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Uncertainty in Estimates of Streamflow, Precipitation, and Runoff

By Gregory E. Granato

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This report, the associated computer applications, and data provide tools and techniques for developing planning-level estimates of stormflows at sites receiving highway runoff. This information is vital for assessing the potential for adverse effects of runoff on receiving waters throughout the Nation and it should provide transportation agencies with the tools and information to improve project delivery without compromising environmental protection.

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Uncertainty in Estimates of Streamflow, Precipitation, and Runoff

By Gregory E. Granato

Introduction

The stochastic empirical loading and dilution model (SELDM) uses statistics that define prestorm streamflow, precipitation, and runoff coefficients to calculate runoff from the highway and from the basin upstream of a highway-runoff discharge point. The statistics used by SELDM are derived from the results of available field studies and from National precipitation and streamflow monitoring networks. There are uncertainties in measurement, interpretation, and application of hydrologic data that can affect estimates of stormflow from a highway site and prestorm flow and stormflow from the basin that is upstream of the highway site. For example, Granato and Cazenas (2009) found that about 46 percent of the 84 sites in the highway-runoff database with the information necessary to calculate runoff coefficients had runoff coefficients that vary by more than an order of magnitude from storm to storm. These results may indicate the potential effect of random uncertainties in measurements of precipitation and flow. The results also may indicate the potential effect of random variations in antecedent conditions and random variations in precipitation within each storm. Granato and Cazenas (2009) also noted potential effects of bias in measurements of precipitation, runoff, and drainage areas because they found that about 29 percent of the 84 sites in the highway-runoff database with the information necessary to calculate runoff coefficients had average runoff coefficients that are greater than one and about 11 percent had runoff coefficients that were less than 50 percent of what would be expected based on the impervious fraction. Uncertainties in stormflows from upstream basins also may be substantial because such basins commonly are much larger than highway sites, are much more heterogeneous than highway sites, and have prestorm flows.

Uncertainty is a measure of the errors and losses of information inherent in environmental studies that prevent the characterization of exact properties of the underlying distribution of that information (Ward and Loftis, 1983). The total uncertainty is the sum of uncertainty caused by natural variability, measurement errors, and interpretive generalizations. Environmental data collection always involves some error as an inherent characteristic of the hydrologic environment; sampling design; land-use history of the study area; and methods used for sample collection, sample analysis, and data interpretation (U.S. Environmental Protection Agency, 1986; 1994; 1996; Childress and others, 1987; Brown and others, 1991; Clark and Whitfield, 1993; Granato, and others, 1998).

Uncertainty analysis studies indicate that the greatest source of uncertainty generally defines the total magnitude of uncertainty for estimates of results with random variation (Holman and Gaja, 1984; Harmel and others, 2006). For planning-level analyses uncertainties in water-quality estimates may be large in comparison to uncertainties in estimates of upstream streamflow. This is because estimates in the quality of water upstream of the highway (Granato and others, 2009) and the quality of highway runoff (Granato and Cazenas, 2009) commonly can vary by one or more orders of magnitude. However, uncertainties in prestorm flow, precipitation, and runoff, may be substantial and, therefore, should be considered in estimates of water-quality loads.

The rainfall-runoff data sets compiled for the SELDM study have characteristics that indicate potential effects of natural variability, systematic measurement error (bias), and random measurement error in these data sets. Natural variability in rainfall-runoff transformations is an expected characteristic of all hydrological sets. Natural variability may be caused by seasonal effects and random storm to storm interactions between the atmosphere and the basin of interest. Total measured runoff from a storm is the result of upstream processes that may vary considerably in space and time, even within very small drainage basins. For example, Singh (1977) indicates that interactions among spatial and temporal heterogeneity in basin characteristics, antecedent soil moisture, and precipitation amounts limit the ability to define runoff processes even if good precipitation and runoff records are available. Systematic and random measurement errors also add uncertainties to the magnitude and variation of runoff coefficients for a given site. Systematic errors cause bias in runoff coefficients or curve numbers estimated from precipitation and streamflow. Random errors generally are storm-specific problems in the monitoring data that may accentuate or dampen natural variability in rainfall-runoff estimates at a monitored site. Examination of the potential magnitude of bias and variability in available data sets is necessary because these data sets have been assembled to provide information to develop rainfall-runoff estimates at ungaged sites.

Random and seasonal variations in storm type, volume, duration, and intensity, which are discussed in the section on characterizing storm-event precipitation-statistics, can have a substantial effect on the timing and volume of runoff. Antecedent conditions such as temperature, soil wetness, groundwater levels, and prestorm base flow also may have a substantial effect on the timing and volume of runoff. Natural variability in basin characteristics within a basin, from basin to basin, and region to region may introduce bias and random variability in expected rainfall-runoff relations.

Systematic errors may be difficult to identify unless the bias is sufficient to cause a recognizable anomaly. For example, systematic error may be identifiable if a large proportion of a data set is comprised of runoff coefficients greater than one. For example, Granato and Cazenas (2009) determined that 24 of 84 cataloged highway-runoff data-collection sites had average runoff coefficients that are greater than one. Only 5 of the 306 drainage basins in the rainfall-runoff data set assembled for the SELDM study have an average runoff coefficient that is greater than one. About 15 percent of the sites in the data set (46 sites) have an average runoff coefficient that is two or more times the expected average runoff coefficient for the associated TIA fraction. About 8 percent of the sites in the data set (26 sites) have an average runoff coefficient that is less than one-half of the expected average runoff coefficient for the associated TIA fraction. Such systematic departures from expected values may result from misspecifications of drainage area or the TIA fraction. Systematic bias also may be the result of bias in precipitation measurements, flow measurements, and the method selected for hydrograph separation.

Random errors in streamflow measurements, precipitation measurements, and hydrograph separation techniques may cause considerable random variation in calculated runoff coefficients and curve numbers. Random errors are generally caused by temporary problems with monitoring equipment or monitoring sites; for example, equipment malfunctions, temporary miscalibration of instruments, or fouling of the stage-discharge measurement section by debris (Church and others, 2003). Random errors in a data set may be difficult to distinguish from natural variability in hydrologic processes. Random error may be indicated by a low runoff coefficient for a large storm on an impervious basin. Similarly, a high runoff coefficient for a small storm on a highly pervious basin also may indicate a random error. For example, 43 of the 306 drainage basins in the rainfall-runoff database assembled for this study have one or more runoff coefficients that are greater than one. Among the 6,157 storms in the rainfall-runoff database, the runoff coefficient exceeds 1.0 for 217 storms, exceeds 1.05 for 158 storms, exceeds 1.1 for 133 storms, and exceeds 2 for 37 storms.

