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CUMULATIVE IMPACTS OF LANDUSE ON WATER QUALITY IN A SOUTHERN APPALACHIAN WATERSHED[1]

Paul V. Bolstad and Wayne *T. Swank*[2]

ABSTRACT Water quality variables were sampled over 109 weeks along Coweeta Creek, a fifth-order stream located in the Appalachian mountains of western North Carolina. The purpose of this study was to observe any changes in water quality, over a range of flow conditions, with concomitant downstream changes in the mix of landuses. Variables sampled include pH, HCO_3^{2-}, conductivity. NO_3^--N, NH_4^+-N, PO_4^{3-}-P, Cl-, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, SiO2, turbidity, temperature, dissolved oxygen, total and fecal coliform, and fecal streptococcus. Landcover/landuse was interpreted from 1:20,000 aerial photographs and entered in a GIS, along with information on total and paved road length, building location and density, catchment boundaries, hydrography, and slope. Linear regressions were performed to relate basin and near-stream landscape variables to water quality.

Consistent, cumulative, downstream changes in water quality variables were observed along Coweeta Creek, concomitant with downstream, human-caused changes in landuse. Furthermore, larger downstream changes in water quality variables were observed during stormilow when compared to baseflow, suggesting cumulative impacts due to landscape alteration under study conditions were much greater during storm events. Although most water quality regulations, legislation, and sampling are promulgated for baseflow conditions, this work indicates they should also consider the cumulative impacts of physical, chemical, and biological water quality during stormflow.

(KEY TERMS water quality; cumulative effects; North Carolina; mountain; U.S.; stormilow; baseflow; GIS.)

INTRODUCTION

Environmental planning and regulatory mandates require assessment of water quality changes associated with distributed landuse activities (in this study, as in much of the literature, landuse and landcover will be used interchangeably, and refer to general classes of landcover associated with specific landuses). Such environmental analyses can be approached from a "cumulative effects" or "cumulative impacts" viewpoint (Sidle and Hombeck, 1991). Gosselink .*et al.* (1990) have defined cumulative impacts as the incremental, summed, or interactive effects of human action, added to past, present, and reasonably foreseeable effects. The impetus for cumulative impact analyses on forest land includes the Multiple-Use and Sustained-Yield Act of 1960, the National Forest Management Act of 1976, and the Clean Water Act of 1977 (Sidle and Hornbeck, 1991).

While cumulative impacts analyses have been operationally implemented by some agencies (Coburn, 1989), there is a weak scientific foundation for many specific features of cumulative impacts guidelines, particularly in water quality planning (Sidle and Hombeck, 1991). This is particularly true for upland watersheds. Most published studies of cumulative impacts analyses have primarily focused on wetland ecosystems (Winter, 1988; Childers and Gosselink, 1990; Leibowitz *et al.* 1987) where geographic information systems (GIS), aerial photography, and remote sensing have been valuable tools in assessments (Johnston *et al.*, 1988; Johnston *et al.*, 1990). Cumulative impact of landuse practices on water quality in upland forested watersheds has also received attention (Ziemer *et al.*, 1991). However, the interrelationship between landuse and water quality of upland tributaries which drain from forests into higher-order streams with a variety of downstream landuses has received less attention (Sidle and Hornbeck, 1991). We need to understand the cumulative contributions

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[2] Respectively, Assistant Professor, Department of Forest Resources, University of Minnesota, 1530 North Cleveland Avenue, St. Paul, Minnesota 55196; and Project Deader, Coweeta Hydrologic Laboratory, U.S. Forest Service, 3160 Coweeta Lab Road, Otto, North Carolina 28763.

of different landuses as they change downstream if we are to develop meaningful water quality regulations in many parts of the country. For example, results from a predominantly agricultural midwestern watershed, with some forest and urban development, showed landuse had a distinct overall and seasonal effect on stream water quality (Osborne and Wiley, 1988). In addition, a recent study in the Pinelands of New Jersey showed substantial landuse effects on natural water quality which were related to agricultural development, urban density, and domestic wastewater flow (Zampella, 1995).

Methods for assessing the relative contributions of nonpoint source pollution from different activities would be particularly useful if State environmental programs are to classify watersheds and develop criteria for different levels of development (State of North Carolina, 1994). Toward this goal, we began a study of cumulative impact on Coweeta Creek in western North Carolina (Swank and Bolstad, 1994). Managed forests occupy about 99 percent of the area in the upper Coweeta Creek watershed. Subsequently, the stream flows through agricultural, recreational, and residential lands. The objective of our study is to document any cumulative effects of these landuses on important and commonly-measured water quality variables in a representative southern Appalachian watershed. The study is an effort to identify changes in both baseflow and stormflow water quality associated with changes in downstream landuses and development.

EXPERIMENTAL LOCATION AND DESIGN

This study was conducted within the Coweeta Creek drainage, a fifth-order stream which drains 4350 ha in the Nantahala Mountain Range of western North Carolina, USA, 'latitude 35°02'N, longitude 83°25'W (Figure 1). The Coweeta Hydrologic Laboratory, a research facility of the USDA Forest Service, comprises 2185 ha of the upland drainage area (Swank and Crossley, 1988). Elevations of the study area range from 650 m at the confluence of Coweeta Creek and the Little Tennessee River, to 1592 m at the western side of the basin. The climate is classed as Marine, Humid Temperate due to high moisture and mild temperatures (Swift et al., 1988). Average annual precipitation ranges from 1800 to 2500 mm on a low to high elevation gradient, with frequent low intensity rains in all seasons and little snow (Swift et *al.,* 1988). Average monthly temperatures at 700 m elevation range from 3.3°C in January to 21.6°C in July. The bedrock geology is of late Precambrian and two major lithostratigraphic units occur in the Coweeta Basin (Hatcher, 1988). Metasandstones are interlayered with mafic volcanic rocks and aluminous schists. Quartz, biotite and muscovite micas, plagiocase feldspar, and almandine garnet comprise the most abundant rock-forming minerals (Velbel, 1988). Well developed Ultisols and immature Inceptisols are the most common soil types.

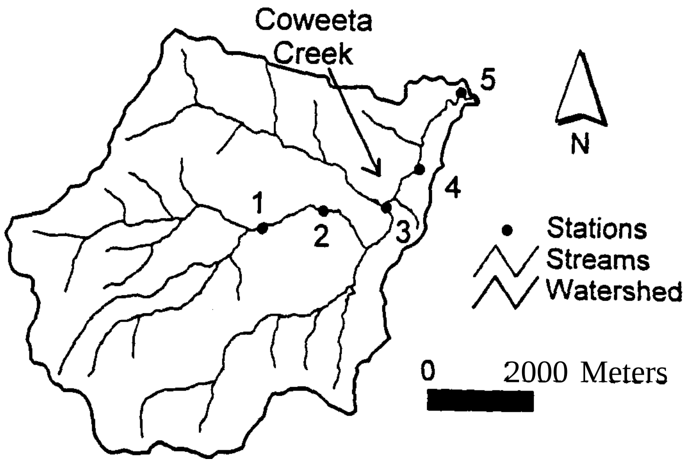

Figure 1. Watershed Boundary and Stream Sampling Locations in the Coweeta Creek Watershed in Western North Carolina. Stations 1 through 5 are arranged down the stream gradient on Coweeta Creek. First order streams are not shown.

