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EFFECTS OF IMPERVIOUS AREA AND BMP IMPLEMENTATION AND DESIGN ON STORM RUNOFF AND WATER QUALITY IN EIGHT SMALL WATERSHEDS[1]

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ABSTRACT: The effects of increases in effective impervious area (EIA) and the implementation of water quality protection designed detention pond best management practices (BMPs) on storm runoff and stormwater quality were assessed in Gwinnett County, Georgia, for the period 2001-2008. Trends among eight small watersheds were compared, using a time trend study design. Significant trends were detected in three storm hydrologic metrics and in five water quality constituents that were adjusted for variability in storm characteristics and climate. Trends in EIA ranged from 0.10 to 1.35, and changes in EIA treated by BMPs ranged from 0.19 to 1.32; both expressed in units of percentage of drainage area per year. Trend relations indicated that for every 1% increase in watershed EIA, about 2.6, 1.1, and 1.5% increases in EIA treated by BMPs would be required to counteract the effects of EIA added to the watersheds on peak streamflow, stormwater yield, and storm streamflow runoff, respectively. Relations between trends in EIA, BMP implementation, and water quality were counterintuitive. This may be the result of (1) changes in constituent inputs in the watersheds, especially downstream of areas treated by BMPs; (2) BMPs may have increased the duration of stormflow that results in downstream channel erosion; and/or (3) spurious relationships between increases in EIA, BMP implementation, and constituent inputs with development rates.

(KEY TERMS: stormwater management; best management practices; urbanization; impervious area; detention ponds; storm runoff; peak storm flow; nonpoint source pollution.)

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INTRODUCTION

Urbanization and, in particular, the associated increases in impervious area (IA) have been shown to have a great impact on rainfall-runoff relations (*e.g.,* Leopold, 1968; Hollis, 1975; Ogden *et al.*, 2011) and stream quality (Schueler, 1994; Schueler *et al.*, 2009). IAs include buildings and transportation infrastructure such as roads, parking lots, and sidewalks. Some of the more important impacts of increased IA on hydrology (Jacobson, 2011) include (1) increased storm runoff, peak discharges, and flood flows (Leopold, 1968), (2) increased storm flashiness —higher peak storm-flow response with a shorter duration (Seaburn, 1969; Graf, 1977) and decreased lag time between precipitation and peak discharge (Espey *et al.*, 1966), (3) increased recurrence interval

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of floods, especially small floods (Hollis, 1975), and (4) decreasing rainfall infiltration and groundwater recharge rates, resulting in lower stream base flow (Simmons and Reynolds, 1982). More frequent and higher magnitude flooding can also increase erosion and transport of land surface and stream sediments and associated pollutants, altering stream-channel stability and affecting surface water quality. For example, Joiner *et al.* (2014) indicated that in the small urban watersheds studied, the majority of suspended sediment was transported by the few largest storms of the year. Decreases in rainfall infiltration reduce groundwater availability and the stream base flows necessary for ecological services (*e.g.*, Poff *et al.*, 1997; Swirepik *et al.*, 2015); both of which can become critically important during periods of drought. Many studies have also shown that the impacts of urbanization on the flow regime may decrease stream biological richness (*e.g.*, DeGasperi *et al.*, 2009) and that native stream biota is best adapted to natural, unimpacted streamflows (Richter *et al.*, 1996, 1997).

The relationship between the overall size and spatial patterns of IA and stream hydrology is complex (MacDonald, 2000). Yang *et al.* (2010) indicated that a watershed IA of 3 to 5% can have a significant influence on stream hydrology, and Booth and Jackson (1997) indicated that the effects of IA become readily measurable when impervious coverage is greater than 10%. McMahon *et al.* (2003) showed that the effects of IA on hydrologic response were lower when areas were more fragmented. The connectedness of IAs to the drainage network also affects hydrologic response. Landers *et al.* (2007) showed that watersheds with IAs within a 25-foot stream buffer ranging from 1.6 to 4.4% of watershed area appeared to affect base flow and storm flow. Shuster *et al.* (2005) defined an effective IA (EIA) as including only IAs that are directly connected to the stream network as opposed to areas that drain to pervious areas. Furthermore, there are many other factors within a watershed that affect rainfall-runoff relations, such as basin slope (Liu *et al.*, 2006), vegetative cover (Leopold, 1968), drainage area size and network configuration, soil types and depths, bedrock geology, soil and aquifer hydraulic conductivities, and climate.

Many hydrologic metrics have been defined to quantify variations in hydrologic responses and are typically derived from daily average streamflow data. These include various permutations of occurrence (frequency, duration, and duration range) of low and high daily flows, frequency and average rates of change in rising and falling portions of the hydrograph, measures of flashiness, and magnitude and timing of annual minimum streamflows of various durations (Richter *et al.*, 1996, 1997, 1998; Baker *et al.*, 2004; DeGasperi *et al.*, 2009). Many of these metrics are sensitive to climatic patterns and watershed size, and require similar climatic conditions or longer periods of quantification to make unbiased comparisons between watersheds or time periods.

Stormwater management best management practices (BMPs), also known as stormwater management controls, are used to reduce and mitigate the effects of urban development and land use on stream hydrology and water quality. Stormwater management BMPs include both structural controls, those constructed or installed on site (*e.g.,* stormwater detention ponds and wetlands, infiltration basins, bioretention cells, grass swales, and diversion structures); and nonstructural controls, procedural changes such as modifications in construction codes, landscape practices (*e.g.*, stream buffers and rain gardens) and reducing pollutants (*e.g.*, product substitution and reducing fertilizer applications; National Research Council, 2009).

The effectiveness of stormwater management BMPs has been assessed in many studies, and BMPs have been shown to decrease flood peak discharges (*e.g.,* Soong *et al.*, 2009; Gebert *et al.*, 2012), decrease sediment and nutrient loads (*e.g.,* Park *et al.*, 1994; Inamdar *et al.*, 2001), and increase infiltration (*e.g.,* Ku *et al.*, 1992). Most studies have assessed the effectiveness of individual BMPs, while other studies have employed a watershed approach (*e.g.,* McCuen, 1979; Hess and Inman, 1994; Emerson *et al.*, 2005) to determine the overall effectiveness of a network of BMPs, including the downstream impacts of changes in runoff from the BMPs. Studies typically use one or more design strategies, including (1) monitoring above and below BMPs, (2) time trend designs, and (3) paired watershed designs (*e.g.,* Spooner *et al.*, 1985). The effects of climatic variability and other processes occurring within a study area often obscure assessments of BMP effectiveness, and these fluctuations need to be either averaged out, requiring a long monitoring period, or be removed via modeling.

Gwinnett County, Georgia, is a densely populated (about 710 people per km^2 in 2009, U.S. Census Bureau, population of Gwinnett County, Georgia. *Accessed* October 20, 2011, http://quickfacts.census.gov/qfd/states/13/13135.html.), suburban county of the Atlanta metropolitan area. The county has undergone rapid population growth since 1980, and land use has changed from what was once predominantly agriculture and forest to a highly developed area. The U.S. Geological Survey (USGS), in cooperation with Gwinnett County Department of Water Resources, established a comprehensive long-term streamflow and water quality watershed monitoring program in 1996 to estimate streamwater pollutant loads and assess effects of urbanization on stream hydrology and water quality (Landers *et al.*, 2007; Joiner *et al.*, 2014). Landers *et al.* (2007) and Joiner *et al.* (2014) have shown that variations in hydrologic response and water quality between 12 of the county watersheds are related to both their watershed percent EIA and basin slope.

Gwinnett County has a stormwater management plan that incorporates structural BMPs consisting mostly of wet, dry, and dry-extended detention ponds and constructed wetlands. Older detention ponds were designed to mitigate peakflows and were not particularly effective in providing water quality or channel protection. In January 2001, new rules took effect such that all new detention ponds would be constructed with water quality protections (*e.g.,* Whipple *et al.*, 1987); which include the implementation of vegetation and higher pond outlet designs to retain sediment with design efficiencies of 50 to 80%, depending on BMP type, and inlet engineering controls to improve pond oxygenation, and are required to provide 24-h detention of runoff for a storm with a one-year return interval (a storm with a size that is likely to occur only once per given year; Gwinnett County Department of Planning and Development, 2006).

