VARIATIONS IN PRECIPITATION AND RUNOFF IN AN URBANIZING WATERSHED

Bruce K. Ferguson[1] and Philip W. Suckling[2]

AUTHORS: [1]School of Environmental Design, [2]Department of Geography, The University of Georgia, Athens, GA 30602.

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INTRODUCTION

Urban hydrologic theory focuses on the impervious surfaces of roofs and pavements, and the relatively impervious compacted soil that surrounds them (Dunne and Leopold, 1978; Leopold, 1968). Application of almost any available hydrologic model indicates that, as a watershed becomes more urbanized, floods resulting from a given storm get bigger and peak faster, endangering streamside properties. A corollary is that groundwater levels and stream low flows would decline following reduced infiltration, endangering water supplies.

This study is an attempt to observe the combination of increasing peak flows and declining low flows which theory predicts should occur simultaneously in an urbanizing watershed. It focuses particularly on the low flows, which have not been emphasized in previous research.

The watershed of Peachtree Creek is located in and near Atlanta, Georgia. It was selected for study because of availability of stream runoff data from the U.S. Geological Survey since 1958, and previous study by Wallace (1971) indicating increasing urbanization and effects on flood runoff. The watershed's area upstream from the U.S.G.S. gaging station is 86.8 square miles.

The watershed is underlain by crystalline rocks which characteristically contain little groundwater except at more or less isolated fractures (Cressler et al, 1983; Heath, 1984, pages 46-48). However, the bedrock is mantled by weathered residuum which is locally up to 50 feet deep. Precipitation that infiltrates into this residuum through vegetated surfaces can move laterally, downward, or upward depending on gradients of tension resulting from evapotranspiration and gravity drainage, and be stored for significant periods of time before discharging into streams (Hewlett,1982, pages 20, 38, 127-128).

The period during which the USGS has monitored runoff represents a period of rapidly increasing urbanization. Wallace (1971) found that the watershed had significant and increasing impervious coverage in the middle of this century, reaching about 30 percent at the time the U.S.G.S. installed the gaging station in 1958. The population of Dekalb county, in which 90 percent of the watershed area lies, more than doubled from about 215,450 in 1960 to 473,600 in 1985 (Clark, 1988). If impervious area is roughly proportional to population, then the watershed would be expected to be more than 50 percent impervious by 1987. The land areas that are not functionally in urban uses are forested (Wallace, 1971).

PREVIOUS STUDIES

Leopold (1968) pointed out that urbanization is accompanied by increases in short-term flood peaks due to increased volumes of storm runoff from impervious surfaces, and greater velocity of flow across impervious surfaces and through storm sewers. He also pointed out but did not emphasize the decrease in low flows which would likely result from decreased infiltration.

Seaburn (1969) separated "direct runoff" from flood hydrographs on an urbanizing stream on Long Island. As urbanization increased, average annual direct runoff increased in relation to precipitation, magnitude of short-term peak flows increased, and entire hydrographs were faster.

For six streams in the same area of Long Island, Simmons and Reynolds (1982) estimated "base flow" using the same hydrograph separation technique. Volume of base flow declined with increasing urbanization, which was attributed primarily to decreased groundwater recharge. Base flow remained unchanged in two nearby rural drainage areas during the same period.

Also working in the same area of Long Island, Pluhowski and Spinello (1978) suggested that poorly sealed sanitary sewers, where located below the ground water table, could reduce stream base flows by intercepting groundwater. The magnitude of this effect suggested by their results is uncertain.

Riggs (1965) monitored summer and fall runoff in nine adjoining rural watersheds in the crystalline Piedmont area of Virginia and found that low-flow discharge was directly related to percentage of the drainage basin that was cleared of trees and brush and given over to pasture and hay. Clearing of land along the stream channel seemed to produce a greater effect than clearing over the basin generally. The effect of clearing was negligible during periods of high discharge.

