THE EFFECTS OF ANTECEDENT RAINFALL UPON STREAM RUNOFF IN THE COASTAL PLAIN OF GEORGIA

Seth Rose

AUTHOR:: Associate Professor, Department of Geology, Georgia State University, Atlanta, Georgia 30303.
REFERENCE: *Proceedings of the 1999 Georgia Water Resources Conference*, held March 30-31, 1999, at the University of Georgia. Kathryn J. Hatcher, editor, Institute of Ecology, The University of Georgia, Athens, Georgia.

Abstract. A 47-year data base (1948-1994) derived from 15 stream and 8 rain gaging stations was used to analyze the effects of antecedent rainfall upon subsequent runoff within the Coastal Plain of Georgia. One hundred and twenty 12-month periods were used to classify antecedent rainfall into "high" (+15 to +59% normal), "low" (-11 to -42% normal), and "normal" (-9 to + 8% normal) populations. Subsequent rainfall following each of these 120 periods was classified in a similar manner. A "production ratio" (runoff/rainfall) was defined for each subsequent period and then normalized with the long-term (47-year study period) average production ratio for those months. This permitted the comparison of normalized production ratios for nine subpopulations consisting of various pairings of antecedent and subsequent rainfall conditions. Drought (below normal rainfall for at least one year) depresses streamflow in southern Georgia for a period of one to two years, given a return to normal rainfall. Production ratios associated with above normal antecedent rainfall remain greater than normal for a period of two years following a return to normal rainfall conditions.

INTRODUCTION

Streamflow in the Coastal Plain of Georgia is partially generated by the influx of ground water. Pronounced deviation from normal rainfall can have long-term effects upon the elevation of the water table and thereby effect discharge after yearly rainfall totals return to normal. This paper presents a systematic means of analyzing the effects of excess and deficient rainfall upon subsequent streamflow. An approach has been devised in which nine subpopulations consisting of various combinations of antecedent and subsequent rainfall conditions are designated for statistical comparison. This approach is not predictive in terms of the response made by individual streams to individual storms. Rather it was devised to assess the effects of long-term (i.e. one year) antecedent rainfall variation upon regional runoff.

METHODS

The study period between 1948-1994 (47 years) was chosen based upon the availability of rainfall and runoff data. The average monthly precipitation value was calculated for each of the eight gage locations shown in Figure 1. Data for these sites are from the National Climatic Data Center records and have been summarized on CD ROM (EarthInfo Inc., 1995). A regional monthly average for each of the 564 months during the study period was calculated from these eight stations.

An average monthly runoff value for the same study period was calculated based upon discharge (runoff = discharge/upstream watershed area) data from the 15 United States Geological Survey stream gaging stations shown on Figure 1 (EarthInfo Inc., 1996). The watershed area varied between 117 and 7,228 km^2 and flow within these streams has not been regulated by engineering structures. A runoff/rainfall ratio ("production ratio") was calculated for each month during the study period. Finally, a "normalized production ratio" (NPR) was calculated which represents the

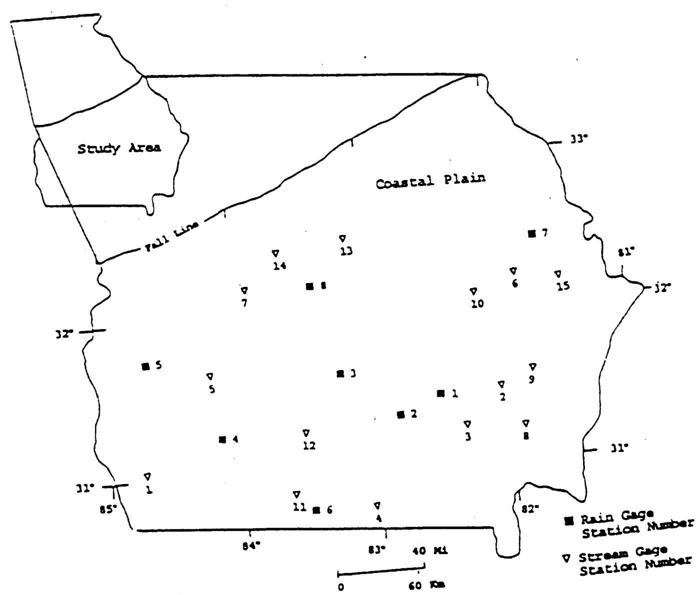

Figure 1. Map of the Georgia Coastal Plain study area showing precipitation and stream monitoring gages used in this study.

production ratio for an individual month divided by the average production ratio for that given month during the study period. This normalization procedure accounts for short-term variation from seasonal evapotranspiration variability and other factors.