Purpose and Scope

The purpose of this analysis is to assess the effects of urbanization (specifically the effects of increases in EIA), the effectiveness of detention pond BMPs, and the 2001 implementation of water quality protection design requirements for detention ponds, on storm runoff and stormwater quality in eight small watersheds in Gwinnett County for the period 2001 to 2008. A watershed approach was used to determine the overall effectiveness of the county's BMP program. A time trend study design was implemented, comparing trends in storm hydrologic metrics, storm composite water quality concentrations, watershed EIA, and BMP implementation across the eight watersheds.

METHODS

Overview

A time trend study design was necessary, as the period prior to the BMP design changes was not monitored and the rapid growth and urbanization in Gwinnett County resulted in continuous increases in EIA and BMP implementation throughout the study period. Trends were compared across the eight watersheds to distinguish relationships between the various trends as there was no control watershed where few to no BMPs were being implemented for comparison. In order to assess changes in storm hydrologic response and water quality with respect to changes in EIA and BMP implementation, the changes and trends of these variables need to be quantified and compared. The lack of a control watershed requires sufficient variability in trends in EIA and changes in BMP implementation rates amongst the eight watersheds to be able to distinguish their impacts.

The interpretation of the various metrics is complicated in that increases in EIA due to development are synchronous with BMP implementation. Although they are expected to have opposite impacts on storm runoff and water quality, if these variables are well correlated across watersheds, it would be impossible to distinguish the impacts of these variables independently. Other challenges to the study are the use of a time trend design, rapid changes in urbanization and BMP implementation, and a relatively short study period. Addressing these challenges necessitated the removal of the effects of storm characteristics and climatic variability on storm hydrologic and water quality responses to better identify and quantify any trends and then relate these trends to impacts of EIA and changes in BMP implementation.

Hydrologic events were identified from the streamflow hydrographs and using hydrograph separation techniques. Three storm hydrologic metrics were determined, peak streamflow, storm streamflow runoff, and stormwater yield (storm streamflow runoff divided by storm precipitation), to quantify the effects of urbanization on storm hydrologic response. Trends in these storm metrics accounted for climatic variability using pre-event base-flow and storm precipitation characteristics. Trends in water quality were determined while accounting for base-flow and storm runoff characteristics. Effective IA trends were determined from multiple IA spatial datasets from 2000-2009. Numbers of detention pond BMPs and their characteristics (size and locations) were determined for snapshots in 2001 and 2008, with the 2001 snapshot representing the period before changes in the detention pond design rule. The trends in EIA and rates of change in EIA treated by BMPs were then compared to trends in storm hydrologic response and water quality across the eight watersheds to identify significant interrelationships between these variables. All trends were treated as linear, due to the relatively short time period of the analysis and that EIA treated by BMPs was determined only for 2001 and 2008; and were compared on a per-year rate basis to account for some differences in time periods of some of the trends.

Description of Monitored Watersheds

Gwinnett County is located in north-central Georgia, centered about 25 km northeast of Atlanta (Figure 1). The county, which encompasses about 1,130 km^2, is located in the Piedmont physiographic province, a region that has undergone widespread severe erosion (Trimble, 1975). The geology of the county is a mixture of complex and varied metamorphic rocks (USGS, mineral resources online spatial data, geologic units in Gwinnett County, Georgia. *Accessed* May 16, 2014, http://mrdata.usgs.gov/geology/state/fips-unit.php?code=f13135.).

Gwinnett County has a humid, subtropical climate characterized by warm, humid summers and cool, wet winters. Mean annual precipitation is about 1,390 mm and is fairly evenly distributed throughout the year (1981-2010 30-year average for Norcross station USC00096407, National Oceanic and Atmospheric Administration, National Climatic Data Center, U.S. climate normals. *Accessed* May 1, 2014, http://www.ncdc.noaa.gov/oa/ncdc.html.). Winter rainstorms are characterized by long duration, even distribution, and typically low-intensity frontal systems. In contrast, spring and summer rainstorms are characterized by short duration, unevenly distributed, intense convective thunderstorms. Mean annual evapotranspiration, ignoring the effects of urbanization, is estimated to account for about 50 to 60% of the annual precipitation in the study area (Sanford and Selnick, 2013). The seasonal pattern of evapotranspiration results in declining base flows throughout the growing season (April-September) and progressively increasing base flows from event recharge during the dormant season (November-February; Joiner *et al.*, 2014). The county experienced severe to exceptional drought conditions for much of 2007 and 2008 (U.S. Drought Monitor. *Accessed* April 28, 2014, http://droughtmonitor.unl.edu/MapsAndData/MapArchive.aspx (map archive) and http://droughtmonitor.unl.edu/AboutUs/ClassificationScheme.aspx (drought severity classification scheme).).

Gwinnett County is composed predominantly of headwater streams. Eight of the 15 watersheds that are currently monitored by the USGS in Gwinnett County were included in this analysis (Al-Malla, Finding pairs of watersheds to compare the effectiveness of BMPs in Gwinnett County, Gwinnett County Department of Water Resources, Stormwater Division Report, 2012, 5 pp., unpublished report). These

