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RELATIONSHIPS BETWEEN SNOW COVER AND WINTER LOSSES OF DISSOLVED SUBSTANCES FROM A MOUNTAIN WATERSHED

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ABSTRACT

The yield of dissolved materials from a mountain watershed at 2900 m elevation near the Continental Divide in Colorado was computed for 3 yr with very different snowpack conditions. The analysis focuses on the loss of materials during the low-flow season, which extends from fall prior to snow cover through winter. Snowpack was normal the first year, low the second year, and higher than normal the third year. Under a substantial snow cover, the ground surface typically remains unfrozen, whereas bare areas freeze all the way to bedrock. The variation in snowpack thus implies considerable variation in soil frost. The yield of dissolved materials was significantly different between years for Ca^{++}, Mg^{++}, K^{+}, PO_4-P, NO_3-N, Dissolved Organic Phosphorus, HCO_3^{-}, and H^{+}. There were no significant differences between years ($P > 0.05$) for SO_4^{--}, Na^{+}, NO_2-N, NH_4-N, Dissolved Organic Carbon, and Dissolved Organic Nitrogen. Substances the yields of which differed significantly between years always showed a strong tendency for yield to be negatively related to the amount of snow cover. In the comparison between years, statistical corrections were made for discharge, so the differences between years must be largely explained by factors related to snow cover, of which soil frost is the most obvious. The effect of low snowpack and the associated extensive soil frost on losses of nitrate from the system is much more extreme than for any of the other dissolved constituents. Exports of nitrate were approximately tripled in the year of minimum snowpack and maximum soil frost. The response of biologically active substances such as phosphate and potassium is generally higher than the response of other substances which are not in such great biological demand, suggesting that soil frost increases the yield of substances from the watershed by interfering with biological sequestering mechanisms which would ordinarily trap these substances in the terrestrial system.

INTRODUCTION

The sensitivity of watershed mineral cycling processes to variations in physical conditions associated with weather variations has been very little studied. Drastic differences from year to year in the amount of water flowing through the terrestrial system, the timing and duration of freeze and thaw cycles, the amount or depth of soil frost, the temperature of the upper soil, and other associated variables potentially affect the yield of dissolved materials from watersheds and thus the overall mass balance of terrestrial systems. Studies of the response of watersheds to alterations in these variables would provide insights into the robustness of mineral retention mechanisms in terrestrial systems.

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Our 3-yr study of the chemical output of the watershed of Como Creek, near the Continental Divide in Colorado (Figure 1), coincided with an extreme range in the amount of winter snowpack. The first year of the study was characterized by average snowpack, the second year by extremely low snowpack, and the third year by high snowpack. It is our purpose here to contrast the yield of dissolved materials from the watershed in the fall-winter periods of these 3 yr with attention to the possible effects of snowpack on the loss of dissolved materials.

We have previously analyzed the relationship of stream discharge to the concentration of dissolved substances in stream water and to the yield of dissolved substances from the terrestrial system (Lewis and Grant, 1979). The study showed that (1) the yield of some substances increases at a slower rate than discharge (HCO_3^-, NO_3^-, Ca^{++}, Mg^{++}, Na^+), (2) the yield of some substances increases at approximately the same rate as discharge (NH_4^+, Dissolved Organic Nitrogen), and (3) the yield of some substances increases at a faster rate than discharge (Dissolved Organic Phosphorus, K^+, SO_4^{--}, Dissolved Organic Carbon, H^+, PO_4^{---}). The study also showed, however, that there is seldom any significant difference in the relationship between discharge and yield between years with very different weather patterns. The relationship between yield and discharge differs considerably between dissolved substances, but tends to be very similar between years for a given substance, even though the weather varies considerably between years. These relationships are particularly applicable during the runoff season, when discharge first increases radically and then decreases radically as the snowpack melts and flushes through the terrestrial system. We have not investigated in detail any changes in the yield of substances over that portion of the year when discharge is continuously low (fall-winter). The period of low flow is particularly interesting because of the radical change in physical conditions which occurs as the warmer temperatures of late summer give way to extremely low temperatures and snowpack in the winter months without substantial change in discharge.