This appendix describes potential sources of uncertainty in estimates of streamflow, precipitation, and runoff that may affect the statistics that are used with SELDM to assess potential effects of highway runoff on the quality of receiving waters. Knowledge of potential uncertainties is needed to interpret and apply available data for use at a site of interest. Some uncertainties, such as estimates of the drainage area and impervious fraction of the drainage basin can introduce systematic bias in rainfall-runoff estimates. Other uncertainties, such as varying antecedent conditions, can introduce random variations in rainfall-runoff estimates.

Potential Sources of Uncertainty in Estimates of Streamflow, Precipitation, and Runoff

Basin Drainage Area

Misspecification of basin drainage areas introduces systematic bias in stormflow estimates. Uncertainties in areas of drainage basins for index streamgages will affect streamflow statistics that are normalized by drainage area. Uncertainties in the drainage-basin area for the site of interest will affect drainage-area ratio estimates of streamflow at these ungaged sites. Uncertainties in drainage-basin areas will affect estimates of normalized precipitation and runoff data needed to calculate runoff coefficients. Misspecification of basin drainage areas may be caused by human errors, limitations in the methods that are used, limitations in the data that are used, ambiguity in surface-drainage features, changes caused by man-made drainage structures, and differences in surface water and groundwater divides. Basin drainage areas also may change seasonally or with antecedent stormflow conditions. For example, a headwater wetland located in a saddle between two hills may drain to one stream basin during normal conditions and to two basins once water levels reach the spill point at the opposite end of the saddle.

Differences between drainage-area delineation efforts can be substantial. The U.S. Geological Survey (1980) specifies a maximum error of plus or minus five percent for manual surface water basin delineation methods. Figure 1-1 shows the absolute values of percent differences between older stream-basin drainage areas and more recent drainage areas, in Virginia and Rhode Island. Boxplots for all delineated basins in each state and basins segregated by drainage area are shown in the figure in comparison to the 5-percent error threshold. In general drainage-basin delineations have smaller errors in Virginia than in Rhode Island. These differences may be attributed to lower relief and therefore less distinct drainage-basin divides in Rhode Island. About 85 percent of all Virginia basins and 77 percent of all Rhode Island basins meet the 5-percent accuracy criterion. With the exception of a few outliers, the smaller basins have the larger errors. About 51 percent of the smallest basins (less than 1 square mile) in Virginia and about 70 percent of the smallest basins in Rhode Island meet the 5-percent accuracy criterion. These differences could be caused by errors in boundary delineation, errors in calculating the original basin areas (the newer values were manually digitized in GIS), or differences in professional judgment in areas where the boundary may be ambiguous. Neither Virginia nor Rhode Island is considered to be low-relief areas in comparison to areas in the Great Plains. The uncertainties in drainage-area delineation may be much higher than the differences shown in figure 1-1 in areas with very low relief.

Small variations in drainage-basin boundary location can result in large percent differences in small basins. For example, Miller and Morrice (2007) indicate that a 0.2 inch thick line used to delineate a watershed on a 1:25,000 scale map may introduce an error of about plus or minus 49 feet to the location of the drainage divide. Assuming an elliptical shape and a perfectly specified basin boundary, this line-thickness error could introduce drainage-area errors of about plus or minus 6 percent for drainage-basin areas in the range from 0.1 to 1 mi^2, errors of about plus or minus 2 percent for drainage-basin areas in the range from 1 to 10 mi^2, and diminishing errors for larger watersheds. In theory, random variations around the true boundary locations would tend to cancel out, but the example shows the potential magnitude of imperceptible errors for small basins.

There may be substantial differences in the accuracy of different drainage-area delineation methods. Manual methods commonly are considered to be the more accurate than GIS methods. Stuebe and Johnston (1990) compared results of manual and GIS drainage-area delineation methods. They found errors in GIS based watershed delineation ranging from 0.4 to 38 percent of the total drainage area. Oksanen and Sarjakoski (2005) examined manual and digital-elevation model (DEM) based watershed delineation methods. They indicated that different segments of a basin boundary will have different uncertainties. These uncertainties depend on the topographic characteristics of the basin. They classified such segments as sharp (clearly visible boundaries with little uncertainty or ambiguity), alternate (segments with different plausible boundaries) and diffuse (segments, generally in low slope

