Water, Energy, and Biogeochemical Budgets at Sleepers River, Danville, Vermont

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ABSTRACT

Forecasting the global effects of human activity (global change) requires a broad-based understanding of earth system processes. To this end, a joint Global Change research project by the U.S. Geological Survey (USGS) and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), under the USGS Water, Energy, and Biogeochemical Budgets (WEBB) program, was recently initiated at Sleepers River Research Watershed, a 112-km^2 upland basin in rural northeastern Vermont with a 30-year hydrologic and energy data base. Vertical and lateral patterns of water and solute movement will be studied on forested and agricultural hillslopes using a network of soil-moisture sensors, lysimeters, and wells. Spatial and temporal patterns of major solute chemistry and carbon- and oxygen-isotope ratios will be coupled with water-flux data to identify the dominant hydrologic flow paths and biogeochemical reaction pathways. Trace gas fluxes to and from the soil also will be measured. The response of the soil thermal regime to incoming surface energy and geothermal flux will be investigated by simultaneous measurements of soil-temperature profiles and energy fluxes. The core information at the hillslope scale will be evaluated from the larger-scale perspective to determine the relative importance of hydrochemical processes as basin size increases.

INTRODUCTION

Recent concern over the cumulative effects of human activity on the global environment has prompted a national effort to assess the causes, effects and consequences of human-induced alteration of the earth system (Office of Science and Technology Policy, 1990). This program, the U.S. Global Change Research Program (USGCRP), has as one of its basic precepts the notion that the impact of global change on the earth system cannot be predicted without a more fundamental understanding of earth system processes. The U.S. Geological Survey (USGS), with its expertise in hydrological and biogeochemical processes, is well-suited to making a fundamental contribution to this effort. Foremost among the USGS global change research efforts is the Water, Energy, and Biogeochemical Budgets (WEBB) progam. In keeping with the USGCRP philsophy, the WEBB program has as its core objective a more refined understanding of basic watershed processes.

The Sleepers River Research Watershed in Danville, Vermont, has been selected as one of five initial WEBB sites. The USGS will collaborate closely at Sleepers River with the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), current operators of the site. Sleepers River has one of the longest historical data bases and continuous research programs for a cold-region area in the U.S. Hydrologic and energy data have been collected continuously since 1957 (Pionke et al., 1986). The site has been administered by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture (1957-1966), the Office of Hydrology of the National Weather Service (NWS) (1966-1979) and CRREL (1979-present). Numerous other institutions and agencies also have performed research at Sleepers during its history. The Sleepers River dataset was selected by the World Meteorological Society (WMO) as one of six high-quality data sets for the WMO project on the Intercomparison of Models of Snowmelt Runoff (WMO, 1986). Although the research emphasis at Sleepers River has always been hydrology, resulting in numerous often-cited papers (e.g. Dunne and Black, 1970a,b;1971), several investigations of stream chemistry also have been conducted (Hall, 1971; Kunkle, 1971; Pangburn, 1981; Thorne, 1985). The proposed research approach will integrate the complementary talents of the USGS (hydrology, biogeochemistry) and CRREL (energy, cold-regions instrumentation), and will lead to improved understanding of watershed processes in this important northern forest region.

In the northern U.S., watershed processes are strongly if not dominantly controlled by spatial and temporal variations of snow cover, freezing, and melting. The pattern of snow accumulation and snowmelt, the dominant hydrologic feature of cold temperate regions, can be greatly altered by even small changes in incoming surface energy and geothermal flux. The pronounced seasonal pattern of runoff in northern forests, governed by seasonal snowpack development and groundwater recharge by snowmelt, may undergo dramatic shifts in response to global change. The potential for future summer drying in mid-latitudes, suggested by some climate models, may be critically sensitive to interactions between soil water and energy balances during periods of snowmelt (Mitchell and Warrilow, 1987). Changes in runoff quantity and distribution would have important implications for overall water yield and water-supply management strategies, and for solute transport.

At Sleepers River, there is a unique opportunity to elucidate the processes affected by snow cover, freezing, and melting, and to use historical data to estimate relationships between these processes and climatic and other parameters. Integrated studies of biogeochemical processes (e.g., trace gas fluxes, acid precipitation buffering) will elucidate the relationships of these processes to the dynamic seasonal variations in water and energy fluxes. Thus, WEBB studies at Sleepers will contribute fundamentally toward anticipating potential future effects of changes in climate and land use and other anthropogenic perturbations on watershed processes affected by snow cover, freezing, and melting.

