USE OF STAGE DATA TO CHARACTERIZE HYDROLOGIC CONDITIONS IN AN URBANIZING ENVIRONMENT[1]

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ABSTRACT: This paper presents the results of a study on the use of continuous stage data to describe the relation between urban development and three aspects of hydrologic condition that are thought to influence stream ecosystems – overall stage variability, stream flashiness, and the duration of extreme-stage conditions. This relation is examined using data from more than 70 watersheds in three contrasting environmental settings – the humid Northeast (the metropolitan Boston, Massachusetts, area); the very humid Southeast (the metropolitan Birmingham, Alabama, area); and the semiarid West (the metropolitan Salt Lake City, Utah, area). Results from the Birmingham and Boston studies provide evidence linking increased urbanization with stream flashiness. Fragmentation of developed land cover patches appears to ameliorate the effects of urbanization on overall variability and flashiness. There was less success in relating urbanization and streamflow conditions in the Salt Lake City study. A related investigation of six North Carolina sites with long term discharge and stage data indicated that hydrologic condition metrics developed using continuous stage data are comparable to flow based metrics, particularly for stream flashiness measures.
(KEY TERMS: hydrologic variability; watershed management; surface water hydrology; urban water management; stream ecology.)

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INTRODUCTION

Streams are dynamic physical, chemical, and biological systems that are influenced by their natural environmental setting as well as by human values and activities, including urban development (Fairweather, 1999; Norris and Thoms, 1999). The effects on stream hydrology of urban development are well documented (USEPA, 1997; American Planning Association, 2002). Increased impervious surface area can alter streamflow generation processes, affecting the movement of water above and below the land surface, changing the frequency, magnitude, duration, and timing of extreme low flow and high flow events (Seaburn, 1969; Hammer, 1972; Beven, 1986; Ferguson and Suckling, 1990; Pitt, 1991; Poff *et al.,* 1997; USEPA, 1997). Altered runoff patterns and subsequent changes in stream hydrologic conditions can change channel morphology and riparian habitat (Resh *et al.,* 1988; USEPA, 1997).

Changes in stream hydrologic conditions also can have a substantial effect on aquatic species recruitment, age structure, taxa richness, and taxonomic composition (Poff and Ward, 1989; Poff, 1996; Clausen and Biggs, 1997, 2000). Five streamflow characteristics have been proposed as having a particularly important effect on stream ecosystems (Poff and Ward, 1989; Richter *et al.,* 1996; Poff *et al.,* 1997).

Overall variability can refer to both the overall variability of stream conditions (e.g., coefficient of variation, or the ratio of mean flow conditions over a period of record to the standard deviation of flow conditions) and the timing, or predictability, of flows of a defined magnitude (i.e., the regularity with which the flow occurs) (Colwell, 1974; Poff, 1996). The *rate of change*, or *flashiness*, refers to how quickly flow changes from one magnitude to another. At extremes, hydrologically flashy streams have rapid rates of flow change, and hydrologically stable streams have slow rates of flow change. The *duration* is the length of

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time associated with a specific flow condition. Duration can be defined relative to a particular flow event (e.g., a floodplain may be inundated for a specific number of days by a 10-year flood), or it can be a defined as a composite expressed over a specified time period (e.g., the number of days in a year when flow exceeds a specific value, or alternately the largest number of consecutive days in a year when flow exceeds a specific magnitude). The *magnitude* of streamflow during any given time interval is the amount of water moving past a fixed location per unit of time. The *frequency* of occurrence refers to how often a flow above or below a given magnitude recurs during a specified time interval.

The question of how urbanization affects stream ecology is the focus of an investigation conducted as part of the U.S. Geological Survey (USGS) National Water Quality Assessment (NAWQA) Program (USGS, 2000). A gradient design (McMahon and Cuffney, 2000) was used to investigate the relation between urbanization and stream ecosystem response in three contrasting environmental settings – the humid Northeast (the Boston area), the very humid Southeast (the Birmingham area), and the arid West (the Salt Lake City area, hereinafter referenced by city name) (Table 1). Measurements of physical (including continuous stream stage), chemical, and biological conditions were made at the outlet of a total of 72 drainage basins. Study basins within each of the three study locations were chosen to fall within a relatively homogeneous environmental setting, including a narrow range of drainage areas, although practical constraints of site selection resulted in a somewhat larger range of drainage basin area than originally intended. If urbanization, through its effects on stream hydrologic conditions, can exert a strong influence on stream ecological conditions, then any investigation of the relation of urbanization and stream ecology must consider the relation between urbanization and stream hydrology.

The purpose of this paper is to improve the understanding of the association between urban development and stream hydrology by addressing two questions: (1) can measures of stream hydrologic condition appropriate for assessing the relation between hydrologic conditions and urbanization be developed from continuous measurements of stage? and (2) can stage based metrics be used to describe the association between hydrologic conditions and urbanization?

To address the first question we present metrics to describe aspects of stream hydrologic conditions that are important in stream ecosystem processes and that can be calculated using either continuous stream discharge or stage data. These metrics are calculated for three urban and three nonurban sites in North Carolina that have relatively long term discharge and stage records. We assess whether information represented by the stage based metrics is comparable to that of discharge based metrics and the ability of these metrics to differentiate between urban and nonurban sites.

Why is it important to develop stage based methods for describing hydrologic variability? Metrics for describing streamflow characteristics (e.g., overall variability, flashiness, duration, magnitude, and frequency) that influence stream ecosystems have commonly been calculated using flow data (Poff and Ward, 1989; Poff and Allan, 1995; Richter *et al.,* 1996; Clausen and Biggs, 1997). Ideally, continuous records of streamflow, rather than stage, would be used to investigate the association of urbanization and hydrologic conditions. Continuous stage data, however, were used to characterize hydrologic conditions in the three gradient studies, for two reasons. First,

TABLE 1. Study Basin Characteristics.

Study Area	Number of Study Basins	Average Study Basin Area (km2)	Range of Study Basin Area (10th-90th percentile) (km2)	Range of Average Annual Precipitation (1961-1990) (mm)	Range of Annual Runoff (1951-1980) (mm)	Period of Record for Stage Data
Salt Lake City						
Below Canyon Mouth	10	8.48	3.12 to 15.6	305 to 1,270	25 to 510	July 1, 2000, to September 30, 2000
Entire Basin		336	12.5 to 950			
Birmingham	30	32.2	12.0 to 52.6	1,270 to 1,520	460 to 760	July 10, 2000, to July 29, 2001
Boston	32	75.7	52.6 to 113	1,020 to 1,270	510 to 640	April 26, 2000, to March 29, 2001

constraints imposed by the study design made it impractical to use streamflow data. The study design called for water quality monitoring at 72 stream sites for one year. None of the three study areas had large existing stream gaging networks, and the installation of new gages was impractical because of funding constraints and because the relation between stream stage and streamflow that is required to calculate flow could not be adequately developed within the one-year study period.

A second, more general reason for using stage data to assess hydrologic conditions is associated with the synoptic approach used in many stream ecology studies (e.g., Cuffney *et al.,* 2000). In a synoptic study design, water quality samples are collected at approximately the same time at a large number of sites to characterize the aquatic ecosystem response to variations in a driving factor (e.g., degree of urbanization) of interest. The studies are designed so that other factors that might influence the ecosystem response, such as weather or other aspects of the environmental setting (e.g., soil geology, basin size), are relatively invariant in all the study watersheds.

Although it is widely recognized that hydrologic regime provides an important constraint of the structure of stream biotic assemblages (Poff and Allan, 1995), few sites used in synoptic stream ecology studies are typically gaged, particularly with long term gages. As a result, ecological researchers forego the use of long term streamflow information in analyzing data from all study sites, attempt to transfer streamflow information from gaged sites to nearby ungaged study sites, or attempt to simulate streamflow information. Each option has limitations, but the second option, using data from nearby gages, is unworkable in an urbanizing setting where land use in adjoining basins may be substantially different or undergoing rapid change.

The development of relatively inexpensive methods to characterize hydrologic conditions at ungaged sites would represent an important methodological advancement for conducting synoptic ecological studies. It would enhance the possibility of using synoptic studies to understand the relation between urbanization and hydrologic conditions as well as to answer more general questions about the stream ecology effects of urbanization.

The second question addressed by this paper is whether stage based metrics can be used to describe the association between hydrologic conditions and urbanization. We hypothesize that urbanization has a generally positive association with overall variability in streamflow conditions and with stream flashiness, as measured by the stage based metrics. It follows that increased flashiness results in a shorter duration (i.e., length of time) of high stage conditions and a longer duration of low stage conditions (Figure 1). Therefore, we also hypothesize that increasing urbanization has an inverse relation with the duration of high stage (i.e., increasing urbanization results in high stage conditions lasting for shorter periods of time), and a positive association with duration of low stage conditions (i.e., in a less urbanized basin, the recession limb would have a more gradual slope and a shorter length of time in low flow conditions). These associations are explored using correlation analysis between stage based metrics and several measures of drainage basin development. This paper does not address the relation of streamflow variability and ecological conditions; the NAWQA urban gradient study design does, however, include plans for this type of analysis.

