LONG-TERM RESPONSES OF A PIEDMONT HEADWATER STREAM TO THE RAPID URBANIZATION OF ITS WATERSHED

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REFERENCE: *Proceedings of the 2019 Georgia Water Resources Conference*, held April 16-17, 2019, at the University of Georgia.

Abstract. While the literature abounds in studies which have drawn inferences regarding the long-term impact of urbanization on relatively undisturbed control streams, few studies (Trimble, 1997; Leopold, et al., 2005; and Colosimo, et al., 2007) have evaluated the responses of relatively undisturbed streams to the onset and long-term impacts of urbanization. This study evaluates the long-term (22-year) physical, geomorphological, and biological responses of a Piedmont headwater stream to a rapid increase in impervious area within its 1.4 mi^2 watershed over a ten-year period, a three-year transitional period as development crested, and a nine-year period of adjustment to little further development.

INTRODUCTION, MEASUREMENTS & OBJECTIVES

This paper describes and evaluates the physical, geomorphological, and aquatic biology response of a stream draining a 1.4 mi^2 watershed (more fully described in Mikalsen and Bourne, 2007) in the rapidly developing northern sector of the Atlanta Metropolitan Area, whose 21.3 % percent impervious area increased rapidly from 1996-2006, crested between 2006-2009 at 41.8% impervious and an estimated 96.2% buildout, and then increased very little from 2009-2017, the latest year that land cover data were available.

Measures of Response

Measurements (more fully described in earlier papers) employed to evaluate stream response included channel plan and profile, channel geometry, sediment characteristics, and aquatic biology were collected annually from 1996-2006 and follow-up investigations in 2009 and 2018. They were evaluated over the three time periods and for differences between the responses of the <u>upper</u> (X4-6) straighter, lower gradient, riffle dominated and the <u>lower</u> (X1-3) sinuous, higher gradient sections of the selected study reach. Cross-section measurements included field measurements of bankfull depth, bankfull and channel cross-sections and derivation of descriptive measures such as area, width/depth ratio, and calculated estimates of bankfull quantity derived from the Manning equation, and shear stress. Measures employed to evaluate the response of the aquatic community included macroinvertebrate surveys, diversity indices, and habitat assessments.

STUDY OBJECTIVES AND QUESTIONS

Study objectives to evaluate the response of the entire study reach and its two distinct sections to changes in sediment input and stormwater regime associated with the initial rapid development, crest, and stable phases of its watershed development were to identify and evaluate:

- The major phases of the development of the watershed over the 22-year study period;
- Changes in planform and gradient, bedform, and the associated effects of storm flows and surface slope;
- The resultant hydraulic driven response of the study reach such as bankfull and channel quantity and shear stress;
- Changes in cross-section channel geometry such as bankfull stage and derived measures such as width depth and entrenchment ratios;
- Changes in sediment and particle size deposition; and
- Changes in macroinvertebrate population and habitat.

Among the questions addressed were: Have slope and sinuosity substantially changed to respond to changes stormflow and sediment input? Has channel geometry changed sufficiently to warrant a change in Rosgen stream classification? Has the stream experienced sediment starvation? Has the stream re-attained a physical dynamic equilibrium? And, has the benthic habitat and macroinvertebrate community recovered?

IMPACTS OF URBANIZATION ON WATERSHEDS AND TYPICAL MAIN CHANNEL RESPONSES

The well-founded major effects of urbanization on relatively undisturbed watersheds are sediment yields 2-200 times natural yields, leading to substantially increased silt and sand caliber loads during the early phase of development which decrease after impervious areas dominate. As the portion and volume of stormwater runoff more efficiently delivered to the surface drainage system increases, so does the frequency, intensity, and peakedness of stormwater events capable of shaping stream channels, with a concurrent reduction in percolation to and groundwater interflow.

THE PROCTOR CREEK TRIBUTARY WATERSHED AND STUDY REACH

Watershed Development

This unnamed tributary to Proctor Creek, is a first order stream draining a 1.4 mi^2 basin with dominant upland clay loam soils and alluvial soils in the floodplain covered by a dense growth of hardwoods, whose root masses proved to be an important barrier to channel expansion. Mean annual rainfall for the study period, recorded at the Georgia Automated Environmental Monitoring Network's (www.uga.edu/aemn) Dunwoody gauge was 51.6", with a peak of 76.8" in 2009.

