# Overview of the Water, Energy, Biogeochemical Budgets Program of the U.S. Geological Survey


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### Abstract

Small watershed studies serve as an important mechanism to understand changes in a broad range of hydrologic environments at a scale where multiple processes can be understood. The U. S. Geological Survey's (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) program was designed to understand processes in small watersheds located in geographically diverse environments that represent a range of hydrologic, ecologic, and climatic conditions. Five watersheds have been the focus of long-term monitoring and research since 1991, with emphasis on changes in hydrochemistry caused by natural and anthropogenic disturbances such as atmospheric deposition, land-use change, and climate change. This paper provides a review of recent studies from the WEBB sites related to hydrologic trends and the influence of climate, biogeochemistry and chemical weathering, and geomorphology and sediment disturbances. Our program seeks to scale-up information from these intensive studies on individual watersheds to understand processes in larger systems. One of the challenges for scientists is to demonstrate transferability of their findings beyond an intensively studied watershed to other watersheds with sparse data.



**Keywords:** small watersheds, hydrology, biogeochemistry


### Introduction

The U S. Geological Survey's (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) Program was designed to understand processes in small watersheds in geographically and ecologically diverse environments that represent a range of hydrologic and climatic conditions. The five WEBB watershed sites described below have diverse precipitation and temperature ranges and, although they are located in relatively pristine environments, they are impacted to varying degrees by human activities. The selection of sites was based in part on the existence of long-term data sets and infrastructure provided by other federal agencies on which the program could build. The WEBB watersheds have been the focus of intensive monitoring and research since 1991.

Specific goals of the program are (1) to understand the coupled effects of the geologic and physiographic framework, land use, landscape characteristics, and climatic setting of a watershed on the water balance and associated generation of streamflow or fluctuations of lake levels; (2) to increase our understanding of temporal and climatic factors that affect solute input, export, and retention; and (3) to quantify the impacts of human and natural disturbances on terrestrial and aquatic ecosystems, such as the effects of land-use change on erosion and water- and soil-resource degradation, and the effects of atmospheric deposition of forest health and aquatic biota. An overarching goal is to compare responses observed among the WEBB sites, providing information about controls on ecosystem processes that allows the extension of work on these individual small watersheds to other areas and to larger regions. The purpose of this paper is to provide examples of recent USGS studies at the sites and to discuss the future challenges. More information about the program and the individual


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sites can be found at http://water.usgs.gov/ nrp/webb/

## WEBB Research Watershed Sites

Below is a brief description of each site in the Program. In addition to being supported by the USGS, all of the WEBB sites have received substantial support from partnerships with other state and federal agencies and with academic institutions.

### Sleepers River watershed

Located in Vermont, it is predominantly a typical northern hardwood forest developed on glacial till with about one-third of the watershed in pasture land used for dairy farming. Research in the watershed was begun by the Department of Agriculture 's Agricultural Research Service in 1959 and was supported for many years by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL).

### Luquillo experimental forest

Located in Puerto Rico, it is a tropical rainforest developed on volcanic rocks. It is administered by the U.S. Forest Service and is supported by the National Science Foundation (NSF) as a Long-Term Ecological Research (LTER) site and is an UNESCO-designated International Biosphere Reserve. WEBB research is also conducted in a nearby urban and agriculturally developed watershed.

### Panola Mountain watershed

Located in Georgia, it is a forested watershed in the Piedmont region, with bedrock outcrops covering a small fraction of the area. It is in a State Department of Natural Resources Conservation Park.

### Loch Vale watershed

Located in Colorado, is a subalpine watershed within Rocky Mountain National Park. It is predominantly forested with bedrock outcrops on the steep valley sidewalls. It is administered by the National Park Service and is part of the interagency National Atmospheric Deposition Program/ National Trends Network. In addition, it is part of an UNESCO-designated International Biosphere Reserve.