METHODS FOR STUDYING THE RELATION BETWEEN URBANIZATION AND STREAMFLOW CONDITIONS

The central focus of this paper is whether hydrologic metrics appropriate for assessing the relation between hydrologic conditions and urbanization can be developed using continuous measurements of stage. For six sites in North Carolina, metrics were calculated using historical flow and stage data to determine if there is a relation between flow based and stage based versions of the metrics. Metrics also were calculated using stage data at 72 sites that are part of an investigation of the effects of urbanization on stream ecology.

Stage Data Collection

Global Water WL-14 pressure transducers, which have internal data loggers, were used to collect stage data at the urban gradient sites. Stage was measured in English units (i.e., feet) relative to an arbitrary datum. Recording intervals were initially set to 15 minutes and later adjusted to one hour (Steven Gerner, USGS, personal communication, November 2000). All data were analyzed based on an hourly collection time interval. Data from the ten Salt Lake City sites were analyzed for the period July 2000 through September 2000. The short record for data analysis was due, in part, to problems with some data recorders over the winter of 2000. Stage data for the 30 Birmingham sites were analyzed for the period July 2000 to July 2001. Stage data from the 32 Boston sites were analyzed for a six-month data collection period that was common among all Boston sites between May 2000 and June 2001. A relation between cross sectional flow area and stage was developed at each of the ten Salt Lake City sites, so that a continuous record of flow area was available. Salt Lake City streamflow metrics were calculated using both stage and cross sectional area data. Data from sites within each of the three study areas were analyzed using a common period of record (POR) for all sites in the study area.

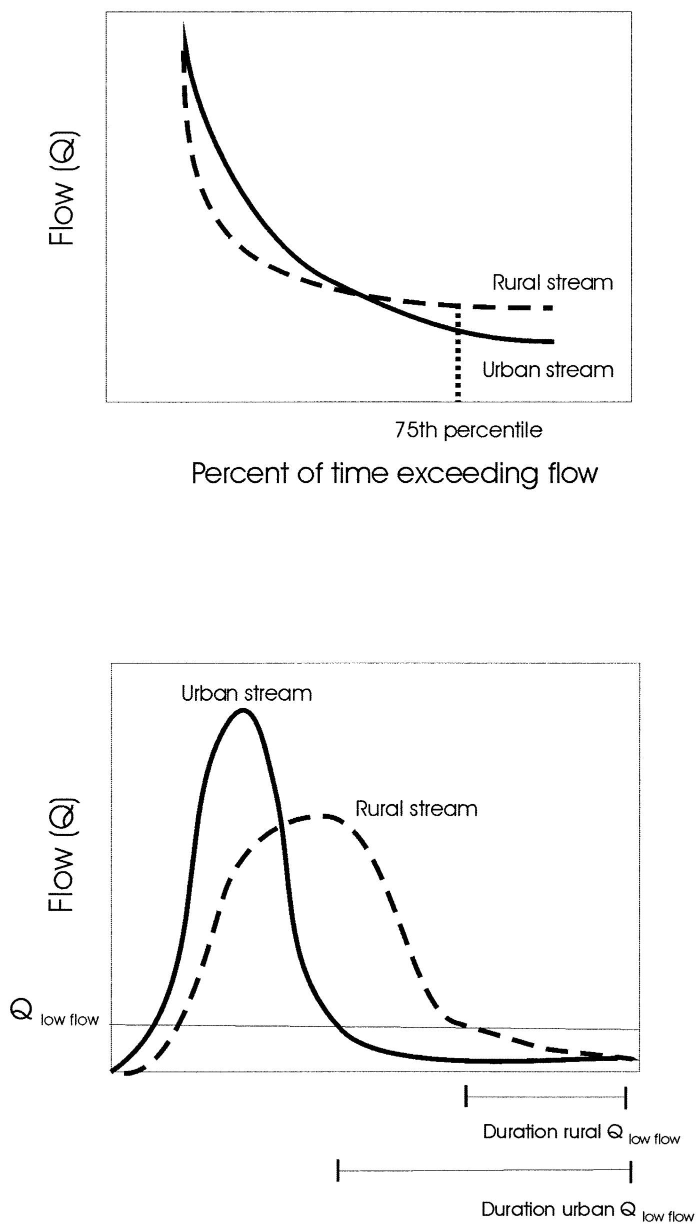

Figure 1. Conceptual Diagram of Hypothesized Duration, or Length of Time, of Low Flow Conditions in Urban and Rural Catchments.

Hydrologic Condition Metrics

Because no single hydrologic descriptor is likely to express all the major streamflow attributes that affect ecosystem response, Clausen and Biggs (2000) recommended that a suite of metrics describing hydrologic conditions be used in stream ecological studies. Two criteria were used in this investigation to assess candidate metrics for describing hydrologic conditions. Because of the overall objective of understanding the relation between urbanization and stream ecology in the three urban gradient studies, hydrologic condition metrics had to have been shown previously to be useful in explaining stream ecological conditions. Prospective hydrologic condition metrics also had to be amenable to being calculated by using stage as well as flow data (see Poff and Ward, 1989; Jowett and Duncan, 1990; Poff and Allan, 1995; Richter *et al.,* 1996; Clausen and Biggs, 1997; Poff *et al.,* 1997; Richter *et al.,* 1997; Richter *et al.,* 1998). We used metrics representing three aspects of hydrologic condition meeting both these criteria: overall variability, frequency of change (or flashiness), and duration of high flow and low flow or stage conditions (Table 2). Stage data alone cannot be used to develop estimates of streamflow magnitude, frequency, and predictability that can be compared between stations.

One overall variability metric was calculated. The coefficient of variation of hourly flow or stage data (CVHR) is a measure of the variability of flow or stage conditions relative to mean flow or stage, a value that can be used to compare overall variability among stations. For the North Carolina stations where flow based and stage based metrics were calculated, CVHR was calculated using hourly stage and flow measurements (Table 3). For the 72 urban gradient sites, only stage data were used.

Several measures of stream flashiness were calculated. Rising stage frequency was calculated for stage increases of at least 0.1 foot per hour (PERIODR1), 0.3 foot (PERIODR3), 0.5 foot (PERIODR5), 0.7 foot (PERIODR7), and 0.9 foot (PERIODR9) per hour (Table 3). Similar measures were calculated for stage decreases, including a decrease of at least 0.1 foot per hour (PERIODF1), 0.3 foot (PERIODF3), 0.5 foot (PERIODF5), 0.7 foot (PERIODF7), and 0.9 foot (PERIODF9) per hour. The value for this metric represents a count of the number of hourly time periods over the period of record where there was a stage change of the indicated magnitude. For all 72 stations in the urban gradient study, the median hourly stage change over the period of record was 0.1 foot.

The calculation of stage change, or flashiness, metrics was slightly different for the subset of the Salt Lake City metrics that are based on cross sectional

TABLE 2. Measures of Stage Variability, Change, and Duration Used to Study the Effects of Urbanization.

CVHR	**CV of Stage Over All Hours in POR***
	Frequency of Stage Change (flashiness)
HYD1	Principal components analysis based index of hydrologic variability; measures flashiness.
PERIODR1	Rising stage frequency 1 (Number of time periods (hrs) when stage rises by at least 0.1 foot)
PERIODR3	Rising stage frequency 3 (Number of time periods (hrs) when stage rises by at least 0.3 foot)
PERIODR5	Rising stage frequency 5 (Number of time periods (hrs) when stage rises by at least 0.5 foot)
PERIODR7	Rising stage frequency 7 (Number of time periods (hrs) when stage rises by at least 0.7 foot)
PERIODR9	Rising stage frequency 9 (Number of time periods (hrs) when stage rises by at least 0.9 foot)
PERIODF1	Falling stage frequency 1 (Number of time periods (hrs) when stage falls by at least 0.1 foot)
PERIODF3	Falling stage frequency 3 (Number of time periods (hrs) when stage falls by at least 0.3 foot)
PERIODF5	Falling stage frequency 5 (Number of time periods (hrs) when stage falls by at least 0.5 foot)
PERIODF7	Falling stage frequency 7 (Number of time periods (hrs) when stage falls by at least 0.7 foot)
PERIODF9	Falling stage frequency 9 (Number of time periods (hrs) when stage falls by at least 0.9 foot)
	Duration of High Stage Conditions
MXH_75	Maximum duration of high stage pulses over POR (hr); high stage > 75th percentile
MXH_90	Maximum duration of high stage pulses over POR (hr); high stage > 90th percentile
MXH_95	Maximum duration of high stage pulses over POR (hr); high stage > 95th percentile
MDH_75	Median duration of high stage pulses over POR (hr); high stage > 75th percentile
MDH_90	Median duration of high stage pulses over POR (hr); high stage > 90th percentile
MDH_95	Median duration of high stage pulses over POR (hr); high stage > 95th percentile
	Duration of Low Stage Conditions
MXL_25	Maximum duration of low stage pulses over POR (hr); low stage < 25th percentile
MXL_10	Maximum duration of low stage pulses over POR (hr); low stage < 10th percentile
MXL_5	Maximum duration of low stage pulses over POR (hr); low stage < 5th percentile
MDL_25	Median duration of low stage pulses over POR (hr); low stage < 25th percentile
MDL_10	Median duration of low stage pulses over POR (hr); low stage < 10th percentile
MDL_5	Median duration of low stage pulses over POR (hr); low stage < 5th percentile

*POR = Period of record.