Monitoring Stations

Five water quality monitoring stations were located over 8.7 km of Coweeta Creek (Figure 1). Stations were designated as 1 through 5 from upstream to downstream. Along Coweeta Creek, stream size and permanent landscape alteration increases (*e.g.*, conversion of forests to agriculture and increases in road density) from lower to higher station numbers (Figure 1, Table 1). Sites were selected to encompass incremental additions and a variety of landuses. Criteria for station selections were largely subjective and partly based on potential influences of near-stream landuse activities. Most of the area above Station 1 was covered with mature deciduous forest and paved road density was low, while unpaved road density was relatively high. Downstream stations were selected to encompass additional landuse features such as residences along the stream, grazing and other agricultural practices, plus additional roads. Stations 2 through 4 were characterized by a two to six-meter wide riparian shrub strip (chiefly *Alnus, Rubus,* and *Salix)* with a mix of pastures, homesites, and farmland beyond the riparian strip. Station 5 was in a low-density suburban mix, with mown grass up to the stream edge.

TABLE 1. **Summary Data for the Catchments Above Five Sampling Stations Used** in This Study.

Characteristics Upstream of Sample Station	Sampling Station Number **Upstream** 1	a	3	4	Downstream 5
Total Area (ha)	1605	1798	3099	4163	4456
Forest Area (ha)	1600	1782	2986	3904	4113
Agricultural Area (ha)	4	13	89	155	192
Urban/Suburban Area (ha)	1	3	24	104	151
Total Road Length (km)	39.8	45.2	80.8	106.8	122.6
Unpaved Road Length (km)	38.6	43.9	73.4	96.4	106.5
Total Road Density (km/km^2)	2.49	2.51	2.61	2.60	2.75
Unpaved Road Density (km/km^2)	2.41	2.44	2.37	2.33	2.39
Structures/Area (# I 100 ha)	0.37	3.06	5.36	6.01	9.23

Stream Sampling

Stream water samples were collected during baseflow and stormflow periods. During baseflow, grab samples were collected in 1-liter bottles from the free-flowing section of the stream at each station; eddies and pools were avoided. Samples were prepared within 45 minutes after sampling, and stored until analytical processing. Sampling was initiated the first week of June 1991 and was conducted twice weekly through August. Thereafter, baseflow sampling was conducted approximately weekly through the first week of November 1993.

During selected storm events, two different sampling methods were used. Grab samples were taken on the rising limb of the hydrograph, near peak flow, and on the hydrograph recession. Repeat samples were collected at approximately the same point in the channel, near the surface, approximately 1 meter from channel edge. Sampling frequency and timing during a storm varied in accordance with storm patterns. Because of limited personnel, not all stations were sampled at all storm events, nor were samples simultaneous across stations. However most samples were taken within a one-hour period, and no "standard route" was used, to preclude time bias associated with any station. Some storm events were also sampled using a time-proportional automated sampler which was activated near storm onset. Samplers *were* programmed to collect 24 samples at either one- or two-hour intervals during storms. We attempted to sample during periods of "significant" rainfall, defined subjectively as greater than 1cm of precipitation. We did not sample based on time between storms or intensity of rainfall.

Stream discharge was estimated at Station 1 by extrapolating hydrologic records taken approximately 100m above Station 1 near the confluence of two fourth-order streams which form Coweeta Creek (Figure 1). Discharge is measured continuously on each stream with 3.66 *m* Cipolletti weirs. Flow rates for the gaged 1484 ha were prorated to the 1626 ha represented by Station 1, with appropriate proportional area corrections for precipitation amounts.

Water Quality Parameters and Methods

Water samples were analyzed for a variety of physical, chemical, and biological characteristics. Dissolved oxygen and temperature were measured on-site with a YSI Model 59 portable meter standardized to 93.0 percent to account for altitude. All other analyses were conducted using previously established procedures (Deal *et al.*, 1996). Turbidity was measured with a Hack Model 2100A turbidimeter standardized to 12 NTUs. Conductivity was determined with a Fisher Conductivity Meter Model 152 standardized to 75 umhos/cm. Determinations of pH were made with an Orion digital pH meter, Model 611, calibrated with pH 7 and pH 4 buffers. Concentrations of dissolved inorganic ions were measured using the following methods: K+, Na+, Ca^{2+}, Mg^{2+} with a Perkin Elmer 2100 Atomic Absorption Spectrophotometer; PO_4s--P, SO_4^{2-}, NO_3^--N, Cl- with a Dionex Series 4500i Ion Chromatograph; NH,+-N, SiO_2 with a Technicon AutoAnalyzer; and HCO_3^- with 0.01 N H_2SO_4 titration.

Water samples for bacteria determination were collected in autoclaved 1-liter bottles and refrigerated until filtered, usually within four hours of sampling.

Filtration methods followed standard procedures (Millipore, 1986) using pre-sterilized HA-type (0.45 um pore size) membrane filters for Streptococcus and total coliform and HC-type (0.7 urn pore size) filters for fecal coliform. Pre-prepared commercial media were used for total and fecal coliform and the agar for fecal Streptococcus was prepared from dehydrate. Filtered volumes varied for each site, flow condition, and each type of bacteria to obtain counts that corresponded to testing guidelines (Millipore, 1986). Dissolved oxygen, total coliform, fecal coliform, and Streptococcus were measured only during select baseflow and stormflow events, resulting in reduced sample numbers for those parameters.

Spatial data

Nine spatial base data layers were developed for the entire Coweeta Creek watershed: catchment boundaries, hydrography, landcover, roads, dwellings (including all enclosed buildings), slope, soils, surficial geology, and bedrock geology. All data were converted to a vector digital format and co-registered to the UTM Zone 17 coordinate system. An error limit of 15 m was established for both digitization and registration of all data layers. Catchment boundaries were visually interpreted on paper 1:24,000 scale, 7.5' series United Stated Geological Survey (USGS) maps, and manually digitized. Hydrography and roads layers were digitized from 1:24,000 USGS maps, with newer roads added through the interpretation of 1:40,000 aerial photographs. Attributes for roads included length and surface type (paved or unpaved). Attributes for hydrographic data included stream length, stream order, and water sampling locations. Building (structure) locations were identified from nine-inch, 1:6,000 color infrared photographs taken September 1991. Soils mapping unit boundaries were manually digitized from 1:20,000 USDA Soil Conservation Service maps from the Macon County Soil Survey. Slope data were derived from the 7 m USGS digital elevation model, using a Rook's Case algorithm (Burrough, 1986). Bedrock and surficial geology were manually digitized from a paper 1:24,000 geologic map published by the North Carolina Department of Natural Resources and Community Development. Surface geology was categorized into six classes, while bedrock geology was represented by 14 rock unit types. Landcover was interpreted on screen from digitally rectified, scanned photography (Wolf, 1983). Landcover was categorized into 32 classes at the Anderson Level III (Anderson *et al.*, 1976)

Catchment characteristics were determined above each sampling point through a cartographic overlay processes. First, catchment boundaries defining the areas draining into each sample point were identified on 1:24,000 USGS quadrangle maps and digitized. Digital spatial data layers were then aggregated based on pertinent attribute values, and overlain with catchment boundaries to provide specific characteristics on a catchment basis. Landuse classes were combined to form three broad classes (forest, agriculture, and urban/suburban). Aggregate statistics were computed for each catchment and included percent landuse for each broad landuse class, building density (buildings/km?, total road length, paved road length, number of buildings, percent area by soil order, and percent area underlain by colluvial deposits.

