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Ivan J. Fernandez

Joseph E. Karem

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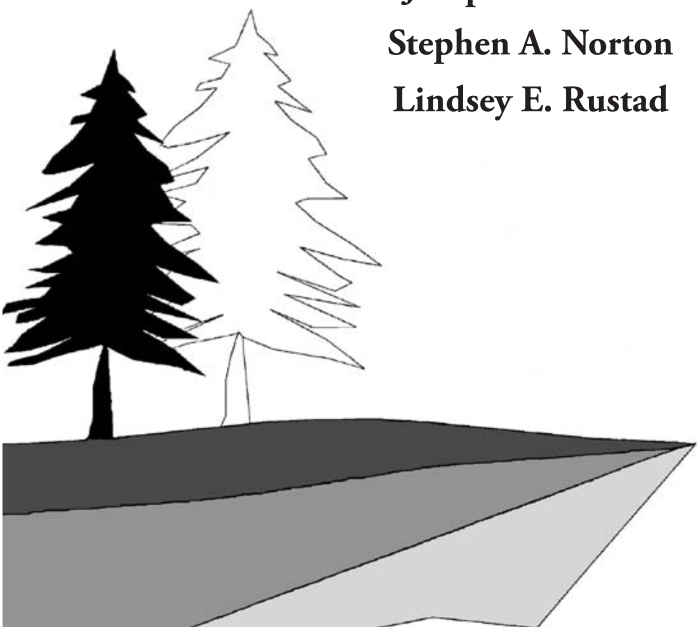

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Temperature, Soil Moisture, and Streamflow at the Bear Brook Watershed in Maine (BBWM)

Ivan J. Fernandez
Professor, Department of Plant, Soil & Environmental Sciences

Joseph E. Karem
Scientific Technician, Department of Plant, Soil & Environmental Sciences

Stephen A. Norton
Professor, Department of Earth Sciences

Lindsey E. Rustad
Forest Ecologist, USDA Forest Service

Maine Agricultural & Forest Experiment Station
5782 Winslow Hall
University of Maine
Orono, ME 04469-5782

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INTRODUCTION

The chemical and physical characteristics of our atmosphere have profound influences on natural ecosystems and the quality of life for all living organisms, including human beings. At the dawn of the 21st century we can begin to evaluate the progress we have made through environmental regulations in limiting chemical air pollutants such as sulfur (S) and nitrogen (N) that cause acid deposition (Stoddard et al. 2003). At the same time we are coming to grips with the gravity of greenhouse gas emission effects on climate (IPCC 2007) and associated consequences such as climatic warming, increased drought (Hayhoe et al. 2006), and an intensification of the hydrologic cycle (Huntington 2006). Evidence to date suggests we are seeing dramatic reductions in S deposition, little change in N deposition, and mixed results on how surface waters in the region have recovered in light of these trends. Nitrogen is often a limiting nutrient in terrestrial ecosystems and both atmospheric deposition and climate change alter N cycling in ecosystems. In fact, most of the effects of chemical air pollutants on terrestrial and aquatic ecosystems are strongly affected by the physical climate influencing them. Therefore, it is increasingly important to understand how the interactive effects of chemical and physical changes in climate influence the physical, chemical, and biological mechanisms that define ecosystems.

The Bear Brook Watershed in Maine (BBWM) is a whole-ecosystem chemical manipulation initiated in 1987 to study the effects of acid deposition on forests and surface waters (Norton and Fernandez 1999). The focus of this research was to understand the biogeochemical response of watersheds with emphasis on chemistry and hydrology. In 2001 a program was initiated to provide more detailed measurements of temperature and moisture to examine critical linkages amongst chemical, biological, and physical processes that ultimately work together to define ecosystem function. The purpose of this publication is to provide data from the initial phase of soil temperature, air temperature, and soil moisture measurements at the site. In addition, we have incorporated aspects of relevant precipitation and streamflow characteristics available for the full project period.