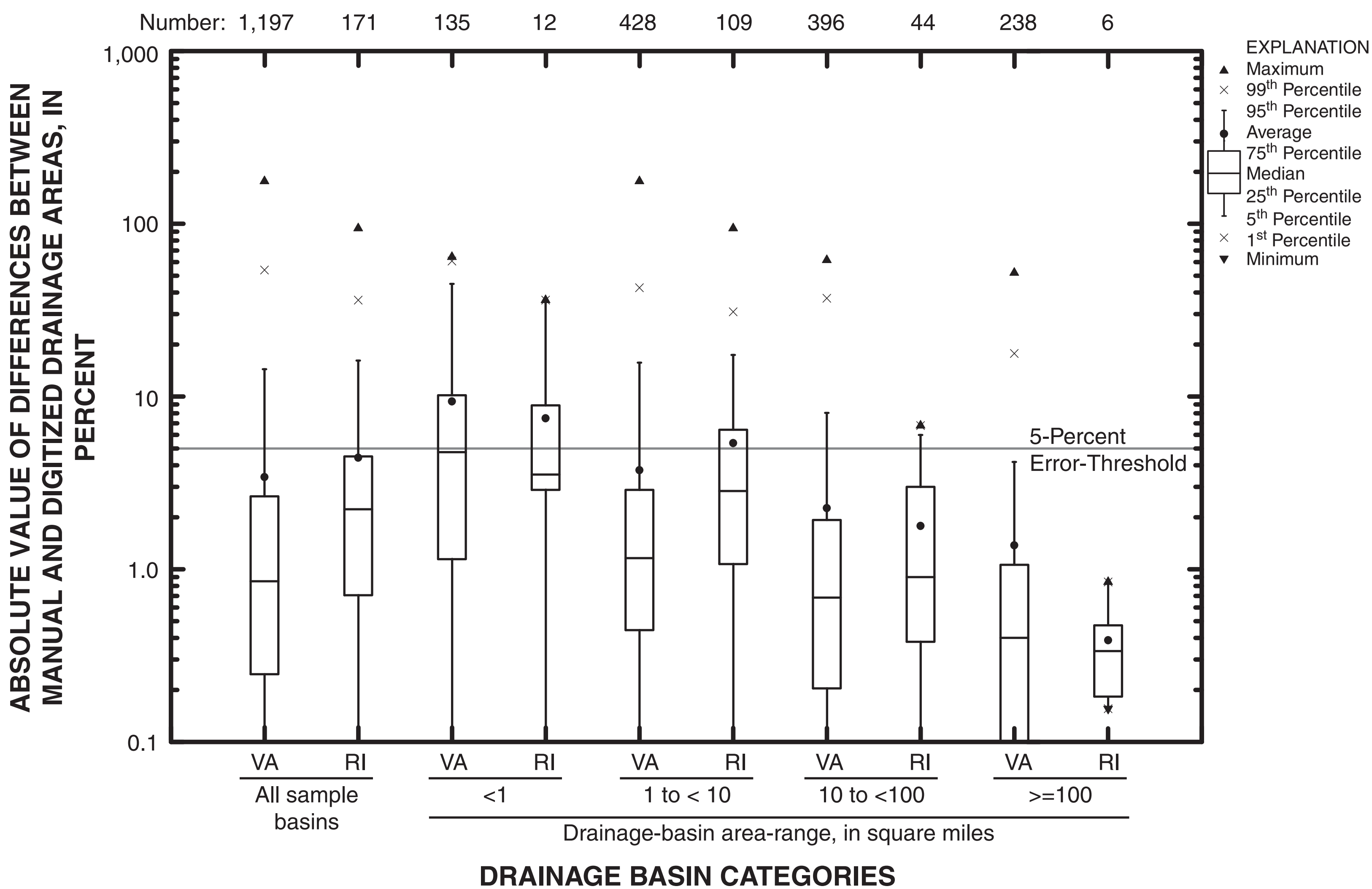

Figure 1-1. Boxplot showing the absolute value of the differences between basin drainage areas developed using manual methods and digitizing basin boundaries using a geographic information system. [Data for Virginia (VA) basins from Hayes and Wiegand, 2006; Data for Rhode Island (RI) basins from Gardner Bent, U.S. Geological Survey, written commun. 2009].

areas, with substantial ambiguity in boundary location). Oksanen and Sarjakoski (2005) indicated that drainage delineation errors are scale dependent with errors in their study of 10 to 24 percent for small basins (less than 0.39 mi^2), errors of 3 to 16 percent in midsized basins (0.39 to 3.9 mi^2), and errors of 0 to 4 percent in larger basins (greater than 3.9 mi^2). Moglen and Hartman (2001) compared drainage area estimates from 44 basins in MD with drainage areas ranging in size from 0.13 to 15 square miles to examine the effect of DEM resolution on drainage-area accuracy. They used a very dense high-resolution data set to create a 12-ft square cell DEM. They used drainage areas calculated with the 12-ft square cell DEM as known values for comparing the accuracy of DEMs generated from the same data set with 36, 60 and 94-ft square cells. They also used the high-resolution DEM to asses the accuracy of National DEMs with 30 and 90-m square cells. Moglen and Hartman (2001) found that the 95-percent error envelopes were from plus or minus 16, 31, 47, 130, and 730 percent for the 36-ft, 60-ft, 96-ft, 30-m, and 90-m DEMs, respectively. They found that the highest errors occurred for basins with the smallest drainage area and that the 95-percent error envelopes decreased exponentially with increasing drainage area. For this data, the plus-or-minus five-percent drainage-area accuracy criterion (for the 95-percent confidence interval) was achievable for the 36-ft, 60-ft, 96-ft, 30-m, and 90-m DEMs if drainage areas exceeded about 0.4, 0.8, 1.1, 3.4 and 7.8 mi^2, respectively. As with the Virginia and Rhode Island examples, Maryland is not a low-relief area so these drainage-area delineation uncertainties may be much greater in other areas of the Nation. For example, Wiche and others (1992) indicated it is difficult to determine drainage-area boundaries, especially at the divide where the James River, Missouri River, and Hudson Bay drainages meet because of the low-gradient topography that includes many closely spaced hummocks alternating with marshy depressions called prairie potholes.

Large differences between mapped (surface water) drainage areas and streamflow contributing areas occur where surface and groundwater divides are substantially different. Taylor (1982) indicated that uncertainties caused by differences in the groundwater and surface water divides precluded use of water-balance methods for interpreting rainfall-runoff relations in his study area in Ontario, Canada. Granato, and others (2003) detected a large difference in streamflows caused by differences in groundwater and surface water divides using a groundwater model to simulate the hydrogeology of the Big River Area in Rhode Island. In this study, the surface water drainage area of the Mishnock River at Route 3 was measured as 0.29 mi^2 and streamflow measurements indicated that the long-term average flow would be about 14.9 ft^3/mi^2. However, the modeling effort indicated that the groundwater contributing area to Lake Mishnock is 1.6 mi^2. The normalized average flow from the Lake Mishnock groundwater contributing area is about 2.7 ft^3/mi^2, which is much closer to the average ecoregion value of 1.75 ft^3/mi^2 for Ecoregion 59, the Northeast Coastal Zone.

In developed areas and agricultural areas drainage structures can change the contributing drainage area for a site of interest. For example, Duke and others (2006) examined the effects of modified terrain features such as roads, ditches and irrigation canals and found that such features could substantially affect drainage-area delineation. They found that in areas with low-relief topography (average slopes of about one degree) such features could modify delineated drainage areas by about 50 percent. Strecker and others, (2001) indicate that it is difficult to obtain precise estimates of drainage area in small highly impervious basins because small surface features in small low-slope areas (such as parking lots) within these basins have an inordinate effect on drainage patterns. Richards and Brenner (2004) indicate that 5 to 95 percent of subbasin areas did not have a surface water outlet in an undulating glacial terrain. They calculated that installation of storm sewers in the study basin may double storm flows by connecting these previously isolated drainage areas. Roy and Shuster (2009) noted that differences between topographic drainage divides and storm sewer drainage areas were about 1 to 6 percent of the drainage basin areas of small suburban subbasins in Cincinnati, Ohio.

Imperviousness

Misspecification of the extent, location, and hydraulic connection of natural and anthropogenic impervious areas are sources of potential uncertainty in estimating runoff coefficients at ungaged sites. Uncertainties in identifying the extent of impervious areas can affect the development and application of rainfall-runoff estimates. If the extent of impervious area is misspecified in rainfall-runoff studies, predictive equations that are based on imperviousness may be biased. The location of impervious areas within a basin also may introduce uncertainties in estimating runoff coefficients, especially if there is a systematic relation between precipitation patterns and development patterns. For example, a runoff estimate based on the TIA of the basin may over predict total runoff if development occurs on the lowlands and the bulk of precipitation falls on the relatively undeveloped highlands within a basin. Uncertainties in the proportions of TIA and DCIA also introduce systematic data-set specification uncertainties that may affect development and application of predictive rainfall-runoff equations based on imperviousness.

