adjusted ratios, $R_a(t)$, time series would indicate a significant trend (i.e., critical probability), where a significant trend at a 1 percent level of significance, in parentheses, implies the discharge signal is nonstationary. For comparison to the measured time series, Table 3 also lists the critical probabilities for the $Q_p(t)$ and $R(t)$ series.

[33] Given that the watersheds used in this case study were urbanized during their gauging period, we hypothesize that the measured discharge series contain an urbanization signal (i.e., the measured discharge signal is nonstationary). Table 3 shows that the adjustment process was able to remove the urbanization signal from the discharge signal, as indicated by no significant trends in the adjusted ratio $R_a(t)$ series for a 1 percent level of significance compared to six significant trends in the measured ratio, $R(t)$, series. For a 5 percent level of significance, there are only two significant trends in the $R_a(t)$ series compared with six significant trends in the $R(t)$ series. For gauges 01650500 and 01653500, the $R(t)$ series do not have significant trends because the majority of the urbanization took place after the primary gauging period. While their ratio signals are stationary (i.e., no significant trend), their $R(t)$ series are not representative of the current urban watershed. The overall assessment of the adjusted discharge series shows that the discharge signals are stationary and representative of the year 2000 land use conditions. Thus they are appropriate for various applications in the current urban watersheds.

5. Application of Procedure

[34] A common use for the annual maximum discharge series is to develop a flood frequency distribution, which may be used to design various hydraulic structures such as bridges or culverts. However, one of the main assumptions in developing a flood frequency distribution is that the discharge signal is stationary. As shown throughout this study and by *Beighley and Moglen* [2002], this assumption may not be valid for watersheds that have urbanized during their gauging period. The GIS adjustment procedure provides a means to overcome this problem.

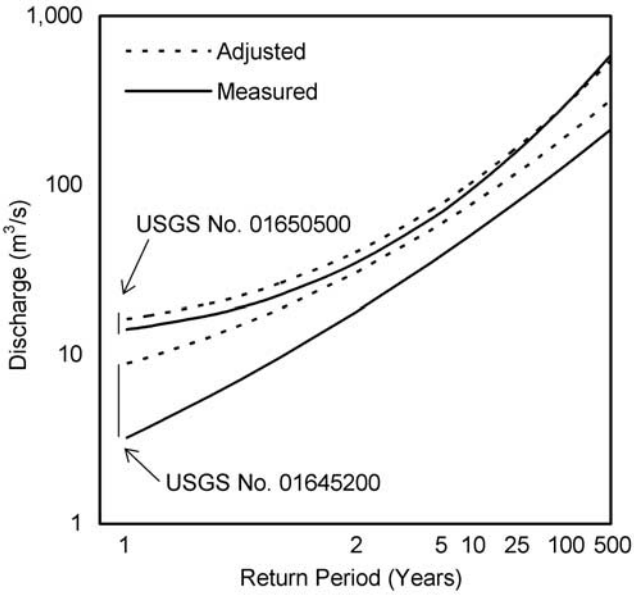

Figure 5. Measured and adjusted (to year 2000 land use conditions) flood frequency distributions for the Watts Branch (USGS 01645200) and the Northwest Branch Anacostia (USGS 01650500) watersheds.

[35] Using *IACWD* [1982], flood frequency distributions were developed for both the measured and adjusted discharges. Figure 5 shows the comparison between the measured and adjusted flood frequency distributions for two watersheds: Watts Branch (USGS 01645200) and Northwest Branch Anacostia (USGS 01650500), which show that the adjusted frequency distribution generally results in larger floods. These two watersheds were selected to illustrate the range of increased flood flows from the adjustment procedure. Table 5 shows the comparison between the measured and adjusted flood frequency distributions for all eight watersheds. Generally, flood flows are larger for the adjusted discharges, with the magnitude of the difference decreasing with increasing return period. For example, the adjusted 2-, 50-, and 100-year floods (common hydraulic design floods) for the Northwest Branch Anacostia watershed are 16, 3, and 0 percent, respectively, larger than the floods based on the measured discharges.