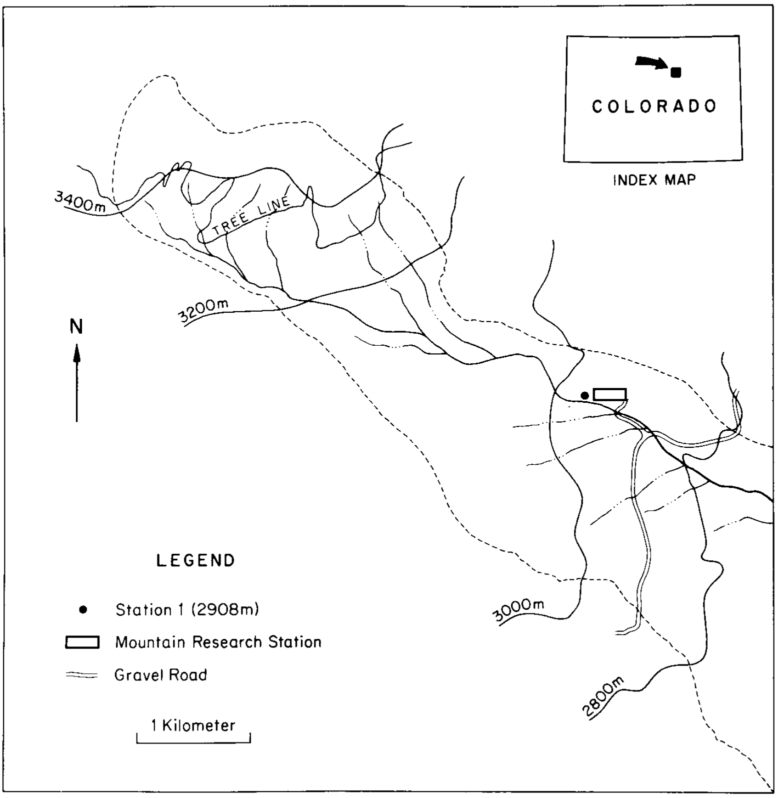

FIGURE 1. Map of the Como Creek watershed and surrounding areas showing the location of the sampling station.

METHODS AND WATERSHED CHARACTERISTICS

Stream samples and discharge measurements were taken at weekly intervals between June 1975 and April 1978. Methods of measurement and chemical analysis are described by Lewis and Grant (1979). The present analysis deals with the principal dissolved components of streamwater plus dissolved materials such as nitrate and phosphate that are of specific interest with regard to the nutrition of organisms in the terrestrial system. The analysis is restricted to the low-flow periods (Figure 2).

The Como Creek Watershed is located 6 km east of the Continental Divide in north-central Colorado (Figure 1). The sampling station used in the present study has an elevation of 2908 m. The upper regions of the watershed extend to elevations as high as 3560 m. Approximately 20% of the watershed is above the treeline or lacks trees because it was not completely reseeded following deforestation some 75 yr ago. The remaining portion of the watershed is covered primarily with conifers and some aspen. The dominant trees and shrubs include *Abies lasiocarpa, Picea engelmannii, Pinus contorta, Pinus flexilis, Populus tremuloides,* and *Salix*. The watershed area above the Station 1 sampling site as shown in Figure 1 is 664 ha. The soils are thin (mean, 60 cm) and overlie granitic parent material. Cation exchange capacities average about 20 meq · 100 g^{-1} soil and the pH values range for the most part between 4.5 and 6.0 (S. Burns, pers. comm., 1979).

Although detailed annual temperature records for the soil profile are not available, occasional profiles taken by Fahey (1971) show that, in treeless areas with little or no snow protection at the 3000 m level, the upper 10 to 20 cm of soil would be above 0°C between April and October and below 0°C between November and March. Small amounts of permafrost may even be found in very open locations above treeline (Ives and Fahey, 1971). Fahey's data also show that in such locations soil temperatures at depths as great as 80 cm would fall slightly below 0°C. This does not happen in forested areas where the snow is trapped, however. Under snow cover, even the surface of the soil remains unfrozen, despite the very low air temperatures (J. D. Ives, pers. comm., 1978). Snow pits dug throughout the winter in the San Juan Mountains at similar or higher altitudes re-