In this paper, the research plan for the Sleepers River WEBB project is outlined, and some preliminary results are reported. Interpretations of streamwater chemistry and observations of surficial geology and hydrology have resulted in slight modifications to the research plan, and these new research directions are discussed.

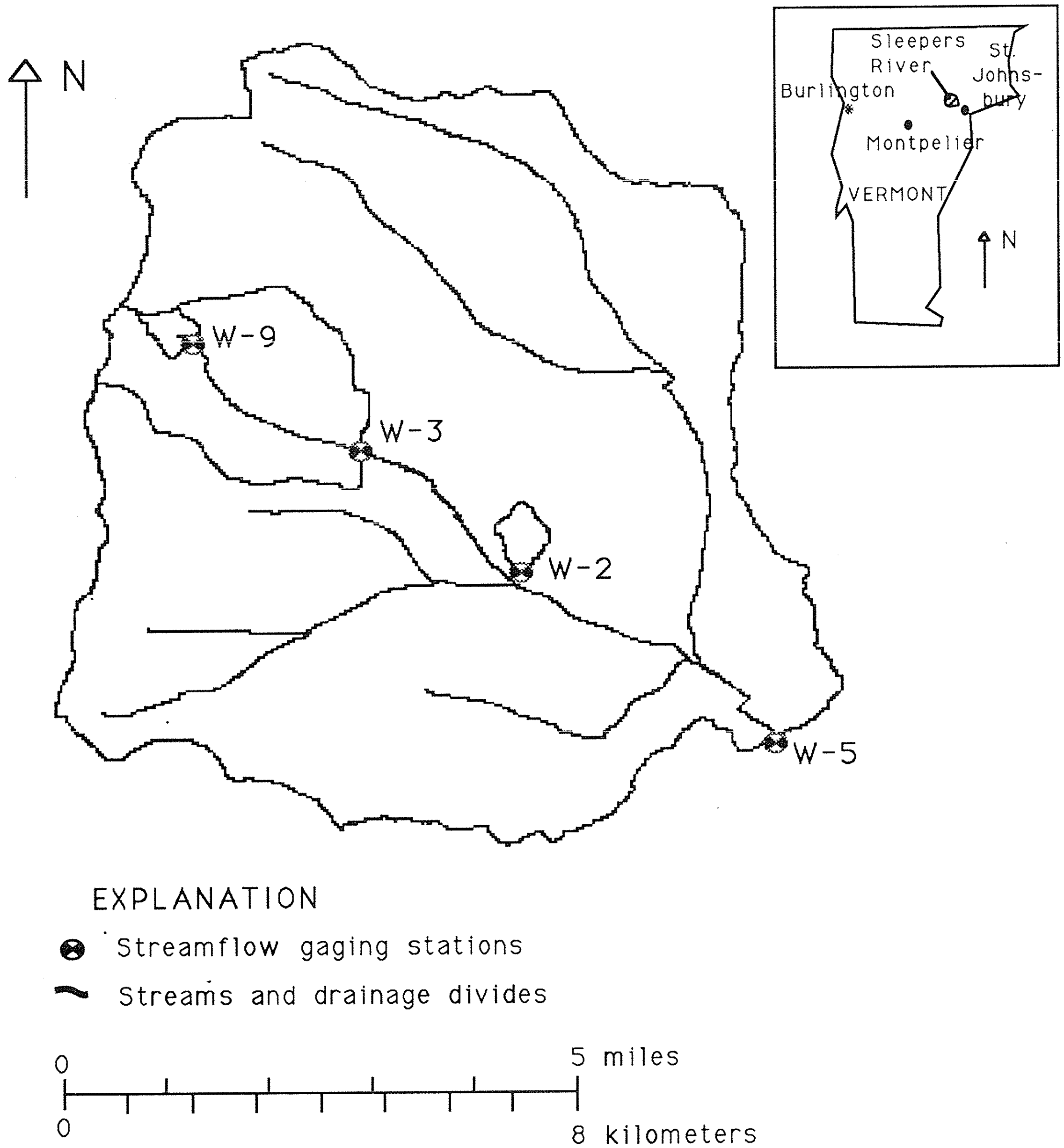

Figure 1. Sleepers River Research Watershed

SITE DESCRIPTION

The Sleepers River Research Watershed of northeastern Vermont is a rural 112-km^2 subwatershed of the Passumpsic River watershed, which is part of the Connecticut River basin (Figure 1). The rolling to mountainous Sleepers River Watershed is 67 percent forested in conifers, hardwoods, and mixtures of both. Most of the remaining land is open pasture; about 1 percent of the basin is planted in corn. The major agricultural industry is dairy farming. Elevations within the watershed range from 201 to 790 m above sea level. The soils generally are well-drained podzols developed on a variable thickness of glacial till, which in turn overlies the Waits River Formation, comprised of 50 percent calcareous rock and 50 percent interbedded quartz mica schists. The climate of the area is characterized by long, cold winters and cool summers. The mean annual temperature is 6 °C. Precipitation ranges from 88 to 127 cm per year within the basin; more than 25 percent falls as snow. A snow cover persists from late November through early April.