Catchment characteristics were determined for all land in the basin, and characteristics for near-stream area were determined by applying a cartographic buffering operation in a GIS. Cartographic buffer regions were defined by identifying areas within 50, 100, 150, 200, 250, and 300 meters of the nearest stream. The 50 m lower limit was chosen because it is more than three times the approximate root-mean-square positional error for the spatial data, while characteristics for the 300 m cartographic buffer regions approached those for the entire basin. These cartographic buffers were then used to characterize near-stream conditions from each of the digital data layers through a cartographic overlay process. Summary landuse characteristics and aggregate statistics were calculated for each sampling station, using each of the cartographic buffer distances. For example, percent non-forest landcover was determined for each stream sampling station, based on areas within 50m of the stream, areas within 100m of the stream, etc., up to 300 meters from the stream, and for the entire catchment.

Pearson's and Spearman's correlations were used to reduce the number of landscape variables in subsequent water-quality regression models. High correlation was expected among some landuse variables, e.g., building density and percent developed landcover. This could lead to regression models with correlated predictor variables, which often results in poor regression parameter estimates (Draper and Smith, 1981). Because the objectives focused on identifying downstream changes in the water quality variables and not the development of regional models or methods to estimate landuse impacts (both of which would require a much larger sampling effort, across a broader range of conditions), stepwise regression, principal components regression, or other multi-variable methods were not used. Upstream aggregated catchment areas were used to calculate summary landuse variables for each of the five stations. Variables included percent agricultural, percent (sub)urban, percent non-forest, building density, total road density (km/km^2), paved and unpaved road density, percent area underlain by colluvial deposits, and percent area with less than 5 percent slope. Correlations were calculated for data derived from the entire catchment, and from each of the near-stream cartographic buffer distances.

Statistical Analysis

Summary statistics were calculated for all water quality variables. Values near peak flow were used for stormflow samples, Peak was determined either during sampling, from recorded hydrographs, or by visual inspection of time-series plots for turbidity to estimate peak discharge. Near coincident peak turbidity and discharge were observed at Station 1 for all storm events, and personal observations indicate turbidity peaks generally occurred within 1 hour at all stations at our sample sites. Therefore, we assumed peak discharge at downstream stations coincided with peak turbidity. Scatter plots were produced for sufficient sample sets, defined as near-simultaneous collections for at least three stations. Regression analyses were performed on each set, and after pooling sets based on season (spring for March through May, summer for June through August, fall for September through November, and winter for December through February). Measured sample variables were entered as dependent variables, predicted by landscape (independent) variables in simple linear regression models. Independent variables tested included absolute and percent non-forest, paved and unpaved road density, building density, total road density, absolute and percent area less than 5 percent slope, and percent area in colluvial deposits. Landscape variable values were for areas above each sampling point, using the entire basin and the various cartographic buffer distances. Because regressions which were significant at one buffer distance were generally significant for all buffer distances, regression results are reported only for the 50 m buffer data. Correlation among independent variables (described in results, below) led to the selection of building density as an independent variable in separate simple linear regressions, and water quality variables as the dependent variable in each regression. Models were fit with an intercept; baseflow models were typically fit with 105 to 109 weeks of samples, and stormflow models were typically fit with 35 to 45 storms for most physical and chemical variables, Due to more limited sampling, total coliform, fecal coliform, and fecal streptococcus models were fit with between six and 19 sample sets. Bacterial counts were log-transformed prior to regression.

RESULTS AND DISCUSSION

Landuse Characteristics

Overall, the study area was predominantly forested, with less than 6 percent of the total land area dedicated to developed or agricultural landuses (Table 1). The proportion of non-forest landuse increased downstream, a characteristic of many watersheds in the southern Appalachian Mountains. Most other landscape variables increased proportionally downstream, with the exception of unpaved road density (Table 1).

Correlations indicate there are two groups of landcover variables. A first set of variables was highly correlated, including paved road density, percent non-forest, building density, percent area with < 5 percent slope, and percent area underlain by colluvial deposits. Pearson's correlations ranged from 0.65 to 0.91, and were significantly different than zero. Agriculture and urban/suburban landuses and concomitant development were concentrated in the flatter areas near streams, and thus landscape variables related to development increased downstream, as the proportion of flat, near-stream area increased. These trends were reflected in building density (Figure 2), which increased downstream, both for the entire basin and for all cartographic buffer distances. Landscape analyses based on most of the development-related variables lead to similar conclusions due to the inter-correlation. Total road density and unpaved road density were not highly correlated with the other landscape variables, due to the extensive unpaved road network in the Coweeta Basin. Roads have been constructed to test road designs and to support research.

Near-stream patterns of building density were complex. Building density increased downstream for all cartographic buffer distances (Figure 2). Below Station 2, densities were lowest for the shortest cartographic buffer distances (50 and 100 m), highest for the 150m cartographic buffer distance, and intermediate for larger cartographic buffer distances. We attribute this to a strong desire to be near streams yet above floodplain areas, particularly for downstream stations. Building density increased most rapidly from stations 1 to 2 and 4 to 5.

Baseflow Water Quality

Water quality was good during baseflow conditions, as indicated by baseflow sampling over the three-year study period (Table 2). Concentrations of most solutes averaged less than 1 mg/l, typical of stream chemistry

