Vertical and Lateral Components of Soil Nutrient Flux in a Hillslope

J. W. Gaskin,* J. F. Dowd, W. L. Nutter, and W. T. Swank

ABSTRACT

The vertical and lateral components of chemical flux during storm events were investigated in a Typic Hapludult to assess their importance in understanding the effects of atmospheric deposition on hillslope sites. Vertical and lateral water fluxes were calculated from soil water potential data and hydraulic conductivity curves. Throughfall, stemflow, forest floor leachate, and soil solution from the BA, Bt, and BC horizons were sampled and analyzed for SO\(_4\), NO\(_3\)-N, Cl, HCO\(_3\), H, K, Ca, Mg, and Na. Total lateral flow as a ratio of total vertical flow averaged 0.23 and 0.30 in the A and BA horizons, respectively, indicating lateral fluxes were an important path of nutrient movement in the surface horizons. The highest lateral flow occurred in the A horizon during dry antecedent moisture conditions and in the BA horizon during wet antecedent moisture conditions. Fluxes of all ions except HCO\(_3\), NO\(_3\)-N, and H peaked in the forest floor leachate and the BA soil solution, then decreased with depth. Decreases of SO\(_4\) flux between the BA and BC horizons could not be explained by the lag of solute movement or by lateral solute losses, demonstrating the system was an effective SO\(_4\) sink.

Accelerated soil nutrient leaching due to acid deposition is an environmental concern. Field studies have examined the effects on forest nutrient status and nutrient cycling by measuring soil solution concentrations (Johnson et al., 1985; Cronan et al., 1978; Ulrich et al., 1980). Chemical mechanisms of leaching have been identified with models (Reuss, 1980, 1983) and in the laboratory (Johnson and Henderson, 1979; Johnson and Todd, 1983), and the hypotheses generated have been tested in the field (Johnson et al., 1986; Khanna et al., 1987). Results from these simulations and field studies have shown the importance of determining nutrient flux through the soil for a complete understanding of the environmental impacts of acid deposition.

Nutrient flux is commonly estimated by multiplying the measured nutrient concentrations times an estimated water flux. Although uncertainty exists concerning methods of obtaining representative soil nutrient concentrations, the estimate of water flux is the source of the greatest uncertainty in the nutrient-flux calculation. Direct measurement of water flux is not possible. Van der Ploeg and Beebe (1977) have shown that tension lysimeter volumes cannot be used to estimate water flux. Therefore, a separate estimate must be made. Two methods are primarily used: (i) water balance, and (ii) calculation of flux based on Darcy’s Law. The water-balance approach estimates water flux as the residual of the mass-balance equation, using inputs to the soil, losses to interception, evapotranspiration and changes in soil storage. Usually, the water is assumed to percolate vertically to the next level or out of the soil system. Flux calculations can be a direct computation of Darcy’s Law, or an indirect calculation such as the Richard’s Equation. Darcy’s Law states that flux is the product of the hydraulic conductivity and the energy gradient in the soil. Soil water potential can be measured with tensiometers and coupled with hydraulic conductivity data to predict flux. Both vertical and lateral flux can be determined.

Russell and Ewel (1985) compared the two methods and conclude the water-balance approach is superior. They assumed vertical percolation because there was no impeding soil layer. This is a poor assumption on hillslopes where water movement is known to have a lateral component (Harr, 1977; Weyman, 1973; Whipple, 1965). Although lateral flow is associated with an impeding layer or a decrease in hydraulic conductivity with depth (Zaslavsky and Rogowski, 1969), Nutter (1975) showed that lateral flow occurs under homogeneous soil conditions in a sloping soil model, and McCord and Stephens (1987) provided field evidence for this phenomenon. Therefore, lateral flow should not be ignored in hillslope sites. In order to determine the importance of the lateral component of flow, Darcy’s Law must be used.

Many of the forest ecosystems impacted by acid deposition are in mountainous regions where the evaluation of leaching in the soil may be complicated by lateral flow. Therefore, the objectives of this study were: (i) to determine the importance of vertical and lateral flow in a forested hillslope receiving atmospheric deposition and (ii) to estimate chemical flux during and immediately after a storm.