RESEARCH ELEMENTS

The multiple subwatersheds within the Sleepers River Research Watershed present an excellent opportunity to investigate watershed processes over a variety of spatial and temporal scales. The study will incorporate fundamental research on processes and process rates at the plot scale (in this case, a hillslope); knowledge of processes at the hillslope level will be used when "scaling up" to interpret the hydrochemical response of higher-order basins. The proposal has five research elements. Individually, each of the five elements is designed to investigate specific water, energy, and biogeochemical processes (e.g., trace gas fluxes), address specific WEBB program issues (e.g., scaling, flowpaths), or employ specific research approaches (e.g., integrated chemical and physical study of a hillslope). Collectively, the five elements comprise an integrated approach towards the comprehensive understanding of watershed processes needed to predict the effects of global change. The research elements overlap such that many of the processes investigated will be assessed in more than one way to provide independent verification of research results. For example, flowpath information will be derived separately from isotopic tracers, conservative chemical solutes, and soil moisture fluxes. The research elements also are closely integrated to take full advantage of this opportunity to coordinate interdisciplinary studies of water, energy, and biogeochemical budgets.

I. Hillslope hydrochemistry. The core data on water, energy, and biogeochemical processes will be collected at two headwater hillslopes (from ridge to stream channel) representing forested and agricultural (pasture, corn fields) land usage. The hillslopes will be extensively instrumented to yield a detailed two-dimensional profile of soil wetting and drying patterns; water flux through the soil column; saturated zone development and water table fluctuations; chemical evolution of soil water as it moves toward the stream; isotopic information that constrains the possibilities of flowpaths to the stream (research element II); and determinations of trace gas fluxes (element III). Data collection will be most intensive at the riparian zone, given the increasing recognition of the importance of this zone in controlling streamwater chemistry (Bishop and Rodhe, 1989). The intensive data from the hillslope plots will form the basis for the identification of the important hydrochemical processes in the basin. This core information then will be evaluated from the larger-scale perspective to determine the relative importance of hydrochemical processes in progressively larger basins.

II. Flowpath delineation. Recent advances in analytical automation have simplified the analysis of deuterium and $\partial^{18}O$, conservative isotopes that will be used in conjunction with conservative chemical tracers to identify hydrologic flowpaths. $\partial^{18}O$ will be used in conjunction with conservative chemical tracers at the hillslope scale and in larger basins to elucidate hydrologic flowpaths. New techniques utilizing the $\partial^{13}C$ of dissolved inorganic carbon (DIC) to determine the source of carbon (Mills and Kendall, 1987) will yield information on how alkalinity is generated at Sleepers. ^{13}C is also another potential hydrologic tracer. Because each type of chemical and isotopic tracer varies in its applicability, the several tracers that will be used at Sleepers improve the chances for success at flowpath delineation.

III. Trace gas fluxes. Recent research has emphasized the potential importance of trace gas budgets in northern temperate regions. The magnitudes of the terrestrial sources and sinks of the greenhouse gases CO_2, N_2O, and CH_4 are very uncertain (Tans et al., 1990). In particular, the effects of seasonal snowpack and freezing on trace gas budgets are virtually unknown. In this study, seasonal fluxes and concentrations of soil CO_2, N_2O, and CH_4 will be measured in forested and agricultural settings, and will be related to experiments and models designed to determine which processes are the most important in controlling trace gas budgets.

IV. Effect of scale on hydrologic processes. The process research at the hillslope level will be applied to higher-order basins in two ways: by determining the relative partitioning of hydrologic pathways as basin scale increases, and by assessing whether shifts in that partitioning are related to differences in basin physical factors. Relative flowpath partitioning will be determined from the chemical and isotopic compositions of streamwater in the three nested basins. TOPMODEL (Beven and Kirkby, 1979), which predicts runoff from variable contributing areas based on topography and the spatial distribution of hydraulic conductivity and soil depth, will be applied to assess the importance of variations in these physical factors among basins, and to see how relative proportions of near-surface and subsurface flow change with increasing basin size. Saturated contributing areas near the channels will be mapped to compare to the areas predicted from flowpath partitioning and the TOPMODEL output.