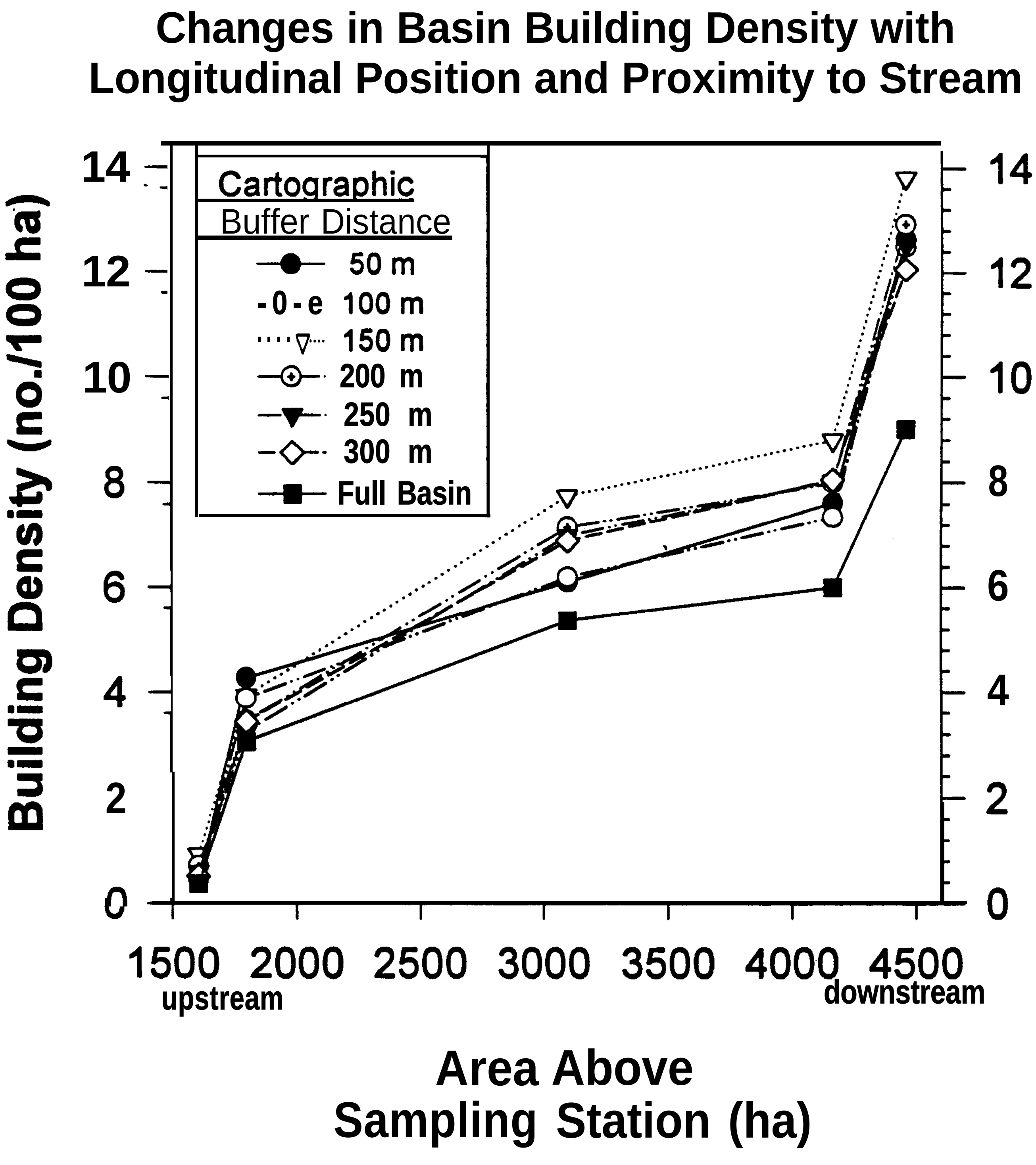

Figure 2. Percent Area Plotted by Stream Sampling Location, for Each of Several Different Distances from Streams. The percent of land with non-forested landuses increases as on moves from upstream to downstream sampling stations (1 to 6). Building density is higher when only considering areas nearer the stream (within 50 m) than farther away (within 300 m). These indicate non-forest landuses are concentrated near-stream and downstream.

for lightly-disturbed forest watersheds in the southern Appalachians (Swank and Waide, 1988). NO_3^--N, NH_4^+-N, and PO_4^{3-}-P were very low, indicating the absence of point sources of inorganic solutes into the stream. Turbidity during baseflow was generally low, typical for the southern Appalachians (Swank and Crossley, 1988), averaging less than 6 NTU for all stations. Mean counts of total fecal coliform and fecal

TABLE 2. Summary Water Quality Data from Baseflow Grab Samples at Each of Five Sampling Stations. Means and standard errors (in parentheses) are based on from 106 to 109 samples for all physical and chemical variables, except for Station 3 ($n = 31$). Summary data for fecal coliform (FC), total coliform (TC), fecal streptococcus (FS), and dissolved oxygen (DO) are based on 11 samples.

Variable	Station Number 1	2	3	4	5
pH	6.85 (.013)	6.77 (.009)	6.83 (.011)	6.89 (.011)	6.91 (.012)
HCO_3^{2-} mg/ℓ	4.51 (.076)	4.35 (.065)	5.02 (.096)	5.63 (.095)	5.76 (.100)
Conductivity µS	13.82 (.162)	14.26 (.160)	16.13 (.223)	17.38 (.189)	17.92 (.216)
NO_3^--N mg/ℓ	0.042 (.0017)	0.041 (.0016)	0.042 (.0017)	0.041 (.0017)	0.045 (.0018)
NH_4^--N mg/ℓ	0.003 (.000472)	0.003 (.000618)	0.003 (.000282)	0.003 (.000331)	0.004 (.000717)
PO_4^{3-}-P mg/ℓ	0.002 (.000374)	0.002 (.000235)	0.003 (.000946)	0.003 (.000605)	0.002 (.000351)
Cl^- mg/ℓ	0.521 (.0042)	0.533 (.0036)	0.606 (.0049)	0.630 (.0058)	0.664 (.0066)
K^+ mg/ℓ	0.399 (.0052)	0.408 (.0061)	0.447 (.0087)	0.465 (.0097)	0.483 (.0106)
Na^+ mg/ℓ	0.834 (.0094)	0.848 (.0101)	0.989 (.0150)	1.015 (.0158)	1.037 (.0171)
Ca^{2+} mg/ℓ	0.826 (.0140)	0.841 (.0158)	0.959 (.0164)	1.088 (.0179)	1.117 (.0 189)
Mg^{2+} mg/ℓ	0.342 (.0037)	0.361 (.0037)	0.374 (.0044)	0.467 (.0060)	0.478 (.0064)
SO_4^{2-} mg/ℓ	0.603 LO1201	0.631 (.0120)	0.883 (.0140)	0.672 (.0137)	0.696 (.0142)
SiO_2 mg/ℓ	8.81 (.089)	6.74 (.084)	7.32 (.097)	7.53 (.102)	7.45 (.099)
Turbidity (NTU)	2.86 (.40)	3.13 (.47)	3.91 (.62)	5.13 (.85)	5.52 (.93)
Temperature (°C)	11.[illegible] (0.43)	12.1 (.43)	12.4 (.44)	12.7 (.45)	12.8 (.47)
DO mg/ℓ	9.92 (0.11)	9.65 (.11)	9.66 (.11)	9.65 (.11)	9.63 (.12)
TC counts/100 mℓ	9470 (5046)	13660 (5599)	40040 (20765)	30740 (18734)	52140 (29861)
FC counts/100 mℓ	200 (125)	340 (293)	460 (227)	1130 (547)	840 (308)
FS counts/100 mℓ	710 (223)	1310 (491)	2180 (948)	1590 (720)	1840 (793)
FWFS	.16	.17	.17	.27	.65

streptococci at Station 1 were typical of mean values reported for other streams draining relatively undisturbed forested watersheds in western North Carolina (McSwain and Swank, 1977; McSwain, 1977).