### Northern temperate lakes watershed

Located in Wisconsin, it is in a forested upland area characterized by a moderately dense distribution of lakes, typical of the low-relief, glaciated terrain in over much of the upper Midwest and southern Canada. The network of lakes in the watershed is interconnected by ground water. The watershed is supported by NSF as an LTER site and operated through the University of Wisconsin.

## Current Research at the WEBB Sites

Research at these sites focuses on interactions of the geology, climate, hydrology, and ecology under the broad topics of hydrologic trends and the influence of climate, biogeochemistry and chemical weathering, and geomorphology and sediment disturbances. Long-term data collection has been a key component of the WEBB program to examine trends and the influence of climate and human intervention. Monitoring data, mass-balance budgets, and watershed models are being used to understand controls on surface- and ground-water contributions to streamflow at nested catchments, to relate the hydrology to biogeochemical cycling and climate variability, and to provide the basis for examining fluxes and mass balances of water and solutes.

### Biogeochemistry and chemical weathering

Carbon and nitrogen cycling have been a major focus of the studies in the WEBB watersheds since the beginning of the program in 1991. A recent study on carbon dioxide and methane fluxes from the Loch Vale watershed demonstrated that although over the last 7000 years a subalpine wetland in the watershed has accumulated carbon, the net carbon flux during 1996 to 1998 was from the wetland to the atmosphere (Wickland et al. 2001). This may reflect a change in the primary productivity of the wetland and the study demonstrates the annual variability of carbon fluxes. Studies on nitrogen (nitrate and ammonia) at the same watershed for a 6-year period indicated that annual atmospheric deposition was in excess of the annual export of nitrogen. Concentrations of nitrate in different landscapes compared to snowpack and snowmelt for 1994 to 1995 indicated that the highest concentrations were found in water from the tundra and talus (Figure 1) (Campbell et al. 2000). The results suggest that alpine watersheds are sensitive to moderate rates of atmospheric deposition of nitrogen in part because minimal vegetation limits nitrogen assimilation by plants in the talus, which is well-connected to the surface waters. The export of nitrogen is a combination of direct flushing from atmospheric sources and from biogeochemical processes. Further studies on the delta$^{15}$N and delta$^{18}$O of nitrate confirmed that much of the nitrate exported in alpine streams is transported from the talus deposits and that nitrate from microbial nitrification is a major component of the total nitrate (Campbell et al. 2002).

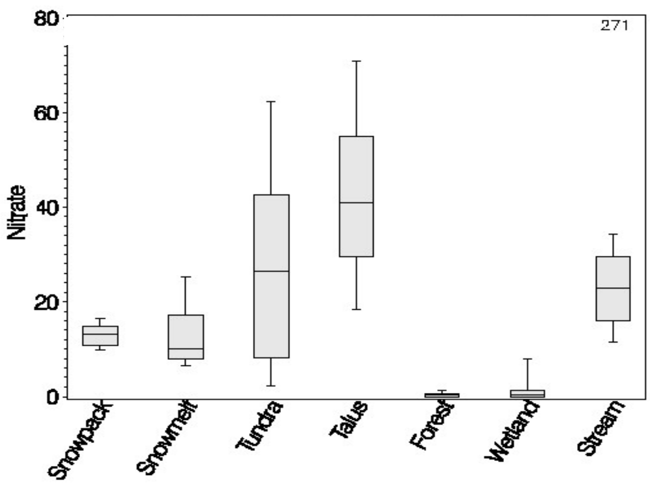


Figure 1. Distribution of nitrate concentrations (μeq L$^{-1}$) in atmospheric deposition (snow and snowmelt), surface water (tundra rivulets and sub-basin streams), and ground water (talus, forest, and wetlands). Boxes represent 25$^{th}$, 50$^{th}$ (median), and 75$^{th}$ percentiles of population; whiskers represent 10$^{th}$ and 90$^{th}$ percentiles. [Modified from Campbell et al. 2002].