V. Energy processes. The response of the soil thermal regime to incoming surface energy and geothermal flux will be investigated by simultaneous measurements of soil temperature profiles and energy fluxes at several points in the basin. One goal is to assess the spatial variability of the soil thermal regime, caused by differences in slope, aspect, and vegetation among sites, and thus to evaluate whether energy balances at a point can be extrapolated to the watershed scale. Another goal is to use changes in the soil thermal regime to identify the origin and pathways of infiltrating waters. This work will be done at the hillslope sites and will be coordinated with the chemical and isotopic flowpath work of research elements I and II. A second goal of the energy process work is to couple a thermal or heat transport model to a runoff model at the point, plot, and basin scales. Physically based modules will be tested to integrate thermal processes into runoff models. Several approaches are planned, including analyses of the historical patterns of heat and mass storage, and analyses of short duration events of high energy input.

PRELIMINARY FINDINGS

In the fall of 1990, the USGS assumed operation of the W-3 and W-5 stream gaging stations and a network of nine meteorological stations (preciptation quantity, temperature, and relative humidity) (Figure 1). This ensured continuation of the long-term data base vital to the types of analyses envisioned for the WEBB project, and allowed CRREL to focus on the completion of tasks that will benefit the WEBB in the near term, i.e., completing GIS coverages of the intermediate scale basin (W-3, 8.3 km^2) and streamlining the data base by assembling it in a common format. In addition, a pilot soil pit was instrumented to test lysimeter design and soil moisture sensors over the winter.

Reconnaissance work during the snowmelt period of 1991 in W-9 (0.47 km^2), the forested headwater basin, has led to some rethinking of the proposed hillslope hydrochemistry research plan. Most significantly, observations of snowmelt patterns and runoff processes have raised questions about the relative importance of the saturated and unsaturated zones to streamflow generation. As expected, during snowmelt, saturation overland flow prevailed. The near-stream area was saturated at land surface, and runoff over this zone appeared to be the dominant streamflow generation mechanism. Surprisingly, however, saturation overland flow was not limited to the riparian zone. Water was observed flowing over the surface in midslope and headwater areas with relatively steep slopes and small contributing areas. Other hillslope areas, by contrast, clearly were drained by subsurface flow. These field observations revealed variations in hillslope hydrologic processes that may be a function of differences in surficial geologic materials.

Observations of soil and till material excavated during the course of seismic refraction work conducted in late May 1991 confirmed the presence of two contrasting surficial materials. Poorly-drained hillslopes usually have a surficial horizon of organic muck underlain by a compact silt/clay till, sometimes with a fragipan near 0.5 m depth. Well-drained slopes are underlain by till of silt and fine sand with lower clay content. Some well-drained sites exhibit incipient podzolization. The contrast is immediately apparent at the W-9 weir. The riparian zone on the west side of the stream at the control structure was still saturated well into the summer, whereas the the hillslope on the east side of the weir was well-drained and showed no sign of surface runoff at any time during the snowmelt period.

CURRENT AND FUTURE RESEARCH

The unexpectedly wide distribution of surface saturation has led to a commitment to more effort to understand watershed hydrology before installation of soil pits, to assure proper focus of the subsurface hydrologic investigations and to avoid unrepresentative siting of intensive data collection activity. Groundwater hydrology will be investigated with a network of 40 piezometers sited within W-9 based on the distribution of the two soil/till types and the results of recent till thickness determinations from seismic refraction lines. Some piezometers will be nested to assess the hydraulic communication between different levels in the unsaturated zone. Seasonal variations in groundwater levels and gradients will be monitored and analyzed in conjunction with stream discharge. Saturated hydraulic conductivity of the surficial deposits will be determined from slug tests in the wells. Streamflow in the three tributaries of W-9 will be related to the areal extent of the two till types in each of the three subbasins to provide additional clues on the hydrologic processes important to each till type.