Since 1996, when the co-authors recognized the opportunity to study the impact of imminent development on this then lightly developed watershed, the impervious portion, derived primarily from Atlanta Regional Commission LandPro landcover data, increased 68% to 2006, almost doubled by 2009, and increased slightly from 2009-2017, when it approached a fully built-out state.

Table 1 presents a summary history of the watershed since 1996, when low density uses and woodlands in the interior were encased by scattered commercial development on the periphery and a recently constructed swath of interstate highway across the upper portion of the basin and a single-family residential development just above the sampling site were already exerting an effect on the stream channel.

Table 1. Watershed Development History

Period	Impervious	Development History
1996	21.3%	A recently constructed Interstate 75 with a 0.7 impervious coefficient occupied 7% of the upper portion of the watershed. drainage basin likely contributed to some cantilever failure of outside bends in the lower section of the study reach.
1997	23.0%	A single elliptical culvert beneath Baker Road, approximately 150 ft below the study reach, was replaced by substantially higher capacity set of three box culverts at the same invert elevation.
1996- 2001	21.3-28.7%	Construction had started on what would eventually become a 300-ac single family residential development in the lower portion of the drainage basin. Despite a local E&S ordinance, there were frequent violations and this development continued to be a major source of orange-hued upland sediment beyond its completion in 2001. During this period commercial and commercial industrial development increased in the upper portions of the basin.
2001-2006	28.7-35.8%	Commercial, commercial industrial, and multi-family development continued in the upper portion of and along the perimeter of the basin, attaining approximately 85% of potential buildout.
2006-2009	35.8-41.8%	Development continued, but crested in 2009, as impervious area almost doubled to 42% and attained approximately 95% of potential buildout.
2009-2017	41.8-43.6%	Development slowed to a crawl, with a corresponding increase of but 4.4% in impervious area, with the estimated increase of but 0.2% in buildout inhibited by the reversion of some land to an agricultural use and some minor corrections

The Study Reach

As shown in Figure 1, a 288.5 ft (valley distance) stream segment, approximately 150' upstream of a culvert beneath a major arterial was selected for evaluation. Note that the stream flows from left to right. The four initially selected cross-sections, labeled X-4 to X-1 going dowwstream were supplemented by two additional cross-sections, X-5 and X-6, added in 2002 and 2006, respectively. That expansion allowed an evaluation of two distinctly different responses of the lower more sinuous and steeper gradient section of the reach from X1-3 and the straighter, lower gradient, riffle-dominated X4-6 upper section.

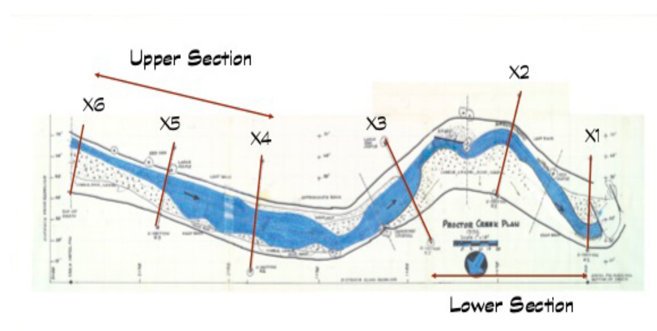

Figure 1. The Study Reach

PLANFORM AND GRADIENT RESPONSES

Physical Channel Responses to Urbanization

While there are several explanations of the dynamics, a stream channel has a limited number of outcomes to handle the changed flow regime forces and conveyed sediment loads resulting from urbanization. The channel may expand, aggrade, degrade, change its sinuosity, in response to the increased energy available to convey and distribute the sediment loads. Planform indicators of stream response such as thalweg location and length, riffles, pools, runs, stream bed, bank and bankfull widths, were mapped and photographed most years from 1996-2006, in 2009, and 2018, from which such measures as sinuosity, spacing and percent of the study reach in pools, riffles, runs, and Manning "n" were derived. In conjunction with field measurements of surface and bed slope, calculations of bankfull quantity, velocity, and shear stress derived.

