A Long Term Study of the Response of a Piedmont Headwater Stream to Rapid Development: An Evaluation of Relationships Between Trends in Bankfull Width/Depth Ratios, Bankfull Quantity, Bankfull Area, and Shear Stress

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Abstract. This continued assessment of a long-term study of the response of a Piedmont headwater stream to rapid development addresses trends and behavior of selected physical attributes of stream morphology including bank-full width/depth ratio, bankfull area, bankfull quantity, and shear strength. For the five study reach cross-sections reported, annual mean bankfull area and mean percent silt and sand in pebble counts were highly correlated (n=5) with and followed a similar trend to annual rainfall lagged two years, while mean bankfull width/depth ratio, and to a lesser, extent mean bed elevation are negatively correlated, suggesting an approximately two-year lagged response to annual rainfall. On the other hand mean calculated quantity, mean bankfull width, and mean bankfull depth were highly inter-correlated and followed the same gradually increasing trend as the increase in the percent of the impervious portion of the watershed. The mean width depth ratio for the cross-sections has decreased over time indicating that the bankfull cross-sections are deepening more rapidly than widening in response to the development of the watershed. Initial estimates of the bankfull area at the study cross-section ranged from 23.3 to 44.2 ft_2 and enlarged at widely varied rates (9.4-121.4% over the ten-year study period. The bankfull areas were higher and increased at a greater rate in the lower sinuous and pooled portion of the study reach as compared to the upper and straight, riffle-run cross-sections. Proffered explanations for these widely varied estimates were that varied bankfull areas could satisfy the continuity equation ($Q_{bf} = A_{bf} * V$) for open channels, varied physical conditions at cross-sections could affect flow dynamics, particularly velocity, rapid and pronounced changes in channel configurations could mask or obscure the key visual determination of bankfull elevation, and other influences. Mean cross-sectional calculations of bankfull quantity with the Manning equation increased 14.1% from 103.3 CFS in 1999 to 117.9 CFS in 2006, with a substantial range in the mean quantities for individual cross-sections (68.7 to 92.1 and 179.5 CFS for lower Cross-sections #1 and 2). These variations in calculated bankfull flow suggest that the continuity equation does not completely explain cross-section variations in bankfull area. Closer examination of the pronounced upstream changes in channel configuration, widely varied velocities, and pronounced changes at Cross-section #2 suggest that e masking or distortion of key visual indicators of bankfull elevation may have contributed to overestimating bankfull area and consequently quantity calculations. Backwater effects, downstream flow impediments, and substantial degradation of the mean channel bed elevation in advance of adjustments in visual indications of bankfull elevation may have contributed to relatively greater estimates of bankfull area and estimates of Q_{bf} at Cross-section #1.

