Cumulative effects of land use practices on water quality

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Abstract Trends in water quality parameters ($K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $PO_4^{3-}$, $SO_4^{2-}$, $NO_3^-$, $Cl^-$, $SiO_2$, pH, turbidity, conductivity, temperature, faecal and total coliform bacteria, and faecal streptococcus) were observed down a Southern Appalachian stream-order gradient, and these trends were then related to cumulative changes in landscape variables. Water samples were collected bi-weekly at six stations along a first- to fifth-order stream gradient, and landscape variables (hydrography, landcover, roads, slope, surficial geology, bedrock geology, soils) were mapped for the contributing watersheds above each station. Water quality was high under baseflow conditions in the predominantly forested study area, with solute concentrations usually less than 1 mg l$^{-1}$ and turbidity values less than 3 NTU, with small, consistent increases downstream. In contrast, large, steep gradients in water quality parameters were observed under stormflow conditions, in some cases increasing three- to six-fold. A number of water quality parameters (Cr, $K^+$, $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $SO_4^{2-}$, $SiO_2$, turbidity, faecal streptococcus, and faecal coliform) exhibited significant linear relationships with several landscape variables (percent non-forest, structure density, and paved road density).

INTRODUCTION

Watershed research has traditionally been oriented toward investigating the effects of individual land use practices on the water resource using small experimental catchments. However, environmental planning and regulatory mandates also require empirical information and assessment methods which encompass environmental changes associated with land use activities distributed through space and/or time. A landscape scale environmental analysis can be approached from a "cumulative impacts" viewpoint. The term, cumulative impacts, is defined as the incremental, summed, or interactive effect of an impact added to other past, present, and reasonably foreseeable future impacts (Gosselink et al., 1990). The legal impetus for analysis of cumulative impacts on forested 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 & Hornbeck, 1991).
Cumulative environmental impact assessment has primarily focused on wetlands (Winter, 1988; Childers & Gosselink, 1990; Leibowitz et al., 1987) where geographic information systems, aerial photography, and remote sensing have proved useful in the analyses (Johnston et al., 1988, 1990). The cumulative impacts of land use practices in upland forested watersheds is also of concern (Sidle & Hornbeck, 1991; Ziemer et al., 1991). Moreover, the interrelationship between water quality of upland tributaries to higher order streams with a variety of land uses must be understood to develop appropriate regulatory criteria and management practices.

To address this topic we initiated a study on Coweeta Creek, a fifth-order stream draining 4350 ha in western North Carolina. Coweeta Creek drains managed forested areas (about 50% of the total area) and subsequently flows through agricultural, residential, and recreational lands. The overall objective of the study is to measure and evaluate the cumulative effects of these land use practices on water quality along the stream gradient.

The study is an interdisciplinary effort which entails research on water quality characterization, development of land use indices that relate to water quality, and potential linkages between water quality and populations of benthic macroinvertebrates. The specific objective of this paper is to report on some of the initial results of the project with an emphasis on changes in physical, chemical, and biological parameters along the stream gradient in relation to land uses.

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 (Fig. 1). The Coweeta Hydrologic Laboratory, a research facility of the USDA Forest Service, comprises 2185 ha of the upland drainage area. This is a site of long-
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term (nearly 60 years) catchment research with a focus on water quality, quantity, and
timing in association with a wide range of other forest ecosystem studies (Swank &
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 Albert Mountain. The
climate is classed as marine, humid temperate due to high moisture and mild
temperatures. Average annual precipitation ranges from 180 to 250 cm, with the
highest values at higher elevations, and is characterized by frequent, small, low
intensity rains in all seasons with little snow (Swift et al., 1988). Average monthly
temperatures near Station 1 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). Quartz, biotite and muscovite micas, plagioclase
feldspar, and almandine garnet comprise the most abundant rock-forming minerals
(Velbel, 1988). Soils are dominated by well developed Ultisols and immature
Inceptisols.

Monitoring stations

Six water quality monitoring stations were located over the 8.7 km gradient of
Coweeta Creek and designated as 1 through 6 with stream size and landscape alteration
increasing from lower to higher station numbers (Fig. 1). Sites were selected to
encompass incremental additions and varieties of land uses. For example, at Station
1, located on upper Coweeta Creek, the catchment is almost entirely forested with
widely scattered small watershed (12 ha) experimental cutting disturbances of varying
ages. Most of the catchment is covered with mature deciduous forest and paved road
density is low. In contrast, Station 3 which is located 2.6 km downstream is influenced
by additional land use features such as residences along the stream, discharge from a
small secondary water treatment plant from a summer tourist development, grazing
and other agricultural practices, plus additional roads. Criteria for station selections
were largely subjective and partly based on potential influences of near-stream land
use activities. Quantitative analysis of land uses were subsequently derived from the
land classification phase of the study as given later in the results section.