MATERIALS AND METHODS

Site Description

The Bear Brook Watershed in Maine is the site of a long-term, gauged, forested, first-order paired-stream watershed study located in eastern Maine (44°52' N lat., 68°6' W long.) approximately 40 km from the Atlantic Ocean. The site lies on the southeastern slope of Lead Mountain, with a total relief of 210 m and maximum elevation of 475 m. Two nearly perennial, low dissolved organic carbon (DOC), and low acid neutralizing capacity (ANC) streams (East Bear and West Bear) drain 10.3- and 11.0-ha contiguous watersheds. Vegetation in each stream watershed is dominated by northern hardwoods (*Fagus grandifolia* Ehrb., *Acer rubrum* L., *Acer saccharum* Marsh., *Betula alleghaniensis* Britt., *Betula papyrifera* Marsh., and *Acer pensylvanicum* Marsh.), with stands of softwoods at higher elevations dominated by red spruce (*Picea rubens* Sarg.) with minor balsam fir and hemlock (*Abies balsamea* Mill. and *Tsuga canadensis* (L.) Carr.). There is a mixed wood zone that is transitional between the upper softwood and lower hardwood zones in these watersheds. For the purposes of this research, we focused on the end members of the forest composition spectrum: softwoods and hardwoods. This species focus resulted in an experimental design consisting of four compartments represented by two forest types (hardwood and softwood) in each of two watersheds (East Bear and West Bear). Soils are primarily coarse, loamy, isotic, frigid Typic Haplorthods developed on till averaging 1 m in thickness, with coarse-loamy, isotic, frigid Typic Haplohumods in some areas of the upper elevations supporting softwood forest types. There are minor occurrences of Folists in the uppermost portions of the watershed. Bedrock is predominantly quartzites and meta-pelites, intruded locally by granite.

Temperature

Air and soil temperatures were measured using HOBO™ H8 Outdoor/Industrial four-channel data loggers manufactured by Onset Computer Corporation, Bourne, MA. In July 2001, two data loggers were installed in each of the four compartments at BBWM (eight total) representing both forest types and watersheds. In June 2003, two additional data loggers were installed in each compartment bringing the total to four per compartment (16 total). Each data logger was equipped with four external temperature sensors at the terminal end of a 183 cm (i.e., -ft) input cable. This allowed temperature data to be collected by each data logger from four

sources. Sensor positions included (1) air temperature at 100 cm above the surface to minimize interference from the snowpack, (2) organic horizon (O horizon) temperature where sensors were threaded into the center of the organic soil horizon, (3) at a depth of 10 cm from the top of the mineral soil that typically corresponded to the upper B horizon, and (4) at 25-cm depth from the top of the mineral soil that typically corresponded to the lower B or BC horizon. Temperature was recorded by all data loggers continuously at 3-hour time intervals starting at 00:00 (midnight).

Precipitation

Precipitation depth was determined using a Belfort™ Universal Precipitation Gauge (Belfort Instrument, Baltimore, MD) located on a stage in a clearing next to the East Bear weir above the gauge house. The precipitation gauge collected precipitation (e.g., rain, snow, hail) in a weighing chamber and was designed to convert the weight of accumulating precipitation into depth equivalents (i.e., cm). These data were continually recorded on a mechanical rotating chart. For the results reported here, data were summed at 3-hour time intervals starting at 00:00.

Soil Moisture

A single HOBO™ Micro Station data logger (Onset Computer Corporation, Bourne, MA) was installed in each of the hardwood and softwood stands in the East Bear watershed during June of 2003 and 2004, respectively (two total). These were intended as a pilot program of soil moisture measurements to evaluate the equipment and data. The data logger in the hardwood stand was equipped with a single ECH2O™ soil moisture sensor with a 64-cm^2 (3.2 × 20 cm) sensing surface at the terminal end of a 3.5-m input cable. The sensor was inserted vertically into the mineral soil after cutting a thin slice through the O horizon and upper mineral soil with a tile spade. The sensor was then inserted into the mineral soil so the top of the sensor area was at the top of the mineral soil and an integrated measure of volumetric soil moisture content (i.e., m^3 water per m^3 soil) in the upper 20 cm of mineral soil was obtained. Soil moisture readings were collected continuously at 3-hour intervals starting at 00:00. The HOBO™ Micro Station in the softwood stand was installed as described above, but had two ECH2O™ soil moisture sensors. Both moisture sensors were installed in the same manner and were located 2 m apart at the data logger station. Replicate soil moisture sensors were installed to evaluate precision

in the measurements of soil moisture in the top 20 cm of mineral soil. According to Onset Computer Corporation, accuracy of these sensors is ± 3%. Data presented in this study for soil moisture in the East Bear softwood stand represent the mean of the two readings. Based on these data, the average difference in soil moisture between probes was 0.9%.