Trimble, Weirich and Hoag (1987) estimated land use and annual precipitation and runoff for 12 large watersheds in the southeastern Piedmont. They found that annual runoff as a proportion of precipitation declined in association with growth of forests on previously agricultural land, which was attributed to evapotranspiration from large deeply rooted forest trees. The reduction was greater in dry years than in wet, possibly because trees are able to draw moisture from deep in the soil when it is not available near the surface.

Wallace (1971) estimated land use in the Peachtree Creek watershed at three periods. He modeled individual Peachtree Creek flow events, finding that with increasing urbanization short-term flood peaks tended to increase, and that time to peak tended to decrease.

DATA

The U.S.G.S. gaging station on Northside Drive was installed in 1958. Although the gage was moved in 1963, the move caused no measurable change in watershed area. The period from late 1958 to the end of September 1987 gives 28 water years of data. Daily and annual runoff in cfs and inches for 1965 through 1986 were taken from *Water Resources of Georgia* (U.S. Geological Survey, annual). Unpublished data for 1958 through 1964 were generously made available by the U.S.G.S. office in Doraville, Georgia.

Daily and annual precipitation in inches for the Atlanta airport and Norcross were taken from the climatological data records maintained by the National Climatic Data Center. The airport is located about 15 miles southwest of the watershed; Norcross is located a similar distance northeast. A simple average of annual data from the airport and Norcross was found to be more highly correlated with runoff than precipitation from the Atlanta airport alone, so such an average was used in this study. For two months (January 1972 and November 1973) Norcross data were missing, so data from nearby Alpharetta were substituted in the average.

For analysis the data were divided into two equal periods of 14 years each, 1959-1972 and 1973-1986. The later period represents more urbanized conditions than the earlier period.

RESULTS

1. Annual Runoff and Precipitation

For annual analysis the precipitation and runoff data were formatted in water years from October 1 to September 30. Both precipitation and runoff were in units of inches per year. During the entire 28-year period, annual runoff was highly correlated with annual precipitation, having simple r of 0.894 (or $r^2 = 0.799$).

In order to assess whether the less-urbanized early period (1959-1972) and more-urbanized late period (1973-1986) were different, a regression model of annual runoff (Q_{ann}) against annual precipitation (P_{ann}) was analyzed in the form:

$$Q_{ann} = a + bP_{ann} + cX*P_{ann} + dX \quad (1)$$

where X is a binary term with value of 0 for the early period and 1 for the late period. If the coefficients c and d are statistically significant, then a significant difference exists between the two periods. Results from the regression analysis yielded the following relationship (with both Q_{ann} and P_{ann} in inches):

$$Q_{ann} = -3.97 + 0.48P_{ann} + 0.23X*P_{ann} - 12.26X \quad (2)$$

with $r^2 = 0.824$. The significance levels for the regression coefficients in equation 2 are 0.0001 for b, 0.08 for c, and 0.08 for d. The values for c and d, although not highly significant, suggest that a difference between the two periods may indeed exist. From equation 2, the resulting relationships for the two periods are (with both Q_{ann} and P_{ann} in inches):

$$Q_{ann(1959\text{-}1972)} = -3.97 + 0.48P_{ann} \quad (3)$$

$$Q_{ann(1973\text{-}1986)} = -16.23 + 0.71P_{ann} \quad (4)$$

These are illustrated in Figure 1 where an increase in runoff during wet years is evident for the more urbanized (late) period while a decrease in runoff is implied during dry years.

The increase in runoff in wet years with increasing urbanization would be predicted by urban hydrologic theory. High rainfall creates an opportunity for large amounts of rapid runoff from urban impervious surfaces to dominate the water balance.

Despite the reduced ground water levels expected due to less infiltration under urbanization, the decline in annual runoff for dry years is not as clearly expected. Over a period as long as a year, rainfall that did not eventually emerge as runoff must have been discharged by increased evapotranspiration.