A summary of planform and gradient responses of the study reach stream channel over the entire study period and the three defined periods of watershed development follows.

Planform Response Over the Study Period

The general response of the reach planform to the initial large input of upland soils and changing stormwater regime was:

- Very little change in reach sinuosity and gradient over the study period and follow-up investigations, though slope changed considerably within sections of the study reach.
- During the initial phase of the study period (1996-2009) channel width, constrained by dense root mats, increased very little, while bankfull stage, as indicated by field measurements increased more rapidly in response to the changing stormwater regime.
- During the latter portion of the study period (2009-2018), as impervious area increased very little, an increased width/depth ratio indicated that the trend had reversed and the channel was that the channel was widening more rapidly than deepening.

Planform Changes From 1996-2006. Figure 2 shows mapped planform changes from 1996-2002, the period of rapid development with the heaviest upland sediment input. During this period there was little change in the width of the upper "straight" section channel and scouring of the outside bends in the sinuous lower section was balanced by deposition on the inside bends. The most significant change in the planform was the progression from a sinuous to braiding of the lower section with large cobble bars.

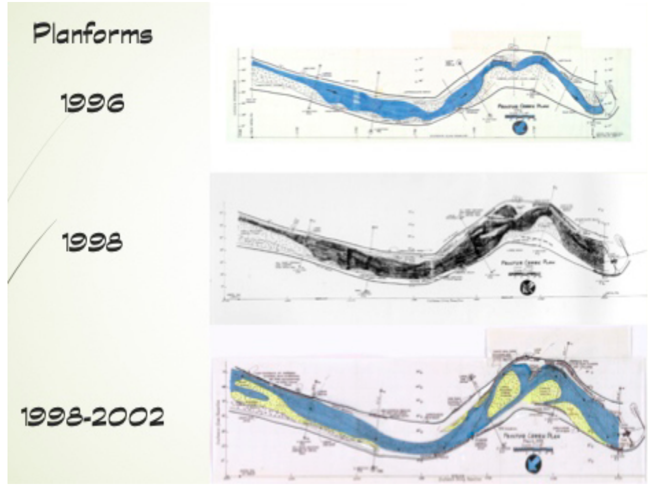

Figure 2. Early Planform Changes

Planform Changes 2009-2018. During this period, after development crested (Figure 3), the high flow vectors which had been shaping the stream channel were only slightly altered by embedded tree trunks and cobble bars, though a tree trunk in the upper section, observed in 2018, appears to be accelerating the scouring and curvature of the upper left bank of the upper section. Channel bank continued on the outside bends of the lower sinuous section with some scouring on the inside bends. The major change in the planform was the transition from a braided system to a large predominantly cobble caliber bar in the inside bend of the lower section, its influence on increased scouring of the outside bend, and evolution to a predominantly sand caliber bar nine years after development had crested.