[36] Focusing on the 100-year design return frequency for the Watts Branch watershed, we see that the measured discharge series provides a design flow of 125.9 m^3/s. However, because of urbanization that took place during and after the gauging period, the discharge series adjusted for the year 2000 land use conditions has a larger 100-year discharge of 185.3 m^3/s. This implies that if the measured discharge series were used to develop the 100-year flood, the resulting design would be undersized by 59.4 m^3/s (47 percent) for the current land used conditions. Depending on the design application for which the 100-year discharge is required, this difference in discharge could result in more frequent flooding or even failure. This clearly illustrates the importance of this research and cautions the use of measured discharge data tainted from urbanization as a representative index for current watershed responses.

[37] Another application of the GIS adjustment procedure is to develop relationships between the increase in the

Table 5. Difference (in Percent) Between the Measured and Adjusted (to Year 2000 Land Use Conditions) Flood Frequency Distributions, Where a Positive Value Indicates the Adjusted Flood is Larger, and T_r Refers to Return Period (Years)

	U.S. Geological Survey Streamflow Gauge							
T_r	1585100	1585300	1589300	1589330	1593500	1645200	1650500	1653500
1.005	75.7	89.7	14.8	64.7	177.4	89.5	69.8	60.4
1.01	72.3	77.6	15.4	59.8	161.5	83.2	65.5	54.1
1.05	62.4	51.3	16.5	48.3	125.0	66.5	54.2	39.9
1.11	56.9	40.6	16.9	43.1	109.2	58.2	48.5	33.8
1.25	50.6	30.2	17.0	37.6	93.0	49.3	42.2	27.7
2	39.6	16.8	15.8	29.3	69.9	36.1	31.8	19.6
5	30.8	10.4	12.2	23.7	55.2	28.6	23.9	15.9
10	27.0	9.5	9.4	21.7	50.6	27.1	20.9	15.5
25	23.9	10.5	5.7	20.3	47.7	27.4	18.4	16.5
50	22.2	12.3	2.9	19.8	47.0	28.7	17.2	17.8
100	21.0	14.6	0.1	19.6	47.1	30.6	16.4	19.6
200	20.2	17.4	−2.6	19.7	47.9	33.1	16.0	21.6
500	19.5	21.8	−6.1	20.0	49.6	37.0	15.7	24.8

adjusted flood frequency distributions and various measures of urbanization for estimating increased flood flows in ungauged watersheds and for rapid urbanization impact assessment. *Beighley and Moglen* [2002] present three measures of urbanization that provide general insight into the likelihood of a significant trend in the discharge-precipitation signal: (1) overall increase in urban land use, (2) decrease in forested land use, and (3) percentage of high-density development (i.e., lot sizes =0.1 ha). A fourth measure, which did not provide any predictive power, was the spatial development pattern. To determine if any relationships exists between increased flow and urbanization measures, a multivariable regression analysis between increase in flood flows and the four measures of urbanization was performed. In our analysis, the spatial development pattern was defined as the percentage of total development that occurred within 50 percent of the longest drainage path length from the watershed outlet (i.e., gauge location). The intent of the measures is to quantify the spatial development pattern, which is classified, qualitatively, as top-down or bottom-up. Typically, the top-down development pattern results in larger peak discharges compared with the bottom-up pattern because the top-down pattern tends to align the superposition of more subareas by decreasing the time of concentration of those portions of the watershed most removed from the outlet, while those portions of the watershed closest to the outlet maintain their time of concentration. This allows the contributions to the overall peak discharge from these two different regions to reach their peaks at similar times. Table 6 summarizes the increase in the 2- and 100-year flood flows and these four measures of urbanization.

[38] While *Beighley and Moglen* [2002] showed general relationships between three of the above urbanization measures, the regression analysis results suggest no clear relationships exist between the increases in peak discharges and measures of urbanization. For the increase in the 2-and 100-year floods, the R^2 values for each individual urban measures ranges from 0.00 to 0.12 and 0.02 to 0.36, respectively. Using all four measures, R^2 values were 0.52 and 0.45 for the 2- and 100-year floods, respectively. Overall, the increase in high-density development had the best correlation with both increases in the 2- and 100-year floods. The remaining measures are listed in order of highest correlation: spatial development pattern, total increase in urbanization, and the decrease in forested land use. While no useful relationships were developed, the spatial development pattern appears consistent with the largest and smallest increases in flood flows. Generally, the largest increase in discharge occurred in watersheds classified as having a top-down development pattern, which was expected. However, no single measure can accurately predict the potential magnitude of the increase in flood flow. Thus the combined effects of urbanization on changes in peak discharge can