With the interest in mercury in the environment stemming from atmospheric deposition, an investigation at the Sleepers River watershed was expanded to include monitoring for mercury along with dissolved organic carbon (DOC) and nitrate during the 2000 snowmelt period. The mercury concentrations strongly correlated with the DOC concentrations throughout the snowmelt period despite the large difference in concentrations (Figure 2). These data suggest that either the mercury and DOC share a common source or the mercury, through association with the DOC, is not removed by the soils (Shanley et al. 2002b). The nitrate peaked in streamflow during the initial snowmelt and then progressively was depleted. A high mercury concentration in the particulate phase was occasionally observed (up to 16 ng/L) compared to an event maximum of 2 ng/L dissolved mercury. These results indicate that mercury fluxes in watersheds may be controlled by highly episodic mobilization during snowmelt periods and that the contribution from particulate sources may be significant.

In weathering experiments run for five years, data from flow-through columns with fresh granitoids from the Loch Vale, Panola, and Luquillo watersheds indicated significant and selective temperature effects on rates of chemical weathering. Effluent Ca, Mg, and Sr concentrations did not exhibit positive correlations with temperature, which is likely due to competing processes such as nutrient cycling and acidification (White et al. 1999). The result that temperature does not significantly impact natural silicate weathering rates has implications for atmospheric $CO_2$ drawdown by weathering of silicates.

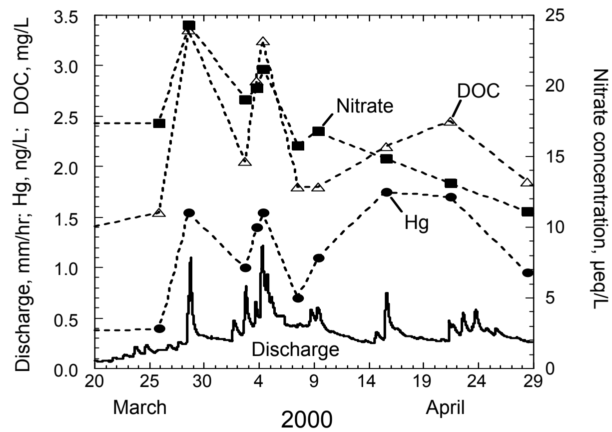


Figure 2. Discharge in Sleepers River Stream B during the 2000 snowmelt period, with concentrations of dissolved Hg, DOC, and nitrate. Note the diurnal snowmelt peaks and larger rain-on-snow event peaks, and the emphasis on high-flow sampling. [Modified from Shanley et al. 2002b].

## Hydrology, geomorphology, and sediment disturbances

The WEBB data have had very practical uses and have contributed to the fundamental understanding of how watersheds function. For example, in Puerto Rico, one hundred years of hydrologic data from small watersheds were scaled-up to characterize drought and water resources throughout the island. Anomalously low rainfall in the 1990s had an economic impact that was more severe than previous droughts. Changes in the socioeconomic conditions appear to have caused the difference between the recent droughts and historic droughts. Although there were droughts recorded in the last hundred years, the population, public- supply withdrawal, and per capita consumption of water have been increasing and reservoir capacity has been declining over this interval (Larsen 2000).

One goal in using mixing models to describe the hydrologic response is to understand the sources and flow paths of water in small catchments. A detailed study at the Panola Mountain WEBB site during a three-day storm event quantified the contributions of geographic sources of stormflow to stream runoff—outcrop runoff, hillslope runoff, and riparian ground-water runoff (Burns et al. 2001). Riparian ground-water runoff dominated stream runoff on the ascending and receding limbs of the stream hydrograph, whereas runoff from an outcrop dominated stream runoff during peak-flow conditions. Controls on the contributions and the variability of the sources of snowmelt water to streamflow were examined at the Sleepers River site. In 1993 the meltwater input to the stream ranged from 41 to 74 percent, whereas in 1994 the input ranged from 30 to 36 percent (Shanley et al. 2002a).