Streamwater chemical and stable isotope composition also will be used to aid in the interpretation of watershed hydrology. Initially, three sampling runs are planned along transects of each of the three tributaries of W-9, with the idea that abrupt spatial changes in chemistry can be linked to changes in relative importance of hydrologic processes. Additional samples will be collected concurrently from groundwater seeps in W-9, from other streams near W-9, and from larger streams at the W-3 and W-5 gages. The first sampling was conducted during the post-snowmelt high flow period during the spring. Two additional sampling runs will be conducted during summer base flow conditions and a summer storm event. Results of the first survey indicate that chemical changes are gradual, and that stream-to stream variability in chemistry is greater than within-stream variability. A strong linear relation between calcium and specific conductance (Figure 2) suggests that streamwater composition is controlled by differential amounts of calcite weathering. High concentrations of nitrate in the seeps (Figure 3) suggests contributions from flow through the surficial organic horizon.

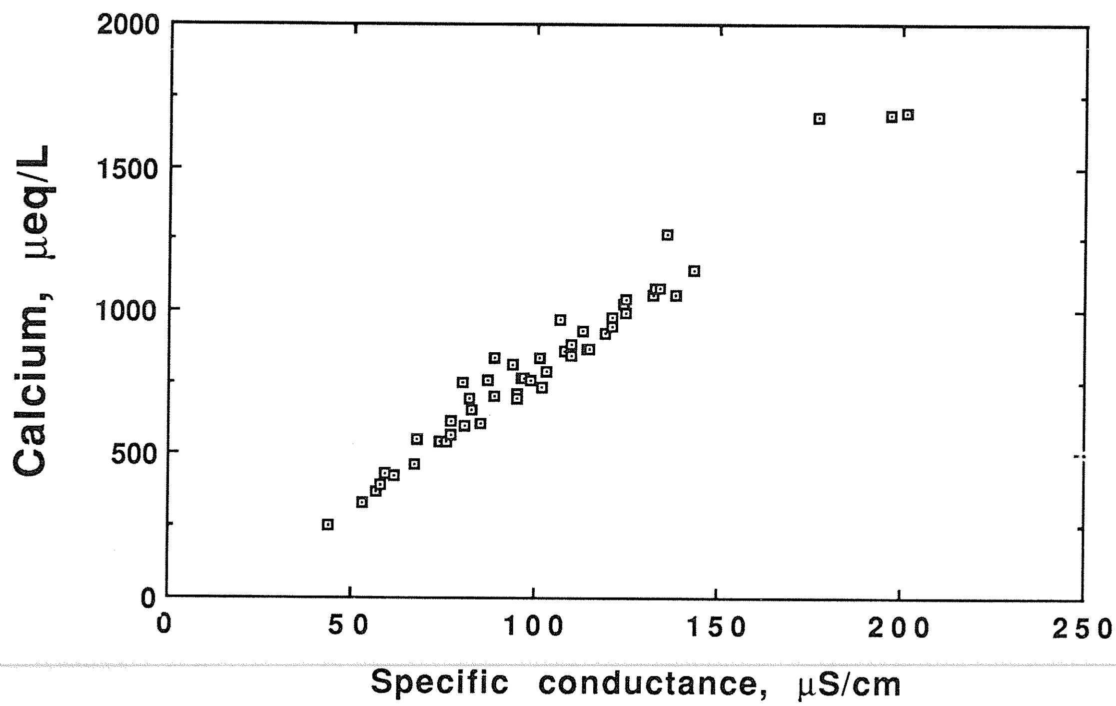

Figure 2. Calcium concentrations versus specific conductance for streams and seeps at Sleepers River, in samples collected on or about May 2, 1991.

