AN EVALUATION OF THE PHYSICAL, CHEMICAL, AND BIOLOGICAL RESPONSE OF A PIEDMONT HEADWATER STREAM TO TEN YEARS OF RAPID DEVELOPMENT: A FINAL REPORT

Ted Mikalsen[1] and Robert L. Bourne[2]

AUTHORS: [1]TMDL Implementation Coordinator, Georgia Environmental Protection Division, 4220 International Parkway, Suite 101 Atlanta, GA 30340 and [2]Environmental Compliance Supervisor, Cobb County Water System, Central Laboratory, 622 South Cobb Drive, Marietta, GA 30060.
REFERENCE: *Proceedings of the 2007 Georgia Water Resources Conference*, held March 27-29, 2007 at the University of Georgia

INTRODUCTION AND OVERVIEW

The few long-term studies of the response of a stream to urbanization (Trimble, 1997 and Krug & Goddard, 1986) address only sediment transport and stream and channel morphology. This paper summarizes the final results of a ten-year study conducted to measure and evaluate the physical, chemical, and biological response of a Georgia Piedmont headwater stream to the rapid development of its watershed. Interim results of this study that have periodically been reported in these Proceedings are identified in the literature cited.

THE PROCTOR CREEK TRIBUTARY WATERSHED AND STUDY REACH

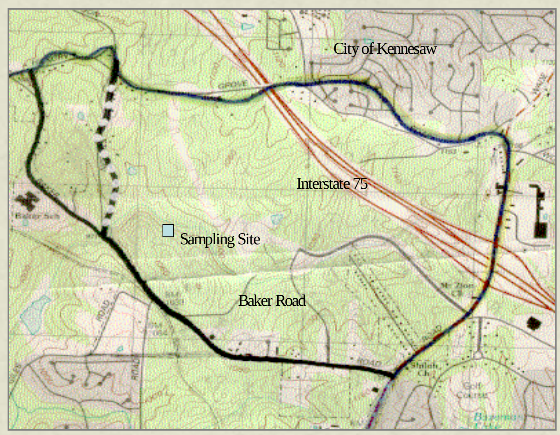
Watershed Characteristics, Development, and Rainfall

The unnamed tributary to Proctor Creek is a first order stream draining a 1.4 mi^2 watershed near the City of Kennesaw on the northern arc of the Atlanta metropolitan area. Figure 1 shows the watershed superimposed on a 1993 Kennesaw U.S.G.S. quadrangle map. The western portion of the watershed does not drain to the study reach.

The 7800' main channel has a 0.016 ft/ft slope; the watershed has a 190' difference in relief. Dominant upland soils are Gwinnett and Madison clay loams and Cartecay soils are the dominant valley series. In 1996, woodlands (38.9%) were the major land cover and the watershed was an estimated 21.3% impervious. A residential development immediately upstream of the sampling reach, which had delivered substantial upland soil-derived sediment loads to the stream during construction, was completed by 2000. The remainder of the watershed developed rapidly, to an estimated 35.8 % impervious by 2006, with commercial-industrial parks and medium and high density residential the major land uses. The 1997 replacement of an original single span bridge immediately downstream at Baker Road also influenced stream morphology.

Annual rainfall at the nearby Georgia Automated Environmental Monitoring Network Dunwoody gauge (www.uga.edu/aemn) exceeded 60" from 2001-04, with a peak of 69.3" in 2002, and was less than 50" in 1999 and 2006. The mean 56.7" annual rainfall for the study period exceeded the 54.7" long-term annual mean at the site.

Figure 1: Tributary to Proctor Creek Watershed



The Study Reach

As shown in attached Figures 2 and 3, the 288.5' (along a baseline parallel to the stream) sampling reach is located 100' upstream of Baker Road and flows from left to right, with now six measured cross-sections. Since cross-sections X #5 and #6 were added after 2001, mean measurements of cross-sections reported normally include only X #1-4. Intermediate sections X #4a and #3a were identified only for map and photographic reference.

In 1996, the upper portion of the study reach (above X #4a) was an undisturbed, relatively straight, moderate gradient, riffle-run sequence. The lower, more sinuous portion of the reach, was a meandering, alternating sequence of pools, riffles, and runs.

STUDY OBJECTIVES AND MEASURES

The objectives of the study were to measure and evaluate the long-term response of the stream plan-form and profile, bed and bank characteristics, channel cross-sections, water chemistry, macroinvertebrate community, and annual habitat responses to rapid development, as measured by estimates of percent impervious area.

Generally annual plan-form and profile and cross-sectional measurements and methods are described in Mikalsen, Bourne, and Sukenik (2001) and Bourne, Mikalsen, and Shelton (2005) and clarified as appropriate. Note that individual cross-section measurements were taken in reference to permanently established baseline elevations arbitrarily set at 20'. The study reach was mapped and photographed approximately yearly. Macroinvertebrate surveys were conducted yearly and water chemistry samples collected quarterly and compiled as annual means. Land use (and corresponding estimates of percent impervious cover) were derived from Cobb County land use maps, periodic Atlanta Regional Commission land activity coverage, and interpretation and field confirmation and a September 2006 field update of 2005 aerial photography.

