

Is Baseflow Decreasing in Southeast Pennsylvania?

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Abstract

Rapid land development in portions of Pennsylvania (PA) is raising concern not only for the effects of stormwater discharges on stream integrity and biota, but also for the ability of developed watersheds to sustain adequate baseflow during periods of drought. Research is needed to document such effects, as well as to examine the mechanisms and parameters controlling the low-flow response of small watersheds subject to the combined stresses of land development, drought, and groundwater withdrawal. This paper reports on a preliminary study examining long-term streamflow records from unregulated watersheds in urbanizing areas of southeast PA. Results indicate that although stormflow volumes are increasing, the expected complementary effect of declining baseflow volumes due to reduced recharge associated with land development is not readily observable in the streamflow records. Possible reasons include: land development density is below a threshold at which effects are observable, increased delayed drainage from bank storage and detention basins resulting from higher stormflows, declines in basin evapotranspiration, increasing point discharges, and increasing volumes of leakage from sewer systems.

Introduction

Urbanization has been widely shown to have significant deleterious impacts on the integrity of small streams, largely due to increased magnitude and duration of flood events that bring increased erosion and sedimentation. Ongoing land development surrounding the major urban centers of Pennsylvania (PA) and other areas of the eastern U.S. is also raising a concern that reductions in groundwater recharge due to increased runoff from impervious surfaces may compromise the ability of small watersheds to sustain baseflow during drought. A few published studies have shown decreases in baseflow over time due to urbanization (e.g., Klein, 1979; Simmons and Reynolds, 1982). Further research is needed to examine if baseflow volumes are declining throughout the region, and whether some areas are more susceptible than others, based on factors such as geology, land use patterns, and groundwater use. This paper reports preliminary results of an analysis based on hydrograph separation of long-term streamflow records from watersheds in southeast PA, a region that has experienced rapid population growth and land development over the past 40-60 years. Results are interpreted in terms of changes in annual baseflow volumes and annual runoff ratios over time.

Methods

Basin selection. USGS streamflow gage data was chosen based on four criteria. First, gages selected were located in areas of high population density (> 500 persons/ mi² based on 2000 county census data) and rapid population growth during the period of streamflow record. This includes suburban counties north and west of Philadelphia (Bucks, Chester, Delaware, Montgomery) and the Lehigh Valley (Lehigh and Northampton Counties). Second, daily

streamflow records of at least 30 years length were selected so that temporal changes in baseflow would be distinguishable from variations due to changes in annual precipitation. Third, watershed area was limited to approximately 80 mi² (200 km²) to reduce within-basin heterogeneity of watershed parameters with strong effects on baseflow (e.g. geology). Fourth, basins with significant known anthropogenic influences, such as regulated reservoirs, were eliminated from consideration. This was determined based on published data (White and Sloto, 1990) and review of topographic maps of the watersheds. Using these criteria, seven stream gages were chosen for hydrograph analysis, as summarized in Table 1. Of these seven, four (Little Lehigh, Monocacy, Chester, Skippack) were considered likely to show a hydrologic impact of development, based on their relatively high population density. The other three were retained for comparison purposes. Geologic information is also included in Table 1, as previous research has shown the dominant influence of geology on baseflow (e.g., Hely and Olmsted, 1963; Farvolden, 1963; White and Sloto, 1990).

Table 1. Summary of gages/watersheds used.

Stream	USGS Gage	Dates (WY)	Watershed Area (mi ²)	2000 Pop Dens (/mi ²)	Watershed Geology ⁽¹⁾
-- Great Valley Physiography --					
Little Lehigh Creek	1451500	1946-2001	80.8	620	Carbonate
Monocacy Creek	1452500	1949-2001	44.5	670	Carbonate & Shale (Martinsburg fm)
Jordon Creek	1452000	1945-2001	75.8	210	Shale (Martinsburg fm) & Carbonate
-- Piedmont Physiography --					
Chester Creek	1477000	1932-2001	61.1	1370	Crystalline
Skippack Creek	1473120	1966-1994	53.7	990	Shale (Brunswick fm)
W Br Brandywine Cr	1480300	1961-2001	18.7	240	Crystalline
French Creek	1472157	1969-2001	59.1	180	Shale/Sandstone (Stockton fm) & Crystalline

Notes: (1) based on Berg et al. (1980)

Baseflow separation. A baseflow separation method is necessary to separate the streamflow records into direct storm runoff and baseflow. A variety of automated computer methods are available for separating continuous hydrographs (Nathan and McMahon, 1990; Arnold and Allen, 1999). Because the USGS HYSEP program (Sloto and Crouse, 1996) has been used previously in this region and is well documented, it was selected for this study. The local-minimum method was used in HYSEP to perform the hydrograph separations. The fixed-interval and sliding-interval methods were also investigated, and it was found that the results of the study (i.e., trends in baseflow volumes and runoff ratios) were not affected by the method chosen.