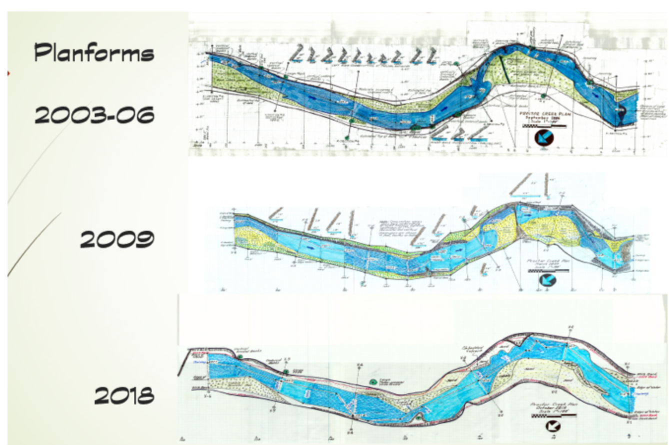

Figure 3. Later Planform Changes

Gradient Changes

Changes in the overall study reach measured water surface slope (ft/ft) of -5.0% from 1996-2006, +5.6% from 2006-2009, and 0% from 2009-2018, possibly controlled by a set of box culverts 150 ft downstream from the study reach, indicate that the overall study reach is neither aggrading or degrading. However, there have been substantial changes within the upper (X4-6) relatively straight section where slope increased 98% between 2006-2009 and over 300% from 2009-18 and the slope within the lower (X1-3) section increased 179% between 2006-2009 and decreased 31% by 2018. A 35% increase in X1-3 slope from 1996-2006 and a 36% increase in calculated shear stress (τ in lbs/ft^2) were associated with the evolution of the streambed from meandering to braided and the accumulation of a massive cobble bar by 2006 which created a substantial elevation difference between cross-sections #3 and #1. The seemingly substantial increase in slope from 2009-18 for Section X4-6 is due to a 0.86" increase in the mean bed elevation of the upper cross-section of this relatively flat section. From 2009-18, as Section X1-3 slope (-31%) and shear stress (-47%) decreased as the size and sediment caliber of the large cobble bar decreased.

BEDFORM RESPONSES TO SLOPE & QUANTITY

Leopold and Wolman (1957) and Ackers and Charlton (1971) plotted relationships between slope and quantity and thresholds separating straight, meandering, and braided stream reaches. These show that changes in stream bedform can be partially accounted for by the relationship between stream slope and flow quantity.

Relationships Between Slope, Quantity and Straight/Meandering/Braiding Bedform Thresholds

Figure 4 on the following page shows that annual measurements of slope and calculations of bankfull flow for the lower, more sinuous, and steeper sloped Section X1-3 superimposed on Leopold and Wolman's plot of the meandering/braided threshold, which generally corresponds with the previously discussed evolution of the bedform over the study period. A similar plot using Ackers and Charlton's base revealed that values for the upper, relatively straight, and low gradient section 4-6 remained below the straight/meandering threshold until 2018 when there was a significant change in slope and calculated shear stress, perhaps foreshadowing a change in bedform should sediment load and other conditions warrant.

Table 2 on the following page summarizes the evolution of bedforms, associated shear stress at bankfull flows, and relation to the braiding threshold over the study period for Section X1-3.

SUMMARY OF CHANNEL GEOMETRY RESPONSE

Stream channel geometry, succinctly expressed by such measures as: 1) bankfull stage, the equivalent of an estimated 1.5 year return frequency storm event; 2) flood prone stage determined as twice the maximum bankfull depth; 3) and channel and bankfull width and depth, which yield width/depth ratio, entrenchment ratios (the flood prone area width/bankfull width), and hydraulic radius, are but a manifestation of the natural process of constructing a conveyance suitable to accommodate the quantity of flow and the entrained sediment load.

Bankfull Width, Depth, Width/Depth Ratio, and Area

Despite the heavy sediment input and changing stormflow regimes from 1996-2006 and through 2006-2009 as development crested, mean study reach channel and bankfull width, inhibited by extensive system of root mats which armored the alluvial streambanks, changed very little, and did not begin substantially increasing until the period from 2009-18. Concurrent with the modest increases in widths from 1996-2006, was a greater than 60% increase in bankfull depth, as determined by field measures of bankfull stage. During the 2006-2009, crest in development, depth changed little, then from 2009-18, width increased more rapidly than depth, especially in the in the upper riffle dominated, lower gradient upper section.

The channel form response to heavy sediment loads and changing storm flow regime from 1996-2006 was reflected by the overall 68% increase in the bankfull width/depth ratio, indicating the channel was "deepening" faster than widening and becoming more entrenched, with a resultant decrease in bed resistance or friction, and a form more conducive to fine sediment transport. From 2006-2009 as development crested, increases in the lower bankfull width were balanced by decreases in the upper X4-6 depth, leading to virtually unchanged ratios. During the stable period from 2009-18 the trend reversed with mean bank width increasing more than depth, resulting in increased width/ depth ratios.

From 1996-2006, the resultant width and depth adjustments to the changing stormflow regime resulted in a 37% increase in reach mean bankfull cross-sectional area, which also changed little from 2006-2009, despite the 2009 peak annual rainfall. From 2009-2018 bankfull width increases, tempered by bankfull stage decreases in section X4-6, experienced a slight reduction. The reasons for this decrease are under further study.