METHODS

Site Description

The study was conducted on Watershed 1 of the USDA Forest Service Coweeta Hydrologic Laboratory near Otto, NC, which is a site for measurement of atmospheric deposition and nutrient fluxes (Swank and Reynolds, 1987). The Coweeta basin is located in the Blue Ridge province of the southern Appalachians. Underlying rock consists of granite gneiss and schists in the Coweeta Group and the Tallulah Falls Formation (Hatcher, 1979). The climate is considered marine. Annual rainfall is evenly distributed and averages around 1800 mm per year (Swank and Douglass,
Soil water characteristic curves were determined for the A, BA, Bt, and BC horizons with a pressure-plate apparatus (Richards, 1965) using 12 undisturbed cores (5.3-cm diam. by 3.0-cm long) from each horizon. Laboratory estimates of saturated hydraulic conductivity ($K_s$) were determined by the constant-head method (Klute, 1965) using 6 to 7 undisturbed cores (5.3-cm diam. by 6.0-cm long) per horizon. Field measurements of saturated hydraulic conductivity ($K_{fs}$) were made with a Guelph permeameter (Reynolds and Elrick, 1985) using 5- and 10-cm heads in a 3-cm radius well. Seven to 8 measurements of $K_{fs}$ were obtained just below the study plot in the BA (mean depth 17 cm), Bt (mean depth 31 cm) and at the top of the BC (mean depth 60 cm) horizons. Only two of these measurements resulted in a negative estimate of $K_{fs}$ using the Laplace method (one each in the Bt and the BC horizons). The negative values were not used. $K_{fs}$ could not be obtained for the shallow A horizon (9.0 cm). An estimate of $K_{fs}$ for the A horizon was extrapolated using the $K_{fs}$ in the BA horizon and the ratio of the $K_s$ in the A and BA horizons. Unsaturated hydraulic conductivity was calculated from the soil water characteristic curve data, using the saturated hydraulic conductivity as a matching factor by the method of Millington and Quirk (1959) as modified by Kunze et al. (1968). A summary of soil characteristics, the mean of six to seven repetitions of the hydraulic conductivity.
measurements for each method, and parameters of the Millington Quirk equation is presented in Table 1.

Vertical and lateral water fluxes were calculated from tensiometer readings and hydraulic conductivity curves using Darcy's Law. Vertical fluxes were calculated for each time period using the total heads obtained from tensiometers bracketing a horizon for sets 1 and 2, then averaged. Lateral fluxes were calculated from the total heads obtained from tensiometers in the middle of the BA, Bt, and BC horizons. Lateral fluxes were computed between tensiometer sets 2 and 3 and sets 3 and 4, then averaged. Total flux is the sum of the average fluxes over time for a storm. The flux calculations did not account for hysteresis and assumed isotropic conditions within a soil horizon. Because soil water potential in the A horizon was not measured in the lateral tensiometer sets, lateral flux over time in the A horizon was not calculated. However, total lateral flux in the A horizon for a storm event was estimated by difference:

$$q_{\text{AL}} = q_{\text{AV}} - \Delta A - q_{\text{BA}}$$

where:

- $$q_{\text{AL}}$$ = total lateral flux in the A horizon (cm)
- $$q_{\text{AV}}$$ = total vertical flux in the A horizon (cm)
- $$\Delta A$$ = total change in storage in the A horizon (cm)
- $$q_{\text{BA}}$$ = total flux into the BA horizon (cm)

Mass balance computations assuming negligible evapotranspiration during a storm event were used as a check of the Darcy flux. Each soil horizon was considered a slab of unit width, horizon depth, and slope length. The slope length extended from the watershed boundary to the plot boundary, which allowed the assumption of zero lateral flux across the upper face of the slab. The change in storage for each soil horizon determined by mass balance was compared with the change in storage obtained from the tensiometers using the moisture characteristic curves.