Interpretation of results. For each year, the streamflow volume (in) was divided into stormflow (SF) and baseflow (BF), and the log of these volumes were plotted vs. time. Log-transformed data were used because streamflow is approximately log-normally distributed. Because random variation in precipitation results in high variability in baseflow from year to year, the 5-year moving average was also determined and plotted. Additional plots of runoff ratios (BF/P, SF/P) were also generated. For these plots, precipitation data are from Allentown (ABE airport) for the Lehigh Valley watersheds, or Philadelphia (PHL airport) for the remaining watersheds. For the preliminary study, trends were assessed based on the slope of a linear regression. Slopes were considered significant if the associated Pearson correlation coefficient (R) exceeds a critical value determined by the two-tailed t-test (McCuen, 1985) at a 5 percent level of significance. As the record length increases, identified regression slopes are significant at lower R values.

Results and Discussion

Table 2 summarizes the results of the baseflow separations. For each gage, the baseflow and runoff ratio trends are identified as positive or negative (based on the linear regression), and an indication of significance is given. Boxed cells indicate significant trends. Plots of annual baseflow volumes as well as runoff ratios vs. time are shown for select gages in Figures 1 through 3 to illustrate the range of results.

Table 2. Summary of results for the selected gages.

Stream	log BF vol Trend ⁽¹⁾	R Signif ? (P<0.05)	BF/P Trend	R Signif ? (P<0.05)	SF/P Trend	R Signif ? (P<0.05)	SF/BF Trend	R Signif ? (P<0.05)
Little Lehigh	+	N	+	N	+	Y	+	Y
Monocacy	+	Y	+	N	+	N	+	N
Jordon	+	N	+	N	+	N	+	N
Chester	+	Y	+	Y	+	Y	+	N
Skippack	+	N	+	Y	+	N	-	N
W Br Brandywine	+	Y	+	Y	+	N	-	N
French	-	Y	+	N	+	N	-	N

Notes: (1) based on 5-yr moving average of the data
 BF = baseflow volume; SF = stormflow volume; P = precipitation volume

Several important points can be made based on the table and figures. The first is that in many cases the identified slopes are not statistically significant (i.e., the magnitude of the slope is small relative to the magnitude of variation in the record), indicating that the effects of development on baseflow as measured at the selected gages are relatively mild. Second, although there are periods of negative trends within the record (e.g., late 1940s through the drought of the mid-1960s in Little Lehigh Creek – see Figure 1), baseflow is generally not decreasing over the long-term, although stormflow is apparently increasing as expected. In fact, in many cases the slopes of the stormflow and baseflow regressions are remarkably similar, indicating that the two processes are coupled (the Chester Creek data shown in Figure 2 is a good example). One explanation is that more frequent flood conditions and higher stream stages leads to more bank storage that subsequently drains back to the stream following the storm. This bank storage