While baseflow water quality was generally high, several variables show distinct downstream increases. Cation concentrations, SiO_2, HCO_3^{2-}, SO_4^{2-}, Cl-, conductivity, turbidity, and temperature generally increased downstream from Station 1 to 5 (Table 2). In many cases these downstream increases in station means were statistically significant (e.g., there were statistically significant differences among stations in mean cation concentrations (a = 0.05)). Many of these differences are not biologically significant, in that they are within the acceptable ranges for most common aquatic vertebrate and invertebrate species found in the southern Appalachians (Grubah et al., 1996). Statistical significance may be due to the large sample sizes and correspondingly small mean standard errors. Phosphorus and both forms of N exhibited generally low concentrations, although downstream values were slightly higher than long-term measurements in the forested portions of the watershed (Swank and Crossley, 1988). There were distinct trends for total coliform, fecal coliform, and fecal streptococcus, with all values generally increasing downstream. However, downstream increases were not statistically significant, due in part to large observed standard errors for these variables. Mean baseflow levels for total coliform, fecal coliform, and streptococci counts increase from three- to eight-fold downstream (Table 2). Thus, there is a cumulative increase in bacteria populations, indicating additive sources downstream. The transport of these bacteria is probably primarily through the soil or direct input by warm-blooded vertebrates (e.g., raccoons, livestock) since baseflow samples represent periods when there is little or no overland flow input from adjacent lands.

Fecal coliform/fecal streptococci ratios (FC/FS) have been used to differentiate between contamination from human (> 4.01, domestic animal (0.1-4.0) and wild animal (< 0.1) sources (Howell et al., 1995). In our study, baseflow FC/FS ratios were < 1 along the entire stream length sampled, indicating a lack of human contamination. Sample sites 1 and 2 drained primarily forested land and had baseflow FC/FS ratios c 0.2, while Stations 4 and 5 had a larger proportion of pasture land and grazing cattle, and baseflow FC/FS ratios which exceeded 0.5. These patterns were not maintained during stormflow.

Stormflow Water Quality

Conductivity, NO_3^--N, HCO_3^-, Cl-, K^+, Na+, Ca^{2+}, Mg^{2+}, SiO_2, turbidity, temperature, and total coliform, often showed cumulative increases downstream (Table 3). Due to small sample sizes and higher inherent variability during storms, few among-station comparisons were statistically different.

Two patterns are particularly obvious in comparing stormflow and baseflow data. First, mean values for most variables at most stations were higher during stormflow. These increases range from slight and nonsignificant ($\alpha > 0.05$; e.g., mean Cl- concentration of 0.52 mg/l at Station 1 during baseflow vs. 0.55 mg/l during stormflow), to quite large (e.g., mean turbidity at Station 5 of 4.0 NTU during baseflow and 21.8 NTU during stormflow). Bacteria levels were among the most responsive water quality variables during storm events although patterns were highly variable among storms and among seasons. Total coliform, fecal coliform, and fecal streptococci typically increased two- to three-fold during storm events compared to baseflow populations. However, while bacteria levels typically increased downstream, they were highly variable. For some storms, levels decreased from a station to a downstream station, whereas for other storms increases were as high as seven-fold. Elevated bacterial counts during storms at Station 1 are similar to previous responses observed at Coweeta (McSwain, 1977). The source of these large downstream increases in bacteria may be attributed to observed overland flow from adjacent lands directly into streams during large storms, disturbance of bottom sediments, and streambank flushing.

The second noticeable difference between stormflow and baseflow are larger downstream increases for some variables. For example, NO_3^--N concentrations increased by 7 percent as one moved from Stations 1 to 5 during baseflow, and by 34 percent during stormflow. Mean Mg+ concentrations increased by 33 percent between Stations 1 and 5 during baseflow and 60 percent during stormflow. Not all variables exhibited steeper downstream increases, e.g., dissolved oxygen decreased approximately 3 percent downstream during both baseflow and stormflow, Cl- concentration increased downstream by approximately 21 percent during both baseflow and stormflow, and SiO_2 increased by 9 percent downstream for both sampling sets. Some variables (e.g., temperature and SO_4^{2-}) showed no pattern or only slight increases or decreases during storm events.

TABLE 3. Summary **Stormflow** Water Quality Data Stream Samples at Each of the Five Sampling Stations, Means and standard errors (in parentheses) are based on 72 storms for physical and chemical variables and nine storms for biotic variables.

Variable	Station Number				
	1	2	3	4	**5**
pH	6.62	6.59	6.98	6.69	6.63
	(.012)	(0.023)	(0.055)	(0.032)	(0.044)
HCO_3^{2-}	3.54	3.43	5.55	4.20	4.27
mg/ℓ	(0.077)	(0.118)	(0.199)	(0.132)	(0.261)
Conductivity	15.06	16.41	15.25	16.72	17.8
µS	**(0.191)**	(0.333)	(0.250)	(0.277)	(0.430)
NO_3^--N	0.060	0.060	0.054	0.082	0.067
mg/ℓ	(0.0033)	(0.0047)	(0.0080)	**(0.0057)**	(0.0079)
NH,+-N	0.006	0.008	0.017	0.007	0.008
mg/ℓ	**(.000461)**	**(.000145)**	**(.000100)**	**(.000062)**	**(.000116)**
PO_4^{3-}-P	0.002	0.004	0.001	0.006	0.005
mg/ℓ	**(.00019)**	(0.001592)		(0.000616)	(0.00188)
Cl^-	0.549	0.555	0.568	0.754	0.663
mg/ℓ	**(0.0148)**	**(0.0241)**	**(0.0145)**	(0.0297)	(0.0237)
K^+	0.511	0.610	0.497	0.774	0.742
mg/ℓ	(0.0148)	**(0.0235)**	(0.0050)	(0.0346)	(0.0548)
Na^+	0.716	0.738	1.106	0.665	**0.8324**
mg/ℓ	(0.0108)	(0.0181)	(0.0215)	(0.0172)	(0.0411)
Ca^{2+}	0.869	0.644	1.053	1.161	1.239
mg/ℓ	(0.0139)	(0.0179)	**(0.0215)**	(0.0238)	(0.0564)
Mg^{2+}	0.369	0.384	0.393	0.431	0.466
mg/ℓ	(0.0047)	**(0.0055)**	(0.0005)	(0.0059)	(0.0156)
SO_4^{2-}	1.038	1.143	0.094	1.237	1.149
mg/ℓ	(0.0309)	(0.0427)	(0.0700)	(0.0460)	(0.0706)
SiO_2	5.12	**5.25**	7.97	5.61	5.57
mg/ℓ	(0.124)	**(0.149)**	(0.233)	**(0.144)**	**(0.394)**
Turbidity	12.58	20.10		41.27	37 .00
(NTU)	(1.41)	(2.77)		(6.36)	(6.95)
Temperature	12.38	12.48		12.6	12.7
(°C)	**(1.26)**	**(1.29)**		(1.34)	(1.65)
DO	9.78	9.53		9.51	9.43
mg/ℓ	(0.346)	**(0.308)**		(0.355)	(0.447)
TC	18790	**34640**		77 160	98390
counts/100 mℓ	(7822)	(16697)		**(52278)**	**(73504)**
FC	880	**130**		970	1260
counts/100 mℓ	**(49)**	**(67)**		**(694)**	**(896)**
FS	450	8710		3260	4190
counts/100 mℓ	**(297)**	**(491)**		(2733)	**(3854)**
FC/FS	0.52	0.22		0.32	0.49

Regression Analyses and Comparisons

Regression analyses indicate single variable models were best when trying to relate specific landuse characteristics to downstream trends in water quality variables. Percent cover, building density, percent colluvium, and paved road density were all consistently good predictors of water quality variables when used singly in regression analysis. Multi-colinearity was indicated by tolerance values, variance inflation factors, variance proportions, and other diagnostics of multicolinearity (Belsley et *al.,* 1980). Thus, regression models were restricted to individual independent variables, with intercept. As noted earlier, we used building density within 50m of a stream as the predictor variable. This variable is easily estimated, highly correlated with the other noted landuse variables, and representative of the suite of landuse characteristics which changed in the downstream direction.