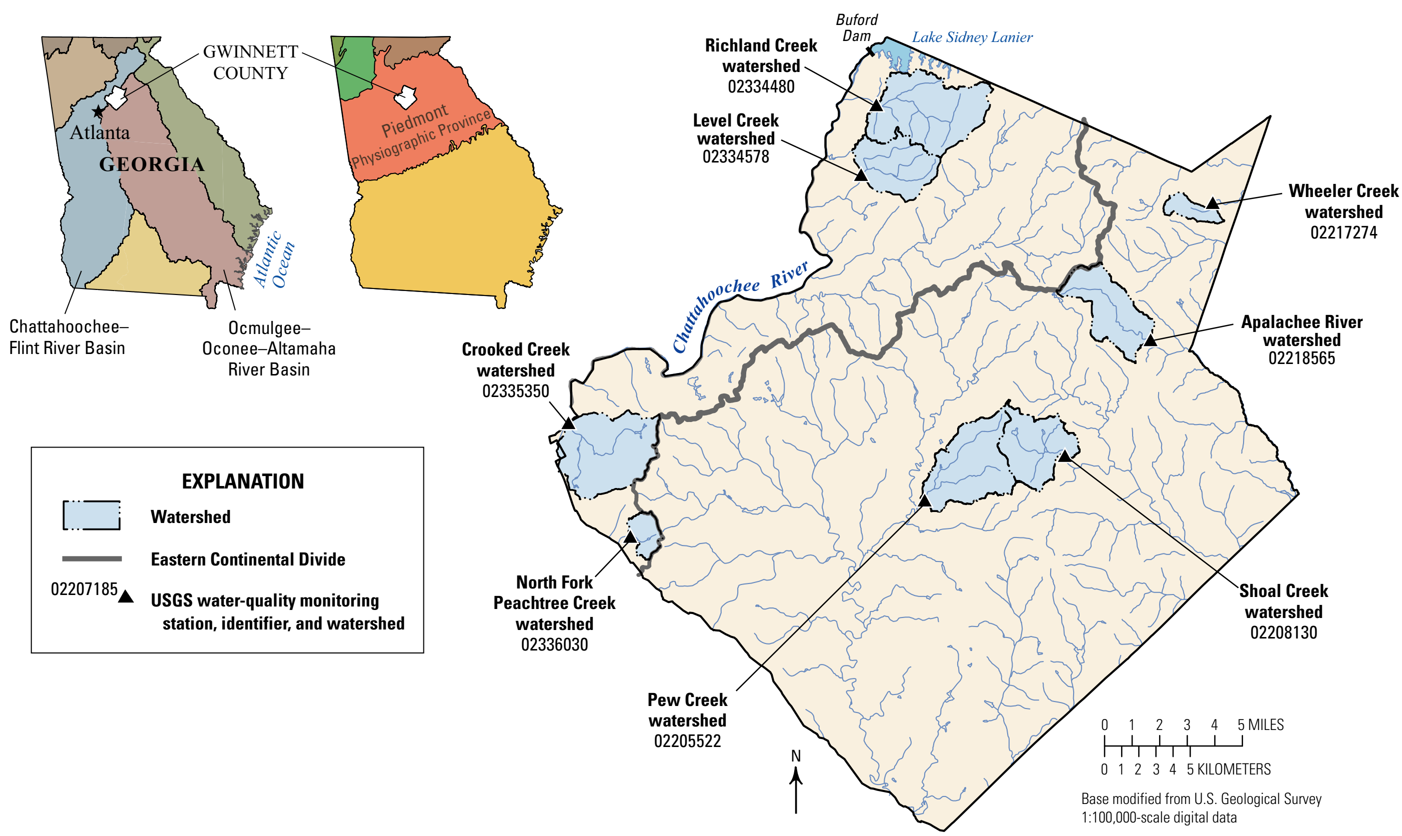

FIGURE 1. Location of the Study Area Showing the Eight Monitored Watersheds and the Monitoring Stations, Gwinnett County, Georgia. USGS, U.S. Geological Survey.

watersheds were selected for their small drainage area size, which better controlled for factors such as the distribution of precipitation within the basin and the distribution of IAs. The eight watersheds ranged in size from 3.39 to 24.2 km^2 (Figure 1 and Table 1), mean elevation ranged from 302.4 to 329.5 m, and basin slopes ranged from 5.3% (North Fork Peachtree Creek watershed) to 12.8% (Richland Creek watershed).

Precipitation, Streamflow, and Water Quality Monitoring

Watersheds were monitored at their outlets for precipitation, streamwater stage and discharge, and water quality. The months that precipitation, streamflow, and water quality monitoring began are summarized in Table 1. Precipitation was measured at 15-min intervals, using self-calibrating tipping bucket rain gages that measure precipitation in 0.254 mm (0.01 inch) increments. Stage is recorded every 15 min to the nearest 3.05 mm (0.01 foot) and streamflow is calculated by following standard USGS protocols for measuring stage, making streamflow measurements, and developing a stage-discharge relation to compute discharge (Rantz *et al.*, 1982a, b).

From 2001-2009, there were occasional issues with the 15-min "unit value" streamflow where stage data were compromised or missing. In these cases, daily average streamflows were typically estimated using a streamflow relationship with a similar nearby watershed. For this analysis, storms were excluded from analysis on days when calculations of daily average streamflow from unit values were not within 10% of published daily average streamflows, or when there was a substantial gap in unit values. Storms were also excluded due to missing precipitation, if they were small (<5.1 mm of precipitation), or if the storm duration was longer than three days.

Particular watersheds had specific longer-term issues with their unit values, which particularly affected measurements during base-flow conditions. The Crooked Creek gaging station was occasionally affected by backwater conditions from the downstream Chattahoochee River during large dam releases that resulted in a false increase in stage and discharge. North Fork Peachtree Creek is a small stream that is susceptible to sediment buildup that can affect stage measurements and alter the stage-discharge relation at low flows, resulting in unreliable base-flow values. Richland Creek watershed contains an upstream sewage treatment plant that released water for extended periods of time during 2006-2009, resulting in variable base flow throughout the day and some minor effects during storms. When any of these issues affected storm hydrographs, they were either removed (if it could be done easily without substantially affecting the hydrograph response), or the storm was excluded from analysis. The effect of these issues on stormwater quality was minimal for Crooked Creek and North Fork Peachtree Creek,

TABLE 1. Eight Gwinnett County, Georgia Watersheds Used in This Analysis, Including Drainage Area, Watershed Mean Elevation, Basin Slope, and Start Month of Monitoring of Precipitation, Streamflow and Stormwater Quality.

USGS Station Number	Station Name (abbreviation)	Drainage Area (km^2)	Watershed Mean Elevation (meters)	Basin Slope (%)	Start Month of Precipitation and Streamflow Monitoring	Start Month of Storm Water Quality Sampling
02218565	Apalachee River at Fence Road, near Dacula, Georgia (APL)	14.7	324.2	8.0	7/2001	8/2004
02335350	Crooked Creek near Norcross, Georgia (CRK)	23.0	302.7	7.7	3/2001	4/2001
02334578	Level Creek at Suwanee Dam Road, near Suwanee, Georgia (LVL)	13.1	324.6	8.6	5/2001	8/2004
02336030	North Fork Peachtree Creek at Graves Road, near Doraville, Georgia (NFP)	3.68	310.9	5.3	6/2001	8/2004
02205522	Pew Creek at Patterson Road, near Lawrenceville, Georgia (PEW)	19.2	308.1	6.9	3/2003	1/2006
02334480	Richland Creek at Suwanee Dam Road, near Buford, Georgia (RCH)	24.2	329.5	12.8	5/2001	9/2004
02208130	Shoal Creek at Paper Mill Road, near Lawrenceville, Georgia (SHL)	14.1	314.1	7.2	10/2005	12/2005
02217274	Wheeler Creek at Bill Cheek Road, near Grayson, Georgia (WHL)	3.39	302.4	7.7	6/2001	9/2004

Note: USGS, U.S. Geological Survey.

as the backwater and sediment issues were rectified during higher storm streamflows. The sewage treatment plant releases in the Richland Creek watershed did not have an obvious effect on trends in water quality. Of the 3,392 storms identified by hydrologic separation, about one-third (1,144 storms) were excluded from analysis due to any of the various reasons noted above.

Six composite storm samples per year were collected at the outlet of each watershed; three in the summer (May through October) and three in the winter (November through April). Sampled storms required a minimum of 7.6 mm of precipitation (average ~22 mm) and there must have been at least 72 h since the end of the previous event. The storm samples were collected using automated samplers, which collected a sample each time a specified volume of water flowed by the station into a single discharge-weighted composite that represented the average constituent concentration during the storm. Sampler volume settings were adjusted in advance of each storm depending on the expected amount of storm runoff (based on predicted precipitation and seasonal base flow) in an attempt to sample the entire storm while also insuring that a sufficient amount of sample was collected for water quality analyses. Due to the difficulty in accurately estimating the amount of storm runoff in advance of the storm along with other technical issues, the storm composite samples did not always fully represent the complete storm hydrograph. Samples were analyzed for total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), total lead (Pb), and total zinc (Zn). Total suspended solids annual loads have been identified in Gwinnett County's Watershed Protection Plan for target performance criterion (Gwinnett County Department of Public Utilities, 2000). Water quality was reviewed and 25 sample concentrations from 16 samples that were substantially greater than the overall concentration-discharge and temporal patterns were removed from the analysis (2.2% of total concentrations). Of these sample concentrations, 23 were greater than two standard deviations (SDs), and 16 were greater than three SDs higher, compared to the mean concentrations for its watershed (including the outliers). These few concentrations would have had undue influence on the regression models used for removing natural variability and on the inherent temporal trends that we are trying to quantify. These concentrations may represent actual conditions, but of conditions ephemeral in nature (*e.g.,* a point source release) that do not represent the long-term effects of urbanization and BMP implementation this study is attempting to quantify.

All precipitation, streamflow, and water quality data used in this analysis are available from the U.S. Geological Survey National Water Information System web interface at http://waterdata.usgs.gov/usa/nwis/nwis using the USGS station numbers in Table 1.