The *antecedent* period was 12 consecutive months and no one particular month was used for starting purposes. A 12-month period should be sufficient in most cases to represent "drought" or "excess" rainfall conditions. The utility of applying these designations to periods substantially less than 12 months is marginal. There were only several periods in which above-normal or below-normal rainfall conditions persisted for periods greater than 12 months. The specification of any one antecedent period is a bias inherent to this method in that rainfall intensities prior to this period are ignored. However, the one-year interval chosen for this study is believed to represent a realistic period to assess the effects of "long-term" antecedent rainfall upon subsequent runoff.

A *residual* rainfall total was calculated for each month during the study period, representing the difference between each monthly value and the 47-year mean for that month. A total of 120 antecedent periods were identified and subclassified into three equal sets based upon the following procedure. Forty 12-month continuous periods were identified during which the residual rainfall ranged between 177 and 713 mm greater than normal. This set was designated as "high antecedent" rainfall. Forty 12-month continuous periods were designated as "normal antecedent" based upon residual rainfall values that ranged between -115 and +98 mm. Finally, a third set of 40 12-month continuous periods was chosen based upon residual rainfall values that ranged between -138 and -515 mm. This set was designated as "low antecedent" rainfall. The average percentage difference from normal for the "low", "normal", and "high" populations were -22.4%, -1.1%, and +26.8% respectively. There was no special criteria for choosing 40-member subsets; however, this number was deemed reasonable and representative upon inspection of the total 564-month data set.

Each of the 120 antecedent periods (the three set total) was then associated with "subsequent" periods of rainfall and runoff. These were periods of 3, 6, 12, and 24 months directly following a given antecedent period. Rainfall during these periods was designated as either "high", "normal" or "low" on a basis very similar to that used for the characterization of antecedent rainfall. "High" subsequent rainfall was +11% or greater than the normal long-term average for the given n-month period. "Low" subsequent rainfall was less than 11% normal and "normal" subsequent rainfall was between ±11% of the n-month long-term average.

A set of nine subpopulations (Figure 2) now exist for any given n-month period subsequent to a designated antecedent period. These are "low antecedent/low subsequent" (abbreviated A_LS_L), "low antecedent/normal subsequent" (A_LS_N), "low antecedent/high subsequent" (A_LS_H), "normal antecedent/low subsequent" (A_NS_L), "normal antecedent/normal subsequent" (A_NS_N), "normal antecedent/high subsequent" (A_NS_H), "high antecedent/low subsequent" (A_HS_L), "high antecedent/normal subsequent" (A_HS_N), and "high antecedent/high subsequent" (A_HS_H). An average NPR value along with a standard deviation is then calculated for each subpopulation for each n-month interval.

There is some overlap within these data in that some of the months comprising one 12-month antecedent period may also be incorporated within another 12-month period. However, the 480-month sets used to represent the three antecedent rainfall groups were chosen to avoid as much overlap as possible and are 94-97% unique. The nine subpopulations used for the statistical comparisons (represented by the nine connecting lines on Figure 2) are independent in that a given antecedent period is followed by a unique set of subsequent rainfall conditions (i.e. > +11%, ±11%, and < -11% normal).

A statistical hypothesis test can now be constructed to evaluate possible differences with respect to mean production ratios for the nine subpopulations for any n-month interval. Given a set of nine subpopulations, 36 unique comparisons of any two subpopulations are possible. However, most of these comparisons are neither logical nor hydrologically significant. The most meaningful comparisons are those which hold subsequent conditions constant and compare either high with normal or low with normal antecedent conditions. For example, a null-hypothesis can be constructed to test the effects of below-normal antecedent rainfall upon subsequent runoff.

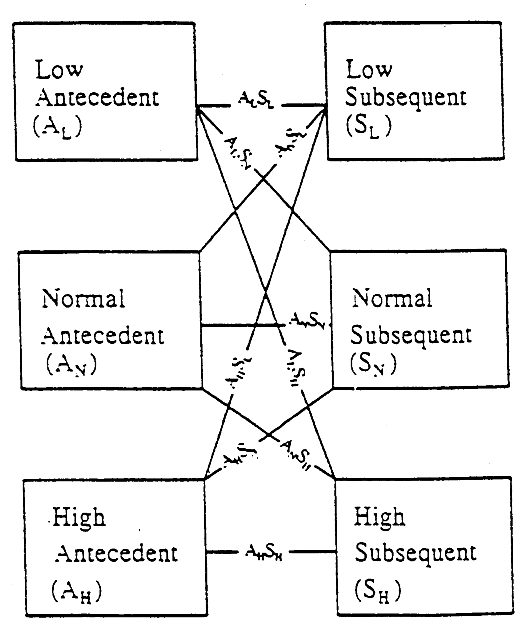

Figure 2. Schematic of the nine subpopulations (represented by the tie-lines) created by grouping the three sets of antecedent rainfall data (one year) with the three sets of subsequent rainfall data for a given n-month period.