When water quality variables were regressed against building density above the sampling station, variable responses were observed (Table 4). A positive regression slope indicates an increase in the water quality variable with an increase in building density above the sampling station. As building density increases, so does the level or concentration of the variable. A larger slope coefficient, either among seasons or for storm vs. baseflow, indicates a more rapid increase in the variable with an increase in building density. We observed all combinations of slope increase and decrease in comparisons among stormflow and baseflow, and in comparisons among seasons. However, the regression results indicate that there are two groups of variables defined according to how their regression slopes differ between baseflow and stormflow.

The first group was comprised of those which showed some significant differences in regression slope between baseflow and stormflow (a = 0.11, and which generally showed more rapid downstream increases during storms than during baseflow. This group included of NO_3^--N, NH_4^+-N, turbidity, and total coliform. These variables showed a marked increase when baseflow levels were compared to stormflow (Figures 3 and 4; Table 4), for some seasons, and on an annual basis. These stormflow increases *were* notably higher for four important water quality variables: turbidity, NO_3^--N, NH_4^+-N, and total coliform bacteria. Downstream rates of turbidity increased by 0.08 to 0.61 NTU/building/100 ha, with the highest rates of increase observed during winter (Table 4). Rates of downstream increase during stormflow ranged from slightly below those observed during baseflow (spring observations) to more than four times greater (winter). Nitrate-nitrogen during baseflow showed slight increases with increased downstream building density. However, during stormflow, there were large, consistent increases in NO_3^--N concentration as building density increased, with the highest rates of increase observed for fall samples (Table 4).

These more rapid downstream increases in water quality variable concentration are most likely caused by increasing inputs from overland flow. Overland flow was observed during storms, in pastures, pavement, compacted unpaved roads, and other developed areas. Overland flow, coupled with fertilizer amendments, animal waste, and human-caused soil disturbance in urban and agricultural lands, most probably led to increased inputs along the upstream to downstream gradient. Lower rates of NO_3^- increase during spring are consistent with this explanation, in that most human soil disturbance and fertilization occurs during the late spring and summer, and frequent overland flow during fall, winter, and early spring would "flush" the system. This may cause lower downstream increases during spring. Turbidity increases may be due to overland inputs, increased streambank erosion, and increased entrainment of bedload sediments during stormflow. Logging, farming, and construction has occurred over much of the Coweeta Creek Basin, which undoubtedly increased sediment loads. Farming and construction were more frequent in the downstream, nearstream areas. Sediments deposited as a result of these activities may still be present, picked up and re-deposited with each storm. Thus, turbidity increases may be due to past, as well as present, landuse activities.

A second group, including all the remaining water quality variables, exhibited non-significant differences in regression slope values when stormflow data were compared to baseflow data (Table 4). Some variables in this group, including pH, Na+, Mg^{+2}, temperature, and DO, had small and inconsistent differences in regression slopes between baseflow and stormflow and across season. For these water quality variables, stormflow regression slopes, when compared to baseflow, were higher for some seasons, and lower or equal for others, and hence no trends could be detected. Other water quality variables showed variable but often increasing regression slopes (and hence increased downstream rates of change) for stormflow, relative to baseflow. Regression results suggest there may be some relationship here, however they appeared weak and were not statistically significant in our study. This set of variables included conductivity, PO_4^{-3}-P, K+, Cl-, fecal streptococcus, and fecal coliform. Finally, there is a third set of these non-significant variables for which regression slopes decreased under stormflow conditions, compared to baseflow conditions. These variables included Ca^{2+},

TABLE 4. Regression Slopes for Models Variable = Constant + Slope * Building Density in the 50 m Cartographic Buffer. Building density recorded as buildings per square kilometer. Regressions based on baseflow grab samples, with sample size typically from 84 to 103. Peak storm values based on samples collected near estimated stormflow peak, determined from field observations for grab samples and from hydrographs from ISCO-obtained samples, with sample size typically from 22 to 41. Table entry of n.s. indicates the regression slope was not significantly different fmm zero. A * indicates the regression slope for storm samples was significantly different fmm baseflow samples, a = 0.05.

Variable	Baseflow				Peak Storm			
	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter
pH	0.01	0.01	0.01	0.01	n.s.	n.s.	n.s.	n.s.
HCO_3^- mg/ℓ	0.17	0.19	0.19	0.14	n.s.	n.s.	0.15	n.s.
Conductivity µS	0.47	0.49	0.65	0.58	n.s.	0.88	0.66	n.s.
NO_3^--N mg/ℓ	0.081	n.s.	n.s.	0.170	0.177*	0.143	0.584’	0.510*
NH_4^+-N mg/ℓ	0.008	n.s.	n.s.	0.009	0.201*	0.019	0.051	0.105*
PO_4^{3-}-P mg/ℓ	0.007	0.008	n.s.	n.s.	n.s.	n.s.	0.059	n.s.
Cl^- mg/ℓ	0.014	0.017	0.018	0.015	n.s.	n.s.	n.s.	n.s.
Na^+ mg/ℓ	0.021	0.026	0.029	0.020	n.s.	0.029	0.018	0.017
K^+ mg/ℓ	0.008	0.013	0.013	0.009	n.s.	0.020	0.038	0.025
Ca^{2+} mg/ℓ	0.038	0.039	0.043	0.039	0.040	0.050	0.039	0.017
Mg^{2+} mg/ℓ	0.018	0.019	0.021	0.018	n.s.	0.019	0.020	0.013
SO_4^{2-} mg/ℓ	0.010	0.012	0.011	0.012	n.s.	0.011	0.034	n.s.
SiO_2 mg/ℓ	0.089	0.082	0.085	0.088	n.s.	n.s.	n.s.	n.s.
Turbidity (NTU)	0.09	0.08	0.14	0.15	0.08	0.22	0.33*	0.61*
Temperature (°C)	0.141	0.121	0.097	0.099	0.140	0.112	0.170	
Do mg/ℓ	-0.042	-0.021	-0.039	-0.028	-0.039	-0.038	-0.025	
TC counts/100 mℓ	n.s.	n.s.	n.s.		n.s.	24,425’	2,950	
FC counts/100 mℓ	n.s.	n.s.	n.s.		n.s.	n.s.	n.s.	
FS counts/100 mℓ	n.s.	n.s	n.s.		n.s.	1277	n.s.	

HCO_3^-, and SiO_2. Some of these reductions may be due to a dilution effect from increased flow volumes downstream.