Trends in Storm Hydrologic Metrics

Temporal trends in three storm hydrologic metrics, peak streamflow, storm streamflow runoff (volume, not average discharge), and stormwater yield, were used to assess changes in storm hydrologic response at each watershed. These metrics were selected based on previous studies indicating responses to changes in watershed IA. The metrics were determined from hydrologic events identified from hydrograph separation. Hydrograph separations were performed using the Eckhardt filter (Eckhardt, 2005, 2008), a two-parameter digital filter that provides a consistent, dynamic, and realistic separation; and is detailed in the Supporting Information. The storm streamflow runoff and stormwater yield metrics were determined for the period of the storm, as determined from the hydrograph separations. Trends in these metrics were modeled as a linear time trend. In order to improve the ability to detect changes in the storm hydrologic metrics related to urbanization and BMP implementation, the effects of natural variability in storm precipitation (the main driver controlling storm runoff) and antecedent moisture conditions (which can affect storm runoff response) was accounted for by modeling each metric as a function of various storm precipitation characteristics, the number of hydrograph peaks within a storm and pre-event stream base flow. Both patterns in base-flow conditions and precipitation magnitude and frequency vary with patterns in climate. Due to the severe to exceptional drought the county experienced for much of 2007 and 2008 that corresponds with the end of the study period, it was critical to remove the effects of variations in precipitation and moisture conditions to avoid this climate pattern from inducing trends in the storm hydrologic metrics.

The explanatory variables were selected and fit using a stepwise multiple linear regression approach using the corrected Akaike information criterion (AICc) (Akaike, 1974; Burnham and Anderson, 2002). Time trend variables not included in models due to insignificance were noted and then added to the model so that the magnitude of this fitted value could be determined for later statistical comparisons with trends in EIA and BMP implementation. Further details on the explanatory variables used in the models, the stepwise regression methodology, and a summary of the models developed and explanatory variables incorporated into the models are documented in the Supporting Information.

Water Quality Concentration Trend Analysis

Changes in storm composited concentrations of TSS, TN, TP, Pb, and Zn were assessed similarly to the storm hydrologic metrics, but in this case, accounting for the relationship between streamwater concentrations and storm streamflow response. It was necessary to account for streamflow due to the moderate to strong positive relationships observed between storm composite sample concentrations and storm streamflow for most of the water quality constituents and watershed combinations. This approach results in trends in concentrations that are independent of any changes in hydrologic responses, including those attributed to the trends detected in the storm hydrologic metrics. Further details are documented in the Supporting Information. Trends in concentrations were used to assess changes in water quality due to the difficulties in accurately estimating annual loads from only six storm composite samples per year and in removing annual climatic variability in loads.

In addition to these trends, the effects of the trends in two of the storm hydrologic metrics on water-quality concentrations at each of the watersheds was approximated by quantifying the change in predictions from the water quality models developed previously. The average streamflow and peak streamflow values for each storm composite sample were adjusted for the temporal trends in the stormwater yields and peak streamflows, respectively, to represent values adjusted for trends in 2001 and 2008. Predicted concentrations for each sample were then calculated for 2001 and 2008 by entering the metric trend-adjusted values into the average and peak streamflow variables in the corresponding water quality models. The effects of the storm hydrologic metric trends on water quality at each watershed were then approximated as the average change in concentration of all its storm composite samples.

Trends in EIA

Effective IAs in each watershed were determined from detailed, countywide IA spatial dataset developed to support the Gwinnett County stormwater utility (Gwinnett County Department of Public Utilities, 2009, unpublished data). A spatial dataset with a 1-m^2 grid size was created by digitizing polygons of impervious surfaces from 1:1,200-scale aerial photography. First created in 2000, the dataset was updated in 2005, 2006, 2008, and 2009 using new aerial photography.

Effective IAs are defined as IAs that are adjacent to and contribute directly to the stream drainage network, as opposed to IAs further away from the streams where runoff would more likely result in infiltration into adjacent soils. Therefore, EIAs were approximated by designating EIAs based on land coverage type and the likelihood of elements within that coverage type to contribute runoff directly to streams. Transportation element polygons that were also designated impervious (such as roads, parking lots, driveways, and sidewalks) along with all building elements were designated as EIAs, as runoff from these features predominantly drain directly to the stream drainage network due to the presence of storm drainage systems predominant in high-density developed areas. IAs from other land covers, such as recreational areas, structures, and utilities were not designated as EIAs, as the IAs within these features tended to be more isolated and disconnected from direct drainage pathways. Because not all buildings are necessarily directly connected to the stream drainage network, for example in medium density residential areas, EIA is likely overestimated, but was consistently determined for all watersheds and should be an improvement over using just IA. Linear trends in EIA were determined for each watershed by regressing the area of EIA *vs.* year for the five years of data between 2000 and 2009 and the statistical significance was assessed ($p < 0.05$).

Detention Pond Characterization and Changes

A dataset of detention ponds and their characteristics in the eight watersheds were compiled using a combination of GIS inventories and county records, and is detailed in the Supporting Information. The EIA treated by BMPs was used as the metric to assess the effectiveness of BMP implementation in this study due to the importance of EIAs on storm runoff and water quality. The EIA treated metric includes not only the newly constructed IAs, for which the detention ponds were designed, but also for any other existing EIAs within the drainage of the BMPs. Detention ponds constructed since 2001, are designed to detain water from a one-year return interval storm for a 24-h period. As most storms are smaller that this design storm, BMPs have, to varying extents, the capacity to mitigate additional IAs within their drainages depending on storm characteristics. Hence, this EIA treated by BMP metric should be a reasonable metric for most storms except for the largest storms where runoff in the entire drainage area exceeds the capacity the BMPs were designed to treat. Effective IA treated by BMPs was calculated from overlays of the drainage areas of the BMPs in 2001 and 2008 and the EIA datasets from 2000 and 2008. Effective IAs treated accounted for any nesting of BMPs such that areas were counted only once. The rate of change in EIA treated was calculated for each watershed as the difference in EIA treated between 2008 and 2001 divided by seven years, and had units of percentage change in watershed EIA treated per year.

Relating Changes in EIA and BMP Implementation to Trends in Storm Hydrologic Metrics and Water Quality

Trends in EIA and the rate of change in EIA treated by BMPs were used as explanatory variables in a stepwise regression analysis in models of trends in the three storm hydrologic metrics (peak streamflow, stormwater yield, and storm runoff) and of the trends in the five water quality constituents. Four additional explanatory variables were included in the regression models that might help differentiate trends in EIAs and changes in BMP implementation among the various watersheds. These included watershed drainage area and basin slope, which were found to be important in explaining differences in water yields in some of these watersheds (Joiner *et al.*, 2014), and initial levels of EIAs and EIAs treated by BMPs at the beginning of the study period in 2001.

Because the goal of this regression analysis is to identify the explanatory variables that relate to trends, the Bayesian information criterion (BIC) (Schwarz, 1978; $p < 0.05$) was used in the stepwise regression. The purpose of this statistic differs from AICc (which was used for modeling the trends in storm hydrologic metrics and water quality data) in that it selects the "true" model that best explains the variability instead of the best predictive model. This criterion is similar to the AICc in that it determines the best model without overfitting, but has this different model selection purpose.

RESULTS

Trends in Storm Hydrologic Metrics

Of the 24 combinations of eight watersheds and three storm hydrologic metrics, 10 had significant temporal trends, 5 increasing trends and 5 decreasing trends (Table 2). Significant trends ranged from −3.80 to 0.44 mm/day per year for peak streamflow, from −2.45 to 0.57% per year for stormwater yield, and from −0.40 to 0.24 mm of runoff per year for storm streamflow runoff. There were significant increasing trends at Apalachee River watershed for peak streamflow, and at Richland and Wheeler Creek watersheds for both stormwater yield and total storm streamflow runoff. There were significant decreasing trends at Level Creek watershed for peak streamflow, at North Fork Peachtree Creek watershed for all three storm metrics, and at Shoal Creek watershed for stormwater yield. All significant trend directions at individual watersheds were consistent with each other. The lack of a significant trend could either be an indication that the metric was not changing, or that any change was not large enough to be detectable relative to the metric's variability.