Stream sampling

Stream water samples were collected during baseflow and stormflow periods. During
baseflow, grab samples were collected in 1-litre bottles from the free-flowing section
of the stream at each station; eddies and pools were avoided. Samples were returned
to the laboratory within 45 min and prepared for analytical processing. Sampling was
initiated the first week of June 1991 and was conducted twice weekly through August.
Thereafter, baseflow sampling was conducted weekly.

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. Sampling frequency and timing during a storm varied in
accordance with storm patterns. Some storm events were also sampled using a time-
proportional automated sampler which was activated near the onset of the storm.
Samplers were programmed to collect 24 samples at either 1-h or 2-h intervals during
storms.
Stream discharge was estimated at Station 1 by extrapolating hydrologic records taken near the confluence of two fourth-order streams which form Coweeta Creek just above Station 1. Discharge is measured continuously on each stream with 3.66 m Cipolletti weirs and flow rates for the gauged 1484 ha was prorated to the 1626 ha represented by Station 1 with appropriate corrections for precipitation amounts.

Water quality parameters and methods

Water samples were analysed 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% to account for altitude. All other analyses were conducted in the Laboratory at Coweeta using previously established procedures (Reynolds & Deal, 1989). Turbidity was measured with a Hack Model 2100A turbidimeter standardized to 12 NTU's and conductivity was determined with a Fisher Conductivity Meter Model 152 standardized to 75 \( \mu \)mhos cm\(^{-1}\). Determinations of pH were made with an Orion digital pH meter, Model 611.

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\(_{4}^{3-}\), SO\(_{4}^{2-}\), NO\(_{3}^{-}\), Cl\(^{-}\) with a Dionex Series 450i Ion Chromatograph; NH\(_{4}^{+}\), SiO\(_{2}\) with a Technicon AutoAnalyzer; and HCO\(_{3}^{-}\) with 0.01 N H\(_{2}\)SO\(_{4}\) titration.

Water samples for bacteria determination were collected in autoclaved 1-litre bottles and refrigerated until filtered, usually within 4 h of sampling. Filtration methods followed standard procedures (Millipore Corporation, 1986) using pre-sterilized HA-type (0.45 \( \mu \)m pore size) membrane filters for streptococcus and total coliform and HC-type (0.7 \( \mu \)m pore size) filters for faecal coliform. Pre-prepared commercial media was used for total and faecal coliform and the agar for faecal 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 Corporation, 1990).

Spatial data

Nine basic spatial data layers were developed for the entire Coweeta Creek watershed: catchment boundaries, hydrography, landcover, roads, dwellings (including all enclosed structures), 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, Prentiss Quadrangle, and manually digitized. Hydrography and roads layers were digitized from 1:24 000 USGS maps, with post-production roads added through the interpretation of 1:40 000 aerial photographs. Attributes for roads include length and surface type (paved or unpaved). Attributes for hydrographic data include stream length, stream order, and water sampling locations. Dwelling locations were identified from 9-inch, 1:6000 colour infrared photographs taken in September 1991. Soils map-
ping unit boundaries were manually digitized from 1:20,000 USDA Soil Conservation Service maps from the Macon County Soil Survey. Several soil attributes were available describing the chemical and physical characteristics of the mapping unit, including texture, organic matter content, pH, and other chemical and physical characteristics. 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. Current landcover was interpreted on screen from digitally rectified, scanned photography. Leaf-off 1:58,000 colour infrared photography was scanned at 50 µm on an Optronics rotating drum scanner. This yielded an approximately 6 m resolution. These data were then ortho-rectified using standard single-photo resection methods (Wolf, 1983). This digital orthophoto was then used as a base onto which 1991 1:6000 leaf-on colour infrared photos were interpreted. Landcover was categorized into 32 classes at the Anderson Level III (Anderson et al., 1976).

Catchment characteristics above each sampling point were determined through digital 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. Landcover/landuse classes were combined to form three broad classes (forest, agriculture, urban/suburban). Aggregate statistics for each catchment include percent landcover for each broad class, dwelling density (dwelling km\(^{-2}\)), total road length, paved road length, number of dwellings, percent area by soil order, and percent area underlain by colluvial deposits.