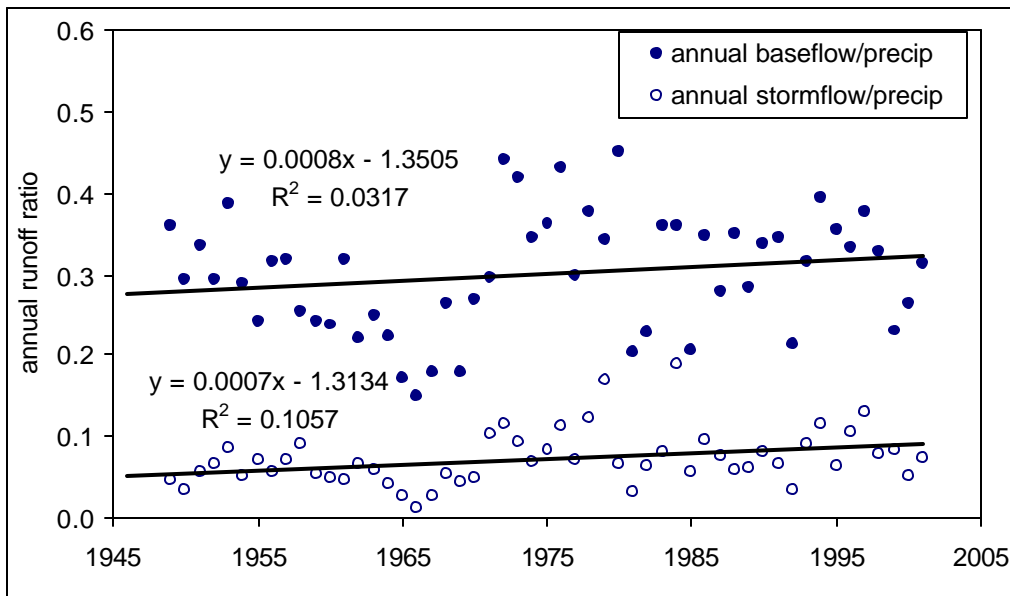
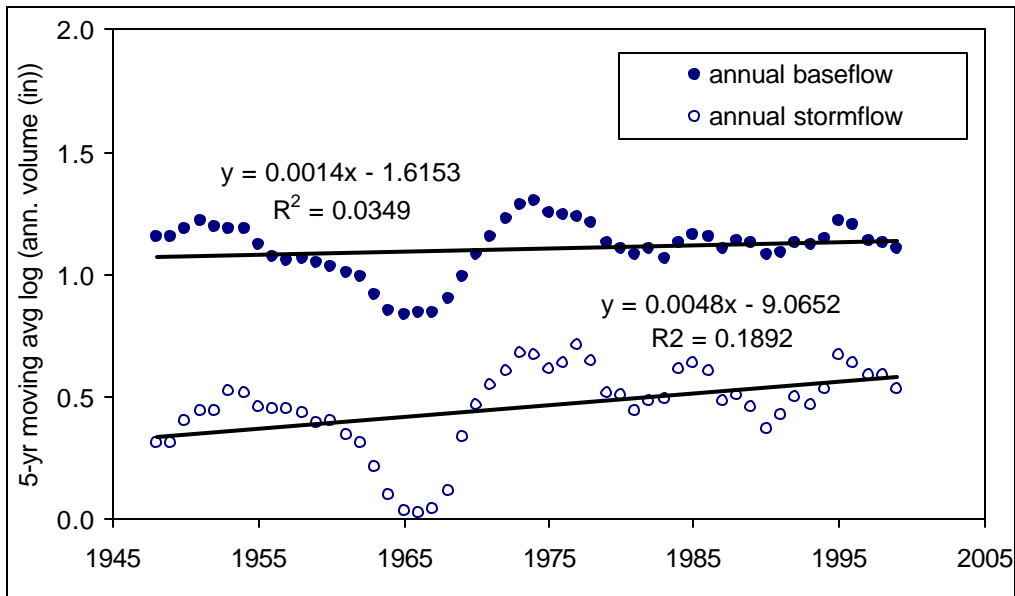


Figure 1. Five-year moving average baseflow volumes and runoff ratios for Little Lehigh Creek, Lehigh County. Precipitation data from Lehigh Valley Airport (ABE). Note the pronounced effect of drought in the mid-1960s and wet conditions in the early-1970s on baseflow in this carbonate watershed.