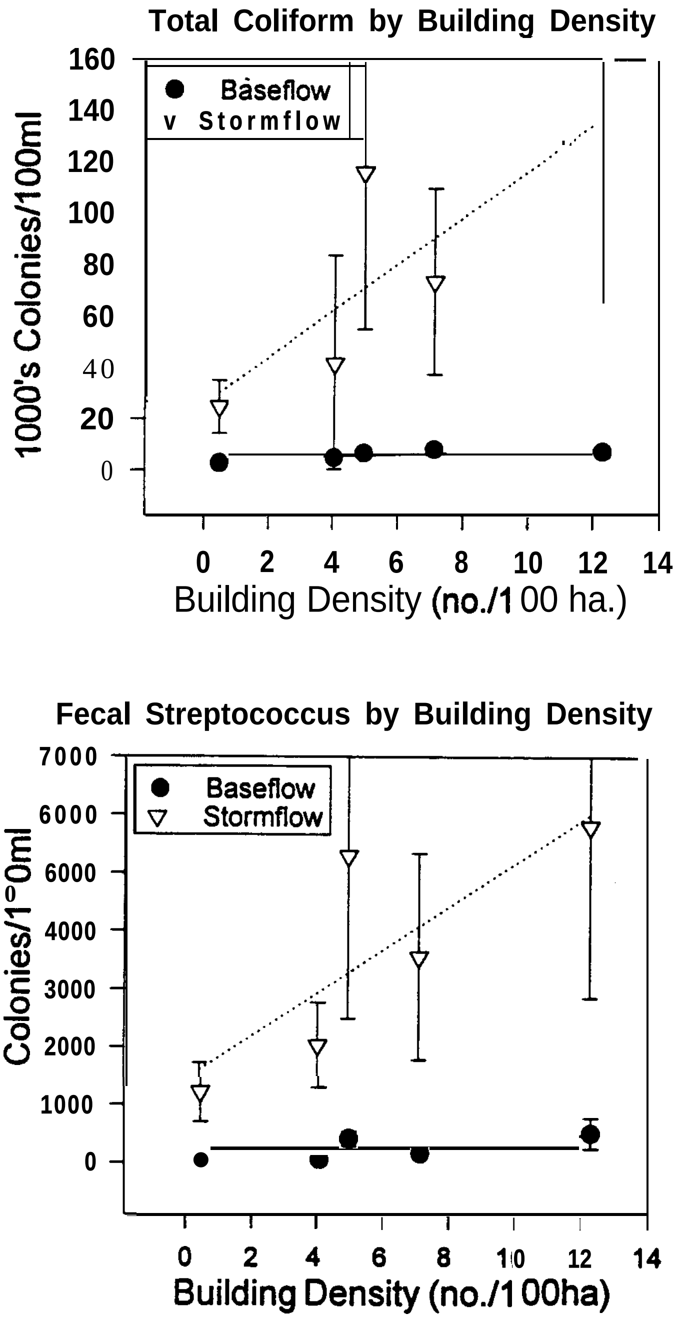

Figure 3. Mean and Standard Error (bars) for Total Coliform and Fecal Streptococcus, Plotted Against Building Density for Each Sampling Conditions (baseflow and storm samples during stormflow). Subset of data were selected to balance station samples. Regression lines for stormflow date are significant, while they were not for baseflow samples (a = 0.06).

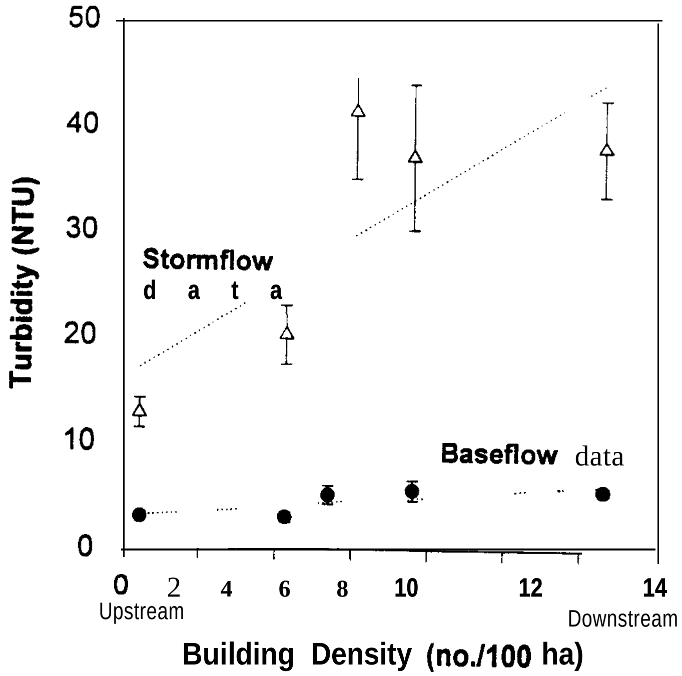

Figure 4. Mean and Standard Error (bars) for Turbidity, Plotted Against Building Density for Each Sampling Condition (baseflow and stormflow). Turbidity increases were significant (a = 0.05) for both baseflow and stormflow collections based on linear regression. In addition, slopes of the regression lines for baseflow and stormtlow samples were significantly different (α = 0.05).

Coincident plots of flow rate and water quality variables during storms indicate discharge and water quality values reached their maximum at approximately the same times, a finding consistent with previous studies at Coweeta Creek. Figure 5 illustrates the course of streamflow, turbidity, and NO_3^--N at Station 1 during a representative winter storm. Variables are plotted as a percent of their respective peak observed during the storm event. As with most observed storms, the turbidity peak is nearly coincident with flow rate, and recedes concomitantly. Nitrate in this instance peaks after maximum flow, is more variable, and maintains a higher level for a longer period of time. In general, nitrogen and phosphorus were more variable, peaked near but not always coincident with stormflow, and varied considerably during storms.

Comparisons with Other Studies

Mean anion and cation concentrations, and turbidity values reported here are quite low when compared to measurements reported for other human-impacted waters (Osborne and Wiley, 1988; Jordan *et al.*, 1993).