CHANGES IN CHANNEL PLAN-FORM, SEDIMENT DEPOSITION, CROSS-SECTIONS, WATER CHEMISTRY, AND MACROINVERTEBRATES

Observed changes in measurements over the ten-year study period may be summarized as follows:

Changes in Channel Form

Major changes in channel plan-form and profile (Figure 2) were the growth and stabilization of gravel, rock, cobble, and eventually boulder bars that diverted sufficient flow to scour, undercut, and cause the recession of opposite banks indicative of a future increase in the degree of curvature and sinuosity of the stream channel. Supporting field observations over the period were:

- The evolution and growth of two large gravel, rock, cobble, and eventually boulder bars above X #5 and between X #2-3 from point bars on the right side of the channel (looking downstream) to point and mid-channel bars or braiding, back to the growth and evident consolidation as stable point bars.
- The resultant movement and diversion of channel forming flows toward the outside bend of the channel and resultant scouring, undercutting and recession of the banks on the left sides of the stream channel.
- The scouring and undercutting of the right bank at and above X #3 and the deepening and expansion of a large adjoining scour pool.
- The scouring, undercutting, cantilever failure, and recession of the outside left bank above and below X #3 and the associated growth and consolidation of the opposite point bar.
- The pool which formed above the new culverts installed in 1997, extended above X #1 by August 1998, and continued to deepen until 2000
- Scouring of the other (right) bank of the upper portion of the channel from X # 4-6 observed in 2006 suggests the onset of lateral expansion of this relatively straight, low gradient portion of the channel.

As shown in Table 1, sinuosity (measured as segment thalweg/baseline length in feet) increased slightly over the study period, while water surface slope decreased slightly. This decrease is difficult to interpret because the overall difference in surface elevation over the study reach may be accounted for by a later discussed approximately 0.25' lowering of the streambed (wetted perimeter) elevation of the upper portion of the reach. While riffles have remained in approximately the same locations since 1996, an overall decrease in length caused a 38% increase in their intermediate spacing. Despite the migration of a pool above X #1, expansions of runs elsewhere decreased the total percentage of the reach in pools.

Table 1. Major Changes in Channel Form: 1996-2006

Ratio or Measure	1996	2000	% Chg 96-00	2006	%Chg Total
Sinuosity	1.21	1.20	-0.8	1.23	1.7
Slope (ft/ft)	--	.0074	--	.0066	10.8
Riffle Spacing (ft)	52	65*	25.0	83.5	38.2
% in Pool	46	67*	45.7	39	-15.2

*****1999 Measurements

Changes in Sediment Deposition and Bank Recession

Major changes in selected measurements and observations of sediment deposition (Table 2) were the overall, albeit annually variant, increase in the mean percent of silt and sand in pebble counts and the mean decrease in streambed elevations for X #1-4. While the slight increases in observed habitat assessment scores for embeddedness or sediment deposition suggest a reduction

Table 2. Changes in Sediment Deposition: 1996-2006

Measurement/ Observation	1996	2000	% Chg 96-00	2006	Chg 00-06
% Silt/Sand*	24	36*	50.0	44	83.3
Embedded ness Score	11	12	9.1	14	27.3
Sediment Deposit. Score	10	12	20.0	14	40.0
Bed Elev.*	15.59	15.16	-2.8	15.18	-2.6

***Includes only Cross-Sections X#1-4

in silt and sand distribution, habitat assessments were not sensitive indicators of response. By 2000 mean streambed elevations degraded 0.43', mostly due to degradation at X #1, and remained virtually unchanged since.

Major changes in bank recession, undercutting, and sediment deposition for portions of the study reach, progressing downstream, were:

Left bank--X #6 to below X #4. Moderate scouring of this alluvial soil bank, first observed in 1999, evolved to bank undercutting by 2002 and a mean 0.75 X 1.0' base and height undercut for the portions of the bank not armored by tree roots by 2006. Between 2002-06 there was an associated 1' increase (at X# 6) in the elevation of the gravel, rock, and cobble bar on the opposite side.

Right bank—X #4a to below X# 3. By 2006, the initially scoured and vertical alluvial outside bank in the vicinity of X #3 had extended up and downstream and receded approximately 1.5', where unarmored. Banks in vicinity of X #3 had a mean 1.75 X 1.5' undercut. The adjoining scour pool had expanded and deepened over 1'.

Left bank--vicinity of X #3a. Bank scouring, first observed in 1999, rapidly eroded this alluvial outside bank to vertical with toe undercuts that induced cantilever bank failure. Annual mapping since 2003 has revealed a 3-4' recession of the upper bank from X #3 to above X# 3a and 2.5 to 3' recession in the vicinity of X #3a, with a mean 1.0 X 1.5' undercut. Several large clusters of trees that had anchored bank resistance to erosion were severely undercut. These changes were associated with growth and consolidation of large gravel, rock, and cobble bar on the opposite side

Left bank--vicinity of X# 2. This vertical outside bank was being scoured when first observed. By 2006 mapping showed an approximately 1.5' recession of the upper bank resulting from cantilever failure of the less consolidated alluvial bank above X #2, a nearly 2' recession of the bank at X #2, and a 2-3' recession of the lower consolidated clay bank, largely due to planar failure. The opposite gravel, rock, and cobble bar increased as much as 2.0' beneath X #2.

Vicinity of X #1. By 1998, portions of the channel bed had degraded over 1.0', following replacement of the Baker Road bridge in 1997. Scouring of the right bank above and below X #1 and both banks around a massive root wad that lodged in the channel just below the cross-section in 2003 has continued.