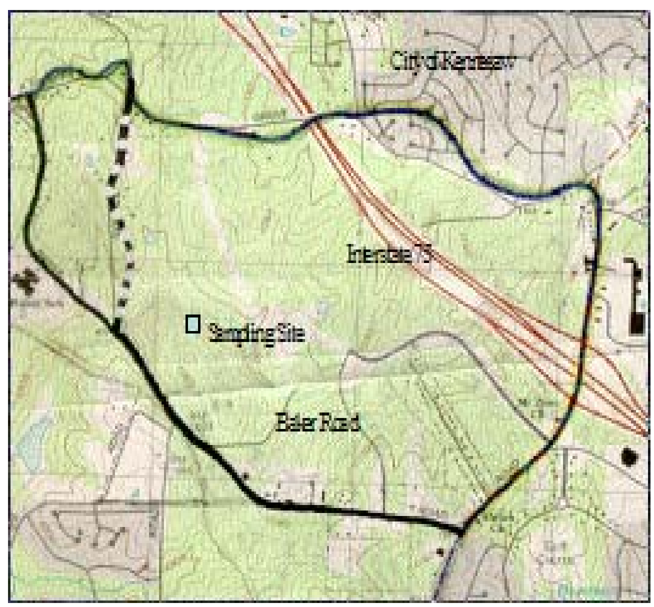

Figure 1. Tributary to Proctor Creek Watershed

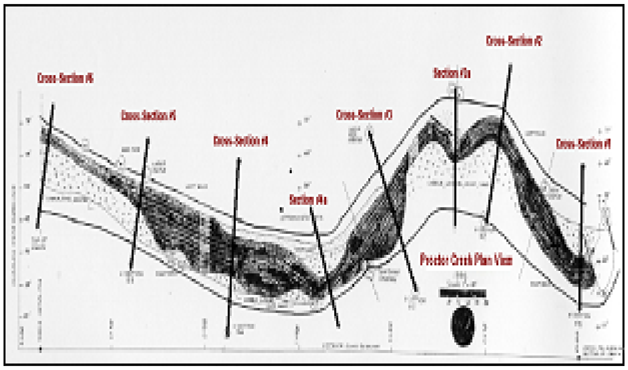

Figure 2. Stream Reach and Cross-sections

INTRODUCTION AND OVERVIEW

An ongoing long-term geomorphology study of a stream reach and selected cross-sections (See Figures 1 & 2) located on an un-named tributary of Procter Creek in Northwest Cobb County began in the Summer of 1996. The initial presentation in 1997 discussed the reach and watershed selection process and the evaluation techniques used to gather the data. Updates on the observations from the study have been presented at the Georgia Water Resource Conference since 1997. These updates included empirical geomorphologic evaluations along with discussions on dimensional changes. Correlations between the geomorphologic evaluations and land use, water chemistry and biological data were examined. For information on the methods used and observations made, please reference papers presented in past Georgia Water Resource Conferences (Mikalsen, et al., 2001, Bourne, et al., 2005, and Mikalsen, et al.., 2007).

Due to space limitations, this paper discusses only the relationships between trends and the behavior in bankfull width/depth ratios (W/D_{bf}), bankfull area (A_{bf}), bankfull quantity (Q_{bf}), shear stress and selected variables during the latter portion of the study period.

SUMMARY OF RESULTS

Evaluation Procedures. Estimates of bankfull quantity (Q_{bf}) and shear stress (τ) for Cross-sections #1-5 were derived from existing field data for the years from 1999 to 2006 when water surface and bed elevations surveys were conducted. These variables, width/depth ratio, and other potentially related variables (n = 23) were subject to pair wise correlation analysis (Table 1) to discern stronger associations between variables and cull less influential variables from further analysis. Changes in the annual means of selected variables for Cross-sections #1-4 (only three years of data were available for Cross-section #5) were rescaled where needed, plotted, and graphs visually examined to identify comparable cyclic or linear trends between variables over time. Pair wise correlation analysis between variables for albeit small annual means for the four cross-sections (n = 5) was conducted to visually discern the general strength of relationships between variables. Then the relationships between width/depth ratio, quantity, shear stress and other variables over time were evaluated and summarized here. Due to space constraints most supporting figures and discussion of the dynamics of changes at individual cross-sections must be deferred until the conference presentation.

Table 1. Pairwise Correlation of Selected Variables

	W/D_{bf} Ratio	*$Area_{bf}$ (ft2)*	*$Width_{bf}$ (ft)*	*Mean D_{bf} (ft)*	*U.S. Slope (ft/ft)*	*Mean Bed Elev*
W/D_{bf} Ratio	1					
$Area_{bf}$ (ft2)	0.47	1				
$Width_{bf}$ (ft)	0.69	0.92	1			
Mean $Dpth_{bf}$ (ft)	-0.56	0.38	0.20	1		
U.S. Slope (ft/ft)	0.30	0.27	0.36	-0.01	1	
Mean Bed Elev	-0.51	-0.75	-0.66	0.10	-0.66	1
Velocity (fps)	0.16	0.12	0.18	-0.04	0.87	-0.40
Quantity (cfs)	0.32	0.59	0.59	0.19	0.83	0.27
Shear Stress (t)	0.29	0.33	0.39	0.04	0.99	-0.68
Angle	0.58	0.48	0.53	-0.18	-0.23	-0.31
Manning "n"	0.4	0.50	0.55	0.05	0.90	-0.84

Trends. Visual evaluation of annual mean values of selected variables from 1999 to 2006 (following Figure 3) revealed two general patterns: 1) a cyclical pattern which was directly or inversely related to the roughly cyclical albeit spurious pattern of mean annual rainfall which occurred approximately two years prior to the corresponding annual mean cross-section measurements; and 2) generally linear increases or decreases in annual mean values over time.