This is accomplished by determining whether the mean A_LS_N NPR value for a designated n-month period is significantly lower than the mean A_NS_N NPR value for that period. Conversely, there is less value in comparing mean A_LS_N NPR values with mean A_NS_L or A_NS_H NPR values because subsequent as well as antecedent rainfall conditions are different.

This procedure is believed to be robust in that it "normalizes" for the effects of subsequent rainfall in two ways. First, a runoff/rainfall ratio rather than a non-processed or "raw" runoff value is used. Second, the manner in which the nine subpopulations were grouped explicitly accounts for the effects of subsequent rainfall. This procedure also permits a limited means of testing for the "persistence" of various antecedent conditions. For instance, the question of how long a drought will effect subsequent runoff can be addressed using these methods. Let us hypothesize that a drought will only effect runoff for one year following the return of normal rainfall. If this was the case, the mean A_LS_N $NPR_{24\text{-month}}$ value should approach unity and not be statistically different from the A_NS_N $NPR_{24\text{-month}}$ value while the mean A_LS_N $NPR_{12\text{-month}}$ value should be both less than unity and significantly less than the mean A_NS_N $NPR_{12\text{-month}}$ value.

The following procedures were used to determine the significance of differences between mean NPR values for the nine subpopulations. First, the set of NPR values for each subpopulation were tested for "normalcy" using the standard deviation/range ratio method (95% confidence interval) described by Sachs (1984). It was determined from this analysis that ~30% of the 36 test-populations (9 subpopulations x 4 n-months periods for each subpopulation) were non-normally distributed even after several outliers (NPR values considerably greater than 2.0) were removed. Therefore, the Wilcoxon-Mann-Whitney (WMW) test (95% confidence interval) which is essentially the non-parametric analog of the Students-t test was used for comparison of the means for a given n-month period. For purposes of brevity, only two cases are discussed in this paper. These involve the effects of lower and higher than normal rainfall upon runoff given the return to normal rainfall.

DISCUSSION

Effects of low antecedent rainfall followed by normal rainfall

This hypothesis is designed to test the effects of below-normal rainfall upon subsequent runoff and is perhaps the most important issue in terms of water planning. Specifically, is streamflow affected by antecedent drought conditions, once rainfall returns to normal? If so, how long do these "memory" effects persist?

Normalized production ratios between six months and one year following a period of below-normal rainfall are significantly lower than when normal antecedent rainfall conditions prevail (Figure 3). Mean NPR values for the A_LS_N $_{6\text{-month}}$ and A_LS_N $_{12\text{-month}}$ subpopulations are 0.66 and 0.81 respectively. Mean NPR values for the A_NS_N were near unity (0.96 and 1.09) for these respective periods, as would be expected. Interestingly, mean A_LS_N NPR values progressively increase to near-unity following the one-year period after the return of normal rainfall intensities. The 24-month A_LS_N NPR value is 0.95 indicating that two years of normal rainfall conditions is sufficient for Georgia Coastal Plain watersheds to nearly recover from antecedent drought conditions.

It seems logical that below-normal antecedent rainfall would not appreciably effect "quickflow" discharge. Rather these results suggest that given an end to drought conditions, approximately one to two years are required for water table conditions to return to their pre-drought normal position. We might infer that between one or two years are required for localized ground-water flow systems Atkins et al. (1996) to return to normal following the end of deficit rainfall conditions.

The effects of above-normal antecedent rainfall followed by a return to normal rainfall

What are the effects of above-normal antecedent rainfall conditions upon Coastal Plain runoff after the return to normal rainfall? Above-normal rates of antecedent rainfall (residual values of 15-59% greater than normal) resulted in mean NPR values that were between 17 and 25% greater than normal (Figure 4). In all cases, with the exception of the 12-month subsequent period, mean A_HS_N NPR values were significantly higher than related mean A_NS_N NPR values (WMW test, 95% confidence interval).

