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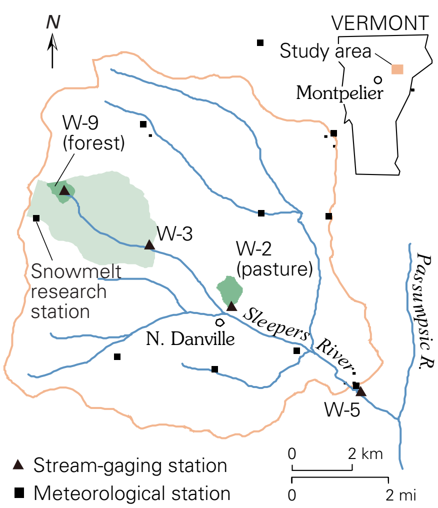
Sleepers River, Vermont

A Water, Energy, and Biogeochemical Budgets Program Site

The Sleepers River Research Watershed in northeastern Vermont was established by the Agricultural Research Service (ARS) of the U.S. Department of Agriculture in 1959 and is now operated jointly by the U.S. Geological Survey (USGS) and the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), with collaboration from several other Federal Agencies and Universities. The USGS has contributed to the understanding of hydrological processes and added a major biogeochemical cycling research component in the last 10 years of Sleepers River's 40-year history as a field laboratory. The USGS uses hydrologic measurements and chemical and isotopic tracing techniques to determine how water moves from the hillslope to the stream, and what processes cause chemical changes, such as the neutralization of acid rain. Research results provide insights on how pollutants move through ecosystems, and how ecosystems may respond to climatic change.

The glaciers that covered New England until 10,000 years ago were a dominant force that shaped the present-day landscape and influenced its hydrologic and chemical characteristics. Most of the Sleepers River watershed is covered by 1–4 meters of glacial till, a compacted fine silty material that formed underneath the glacial ice as it moved overland. The till was formed primarily from the local bedrock, which is a calcareous granulite/quartz-mica phyllite. About 60 to 80 centimeters of soil has developed in the till. Weathering of calcite in the till and bedrock causes highly buffered streamflow (compared to most streams in New England) and a nutrient-rich biological environment, which makes Sleepers River an end member in regional biogeochemical cycling studies (Hornbeck and others, 1997).

Streamgage placement in the Sleepers River Research Watershed was designed for nested- and paired-catchment studies.



Like much of northern New England during the last century, the Sleepers River area has reverted from a predominately cleared, agricultural landscape to a mostly forested one. A Northern Hardwood forest, dominated by sugar maple, white ash, yellow birch, and beech, with lesser amounts of red spruce and balsam fir, now covers two-thirds of the area; the remaining open land is primarily pasture and hayfields. Dairy farming and logging are the primary human enterprises in the watershed.

Sleepers River has a humid continental climate. The average annual temperature is 6 degrees Celsius and average annual precipitation is 1,100 millimeters, 20–30 percent of which falls as snow. The abundant snowfall at Sleepers River has driven much of the research activity. The National Weather Service established a snowmelt research station in 1968, and the modeling routines they developed are still used in their flood forecasting. Freeze/thaw cycles and winter rain and ice storms tend to produce highly layered snowpacks in the eastern United

Permeable brown soil rich in fine roots overlies the dense olive-gray glacial till. The tubing and collection vessels are part of devices that collect water from the unsaturated zone of the soil.

THE WEBB PROGRAM

The Water, Energy, and Biogeochemical Budgets (WEBB) Program was started in 1991 at five small watersheds in the United States to examine water, energy, and biogeochemical fluxes and to determine the effects of atmospheric deposition, climatic variables, and human influences on watershed processes.

The five sites are at Loch Vale, Colorado; Luquillo Experimental Forest, Puerto Rico; Panola Mountain, Georgia; Sleepers River, Vermont; and Trout Lake, Wisconsin. These sites are supported, in part, by other programs in the USGS, other Federal and State Agencies, and Universities.

U.S. Department of the Interior
U.S. Geological Survey

Fact Sheet-166-99
June 2000

This streamflow-gaging station (W-2) records streamflow from a 59-hectare agricultural catchment. The USGS operates 4 of the original 17 Sleepers River streamgages, as well as 5 new gages on small streams within the forested headwater catchment W-9.