The previously described (Mikalsen and Bourne, 2007) correspondence and correlation (n=5) between (see Figure 4) the pattern of rainfall lagged two years and percent sand and silt composition of bed samples (0.96) is also replicated for mean bankfull area (0.86) and depth (0.86). All of these variables were highly intercorrelated (>0.90). The pattern of rainfall lagged two years was inversely related and negatively correlated with bankfull width/depth ratio (-0.91) and to a lesser extent mean bed elevation (-0.63). Mean bankfull area is generally increasing over time in a pattern that suggests the influence of variables associated with the effects of the magnitude of prior rainfall. Percent silt and sand in the bed samples peaked in 1999 following elevated rainfall and intensive development in the vicinity of the sample reach and again in 2004, approximately two years after the peak recorded annual rainfall of 69.1". An increase in the percentage of silt and sand and associated visual observations of oxidized soil indicate an increase in the upland soils that were being conveyed to and through the sample reach. Positive variations in mean bankfull area and depth with lagged rainfall and percent sand and silt and inverse relations with W/D ratio and mean bed elevation indicate that increased percentages of silt and sand are associated with degraded or lower mean bed elevations (n=6, -0.85) and the resultant increase in mean bankfull depth has resulted in an expected decrease in the width/depth ratio. This tendency corresponds with the generally observed association of fine sediments or increases with narrower, deeper channel cross-sections.

Calculated bankfull quantity and mean bankfull width both showed a gradual linear increase (respectively 12.5% and 8.8%) from 1999 to 2006. Changes in estimates of calculated bankfull quantity over time were most positively correlated with bankfull width (0.90), depth (0.83), area (0.73), and percent silt and sand, (0.62) and negatively with width/depth ratio (-0.78). Shear stress, an estimate of stream's capacity to entrain bed material and highly correlated (0.95) immediately upstream slope both followed a similar pattern of decreasing from 1999 to a minimum in 2004 and then increasing to 2006. The minimum mean bed elevations were associated with maximum annual mean values for lagged rainfall, bankfull area, mean depth, and percent silt and sand.

Bankfull Width/Depth Ratio. Bankfull width/depth ratio, derived from the division of bankfull channel width by mean bankfull channel depth, is a convenient shorthand for describing channel shape. Wide, shallow channels have higher ratios than narrower, deeper channels. Generally width/depth ratios tend to increase as channels widen and decrease as channels incise. In theory, the width/depth ratio reflects equilibrium between sediment caliber and load and stream quantity and slope or between the measures of stress (flow vectors, stream competence, shear stress, etc). Thus the physical characteristics (pooling, riffles, braids, bar formation, degree of curvature, shape, and width/depth ratio) of a cross-section should be more or less associated with variables measuring the above attributes. The 11.8% decline in the width/depth ratio for cross-sections #1-4 from 1999 to 2006 and associated increase in mean bankfull area (17.3%) is best explained by the more pronounced increase in bankfull depth (23.5%) as compared to bankfull width (8.0%), indicating that the bankfull cross-sections are tending to deepen more rapidly than widen in response to the increasing calculated bankfull quantity. As expected, mean bed elevations were inversely related (-0.51) to mean bankfull depth. However, the unexpected inverse relationship with mean bed elevation and bankfull width (-0.66) and width/depth ratio (-0.51) are more likely due to the stratification of cross-sectional measurements by mean bed depth, where lower bed elevations (14-15') of Cross-sections #1-2 had wider, deeper channels and higher width/depth ratios than those of the upper Cross-sections #3-5 (15.4-16.4').

Variations and Changes in Bankfull Area. The 1996 measured bankfull areas for Cross-sections #1-4 ranged from 23.3 ft^2 to 44.2 ft^2 with an overall mean of 35.0 ft^2 that increased 30.4% to 45.7 ft^2 in 1999 and 52.9% to 53.56 ft^2 by 2006. The 1996-2006 increases in bankfull cross-sectional areas were greater for the sinuous and pooled lower cross-sections X#3 (124.1% from 23.3 to 52.3 ft^2), X#2 (45.9% from 44.4 to 64.6 ft^2), and X#1 (59.9% from 34.9 to 55.7 ft^2) than for the upper relatively straight riffle and run C,ross-sections X#4 (10.4% from 37.7 to 41.6 ft^2) and X#5 (9.4% from 32.0 ft^2 in 2002 to 35.0 ft^2 in 2006). Thus there was a substantial variation in both the bankfull area of the cross-sections in 1996 as well as the rate of expansion associated with changing conditions in the watershed including increases in percent impervious. These differences may be attributed to relationships between flow velocity and cross-sectional area expressed by the continuity equation, physical differences between the cross-sections, or error in the determination of bankfull elevations.

The continuity equation expresses the relationship that quantity (volume) flowing through a conduit is the product of cross-sectional area and velocity. Thus for a bankfull (approximately 1.5 year return frequency) volume flowing through a channel the bankfull cross-sectional area needed to accommodate that volume will vary with the velocity of flow. Grossly put, in portions of the channel where the velocity decreases, the cross-sectional area must increase to accommodate a given quantity of flow. Accordingly, bankfull cross-sectional area and changes over a reach should be influenced by velocity and the attributes of the channel cross-sections which influence velocity (resistance, upstream channel slope and sinuosity, bankfull width-depth ratio) and estimates of the actual bankfull elevation for the channel cross-section.