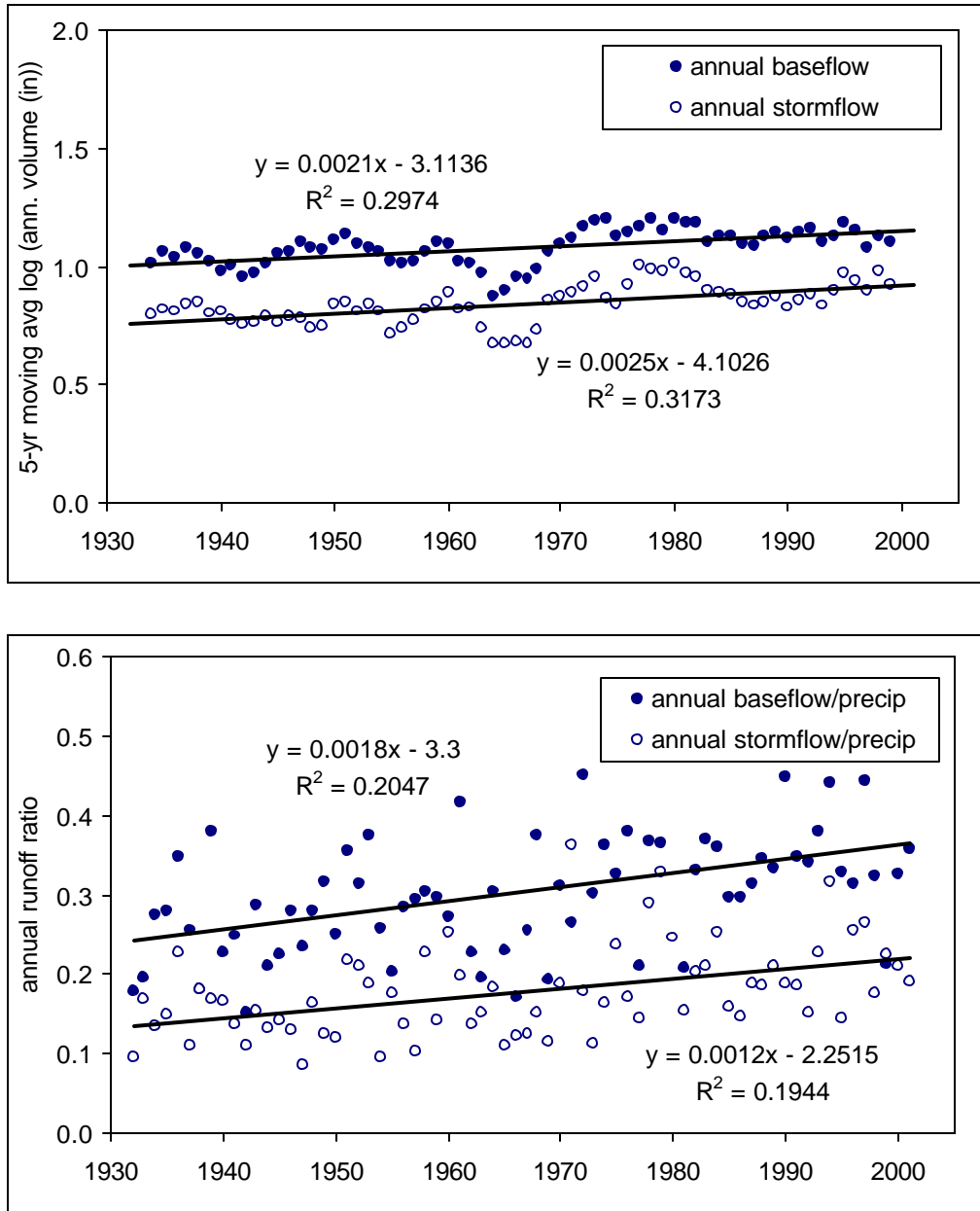


Figure 2. Five-year moving average baseflow volumes and runoff ratios for Chester Creek, Chester County. Precipitation data from Philadelphia Airport (PHL). Note the similar trends in stormflow and baseflow.