Statistical analysis

Sample data for all stations were stratified into baseflow and stormflow groups based on Station 1 flow rate. Baseflow was defined as less than 0.75 m\(^3\) s\(^{-1}\), and stormflow as more than 0.9 m\(^3\) s\(^{-1}\). A gradient set consisted of near simultaneous samples for at least three stations. The low flow (\(n = 32\)) and high flow (\(n = 5\)) sets were then analysed separately. Summary statistics for water chemistry and quality parameters were calculated by flow rate group and sample station. Scatter plots were constructed for each gradient set, depicting measured water parameters against station. A series of regression analyses were then conducted relating measured water parameters (dependent variables) to landscape variables (independent variables). First-order regressions with intercepts were fit for selected sets of dependent and independent variables. Separate regression models were fit for low and high flow observations.

RESULTS AND DISCUSSION

Land classification

Results for basin characteristics above each sample station are summarized in Table 1.
Urban/suburban and agricultural land classes, while a minority percentage for all stations, increases in both absolute and percent areas in the downstream direction. This is expected and characteristic of watersheds in the southern Appalachian Mountains, which have predominantly forested slopes and human-altered valley bottoms. The entire study area can be characterized as largely forest: at no point is more than 6% of a contributing drainage for any station non-forest. Many other landscape variables also increase in a downstream direction, most of which are related to urban/suburban and agricultural landuses. For example, the number of structures per unit area increases more than 30-fold from Station 1 (0.37 structures km$^{-2}$) to Station 6 (9.23 structures km$^{-2}$). Similarly, percent area in colluvial deposits and total road length increase downstream. However on a per-unit basis, landscape characteristics, such as total unpaved road length or percent Ultisol area, show weak or no distinct trends. Hillslopes have a well-developed network of access roads, offsetting the impact of high road densities associated with human activities.

Table 1 Landscape characteristics for the areas above each sampling station.

<table>
<thead>
<tr>
<th>Sampling station number:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest area (ha)</td>
<td>1600</td>
<td>1782</td>
<td>2949</td>
<td>2986</td>
<td>3904</td>
<td>4113</td>
</tr>
<tr>
<td>Agricultural area (ha)</td>
<td>4</td>
<td>13</td>
<td>81</td>
<td>89</td>
<td>155</td>
<td>192</td>
</tr>
<tr>
<td>Urban/suburban area (ha)</td>
<td>1</td>
<td>3</td>
<td>22</td>
<td>24</td>
<td>104</td>
<td>151</td>
</tr>
<tr>
<td>Total road length (km)</td>
<td>39.8</td>
<td>45.2</td>
<td>77.4</td>
<td>80.8</td>
<td>106.8</td>
<td>122.6</td>
</tr>
<tr>
<td>Unpaved road length (km)</td>
<td>38.7</td>
<td>43.9</td>
<td>70.7</td>
<td>73.4</td>
<td>96.4</td>
<td>106.5</td>
</tr>
<tr>
<td>Structures/area (# km$^{-2}$)</td>
<td>0.37</td>
<td>3.06</td>
<td>4.95</td>
<td>5.36</td>
<td>6.01</td>
<td>9.23</td>
</tr>
<tr>
<td>Colluvial deposits (%)</td>
<td>9.9</td>
<td>12.2</td>
<td>17.1</td>
<td>17.4</td>
<td>19.9</td>
<td>21.4</td>
</tr>
<tr>
<td>Ultisols (%)</td>
<td>34.0</td>
<td>44.4</td>
<td>44.5</td>
<td>44.5</td>
<td>53.2</td>
<td>56.4</td>
</tr>
</tbody>
</table>

Baseflow patterns of water quality

During baseflow conditions stream water over the entire stream gradient was of high quality as indicated by average chemical and physical parameters (Table 2). Concentrations of solutes were usually less than 1 mg l$^{-1}$ and are typical of stream chemistry for southern Appalachian forested watersheds. Concentrations of NO$_3^-$, NH$_4^+$, and PO$_4^{3-}$ are very low, indicating the absence of point sources of inorganic solutes to the stream. Average concentrations of cations, SO$_4^{2-}$, HCO$_3^-$, and SiO$_2$ show small incremental increases from Station 1 to Station 6, which is probably due to increasing contributions of groundwater to discharge in the lower valley.