TABLE 3. Description of Basins Used to Compare Flow Based and Stage Based Hydrologic Variability Metrics.

USGS Stream Gaging Station Number	**Station Name**	**Basin Area (km^2)**	**Developed Land Area (percent)**	**Period of Record for Analysis**	**Mean Flow During Period of Analysis (m^3/s)**	**Flow Coefficient of Variation During Period of Analysis (dimensionless)**
02146409	Little Sugar Creek at Medical Center Dr. at Charlotte, North Carolina	30.7	79	January 1995 to December 2001	0.501	542.9
0208732885	Marsh Creek near New Hope, North Carolina	17.7	56	January 1995 to December 2001	0.323	543.5
02146211	Irwin Creek at Statesville Ave. at. Charlotte, North Carolina	15.6	47	January 1998 to December 2001	0.153	430.8
02084160	Chicod Creek at SR 1760 near Simpson, North Carolina	117	1	January 1995 to December 2001	1.570	318.1
02097464	Morgan Creek near White Cross, North Carolina	21.9	1	January 1995 to December 2001	0.227	567.8
02142000	Lower Little River near All Healing Springs, North Carolina	73.4	0	January 1998 to December 2001	0.706	208.1

area. Flashiness metrics were determined by cross sectional area changes of at least 1, 3, 5, 7, and 9 times the median hourly cross sectional area change during the study period. This approach is analogous to the approach used for stage in that the median stage change during the study period at all sites was 0.1 foot. Calculation of flow based flashiness metrics for the North Carolina sites followed an analogous procedure: flashiness metrics were determined by flow changes of at least 1, 3, 5, 7, and 9 times the median hourly flow change during the study period. As with the stage data, the metric value represents the number of hourly time periods over the period of record when there was a change in cross sectional area or flow of the indicated magnitude.

Six measures of high stage duration were calculated. In general, duration of high stage was a measure of the length of time, in consecutive hours, that stage conditions remained above a designated high stage threshold. The maximum duration represents the number of hours of the longest consecutive pulse of high stage or flow conditions. The median duration represents the median duration of all distinct periods of high stage conditions. The maximum duration of a high stage (MXH) pulse over the POR was calculated by using three different thresholds for defining a high stage event – stage greater than the 75th percentile (MXH_75), stage greater than the 90th percentile (MXH_90), and stage greater that the 95th percentile (MXH_95). The median duration of high stage (MDH) pulses over the POR was calculated by using the same three thresholds (Table 2). An analogous approach was used for the cross sectional area calculations for Salt Lake City and the flow data for the North Carolina sites.

Six measures of low stage duration were calculated in a manner analogous to that used for high stage conditions. Duration of low stage was a measure of the length of time, in consecutive hours, that stage conditions remained below a designated low stage threshold. The maximum duration represents the number of hours of the longest consecutive pulse of low stage or flow conditions, while the median duration represents the median duration of all distinct period of low stage conditions. The maximum duration of low stage (MXL) pulses over the POR was calculated by using three different thresholds for defining a low stage event – stage less than the 25th percentile (MXL_25), stage less than the 10th percentile (MXL_10), and stage less that the 5th percentile (MXL_5). The median duration of low stage (MDL) pulses over the POR was calculated by using the same three thresholds (Table 2). Cross sectional area values also were used in these calculations for Salt Lake City and flow values for the North Carolina sites. The low stage or flow duration measure represents the number of hours, over the POR, of the longest consecutive pulse of low stage or flow conditions.

Principal components analysis (PCA) was used to construct an index that summarizes information contained in the 23 individual hydrologic condition metrics for the Birmingham, Boston, and Salt Lake City sites. PCA can be used to identify one or more variables that are responsible for most of the variability among the sites in each of these three studies.

Comparison of Metrics Based on Stage, Cross Sectional Area, and Flow

Comparisons of metrics based on stage and flow were made using data from six sites in North Carolina (Table 3). At least four years of streamflow and stage data measured at hourly intervals were available from each of these sites. Three of the sites were relatively urbanized; the others were relatively undeveloped. The metrics described above were calculated for each year in the POR using hourly data for all sites. Flow based metrics were calculated by using an algorithm similar to that used for the cross sectional area based metrics for Salt Lake City. Regression analysis was used to test the relation between the flow based and stage based metrics. Principal components and correlation analyses were used to compare composite measures of flow based and stage based metrics. Ranked flow and stage metric values were used in an analysis of variance to test whether there was a difference in the metric values for urban and nonurban sites. A similar regression analysis was used to assess the relation between the metrics based on stage and cross sectional area for Salt Lake City.

Characterization of Urban Intensity

In each of the three urban gradient study areas (Birmingham, Boston, and Salt Lake City), a population of candidate study basins within a limited size range was identified within a single U.S. Environmental Protection Agency level III ecoregion of the conterminous United States (Omernik, 1987) to reduce the variability in broad scale natural factors that influence streamflow and other ecologically relevant processes. Finer scaled information was used to determine a further subset this population of candidate basins. Each subset of potential basins had relatively similar basin scale natural characteristics (e.g., soil, topography, drainage area). The final set of sites selected for each of the three studies represented a gradient of urbanization while having relatively uniform natural characteristics, including basin size and similar stream segment characteristics.

The degree of urban development in each of the potential study basins was characterized by using both individual basin characteristics related to development (e.g., percentage of developed land cover and of road and population density) and a multimetric index of urban intensity. A multimetric index approach allows the integration of multiple sources of information about the urban landscape – for example, urban land area, amount of impervious surface, road density, population density, and social, income, and housing characteristics – into a single measure of urban development intensity containing information not quantified by a single measure such as percentage of developed land cover (Karr and Chu, 1997; Cuffney *et al.,* 2000; McMahon and Cuffney, 2000).

Land cover data were developed by using a Thematic Mapper (TM) Landsat dataset of 30-meter resolution collected for the conterminous United States in the early 1990s (Vogelmann *et al.,* 2001; USGS, 2002). TM derived land cover data were used to describe the structure, or spatial arrangement, of the developed landscape in each Boston and Birmingham basin (Table 4) (McGarigal and Marks, 1995). Landscape structure refers to the composition (e.g., the presence and amount of developed land patches, or discrete areas composed entirely of developed land, in a basin) and configuration (e.g., arrangement of developed land patches in a basin) of the developed landscape. Because of the relatively small size of the Salt Lake City study basins, these land cover data were used only to describe landscape composition (e.g., percentage of developed land) in the Salt Lake City study.

A modified approach for characterizing urban intensity was required in the Salt Lake City study area because of distinctive climatic and topographic conditions. All but two streams in the Salt Lake City study area originate in the Wasatch Mountains east of Salt Lake City. The streams flow in a westward direction through largely undeveloped canyons and across narrow benches onto alluvial valleys along the eastern side of the Basin and Range ecoregion. There is commonly a spatial gradient to the development pattern in these bench and valley areas – the intensity and age of development increase from east to west as the stream moves onto flatter lands closer to the Great Salt Lake and its main tributaries. The two streams that do not originate in the Wasatch Mountains are larger rivers. These rivers also flow east to west, and development along the rivers follows a similar pattern to that of other study area streams. Stage data for the 10 Salt Lake City sites analyzed in this study (Table 1), including the two large river sites,

TABLE 4. Measures of Urbanization.

Variable	Landscape Characteristic	Definition
dev_pct	Composition	Percentage of developed land.
for_pct	Composition	Percentage of forested land.
pop_den	Composition	1999 population density.
road_den	Composition	Road density.
p1_10,100	Composition	Low density residential land (%; in 10-m or 100-m buffer) in riparian corridor area.
p2_10,100	Composition	High density residential and commercial land (%; in 10-m or 100-m buffer) in riparian corridor area.
p3_10,100	Composition	Vegetated land (%; in 10-m or 100-m buffer) in riparian corridor area.
p6_10,100	Composition	Agricultural land (%; in 10-m or 100-m buffer) in riparian corridor area.
LPI	Composition	Percentage of the watershed area composed of the largest patch of the developed land-cover class (percent). Higher value indicates less fragmentation.
MPS	Configuration	Mean developed land patch size (ha).
MNN	Configuration	Mean nearest neighbor distance for patches of developed land (m).
NNCV	Configuration	Nearest neighbor coefficient of variation, or variability as a percent of the mean nearest neighbor distance (percent).
IJI	Configuration	Interspersion and juxtaposition index, or extent to which patch types are interspersed (percent).