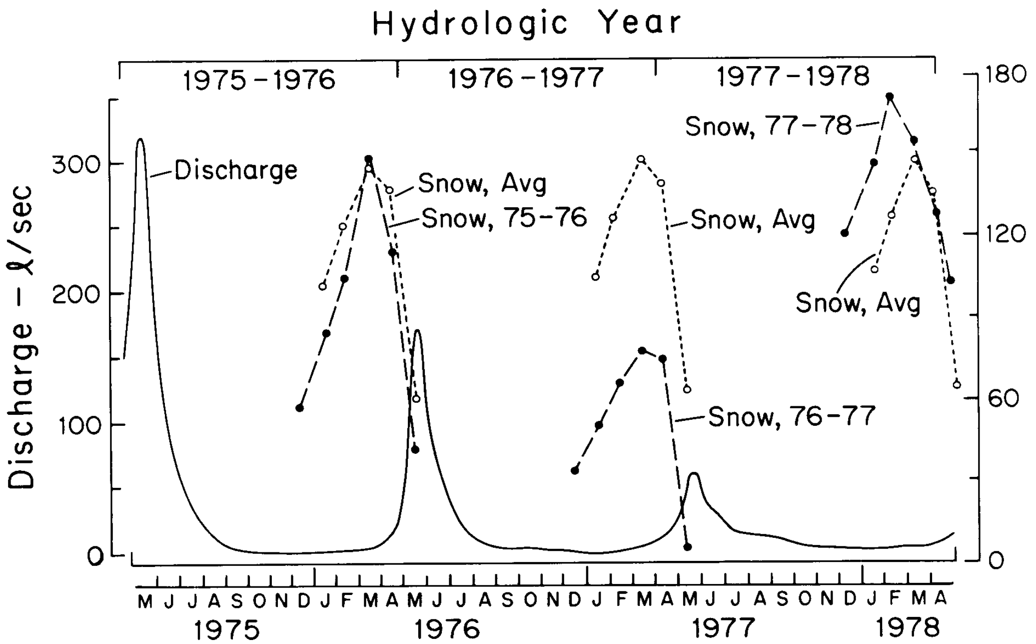

FIGURE 2. Discharge of Como Creek at the sampling station and the amount of snowpack for the three winters.

vealed that the ground surface remains unfrozen after snowfall, although it may freeze to some 5 cm depth before the first heavy snows (R. L. Armstrong, pers. comm., 1978). The majority of the Como Creek watershed could thus be expected to remain unfrozen under normal snowpack. This is confirmed by the flow of Como Creek, which does not freeze and sustains a flow of at least 3.5 L s^{-1} under ice and snow cover in the coldest weather under normal or heavy snowpack (e.g., 1975/76, 1977/78). The situation is very different when snowpack is minimal, as in 1976/77. The ground surface is bare over large regions even within the wooded areas and is frozen to a considerable depth, as illustrated by the bursting of water lines buried as deep as 1 m in the soil. Also the stream itself freezes extensively over the top and flow is restricted to the deepest streambed levels. All of these events occurred in the 1976/77 episode of low snowpack.

The snowpack data reported in this paper are averaged over two different monthly transects in the watershed adjoining Como Creek. Average snowpack data are for 22 consecutive years of such transect measurements. All snowpack data are reported as depth of snow, not as moisture equivalent.

RESULTS

Figure 2 shows the variation in discharge and amount of snowpack for the entire study period. We have divided the study period into hydrologic years to suit our own analytical purposes. Each of our hydrological years begins with the onset of spring runoff. It is clear from Figure 2 that the accumulation of snow during the 1975/76 hydrologic year was near normal, and that the snow accumulation over the hydrologic year 1976/77 was drastically below normal, resulting in a very small spring runoff. Accumulation of snow during the 1977/78 hydrologic year was considerably above the average and resulted in a large runoff the following spring (peak 340 L s^{-1}, not shown in Figure 2).

Table 1 gives the mean yields of dissolved substances from the Como Creek watershed for the combined low-flow periods of the three hydrological years covered by the study. The precise timing of the low flow period varies slightly. For the 3 yr of the study, the low flow period began between mid-August and mid-September and ended between late April and late May. The discharge over the low flow period typically varies between 3 and 20 L s^{-1}, with minimum values in midwinter. No large storm discharges occurred over this period in any of the three years.

The data were subjected to analysis of variance to determine whether or not the years differed significantly with respect to yield. Stream discharge was also entered into the analysis of variance as a covariate so that comparisons could be made between years independent of discharge. This is necessary because there is some variation between years in discharge which can influence the yields independently of the physical factors of primary interest here.

Figure 3 summarizes the results of the analysis of variance. The mean yields for all substances in low-flow periods of each of the 3 yr are depicted in Figure 3 as a percentage of the grand means for all three periods. Wherever the analysis of variance failed to show a significant difference between years, the yield for each year is considered to be equal to the mean. All differences between years depicted in Figure 3 are significant at $P \leq 0.05$.