Composite Changes in Channel Cross-Sections

Changes in selected composite measures of measures of channel cross-sections X #1-4 are reported in Table 3. Mean bankfull area, the cross-sectional area of the channel at field estimates (using visual guidelines) of the elevation or stage of the presumed channel building (approximately 1.5 year return frequency) storm flow, increased 53.5% since 1996. In comparison, the mean channel area (the cross-sectional area beneath the elevation of the lower bank) increased but 13.7% to 2000 and then decreased slightly, largely due to a net increase in overall channel bed (not the streambed or wetted perimeter) aggradation over bank recession, by 2006. Mean field estimates of mean bankfull elevation or stage, which increased 0.35' over the study period, were partially responsible for the 50.8% increase in mean bankfull depth. While the mean width of the channel at estimated bankfull stage increased 9.5%, the 0.67' increase in mean bankfull depth, resulted in a 29.9% reduction in the width/depth ratio. The mean entrenchment ratio of the channel width at flood stage (twice the maximum bankfull depth) divided by the bankfull width, increased slightly.

Table 3. Changes in Cross-Sections: 1996-2006

Mean Measures	1996	2000	Chg. 96-00	2006	Chg. 00-06
Bankfull Area (ft2)	35.04	47.65	36.0	53.8	53.5
Channel Area (ft2)	96.45	110.56	14.6	109.7	13.7.
Bankfull Width (W)	23.48	24.15	2.8	25.7	9.5
W/Dpth W/D Ratio	16.99	13.72	-19.2	11.91	-29.9
Entrench-ment Ratio	1.93	1.92	-0.5	1.96	1.6
Bankfull Depth	1.32	1.75	32.6	1.99	50.8
Bankfull Elevation	17.34	17.36	0.12	17.69	2.0

***Includes only Cross-Sections X#1-4

Changes in Individual Cross-Sections

With little significant change in X #4, only X #1-3 are shown in Figures 4-6 and discussed here, progressing downstream:

X #3. Major changes were the approximately 1.2' deepening and lateral expansion of the scour pool adjacent to the right outside bank and an approximately 1-2' recession of both banks. Mean streambed elevation degraded 0.42’ by 2000 and little since. The increase in bankfull area from 23.34 to 38.43 ft^2 in 2000 and 55.75 ft^2 in 2006 was due primarily to deepening of the scour pool, bank recession, a 2.10’ increase in bankfull width, and increasing estimates of bankfull elevation.

X #2. Major changes were the scouring, planar failure, and 1-2’ or approximately 10 ft^2 recession of the left (outside) bank and leftward migration and up to 0.7’ deepening of the scour pool below, while the gravel, rock, cobble point bar on the right expanded leftward and increased up to 2.1’ in elevation. The mean streambed elevation degraded 0.38’ by 2000 and little since. The increase in bankfull area from 44.24 to 50.94 ft^2 in 2000 and 60.92 ft^2 in 2006 was due primarily to left bank recession, the deepening of the scour pool, and increasing estimates of bankfull elevation.

X #1: The most pronounced changes were the 1.08’ degradation of the mean streambed elevation by 2000 (following installation of the new culverts), followed by a 0.35’ bed aggradation, and the approximately 2’ recession of the right bank by 2006. Bankfull area, largely because of bed degradation, increased 81.2% from 34.95 to 63.16 ft^2 in 2000 and then, in association with bed aggradation, decreased to 57.85 ft^2 by 2006, despite increasing bankfull elevation. The rapid decline in the bankfull width to mean depth ratio from 20.63 to 13.93 in 2006 was due mostly to the increased mean bankfull depth.

Changes in Water Chemistry

Previous analysis of correlation between annual rainfall, percent impervious, and measures of water chemistry (Bourne, Mikalsen, and Shelton, 2005) suggested that annual means of conductivity (micromhos/cm), closely related chlorides (mg/L), and a composite water quality index were the best indicators of the response of water chemistry to the impacts of development. The index (Peters and Kandell, 1997) compiles measures of site water chemistry, compares them to a distribution of values for the Atlanta metropolitan region, and returns a value ranging from 0 to 1, with higher scores indicating more degraded conditions and less than 0.33 “best” conditions.

As shown in Table 4, the index fluctuated slightly, but increased by 50% in 2006 to a level approaching the “average” range. Annual mean conductivity levels and correlated chloride concentrations have gradually increased to respectively 35.7 and 58.6% higher than 1996 levels, versus a 68.1% increase in impervious area.

Table 4. Changes in Water Chemistry: 1996-2006

Measurement	1996	2000	% Chg 96-00	2006	% Chg 00-06
WQ Index	0.16	0.19	18.8	0.24	50.0
Conductivity	61.1	78.6	28.6	82.9	35.7
Chlorides	2.27	2.33	2.6	3.6	58.6
% Impervious	21.3	27.6	26.6	35.8	68.1

Changes in Macroinvertebrate Population and Habitat

Annual macroinvertebrate surveys conducted by the Cobb County Water System disclosed the historic disappearance of sensitive species (Bourne, Mikalsen, and Shelton, 2005) and decline in taxa richness over the study period. However, as shown by Table 6 (and intervening index values), the modified (for the Southeast) Hilsenhoff Index, which returns values of 1-10, with 10 corresponding to a “worst” (derived from a calculation of the number of organisms in each taxon multiplied by an associated pollution tolerance value assigned to the taxon), decreased from 1996 to 2006, contrary to other indicators of macroinvertebrate community health. Habitat assessment scores, which may vary from 0-200, representing the “best” conditions, ranged from 91.0 to 133.5 over the study period, increased in 2006.