Notes: Landscape composition refers to the variety and abundance of patch types but not the spatial location of patches. Landscape configuration refers to the spatial distribution of patches within a landscape, such as patch location relative to other patch types in a basin (see McGarigal and Marks, 1994). A patch is a discrete are composed entirely of a particular land cover type (e.g., developed land cover).

were collected in the bench and valley areas west of the canyon mouths. Basin characteristics were developed only for the portions of the drainage areas outside (west) of the canyons. For example, the Emigration Creek site in Salt Lake City has a total drainage area of about 45 (km^2). The drainage area between the mouth of the canyon and the data collection site is about 3.2 km^2; and the extent of basin development (e.g., percentage of developed land area) was described relative only to the 3.2 km^2 area and not the 45 km^2 area. Landscape configuration metrics were not calculated for the Salt Lake City study areas because of the small size of the drainage areas relative to the accuracy of the land cover data. Additional land cover data were collected for the Salt Lake City study from digital orthophotos for a 3.2 km riparian corridor upstream from all sampling and stage measurement locations (Table 4). The percentage of low intensity and high intensity residential development, vegetated land cover, and agricultural land cover within 10 m and 100 m riparian buffers were extracted from the digital orthophotos (Tim McKinney, USGS, personal communication, October 2001).

Relation Between Urbanization and Hydrologic Conditions

Correlation analysis was used to assess the relation between urbanization and hydrologic conditions in the Birmingham, Boston, and Salt Lake City study areas. Urbanization measures used in the analysis included the urban intensity index, percentage of developed and forested land cover, 1999 population density (except for Salt Lake City, where data of adequate resolution were not available), road density, and several measures of developed land cover fragmentation. Measures of hydrologic conditions included the 23 individual metrics (Table 2) and a PCA based summary measure of hydrologic conditions. Although these urbanization metrics measure somewhat different dimensions of urban development, they are highly correlated. The various urbanization measures were expected to have similar correlations with the measures of hydrologic condition.

RESULTS AND DISCUSSION

Comparison of Metrics

Stage based and flow based metrics developed for the six North Carolina sites were compared to answer two questions. First, are stage based and flow based metrics describing hydrologic conditions (Table 2) related in some way? Second, when the values for each pair of flow based and stage based metrics are ranked over all stations and all years of calculation, is there a difference in these rankings for urbanized and nonurbanized catchments? For example, if the rankings for the urban catchments were different (e.g., the rankings of the flow based version of PERIODR5 are all high while the rankings of the stage based metrics are all low), this would suggest that the flow based and stage based metrics were inconsistent in the way they describe hydrologic conditions. Metrics based on stage and cross sectional area were also compared for the Salt Lake City study to determine which type of hydrologic metric to use in this study.

The coefficient of determination (R^2) indicates a moderate to strong relation between flow based and stage based flashiness metrics (Table 5). The strongest relation was between metrics that defined flashiness in terms of relatively large increases in stage (or flow) (i.e., those with a change greater than 3, 5, 7, or 9 times the median change over the POR). The two exceptions were the metrics for PERIODR1 and PERIODF1, which describe changes (increases or decreases) in flow and stage occurring at intervals of one hour. These results suggest that the metrics PERIODR1 and PERIODF1 are not useful for describing the effects of urbanization on hydrologic variability. A scatter plot of the flow and stage data for PERIODR5 (see Table 2) illustrates several aspects of the relation between the flow based and stage based flashiness metrics (Figure 2). The scatter plot and associated linear regression line indicate a strong overall relationship. Sites with a relatively high level of urban development have a greater number of flow changes of this magnitude. While there may be a different slope if regressions are developed separately for urban and nonurban sites, the tight clustering of data indicates that there would still be a clear relation between the stage based and flow based flashiness metrics.

It is unclear why coefficient of determination values for rising stream changes generally are higher than for falling stream changes. The difference in the relations for rising and falling stage metrics suggests a looped rating curve in which the relation between stage and discharge is different for the rising limb of the hydrograph than for the falling limb. In theory, a looped rating exists for all natural streams, in part because of inertial differences between rising and falling stages. In most cases, however, the difference between the stage discharge relation for rising and falling limbs of a hydrograph can be ignored, except when the stream corridor includes a broad floodplain or when backwater effects occur. The streams used in the analysis drained fairly small basins, did not have

TABLE 5. Comparison of Stage-Based and Flow-Based Hydrologic Condition Metrics.

	Regression of Flow Based Statistic on Stage Based Statistic[a]	Mean Rankings of Flow and and Stage Based Metrics for Urban and Nonurban Sites[b]			
		Urban Basins		Nonurban Basins	
	R^2	Flow	Stage	Flow	Stage
Overall Variability					
CVHR	0.03	23.7	22.9	13.3	12.7
Frequency of Stage/Flow Change					
PERIODR1	0.07	22.7	24.1	14.3	11.6
PERIODR3	**0.68**	26.2	26.5	10.8	9.0
PERIODR5	**0.86**	27.4	26.5	9.6	9.0
PERIODR7	**0.88**	27.5	26.5	9.5	9.0
PERIODR9	**0.86**	27.5	26.5	9.5	9.0
PERIODF1	0.03	21.4	24.4	15.6	11.2
PERIODF3	**0.36**	23.9	26.5	13.1	9.0
PERIODF5	**0.68**	26.6	25.5	10.4	8.5
PERIODF7	**0.75**	27.1	22.5	9.8	7.0
PERIODF9	**0.77**	27.4	22.4	9.6	7.1
Duration of High Stage/Flow Conditions					
MXH_75	0.03	11.6	13.6	25.3	22.6
MXH_90	**0.42**	9.5	10.4	27.5	26.1
MXH_95	**0.75**	9.7	10.5	27.3	26.0
MDH_75	**0.72**	15.3	14.3	21.7	21.9
MDH_90	**0.78**	12.3	11.5	24.7	24.9
MDH_95	**0.84**	10.0	9.8	27.0	26.7
Duration of Low Stage/Flow Conditions					
MXL_25	**0.13**	11.6	14.9	25.4	20.1
MXL_10	0.07	13.5	18.8	22.8	17.8
MXL_5	0.00	13.5	12.6	22.0	16.0
MDL_25	**0.50**	14.4	14.6	22.6	20.4
MDL_10	**0.21**	15.3	13.7	20.8	17.9
MDL_5	**0.65**	15.1	11.9	20.2	16.4

[a]Comparison of the relationship between flow based and stage based metrics based on regressing metric on stage based metric. R^2, the coefficient of determination, is a measure of the variation in the flow based analysis of variance of stage based statistic explained by the flow based statistic. R^2 values shown in bold indicate that the regression was significant at $\alpha = 0.10$.

[b]Comparison of flow based and stage based metrics across urban and nonurban sites, based on ranked flow and stage metric scores. Higher rank values indicate higher metric values. Mean rankings in bold indicate a statistically significant difference between mean rankings of flow based and stage based metric values.

broad floodplains, and were not subject to backwater for most conditions.

It should not be surprising that the stage based metric for overall hydrologic variability (CVHR) (Table 5) is not closely related to flow based metrics. The relation between stage based and flow based metrics for hydrologic variability directly reflects the stream specific relation between stage and discharge. In broad streams, a small change in stage can be associated with a very large change in streamflow, which is in contrast to deep, narrow stream channels where large changes in stage are required to generate an equivalent change in streamflow. On the other hand, stage based and flow based flashiness metrics should be directly related.

The strongest relation between high flow duration metrics based on flow and stage occurred when high flow was defined by using median, rather than maximum, duration of the high flow event (which also was true for low flow durations) and for high flow defined by 95th and 90th percentile conditions, rather than 75th percentile conditions, over the POR. The coefficient of determination (R^2) for the median high stage duration metrics increases as the threshold for defining a high flow event increases (i.e., from defining a high stage as the 75th percentile stage or flow to a 95th percentile flow event), indicating a closer alignment between the flow based and stage based duration metrics when a more restrictive definition of high flow is used (Table 5). Duration of high flow conditions reflects the combined effects of streamflow generation (rapid runoff results in relatively short high flow durations) and channel configuration (the stage-discharge relation), so the relation between high flow and high stage duration would not be as strong as for flashiness. The relation among four of the six stage based and flow based metrics for low flow duration was weak, suggesting that in the six North Carolina basins the stage based low flow duration metrics did not describe the same aspects of stream variability as the flow based metrics.