States. USGS and CRREL research shows that ice layers within the snowpack retard the downward movement of meltwater and solutes (Shanley and others, 1995). Sleepers River has one of the longest historical hydrologic and climatologic data bases for a cold-region area in the United States, featuring measurements of precipitation and streamflow since 1959, snow depth and corresponding water content since 1960, soil frost depth since 1984 (Shanley and Chalmers, 1999), and ground-water levels since 1991. These and other measurements constitute a valuable resource for hydrologic modeling and for the evaluation of climatic changes.

Water Budget

In an average year, 55 percent of the total water input in precipitation runs off as streamflow and 45 percent returns to the atmosphere by evapotranspiration, or water evaporated from watershed surfaces and water transpired by trees. Water availability is rarely a problem in forests of the humid, temperate northeastern United States, so the amount of evapotranspiration is fairly constant from year to year. As a general rule, the total streamflow each year is simply the amount of precipitation minus the amount of evapotranspiration.

From oxygen isotope ratios we know that under most conditions, streamflow is composed primarily of ground water that was present in the catchment before the runoff event, not the rain or snowmelt causing the event.

Snow plays a key role in the hydrology at Sleepers River. Precipitation is stored in the snowpack during the winter months and is released in a short time during the spring. Spring snowmelt causes most of the annual ground-water recharge, and nearly half of the annual streamflow in March and April.

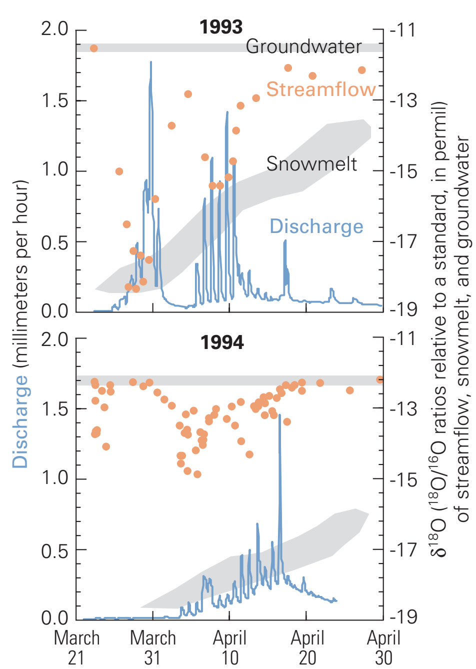
Much of the streamflow at Sleepers River is generated by rain falling or snow melting directly onto saturated areas adjacent to streams.

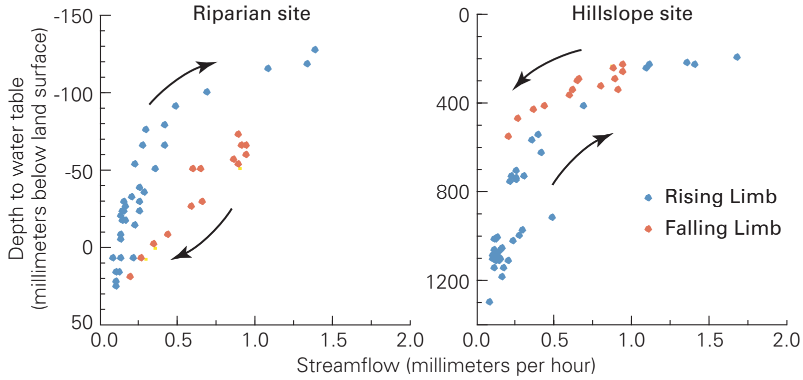
Water Flowpaths

Knowledge of how rain or snowmelt moves to a stream is fundamental to understanding many environmental contamination problems. In the late 1960s, Tom Dunne of the ARS dug a trench at the base of a hillslope at Sleepers River and determined that most of the runoff from the hillslope occurred as surface flow where the soils at the land surface were saturated (Dunne and Black, 1970). The term "Dunnean flow" is sometimes used to describe this runoff process, which is widely accepted as the dominant streamflow generation mechanism in humid, temperate environments. Fundamental questions remain, however, about how the saturated areas develop, and how much of the surface runoff is from direct rainwater/snowmelt on saturated areas compared to the discharge of shallow groundwater from upslope (return flow) onto saturated areas.