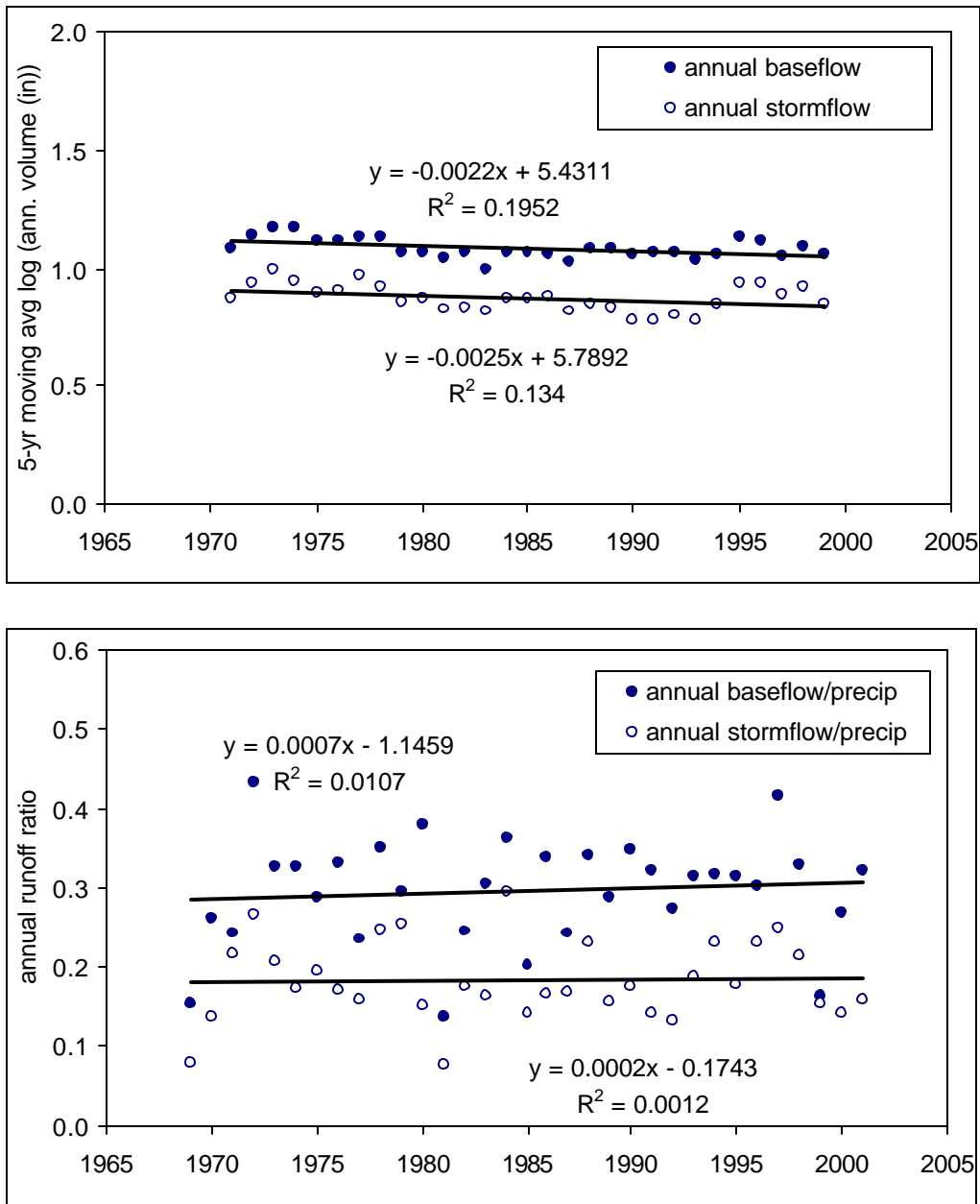


Figure 3. Five-year moving average baseflow volumes and runoff ratios for French Creek, Chester County. Precipitation data from Philadelphia Airport (PHL). The decline in annual baseflow volumes is removed when normalized by annual precipitation.

mechanism is a well-known component of baseflow (Kunkle, 1962) for streams with broad floodplain deposits. Such behavior would also be mimicked by the slow release of water from detention basins in use over the last two decades.

The finding of unchanged or increasing baseflow while stormflow is increasing may seem counterintuitive; however, the hydrologic impacts of development can be complex. Increases in runoff at the local scale may not always transfer to an observable effect at the watershed level as measured at an outlet streamgage. First, the landscape is heterogeneous, and unless conveyed directly to the stream, runoff at one location may infiltrate at another - particularly in areas where the density of development is low. Second, the pattern of development relative to the hydrologic functioning of different portions of the watershed must be considered. For example, development distributed in lower elevation, discharge portions of a basin is likely to have less effect on groundwater recharge as development in upland recharge areas. These patterns of development are typical of the Lehigh Valley watersheds investigated. Furthermore, the reduction in evapotranspiration as forested and agricultural land is converted to subdivisions would tend to moderate the loss of infiltration and recharge.

Other possible explanations include increasing anthropogenic effects such as artificial recharge due to leaky sewer systems, and artificial baseflow due to increased wastewater/process water discharges (gages cannot differentiate between baseflow that derives from basin-wide infiltration and recharge, and baseflow that results from continuous discharges to the stream). These impacts would be particularly significant where the water supply is outside the watershed. Such issues require further investigation, but it is clear that the assumption that increasing stormflow is accompanied by decreasing baseflow should be examined more carefully.

Conclusions

The results of the study suggest that baseflow has not systematically decreased in developing areas of southeast PA over the last 30-60 years. Rather, the streamflow records consistently show similar trends (unchanged to increasing) in both stormflow and baseflow. Possible hydrologic reasons include that land development density is still below a threshold at which effects are observable, increased drainage from bank storage and detention basins resulting from higher stormflows, and declines in basin evapotranspiration. Possible anthropogenic reasons include increasing point discharges to the streams, and increasing volumes of leakage from sewer systems. Work is ongoing to examine these issues.

Limitations

There are three principal limitations to the preliminary results reported here. First, additional and more robust statistical tests (e.g. nonparametric trend tests) need to be performed to better quantify the significance of the trends observed in the records. Second, more detailed information on direct anthropogenic effects (discharges and withdrawals) on streamflow in the watersheds needs to be gathered and assessed. Large-scale commercial/industrial water pumping and export from/import to the subject watersheds could have a significant effect on baseflow. Industrial discharges will tend to mask the effects of land development by providing a “baseflow” unrelated to infiltration and recharge. Third, additional data needs to be gathered (e.g., population changes over time, changes in water supply/sewerage, imperviousness) to better characterize the history of development of the watersheds in relation to the observed trends.

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