Trends in Water Quality

The trends in storm composite concentrations represent the trends in water quality after accounting for the effects of storm streamflow response on streamwater concentrations (Table 3). Despite the high rates of development within most of these watersheds during the study period, water quality improvements were observed more often than declines. Seven significant decreasing trends (Apalachee River watershed for TSS and TP, Crooked Creek watershed for TN and TP, Level Creek watershed for TP, and Richland Creek watershed for TSS and TP), and three significant increasing trends (all at Shoal Creek watershed for TSS, TN, and Zn) were detected. All significant trends at individual watersheds were consistently in the same direction. Only two watersheds, Pew and Shoal Creeks had constituents with increasing concentrations. The direction, and to a lesser extent, the magnitude of the trends in Pb and Zn were fairly consistent with those for TSS, as expected since these constituents are a component of TSS and have no dissolved component. Total phosphorus had the most significant trends of any of the constituents (four) and the magnitudes of the trends were negative for all eight watersheds. The differences in trends between TP and TSS suggest that the ubiquitous decreases in TP throughout the study area may have been the result of its dissolved component. Water quality trends at the Shoal Creek watershed were much higher than the other watersheds for four of the five constituents.

Approximate changes in water quality expected from trends in the storm hydrologic metrics peak streamflow and stormwater yield, which were based on predictions from the water quality models, are summarized in Table 4. The ranges in constituent trends from the storm hydrologic metrics were smaller than the ranges from the trends determined from the storm composite samples, and varied from a low of 4% (TN) to a high of 34% (TP). The differences in the range in trends might reflect an appreciable ability of the detention pond BMP designs in reducing sediment

TABLE 2. Summary of Storm Hydrologic Metric Trends.

Watershed Name	Peak Streamflow (mm/day per year)	Stormwater Yield (% per year)	Storm Streamflow Runoff (mm per year)
Apalachee River	**0.44**	0.02	0.11
Crooked Creek	−0.32	−0.23	−0.01
Level Creek	−**1.07**	−0.23	0.00
North Fork Peachtree Creek	−**3.80**	−**2.45**	−**0.40**
Pew Creek	−0.42	−0.28	0.07
Richland Creek	−0.21	**0.57**	**0.24**
Shoal Creek	−1.65	−**1.78**	−0.18
Wheeler Creek	−0.05	**0.40**	**0.17**

Note: Bold values indicate trend term statistically significant in stepwise regression.

TABLE 3. Summary of Storm Composite Concentration Trends.

Watershed Name	Total Suspended Solids (mg/L per year)	Total Nitrogen (mg/L as N per year)	Total Phosphorus (mg/L as P per year)	Total Lead (µg/L per year)	Total Zinc (µg/L per year)
Apalachee River	−**56.7**	−0.037	−**0.033**	−1.20	−0.3
Crooked Creek	−4.5	−**0.111**	−**0.022**	−0.40	−1.4
Level Creek	−12.8	−0.077	−**0.040**	−0.84	−2.5
North Fork Peachtree Creek	−0.6	−0.017	−0.012	−0.58	−1.6
Pew Creek	−52.7	−0.025	−0.012	0.05	−7.7
Richland Creek	−**123.1**	−0.052	−**0.060**	−0.34	−7.0
Shoal Creek	**62.9**	**0.343**	−0.009	1.90	**13.1**
Wheeler Creek	−12.4	−0.053	−0.015	−0.61	−1.3

Note: Bold values indicate trend term statistically significant in stepwise regression.

TABLE 4. Approximate Concentration Trends Expected from Trends in the Storm Hydrologic Metrics Peak Streamflow and Stormwater Yield.

Watershed Name	Total Suspended Solids (mg/L per year)	Total Nitrogen (mg/L as N per year)	Total Phosphorus (mg/L as P per year)	Total Lead (µg/L per year)	Total Zinc (µg/L per year)
Apalachee River	−18.9	0.000	0.000	0.31	−1.6
Crooked Creek	−4.2	−0.001	−0.002	−0.13	−0.8
Level Creek	−15.0	−0.016	−0.017	−0.03	−0.1
North Fork Peachtree Creek	−10.7	−0.007	−0.001	−0.08	−0.4
Pew Creek	−9.8	0.000	−0.010	0.00	−5.4
Richland Creek	−0.5	0.003	−0.008	0.28	−1.8
Shoal Creek	−3.3	0.002	0[1]	0[1]	0[1]
Wheeler Creek	−0.7	0.000	0.000	−0.03	0.3

[1]Water-quality model had no average or peak streamflow variables, hence no trend.

transport above reductions in transport resulting solely from BMP improvements in storm runoff.

Trends in Watershed EIA

Five of the eight watersheds had significantly increasing trends in watershed EIA over the period 2000 to 2009; Apalachee River, Level Creek, Pew Creek, Richland Creek, and Wheeler Creek watersheds (Figure 2, Table 5). Trends in watershed EIA ranged from 0.10 (North Fork Peachtree Creek watershed; not significantly different than zero) to 1.35% (Wheeler Creek watershed) of watershed drainage area per year.

Changes in BMP Implementation

The total number of BMPs in the eight watersheds increased substantially between 2001 and 2008 from 469 to 679 (Table 6). The upstream drainage areas of the BMPs as a percent of watershed drainage area ranged from 11.2 to 45.5% in 2001 and

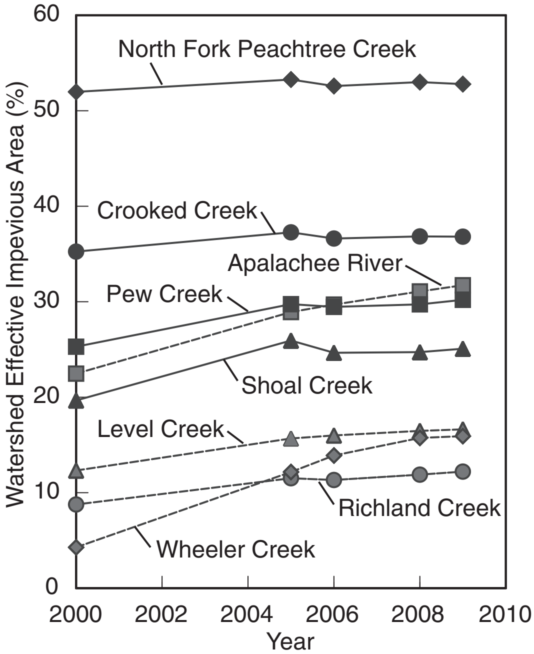

FIGURE 2. Changes in Watershed Effective Impervious Area for the Eight Monitored Watersheds from 2000 to 2009.

TABLE 5. Trends in Watershed Effective Impervious Area from 2000 to 2009.

Watershed Name	Adjusted Model R^2	Trend in Effective Impervious Area (% per year)	*p*-value
Apalachee River	0.97	1.04	**0.002**
Crooked Creek	0.62	0.17	0.115
Level Creek	0.94	0.49	**0.007**
North Fork Peachtree Creek	0.47	0.10	0.202
Pew Creek	0.86	0.54	**0.024**
Richland Creek	0.93	0.38	**0.008**
Shoal Creek	0.68	0.59	0.085
Wheeler Creek	0.97	1.35	**0.002**

Note: Bold indicates significance for a *p*-value of <0.05.

from 18.1 to 64.0% in 2008. The sum of the EIAs treated by the BMPs in each watershed ranged from between 0.7 and 18.3% of its watershed drainage area in 2001 to between 5.0 and 22.2% of its drainage area in 2008.

Increases in EIA treated by BMPs from 2001 to 2008 ranged from 0.19 (North Fork Peachtree Creek watershed) to 1.32% (Shoal Creek watershed) of its watershed drainage area per year. These rates are expressed in the same units as the trends in watershed EIA. The range in changes in BMP implementation was similar to the range in trends in watershed EIA (Table 5). In five of the eight watersheds, the change in treatment of EIA by BMPs exceeded the rate of increases in EIA.