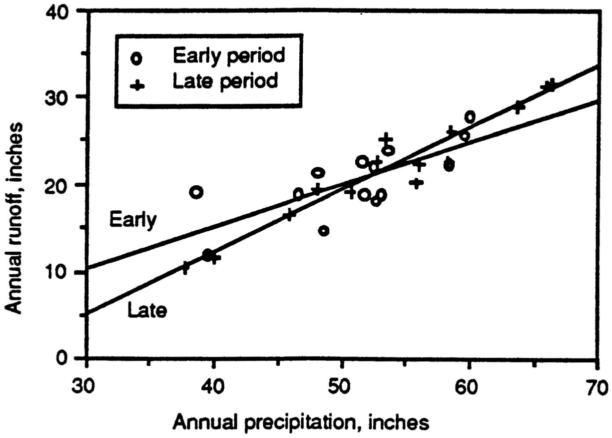

FIGURE 1. RELATIONSHIP BETWEEN ANNUAL RUNOFF AND ANNUAL PRECIPITATION, DURING EARLY (LESS URBANIZED) AND LATE (MORE URBANIZED) PERIODS.

2. Low-flow Runoff and Precipitation

In order to further assess the impact of increasing urbanization under dry conditions, analysis of low flows was undertaken. For this analysis the data were reformatted into water years from April 1 to March 31. The annual seven-day low flow and its starting date were identified in the runoff records. All of the low flows occurred in the months of August, September and October. The precipitation for periods of 30, 60, 90 and 120 days before the first day of the low-flow period was determined.

Simple correlation analysis between annual seven-day low flows (Q_7) and preceding precipitation based on the entire 28-year record revealed r of 0.293 ($r^2 = 0.086$) with precipitation of the preceding 30 days (P_{30}), r of 0.480 ($r^2 = 0.230$) with P_{60}, r of 0.463 ($r^2 = 0.214$) with P_{90}, and r of 0.710 ($r^2 = 0.504$) with P_{120}. The relationship between annual seven-day low flows and the precipitation of the preceding 120 days was by far the strongest.

Comparison of the early and late (more urbanized) periods was undertaken again using the regression model form presented in equation 1. The following relationship between Q_7 and the preceding 120-day precipitation was attained (with Q_7 in cfs and P_{120} in inches):

$$Q_7 = 1.89 + 1.19P_{120} + 0.73X*P_{120} - 11.28X \quad (5)$$

with $r^2 = 0.529$. The significance levels for the regression coefficients in equation 5 are 0.03 for b, 0.28 for c, and 0.27 for d. The values for c and d are not significant and the r^2 value of 0.529 for equation 5 is only slightly better than that for the simple correlation between Q_7 and P_{120} for the entire 28-year record ($r^2 = 0.504$). From equation 5, the resulting relationships for the two periods are (with Q_7 in cfs and P_{120} in inches):

$$Q_{7(1959\text{-}1972)} = 1.89 + 1.19P_{120} \qquad (6)$$

$$Q_{7(1973\text{-}1986)} = -9.39 + 1.92P_{120} \qquad (7)$$

These are illustrated in Figure 2 where a similar difference to that found for the annual analysis between the two periods is evident. Although the difference between the two lines in Figure 2 is not statistically significant according to the analysis presented for equation 5, it should be noted that the small size of the data set (28 years with only 14 years in each subperiod) limits the statistical confidence of the results.

DISCUSSION AND CONCLUSIONS

Several factors not considered in this analysis may have complicated the relationship between runoff and precipitation. Landscape irrigation is believed to have grown greatly in the Atlanta area in recent years; if irrigation water is applied lavishly enough, this artificial importation might measurably supplement stream flows. Some irrigation water migh be pumped from streams, which would reduce flows. Another factor is poorly sealed sanitary sewers, which could drain groundwater from floodplains and other places where the soil is saturated, thereby reducing stream flows. In addition, meteorological factors such as temperature and wind were not considered.

However, the results are suggestive of the type of effect that urbanization has on the relationship between total runoff to precipitation. Increasing urbanization appears to be accompanied by both increasing runoff in wet years and declining runoff in dry years. Although declining low flows have been a corollary of urban hydrologic theory for some time, little field support for this can be found in the literature.