Table 5. Changes in Macroinvertebrate Population and Habitat Assessment: 1996-2006

Measurement	1996	2002	% Chg 96-02	2006	% Chg 00-06
# Taxa	29	10	-65.5	19	-34.5
# Individ.	281	135	-52.0	191	32.0
Hilsenhoff I.	5.9	5.7	-3.4	4.7	-20.3
Habitat Assmt	123	115.6	-6.0	133.5	8.3
Embeddedness	11	10	-0.9	14	27.3

STREAM RESPONSE TO RAPID DEVELOPMENT

Following are evaluations of the responses of measures of water chemistry, macroinvertebrate communities and habitats, channel cross-sections, sediment deposition and bank recession, and channel plan-form to the rapid development of the watershed from 1996-2000. Where used in this evaluation, statistical tests (calculated with Microsoft Excel) were intended only to draw inferences about relationships between measurements, and not as rigorous tests of hypotheses. Sample sizes (n = 10) are small and some measures imprecise, interpolated, or annual summaries of temporally and spatial variant phenomena.

Water Chemistry, Biology, and Habitat

Assessment of scatter plots and trend lines (fitted by linear regression) of annual measurements of selected constituents (Figure 7) revealed parallel upward trend lines for the water quality index and percent impervious and greater increasing slope for mean annual conductivity levels, distorted by an inexplicably high outlier in the 2004 annual mean. Both the annual mean conductivity (+35.7%) and the water quality index (+50.0%) increased as the impervious portion of the watershed increased 68.1% over the study period. While the index and conductivity are intercorrelated (Pearson r = 0.559), the water quality index is most strongly correlated with percent impervious.

Table 6. Correlation Between Water Quality, Percent Impervious Area, and Annual Rainfall

Measurement	Percent impervious	Annual Rainfall
Percent impervious	1.000	
Annual Rainfall (in)	0.085	1.000
Conductivity (micromhos/cm)	0.477	0.377
Water Quality Index	0.778	0.028

While earlier analysis suggests that conductivity may also be associated with annual rainfall amount (r = 0.377), it is also moderately and positively associated with percent impervious. The water quality index, which increases as water quality decreases, is strongly associated with annual percentages of impervious area. Increased conductivity levels in urban streams (Mikalsen, 2005) are likely caused by increased alkalinity and calcium concentrations derived from the weathering and dissolution of calcium carbonate, sulfate ions, and closely correlated chloride ions derived from increased urban land surfaces and activity.

Of the biological measures, the observations of the disappearance of sensitive species and reduction of the number of macroinvertebrate taxa observed were the most useful indicators of biological response. Other measures evaluated showed little relationship with changes in impervious area. The Hilsenhoff Index, which shows a contrary "improvement" in the macroinvertebrate community, may be due, as suggested by Cobb County biologist Adam Sukenik, to an over-emphasis on Chronimids (midges), which can be very tolerant and found in large numbers in the study reach, while insufficient weight given to less abundant sensitive species. Habitat assessments and internal scores as influenced by different observers, change in methods, and varied streambed conditions, were not considered a sensitive indicator of the potential impacts of development over the study period.

Channel Cross-Sections

Scatter plots and trend lines for annual measurements of channel cross-sections showed virtually parallel slopes for highly correlated (r = 0.904) mean bankfull area and mean bankfull depth (r = 0.885) with percent impervious and inverse relationships, respectively r = -0.718 and r = -0.788, with annual percent increase in impervious area. Mean bankfull area, bankfull depth and percent impervious area increased at comparable rates over the study period, to by respectively 53.5, 50.8 and 68.1%.

The rapid increase in bankfull area was due mostly to the increasing field observations of bankfull elevation or stage rather than increases in mean bankfull width or changes in channel and streambed elevations. Mean channel area, though well correlated with bankfull area (r = 0.861), increased but a modest 13.7%. This figure represents the actual mean 13.26 ft^2 increase in the channel area caused by bank recession and bed aggradation or degradation.

As mean bankfull depth increased substantially, mean bankfull width increased a modest 9.5%, and mean streambed elevation (wetted perimeter) decreased 2.6%. With mean bankfull depth increasing substantially, largely due to the increasing estimates of bankfull elevation or stage, and the bed elevation and bankfull width changing only slightly, the width depth ratio (bankfull width divided by depth) decreased 29.9% and was strongly negatively correlated with both bankfull area (r = -0.859) and percent impervious area (r = -0.872).

In a developing watershed where the frequency, volume, and shape of the hydrograph of the bankfull or channel building flood is be altered by changes in the hydrology of the watershed, the visual indications of the elevation or stage of the "bankfull" event will increase. Increases in bankfull elevation, aggradation or degradation of the channel bed, and changes in bankfull width influence measurements of channel geometry. In this watershed, measurements of channel geometry, particularly mean bankfull area were closely associated with increasing impervious area over the duration of the study period.

Sediment Deposition, Bed Change, and Bank Recession

Trends in the relationship between the annual increase in percent impervious area, annual rainfall, mean stream bed elevation, and the mean percent silt and sand disclosed by pebble counts were examined to evaluate the response of measurements of sediment deposition to annual development and rainfall. Visual analysis, confirmed by the distribution-free Spearman rank-correlation test (at the 0.05 significance level) indicated these variables were independent, with no relationship with percent impervious area. However, when data plots revealed that the ten-year pattern of percent silt and sand was similar to but lagged two years behind the annual rainfall pattern, a Spearman rank correlation of annual mean percent sand and silt and annual rainfall lagged two years (Figure 8) supported the hypothesis that the two variables were not independent (correlated) at the 0.05 significance level. Though many factors could influence the rate of delivery and accumulation of sediment in the streambed, there is an indication of a delayed positive relationship between high annual rainfall and elevated percentages of silt and sand in pebble counts.