Relating Changes in EIA and BMP Implementation to Changes in Storm Hydrologic Metrics and Water Quality

Both trends in EIA and in EIA treated by BMPs were significant variables in the stepwise regressions of trends in the three storm hydrologic metrics (peak streamflow, stormwater yield, and storm runoff; Table 7). As might be expected, increases in metrics were related to increases in EIA while decreases in the metrics were related to increases in BMP implementation, as indicated by the signs of the model coefficients for these variables. Three to four of the watershed characteristic explanatory variables were included in each of the three metrics, indicating that they were useful in explaining some of the variability in the trend relationships between watersheds. Explanatory variables included in the models were quite consistent, with trends in the storm hydrologic metrics being positively related to drainage area and the amount of EIA treated by BMPs in 2001, and negatively related to the amount of EIA in 2001.

The significant relationships for trends in the water quality constituents are not as expected for the watersheds evaluated in this study, as increases in EIA are related to decreases in constituent concentrations, and increases in BMP implementation are related to increases in constituent concentrations for four of the constituents. The exception was for TP, which had a significant relationship with only BMP implementation, which was very close to zero. The watershed characteristic explanatory variables included in the water quality trend models varied by constituent and models included between zero and four variables. When significant, EIA in 2001 was positively related to constituent trends, and drainage area and EIA treated by BMPs in 2001 were negatively related to constituent trends; opposite of the relationships observed for the storm hydrologic metrics. This indicates that expected water quality improvements from BMP implementation do not directly translate to improvements in water quality at the watershed scale.

DISCUSSION

Relationship between EIA and EIA Treated by BMPs

There was a moderate correlation between trends in EIA treated by BMPs and trends in EIA (Figure 3; adjusted R^2 = 0.53). The close to one-to-one correlation was as to be expected, as current county

TABLE 6. Summary of Best Management Practices (BMPs) in Watersheds in 2001 and 2008. Areas upstream of BMPs are unnested areas.

Watershed Name	Drainage Area (ha)	Number of BMPs		Sum of Drainage Areas Upstream of BMPs				Sum of Effective Impervious Areas Treated by BMPs				Change in Effective Impervious Areas Treated by BMPs 2001-2008 (% of DA per year)
				2001		2008		2001		2008		
		2001	2008	(ha)	(% of DA)	(ha)	(% of DA)	(ha)	(% of DA)	(ha)	(% of DA)	
Apalachee River	1,463	42	80	365	25.0	635	43.4	45	3.1	141	9.6	0.93
Crooked Creek	2,298	139	174	1,045	45.5	1,192	51.9	420	18.3	511	22.2	0.57
Level Creek	1,309	39	67	264	20.2	466	35.6	38	2.9	94	7.2	0.61
North Fork Peachtree Creek	396	13	24	63	16.0	72	18.1	35	8.8	40	10.1	0.19
Pew Creek	1,920	100	119	577	30.0	681	35.5	179	9.3	260	13.5	0.60
Richland Creek	2,427	48	90	471	19.4	644	26.5	67	2.8	121	5.0	0.31
Shoal Creek	1,413	85	111	609	43.1	905	64.0	116	8.2	247	17.5	1.32
Wheeler Creek	339	3	14	38	11.2	122	36.0	2.4	0.7	33	9.7	1.29
Total	11,564	469	679	3,432	29.7	4,716	40.8	904	7.8	1,446	12.5	0.67

Note: DA, drainage area.

TABLE 7. Summary of Multiple Regression Models Used to Explain Trends in Storm Hydrologic Metrics and Water Quality at the Eight Watersheds.

Storm Hydrologic Metric Trend or Water Quality Trend	Adjusted Model R^2	Trend in Watershed EIA	Change in EIA Treated by BMPs	Watershed Characteristics			
				Drainage Area	Basin Slope	EIA in 2001	EIA Treated by BMPs in 2001
Peak streamflow (mm/day per year)	0.93	4.0	−1.6	+		–	+
Stormwater yield (% per year)	0.94	3.1	−2.7	+		–	+
Storm streamflow runoff (mm per year)	1.00	0.56	−0.38	+	+	–	+
Total suspended solids (mg/L per year)	0.93	−138	153	–	–		
Total nitrogen (mg/L as N per year)	0.67	−0.53	0.67	+		+	–
Total phosphorus (mg/L as P per year)	0.83	0.00	0.01		–		
Total lead (μg/L per year)	0.60	−2.6	3.0				
Total zinc (μg/L per year)	0.92	−18	30	–	+	+	–

Note: Effective impervious area (EIA) and change in EIA treated by best management practices (BMPs) are in units of % of drainage area per year. + indicates positive significant explanatory variable and − indicates negative significant explanatory variable.

regulations require that large, newly constructed IAs have BMPs to treat them. But the lack of a stronger correlation between these variables was crucial for differentiating the relationship of these two trends with the trends in the storm hydrologic metric and water quality constituents. More variability in these trends between watersheds would have been preferred. Many of the watersheds have a higher trend magnitude in EIA treated by BMPs than for EIA, indicating that BMPs installed during the study period are additionally treating some pre-existing untreated EIAs within their drainages. The Shoal Creek watershed differs the most from the other watersheds, with a much higher change in EIA treated by BMPs relative to the rate of change in EIA.

Storm Hydrologic Metric Trends Assessment

The effects of moderately correlated trends in EIA and EIA treated by BMPs on the storm hydrologic metrics had to be combined in order to properly discern the relationships between them and the metrics' trends. Watershed EIA and EIA treated by BMPs both increased with increasing trends in all three storm hydrologic metrics, but the slopes were higher for EIA (Figure 4). The lower slopes for the EIA treated by BMPs relationships along with that storm hydrologic metrics were improving in some of the watersheds (trends < 0) indicates an improvement in the storm hydrologic metrics with BMP implementation, as quantified in Table 7. The relative magnitude of the model coefficients between the EIA and BMP

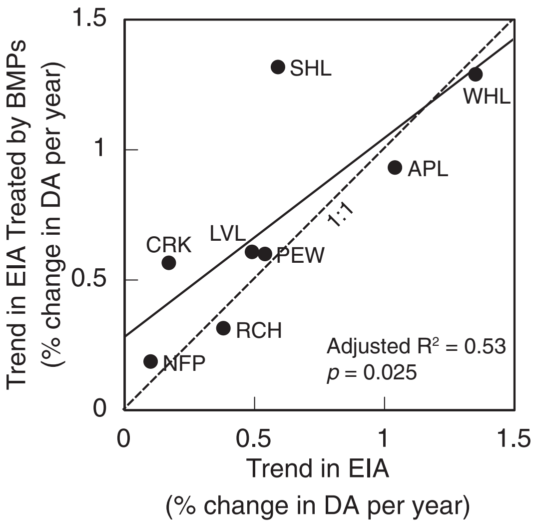

FIGURE 3. Relationship between Trends in Effective Impervious Areas (EIA) Treated by Best Management Practices (BMPs) *vs.* Trends in EIA in the Eight Monitored Watersheds for Period 2001 to 2008. DA is drainage area; watershed abbreviations from Table 1.

implementation suggests that for every 1% increase in EIA drainage area, about 2.6, 1.1, and 1.5% increases in EIA drainage areas treated by BMPs would be required to compensate for the effects of the EIAs added to the watersheds (some of which may have been untreated) on peak streamflow, stormwater yield, and storm runoff, respectively. These results suggest that the implementation of BMPs does not improve these three storm hydrologic metrics equally, and was best at improving stormwater yields and worst at improving peak streamflow. These results should not be considered as the specific effectiveness of the BMPs, as the watershed approach used herein is a measure of the effectiveness of BMP implementation within their entire watersheds, incorporating the effects of areas downstream of BMPs that include EIAs that are untreated. The fact that the effects of the BMP implementation are observable at the outlet of the watersheds indicates that the benefits of the BMPs on storm runoff are perpetuated despite contributions of areas with untreated EIAs.