Entrenchment Ratios

Entrenchment ratios describe the degree of vertical confinement of the stream channel and floodplain. According to Rosgen (1996), entrenchment ratios of 1-1.4

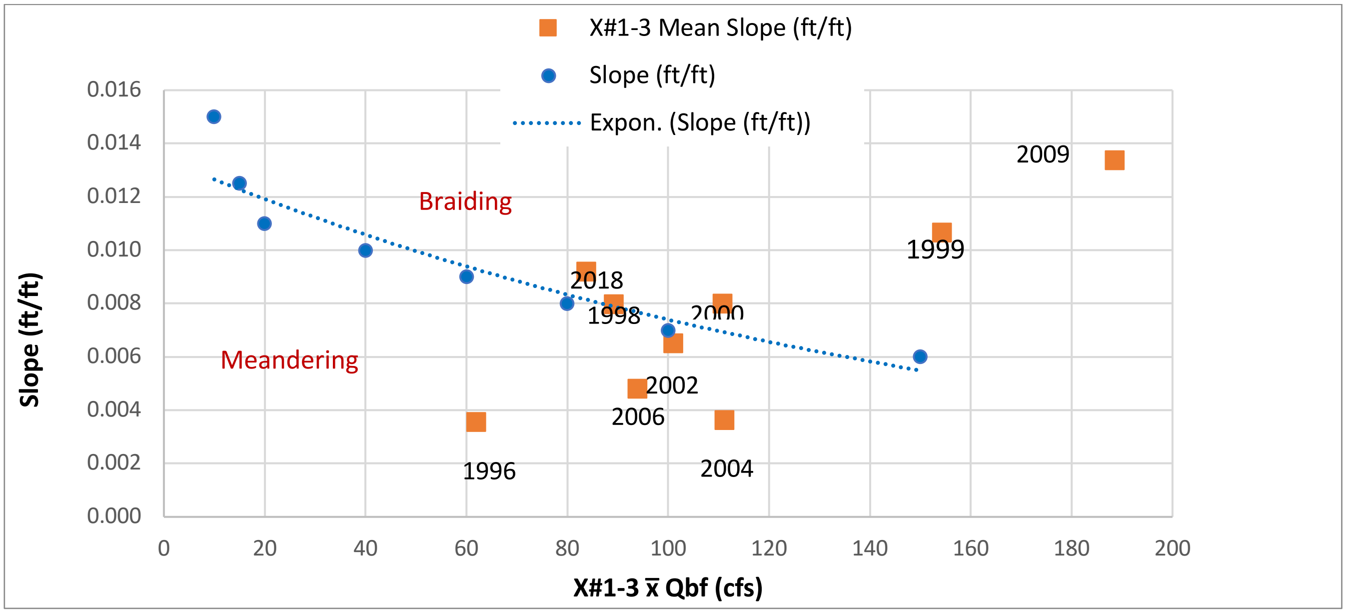

Figure 4. X1-3 annual mean slope (ft/ft) vs mean bankfull quantity (cfs) with braiding/meandering threshold (Leopold & Wolman, 1957)

Table 2. X# 1-3 Bedform besponses to shear stress (τ in lbs/ft^2) and meandering/Braiding threshold over study