Since the time of Dunne's experiments, hydrologists have made considerable use of the $^{18}O/^{16}O$ isotope ratio, which is an ideal tracer because it is a fundamental property of the water molecule. Precipitation that forms at cold temperatures tends to have a low $^{18}O/^{16}O$; when the snow melts in spring, the $^{18}O/^{16}O$ of the meltwater contrasts with the higher $^{18}O/^{16}O$ of ground water, which reflects the annual average isotopic ratio of precipitation. As flow rises from melting snow, the $^{18}O/^{16}O$ of streamflow, which is close to that of ground water during low flow in winter, deflects only slightly toward the $^{18}O/^{16}O$ of snow meltwater. This subdued response indicates that the snowmelt triggering the flow increase comprises only a small fraction of streamflow; most of the streamflow is composed of pre-existing ground water or "old" water already present in

At the agricultural catchment W-2, frozen ground during the 1993 snowmelt season led to direct runoff of snowmelt water to the stream; the $^{18}O/^{16}O$ of streamflow (circles) decreased from the value of ground water to nearly the level of snowmelt. In the more typical 1994 snowmelt, the $^{18}O/^{16}O$ of streamflow remained much closer to that of ground water, indicating that ground water contributions dominated the stream snowmelt response.





In riparian areas, ground-water levels rise rapidly as streamflow increases in response to snowmelt, then fall rapidly after peak flow. On hillslopes, by contrast, ground water rises slowly at first but maintains high levels during the snowmelt recession (note opposite direction of time arrows). This pattern suggests that riparian ground water supplies most streamflow during the early part of snowmelt and hillslope ground water supplies most streamflow during the later part of snowmelt. Negative depths indicate the water table is above land surface.

the catchment before snowmelt began (McGlynn and others, 1999). Isotopic data revealed a striking exception to this pattern during one snowmelt season at the agricultural catchment W-2, when frozen soils caused snowmelt to run off directly into the stream channel.

In the forested catchment W-9, nested wells and piezometers were used to distinguish zones of ground-water recharge and discharge and to discern the nature of ground-water/surface-water interactions. Hillslopes are recharge areas where ground water rises into the soil nearly to land surface during snowmelt. The surficial soil transmits water more readily than the underlying till, such that water moves easily downslope and generates increased streamflow.

Streamflow chemistry provides clues about hydrology. High concentrations of calcium and magnesium indicate a deep ground-water flow path, whereas high concentrations of nitrate and dissolved organic carbon indicate shallow subsurface flow.

Ground-water discharge occurs only in riparian areas and in upland convergent flow areas. The relation between ground-water level and streamflow revealed a hysteresis relation; for a given streamflow, ground-water level at riparian sites was higher on the rising limb of the snowmelt hydrograph than for the same streamflow on the falling limb. The pattern was reversed at hillslope sites (Kendall and others, 1999).

Hydrologic Modeling and Energy Budgets

A topographically based model TOPMODEL was used as a supplementary approach to understanding water movement and storage in the headwater catchment. TOPMODEL simulates soil-saturation deficit and generates overland flow when the deficit is zero. The model is built on the concept that the amount of water draining toward a point on the landscape is controlled by the upslope contributing area, and the amount of water draining away from that point is controlled by the local slope.