Bed response to 1997 culvert installation. The extension of a pool to and above X #1 by August 1997, an increase in water depth at X #1 from 0.10' to approximately 0.40' in 1998 with little subsequent change; the rapid mean 0.45' degradation of X #1-4 mean streambed elevations; and the decrease in streambed elevations from 1997-98 at X #1 (-0.50) and X #2 (-0.98') suggest these changes are due to adjustments to the new culverts installed at Baker Road in 1997. Other potential local causes of causes of changes in streambed and water surface elevations are unlikely. The mean annual streambed elevation of the reach varied little more than 0.10' since 1997; substantial sediment loads delivered from the upstream residential development continued until 2000 and increased delivery of alluvial soils began in approximately 2002; and the elevated annual rainfall years were from 2001-04.

Increased alluvial sediment deposition. Field observations of increased alluvial soil deposition, over oxidized upland soils, suggest that the undercutting and failure of channel banks, perhaps exacerbated by above average rainfall and hydrologic changes in the watershed have annual rainfall, have become the more significant overall source of the sediment loads moving through the study reach.

Bank erosion and sediment bar growth. Surveys of stream surface elevations revealed that the difference in elevation at the top of the stream reach just above X #6 and the downstream extent at X #1, decreased from 2.54' in 2004 (and 2000) to 2.34' in 2006, with the 0.20 decrease being accounted for by a 0.20 drop in water surface elevation at X #1 and approximately 0.35 lowering of the water surface and 0.30 lowering of the streambed elevation from X #4-6. The authors can only speculate that the bed lowering may be associated observations of intensified scouring on both banks that suggest lateral expansion of the channel along this relatively straight, low gradient portion of the reach.

Beginning in 2003, bank stress, indicated by observations and measurements of undercutting, increases in bankfull width, and upper bank recession increased on the outside bends at X #6, X#3, from below X #3 to X #2, and below X #1. Bank undercutting of the left bank around X #6, beginning in 2002, was induced by the growth and consolidation of a point bar on the right inside bank which diverted and compressed flows sufficient to scour and undercut the unarmored alluvial soils channel bank. The intensified and expanded scouring and undercutting of the right bank around X #3 was induced by the deflection of flow across a riffle with sufficient capacity to scour and undercut both unarmored and root protected portions of the alluvial channel bank. The portion of the reach below X #3 with the steepest gradient in the study reach experienced the most complex evolution. The initial sand, gravel, rock, and cobble bar above and below X #3 migrated downstream and evolved from a point bar to braided channels to a large mid channel bar and back by 2003 to a large consolidated rock, cobble, and boulder bar, partially supplied by the growth and deepening of a large upstream scour pool in the vicinity of X #3. Flows diverted almost perpendicular to the bar were sufficient to undercut adjoining trees, undercut and induce cantilever bank collapse and recession of as much as 3-4' on the left outside bank, and wash away a protruding cluster of sweet gums trees which had anchored a debris and sediment bar. At X #2 a similar pattern of growth and consolidation of a point bar caused the deflection of flow sufficient to scour and cause the planar failure and approximately 3' recession of the consolidated clay outside bank. The scouring and recession of both banks below X #1 was caused by the diversion of high flows around both sides of the sweet gum root wad which had been swept downstream from below X #3.

Channel Plan-Form and Profile

Plan-form and profile were the least responsive measures to watershed development over the study period. In contrast to some cross-sectional measures, channel form dimensions such as meander wave length, radius of curvature, and amplitude have shown little discernable change in response to watershed development over the study period. Sinuosity increased slightly from 1.21 in 1996 to 1.23 in 2006 and slope has decreased slightly from 2000 to 2006, albeit in response to a yet explained decrease in the streambed and water surface elevation of the upper portion of the reach.

However, observed recent increases in bank recession portend future longer-term changes in channel plan –form and profile. The size, caliber of materials and stability of several pre-existing inside bars have, partially as the result of the increasing competence and power of extremely high flows, increased. Increased compression or acceleration of extremely high flows at portions of the reach with higher gradients/slopes, and increased agitation at locations where the main portion of the meandering flow is reflected off outside banks, are providing sufficient competence and power to scour and deepen pools and convey and deposit up to boulder-sized material on downstream point bars, thereby increasing the size and stability of the point bars. The stabilized point bars have deflected and compressed flows with sufficient power to undercut and erode the outside banks at a rate and behavior associated with the soil characteristics and armoring of the channel banks. Continued erosion and recession of these banks will increase the curvature and meander bandwidth, and hence the length of the thalweg and sinuosity of the reach. And as the flow path lengthens over a given change in elevation controlled at the foot of the study reach, slope must decrease.

GENERAL CONCLUSIONS

Initially, the authors hypothesized a lag time between increased development and measures of stream response, particularly physical measures. However, after ten years of observations and study, we recognize that watershed development and its surrogate measure, estimated percent impervious, are temporally and spatially variant, infrequent and crudely measured, and continuous, rather than discrete measures that can be adequately represented by annual measurements. Conversely, most of the measurements used to evaluate the response of the stream were annual summaries of time variant conditions, based on single or limited composite samples, taken at varied times of the year. Thus it was impossible to establish a precise instrument to adequately measure the lag between development and stream response. Nevertheless circumspect analysis observations, trends, correlation between measurements, and nonparametric tests led us to conclude that a number of measurements of stream conditions have been continuously associated with increases in percent impervious area of the watershed and some measures of plan form and profile which have responded much more slowly, are likely to continue and become manifest over a longer time duration.