Period	Bedform Characteristics	X1-3 Shear Stress	Meander/ Braiding Threshold	Discussion
1996	Meandering single channel stream	0.380	Well Below	Substantial, uncontrolled upland sediment input from a new immediately upstream residential development.
1998	Mid-channel point bar forms	0.930	On	Heavy sediment input continues
1998-2002	Braiding with sand, gravel, rock, cobble caliber point bars around X 3-2	0.930-0.720	On, Well Above & Above, Slightly Below	Braiding begins as large sediment loads continue, shear stress remains high, and slope/quantity plots are at or well above the braiding threshold.
2003-2006	Large sand, rock, cobble and boulder caliber inside bend bar builds on right bank constricting flow between it and the left bank. By 2006 a dead tree trunk has become embedded laterally across the bar, redirecting flows.	0.520-0.660	Below-Well Below	When sediment loads and shear stress reduced and values fell below the braiding/meander threshold, a large gravel, rock, cobble and boulder caliber bar consolidates on the right bank.
2009	Bar remains, but is receding downstream of the embedded tree trunk. Note annual rainfall was	1.760	Well Above	Perhaps associated with reductions in sediment input due to cresting development or the effects of the study period's highest annual rainfall (76.4"), the large inside bar begins migrating downstream despite slope and quantity levels conducive to braiding.
2018	Bar has changed to predominantly sand caliber with streamside slivers of cobble, gravel, and silt	0.927	Above	By 2018, perhaps due to a reduced sediment supply or bed scouring, the large bar elongates and changes to predominantly sand caliber. The elevated shear stress and related slope and bankfull quantity would suggest conditions conducive to braiding if the adequate caliber sediment was available.

indicate entrenched streams; 1.41-2.2 moderately entrenched streams, and greater than 2.2 only slightly entrenched streams in a well-developed flood plain. The mean ratio for the entire reach, which though remaining in the moderately entrenched range for the entire study period, has, gradually decreased from 1.93 in 1996 to 1.72 in 2018, indicating the study reach has become more entrenched, with the implication of increased shear stress on the channel banks.

Rosgen Stream Classification

The overall study reach classification as a Rosgen Type C stream (entrenchment ratio >2.2, width/depth ratio > 12, sinuosity >1.2, and surface slope < .02) has not changed over the study period.

SEDIMENT DEPOSITION

The effects of the complex forces influencing sediment entrainment, conveyance, and distribution may be inferred from the channel form as well as the composition of bed materials, derived from "pebble counts" taken at the six cross-sections, such as particle caliber and distribution and the proportion of the samples in silt and sand (<2.0 mm) and gravel and larger (>2.0 mm). Annual habitat assessment surveys, conducted by the Cobb County Water System included an evaluation of embeddedness, the extent to which particles on the stream bed are covered or sunken into silt and sand, and sediment deposition which evaluates the amount of sediment that has accumulated and changes to the stream channel resulting from deposition, both with scores ranging from 0-20, with 20 being optimum. A summary of responses follows:

- From 1996-2002, the period of greatest sediment input, the initial mean median particle size of 10 mm decreased to a minimum of 9.65 mm, began increasing to a peak of 16.7 mm in 2009, and then decreased to 9.98 mm in 2018, virtually the same as in 1996.
- The smaller reach mean particle caliber values from 1996-2002 coincided with observations of heavy input of fine orange hued upland soils, which afterwards turned predominantly brown to gray, suggesting a change to bed and gray alluvial bank sources.
- Percent silt and sand (<2.0 mm) also peaked in 2009, and then declined by 27% to 2018, two years later than Wolman's (1954) estimated sevenyear lag before fine sediments are sifted, with the bulk of the decline in the lower gradient, broader, X#4-6 section. The 2018 reach mean particle size of 9.99 mm was virtually the same as the 1996 value of 10.0 mm.
- The 76% of the study reach which had consisted of gravel or larger caliber in 1996, generally declined to approximately 51% in 2009 then increased to 64.6% in 2018, again with most of the increase in the upper section.
- Neither embeddedness nor sediment deposition had a discernable association with particle size distribution, percent silt, or any other potentially related variables.
- Embeddedness scores increased from 11 to 14 from 1996-2006 and remained at approximately 13 through 2017, the last available survey, while sediment deposition scores increased slightly from 10 in 1996 to 11 in 2006, and 13 in 2009, and returned to 10 in 2017.