TABLE 1

Mean yield and standard deviation of dissolved substances from the Como Creek watershed over the low-flow periods for the hydrologic years between 1975 and 1978

Substance	Mean yield ($mg \cdot m^{-2} \cdot wk^{-1}$)	Standard deviation
HCO_3^-	12.8	7.10
SO_4^{--}	.13	.23
Ca^{++}	2.17	1.27
Mg^{++}	.65	.36
Na^+	1.56	.79
K^+	.27	.23
PO_4-P	.00103	.00161
NO_3-N	.00938	.01051
NO_2-N	.00033	.00061
NH_4-N	.01133	.00963
DOC	2.28	4.05
DOP	.00152	.00251
DON	.106	.180
H^+	.000096	.000096

Only about half of the dissolved constituents show significant differences in yield between years after the effect of discharge is removed, as shown in Figure 3. Only two substances (phosphate and nitrate) show really large annual variations from the grand mean. The variation in nitrate yields between years is by far the largest; the year with minimal runoff shows a vastly increased yield over the other two years.

Further examination of Figure 3 for general patterns indicates a strikingly pervasive tendency for the yields of the 1977/78 hydrologic year to be lower than yields for the other 2 yr. Of the eight substances which show statistically significant difference between years, all have the lowest yield in the 1977/78 hydrologic year when snowpack was highest (Figure 3). The probability of this happening purely by chance is extremely low. Figure 3 thus suggests that the high snowpack prevailing during the 1977/78 winter resulted in a significant reduction of the yields of a wide range of substances.

DISCUSSION

We believe that the broad-ranging difference between yields in different years even after correction for discharge is clearly connected with some effect of snowpack on the mobilization of leachable materials in the soil. The most obvious direct effects of snowpack on soil conditions are connected with soil temperatures and soil frost. Heavy snowpack maintains higher soil temperatures and prevents soil frost, as indicated by the soil temperature studies which have been cited above. Soil frost in particular would qualify as a major disruptive force capable of accounting for major changes in discharge-connected

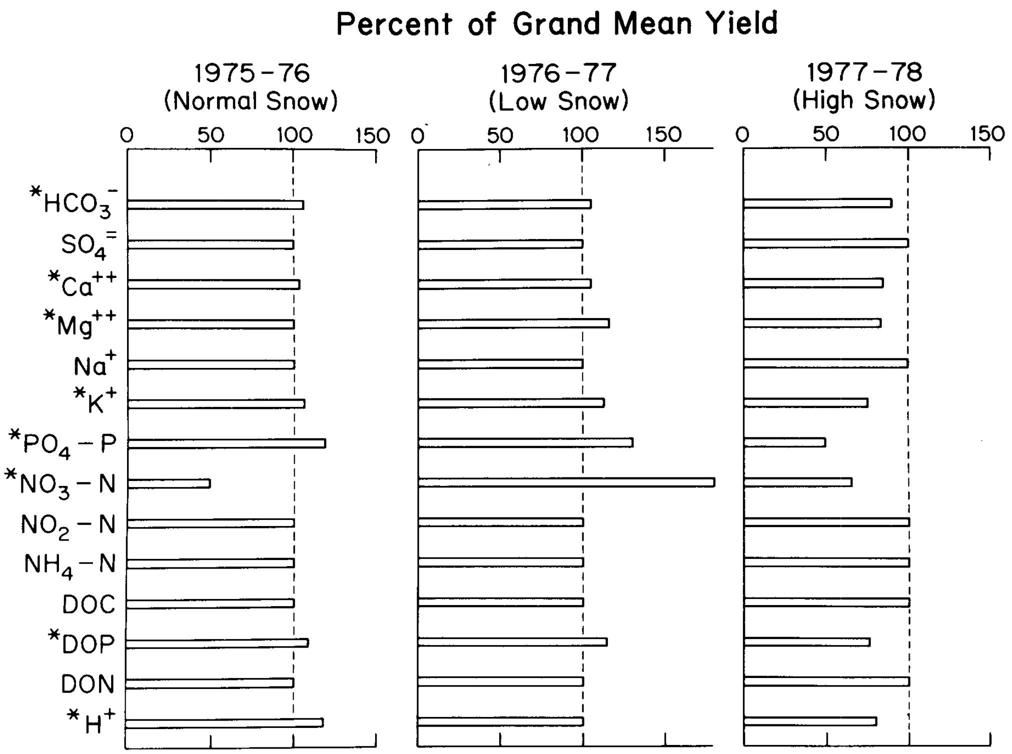

FIGURE 3. Yield for the low-flow periods expressed as a percentage of the grand mean for all three low-flow periods of the study. Asterisk indicates significant differences between years ($P \leq 0.05$). Where no significant statistical differences exist between years, the grand mean is used as the estimate of yield for each of the 3 yr.

yield between years, as shown in Figure 4. It is not entirely clear, however, what the mechanism would be for augmentation of yield by soil frost. Strictly physical explanations could be possible based on the control which soil frost exercises over soil moisture flow or over the physical properties of upper soil layers. Strictly physical explanations of this type are difficult to defend in view of the data, however, as dissolved substances are affected to very different degrees by snowpack variations. Substances which are most strongly affected are subject to strong biological influence (e.g., NO_3^-, PO_4-P, K^+). This suggests that sequestering of substances in biological pools (living or dead) is being disrupted by soil frost and leads to increased leakiness of the system specifically for biologically important substances.