Turbidity during baseflow conditions is also low (<3 NTU) and exhibits only small cumulative increases downstream. Average stream temperature for the period of study increased from 13.0°C at upper Coweeta Creek (Station 1) to 13.8°C at
Table 2 Baseflow stream chemical and physical parameter means and standard errors (in parentheses) for each sampling station (n = 32).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Station number:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>NO$_3$-N</td>
<td>0.040 (0.004)</td>
</tr>
<tr>
<td>NH$_4$-N</td>
<td>0.002 (0.000)</td>
</tr>
<tr>
<td>PO$_4$-P</td>
<td>0.002 (0.001)</td>
</tr>
<tr>
<td>Ca</td>
<td>0.83 (0.02)</td>
</tr>
<tr>
<td>Mg</td>
<td>0.34 (0.01)</td>
</tr>
<tr>
<td>K</td>
<td>0.40 (0.01)</td>
</tr>
<tr>
<td>Na</td>
<td>0.85 (0.01)</td>
</tr>
<tr>
<td>SO$_4$-S</td>
<td>0.571 (0.030)</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>7.043 (0.106)</td>
</tr>
<tr>
<td>HCO$_3$-</td>
<td>4.53 (0.12)</td>
</tr>
<tr>
<td>pH</td>
<td>6.88 (0.02)</td>
</tr>
<tr>
<td>Conductivity (μS)</td>
<td>13.5 (0.29)</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>1.58 (0.24)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>13.00 (0.91)</td>
</tr>
</tbody>
</table>

Station 6. Spatial patterns of stream temperature varied with season with increases of about 2°C during the growing season but no gradient during the winter period (Fig. 2). The gradual downstream temperature increase may be due to reduced riparian cover and thus increased solar radiation to the stream. There were small downstream cumulative increases in conductivity (13.5 to 17.4) and pH (6.88 to 6.95) but dissolved oxygen remained saturated over the stream gradient (data not shown).

Bacteria levels shown for baseflow conditions (Fig. 3) primarily represent the summer period (June-August). Mean total coliform tended to increase downstream from 1000 counts 100ml$^{-1}$ at Station 1, a peak of 5000 counts 100ml$^{-1}$ at Station 4 below a developed campground, and then declined further downstream. Faecal streptococcus counts tended to increase from Station 1 to Station 3 and then remained constant. Mean faecal coliform levels increased downstream, with a 12-fold increase between Stations 1 and 6 (Fig. 3).

Stormflow patterns of water quality

In contrast to baseflow patterns, strong incremental gradients in water quality parameters developed during storms (Table 3). Average values combine storm grab
samples and peak values measured by proportional sampling during storms. Significant increases in solute concentrations were observed over the stream gradient for NO₃⁻, Ca²⁺, Mg²⁺, K⁺, Na⁺, and SO₄²⁻ with large incremental increases in some parameters occurring between Stations 2 and 3 (Fig. 4). Some of the elevated concentrations over the stream gradient may represent subsurface leaching processes but previous analyses for upland streams draining forested catchments have shown very stable solute concentrations during storm events (Swank & Waide, 1988). Thus, the cumulative response is also partly due to land use practices. This interpretation is supported by the turbidity data (Table 3) which show a progressive downstream increase in values with a two-fold difference in turbidity between Stations 1 and 6. Sediment sources during storms include a variety of land use practices.

The cumulative influence of land use is even more apparent during individual storms than is obvious from average data. For example, some solutes such as NO₃-N also showed large gradient responses (three-fold) during some storms (Fig. 5(a)), and
peak turbidity levels increased dramatically downstream during two storms from 10-15 NTUs at Station 1 to about 40 NTUs at Station 6 (Fig. 5(b)). In terms of suspended sediment as measured by filtration methods, the increases are five- to six-fold greater and range from 20 to 400 mg l⁻¹. Bacteria levels were the most responsive water quality parameter during storm events although patterns were highly variable between storms and between seasons. For example, total coliform counts during small summer storms (<2.5 cm) were slightly elevated and tended to gradually increase downstream (Fig. 6). However, during a large summer storm (>5.0 cm), total coliform counts
increased tremendously over the stream gradient, indicating major sources from land use practices. Bacteria levels were low and remained relatively constant during the winter storm. Faecal coliform (FC) and faecal streptococcus (FS) exhibited similar storm response patterns along the stream gradient. During elevated flow the maximum FC/FS ratio was 1.35, indicating that human waste is not a source of pollution in Coweeta Creek.

Storm event water quality criteria showed large temporal variability and at present only a few storms are available for interpretation. However, taken collectively, it is apparent that during stormflow there are large cumulative increments in physical, chemical, and biological parameters that reduce the high quality of stream water from forested lands.