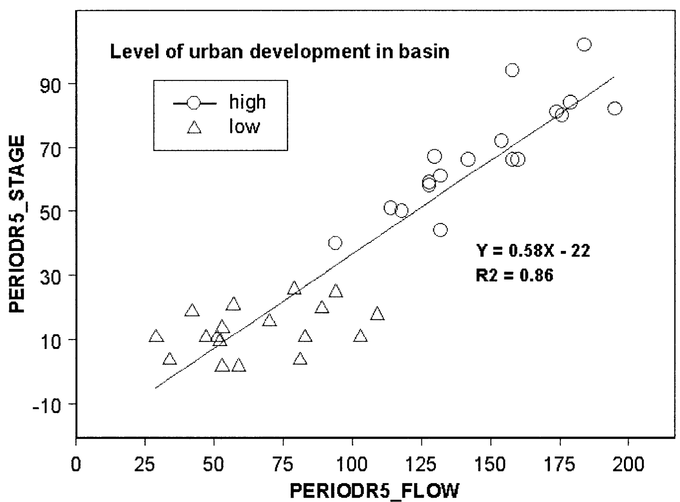

Figure 2. Scatter Plot of PERIODR5_STAGE (Y-axis) and PERIODR5_FLOW (X-axis) and Associated Regression Line. (Note: PERIODR5 is the number of times over the period of record that stage or discharge rises at least five times the median change in stage or flow conditions.)

Separate multivariate analyses of the flow based and stage based metrics were used to summarize the information contained in the 22 individual hydrologic metrics (Table 6). The first two components of the flow based metrics, Flow_1 and Flow_2, account for 54 and 14 percent, respectively, of the standardized variance. Similarly, the first two components of the stage based metrics, Stage_1 and Stage_2, account for 56 and 14 percent, respectively, of the standardized variance of the data. The first axis of the flow based and stage based ordinations provides a measure of flashiness, with the largest eigenvectors for both components associated with the flashiness metrics. Site scores for these first axes are highly correlated (r = 0.93; p value < 0.0001), which suggests a strong relation between the flow based and stage based measures of flashiness. The PCA results reinforce the general comparability between the flow based and stage based metrics for flashiness.

TABLE 6. Eigenvectors Resulting From Principal Components Analysis of Stage Flow and Flow Based Hydrologic Metrics.

	Flow_1	Flow_2	Stage_1	Stage_2
PERIODR1	0.120	-0.159	0.223	0.047
PERIODR3	*0.276*	0.086	*0.297*	0.094
PERIODR5	*0.282*	0.099	*0.290*	0.086
PERIODR7	*0.282*	0.109	*0.293*	0.092
PERIODR9	*0.279*	0.111	*0.292*	0.087
PERIODF1	0.110	-0.082	0.205	0.118
PERIODF3	0.236	0.173	*0.297*	0.052
PERIODF5	*0.270*	0.176	*0.297*	0.067
PERIODF7	*0.278*	0.146	*0.292*	0.067
PERIODF9	*0.280*	0.137	*0.286*	0.062
MXH_75	-0.202	-0.027	-0.132	-0.023
MXH_90	-0.162	***-0.284***	-0.181	-0.101
MXH_95	-0.211	***-0.282***	-0.238	-0.073
MDH_75	-0.127	0.229	-0.086	0.067
MDH_90	-0.205	*0.306*	-0.116	0.016
MDH_95	-0.216	0.123	-0.155	-0.015
MXL_25	-0.202	0.042	-0.122	*0.405*
MXL_10	-0.144	*0.258*	-0.129	*0.472*
MXL_5	-0.158	*0.295*	-0.102	*0.517*
MDL_25	-0.156	0.197	-0.094	*0.344*
MDL_10	-0.164	*0.402*	-0.058	0.218
MDL_5	-0.147	*0.385*	-0.122	*0.308*

Note: Eigenvectors with an absolute value greater than or equal to 0.25 (chosen as an arbitrary threshold) are in italics to distinguish relatively high values that are important in understanding the meaning of each principal component. *Light italics* is associated with high positive values; ***bold italics*** is associated with negative values. Hydrologic metrics are defined in Table 2.

The difference between flow based and stage based metrics in urban and nonurban catchments was estimated using analysis of variance on the ranks of the metric values (Table 5). Generally, the mean ranking of three types of flow based and stage based metrics – overall variability, frequency of stream change (i.e., flashiness), and duration of high stream conditions – was similar for urban and nonurban basins, suggesting a consistency in the descriptions that these metrics provide of hydrologic variability in urban and nonurban catchments. High rank values indicate high metric values in this analysis. The stage derived and flow derived metrics for the urban sites had higher values for both overall variability and flashiness. The urban sites had relatively low values for duration of high flow conditions. Although the rankings for flow and stage metrics were statistically different for the maximum duration of low streamflow conditions, the analysis of variance suggests a generally weaker relation between the stage and flow metrics for low streamflow conditions, both in terms of similarity to each other and their ability to distinguish urban and nonurban sites.

The rankings of the metrics for North Carolina urban and nonurban catchments provide mixed support for the hypothesized effects of urbanization on hydrologic conditions (Table 5). The urban sites have a higher rank (and higher value) for the coefficient of variation and for all the flashiness metrics than the nonurban sites. This suggestion of greater variability in overall flow conditions and stream flashiness at urban sites is consistent with the hypothesis that urbanization has a positive correlation with overall variability in streamflow conditions and with stream flashiness. The rankings of the high stage and flow duration metrics indicate that the duration of high stage and flow conditions is lower at the urban sites. This finding is consistent with the hypothesis that increasing urbanization has an inverse effect on the duration of high flows. The rankings of the low stage and flow duration metrics also indicate that the duration of low stage and flow is less at urban sites. This is inconsistent with the hypothesis that urbanization results in an increase in the duration of low flows. Similar analyses correlating flow based and stage based metrics are needed for other environmental settings.

Both stage and cross sectional area data were available to describe hydrologic variability in the Salt Lake City study. To determine which set of these metrics to use in this study, an analysis similar to the assessment of the North Carolina flow based and stage based metrics was conducted. The strongest relations between stage based and area based metrics were for the high flow duration (both maximum and median) measures. There were no relations between area based and stage based stream change (i.e., flashiness) metrics for the Salt Lake City sites. Because of the relatively short POR used for the comparison of stage based and area based metrics, these results should not be considered definitive. Further investigation is needed, including the relation of flow- to area based metrics.

Summary of the Metric Results for the Three Studies

The metric results from the three gradient study areas indicate several common patterns (Table 7). First, an increase in the threshold for defining rising or falling stage resulted in a smaller number of occurrences of the stage condition, as expected. For example, on average across the Salt Lake City basins, the maximum duration of high stage declined as the threshold for defining high stage increased from the 75th percentile of cross sectional area values to the 95th percentile. Next, the maximum low flow or high flow duration was usually more than an order of magnitude greater than the median duration, regardless of which threshold was used. Although not shown in the results in Table 7, flashiness metrics were highly correlated in all three studies (average correlation among flashiness metrics in Birmingham, Boston, and Salt Lake City, respectively, was 0.96, 0.74, and 0.71) suggesting some redundancy of information. There was no clear pattern of correlation among other classes of metrics.

In all three studies, the first PCA axis, which explains the largest amount of the variability in the dataset of all the axes, loaded most heavily on the metrics associated with the rate of change of stage, or flashiness. This result suggests that the primary way that the stage data allow the individual sites to be distinguished is in terms of the frequency of stage changes or flashiness. A stream flashiness index, based on these PCA results (HYD1 in Tables 8, 9, and 10), was used in the analysis of the relation between basin and hydrologic conditions in all three studies.

Birmingham: Hydrologic and Basin Characteristics

Basin characteristics and hydrologic condition metrics are clearly associated in the Birmingham basins (Table 8). All basin scale measures of urbanization (urban intensity index, percentage of developed land, population density, and road density) were positively correlated with stream flashiness (both the stream flashiness index (HYD1), which is a composite measure of flashiness, and individual flashiness metrics). Urbanization measures were negatively correlated with the duration of high flow conditions and positively correlated (at a much weaker level) with the duration of low flow conditions. In contrast, forested land cover was negatively associated with both overall variability and stream flashiness and positively associated with the duration of high flow events.

TABLE 7. Median Values of Hydrologic Condition Metrics in Salt Lake City, Birmingham, and Boston Studies.