Chemistry

Stemflow collection collars were attached to nine dominant and codominant white pines; samples were collected from each tree. Throughfall was collected with 10 26-cm-diam. funnels positioned randomly in the plot. A plastic-screen plug was used in the funnel neck to prevent large particulates from contaminating the sample. Two similar precipitation collectors were placed in a clearing at the base of the watershed. Precipitation, throughfall, and stemflow collectors were covered during dry periods and opened before storm events.

Four lysimeter pits were excavated along the contour of the slope. Lysimeters made of high-flow (100 kPa air entry value, Soil Moisture Equipment Corp., Santa Barbara, CA) ceramic cups and PVC pipe were installed horizontally in the BA (12 cm), the Bt (30 cm), and the BC horizon (75 cm) of each pit. Constant tension was maintained with hanging water columns at 10 kPa in two pits and 30 kPa in two pits. Zero-tension lysimeters (Jordan, 1968) were installed at the forest floor-mineral soil interface upslope from each pit.

Storm events started with the inception of rainfall and ended when tensiometer readings began to rise after reaching a minimum, indicating the soil profile was drying out. Precipitation, throughfall, and stemflow volumes were measured at the end of the storm and a subsample was retained for chemical analysis. Forest-floor leachate and soil-solution samples were collected in 250- and 100-mL increments, respectively, during the storm event. Samples were refrigerated immediately after collection. All samples except soil solution were filtered with Whatman GF/C micropore filters (1.2-μm effective retention). Three filter blanks were run and the average filter-blank concentration was subtracted from the concentrations of the filtered samples.

Samples were analyzed for H, HCO₃, SO₄, Cl, NO₃-N, K, Ca, Mg, and Na. Bicarbonate and H analyses were performed within 24 h of collection. Hydrogen-ion concentration was calculated from pH. Bicarbonate was determined by titration with weak H₂SO₄ (0.005 M or 0.01 M). Anions were determined colorimetrically. Cations were analyzed by atomic absorption spectrophotometry.

The number of soil-solution samples per storm ranged from five to eight in the BA horizon, zero to four in the Bt horizon, and zero to three in the BC horizon. Chemical flux for the soil solution was calculated by multiplying the average water-flux estimates for the time period over which the sample was collected with the concentrations. The resultant chemical fluxes were summed for the storm and averaged by horizon. Vertical and lateral components of flux were considered separately. All ions were reported as mol, m⁻² storm⁻¹. Percent change of an ion between horizons was calculated after subtracting the laterally moving concentrations.

RESULTS AND DISCUSSION

Soil Water Flux

Soil water flux was calculated for five storms occurring between May 1985 and November 1986. Figure 2 shows the initial soil water profile for Storm 1, 3, 4, and 5 obtained from the average of tensiometer sets 1 and 2, and the moisture characteristic curve. The initial soil water profile for Storm 2 (13-15 October 1986; 17 mm precipitation) is not shown due to instrument failure from extremely dry antecedent soil water conditions. Soil solution samples collected from this storm were the first since Storm 1 on 26 May 1986. Storms were grouped into dry antecedent conditions (Storm 1, 2, and 3) and wet antecedent soil water conditions (Storm 4 and 5) for comparison.
Fig. 2. Initial soil water profile for Storm 1 (26–29 May 1986, precipitation of 69 mm), Storm 3 (23–27 Oct. 1986, precipitation of 100 mm), Storm 4 (10–13 Nov. 1986, precipitation of 21 mm) and Storm 5 (19–23 Nov. 1986, precipitation of 32 mm).

Total storm fluxes calculated from hydraulic conductivity curves obtained using \( K_{fs} \) as a matching factor were two orders of magnitude greater than throughfall/stemflow (TF/SF) input. The \( K_{fs} \) measurements were extremely high, even though flow down the sides of the core rings was excluded with cutoff rings. The high laboratory measurements were attributed to small roots and other continuous channels in the cores common to well-developed forest soils. Field measurements were made in an attempt to incorporate a larger soil volume and diminish the effect of continuous channels. Total storm fluxes calculated from unsaturated hydraulic conductivity curves using \( K_{fs} \) were in better agreement with inputs, but still appeared high.