Streamflow

Surface hydrologic flux from each watershed was gauged with 120° V-notch weirs anchored on bedrock. Hydrologic monitoring was carried out in collaboration with the U.S. Geological Survey and real time streamflow data were available for East and West Bear at the time of this writing under the Narraguagus River Basin on the Web (http://waterdata.usgs.gov/me/nwis/current/?type=flow). Streamflow data recorded at 3-hour intervals starting at 00:00 were used for this study.

Statistical Analyses

The experimental design for this research was a split-plot design, with watersheds as the main experimental units. Each watershed was split into hardwood and softwood subunits yielding four compartments. Because no significant temperature differences were detected between East and West Bear, and soil moisture data were only collected in East Bear, the two forest zones were used as the main experimental units for these analyses.

Differences ($P < 0.05$) in temperature and soil moisture between forest types were examined using a one-way ANOVA (PROC GLM, SAS for Windows 8.1). No transformation of temperature or soil moisture data was necessary to meet the assumptions of normality. Normality was assessed by examining skewness, kurtosis, and the Shapiro-Wilk W statistic (PROC Univariate, SAS for Windows 8.1). To detect temperature differences in air and all three soil depths, a separate one-way ANOVA was calculated for data collected at each of the four sensor positions described above. A Tukey's means separation test was used to evaluate differences among soil temperature probe positions.

Correlations between soil moisture and streamflow in East Bear were evaluated using Pearson correlation analysis (PROC CORR, SAS for Windows 8.1). No transformation of data was necessary for this method. Streamflow data collected at the same 3-hour time intervals as soil moisture data were used for this analysis.

RESULTS AND DISCUSSION

Air and Soil Temperature

Figure 1 illustrates the continuous time series for air and soil temperatures at BBWM. The overall annual pattern of temperature fluctuation is sinusoidal. Temperatures reach their minima in January and maxima in August for each year reported here. The January minima for the data in Figure 1 were -14.7, -3.6, -0.8, and 0.33°C for air, the organic horizon (O), 10-cm and 25-cm depth in the mineral soil, respectively. The August maxima were 20.0, 17.4, 15.4, and 13.7°C for air, the O horizon, 10-cm and 25-cm depth in the mineral soil, respectively. At BBWM, the temperatures from above the soil surface and below the forest canopy (air), through the surface O horizon, to the shallow underlying mineral soil (10 cm depth), to the deeper mineral soil (25 cm depth) show a typical vertical profile of characteristics that include

1. a gradient of temporal variability from the most variable (air temperatures) to the least variable (25 cm mineral soil temperatures), and
2. a biannual temperature inversion with air temperatures colder than soils in the winter and warmer than soils in the summer.

Table 1 provides descriptive statistics for the 24-month period of data reported here. The overall mean temperatures for air and soil at BBWM were similar, ranging between 5.06 and 6.18°C during the measurement period. Mean soil temperatures were slightly higher than air temperatures, which is typical. Soil materials and the plants growing on them absorb the greatest part of the radiant energy from the sun, while air absorbs a much smaller amount. The atmosphere receives most of its radiant energy from the soil below (Kohnke 1968). There are limited high-quality long-term data for rural landscapes in Maine to compare these means for air temperature and even fewer for air temperature below a closed forest canopy. The Northeast Regional Climate Center reports a 30-year annual average (1961–1990) air temperature for the open air sites at Caribou and Portland, Maine, to be 3.8 and 7.4°C, respectively (http://met-www.cit.cornell.edu/ccd/nrmavg.html). BBWM is geographically between these sites so the means reported here seem reasonable and reflect the air temperature below a largely closed forest canopy, which is typically cooler. Air temperature exhibited the greatest annual variance ranging from -30.45 to 31.02°C; sensors deepest in the mineral horizon exhibited the least variance, rang-