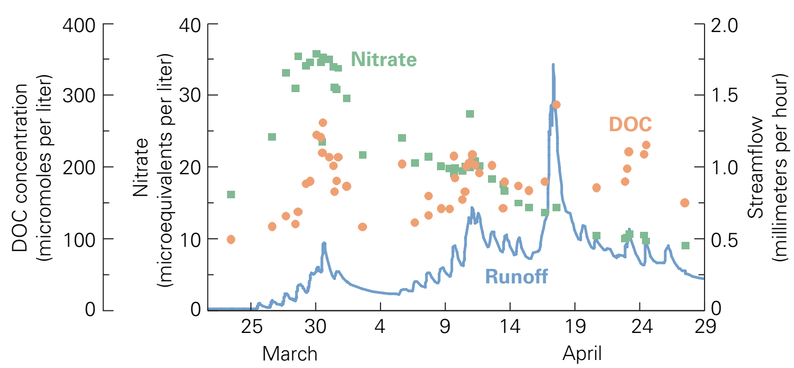
The minimum requirements to run TOPMODEL are topographic and precipitation data; soil hydraulic properties can be incorporated if available. Wolock (1995) applied TOPMODEL to the nested catchments at Sleepers River and determined that the percentage of overland flow in total streamflow increased as catchment size increased up to 5 square kilometers, after which the percentage remained fairly constant.

The energy aspects of the WEBB studies have been investigated primarily by CRREL. CRREL maintains three energy stations for the collection of meteorological and energy data, including temperature, humidity, wind speed, and incoming and outgoing short- and long-wave radiation. This information is used to compute an energy balance, which then is used in a model that simulates how fast the snow melts. Recently CRREL has focused on measurements in the forested environment to quantify how the forest litter in the snow changes the snowpack albedo an important term in the energy balance. The USGS collaborates with CRREL on using the output of the snowmelt model as the input to drive TOPMODEL.

Biogeochemical Budgets

Although the Sleepers River watershed receives significant acidic precipitation, streamflow is well-buffered from the weathering of calcite in the bedrock and glacial till. Calcium (Ca), magnesium (Mg), sodium (Na), and bicarbonate (HCO_3) are products of mineral

During snowmelt, the large volume of water moving through the upper organic soil zone flushes nitrate and dissolved organic carbon (DOC) to the stream. Nitrate concentrations reach a maximum early in the snowmelt period, whereas DOC concentrations continue to peak with individual streamflow peaks throughout the melt period.



weathering in the soil and till. By contrast, nitrate (NO_3) and dissolved organic carbon (DOC) in streamflow are derived primarily from organic matter in shallow soil horizons. At high flow, concentrations of Ca, Mg, Na, and HCO_3 are diluted, whereas concentrations of DOC and NO_3 increase. These opposite trends suggest that as flow increases, greater amounts of water enter the stream through shallow flowpaths in the soil. This is an example of how chemical patterns reveal clues about catchment hydrology.

> CO_2 production and flux out of the soil continue through the cold winter months.

Isotopic tracers of solutes

Whereas oxygen isotopes reveal how much streamflow is derived from ground water and how much is derived from melting snow, isotopes of strontium and lead reveal the source of solutes in streamflow (Bullen and Kendall, 1999). For example, the weathering of calcite yields a lower $^{87}Sr/^{86}Sr$ ratio than the weathering of most silicate minerals. The $^{87}Sr/^{86}Sr$ ratio of streamflow decreases as basin size increases, suggesting that the primary source of solutes shifts from the calcite-depleted soil zone in headwater catchments to deeper soil and bedrock sources downstream. The ratio $^{206}Pb/^{204}Pb$ is greater in ground water (Pb derived from weathering of till and bedrock) than in shallow soil water (Pb derived from the atmosphere). At Sleepers River, Pb isotopes indicate that significant atmospheric Pb is delivered to streamflow by shallow soil water discharge only during the initial phase of a runoff event; the majority of Pb is derived from the weathering of till and bedrock minerals and is delivered to streamflow by ground water.

Nitrogen and carbon

Atmospheric deposition of nitrate is a regional concern because of its acidifying effects on streamflow and forest soils. The fate of nitrate in the forest ecosystem is being investigated by analysis of both the N and O isotopes of the nitrate ion. The isotopic composition of nitrate in streamflow matches that of nitrate produced by mineralization and nitrification in the soil, indicating that streamflow nitrate is derived from the soil and not from the rain or snowmelt that causes the high flow (Kendall and others, 1995). This finding suggests that most incoming atmospheric nitrogen is incorporated at least temporarily in the soil where it is utilized by the biota.