	Salt Lake City Hourly CS Area	Salt Lake City Hourly Stage	Birmingham Hourly Stage	Boston Hourly Stage
Overall Stage Variability				
CVHR	22.33	10.84	48.6	43.3
Frequency of Stage Change				
PERIODR1	201	76	146	109
PERIODR3	74	8	48	8
PERIODR5	37	6	34	5
PERIODR7	29	1	25	2
PERIODR9	21	1	20	2
PERIODF1	219	89	220	139
PERIODF3	81	6	35	2
PERIODF5	42	4	24	1
PERIODF7	25	0	17	1
PERIODF9	20	0	14	0
Duration of High Stage Conditions				
MXH_75	116	70	374	827
MXH_90	62	41	128	292
MXH_95	37	33	80	149
MDH_75	4	6	8	22
MDH_90	4	4	6	20
MDH_95	4	4	5	38
Duration of Low Stage Conditions				
MXL_25	171	157	382	480
MXL_10	67	17	86	184
MXL_5	36	17	11	104
MDL_25	6	8	12	46
MDL_10	5	4	4	20
MDL_5	4	4	3	19

Note: Metrics calculated using hourly unit values. Median refers to the 50th percentile value of the metric across all stations for period of record (Salt Lake City 10 stations; Birmingham 30 stations; Boston 32 stations). CS refers to cross sectional area. Units for all variables defined in Table 2.

Strong correlations exist between hydrologic condition and the spatial arrangement of developed land cover in the Birmingham basins. Two measures of fragmentation (LPI, the percentage of the basin area composed of the largest patch of developed land, and MPS, or mean developed patch size. In both cases the larger the value, the less fragmented the developed landscape) were positively correlated with flashiness. This suggests that the less fragmented the developed landscape in a basin (i.e., higher values of LPI), the greater the flashiness of the associated stream. LPI and MPS were both negatively correlated with duration of high flow events and positively correlated with duration of low flow events, indicating that the less the fragmentation of the developed landscape, the shorter the duration of high flow events and the greater the duration of low flow events. Mean nearest neighbor distance (MNN) and nearest neighbor coefficient of variation (NNCV) are measures of the dispersion of patches of developed land across the landscape. The correlation results were opposite those for LPI and MPS. As the dispersion of developed land patches increased, the flashiness of streamflow decreased. Conversely, the greater the dispersion of developed land patches, the greater the duration of high flow conditions. The interspersion and juxtaposition index (IJI) measures the adjacency of developed land cover patches with other land cover types. A greater interspersion of developed land with other land cover types results in a higher index. IJI was negatively correlated with flashiness; the more interspersed developed land cover patches are with other land cover types, the less flashy the stream conditions.

Boston: Hydrologic and Basin Characteristics

The pattern in the relation between overall urbanization characteristics and hydrologic conditions for the Boston basins was similar to the pattern for the Birmingham basins for flashiness, though with weaker correlations (Table 9). There was a positive relation between urbanization and some individual stream flashiness metrics. A pattern in the relation between urbanization and the duration of low flow and high flow conditions was less clear. The few statistically significant correlations indicate that urbanization is positively associated with the duration of high flow conditions and negatively associated with the duration of low flow conditions.

Some of the patterns in correlations between Boston hydrologic variability and the spatial arrangement of developed land are similar to the Birmingham patterns. The less fragmented the developed landscape (i.e., high values of LPI and MPS), the greater the stream flashiness. There was no clear pattern in the relation between Boston developed land fragmentation and the duration of high flow and low flow conditions. The extent to which developed landscape patches were dispersed across the landscape (i.e., MNN, NNCV) was inversely related to overall variability and flashiness, as was the case in the Birmingham study. There was no clear pattern of association between these dispersion indices and high flow and low flow duration, nor was there a relation

TABLE 8. Correlation Between Birmingham Hydrologic Condition Metrics and Urbanization Characteristics.

	Urban Intensity Index	Developed Land (percent)	1999 Population Density	Road Density	Forested Land (percent)	LPI	MPS	MNN	NNCV	IJI
Overall Stage Variability										
HYD1	*0.81*	*0.82*	*0.79*	*0.79*	***-0.66***	*0.78*	*0.82*	***-0.80***	***-0.53***	***-0.34***
CV	0.05	0.02	0.23	0.09	-0.19	-0.04	-0.03	-0.12	-0.05	-0.11
Frequency of Stage Change										
PERIODR1	*0.35*	*0.37*	*0.35*	*0.40*	-0.26	*0.32*	*0.40*	***-0.38***	-0.03	***-0.42***
PERIODR3	*0.77*	*0.77*	*0.75*	*0.75*	***-0.67***	*0.74*	*0.78*	***-0.73***	***-0.48***	***-0.37***
PERIODR5	*0.75*	*0.77*	*0.75*	*0.75*	***-0.62***	*0.72*	*0.77*	***-0.74***	***-0.49***	***-0.42***
PERIODR7	*0.74*	*0.76*	*0.73*	*0.74*	***-0.59***	*0.71*	*0.76*	***-0.75***	***-0.49***	***-0.42***
PERIODR9	*0.70*	*0.72*	*0.72*	*0.71*	***-0.57***	*0.67*	*0.72*	***-0.71***	***-0.49***	***-0.41***
PERIODF1	0.25	0.27	0.28	*0.30*	-0.17	0.22	0.26	-0.28	-0.10	***-0.41***
PERIODF3	*0.80*	*0.81*	*0.77*	*0.79*	***-0.65***	*0.78*	*0.82*	***-0.78***	***-0.51***	***-0.38***
PERIODF5	*0.77*	*0.80*	*0.74*	*0.77*	***-0.61***	*0.76*	*0.80*	***-0.77***	***-0.52***	***-0.38***
PERIODF7	*0.74*	*0.77*	*0.72*	*0.74*	***-0.57***	*0.72*	*0.77*	***-0.75***	***-0.52***	***-0.37***
PERIODF9	*0.73*	*0.76*	*0.72*	*0.73*	***-0.58***	*0.71*	*0.76*	***-0.73***	***-0.51***	***-0.36***
Duration of High Stage Conditions										
MXH_75	-0.28	-0.26	-0.28	-0.23	0.26	-0.26	-0.24	0.29	0.16	0.05
MXH_90	-0.23	-0.26	-0.27	-0.25	0.20	-0.21	-0.20	0.28	*0.32*	0.18
MXH_95	***-0.64***	***-0.64***	***-0.70***	***-0.64***	*0.58*	***-0.56***	***-0.54***	*0.67*	*0.40*	*0.33*
MDH_75	***-0.52***	***-0.57***	***-0.41***	***-0.53***	*0.46*	***-0.59***	***-0.58***	*0.53*	*0.46*	0.04
MDH_90	***-0.58***	***-0.58***	***-0.53***	***-0.56***	*0.51*	***-0.63***	***-0.64***	*0.53*	*0.58*	-0.07
MDH_95	***-0.60***	***-0.63***	***-0.50***	***-0.59***	*0.44*	***-0.64***	***-0.66***	*0.65*	*0.50*	0.06
Duration of Low Stage Conditions										
MXL_25	*0.34*	*0.33*	*0.44*	0.30	-0.25	0.25	0.27	***-0.33***	-0.26	-0.04
MXL_10	*0.33*	*0.31*	*0.33*	0.24	-0.18	*0.35*	*0.36*	-0.24	-0.12	0.11
MXL_5	*0.37*	*0.37*	*0.32*	*0.32*	-0.23	*0.40*	*0.42*	***-0.31***	***-0.36***	0.04
MDL_25	*0.41*	*0.38*	*0.38*	*0.35*	***-0.33***	*0.38*	*0.41*	***-0.37***	-0.02	0.09
MDL_10	*0.33*	0.29	0.29	0.21	-0.17	*0.35*	*0.38*	-0.22	-0.07	0.18
MDL_5	*0.31*	0.29	0.24	0.23	-0.18	*0.34*	*0.37*	-0.22	-0.21	0.11

Note: Numbers in *italics* are statistically significant correlations at $\alpha = 0.10$; negative correlations are in ***bold italics*** and positive correlations are in *light italics*. Urbanization variables are defined in Table 4. Flow variables are defined in Table 2.

between developed land interspersion (IJI) and stream conditions.

Salt Lake City: Hydrologic and Basin Characteristics

Stage based metrics were used to assess the relation between urbanization and hydrologic conditions to be consistent with the analytical framework used in the Birmingham and Boston studies and because of the poor correlation between the stage based and area based metrics. Generally, there was not a strong correlation between either the basin scale or riparian indicators of urbanization (e.g., urban intensity index, percentage of developed land area, road density) and most of the hydrologic metrics (Table 10), although there were several exceptions. The urban intensity index and the percentage of developed land both had a significant positive relation with coefficient of variation (CV) and were inversely related with several of the low stage duration metrics. Although there was only one statistically significant relation between these urbanization measures and flashiness, there was a general pattern of a positive relation between urbanization and flashiness, consistent with the Birmingham and Boston studies. There were few statistically significant relations between riparian scale land cover and the hydrologic metrics. No overall pattern was noted in these relations.

TABLE 9. Correlation Between Boston Hydrologic Condition Metrics and Urbanization Characteristics.