Decreases in hydraulic conductivity with depth in soils enhances lateral flow. Measurements indicated a decrease in saturated hydraulic conductivity between the A and BA horizons, and also between the BA and Bt horizons. Although the variability of these measurements was high, the increase in soil bulk density and the change in texture with depth (Table 1) supported the existence of the conductivity decreases.

The effect of the difference in hydraulic conductivities between horizons was the greatest when a wet horizon overlaid a drier one. During dry antecedent conditions, the BA could not transmit water as fast as the A could supply it, and water was shunted laterally. The same process occurred at the BA-Bt interface during wet antecedent conditions. The ratio of lateral to vertical flux in the BA horizon was related to precipitation depth as well as the antecedent conditions.

In addition to using TF/SF inputs as a constraint on the flux estimates, the change in storage obtained from mass-balance calculations using the best flux estimates were compared with measured change in storage to help assess flux validity. Calculated change in storage was generally higher than the measured change in storage (Table 3). The higher calculated values indicate vertical fluxes were too high as a result of overestimating vertical hydraulic conductivity, or lateral fluxes were too small as a result of underestimating lateral conductivity, or some degree of both. The \( K_{fs} \) is an average of vertical and lateral conductivity (Reynolds and Elrick, 1985), which may cause overestimates of vertical flux and underestimates of lateral flux in hillslope sites.

The largest decrease in total storm flux occurred between the A and BA horizons during dry antecedent conditions, and between the BA and Bt horizons during wet antecedent conditions. Results in Table 2 indicate these decreases were caused by lateral flux because the mean total lateral flux as a ratio of vertical flux in the A horizon was greater during dry antecedent conditions than during wet ones (dry mean = 0.33 vs. wet mean = 0.12).

Decreases in hydraulic conductivity with depth in soils enhances lateral flow. Measurements indicated a decrease in saturated hydraulic conductivity between the A and BA horizons, and also between the BA and Bt horizons. Although the variability of these measurements was high, the increase in soil bulk density and the change in texture with depth (Table 1) supported the existence of the conductivity decreases.

<table>
<thead>
<tr>
<th>Storm number</th>
<th>Sampling level</th>
<th>Calculated S (cm)</th>
<th>Measured S (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BA</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>2</td>
<td>Bt</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3</td>
<td>Bt</td>
<td>0.7</td>
<td>1.8</td>
</tr>
<tr>
<td>4</td>
<td>BA</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>5</td>
<td>Bt</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>BA</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>–</td>
<td>–</td>
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<td></td>
<td>BA</td>
<td>1.6</td>
<td>1.4</td>
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<tr>
<td></td>
<td>BC</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>BA</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>BA</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>BC</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>BA</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 3. A comparison of calculated change in storage from mass balance calculations (calculated S) and measured in storage from tensiometer data (measured S) for each storm by horizon.

† TF/SF = ratio of throughfall to stemflow.
During the wet antecedent conditions and the driest antecedent conditions (Storm 1 and 2), the ratio of lateral to vertical flux averaged 0.36 and 0.22, respectively. Although Storm 3 occurred during dry antecedent conditions, the large amount of precipitation apparently filled storage in the BA horizon, allowing a high ratio of lateral flow (0.41).

Lateral flow in the Bt horizon did not vary as much with antecedent soil water conditions, the ratio of lateral to vertical flux ranging from 0.9 to 0.17. The consistency of the proportion of lateral to vertical flow in the Bt may be due to the negligible difference in saturated hydraulic conductivity between the Bt and BC. Due to the extremely dry conditions for the year, the proportion of lateral flow may be atypical for this site.

There was no significant lateral flow in the BC horizon.

Storm 3 illustrated the pattern of flux through time during the storm events sampled (Fig. 3). Vertical flux showed a sharp increase after rainfall, with the increase lagged as the wetting front moved through the soil profile. Lateral flux increased sharply in the BA horizon, but was damped with depth. In the desorption phase, lateral flux tended to become constant while vertical flux decreased. These results are consistent with data from physical soil models showing that lateral flux becomes more important as the soil dries (Nutter, 1975).