The Northern Temperate Lakes site has the flattest landscape of the 5 WEBB sites and is a region where the dominant surficial deposits are highly permeable glacial outwash sands. The ground-water system is interconnected and can influence the water budget, nutrient budget and acid buffering capacity of the lake systems. Simulation of lake/ground-water interactions with mathematical models is essential to understand the hydrologic system. Recent work has extended the modeling approaches by formulating an analytic-element lake package for use with ground-water models, such as MODFLOW (Hunt et al. 2003).

In a comparison of four watersheds in Puerto Rico, an examination of land-use conversion to agriculture and landslides in a small montane watershed outside the forested area demonstrated an extreme case of anthropogenic disturbance in the humid tropics. In the watershed, 94 percent of the original forest cover had been eliminated by the 1940s. Based on field surveys and examination of aerial photographs, there were more than 2000 landslides identified over the last 180 years. The landslides were attributed to highly weathered bedrock, episodic heavy rainfall, and intense land-use practices (Larsen and Roman 2001). The study estimated the amount of mass wasting and suggested that the problem will continue for years despite efforts to reforest hillslopes.

### Comparative studies and modeling

Long-term data from the WEBB sites are currently being used to compare and contrast results from these five sites and from other watersheds. Comparative mass-balance budgets that describe the inputs and outputs to the watersheds and the changes in storage for the five sites are being developed. These results will lead to a better understanding of sediment transport and of watershed processing of solutes. Watershed modeling is a recent component of the WEBB studies. At the Panola site, a Dynamic TOPMODEL (a rainfall-runoff model) was used to predict streamflow and catchment responses (Peters et al. 2003). A watershed model is being tested and applied to identify how specific hydroclimatic conditions result in variations in net fluxes of conservative and reactive solutes. This model was built in the Modular Modeling System (Leavesley et al. 1998) and simulates precipitation and temperature distribution, canopy interception, snowpack processes, evapotranspiration, and streamflow-generation mechanisms. New modules, built on the PHREEQC geochemical engine (Parkhurst and Appelo 1999), are being developed and incorporated to simulate geochemical processes and solute fluxes. A first step describing relations between hydrologic conditions and net solute fluxes across the diverse hydroclimatic regimes represented by the WEBB watersheds is presented in this volume (Webb et al. 2003).

## Challenges for Future Studies in Small Watersheds

Long-term data from small watersheds are needed to understand the interaction of physical, chemical, and biological processes at various temporal and spatial scales. Small watersheds can be instrumented for detailed experiments and data collection and are small enough to study inputs, outputs, and apply mass-balance and modeling approaches. The future challenge is for scientists to engage in more comparative studies and to demonstrate how data and interpretations from one small watershed can be transferred to watersheds with less data or to larger systems. What are the key components that can lead to the transfer of information from an intensively studied watershed to one with sparse data?

Environmental policy and management decisions, such as those related to freshwater availability, greenhouse gases, atmospheric deposition, nutrient enrichment, and biodiversity, need a scientific underpinning to be successful. Although understanding processes such as weathering, sediment transport, and geochemistry in small watersheds is important, it is equally important to understand how such processes vary between watersheds and how the information and techniques can be scaled-up. A challenge for future work at small watersheds is the growing trend to devote resources to short-term investigations rather than examine detailed processes that require long-term monitoring. By demonstrating a wider application of techniques and methods used in pristine watersheds to environments impacted by humans, the need for long-term data collection and monitoring activities can be demonstrated.

New methods of investigation are continually being developed in small watershed studies. The application of a variety of new isotope techniques (for example, $^{35}S$ and $^{87}Sr/^{86}Sr$) in addition to the stable isotopes of N, O, S, H, and C can add new dimensions to understanding processes and biogeochemical cycling. Additional studies of trace metals and nutrients can provide insight as to how some of these metals enter hydrologic systems and end up in aquatic ecosystems and food chains.