By 2006, the bankfull areas of the lower more sinuous and pooled Cross-sections #1-3 were substantially larger (52.3-64.6 ft^2) and had a greater increase in area (45.9-124.1%) than the relatively straight, riffle-run, upper Cross-sections #4-5 (respectively 41.6 and 35.0 ft^2 with but a 10.4% increase in the bankfull area of Cross-section #4). The estimated Manning "n", an indication of resistance which incorporates sinuosity, and the angles of flow incidence were lower for the upper Cross-sections #4 and 5, while estimated velocities were higher (except for Cross-section #2) than the lower Cross-sections #1-3. In the upper cross-sections, the lower percent increases in bankfull area were due primarily to increased bankfull width resulting from increased estimates of the bankfull elevation and undercutting and recession of the left channel bank after 2000. In the lower cross-sections the higher increases in bankfull area and associated decreases in width-depth ratio resulted from a combination of increases in the depths of pools, lowered mean channel bed elevations, and bankfull depth increasing at a faster rate than bankfull width (due to an excess of bank erosion on the outside bends over deposition on the inside bend). Two other factors which could contribute to differences in estimates of bankfull area are superelevation of storm flows along the outside bends of curved sections of the channel and the difficulty of determining visual indicators of bankfull elevation on rapidly changing, severely undercut or eroded channel banks.

Calculated Bankfull Quantity. Mean estimates of bankfull quantity for Cross-sections #1-4, derived from the Manning equation (calculated using field data and guidelines for estimating channel roughness--the Manning "n"), increased 14.1% from 103.3 to 117.9 CFS between 1999-2006. Mean calculations of bankfull quantity over the five year period were highest for the lower Cross-sections X2 (179.5 CFS) and X#1 (92.1 CFS) followed by upper Cross-sections X#4 (83.8 CFS), X#3 (73.3 CFS), and X#5 (68.7 CFS). Quantity calculations for Cross-section #2 from 1999-2006 ranged from 121.6 to 215.6 CFS. Given changing conditions in the watershed, particularly the progressively increasing percent impervious area, the mean increase in calculated bankfull quantity is reasonable. However, assuming that the continuity equation balances velocity and bankfull flow area to accommodate a given bankfull volume, why are calculated bankfull quantities for Cross-sections #1-2 substantially higher than the upstream cross-sections?

Of the components of the Manning equation used to calculate bankfull quantity (Q_{bf} = [1.49/"n"] * $Area_{bf}$ * Hydraulic Radius $[Abf/Wbf]^{2/3}$ * $Slope^{1/2}$), quantity was more correlated with Manning "n" (0.85), upstream slope (0.83) and related velocity (0.87) than bankfull area (0.59) and hydraulic radius (0.41), suggesting that for this study reach, Manning "n" and slope (influencing velocity) were more influential determinants of quantity than the hydraulic radius (0.409) or mean bankfull depth. The substantially higher calculations of bankfull quantity at Cross-section #2 are due primarily to the conjunction of the largest estimated bankfull area (64.6 vs the overall mean of 54.6 CFS in 2006) with by far the greatest immediately upstream slope (0.015 vs the overall mean of 0.005 ft/ft) among the five cross-sections.

Cross-section #2 is just downstream from the portion of the study reach which has endured the most pronounced physical changes over the study period. The upper portion of the channel has evolved from a rock and cobble bar on the right side, braided, and reconsolidated as a large stable bolder, cobble, and rock bar on the right side. Storm flows washed away an immediately upstream point bar on the left side by 1999 and have rapidly eroded and undercut the left bank above and at Cross-section #2. Immediately upstream elevation differences, slopes, and calculated velocities have varied substantially between 1999-2006. The channel cross-section has responded with under cutting and erosion of the left bank and the deepening of a scour pool on the left side and the 2003-2006 deposition and accumulation of a cobble and rock bar on the right side. Lacking visual indicators of bankfull elevation on the undercut left bank, the use of the height of the rapidly growing bar on the right side as an indicator of bankfull elevation has led to 0.75' increase in the estimated bankfull elevation since 2002 and a corresponding 2002-2006 increase in the estimated bankfull area from 46.9 to 64.6 ft^2. The substantially higher calculated bankfull quantities, pronounced upstream physical changes, and substantial change in the visual indicators of bankfull area at this cross-section suggest that visual indicators of bankfull elevation may be masked or distorted under rapidly changing physical conditions. Similarly, higher calculations of bankfull quantity for Cross-section #1 may have been influenced by degredation of a stream bed after earlier visual indicators of bankfull elevation had formed. Or backwater pooling caused by the downstream box culverts or pinched stormflows caused by an immediately downstream mid-channel obstruction caused by the deposition of a huge root wad between 2002-2003.