Differences in the TIA values used in a runoff study and actual TIA values in the study basin may occur if development in the basin has substantially changed the amount of TIA during the time between geographic characterization and the study period. Maps, areal photographs, and digital data sets are updated periodically, but may not reflect current conditions in a basin during a rainfall-runoff study. These changes may be substantial. For example, Jones and Jarnagin (2009) compared different methods to estimate TIA and found that changes in TIA that occurred in some sampled areas between collection of areal photographs and satellite imagery had a substantial effect on estimated TIA. They found that the maximum under prediction was reduced from about 54 to about 26 percent, and the maximum over prediction was reduced from about 39 to about 37 percent when temporal errors were removed.

There are uncertainties in estimates of TIA from both land use and land cover methods, but land-cover methods tend to have less uncertainty because they are more site specific (**Appendix 6**). For example, Prisloe and others (2000) indicate that TIA may vary by 100 percent for the same nominal land use among different towns in Connecticut. They report statistics for the variability in measured TIA within their respective study areas. Similarly, Ackerman and Stien (2008) found substantial variation in imperviousness within land-use categories (plus or minus 40 percent of the median value). They indicate that the imperviousness for a given land-use category increases with proximity to an urban center. Land cover estimates are considered to be more accurate than land-use estimates because individual impervious components are measured. For example, Homer and others (2007) indicate that the NLCD impervious-cover dataset has an accuracy that ranged from 8.8 to 11.4 of (anthropogenic) TIA. In general, classification methods tend to overestimate anthropogenic TIA in low density areas and underestimate anthropogenic TIA in high density areas; this is a potential source of bias in rainfall-runoff relations.

Estimates of anthropogenic TIA and DCIA do not address differences in nominal and actual imperviousness. Potential effects of uncertainty in TIA and DCIA may be apparent in the average and COV of runoff coefficients from the NURP sites and for sites characterized in this investigation (**fig. 1-2**). There is a substantial range in drainage areas for different sites with low TIA values, but correlations between drainage area and runoff-coefficient statistics for sites with low TIA fractions are weak. For example, the rank correlations (Spearman's Rho) between average runoff coefficients and drainage area are -35 percent for the 38 NURP sites and about -1 percent for the 120 sites in the StieStorm.mdb database with TIA fractions that are less than or equal to 0.3. The average and COV of runoff coefficients vary by more than 100 percent among sites with low TIA fractions. The NURP runoff-coefficient regression equation is included in **figure 1-2** to indicate the central tendency in the relation between TIA and average runoff coefficients.

Areas without apparent imperviousness may have high runoff coefficients if there is a substantial amount of natural imperviousness or if nominally pervious areas have low permeability because soils are compacted by development (**Appendix 6**). For example, many sites in **figure 1-2** with low TIA values have high runoff coefficients. The focus of many storm-runoff studies has been on runoff from anthropogenic impervious areas but many natural areas (including bedrock outcrops, saturated riparian areas, wetlands and water bodies that are part of the stream network) may act as impervious areas under some conditions (**Appendix 6**). The hydrologic effects of natural TIA also may be more variable than for anthropogenic TIA. For example, wetlands may be a source of saturation overland flow under wet antecedent conditions, but may absorb more precipitation and storm flow under dry antecedent conditions. The higher COVs for sites with low TIA fractions may be affected by variations in natural imperviousness under different antecedent conditions.

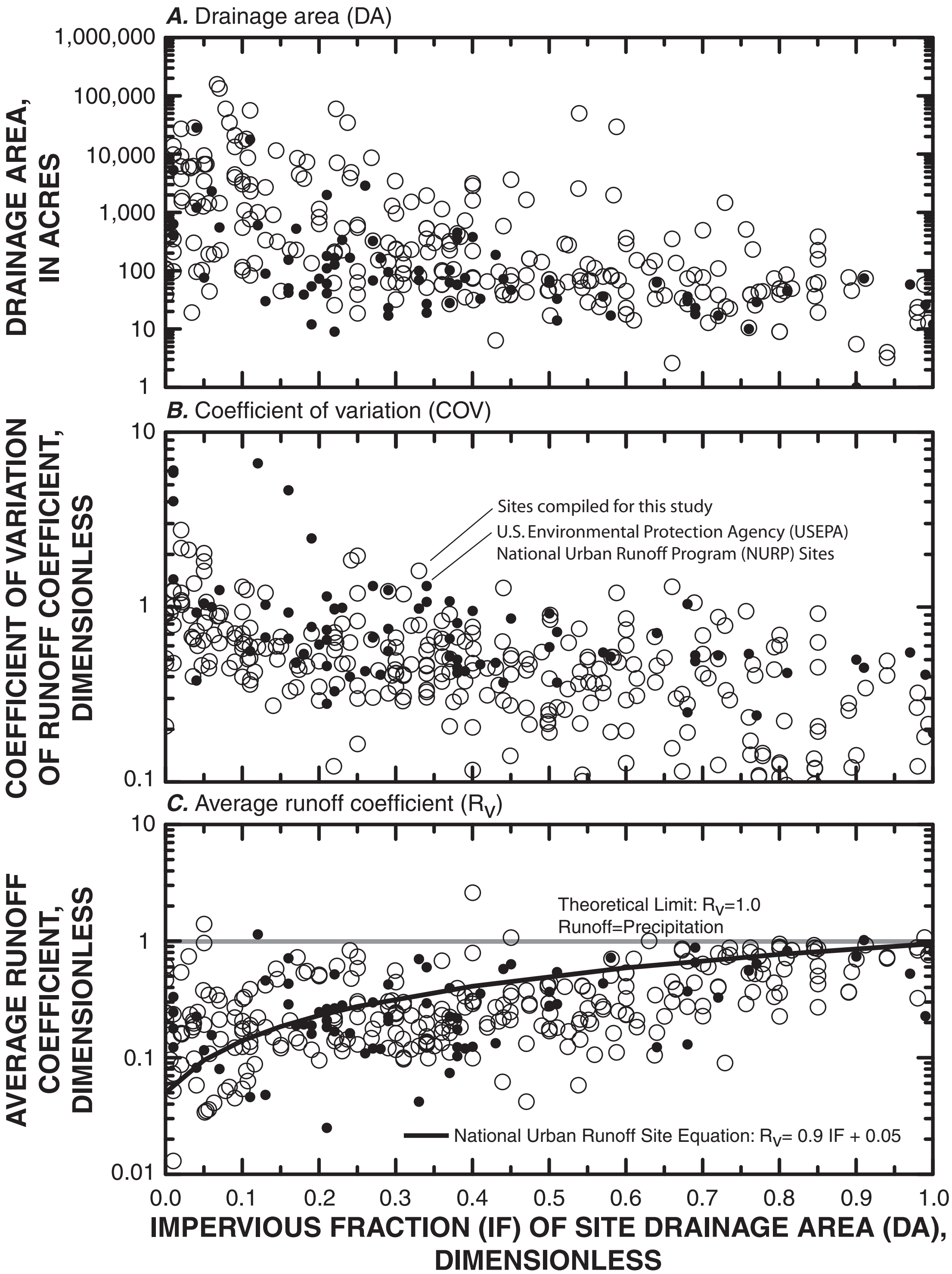

Figure 1-2. Scatterplot showing information and statistics including (A), drainage area estimates; (B), the site coefficient of variation of runoff coefficient values from individual storms; and (C), the site average of runoff coefficient values with the impervious fraction of each drainage area. [Data from 277 sites (with 4 or more storms) cataloged for this study and 76 sites cataloged by the U.S. Environmental Protection Agency National Urban Runoff Program (NURP)].