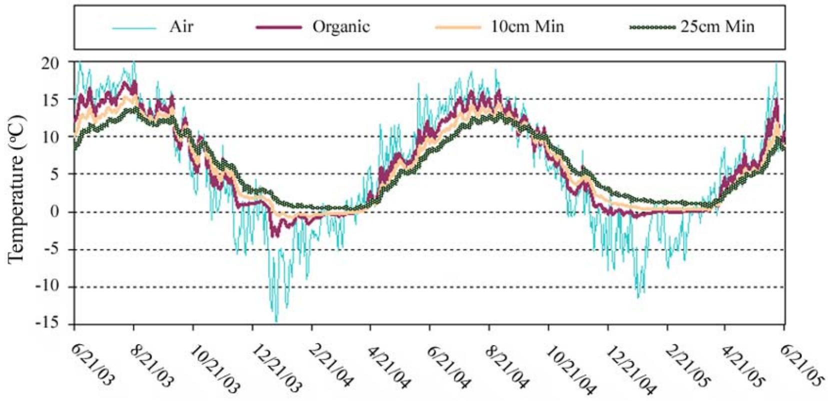

Figure 1. Time series for air and soil temperatures at BBWM from June 2003 to June 2005 by sensor position.

Table 1. Descriptive statistics for air and soil horizon temperatures (°C) at the Bear Brook Watershed in Maine.

	Mean	SE	Median	Min	Max	Range	n
Overall							
Air	5.06	0.07	5.54	-30.45	31.02	61.47	23392
O horizon	6.18	0.04	5.39	-5.64	18.95	24.59	23392
10cm Mineral	5.98	0.03	5.39	-1.75	16.47	18.23	23392
25cm Mineral	6.01	0.03	5.7	-0.61	14.6	15.21	23392
Hardwood Forest Type							
Air	5.18	0.1	5.76	-30.17	30.72	60.89	11696
O horizon	6.66†	0.06	6.52	-4.17	18.95	23.11	11696
10cm Mineral	6.71†	0.05	6.52	-0.77	16.47	17.24	11696
25cm Mineral	6.69†	0.04	6.42	0.14	14.6	14.46	11696
Softwood Forest Type							
Air	4.95	0.1	5.4	-30.45	31.02	61.47	11696
O horizon	5.69	0.05	4.45	-5.64	17.24	22.88	11696
10cm Mineral	5.25	0.05	4.15	-1.75	14.98	16.73	11696
25cm Mineral	5.33	0.04	4.57	-0.61	13.22	13.83	11696

†Indicates significant difference between forest types.

ing from -0.61 to 14.60°C. This amounts to four times the range in temperature for the air below the forest canopy as compared to the mineral subsoil. It is noteworthy that trees, as individual organisms, experience both highly variable air temperature regimes in their aboveground components and relatively modest temperature variations in their rooting environment simultaneously.

There was no statistically significant difference in mean annual air temperature between softwood and hardwood stands at BBWM ($P = 0.152$) (Table 1; Figure 2a). However, soil temperature means were consistently lower in softwood vs hardwood stands ($P < 0.05$) in all soil horizons (Table 1; Figure 2b–d). The lower light infiltration in softwoods is believed to be responsible for the lower soil temperatures. This does not translate into different air temperatures by forest type because of the relatively steeply sloping environment of these watersheds allowing for ease of cold air drainage downslope even without turbulent mixing factors. These differences in soil temperature between forest types appear to increase with depth in the soil. Consistently, the greatest differences in soil temperature between forest types occur during the spring and summer seasons. This likely reflects the increasing influence of a denser canopy in these softwood stands dominated by relatively mature, closed canopy red spruce trees compared to the more heterogeneous and less dense mixed and hardwood stand conditions. The importance of these differences can be illustrated by examining the relative delay for softwood soils to reach a particular temperature in the spring compared to hardwood soils. For example, if we examine more closely the time series of temperature data in the spring and choose a benchmark temperature of 6°C, we see a notable delay in the rate of soil warming for softwood compared to hardwood soil temperatures (Figure 3a–f). In organic soils, it took softwood stands 35 days longer in the spring of 2004 to reach 6°C than hardwood stands, and 22 days longer in the spring of 2005 (Figure 3a,b). This can also be seen in mineral soils where it took softwood stands 38 (2004) and 30 (2005) days longer for sensors at 10-cm depth in minerals soils, and 35 (2004) and 24 (2005) days longer for sensors at 25-cm depth in mineral soils, to reach 6°C in softwoods compared to hardwoods, respectively.