Unlike the well-known peak flows, a decline in low flows does not occur as a result of direct effects of impervious surfaces during storms. During dry periods stream flow is more dependent on base flow resulting from subsurface storage of precipitation in previous months than on the small amount of precipitation during the current month. Low flows in dry years decline with increasing urbanization because of reduction of water stored in the subsurface and available to support base flows.

One cause of the reduction in subsurface stored water is year-round deflection of precipitation from recharge. This effect was suggested two decades ago by Leopold (1968). In times of rain, the impervious surfaces deflect precipitation away from recharge, reducing the volume of water that would be stored in the mantle of weathered residuum and available to support base flows.

An additional factor which could further reduce subsurface stored water is urban evapotranspiration. Oke (1979) found that evapotranspiration in locally vegetated areas is in fact increased by exposure of vegetation in non-homogeneous urban terrain to advection of sensible heat from surrounding surfaces. This "advectively-assisted evapotranspiration" suggests that evapotranspiration in urban areas is not reduced in proportion to loss of vegetated area. The increased rate of evapotranspiration from remaining vegetation at least partially compensates for urbanization's reduction of vegetated area. In a followup study, Suckling (1980) found that the increase of urban evapotranspiration by advection is not as great in larger or more sheltered urban vegetated areas, but is still present.

The results of this study point out the importance of urbanization to stream low flows. After precipitation has been deflected from infiltration and recharge by impervious surfaces, and infiltrated water in the subsurface reduced by evapotranspiration, there is no possible amelioration of declining low flows; the water to support base flows is no longer available in the watershed.

It should be pointed out that even when Peachtree Creek's impervious surfaces were about 35 percent, forest land use was still over 40 percent, and trees and other vegetation also presumably occupied a considerable portion of the remaining 25 percent in urban land uses such as residences (Wallace, 1971). The urban pattern in the Peachtree Creek watershed is a mosaic of impervious and vegetated surfaces. Perhaps the vegetated surfaces have an effect on low flows as do the impervious ones. Both during and between storms, trees and other vegetation draw on moisture from the soil mantle and return it to the atmosphere, denying it to later runoff.

A further cause of reduced flows during dry periods may be related to interception of precipitation by vegetation and subsequent evaporation. Since the canopies of urban trees are exposed to local advective influences, intercepted precipitation could be rapidly evaporated and denied to later runoff. In a more homogeneously forested area, intercepted precipitation may have time for a greater proportion to reach the soil by drip and stemflow, and infiltrate.

The location of vegetation within the watershed may also play a role in determining streamflow. As Riggs (1965) pointed out, adequate moisture for maximum transpiration is more likely to be available near stream channels than on hillsides and ridges. Removing vegetation from upland areas may cause only a small reduction in a watershed's total evapotranspiration. Leaving urban vegetation in floodplains and low areas may expose the most rapidly evapotranspiring vegetation to advective enhancement of evapotranspiration.

The magnitude of low flows in an urban watershed is probably a result of both reduced recharge and ongoing evapotranspirative losses. The reduction of low flows following evapotranspirative losses presumably varies seasonally with changing evapotranspiration rates, and, as Trimble et al (1987) implied, inversely with amount of soil moisture stored from previous rainfall.

Urban runoff represents the worst of all possible

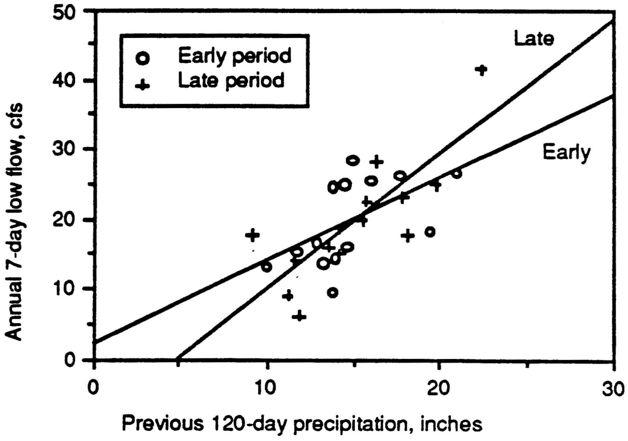

FIGURE 2. RELATIONSHIP BETWEEN ANNUAL SEVEN-DAY LOW FLOW AND PRECIPITATION IN THE 120 DAYS PRECEDING EACH LOW FLOW, DURING EARLY (LESS URBANIZED) AND LATE (MORE URBANIZED) PERIODS.