Streamflow

Misspecification of streamflow measurements may introduce random error and systematic bias in the stream flow record, which can affect estimates of prestorm flow and calculation of runoff coefficients from rainfall-runoff data. Bias in streamflow records will affect the geometric mean flow for a given streamgage. Bias in high flows and in low flows can affect the standard deviation and skew of streamflows, which are used to estimate prestorm flows. Random errors may affect the standard deviation and skew of the streamflow record. Miscalibration of the stream-stage sensor will affect the proportion of dry days if the sensor indicates that there is flow when there is no flow or if it indicates that there is no flow when flow does occur.

Periodic manual stage-discharge measurements, automated stage measurements, and an interpretive stage-discharge rating curve are used to produce a streamflow record (Rantz, 1982; Church and others, 2003). Periodic manual stage-discharge measurements are used to define channel geometry at the measurement point, measure the depth of water at each point (the stage), and the velocity of flow. Automated instantaneous stream-stage measurements are used to monitor the water stage in the channel on a frequent basis. Automated instantaneous stream-stage measurements commonly are recorded every 15 minutes for natural streams and are expected to be within plus or minus 0.01 ft of the actual stage (Rantz, 1982). In urban streams and stormwater conveyances with rapidly varying flows automated instantaneous stream-stage measurements commonly are recorded in varying increments from 1 to 15 minutes. A streamflow rating curve, which is the result of many manual stage-discharge measurements, is used to relate the automated instantaneous stream-stage measurements to estimated streamflow. Instantaneous streamflow estimates are summed to calculate a mean daily flow, which is the parameter that is reported by the U.S. Geological Survey.

Systematic bias may occur if a streamflow monitoring device is inappropriate for monitoring streamflow at the gaged location, if equipment is improperly installed, or miscalibrated (Alley, 1977; Church and others, 2003). Random errors may occur because of many factors including drift in flow-monitoring equipment readings, collection and removal of debris, erosion of the channel bottom, changes in the channel cross section, and use of estimated record from nearby sites during times when recording instruments fail (Church and others, 2003). Errors in streamflow values are generally considered to have relatively low uncertainties in comparison to potential errors in precipitation values. For example, the U.S. Geological Survey rates streamflow data as excellent, good, fair, or poor if errors in 95 percent of the flow record are estimated to be less than 5 percent, within 5 to 10 percent, within 10 to 15 percent, or greater than 15 percent of the true value, respectively (Rantz, 1982).

Individual stream-discharge measurements are generally considered to be a minor source of uncertainty in streamflow records (Winter, 1981; Sauer and Meyer, 1992; Harmel and others, 2006). For example, Sauer and Meyer (1992) indicate that the standard error of individual stage-discharge measurements ranged from about 2 percent under good conditions to about 20 percent under poor conditions (such as sluggish flow and complex channel conditions). Winter (1981) indicates that measurements made using a (properly installed) control structure such as a weir or flume can be expected to be less than 5 percent. Published uncertainties commonly are based on the assumption that measurements are made by a careful well trained hydrographer with equipment that is properly selected for site conditions, fully functional and properly calibrated. These uncertainties also are based on the assumptions that a sufficient number of vertical and horizontal measurements of channel geometry and streamflow are made (for these criteria, see Rantz, 1982). These values do not include uncertainties of extremely low flows and flood flows that exceed the volume of the stream channel. Extreme low flows can be difficult to measure if they are discontinuous within the channel and or are of very limited depth. It is difficult to measure streamflows that have expanded into the flood plain and indirect methods (Rantz, 1982). Such flood-flow measures are expected to be 10-25 percent under the best conditions and can be much higher under poor conditions (Cook, 1987; Tillery and others, 2001).

Streamflow rating curves are relations between stage and discharge that are derived from multiple stream-discharge measurements by statistical curve fitting or graphical analysis (Rantz, 1982. Application of streamflow rating curves is recognized as a major source of uncertainty in streamflow records (Burkham and Dawdy, 1970; Schmidt, 2004; Harmel and others, 2006). Application of streamflow rating curves is subject to effects of extreme flows (very high or low) on the rating curve, effects of extrapolation beyond available data, changes in channel geometry, ice, and effects of backwater from obstructions to flow that occur downstream of the stage-measuring location (Rantz, 1982). Burkham and Dawdy (1970) examined uncertainties in streamflow caused by changes in unstable channels. They found that, depending on the local channel conditions and flow rates, one to two measurements per week were required to keep the standard error within 5-10 percent and one to two measurements per month were required to keep the standard error within 10-25 percent. Cobb (1985) did a survey of data chiefs in the 50 States and Puerto Rico the proportion of active streamgages with unstable channels for all stations was about 17 percent. About 14 percent reported that there were no stations with unstable channels; about 12 percent reported that more than half the stations had unstable channels, and Nebraska reported that about 90 percent of the streamgages in the State had unstable channels. Schmidt (2004) indicated that uncertainties may be about 2.5 percent if a shift in the streamflow rating curves represents a change in measurement conditions and may be as high as 25 percent if the rating is shifted to correct for a short-term condition that affects the measured stage-discharge relation.

Uncertainties in application of streamflow rating curves also may be caused by various factors that affect the stage-measurement mechanism. These factors include erroneous calibration, drift in the calibration point of recorded measurements, and obstruction by sediment or debris (Rantz, 1982). Once a stage measurement error is detected, the effect is prorated to the previous site visit unless a step change in the stage record is detected. These errors represent a short-term bias (weeks to months) in a long-term streamflow record. If the stage-measurement mechanism is out of service the missing record may be estimated from flows at nearby streamgages. These streamflow records are classified as poor (greater than 15 percent error) and identified with a comment code of "e" in the NWIS record. A query of the records for the 2,873 U.S. Geological Survey streamgages used to estimate streamflows for the SELDM project was done to assess uncertainties from estimated values. The maximum percent of estimated record is about 35 percent. About 82 percent of the streamgages have less than 5-percent estimated record and about 96 percent of the streamgages have less than 10-percent estimated record.