Modeling studies of stormwater hydrographs from watersheds with a network of detention ponds incorporating no storage (retention), such that was typically employed in Gwinnett County before 2001, indicated only small reductions in peak streamflows, no reductions in storm runoff, and longer stormflow durations. In a study by Ferguson (1995) from a hypothetical network of detention ponds, it was determined that downstream peak streamflows were reduced by less than the peak streamflow reductions from the individual BMPs. In a study by Emerson *et al.* (2005) of a watershed with 17% IA, of which detention pond BMPs serviced 39% of EIAs, peak streamflows were reduced by an average of 0.3%. Both of these studies indicated that for particular combinations of precipitation distribution and timing and BMP drainage networks, this type of detention pond BMPs could potentially result in increased downstream peak streamflows. The BMP water quality protection controls implemented by the county in 2001 effectively instituted a capture volume to newly constructed detention ponds. Previous studies have shown that reducing storm runoff by either incorporating storage (Emerson *et al.*, 2005) or infiltration (Ferguson, 1995) into the pond design also more effectively reduced peak streamflows and stormflow duration. These findings match the storm hydrologic metric improvements associated with the BMP implementation in this study.

Water Quality Concentration Trends Assessment

While the trends in storm hydrologic metrics were consistent with the expected trends in EIA and in changes in BMP implementation, the trends in water quality appear to be counterintuitive. Watershed EIA treated by BMPs increased with increasing trends in all five constituents, while there was a much weaker relation between watershed EIA and water quality trends (Figure 5). Furthermore, of the four watersheds that had significant trends detected in both storm hydrologic metrics and water quality (Tables 2 and 3), three of the watersheds (Apalachee River, Richland Creek, and Shoal Creek) had trends in water quality that were opposite to the trends in storm metrics. These results are similarly counterintuitive since decreases in EIA and increases in the amount of EIA treated by BMPs should similarly improve both storm runoff and water quality. While the sediment retention efficiencies of the BMPs were not assessed in this study, the design efficiencies are similar to efficiencies measured for similar BMP designs in other studies (Winston *et al.*, 2013; Zhao *et al.*, 2016). A lack of relationship between water quality trends and changes in EIA and BMP implementation could indicate that variability in sources of constituents within individual watersheds, particularly downstream of treated areas, has a more important effect on water quality trends than BMP implementation. However, the consistency of the counterintuitive results taken together indicate that the trends in water quality concentrations might not be fortuitous, but have an underlying cause that affects all the watersheds.

The water quality trends at Shoal Creek had a large influence on the relationship with EIA treated

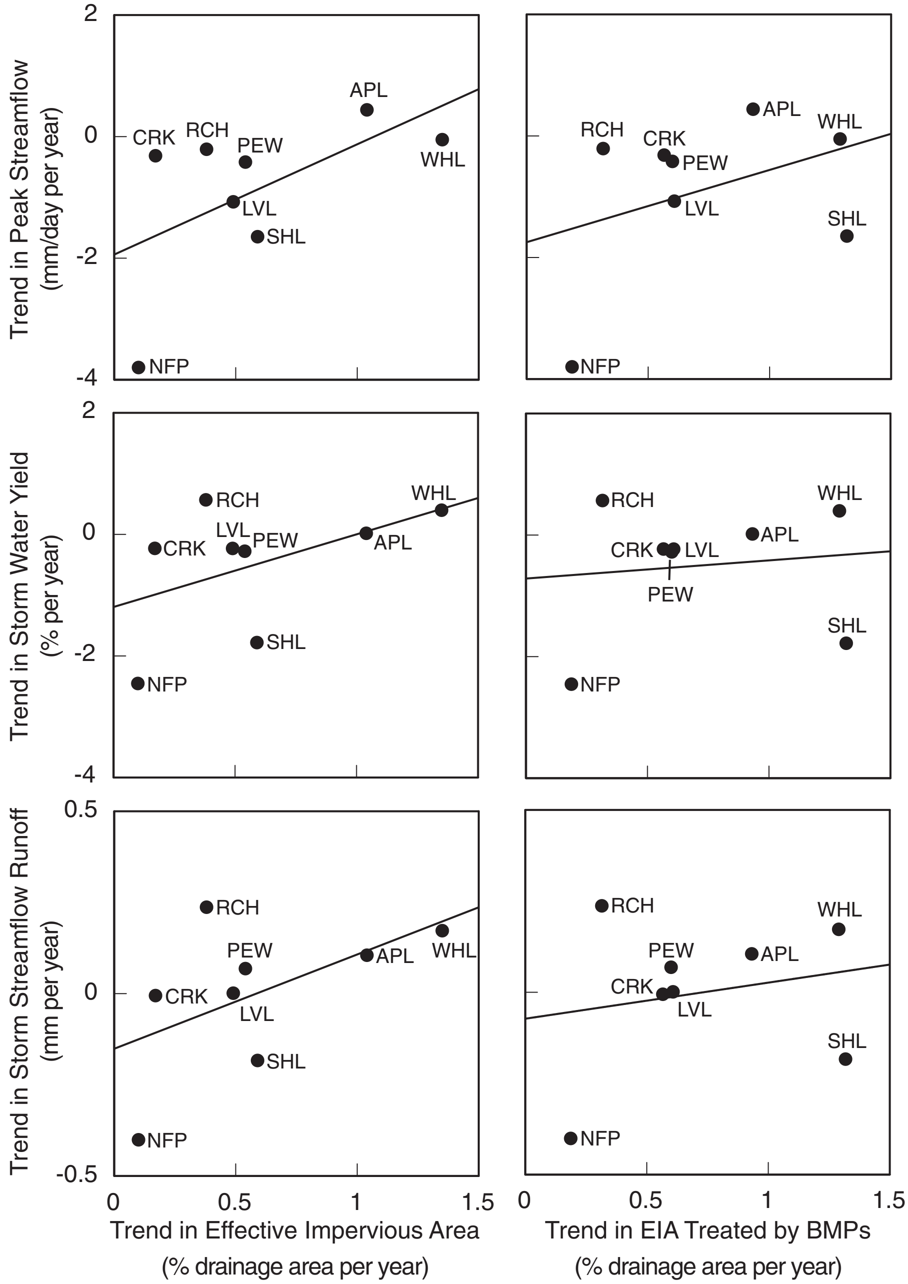

FIGURE 4. Relationships between Trends in Three Storm Hydrologic Metrics *vs.* Trends in Effective Impervious Areas (EIA) Treated by BMPs and Trends in EIA in the Eight Monitored Watersheds for Period 2001 to 2008. Watershed abbreviations from Table 1.

by BMPs, owing to having both high water quality trends (Table 3) and the highest change in EIA treated by BMPs (Table 6). This watershed also had the most dissimilar relationship between trends in EIA and trends in EIA treated by BMPs, making this watershed crucial for distinguishing the relationship between these two moderately correlated variables in this analysis (Figure 3). If the large trends in water quality at the Shoal Creek watershed are related to changes in constituent inputs rather than changes in EIA and BMP implementation, the inclusion of this watershed could easily attribute the water quality trends wrongly between the EIA and BMP implementation trends. Removing the results from the Shoal Creek watershed changed many of the watershed characteristic variables that were significant in the stepwise regressions, but still resulted in positive significant relationships between water quality trends and changes in EIA treated by BMPs for three of the four constituents that initially had this relationship.