Nitrate yield is affected much more drastically by low snowpack than that of any other substance. The very low snowpack and consequent soil frost of the second hydrologic year caused a particularly dramatic increase in nitrate yield, resulting in much higher nitrate concentrations for streamwater (Figure 4).

Several other workers have given evidence that intense freezing of soils increases the nitrate yield from terrestrial ecosystems (McGarity, 1962; Mack, 1963; Harding and Ross, 1964; Likens et al., 1977). Disruption of biological sequestering or nitrogen metabolism is implicated but not proven. The experiments of McGarity (1962) suggest that increased yield of nitrate is explained by inhibition of denitrification when the soil freezes, whereas Mack's data are more suggestive of increased mineralization of organic N in connection with soil frost. Our data suggest that there is a high but critical threshold, not exceeded in the first hydrologic year but definitely exceeded in the second, beyond which soil frost modifies biological processes in such a way as to increase nitrate losses very greatly, but we are unable to specify the mechanism by which this occurs. Our data show no evidence of a compensatory shift in the rate of ammonia or nitrite export, indicating that the entire explanation may not be found in a simple change of forms of inorganic nitrogen. Furthermore, the buildup of nitrate concentration in the stream and associated steadily increasing yield over the winter months as shown in Figure 4 suggests a progressive blockage of some biological process with progressive penetration of the soil frost. One very

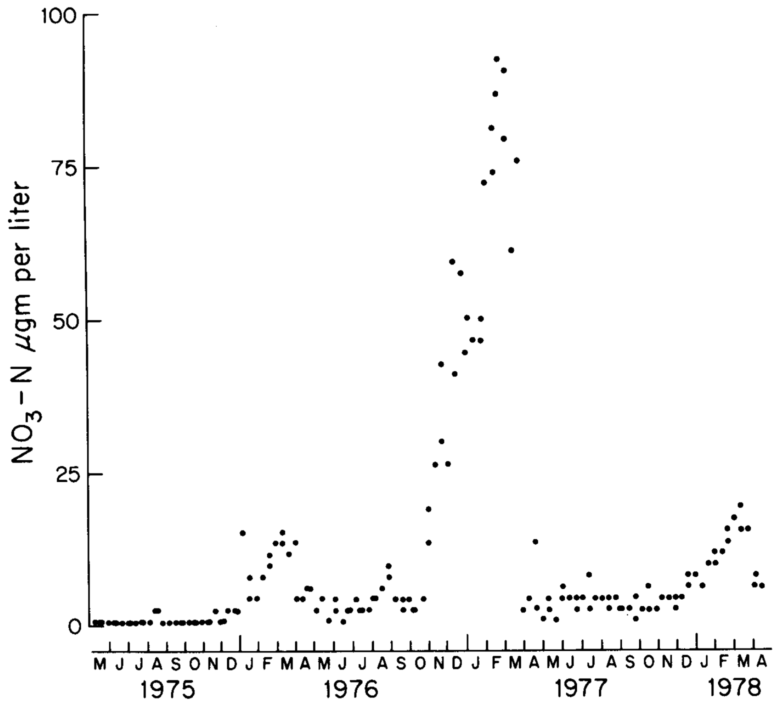

FIGURE 4. Concentration of nitrate-nitrogen in stream water at the sampling station over a 3-yr period, indicating the effect of severe soil frost in the winter of 1976/77.

attractive possibility is progressive physical inactivation of the nutrient intake zone for roots, which would be almost entirely limited to the upper 25 cm of soil. This problem deserves further investigation in view of the considerable implications it has for the total nitrogen loss from terrestrial systems and for stream nitrate levels.

In summary, low snowpack leads to conditions under which mechanisms for retention of a variety of substances are disrupted, thus increasing the loss of these substances despite very low discharges. Furthermore, the nitrate ion is affected in a particularly spectacular way. These findings may be important to the evaluation of natural mineral nutrient retention systems of mountain ecosystems and should also be considered in connection with the modification of snowpack by anthropogenic means, whether intentional or as a byproduct of human activity.

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