The role of carbon in global warming has generated great interest in the carbon cycle within the scientific community. Recent research indicates that North America may be a major sink for atmospheric carbon. The amounts of carbon stored in the soil and vegetation at the Sleepers River watershed are being quantified, and CO_2 fluxes from the soil have been measured. One objective of the CO_2 research is to determine the effect of the snowpack on soil CO_2 fluxes. Research results indicate that CO_2 production and flux out of the soil continue throughout the winter despite the presence of the overlying snowpack.

—James B. Shanley

RESEARCH FINDINGS

- Precipitation is acidic, but streamflow is well-buffered from the weathering of calcite in till and bedrock.
- Infiltrating snowmelt causes ground water to rise into the permeable soil zone, where it moves rapidly downslope.
- Naturally occurring isotopic and chemical tracers indicate that “old” water dominates streamflow, and that water acquires solutes from weathering and biogeochemical processes along deep and shallow flowpaths.
- Nitrate in streamflow is supplied primarily by mineralization and nitrification in the soil, rather than directly by precipitation.

REFERENCES

Bullen, T.D., and Kendall, C., 1999, Tracing of weathering reactions and water flowpaths: a multi-isotope approach, in Kendall, C., and McDonnell, J.J., editors, Isotopes in Catchment Hydrology, Elsevier, Amsterdam, Chapter 18, p. 611-646.

Dunne, T., and Black, R.D., 1970, Partial area contributions to storm runoff in a small New England watershed: Water Resources Research, v. 6, p. 1296-1311.

Hornbeck, J.W., Bailey, S.W., Buso, D.C., and Shanley, J.B., 1997, Streamwater chemistry and nutrient budgets for forested watersheds in New England: variability and management implications: Forest Ecology and Management, v.93, p. 73-89.

Kendall, C., Silva, S.R., Chang, C.C., Campbell, D.H., Burns, D.A., and Shanley, J.B., 1995, Use of oxygen and nitrogen isotopes to trace sources of nitrate during snowmelt in forested catchments: in Tonnessen, K.A., Williams, M.W., and Tranter, M., editors, Biogeochemistry of Seasonally Snow-Covered Catchments, International Association of Hydrologic Sciences, Publication no. 228, p. 339-347.

Kendall, K.A., Shanley, J.B., and McDonnell, J.J., 1999, A hydrometric and geochemical approach to testing the transmissivity feedback hypothesis during snowmelt: Journal of Hydrology, v. 219, p. 188-205.

McGlynn, B.L., McDonnell, J.J., Shanley, J.B., and Kendall, C., 1999, Riparian zone flowpath dynamics in a small headwater catchment: Journal of Hydrology, v. 222, p. 75-92.

Shanley, J.B., and Chalmers, A., 1999, The effect of frozen soil on snowmelt runoff at Sleepers River, Vermont: Hydrological Processes, v. 13, p. 1843-1857.

Shanley, J.B., Kendall, C., Albert, M.R., and Hardy, J.P., 1995, Chemical and isotopic evolution of a layered eastern U.S. snowpack and its relation to streamwater composition: in Tonnessen, K.A., Williams, M.W., and Tranter, M., editors, Biogeochemistry of Seasonally Snow-Covered Catchments, International Association of Hydrologic Sciences, Publication no. 228, p. 329-338.

Wolock, D.M., 1995, Effects of subbasin size on topographic characteristics and simulated flow paths in Sleepers River watershed, Vermont: Water Resources Research, v. 31, p. 1989-1997.

COLLABORATORS

The WEBB research program at Sleepers River watershed relies on collaborations among the USGS, CRREL, U.S. Forest Service, Natural Resources Conservation Service, Vermont Department of Forests, Parks, and Recreation, and academia. Students from the State University of New York—College of Environmental Science and Forestry, the University of New Hampshire, and Dartmouth College have all contributed to the WEBB program at Sleepers River through thesis research projects.

For more information about the Sleepers River Research Watershed WEBB study visit:

http://nh.water.usgs.gov/CurrentProjects/sleepers/

For more information or for reprints, please contact:

Project Chief, WEBB Program
U.S. Geological Survey
P.O. Box 628
Montpelier, VT 05601
802-828-4466 or jshanley@usgs.gov.