Estimated Shear Stress. Shear stress measures the capacity of stream flow to entrain bed materials as particle of a given size. Insufficient data were available to allow representative estimates of critical shear stress. Shear stress (τ [lb/ft] = 62.4 * Hydraulic Radius * Upstream Channel Slope) values were highly correlated with upstream slope (0.99), estimated quantity (0.88), and velocity (0.88), less so with bankfull area (0.33), and very little with width/depth ratio (0.17) and hydraulic radius (0.14), which approximates mean bankfull depth. Individual values of shear stress and cross-section elevation were negatively correlated (-0.68). It is no surprise that shear stress is highly correlated over time and among individual measurements with slope and intercorrelated variables. The negative correlation between shear stress and mean bed elevation suggests both the negative correlation between slope and bed elevation (-0.66) and that shear stress sufficiently exceeds critical shear stress to cause channel bed degradation.

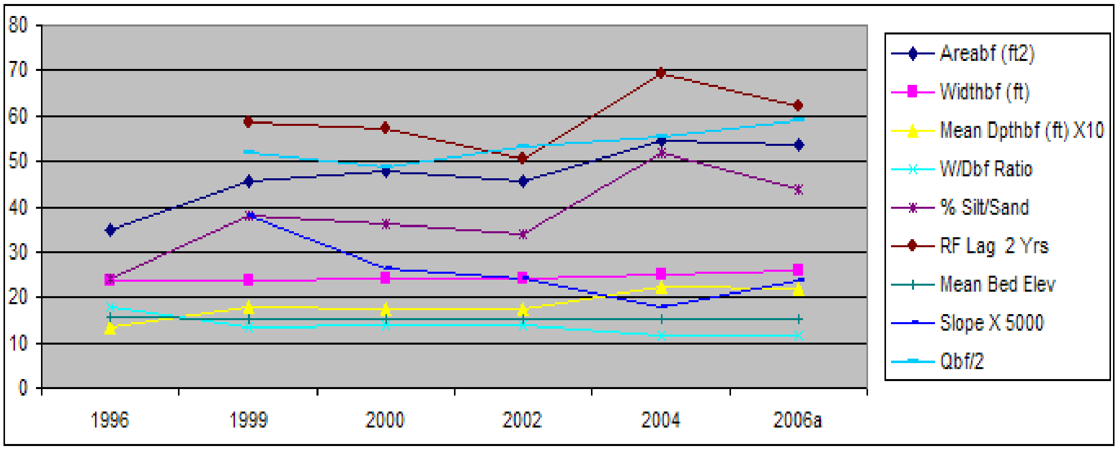

Figure 3. Selected variable trends: 1996-2006a

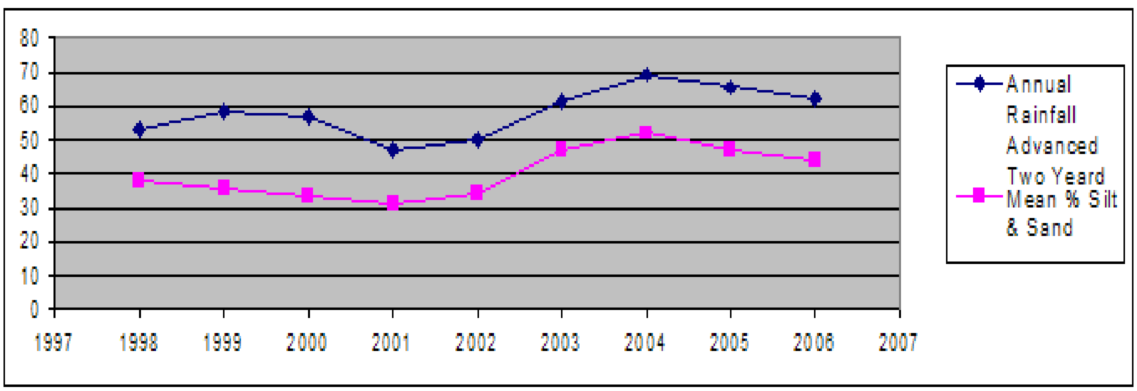

Figure 4. Annual rainfall advanced two years and mean % silt and sand (Source: Mikalsen and Bourne ,2007).

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