	Urban Intensity Index	Developed Land (percent)	1999 Population Density	Road Density	Forested Land (percent)	LPI	MPS	MNN	NNCV	IJI
					Overall Stage Variability					
HYD1	0.23	0.26	0.20	0.15	-0.30	0.29	0.24	-0.25	***-0.33***	-0.05
CV	0.05	0.04	0.08	0.08	-0.03	0.12	0.07	-0.08	-0.14	-0.18
					Frequency of Stage Change					
PERIODR1	-0.22	-0.20	-0.27	-0.27	0.13	-0.18	-0.20	0.19	-0.02	0.03
PERIODR3	*0.37*	*0.42*	*0.39*	0.28	***-0.46***	*0.45*	*0.44*	***-0.41***	***-0.40***	-0.22
PERIODR5	*0.38*	*0.44*	*0.39*	0.29	***-0.46***	*0.46*	*0.46*	***-0.43***	***-0.40***	-0.13
PERIODR7	*0.40*	*0.46*	*0.41*	*0.32*	***-0.46***	*0.46*	*0.46*	***-0.46***	***-0.40***	-0.09
PERIODR9	0.28	*0.33*	0.30	0.19	***-0.34***	*0.34*	*0.31*	***-0.36***	***-0.38***	0.02
PERIODF1	-0.03	-0.02	-0.07	-0.07	-0.05	0.00	0.00	0.03	-0.12	0.06
PERIODF3	0.21	*0.33*	0.26	0.17	-0.26	*0.37*	*0.32*	***-0.36***	***-0.38***	-0.27
PERIODF5	0.19	0.29	0.17	0.14	-0.21	*0.33*	0.26	***-0.32***	-0.29	-0.23
PERIODF7	*0.54*	*0.60*	*0.53*	*0.51*	***-0.56***	*0.61*	*0.59*	***-0.61***	***-0.55***	-0.16
PERIODF9	*0.41*	*0.39*	*0.36*	*0.34*	***-0.41***	*0.42*	*0.41*	***-0.32***	-0.26	0.11
					Duration of High Stage Conditions					
MXH_75	0.01	0.04	0.10	0.18	0.01	0.02	0.08	-0.11	-0.14	***-0.34***
MXH_90	0.18	0.20	0.15	0.23	-0.13	0.16	0.20	-0.27	-0.24	***-0.38***
MXH_95	-0.25	-0.27	***-0.33***	-0.24	0.28	-0.27	-0.25	0.24	0.23	0.11
MDH_75	0.18	0.18	0.19	0.24	-0.16	0.13	0.22	-0.16	-0.04	0.19
MDH_90	*0.34*	*0.33*	*0.35*	*0.33*	-0.27	*0.32*	*0.36*	**-0.33**	-0.03	0.03
MDH_95	0.11	0.16	0.18	0.18	-0.07	0.13	0.20	-0.22	-0.05	-0.05
					Duration of Low Stage Conditions					
MXL_25	-0.24	-0.25	-0.29	***-0.30***	0.28	-0.24	-0.28	0.21	0.22	-0.03
MXL_10	***-0.31***	-0.25	-0.29	-0.26	*0.39*	-0.18	-0.19	0.20	0.21	***-0.30***
MXL_5	***-0.39***	***-0.36***	***-0.33***	***-0.31***	*0.35*	**-0.35**	-0.27	*0.39*	*0.30*	0.16
MDL_25	0.06	0.10	0.16	0.18	-0.09	0.09	0.15	-0.03	-0.09	0.04
MDL_10	0.04	0.09	0.06	0.15	-0.01	0.10	0.16	-0.07	0.02	0.02
MDL_5	0.09	0.10	0.11	0.24	-0.09	0.08	0.18	-0.05	0.05	0.19

Note: Numbers in *italics* are statistically significant correlations at $\alpha = 0.10$; negative correlations are in ***bold italics*** and positive correlations are in *light italics*. Urbanization variables are defined in Table 4. Flow variables are defined in Table 2.

Relation Between Hydrologic Variability and Basin Characteristics

Results from the Birmingham and Boston studies provide evidence to support the hypothesis linking increased urbanization with overall hydrologic variability and stream flashiness. Urbanization is described both in terms of the developed landscape composition of each basin (urban intensity index, percentage of developed land, population density, and road density) and the configuration of developed land-cover patches. All of the developed landscape composition measures in Birmingham and Boston are positively correlated with measures of stream flashiness based on changes 3, 5, 7, and 9 times the median stage change. Forested land cover is inversely correlated with flashiness (Tables 7, 8). Correlation of urbanization with the smallest measure of rise and fall (PERIODR1 and PERIODF1) were small and sometimes negative. Although the overall pattern in both studies supports the first hypothesis, the support is considerably stronger in the Birmingham study. The spatial structure of the developed land in a basin also appears to be correlated with flashiness, although to a lesser degree than the landscape composition measures. Fragmentation (e.g., LPI and MPS) or dispersal (e.g., MNN and NNCV) of developed land

TABLE 10. Correlation Between Salt Lake City Hydrologic Condition Metrics and Urbanization Characteristics.

				Riparian Corridor Variables							
	Urban Intensity Index	Developed Land (percent)	Road Density	Low Density		High Density		Vegetated Land		Agricultural Land	
				p1_10	p1_100	p2_10	p2_100	p3_10	p3_100	p6_10	p6_100
Overall Stage Variability											
HYD1	0.35	0.34	-0.12	0.25	-0.05	0.37	0.24	-0.37	-0.12	-0.27	0.02
CV	*0.56*	*0.51*	0.04	0.31	0.17	-0.25	-0.10	-0.35	-0.22	-0.28	-0.12
Frequency of Stage Change											
PERIODR1	-0.20	-0.29	***-0.51***	-0.24	-0.28	-0.17	-0.35	0.29	0.30	0.47	*0.50*
PERIODR3	0.35	0.29	-0.13	0.20	-0.12	0.27	0.25	-0.29	-0.05	-0.33	-0.02
PERIODR5	0.37	0.31	-0.06	0.18	-0.06	0.34	0.29	-0.30	-0.11	-0.32	-0.04
PERIODR7	0.32	0.25	-0.15	0.11	-0.11	0.36	0.24	-0.25	-0.05	-0.13	0.15
PERIODR9	0.31	0.34	-0.05	0.24	-0.04	0.39	0.24	-0.39	-0.11	-0.14	0.07
PERIODF1	-0.22	-0.30	***-0.55***	-0.14	-0.29	-0.14	-0.34	0.23	0.31	0.34	0.45
PERIODF3	*0.50*	0.41	0.00	0.16	-0.02	0.22	0.26	-0.30	-0.14	-0.25	-0.03
PERIODF5	0.24	0.19	-0.02	-0.15	-0.29	0.43	0.43	0.00	0.07	-0.13	0.11
PERIODF7	-0.01	-0.01	-0.35	-0.05	-0.33	0.32	0.19	-0.08	0.17	0.00	0.33
PERIODF9	0.08	0.08	-0.20	0.13	-0.18	0.40	0.20	-0.20	0.03	-0.18	0.19
Duration of High Stage Conditions											
MXH_75	-0.12	-0.13	-0.27	-0.33	-0.43	-0.45	-0.17	0.42	0.45	0.18	0.22
MXH_90	0.00	-0.08	-0.24	0.14	-0.09	-0.45	-0.35	0.15	0.24	-0.17	-0.02
MXH_95	-0.04	-0.09	-0.39	*0.50*	0.20	0.00	-0.41	-0.29	-0.08	-0.20	0.12
MDH_75	0.11	0.15	-0.23	0.18	-0.09	0.36	0.15	-0.36	-0.11	-0.06	0.17
MDH_90	0.32	0.38	0.11	0.31	0.20	*0.56*	0.26	-0.48	-0.39	-0.27	-0.14
MDH_95	0.25	0.35	0.06	0.31	0.22	0.38	0.23	***-0.53***	-0.34	-0.23	-0.20
Duration of Low Stage Conditions											
MXL_25	0.01	0.01	-0.05	-0.08	-0.03	-0.03	-0.15	0.14	0.07	0.13	0.20
MXL_10	***-0.55***	***-0.63***	-0.48	-0.13	-0.11	-0.17	-0.43	0.31	0.25	0.24	0.49
MXL_5	***-0.55***	***-0.63***	-0.48	-0.13	-0.11	-0.17	-0.43	0.31	0.25	0.24	0.49
MDL_25	0.42	0.40	*0.58*	0.14	0.30	0.21	0.25	-0.16	-0.44	-0.50	-0.29
MDL_10	0.12	0.20	-0.08	0.44	0.39	0.14	-0.17	***-0.52***	-0.27	0.04	0.02
MDL_5	0.12	0.20	-0.08	0.44	0.39	0.14	-0.17	***-0.52***	-0.27	0.04	0.02

Note: Numbers in *italics* are statistically significant correlations at $\alpha = 0.10$; negative correlations are in ***bold italics*** and positive correlations are *light italics*. Urbanization variables are defined in Table 4. Flow variables are defined in Table 2.

cover patches in a basin appears to ameliorate the effects of urbanization on flashiness.