To maintain the excellent watershed networks for collection of long-term data, it is important to expand the original justification for starting many of these sites from studying acidic deposition at the small watershed scale to examining the long-term effects of natural processes and of human intervention. Small watershed investigations should not be viewed as studies of one site but as part of a study of larger landscapes. Many of our studies at the USGS and at other watershed sites have started along that path.

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## References

Burns, D.A., J.J. McDonnell, R.P. Hooper, N.E. Peters, J.E. Freer, C. Kendall, and K. Beven. 2001. Quantifying contributions to storm runoff through end-member mixing analysis and hydrologic measurements at the Panola Mountain Research Watershed (Georgia, USA). Hydrological Processes 15:1903-1924.

Campbell, D.H., C. Kendall, and K.A. Tonnessen. 2002. Pathways for nitrate release from an alpine watershed: Determination using $\delta^{15}N$ and $\delta^{18}O$. Water Resources Research 38(5):101-109.

Campbell, D.H., J.S. Baron, K.A. Tonnessen, P.D. Brooks, and P.F. Schuster. 2000. Controls on nitrogen flux in alpine/subalpine watersheds of Colorado. Water Resources Research 36(1):37-47.

Hunt, R.J., H.M. Haitjema, J.T. Krohelski, and D.T. Feinstein. 2003. Simulating ground water-lake interactions: Approaches and insights. Ground Water 41:227-237.

Larsen, M.C. 2000. Analysis of 20$^{th}$ century rainfall and streamflow to characterize drought and water resources in Puerto Rico. Physical Geography 21(6):494-521.

Larsen, M.C., and A.S. Roman. 2001. Mass wasting and sediment storage in a small montane watershed: An extreme case of anthropogenic disturbance in the humid tropics. In J.M. Dorava, F. Fitzpatrick, B.B. Palcsak, and D.B. Montgomery, eds., Geomorphic processes and riverine habitat, water science, and application. American Geophysical Union Monograph 4:119-138.

Leavesley, G.H., P.J. Restrepo, S.L. Markstrom, M. Dixon, and L.G. Stannard. 1998. The Modular Modeling System (MMS): User's manual. U.S. Geological Survey Open-File Report 96-151.

Parkhurst, D.L., and C.A.J. Appelo. 1999. User's guide to PHREEQC (Version 2)--A computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations. U.S. Geological Survey Water-Resources Investigations Report 99-4259.

Peters, N.E., J. Freer, and K.J. Beven. 2003. Modeling hydrologic responses in a small forested catchment (Panola Mountain, Georgia, USA)--A comparison of the original and a new dynamic TOPMODEL. Hydrological Processes (in press).

Shanley, J.B., C. Kendall, T.E. Smith, D.M. Wolock, and J.J. McDonnell. 2002a. Controls on old and new water contributions to stream flow at some nested catchments in Vermont, USA. Hydrological Processes 16:589-609.

Shanley, J.B., P.F. Schuster, M.M. Reddy, D.A. Roth, H.E. Taylor, and G.R. Aiken. 2002b. Mercury on the move during snowmelt in Vermont. EOS Transactions, American Geophysical Union 83(5):45,47-48.

Webb, R.M.T., N.J. Peters, B.T. Aulenback, and J.B. Shanley. 2003. Relations between hydrology and solute fluxes at the five Water, Energy, and Biogeochemical Budget (WEBB) watersheds of the United States Geological Survey. In Proceedings of the First Interagency Conference on Research in the Watershed, Benson, AZ, October 27-30, 2003.

White, A.F., A.E. Blum, T.D. Bullen, D.V. Vivit, M. Schulz, and J. Fitzpatrick. 1999. The effect of temperature on experimental and natural chemical weathering rates of granitoid rocks. Geochimica et Cosmochimica Acta 63(19/20):3277-3291.

Wickland, K.P., R.G. Striegl, M.A. Mast, and D.W. Clow. 2001. Carbon gas exchange at a southern Rocky Mountain wetland, 1996-1998. Global Biogeochemical Cycles 15(2):321-335.