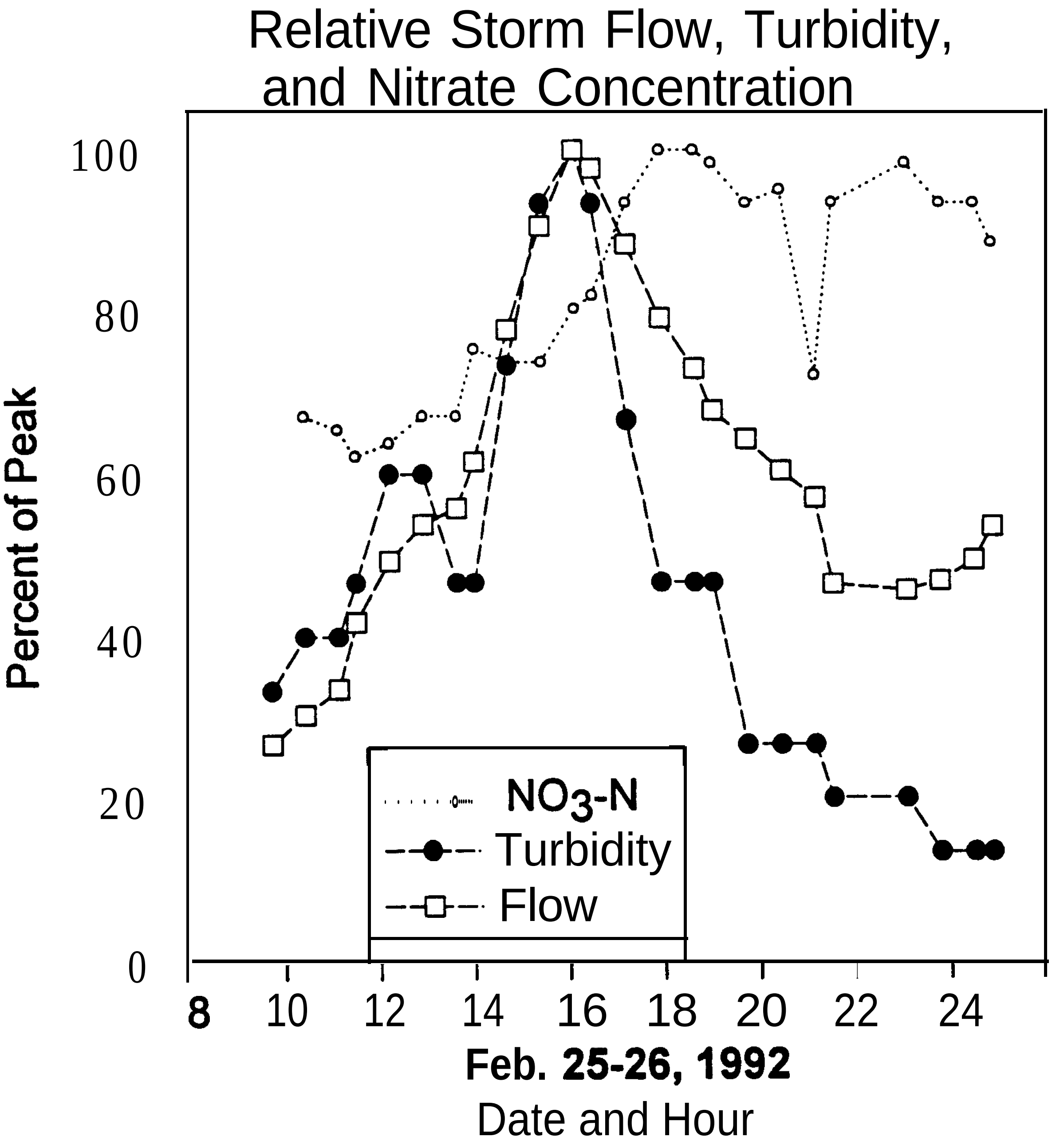

Figure 5. Hydrograph, Turbidity, and Nitrate Concentration, Expressed as a Percent of Peak Value, for a Measured Storm. In this and most storms observed, turbidity peaked at or near flow. Other variables, in this case nitrate nitrogen, increased with water flow, but were more variable in their length of peak and decline.

In particular, phosphorus and both forms of nitrogen are from one to several orders of magnitude lower in Coweeta Creek, both during baseflow and stormflow, than those reported for water quality in watersheds where a majority of the land surface has been converted to agricultural and urban landuses (Osborne and Wiley, 1988; Zampella, 1995). High water quality during baseflow relative to other disturbed watersheds is most likely due to the relatively small extent of development, even though development is concentrated in near-stream areas. There were also no known point source inputs along Coweeta Creek. Stormflow stream chemistry concentrations and turbidity, although elevated relative to baseflow, were still from half to several orders of magnitude lower than concentrations and turbidity levels observed in streams draining areas with more intensive and/or extensive landuse conversion (Lowrance et al., 1984;

Osborne and Wiley, 1988; Jordan et *al.,* 1993). This may be due to the relatively low percentage of the landscape permanently disturbed, even though this disturbance was concentrated near the stream channel, and to the presence of riparian forest or shrub strips along much of Coweeta Creek. The benefits of riparian vegetation have been demonstrated conclusively (Anderson- and Ohmart, 1985). These strips have been documented to retain up to 90 percent of the total N inputs from adjacent cropland (Lowrance et *al.,* 1984; Peterjohn and Correll, 1984), with substantial amounts of NO_3^--N removed within the first 20 m of the forest-field boundary (Petejohn and Correll, 1984; Jacobs and Gilliam, 1985; Jordan et *al.,* 1993). However, the riparian strips in these previous studies were typically wider than the one to four meters commonly observed in Coweeta Creek. The Coweeta Creek basin is representative of landuse patterns in similar sized basins across much of the southern Appalachians. Population growth and associated landuse disturbances are accelerating at an exponential rate over the region, and this study provides evidence for cumulative impacts on important water quality parameters from forested headwaters to downstream landuses, particularly during stormflow periods. The majority of land available for development is located in the middle and lower portions of basins, in close proximity to streams; thus, the long-range sustainability of water quality is of concern. Our research indicates we should be particularly observant of impacts on water quality during stormflow.

CONCLUSIONS

Based on this work, we conclude that during baseflow conditions streamwater quality was high, with generally low concentrations of chemical and biotic constituents, and predominantly influenced by forested source area conditions. There were slight downstream increases for most chemical, biological, and physical variables, and most cations increased downstream. Under baseflow conditions, we observed a weak and variable increase in fecal streptococcus, fecal coliform, and total coliform bacteria in a downstream direction, and small cumulative increases in conductivity and turbidity.

Baseflow/stormflow comparisons suggest that the influence of landuse on water quality changes during storms. During baseflow, the high quality of water flowing from forest sources is only slightly altered downstream. However, during storm events there is a reduction in forest influence on non-point source pollution downstream. We cannot unambiguously establish changes in landuse as the primary cause for this change in water quality, because there are no similar, undisturbed basins nearby for comparison. However water quality, particularly during stormflow, decreases at a much faster rate in our sampling than those observed along the forested, longer, larger stream gradient in the catchments above our study areas. We conclude the cumulative impacts of other landuses appears to greatly increase turbidity, bacteria populations, and some inorganic solutes, particularly during stormflow. Increases in these water quality variables are probably due to increased overland flow and transport of materials directly to the stream.

Water quality variables showed different, more variable trends during stormflow conditions than during baseflow sampling. NO_3^--N, NH,+-N, turbidity, total coliform, fecal coliform, and fecal streptococcus were characterized by higher mean levels downstream and during stormflow. Moreover, these variables increased at greater rates downstream during stormflow as compared to baseflow. Most other variable showed slight to no changes during storm events, with the exception of SiO_2, which showed mean and downstream decreases in concentration during storms.

There were strong, positive relationships among the suite of measures we used to measure human impacts on the landscape. This is particularly true of percent non-forest, paved road density and length, and building number and density. Absolute levels of each variable changed, depending on the cartographic buffer distance used. However, the trend of downstream increases held for most landscape measures of human disturbance.

In summary, this work identifies consistent, cumulative downstream changes in Coweeta Creek concomitant with downstream changes in landuse. Furthermore, this work indicates consistently higher downstream changes during stormflow when compared to baseflow conditions, suggesting cumulative impacts due to landscape alteration, as tested here, are much greater during storm events. Although most water quality regulations, legislation, and sampling are promulgated for baseflow conditions, this work indicates they should also consider the cumulative impacts on physical, chemical, and biological water quality during stormflow.

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