Differences in the thermal input to soil-plant systems can be described by heat units. Heat units, calculated by adding the daily temperatures above some base, are another way of looking at the total heat energy budget for a period of time (Baskerville and Emin 1969; Wang 1960). This cumulative representation of temperature is thought to be better correlated with plant growth functions in

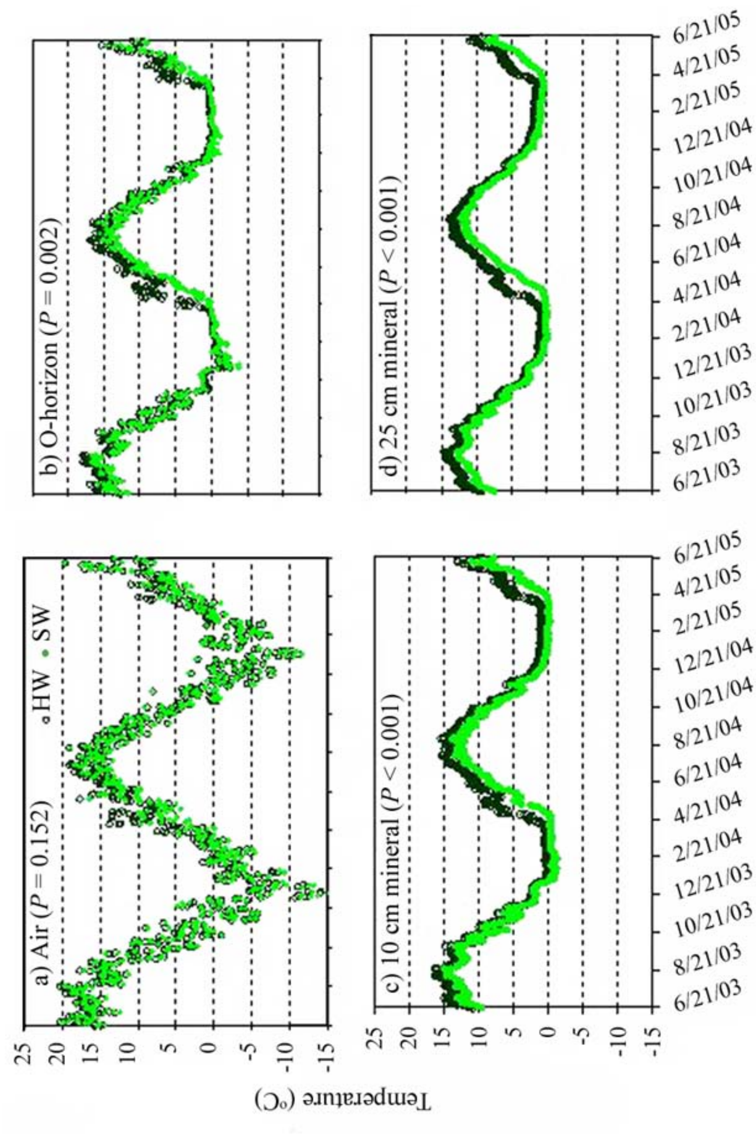

Figure 2. Daily temperatures for hardwood vs softwood stands.