Runoff measurements are flow measurements in stormwater conveyances. Runoff measurements are similar to streamflow measurements, but runoff measurements may include additional uncertainties because runoff flows may be intermittent, rapidly varying, and may transition from subcritical open-channel flow, to supercritical open channel flow, and in some cases pressurized flow. Storm flows also may have a higher proportion of debris and suspended material than many streams. Uncertainties in runoff measurements are commonly recognized as a potential source of bias and random error for determining runoff coefficients. However, results of a controlled experiment by the USGS in cooperation with the FHWA indicate that there can be substantial bias and variability in the results of stormflow measurements using different monitoring methods (Church and others, 2003). Results from concurrent measurements by 18 streamflow monitoring methods indicate that random and systematic errors varied among the methods (**fig. 1-3**). Some methods had random error ranges of about plus or minus 10 percent of the median value. Random error ranges of about plus or minus 25 percent of the median value were common. One method had a random error range of about plus or minus 60 percent of the median value. Many of the methods demonstrated substantial systematic errors (bias) as indicated by median errors that were less than or greater than zero. Median errors were within plus or minus 30 percent for 17 methods, of these 4 were within plus or minus 20 percent, and 9 were within plus or minus 20 percent of the most probable flow value. One method demonstrated a consistent positive bias with a median error of about plus 100 percent of the most probable flow value. Therefore streamflow measurements may introduce substantial random and systematic errors in the population of runoff coefficients in the database of stormflow data collected as part of this report. These uncertainties may be reflected in the large variations in runoff coefficient statistics apparent in **figure 1-2**.

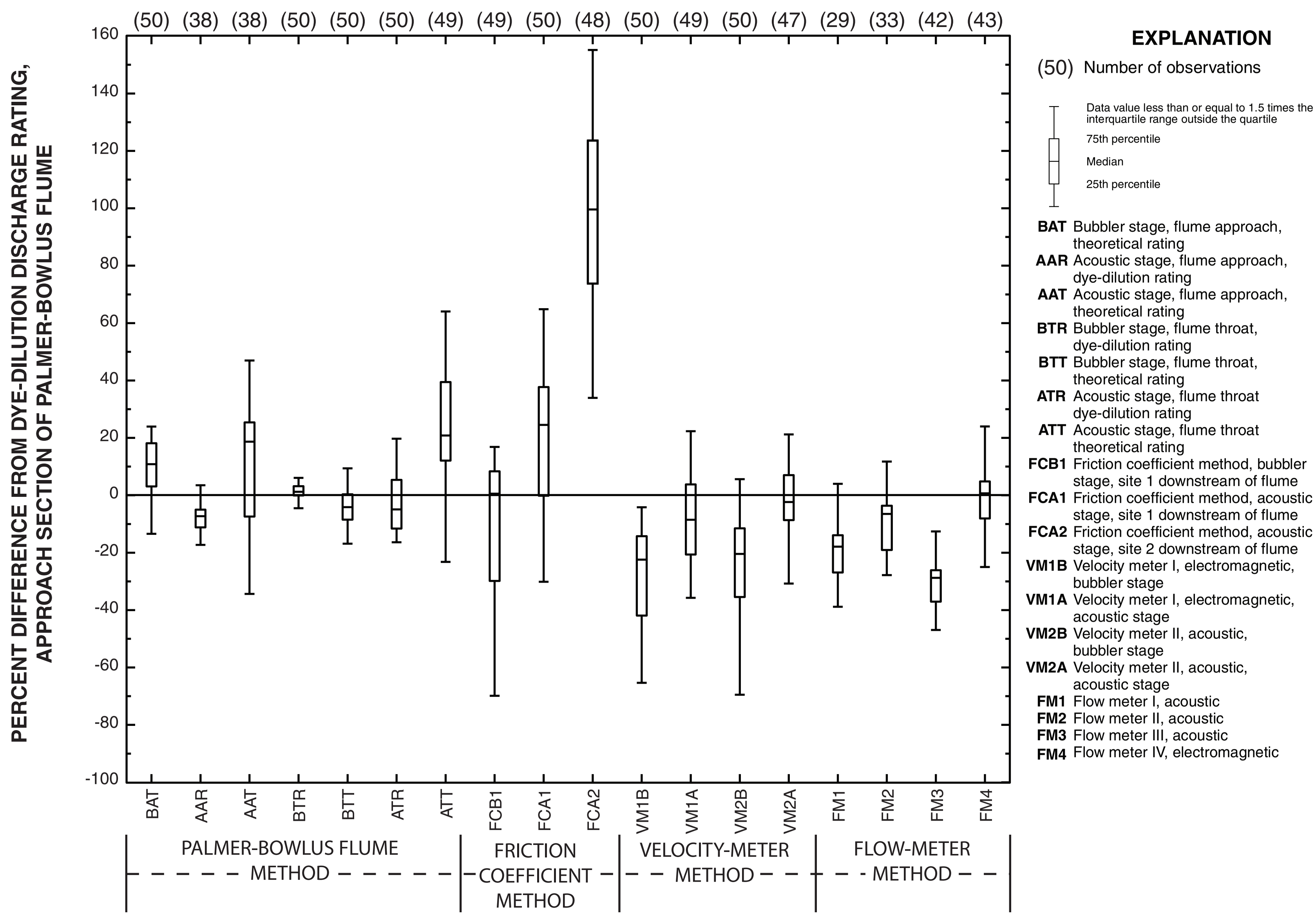

Figure 1-3. Boxplot showing comparison of results from stormwater-flow measuring methods, 1998, Madison, Wisconsin (Church and others, 2003).

Hydrograph Separation

Misspecification of the proportion of runoff and base flow during hydrograph separation will produce systematic bias if the same method is used for an investigation and will introduce random errors in a compilation of stormflow data from multiple studies that use different methods. These uncertainties will affect calculation of runoff coefficients from rainfall-runoff data. The assumptions and methods used for hydrograph separation to determine the runoff coefficients for a given basin may have a substantial effect on calculated runoff volumes, runoff coefficients, data-derived curve numbers, and the estimated characteristics of the runoff-event hydrograph (Chow, 1964; Linsley and others, 1975; Ellis and others, 1984; Pearce and others 1986; Sklash and others, 1986; Chow and others, 1988, Nathan and McMahon, 1990; Mosley and McKerchar, 1993; Pilgrim and Cordery, 1993; Sloto and Crouse, 1996; Halford and Mayer, 2000; Walker and others, 2001; Mishra and others, 2004; Ramos, 2005; Schwartz, 2007). Uncertainties in the proportion of runoff and base flow during hydrograph separation may be reflected in the large variations in runoff coefficient statistics apparent in **figure 1-2**.