worlds, with increased flooding combined in the same regime with decreased flow during dry periods compared to nonurbanized environments. Stormwater management in the Atlanta area, which has focused almost exclusively on reducing floods by temporary stormwater detention, should also be concerned with restoring base flows.

One stormwater management approach that could address low flows is infiltration, in which runoff water is forced to enter the soil (Ferguson, in press; Ferguson and Debo, 1987). In contrast to detention, infiltration can take advantage of the large, long-term storage capacity in subsurface soil voids, transforming short pulses of rainfall runoff into stream base flows.

LITERATURE CITED

Clark, W.A.V., 1988. Racial Transition in Metropolitan Suburbs: Evidence from Atlanta. Urban Geography 9: 269-282.

Cressler, C.W., C.J. Thurmond and W.G. Hester, 1983. Ground Water in the Greater Atlanta Region, Georgia, Information Circular 63. Georgia Department of Natural Resources, Environmental Protection Division, Atlanta, Georgia.

Dunne, Thomas and Luna B. Leopold, 1978. Water in Environmental Planning. Freeman, San Francisco, California.

Ferguson, Bruce K., (in press), Role of the Long-Term Water Balance in Management of Stormwater Infiltration, submitted to Journal of Environmental Management.

Ferguson, Bruce K., and Thomas N. Debo, 1987, On-Site Stormwater Management: Applications for Landscape and Engineering. PDA Publishers, Mesa, Arizona.

Heath, Ralph C., 1984. Ground-Water Regions of the United States, Water-Supply Paper 2242. U.S. Geological Survey, Washington, D.C.

Hewlett John D., 1982. Principles of Forest Hydrology. University of Georgia Press, Athens, Georgia

Leopold, Luna B. 1968. Hydrology for Urban Land Planning, Circular 554. U.S. Geological Survey, Washington, D.C.

Oke, T.R., 1979. Advectively-Assisted Evapotranspiration from Irrigated Urban Vegetation. Boundary-Layer Meteorololgy 17: 167-173.

Pluhowski, E.J. and A.G. Spinello, 1978. Impact of Sewerage Systems on Stream Base Flow and Groundwater Recharge on Long Island, New York. Journal of Research of the U.S. Geological Survey 6: 263-271.

Riggs, H.C., 1965. Effect of Land Use on the Low Flows of Streams in Rappahannock County, Virginia, Professional Paper 525-C, pages 196-198. U.S. Geological Survey, Washington, D.C.

Seaburn, G.E., 1969. Effects of Urban Development on Direct Runoff to East Meadow Brook, Nassau County, Long Island, New York, Professional Paper 627-B. U.S. Geological Survey, , Washington, D.C.

Simmons, Dale L. and Richard J. Reynolds, 1982. Effects of Urbanization on Base Flow of Selected South-Shore Streams, Long Island, New York. Water Resources Bulletin 18: 797-805.

Suckling, Philip W., 1980. The Energy Balance Microclimate of a Suburban Lawn. Journal of Applied Meteorology 19: 606-608.

Trimble, Stanley W., Frank H. Weirich and Barbara L. Hoag, 1987, Reforestation and the Reduction of Water Yield on the Southern Piedmont since circa 1940. Water Resources Research 23: 425-437.

U.S. Geological Survey, (annual). Water Resources Data for Georgia, U.S. Geological Survey, Washington, D.C.

Wallace, James R. 1971. The Effects of Land Use Change on the Hydrology of an Urban Watershed, ERC-0871, Completion Report OWRR Project No. C-1786, Georgia Institute of Technology School of Civil Engineering, Atlanta, Georgia.