The pattern of flux over time was similar for Storm 3, 4, and 5. Ratios of vertical to lateral flux over time for these storms showed high variability at the storm beginning when storage was being filled. As the storm progressed, the ratios for each storm became quite similar in both the BA and Bt horizons (Fig. 4). The ratio of lateral to vertical flux at the point of maximum vertical flux was more consistent across storms, ranging from 0.39 to 0.42 in the BA and 0.12 to 0.13 in the Bt.

These results indicate the amount of lateral flow was controlled by the soil water content and the depth of precipitation. Once the storage was filled to some threshold level, lateral flow was a relatively constant ratio of vertical flow.

The largest source of error associated with the flux calculations was the method of measuring saturated hydraulic conductivity. The problem of obtaining realistic values of saturated hydraulic conductivity was largely caused by the spatial variability of the soil. Although total flux estimates were dependent on the saturated hydraulic conductivity used to generate unsaturated hydraulic conductivity curves, they were reasonable because the total storm fluxes were close to SF/TF inputs.

Error associated with gradient estimates was small because there were only small differences in soil water potential measured at comparable depths (mean, 0.7 kPa). Variability of the difference in soil water potential was strongly influenced by antecedent conditions (standard deviation of 2 kPa for wet storms and 18 kPa for dry storms), suggesting the occurrence of preferential flow zones during dry antecedent conditions. Consequently, errors in flux prediction may be greatest during dry antecedent conditions.

This analysis assumed that the soil was isotropic; the same saturated hydraulic conductivity applied to both directions of flow. Therefore, the ratio of lateral to vertical flux was independent of the saturated hydraulic conductivity (Table 4). In layered soils, where anisotropy occurs, lateral conductivities are often
higher than vertical conductivities. The difference between the measured and calculated change of storage suggested that such a condition may exist for this site. However, measurement of the anisotropy of this site was beyond the scope of this study. We feel the assumption of isotropy in each soil horizon gives a lower bound estimate of the ratio of lateral to vertical flux in each horizon.

Recent research has emphasized the importance of macropore flow in a variety of soils (Beven and Germann, 1982). Some studies in forest soils indicate the major portion of water flux during storms occurs as macropore flow rather than as flow through the soil matrix (DeVries and Chow, 1978). This study did not address the amount of macropore flow occurring during storms; thus an unknown portion of the soil-water flux has been excluded. However, we feel macropore flow is likely to be small on a plot or watershed scale flux in the BC was negligible.

Chemistry

Soil-solution samples were collected at two tensions. The probability distributions of each ion were tested for differences by horizon (Wilcoxon Sum Rank, $\alpha = 0.05$) to see if the two tensions sampled the same population. The BC-horizon soil solution and HCO$_3$ in the BA and the Bt horizon were not tested due to the limited sample size. Eleven of 14 probability distributions were not different, therefore we could not conclude that the samples came from different populations and the samples were pooled by horizon for average equivalents in a storm. Average concentrations and standard errors are given in Table 5.

Average fluxes of SO$_4$, Cl and the base cations for all storms were highest in the forest-floor leachate and the BA-horizon soil solution, then decreased with depth in the soil (Fig. 5). The fluxes of NO$_3$ and H peaked in the precipitation and decreased as they moved through the system. The flux of both these ions was lower (<0.011 and <0.012 mol m$^{-2}$, respectively) in the soil solution. Bicarbonate flux was low in the input samples (mean, 0.015 mol m$^{-2}$) and increased in the soil solution as water dissolved CO$_2$.

Sulfate was the dominant anion throughout the system, except in the BC horizon. The maximum sulfate flux was in the forest-floor leachate. Sulfate flux was approximately five times greater than HCO$_3$ in the BA horizon. The difference decreased in the Bt where SO$_4$ flux was 30% greater than HCO$_3$. In contrast, SO$_4$ flux was 43% less than HCO$_3$ in the BC horizon.