Table 6. Increase in the 2- and 100-Year Return Period Flows for the Adjusted (to Year 2000 Land Use Conditions) Discharges Compared to the Measured Discharges With Four Measures of Urbanization: Spatial Development Patter; Increase in Urbanization, ΔUrban; Decrease in Forested Land Use, ΔForest; and Percentage of ΔUrban on Lot Sizes ≤0.1 ha, ΔHD-Urban

USGS Gauge	$\Delta Q_{2\text{-year}}$, %	$\Delta Q_{100\text{-year}}$, %	Spatial Pattern	ΔUrban, %	ΔForest, %	ΔHD-Urban, %
01585100	16.8	14.6	bottom-up	38.9	−20.3	38.4
01585300	19.6	19.6	top-down	24.2	−8.8	32.9
01589300	36.1	30.6	top-down	39.3	−8.6	41.5
01589330	39.6	21.0	top-down	46.5	−11.2	41.2
01593500	31.8	16.4	bottom-up	64.3	−6.9	14.8
01645200	69.9	47.1	top-down	57.1	−10.6	36.4
01650500	15.8	0.1	bottom-up	66.4	−2.0	13.9
01653500	29.3	19.6	bottom-up	40.6	−21.5	27.4

only be assessed through modeling the rainfall-runoff process with spatially and temporally distributed land use data, which supports the applicability of our GIS adjustment procedure for continued used of gauged flow data tainted by urbanization.

6. Conclusions

[39] This research developed a procedure to adjust gauged streamflow data from watersheds subjected to urbanization during or after their gauging period to be representative of fixed land use conditions. This fixed land use may reflect current or future development conditions. The intent of this adjustment is to determine what an event resulting in a peak discharge in, for example, 1950 (i.e., before urbanization) would produce on the current urbanized watershed. While past approaches assumed uniform spatial and temporal changes in urbanization, this study focused on the use of GIS-based methodologies for determining high spatial and temporal resolution land use data, incorporating those data into a hydrologic model, and simulating the change in discharge as a result of changing land use conditions.

[40] The strength of this methodology is its ability to quantify both the spatial and temporal aspects of urbanization. This was done using historical aerial photographs, GIS-linked tax-map (i.e., parcels) data, and recent land use/land cover data to recreate the development history of gauged watersheds. The benefit of this process is that the change in land use/land cover retains both the knowledge of what land use (generally agriculture or forested) each parcel was developed from and what land use (high or low density residential/commercial) to which each parcel was developed.

[41] The GIS adjustment procedure presented herein consisted of two steps. First, the precipitation series corresponding to the measured annual maximum discharge series was determined. This was done by simulating the NRCS 24-hour type II design storm on the land use conditions in place at the time of each measured discharge and adjusting the magnitude of the design storm until the simulated discharge equaled the observed discharge. Next, the calibrated precipitation series was used in conjunction with a single fixed land use condition to simulate the adjusted discharge series. This process results in an adjusted time series that is reflective of the discharges that would have been observed in the annual maximum record had the specified land use been in place throughout the gauging period.

[42] As a likely application, our procedure was used to develop the flood frequency distribution from watersheds urbanized during or after their gauging period. One of the primary assumptions for determining flood frequency is a stationary discharge signal. Our case study illustrated how this assumption is often not valid in watersheds that urbanized during or after the gauging period. We showed that the discharges adjusted with our procedure were stationary and therefore valid for determining the flood frequency distribution. Comparing the results from the measured and adjusted to current land use conditions frequency distributions showed the adjusted discharges were often 50 percent larger than the measured data, suggesting the potential for hydraulic structures designed for a specific flood frequency discharge (e.g., the 100-year event) to be greatly under-designed if the unadjusted gauge data were used for design purposes.