The Birmingham and Boston studies provide mixed evidence in support of the second hypothesis related to the effects of urbanization on the duration of high (hypothesized to be an inverse relation) and low (hypothesized to be a positive association) stage conditions. In the Birmingham study, development composition (as measured by developed landscape composition metrics – urban intensity index, percentage of developed land, population density, and road density) (Table 7) and the spatial concentration of developed land (e.g., LPI and MPS) are negatively correlated with the duration of high stage conditions, a finding consistent with the second hypothesis. Development composition and concentration are positively correlated with many of the metrics for the duration of low stage conditions, also consistent with this hypothesis.

Although the Boston study provides few statistically significant correlations between urbanization and duration of high stage and low stage conditions and almost no confirmation of the second hypothesis, there are several interesting patterns in the correlations. Urban development has a weak positive correlation with the two less restrictive definitions of the maximum duration of high stage conditions (Table 8) (MXH_75 and MXH_90) (see Table 2 for definitions) along with all the median duration metrics, suggesting that urban development increases the duration of high stage conditions.

This result, which contradicts our second hypothesis, may be influenced by the large number of dams observed during the study within the Boston area basins. Existing dam spatial databases do not recognize many of the small but hydrologically influential detention/retention structures in the Boston study basins (e.g., Ruddy and Hitt, 1990). It was not possible to quantify the location and number of these dams, nor complete a quantitative analysis of the impact of detention/retention structures on stream conditions. It is certain, however, that the dams slow the rate at which water moves through the system; high stage conditions, especially when the high stage is defined at a relatively low threshold, persist longer than is the case in a system without an extensive network of dams. Study results indicate that the dams do not totally remove the expected hydrologic effects of urbanization. Urban development has a positive correlation with most measures of stream flashiness and a negative correlation with the most restrictive measure of duration of high stage conditions (i.e., MXH_95) (see Table 2 for definition). The expected negative effect of urbanization on the duration of high stage conditions occurs only when high stage conditions are defined in a very restrictive manner.

This study design appears to be least successful in relating urbanization and streamflow conditions at the Salt Lake City study sites where there were relatively few significant correlations between the basin characteristics and the streamflow metrics compared with those for the Birmingham and Boston sites. However, several patterns are consistent with the hypotheses expressed earlier. Basin scale measures of urbanization (i.e., urban intensity index and percentage of developed land) generally are related to overall variability (i.e., CVHR) and flashiness in a manner consistent with the first hypothesis. That is, greater urbanization is positively associated with great variability, although at a weak level of correlation. For the duration metrics, there were either weak or conflicting correlation results for basin scale and riparian scale measures of urbanization; at best, these results can be considered inconclusive regarding the second hypothesis.

There are several possible explanations for the limited degree of correlation between basin characteristics and streamflow conditions in the Salt Lake City study. Although restricting the analysis time period to the late summer and early fall months removes the direct effects of snowmelt, indirect effects of this dominant hydrologic characteristic continue to exert an influence throughout the summer because of the extensive management of streamflows in the Salt Lake City study area. Differing percentages of snowmelt are captured in upstream reservoirs for later release. A large number of irrigation control structures are present within many of the basins, allowing substantial transbasin diversion to occur throughout the summer. Most of the streams included in the Salt Lake City study area incur both additions and withdrawals. Although some of the variability associated with these diversions relates to urbanization, other influences are operating at larger scales (e.g., withdrawals for agricultural uses in a basin not included in the study) that make it difficult to identify urban effects, particularly with the small number of basins in the study area. Additionally, the size of the canyon land area relative to the total basin area varies among basins, introducing variability that may obscure the signal associated with urban effects.

SUMMARY AND CONCLUSIONS

This paper addresses the question of whether hydrologic metrics appropriate for assessing the relation between hydrologic variability and urbanization can be developed from continuous measurements of stage. We present the results of an approach for relating urbanization to hydrologic variability that was demonstrated in three studies conducted as part of the USGS NAWQA Program, in which effects of urbanization on stream ecosystems was assessed.

Streamflow and stage data from six stream gages in North Carolina were used to compare three aspects of hydrologic variability that are thought to influence stream ecosystems – overall stage variability, stream flashiness, and the duration of extreme stage conditions. Comparisons of flow based and stage based metrics suggest the greatest comparability for metrics measuring stream flashiness (i.e., frequency of stream stage changes of different magnitudes) and the median duration of high stage conditions.

We hypothesized that increased urbanization would have a positive effect on overall stream stage variability and stream flashiness. The evidence from our studies generally supports this hypothesis. Comparison of the ranked values of flow and stage metrics for urban and nonurban sites included in the North Carolina study supported this hypothesis. Further, basin scale measures of urbanization (i.e., an urban intensity index, percentage of developed land, population density, and road density) in the Birmingham and Boston study areas were positively correlated with measures of overall stream stage variability and stream flashiness, though at a much lower level in

Boston than in Birmingham. This overall pattern occurred in the Salt Lake City study as well, although with weaker correlations and less consistency.

Additional insight about the relation between urbanization and overall stream variability and flashiness is provided by examining the relation among these metrics and several measures of the spatial structure of the developed landscape within the study basins. Developed land fragmentation (i.e., the extent to which developed land is scattered across the study basin rather than being lumped in large contiguous patches) is negatively correlated with overall variability and flashiness. This suggests that the effects of urbanization on stream variability and flashiness appear to be mitigated when developed land patches are spread across the basin (and intermixed with other land cover types) rather than agglomerated into large patches.

We also hypothesized that increased urbanization would have a negative correlation with the duration of high stage conditions and a positive correlation with the duration of low stage conditions. The support for this hypothesis is inconsistent. Analysis of variance of stage based and flow based metrics at the North Carolina sites indicates that the duration of high flow conditions is higher at nonurban than urban sites, consistent with the second hypothesis. This analysis indicates that the duration of low flow conditions is also higher at nonurban sites, which is inconsistent with the second hypothesis. Because low stage and low flow duration statistics are not strongly correlated at the North Carolina sites (suggesting that low stage duration metrics may not be a good measure of low flow duration), the reliability and usefulness of the analysis of variance results for the low flow conditions may be limited.

In the Birmingham study, the effects of urbanization on the duration of high stage and low stage conditions conform to the hypothesis. In the Boston and Salt Lake City study areas, however, there was little evidence of significant correlations between urbanization and the duration metrics, and the signs of the correlation coefficients are mixed. Measures of the spatial structure of developed land in the Birmingham study area indicate that fragmentation of developed land mitigates the effect of the level of urbanization on the duration of extreme conditions. Increased fragmentation increases the duration of high stage conditions and decreases the duration of low stage conditions.

While not unexpected, the results of using stage data to study the relation between urbanization and hydrologic variability are noteworthy in several respects. An investigation at six North Carolina sites indicates that it is possible to develop hydrologic variability metrics using continuous stage data that are comparable to flow based metrics, particularly for stream flashiness. Results from several regional water quality investigations suggest that stage data that are relatively inexpensive to collect can be used to establish the positive correlation between urbanization and stream flashiness in the relatively humid Northeast and Southeast. A high degree of correlation among the flashiness metrics in each of the three studies implies redundancy in information among the metrics. Further investigation is needed to examine whether it is possible to rely on a summary measure of flashiness, either by using a single flashiness metric or by relying on data reduction techniques such as PCA. The nature of this relation depends on the composition and configuration of the developed landscape – the more fragmented the urban landscape, the less increase in stream variability. Further study is needed of the degree to which flow based and stage based metrics, especially flashiness metrics, correspond in a variety of hydroclimatic conditions and the degree to which the relations between urbanization and streamflow conditions described in this study are replicated in other studies. Further investigations also are needed regarding the use of cross sectional area based metrics in lieu of stage based metrics. Additional investigations of the influence of the configuration of developed land on the hydrologic response to urbanization appear to be warranted, as do the impacts of detention/retention structures. Addressing this later concern will require local scale databases of such structures. Finally, the usefulness of these hydrologic variability metrics in an overall assessment of the effects of urbanization on stream ecology needs to be analyzed. For example, does a stage based measure of stream flashiness help explain variations in the structure and function of stream biotic communities? If stage based metrics can be used in this manner, then they may help address important information needs in large synoptic stream ecology investigations. Additional investigations of the stream ecology effects of urbanization have begun as part of the second cycle of the NAWQA Program. These similarly designed studies in rapidly urbanizing areas of North Carolina, Georgia, Texas, Wisconsin, Colorado, and Oregon will allow further study of the relation between stage based metrics, urbanization, and stream ecological conditions.

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