Although results from other temperate forest ecosystems indicate HCO$_3$ and organic acids are the primary mobile anions in the soil solution (McColl and Cole, 1968), Johnson et al (1988) report SO$_4$ is the dominant anion in soil solution collected over a 2- to 3-yr period at Coweeta. High SO$_4$ values are also reported in the soil solution and groundwater from areas that receive sizable atmospheric inputs (Cronan et al., 1978). The Coweeta basin is subject to atmospheric SO$_4$ deposition (Swank and Waide, 1988) and preliminary results from Swank and Reynolds (1987) indicate dry deposition may be a major source of below-canopy fluxes. The amount of SO$_4$ in the soil solution may be higher than normal because the 1985 to 1986

### Table 4: A comparison of the ratio of lateral to vertical fluxes calculated using the mean field-measured saturated hydraulic conductivity ($K_s$) and the low $K_s$. Ratios for the A horizon were not included, as they were obtained by difference. Lateral flux in the BC was negligible.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Storm 1 mean</th>
<th>Storm 1 low</th>
<th>Storm 2 mean</th>
<th>Storm 2 low</th>
<th>Storm 3 mean</th>
<th>Storm 3 low</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA</td>
<td>0.20</td>
<td>0.23</td>
<td>0.20</td>
<td>0.20</td>
<td>0.41</td>
<td>0.14</td>
</tr>
<tr>
<td>Bt</td>
<td>0.08</td>
<td>0.17</td>
<td>0.24</td>
<td>0.00</td>
<td>0.13</td>
<td>0.14</td>
</tr>
</tbody>
</table>

### Table 5: Average storm concentrations and standard errors for anions and cations present in the precipitation (P); throughfall (TF); stemflow (SF); forest floor leachate (FF); and the soil solution from the A, BA, Bt, and BC horizons.

<table>
<thead>
<tr>
<th>Component</th>
<th>SO$_4$</th>
<th>Cl</th>
<th>NO$_3$</th>
<th>HCO$_3$</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
<th>Na</th>
<th>H</th>
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</thead>
<tbody>
<tr>
<td>P</td>
<td>8.88</td>
<td>5.05</td>
<td>7.71</td>
<td>0.56</td>
<td>1.89</td>
<td>12.48</td>
<td>0.62</td>
<td>10.66</td>
<td>17.56</td>
</tr>
<tr>
<td>SE</td>
<td>3.73</td>
<td>0.91</td>
<td>2.75</td>
<td>0.14</td>
<td>0.24</td>
<td>0.21</td>
<td>0.26</td>
<td>2.59</td>
<td>5.63</td>
</tr>
<tr>
<td>TF</td>
<td>15.55</td>
<td>12.19</td>
<td>5.78</td>
<td>0.13</td>
<td>28.44</td>
<td>8.43</td>
<td>4.61</td>
<td>5.87</td>
<td>6.39</td>
</tr>
<tr>
<td>SE</td>
<td>1.50</td>
<td>2.90</td>
<td>2.81</td>
<td>0.61</td>
<td>3.56</td>
<td>1.25</td>
<td>0.59</td>
<td>1.98</td>
<td>2.62</td>
</tr>
<tr>
<td>SF</td>
<td>34.44</td>
<td>23.35</td>
<td>1.29</td>
<td>0.20</td>
<td>77.00</td>
<td>15.82</td>
<td>8.76</td>
<td>8.74</td>
<td>27.78</td>
</tr>
<tr>
<td>SE</td>
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<td>0.22</td>
<td>0.08</td>
<td>14.85</td>
<td>3.17</td>
<td>1.78</td>
<td>1.17</td>
<td>3.15</td>
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<tr>
<td>FF</td>
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<td>50.43</td>
<td>1.50</td>
<td>1.80</td>
<td>58.10</td>
<td>77.50</td>
<td>32.09</td>
<td>18.44</td>
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</tr>
<tr>
<td>SE</td>
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<td>0.21</td>
<td>5.38</td>
<td>6.38</td>
<td>3.00</td>
<td>3.95</td>
<td>0.98</td>
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<tr>
<td>BA</td>
<td>71.73</td>
<td>79.32</td>
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<td>31.25</td>
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<tr>
<td>SE</td>
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<td>Bt</td>
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<td>53.79</td>
<td>25.09</td>
<td>56.81</td>
<td>35.46</td>
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<td>5.23</td>
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<td>1.74</td>
<td>1.38</td>
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</tr>
<tr>
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<td>0.07</td>
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<td>21.93</td>
<td>32.84</td>
<td>0.40</td>
</tr>
<tr>
<td>SE</td>
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<td>3.20</td>
<td>0.03</td>
<td>0.66</td>
<td>0.41</td>
<td>5.86</td>
<td>1.27</td>
<td>1.58</td>
<td>0.04</td>
</tr>
</tbody>
</table>
water year encompassed a 100-yr drought. High rates of mineralization combined with low rates of flushing due to the dry soil conditions may have caused a buildup of SO$_4$ in the surface horizons that was beginning to move through the system with the fall storms. However, SO$_4$ concentrations are within the range reported for a 45-yr-old pitch pine stand 10 km north of the Coweeta basin (Swank and Swank, 1984).