Methods for hydrograph separation are commonly described as an art rather than a science and the choice of method is considered arbitrary (Chow and others, 1988; Nathan and McMahon, 1990; Schwartz, 2007). The method selected may depend on the objective of the analysis. For example, Chow (1964) indicates that base flow separation may not be critical for calculating flood peaks because subsurface discharges may be a small percentage of flood peaks. Ideally, the method selected would quantify the amount of runoff and base flow but the method used may depend on the hydrologist's interpretation of stormflow mechanisms. For example, Jensen (1990) used the prestorm flow to separate storm-flow hydrographs to calculate runoff coefficients. These runoff coefficients represent contributions from each storm-flow process. Differences in the method selected for hydrograph separation and storm separation would introduce systematic bias in the calculated runoff coefficients from study to study. The applicability of the method selected for hydrograph separation for different storm types would introduce random variations in calculated runoff coefficients and data-derived curve numbers within a given study.

It is difficult to distinguish the effect of such uncertainties in the portions of storm-hydrographs that are assigned to the stormflow volume because the studies included in the storm-event database developed for this study do not define hydrograph separation methods that were used. Hydrograph separation methods may result in calculated runoff coefficients that are negative, zero, or greater than one (Arnbjerg-Nielsen and Harremoës, 1996b). Assumptions made about the behavior of groundwater discharge, interflow, and overland flow during a storm event will determine what portion of the hydrograph is assigned to the stormflow volume that is used to calculate the runoff coefficient. For example, Halford and Mayer (2000) indicate that slow storm drainage from bank storage, wetlands, and surface water bodies in the falling limb of the storm hydrograph may contribute a substantial amount of water that is commonly identified as groundwater discharge in the recession curve. If these flows are consistently identified as base flow, runoff coefficients may be consistently low because these slower stormflow mechanisms are subtracted from the storm-event hydrograph. Another important factor is the assumption used to define the end of a stormflow period. For example, Merz and others (2006) indicate that professional judgment is needed to determine an appropriate hydrograph-separation technique and a consistent definition for separating flows from subsequent storms are important factors for determining runoff coefficients in large rural basins.

Hydrograph separation uncertainties are not commonly addressed in the stormwater-quality literature, but studies have examined the variability among different manual and automated methods for identifying groundwater discharge. For example, Bates and Davies (1988) indicate that variations in manual hydrograph separation techniques can introduce differences in calculated stormflows that are on the order of 17 to 71 percent of the total storm flow from individual storms in each basin that was examined. Nathan and McMahon (1990) compared manual and digital base flow separation techniques that were based on similar hydrograph separation definitions and found that digital methods varied from plus or minus 0.3 to 39 percent of expert interpretations with the manual method. Neff and others (2005) examined hydrograph separation techniques with data from 3,936 streamgages in the Great-Lakes basin with six automated hydrograph separation techniques. They determined that, on average, the ratio of base flow to total streamflow varied by about 24 percent among the different hydrograph-separation methods used. Risser and others (2005) examined four hydrograph separation methods with two USGS computer programs, PART (Rutledge, 1993) and HYSEP (Sloto and Crouse, 1996), and found that different methods provided annual base flow estimates that diverged by about 20 to 30 percent. Blume and others (2007) examined the results of baseflow separation techniques on runoff coefficients for a small, forested, mountain stream; their results indicate that the percent difference between the maximum and minimum volumetric runoff coefficients among the five methods ranged from 33 to 145 percent, with a median of 91 percent, in a sample of 19 summer storms. Results of these studies indicate that systematic bias in hydrograph separation techniques may be substantial from study to study.

A substantial amount of uncertainty in hydrograph separation may occur even if a consistent method is used for future studies. For example, Sloto and Crouse (1996) indicate that different hydrologist using the same manual methods commonly will estimate different stormflow and base flow volumes. Arnold and Allen (1999) indicate that there can be differences of about 5 to 50 percent of estimated base flow using different methods based on the same base flow-separation assumptions. Furthermore, commonly used methods do not necessarily eliminate uncertainty in hydrograph separation that may occur from storm to storm with variations in antecedent moisture conditions and groundwater discharge.

Antecedent Conditions

Antecedent (prestorm) conditions affect prestorm streamflow, soil saturation, and groundwater levels; all of which may affect the amount of stormflow that is produced for a given rainfall volume. Random variations in antecedent conditions are expected to cause random variations in stormflow generation at a given site from storm to storm. However, systematic variations in antecedent conditions may introduce bias in runoff coefficients. For example, seasonal or regional differences in storm patterns may introduce systematic bias in runoff coefficients. Records of stormflow data that are collected in conjunction with runoff-quality monitoring data bay be biased if sampling protocols require several dry days prior to a sampling event.

The antecedent moisture condition is a primary stochastic control on the rainfall-runoff transformation for a given site. In theory, the effect of antecedent moisture conditions on the rainfall-runoff transformation should be more pronounced for basins with lower proportions of effective impervious areas than for basins with high proportions of effective impervious areas. This is because antecedent moisture conditions do not have a pronounced effect on runoff from impervious areas in comparison to the effect on runoff from pervious areas. Simple rainfall-runoff models commonly use discrete antecedent moisture conditions with discrete basin responses to predict runoff from precipitation inputs. For example, NRCS uses three different discrete curve numbers to represent dry, average, and wet conditions. Complex rainfall-runoff models are based on data-intensive input variables such as precipitation and temperature data that is used to calculate a continuous series of prestorm soil moisture conditions. These antecedent conditions are used to calculate basin responses to precipitation inputs. Soil wetness parameters are commonly assigned in the model calibration process to match model outputs to the available flow record. However, there are many confounding variables. For example, runoff from residential areas, urban open space, and landscaped commercial and landscaped industrial areas may be affected by lawn watering during dry periods (Williams, 1980). Woods and Sivapalan (1999) indicate that the complex interplay between atmospheric conditions and basin properties make it difficult to characterize the effects of antecedent conditions in various basins.

Prestorm soil-moisture conditions commonly are estimated from precipitation records. Driver and Tasker (1990) use annual precipitation to adjust their rainfall runoff relations in arid basins, in part to account for differences in storm characteristics and average antecedent conditions. Heggen (2001) indicates that a normalized antecedent precipitation index will reduce uncertainties and inconsistencies in different definitions of antecedent conditions and will increase the accuracy and precision of curve-number runoff estimates. Harmel and others (2006) document seasonal differences in the population of runoff coefficients that are caused by seasonal variation in antecedent soil moisture in 18 rural basins in the Texas Blackland Prairies ecoregion. Merz and others (2006) indicate that annual precipitation, and therefore the average prestorm wetness, is more important than soil type for determining average runoff coefficients for otherwise similar rural basins in Austria.