AQUATIC MACROINVERTEBRATES & HABITAT

Annual macroinvertebrate surveys conducted over the study period by the Cobb County Water System, revealed the disappearance of sensitive species (Bourne, et al., 2005), progressive decline in the number of macroinvertebrate taxa found, a slight improvement in Hilsenhoff Biotic Index (which estimates the overall tolerance of the aquatic community), and a slight improvement in habitat assessment grades (with a range from 200 being optimal to 0) which assess the suitability of a benthic environment for aquatic life. The number of taxa found decreased from 29 in 1996, at the onset of major sediment and other impacts of development to 19 in 2006, to 7 in 2011 after development crested, and then to 6 in 2017, the last year that a survey was available. Hilsenhoff scores ranged from a fairly poor (substantial pollution likely) rating of 5.86 in 1996 to a good (some organic pollution probable) rating in 2006 (4.50) through 2011, then a declined to a fair (fairly substantial pollution likely) ratings of 5.28 in 2013 and 5.57 in 2017. A 1996 habitat assessment score of 122 declined to a study period low of 93 in 2001, before increasing to the highest score during the study period of 136.5 in 2006, declined to 127 in 2009 as development crested, and remained in a range of 124.5-131 during the 2009-18 period of minimal increases in development.

Despite an initial low, plunge, and then increase in habitat scores between 1996-2006, the period of greatest upland sediment impact and increase in storm flows, and a modest recovery of in the Hilsenhoff rating over the study period, sensitive species have disappeared, and the diversity and number of taxa, apparently inhibited by the initial surge of sediment delivery and hydraulic and organic effects, have not recovered during the period of little development from 2009-18.

SUMMARY AND CONCLUSIONS

Planform. While there have been changes in slope in the upper straight and lower sinuous sections of the study reach, there has yet little response of the overall study reach to the changes in the stormwater regime and sediment input brought on by rapid urbanization. The most evident planform change has been an increase in depth, initially constrained by roots and root balls, and a subsequent increase in measures of channel width and width/depth ratio which indicate lateral channel expansion during the latter phase of stream response.

Bedform. Bedforms as mapped over the study period were initially shaped by a relatively straight, low gradient, riffle-dominated upper section and a lower steeper gradient lower section of the study reach, which directed channel building storm flow vectors, whose consequent trajectories were influenced by bank armoring, fallen and embedded tree trunks, and a large cobble bar. The bed configuration was influenced by sediment input and caliber and generally conformed to referenced quantity-slope thresholds between straight, braided, and meandering streams. Conditions revealed by the 2018 survey suggest that the upper section could, if sediment input were sufficient, begin braiding.

Channel Geometry. Measures of channel geometry indicated that the stream channel response to the changing stormflow regime between 1996-2006, likely due to the heavily armored stream banks, was to deepen more than widen. Between 2009 and width/depth ratios increased indicating that the channel was widening faster than deepening.

Entrenchment Ratios and Rosgen Stream Classification. The study reach remained in the moderately entrenched range and classified as a Rosgen Type C stream over the study period.

Sediment and Sediment Starvation. Stormwater runoff from increased impervious surfaces may contain lower sediment concentrations, which can reduce the constant supply of sediment needed to build the stream channel and exacerbate bank and bed scouring. While there has been a change in color from orange upland soils to brown and grey hued alluvial and bed material, there has been no indication of bed degradation and bankfull and channel area have at least equilibrated.

Macroinvertebrate Population and Habitat. Despite a modest increase in the suitability of the benthic habitat and Hilsenhoff scores since the initial period of heavy upland sediment delivery and changing stormwater regime, sensitive species have disappeared, and the diversity and number of taxa diminished, suggesting that recovery is also being inhibited by hydraulic effects (scouring of aquatic populations and food sources) and organic or toxic pollution.

Physical Equilibrium. Has the reach channel and bed equilibrated to the changing stormwater regime and sediment input brought on by the onset and culmination of rapid development in 2009? There has been little change in gradient or sinuosity in the study reach over the entire study period. Overall relative bed heights have not changed substantially, albeit with changes between cross-sections, indicating no net change in bed aggradation or degradation. Bankfull area has actually been decreasing though increasing width/depth ratios would suggest the channel will continue to widen more than deepen. Reach median particle size has returned to 1996 level. While a deflected flow vector and increased bank scouring may portend increased sinuosity in the upper section, measures of stream response indicate that by 2018 the study reach had re-established a dynamic equilibrium.

Acknowledgements. We thank the Atlanta Regional Commission and Cobb County Water System for respectively providing the land cover data needed to derive impervious area estimates and habitat surveys and aquatic macroinvertebrate data.

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