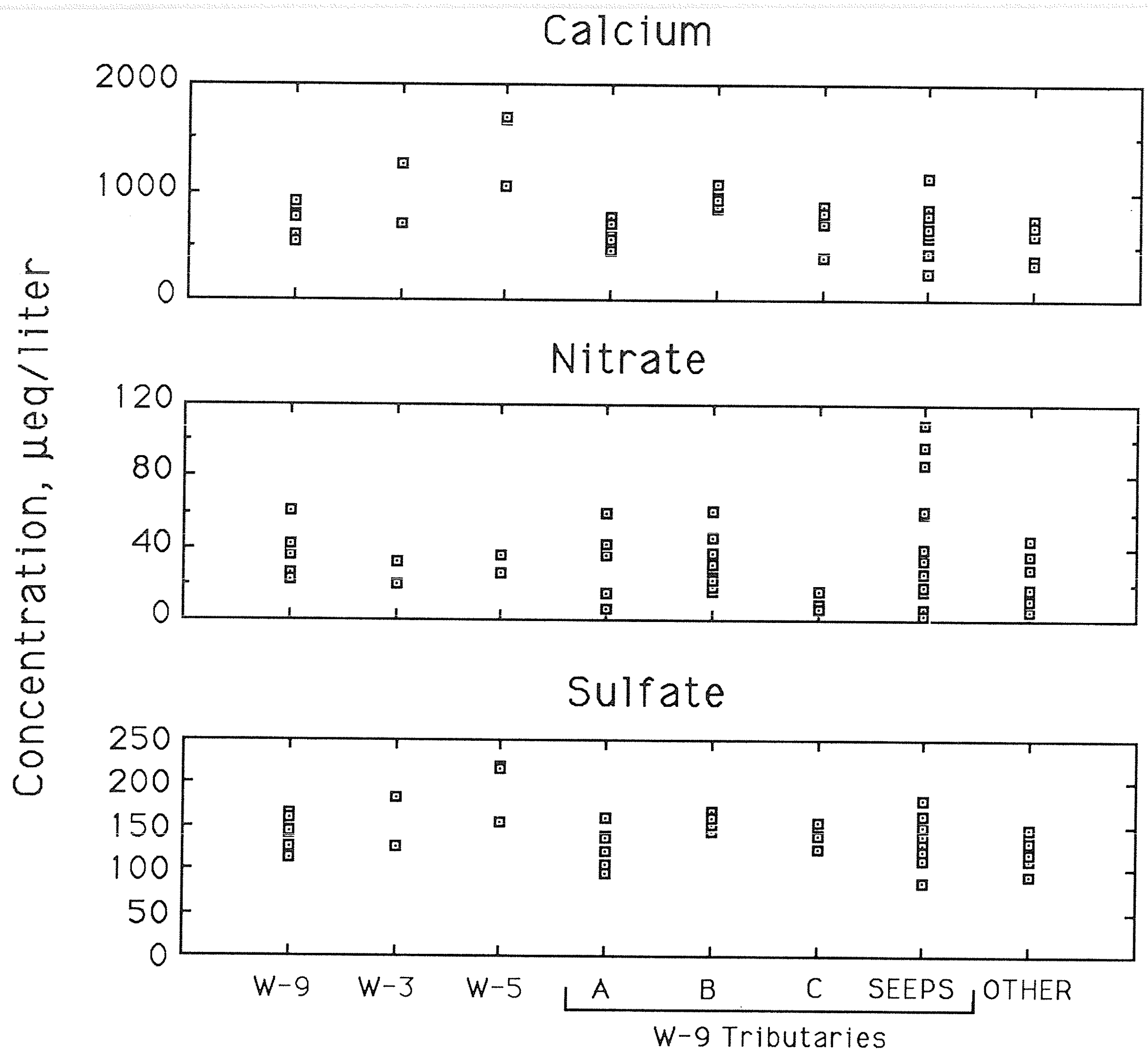

Figure 3. Range of calcium, nitrate and sulfate concentrations at W-9 (0.47 square km), W-3 (8.3 square km), W-5 (112 square km), W-9 tributaries, and other streams in the vicinity of W-9 at Sleepers River, in samples collected on or about May 2, 1991.

W-2, a predominately agricultural basin, will be studied along with W-9 to compare the effect of land use on watershed hydrology. W-2 has less relief than W-9 but it is nearly equal in area. The W-2 gage, where hydrologic measurements were discontinued in 1978, will be reactivated in the summer of 1991. Initial comparisons will be made on the chemical and hydrological response of the two basins to summer thunderstorms. Pastured hillslopes adjacent to the W-2 weir are under consideration as sites for intensive hillslope hydrochemistry investigations.

A longer term objective of the WEBB program is an assessment of the relative importance of water, energy and biogeochemical processes as basin scale increases. This question will be addressed at Sleepers River in the coming years based on investigations of the W-9/W-3/W-5 nested basin system. Each basin increases in size by an order of magnitude. The initial investigations at W-9 (supplemented by those at W-2), the headwater basin, will lay the groundwork by establishing the dominant water, energy and biogeochemical processes in a low-order basin in this cold region setting. Hydrologic, chemical and isotopic data from the larger basins will be used to determine biogeochemical fluxes, and the controls on these fluxes by seasonal and flow-related parameters, at the different basin scales. These data will form the basis for an evaluation of whether processes that are important at the hillslope and small basin scale also are important in larger basins, or whether other processes assume dominant importance. Potentially, existing USGS gages on the Passumpsic River just downstream of its confluence with Sleepers River and on the Connecticut River at Bellows Falls can serve as focal points for comparison at the next two higher orders of magnitude of basin scale.

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