- Of the measures of water quality, mean annual conductivity levels and the site water quality indices were highly correlated with and best tracked the increasing percent impervious area in the watershed.
- Of the biological measures, the observations of the disappearance of sensitive species and reduction of the number of macroinvertebrate taxa observed were the most useful indicators of biological response.
- Several measures of channel cross-section were positively or negatively related to changes in percent impervious over the duration of the study period. Of those mean bankfull area and depth most closely tracked the increase in percent impervious area.
- Measures of plan-form and profile are less responsive, but likely to respond to the effects of development over a longer period of time with increased sinuosity, meandering, and decreased slope.

ACKNOWLEDGEMENTS

Steve Shelton, Adam Sukenik and Erin Feichtner of the Cobb County Water System, Central Laboratory for collecting or providing data, analysis, keen observations, and helpful insights.

LITERATURE CITED

Bourne, R. L., K. T. Mikalsen, and S. Shelton. 2005. Evaluation of the long-term impacts of urbanization on a Piedmont headwater stream: an evaluation of the physical, biological, and chemical indicators of response. In: *Proceedings of the 2005 Georgia Water Resources Conference*, held April 25-27, 2005 at the University of Georgia. Kathryn J. Hatcher, Editor, Institute of Ecology, University of Georgia, Athens, GA.

Krug, W. R. and G. L. Goddard. 1986. The effects of urbanization on stream flow, sediment loads, and channel morphology in Pheasant Hill Branch basin near Middleton, Wisconsin. U. S. Geological Survey Water Resources Investigations, Report 85-4068.

Mikalsen, K. T., R. L. Bourne, and A. Sukenik. 2001. Evaluation of the long-term impacts of urbanization on the physical characteristics of a Piedmont headwater stream. In: *Proceedings of the 2001 Georgia Water Resources Conference*, held March 26-27, 2001, at the University of Georgia, K. J. Hatcher, editor, Institute of Ecology, the University of Georgia, Athens, Georgia.

Mikalsen, K. T. 2005. The components of elevated total dissolved solids and conductivity levels in Georgia urban streams In: *Proceedings of the 2005 Georgia Water Resources Conference*, held April 25-27, 2005, at the University of Georgia, K. J. Hatcher, editor, Institute of Ecology, the University of Georgia, Athens, Georgia.

Peters, N. E. and S. Kandell. 1997. Evaluation of streamwater quality in the Atlanta region. In *Proceedings of the 1997 Georgia Water Resources Conference*, held May 22-22, 1997, at the University of Georgia. Kathryn J. Hatcher, Editor, Institute of Ecology, University of Georgia, Athens, Georgia.

Trimble, S. W., 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science*, 278, 1442-44.