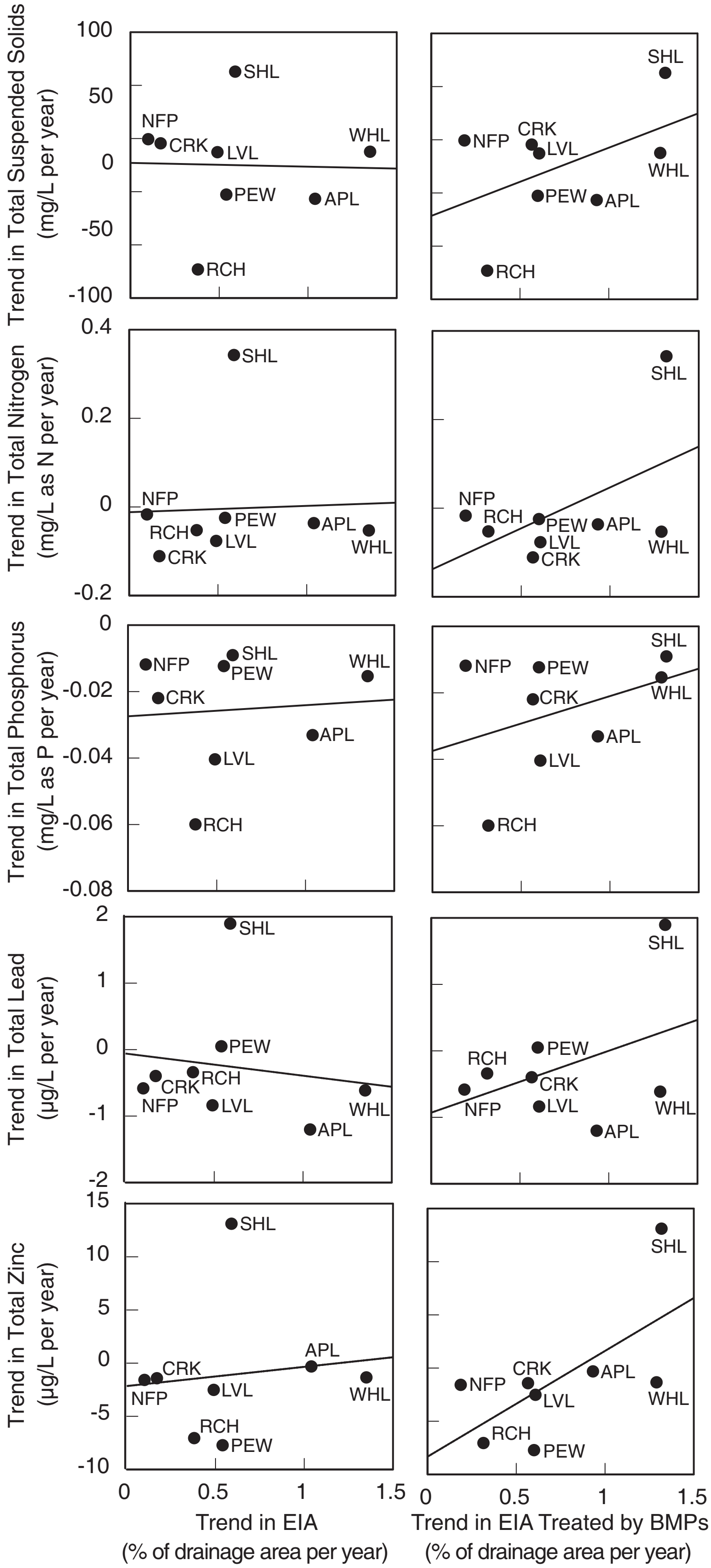

FIGURE 5. Relationships between Trends in Five Water Quality Constituents *vs.* Trends in Effective Impervious Areas (EIA) Treated by BMPs and Trends in EIA in the Eight Monitored Watersheds for Period 2001 to 2008. Watershed abbreviations from Table 1.

One explanation for the counterintuitive relationships is that the BMPs are causing additional channel erosion downstream of the BMPs by increasing the duration of stormflows. Trimble (1997) demonstrated that channel erosion could account for about two-thirds of the total sediment yield of a stream. Booth *et al.* (2002) indicated that even well designed detention ponds were inadequate in preventing channel erosion. McCuen (1979) and Tillinghast *et al.* (2011) indicated that bankfull and sub-bankfull streamflows above critical discharges for channel erosion occurred for longer durations downstream of BMPs that primarily reduce peak streamflows by delaying storm runoff. While the 2001 BMP requirements instituted a retention component, this component was designed for retaining sediment in the BMP and not for decreasing downstream discharges and reducing resulting channel erosion. While improvements in the three storm hydrologic metrics were observed with BMP implementation, these improvements may be insufficient at reducing downstream channel erosion. A BMP design that incorporates both retention of sediment and reduction in downstream channel erosion may be necessary to achieve sediment transport reductions at the watershed scale (*e.g.,* McCuen and Moglen, 1988).

A second explanation for the counterintuitive relationship between water quality trends and trends in EIA and BMP implementation is the possibility of a spurious relationship. Increases in EIA, detention pond BMP implementation, and watershed inputs of constituents are all likely correlated with development rates within the watersheds. While BMPs have been put in place to minimize sediment getting to streams during development, it is still likely that the rate of development is related to inputs of constituents to the stream; particularly affecting watershed water quality downstream of the detention pond BMPs. It could be that changes in EIA treated by BMPs have a stronger relationship than trends in EIA to changes in inputs of constituents, resulting in a spurious and counterintuitive relationship as observed.

SUMMARY

Gwinnett County, Georgia, is a densely populated, suburban county of the Atlanta metropolitan area that has been undergoing rapid population growth and urbanization since about 1980. In 2001, the county implemented water quality protection design requirements for detention pond BMPs. The effectiveness of the design changes was determined by modeling the effects of trends in EIA and changes in BMP implementation on trends determined in storm hydrologic metrics and in water quality across eight small monitored watersheds for the period 2001 to 2008.

Trends were determined in three storm hydrologic metrics (peak streamflow, stormwater yield, and storm runoff) and trends in storm composite samples of five sediment-related water quality constituents (TSS, TN, TP, Pb, and Zn). In the trend analysis, variability in the storm metrics associated with variations in storm precipitation characteristics and climate, and model variability in water quality concentrations associated with variations in storm runoff and climate were accounted for. These explanatory variables provided insight into the controls on storm runoff processes and constituent transport. Of the 24 watershed-storm metric combinations, five significantly increasing trends and five significantly decreasing trends were detected. Watershed water quality concentrations generally appeared to be declining, with three significantly increasing trends and seven significantly decreasing trends detected. A comparison of trends in the storm metrics and water quality concentrations resulted in apparent conflicting trends at three of the watersheds, where trends in water quality were opposite to the trends in storm metrics.

Watershed EIAs increased from 0.10 (not significantly different than zero) to 1.35% of watershed drainage area per year over the period 2000 to 2009. Changes in the EIA treated by BMPs from 2001 to 2008 ranged from 0.19 to 1.32% of its watershed drainage area per year.

Increases in storm hydrologic metrics are related to increases in EIA and decreases in storm hydrologic metrics are related to increases in BMP implementation, as expected. The relative magnitude of the model coefficients suggested that for every 1% increase in watershed effective impervious drainage area, it would take about a 2.6, 1.1, and 1.5% increase in EIA treated by BMPs to mitigate the effects of EIAs added to the watersheds (including some that were untreated) on peak streamflow, stormwater yield, and storm runoff, respectively. The significant relationships for trends in the water quality constituents were not as expected, as increasing trends in concentrations were related to decreasing trends in EIA and increases in BMP implementation for four of the five constituents and were related to decreasing trends in the storm hydrologic metrics. This may be the result of (1) changes in water quality inputs in the watersheds, especially downstream of areas treated by BMPs, (2) BMPs may not have sufficiently reduced, and could be extending, the duration of stormflow that results in downstream channel erosion, and/or (3) spurious relationships between increases in EIA, BMP implementation and watershed inputs of constituents with development rates. Controls on downstream channel erosion may need to be addressed to effectively reduce sediment transport at a watershed scale.

SUPPORTING INFORMATION

Additional supporting information may be found online under the Supporting Information tab for this article: Details on how hydrologic events were identified from the hydrograph that were used for identifying hydrologic metrics. Summary of multiple regression models used to remove climatic effects from storm hydrologic metrics and storm composite concentrations. Details on development of detention pond characterization dataset.

ACKNOWLEDGMENTS

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