Prestorm base flow also may provide the information necessary to improve estimates of the variations above and below the average (or median) rainfall-runoff transformation value for an ungaged basin (Mishra and others, 2004). Correlation between prestorm base flow and the storm-event runoff coefficient is consistent with theoretical runoff-generation mechanisms because higher prestorm flows would be associated with wetter soils, increases in saturated runoff areas, and groundwater mounding. All these conditions are expected to increase the basin response to a given precipitation input. For example, Taylor (1982) demonstrated that saturated areas and runoff were correlated with prestorm streamflows, but that the relations were different in different seasons. O'Loughlin (1986) examined the effects of watershed properties on saturation overland flow with results from about 60 storms and found that the saturated area and percentage of runoff was highly correlated to base flow. Walker and others (2001) derived an exponential relation between prestorm base flow and curve number. The relation was weak, but it was better than antecedent precipitation. Longobardi and others (2003) examined correlations between prestorm base flow and runoff coefficients in 380 catchments in different climates and determined that prestorm base flow could explain 60 to 94 percent of the variability in runoff coefficients in humid areas and about 40 percent of the variability in very humid or arid areas. Longobardi and others (2003) indicated that base flow correlation was more effective than other methods for predicting variations in runoff coefficients from storm to storm. Similarly, Hill and others (1998) examined volumetric runoff coefficients for 20 unregulated basins with drainage areas ranging from 17 to 235 square miles and determined that runoff coefficients increases with increasing prestorm base flow. However, Hill and others (1998) determined that antecedent base flow was not a strong predictor of antecedent wetness in basins with high levels of sustained base flow. Higher prestorm baseflows may be associated with groundwater discharge from a previous storm or from stream discharge from seasonally high groundwater levels (Winter and others, 1998).

Different basins will have different hydrologic responses to short term and seasonal variations in antecedent conditions. Differences in climates, soil, geology, land use, and water use may affect the transferability of prestorm flow statistics and runoff coefficients between sites. Detailed studies would be needed to quantify potential effects of antecedent conditions of transferability of data from index sites to the site of interests in different hydrologic regions.

Precipitation

Uncertainties in precipitation measurements commonly are recognized as a potential source of bias and random error for determining runoff coefficients. Uncertainties in precipitation measurements and the spatial distribution of precipitation in a basin may be reflected in the large variations in runoff coefficient statistics apparent in **figure 1-2**. Systematic bias may occur if a rain gage is improperly installed, miscalibrated, or located in a position that is not representative of basin-average precipitation (Alley, 1977; Groisman and Legates, 1994; Becciu and Paoletti, 2000; Church and others, 2003). Mean areal rainfall estimates at the basin scale are commonly used to estimate runoff, but bias and random error may substantially affect runoff coefficient estimates (Singh, 1977). Runoff-generation is highly sensitive to the spatial and temporal variability of rainfall (Smith and others, 2004). The location of rain gages with respect to the runoff monitoring station and the basin centroid can affect the rainfall-runoff relations. Random errors may occur because of the effect of wind on measurements, collection of debris in a rain gage, and the spatial variation in precipitation from event to event (Church and others, 2003). Rauch and others (1998) placed three rain gages within one meter of each other and noted that random volumetric errors in measured precipitation from storm to storm could be as high as about plus or minus 30 percent among the gages. Although random errors may tend to cancel over a long period, such errors would may have a substantial effect on runoff coefficients or curve numbers derived from rainfall-runoff data from individual storms.

Systematic errors will introduce bias in rainfall-runoff relations for a given site. Groisman and Legates (1994) indicate that measurement bias may be as high as about 40 percent of measured precipitation. Rauch and others (1998) indicate that systematic errors in the measurement process are more important than random errors for estimating rainfall-runoff relations. They indicated that systematic errors in rainfall measurements included the effects of wind (2-15 percent), initial wetting of the rain gage (2-10 percent), evaporation from the gage (0-4 percent), splashing (1-2 percent), design and calibration of the gage (0 to 10 percent), and evaporation from heated rain gages (0-30 percent). Mueller and Kidder (1972) did experiments and analyses indicating that unshielded rain gages may have systematic errors that substantially under represent precipitation totals by as much as 20 percent with a moderate breeze (about 17 miles per hour) and may under represent precipitation totals by as much as 80 percent as winds increase to about 70 miles per hour. This bias may result in runoff coefficients that are too high, including runoff coefficients that are greater than one.

Systematic and random variations in precipitation totals over a watershed area may substantially affect rainfall-runoff relations. The need for multiple rain gages in studies of areal extent is generally recognized (Church and others 2003). The placement of rain gages in a study network should represent catchment topography, and ideally should tie in with historical stations in a larger network, such as the network operated by the National Oceanographic and Atmospheric Administration (Alley, 1977; Winter, 1981; Daly and others, 1994; Church and others 2003; Carpenter and Georgakakos, 2004). For example, Duckstein and others (1973) developed regression equations indicating that the number of storms per year and the volume of precipitation in each storm increased with increasing elevation in southern Arizona. Williams (1980) indicates that variations in the spatial distribution of precipitation could introduce errors in estimates of basin outflows of plus or minus 5 to 50 percent. Niemczynowicz (1988) examined data from 10 storms with a 12-gage network on a 7.7 square mile watershed and determined that the median errors in runoff estimates would be plus 78 and minus 95 percent for the maximum and minimum rain-gage measurements, respectively. In this study the maximum error values were plus 277 and minus 97 percent for the maximum and minimum rain-gage measurements, respectively. Fontaine (1990) examined the effect of rain-gage network density and rain-gage placement on the accuracy of estimates of precipitation input estimated from multiple rain gages with a density of about 1 gage per 10 square miles. In a simulation experiment with measured storm patterns, he found that precipitation estimates for different storms from multiple rain gages ranged from 150 percent too high to about 75 percent too low. In this study, fifty percent of the trials had errors in excess of plus or minus 20 percent for one multiple-gage network experiment. Duncker and Melching (1998) examined data from 27 storms at 3 sites with 2 rain gages per site. They found that percent differences in rainfall and therefore percent error in runoff coefficients ranged from 0.34 to 94 percent of the average. In this study, the median error was 16 percent, the average error was 23 percent, and the coefficient of variation of errors was 0.92 (Duncker and Melching, 1998). Chaubey and others (1999) analyzed data from a network of 17 rain gages with a density of about 4 square miles per gage to estimate that absolute errors in estimates of areal-average rainfall totals may vary from 8 to 51 percent from storm to storm. Engelmann and others (2002) indicate that weighted average precipitation values from multiple rain gages would yield runoff estimates within 2 percent of discharge values but that precipitation estimates from an individual rain gage may lead to 25-percent errors in estimated discharge from a 40 mi^2 basin in Ohio.

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