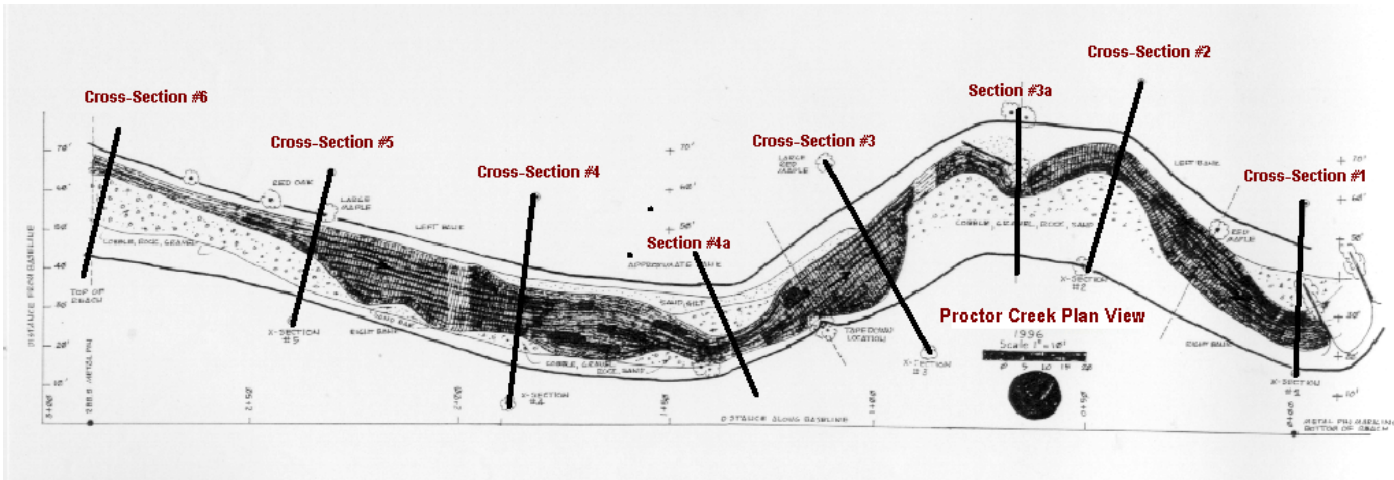


Figure 2: The study reach in 1996

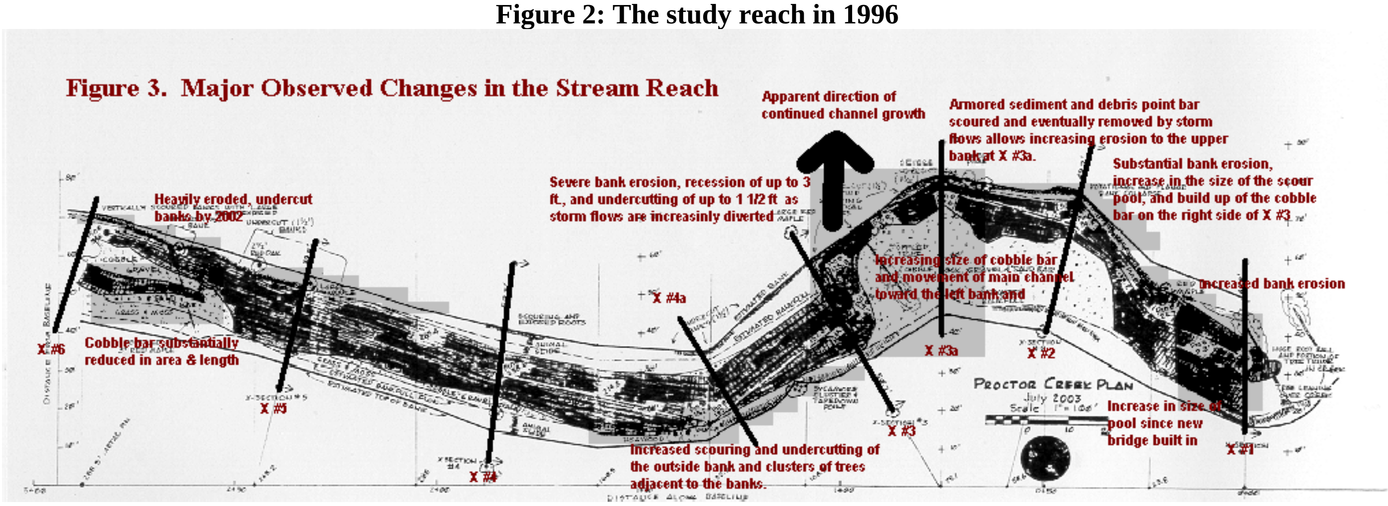


Figure 3: Major changes in channel plan-form from 1996-2006 (Figure to be revised & simplified in final version