[43] Four measures of urbanization were investigated for estimating the magnitude of the increase in flood flows for the adjusted discharges. The overall increase in urban land use, decrease in forested land use, and the percentage of overall urbanization classified as high density development were not effective for estimating the increase in flood flows. While no clear relationships were developed, the spatial development pattern tended to correspond to the relative magnitude of the increase, with top-down patterns typically resulting in the largest increase in flood flows. The lack of any one measure standing out as a significant predictor of expected increase in flood flow highlights the need for a more sophisticated adjustment procedure such as the one we presented here. Our procedure linked GIS techniques and actual hydrologic modeling to quantitatively account for spatial and temporal changes in land use due to urbanization.

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References

Beighley, R. E., and G. E. Moglen, Trend assessment in rainfall-runoff behavior in urbanizing watersheds, *J. Hydrol. Eng.*, *7*(1), 27–34, 2002.

Beven, K. J., *Rainfall-Runoff Modelling: The Primer*, John Wiley, New York, 2001.

Brown, S., Prediction of stream geometry in the Maryland Piedmont based on land use and urbanization, M.S. thesis, 212 pp., Dep. of Civ. and Environ. Eng., Univ. of Md., College Park, 1999.

Chow, V. T., *Open Channel Hydraulics*, McGraw-Hill, New York, 1959.

Cunge, J. A., On the subject of a flood propagation method (Muskingum method), *J. Hydraul. Res.*, *7*(2), 205–230, 1969.

Engelmann, C. J. K., A. D. Ward, A. D. Christy, and E. S. Bair, Application of the basins database and NPSM model on a small Ohio watershed, *J. Am. Water Resour. Assoc.*, *38*(1), 289–300, 2002.

Interagency Advisory Committee on Water Data, Guidelines for determining flood flow frequency, *Bull. 17B,* Off. of Water Data Coord., U.S. Geol. Surv., Reston, Va., 1982.

Leopold, L. B., and T. Maddock Jr., The hydraulic geometry of stream channels and some physiographic implications, *U.S. Geol. Surv. Prof. Pap.*, *252*, 282 pp., 1953.

Levy, B., and R. McCuen, Assessment of storm duration for hydrologic design, *J. Hydrol. Eng.*, *4*(3), 209–213, 1999.

McCuen, R. H., *Hydrologic Analysis and Design*, 2nd ed., 814 pp., Prentice-Hall, Old Tappan, N. J., 1998.

Moglen, G. E., and R. E. Beighley, Spatially explicit hydrologic modeling of land use change, *J. Am. Water Resour. Assoc.*, *38*(1), 241–253, 2002.

Moglen, G. E., and A. Kosicki, Research pays off: GISHydro2000—Performing automated hydrologic analysis in Maryland, *Transp. Res. News*, *210*, 18–19, 2000.

National Weather Service, Rainfall frequency atlas of the United States, *Tech. Pap. 40*, U.S. Dep. of Commer., Washington, D. C., 1961.

Olivera, F., Extracting hydrologic information from spatial data for HMS modeling, *J. Hydrol. Eng.*, *6*(6), 524–530, 2001.

Salas, J. D., Analysis and modeling of hydrologic time series, in *Handbook of Hydrology*, edited by D. R. Maidment, pp. 19.5–19.9, McGraw-Hill, New York, 1993.

Soil Conservation Service, Computer program for project formulation, *Tech. Release 20*, Dep. of Agric., Washington, D. C., 1984.

Soil Conservation Service, *National Engineering Handbook*, suppl. A, sect. 4, chap. 10, U.S. Dep. of Agric., Washington, D. C., 1985.

Soil Conservation Service, Urban hydrology for small watersheds, *Tech. Release 55*, Dep. of Agric., Washington, D. C., 1986.

Soil Conservation Service, State soil geographic (STATSGO) database: Data use information, *Misc. Publ. 1492*, U.S. Dep. of Agric., Washington, D. C., 1994.

United States Army Corps of Engineers, *HEC-HMS Technical Reference Manual*, Hydrol. Eng. Cent., Davis, Calif., 2000a.

United States Army Corps of Engineers, *HEC-GeoHMS User's Manual*, Hydrol. Eng. Cent., Davis, Calif., 2000b.

Urbonas, B. R., J. C. Y. Guo, and M. P. Janesekok, Hyetograph density effects on urban runoff, in *Proceedings of the International Conference on Computer Applications in Water Resources*, pp. 32–37, Tamkang Univ., Tamsui, Taiwan, 1992.

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