Average SO$_4$ flux was not greater than HCO$_3$ in the BC horizon. The decreases in SO$_4$ flux could be due to the lag of water and solute movement to the lower horizons. However, some SO$_4$ was immobilized. The percent decrease of Cl, which may be considered a conservative tracer, was 44% from the BA to the Bt horizon, compared with 61% for SO$_4$. Sulfate retention can be attributed to adsorption (Johnson and Henderson, 1979) or microbial transformation (Fitzgerald and Johnson, 1982) both of which have been shown to be important in Coweeta soils.

It is important to recognize that the percent decrease of solute fluxes excludes losses from lateral water movement. Lateral solute flux was small in the Bt and BC horizons (ratio of lateral to vertical 0.12 and 0.5, respectively), but high in the BA (0.28). The ratio of solutes moving laterally in the A horizon was probably also high. Total amounts of lateral flux may be greater in the lower horizons under more-saturated conditions.

Errors inherent in soil nutrient flux estimates in the soil are associated with the water-flux calculations, which has been previously discussed, and the problem of obtaining a representative concentration. Litaor (1988) questions the validity of soil-solution concentrations obtained from suction lysimeters, but this is the best nondestructive method currently available.

**CONCLUSIONS**

The most significant finding of this study was the importance of the total lateral-flux component in the A and BA horizons, where the ratio of lateral to vertical flux averaged 0.23 and 0.30, respectively. These ratios are conservative, as each horizon was considered isotropic.

Antecedent soil-water conditions determined where the largest portion of lateral flow occurred. During dry antecedent conditions, the greatest lateral flow was in the A horizon. High lateral flow occurred in the BA horizon during wet antecedent conditions and with large-volume storms. After soil storage reached some threshold level during a storm event, the ratio of lateral to vertical flux became relatively constant in the BA and Bt horizons.

The fluxes of SO$_4$, Cl, NO$_3$-N, K, Ca, Mg, and H in the soil solution were greatest in the BA horizon and decreased with depth. The decreases of SO$_4$ could not be explained by the lag of solute movement to the lower horizons or by lateral solute losses, indicating SO$_4$ was being immobilized.

Approximately 0.30 of ion equivalents moved lat-
eraly in the BA horizon. The soil solution moving laterally does not equilibrate with the lower horizons. This may be especially important for SO\textsubscript{4} which is adsorbed in the lower horizons (Johnson and Todd, 1983) and immobilized. Because cation leaching is dependent on mobile anions (Johnson and Cole, 1980), the fact that a considerable portion of the SO\textsubscript{4} was moving laterally in the BA horizon implies greater leaching of cations may take place in the surface horizons during storm events.

Results from this study must be interpreted in light of the extremely low rainfall during the storm collection period. The dry conditions may have affected both the soil-solution chemistry and the proportion and magnitude of vertical and lateral fluxes.

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