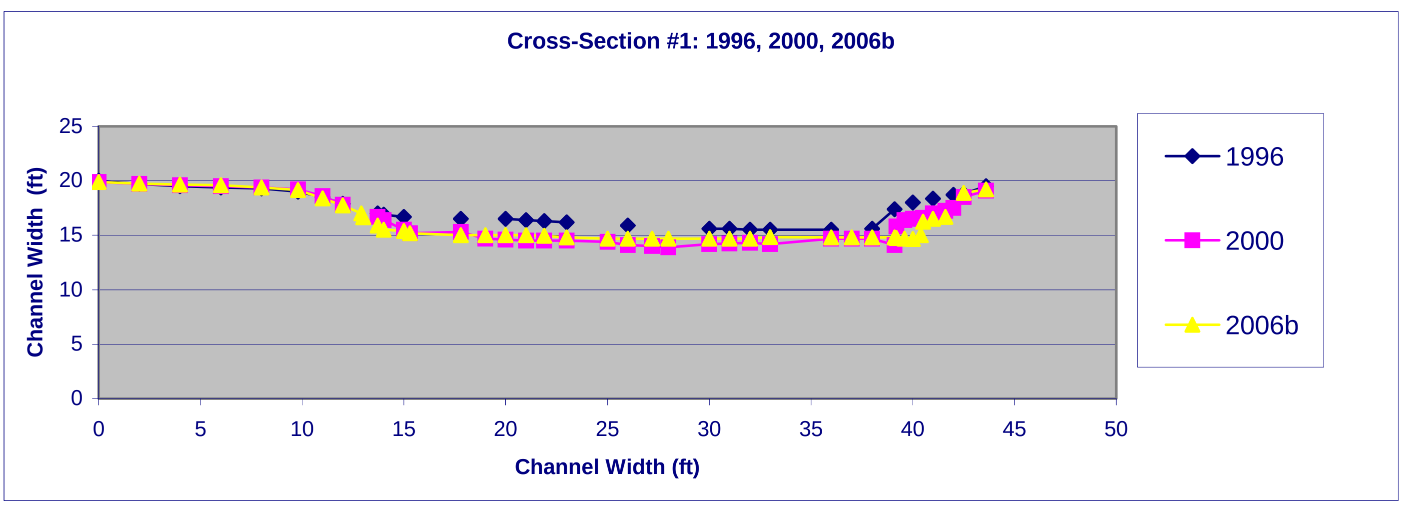


Figure 4: Changes in cross-section #1 1996-2000-2006

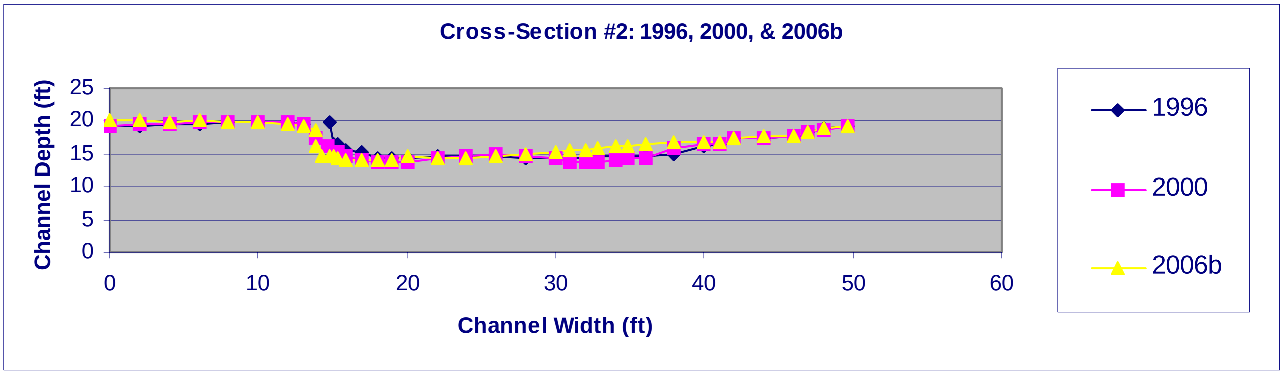


Figure 5 Changes in cross-section #2 1996-2000-2006

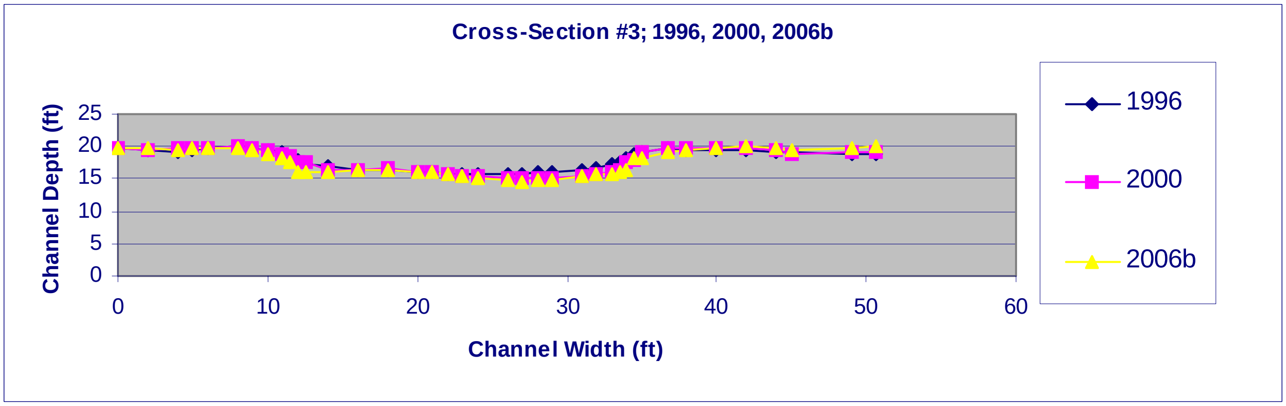


Figure 6 Changes in cross-section #3 1996-2000-2006

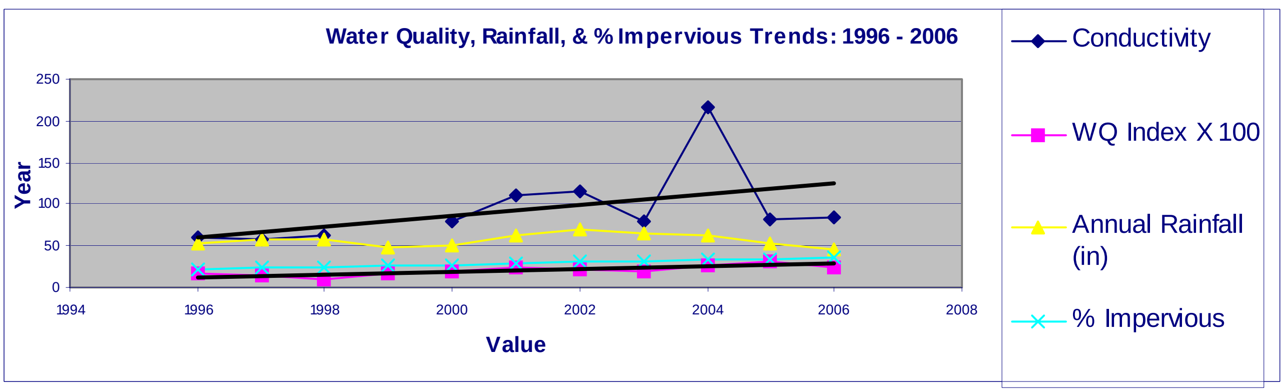


Figure 7 Water quality, rainfall, and impervious area trends 1996-2006

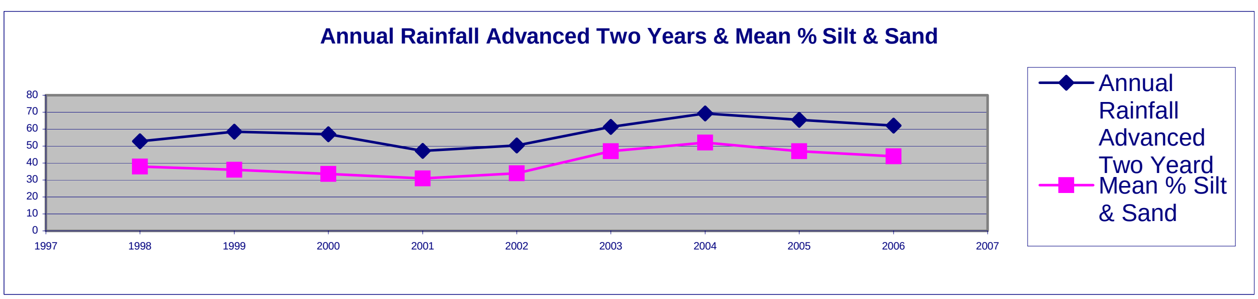


Figure 8 Annual Rainfall advanced two years and percent silt and sand