Landscape analysis

Strong, positive relationships were observed between most measured baseflow water quality variables and landscape variables (Table 4). These include (in decreasing
Table 4 Low flow regression on mean data.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Percent non-forest</th>
<th>Structure density</th>
<th>Paved road density</th>
<th>Percent colluvium</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO₃</td>
<td>--</td>
<td>--</td>
<td>*</td>
<td>--</td>
</tr>
<tr>
<td>NH₄</td>
<td>--</td>
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<tr>
<td>PO₄</td>
<td>--</td>
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<tr>
<td>Cl</td>
<td>**</td>
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<td>**</td>
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<tr>
<td>K</td>
<td>**</td>
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<td>Na</td>
<td>**</td>
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<tr>
<td>Ca</td>
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<tr>
<td>Mg</td>
<td>**</td>
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<td>--</td>
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</tr>
<tr>
<td>SO₄</td>
<td>**</td>
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<td>--</td>
</tr>
<tr>
<td>SiO₂</td>
<td>**</td>
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<td>--</td>
<td>**</td>
</tr>
<tr>
<td>Turbidity</td>
<td>**</td>
<td>**</td>
<td>--</td>
<td>**</td>
</tr>
<tr>
<td>Faecal streptococcus</td>
<td>**</td>
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<td>**</td>
<td>**</td>
</tr>
<tr>
<td>Faecal coliform</td>
<td>**</td>
<td>**</td>
<td>**</td>
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</tr>
</tbody>
</table>

-- not significant regression slope  
* slope significant at 10%  
** slope significant at 5%

number of water quality variables with significant regression slopes) percent area in non-forest, structure density, paved road density, and percent colluvium. There were few to no significant relationships for measured water quality variables and the remaining landscape variables: total road density, total road length, paved road length, percent ultisols, and number of structures. In nearly all cases there were not significant relationships between stormflow water quality variables and landscape variables, due to both storm-related variation and much smaller sample sizes. Further discussion applies only to baseflow measurements, except where noted.

Some inorganic cations and anions were significantly related to percent non-forest area, structure density, paved road density, and percent colluvium (Table 4). Although these relationships are highly significant, knowledge of system function suggests they are likely correlative and not causative. Landscape variables such as percent non-forest and structure density are highly correlated with each other (Pearson’s r-values > 0.9), and are also correlated with percent colluvium (r-values > 0.6). Downstream stations have a higher proportion of areas with low slopes, higher order streams, and most probably a higher baseflow groundwater proportion.

Turbidity, faecal streptococcus, and faecal coliform bacteria were significantly and positively related to the described landscape variables (Table 4). For turbidity, these relationships most likely reflect the effects of both human habitation and associated disturbance, e.g. bare-soil associated with gardens, farming, construction, and other activities. For the faecal streptococcus and coliform bacteria, they may be a result of increased livestock or septic system density associated with increased structure density.

Nitrogen measured as NO₃ and NH₄ and phosphorus were generally not
significantly related to any investigated landscape variables when all samples were pooled for regressions. However, data from individual sampling dates did show strong, positive relationships between nitrogen and landscape variables, and also revealed significantly different relationships for storm and baseflow conditions.

CONCLUSIONS

The results of this study support the following conclusions:

(a) During baseflow conditions, concentrations of constituents in stream water were high and dominated by source area conditions, with generally slight increases observed in a downstream direction for most measured chemical, physical, and biological parameters. Most cations increased incrementally along the entire gradient, indicating an absence of point sources and increasing groundwater discharge in the lower valley. Under baseflow conditions, faecal streptococcus, faecal coliform, and total coliform bacteria increased downstream and there also were small cumulative increases in pH, turbidity, and conductivity. Temperature increased slightly downstream during the growing season, but a gradient was not observed during winter.

(b) Water quality parameters showed steeper, more variable incremental gradients during stormflow conditions than during baseflow. Significant increases in mean solute concentrations were observed for NO$_3^-$, Ca$^{2+}$, Mg$^{2+}$, K$^+$, Na$^+$, and SO$_4^{2-}$, as well as increases in mean turbidity and faecal bacteria. Increases were more pronounced for individual storm events. Moreover, measured values increased downstream at greater rates than under baseflow conditions.

(c) Strong, positive relationships were observed between most water quality parameters and landscape variables, particularly those related to cumulative human activities or alteration of the landscape. For example, significant linear relationships were observed between percent non-forested area and 10 of 14 measured water quality parameters.

In toto, this work identifies consistent, cumulative changes in water quality along a stream-order gradient. Furthermore, they indicate these cumulative impacts due to landuse and landscape alteration are much greater during stormflow than baseflow conditions. While most current water quality legislation, regulations, and sampling establish criteria for baseflow conditions, this work suggests they should also consider the cumulative impacts of physical, chemical, and biological water quality during stormflow.

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