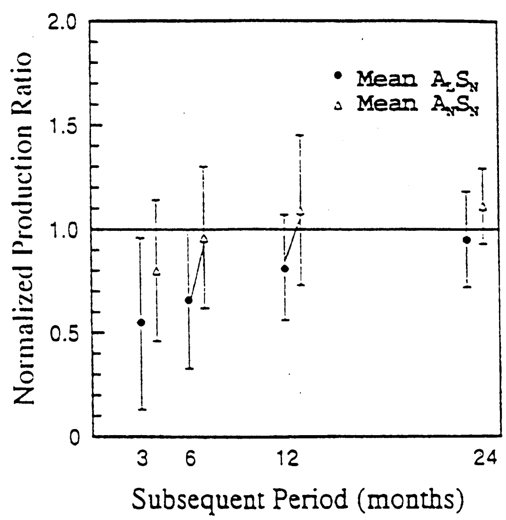

Figure 3. Comparison of mean A_LS_N and A_NS_N NPR values for periods 3-24 months subsequent to the antecedent period. The error bar indicates ± one standard deviation about the mean. A connecting diagonal line indicates that the mean values are significantly different (WMW test, 95% C.I.).

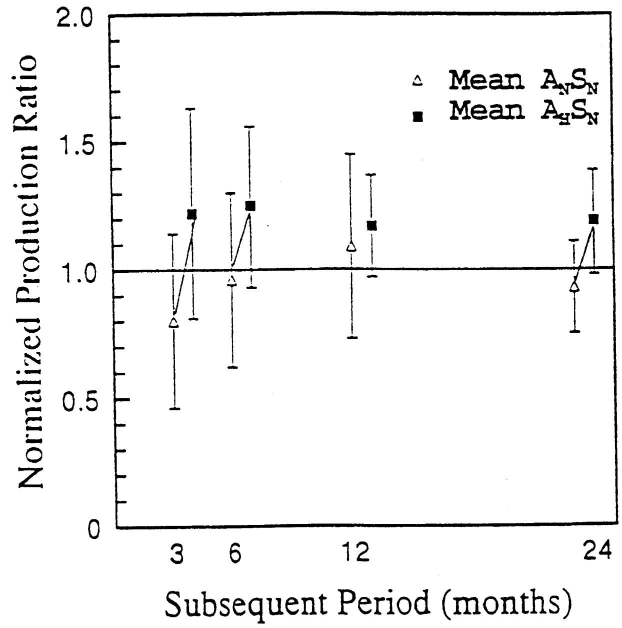

Figure 4. Comparison of mean A_HS_N and A_NS_N NPR valuesfor periods 3-24 months subsequent to the antecedent period.The error bar indicates ± one standard deviation about the mean. A connecting diagonal line indicates that the mean values are significantly different (WMW test, 95% C.I.).

The response the Georgia Coastal Plain made to excess antecedent rainfall was different from that which it made to deficit rainfall. Excess rainfall resulted in mean NPR values that were ~20-25% greater than unity while below-normal antecedent rainfall resulted in mean NPR values that were between 20-40% less than unity during the first year following the return to normal rainfall conditions. We have previously observed that the effects of drought were mitigated between one and two years following the return to normal precipitation. Conversely, mean A_HS_N NPR values were ~20% greater than unity two years after the return to normal rainfall. This likely indicates that excess rainfall has the effect of elevating hydraulic gradients to a limited extent (thereby causing increased rates of baseflow) for many years following a return to normal rates of rainfall.

SUMMARY AND CONCLUSIONS

A method has been presented in which the effects of regional antecedent rainfall conditions upon subsequent stream runoff can be evaluated. This method were used to analyze long term (47 years) rainfall-runoff relationships within the Coastal Plain of Georgia. One of the most important findings was that stream runoff (measured by the "production ratio") returns to near-normal between 1 and 2 years following a drought, given a return to normal rainfall conditions. This possibly represents the period of time required for local ground-water flow systems to return to normal conditions following a drought. Conversely, production ratios associated with excess antecedent rainfall remain considerably greater than normal for a period of at least two years following a return to normal rainfall. Water planners in Georgia could benefit from an awareness of these and other "memory" effects.

LITERATURE CITED

Atkins, J.B., C.A. Journey, and J.S. Clarke J.S. 1996. Estimation of ground-water discharge to streams in the Central Savannah River Basin of Georgia and South Carolina. US Geol. Surv. Water-Resources Investigations Report 96-4179.

EarthInfo, Inc., 1995. Database guide for EarthInfo CD^2 NCDC, Summary of the Day. CD-ROM.

EarthInfo, Inc., 1996. EarthInfo CD^2 Reference Manual for USGS Daily Values. CD-ROM.

Sachs, L. 1984. *Applied Statistics, 2nd ed.* Springer-Verlag, New York.