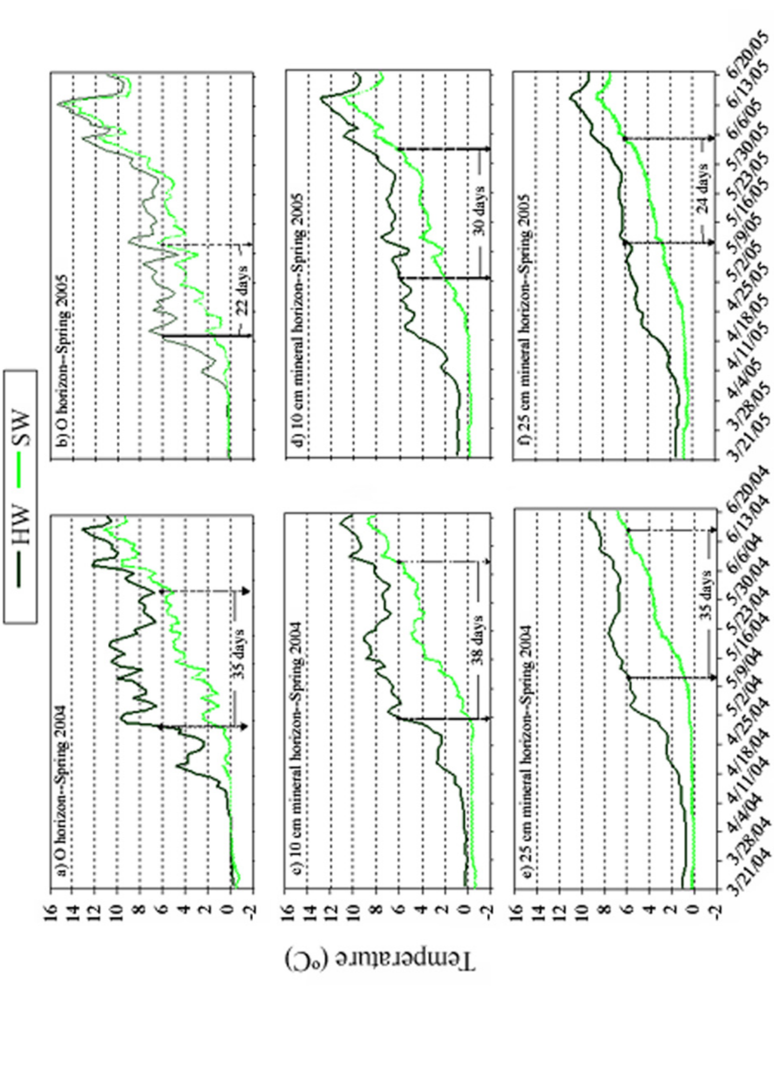

Figure 3. Time lag in seasonal soil temperature change for O and mineral horizons in 2004 and 2005.

some instances (Wang 1960). We calculated the cumulative heat units above a base of 0°C for the two years of data used in this study (Figure 4a–d). These curves show the temporal pattern of heat input and demonstrate the significant difference in softwood vs hardwood stands for energy inputs. Heat accumulation curves are nearly the same for air temperature in both hardwood and softwood stands (Figure 4a). However, less heat accumulation occurred in the soils of softwood stands compared to hardwood stands during both years of measurements (Figure 4b–d). These differences were greater in mineral soils compared to organic soils and may be the result of temperature probes being deeper in softwood soils compared to hardwood soils as a result of thicker O-horizons in softwood stands. In all horizons, heat accumulation curves appear to increase at almost identical rates; however, there was a noticeable delay in the accumulation of heat in soils that was not evident for air (Figure 4a–d). Hardwood soils show heat accumulation earlier, during mid-April of both years, compared to softwood stands, which do not begin to exhibit substantial heat accumulation until mid-May.

Sample Size Estimates

One of the great challenges of research on natural ecosystems is the high degree of variability in nature and the need for suitable replication in physical, chemical, and biological measurements. Research, such as that conducted at BBWM, which includes multiple observations or measurements in space and/or time provides data on variability that can be used to calculate the sample size needed for future research and monitoring activities within the confines of the desired statistical confidence levels. Here we have applied the limited data we collected on soil temperatures at BBWM using our spatially dispersed program of 16 data loggers to the question of sample size. Based on data collected during the 24-month monitoring period from 2003 to 2005, between two and eight sensors would be needed to achieve a 90% CI for estimating mean air and soil temperatures for each forest stand with an error of ±0.5°C (Table 2). Because variance among sensors is the reason for differences in these estimates, the amount of time that a sensor is deployed in the field, but not functional, is an important, practical consideration in sample size calculations. This is part of the reason why the necessary sensor number estimate generated from temperature data collected at 25-cm depth in the mineral layer of the softwood stand at BBWM was only two sensors. The set of four data loggers for the measurement of this compartment and depth averaged only 15 non-operational days during the 24-month monitoring period compared

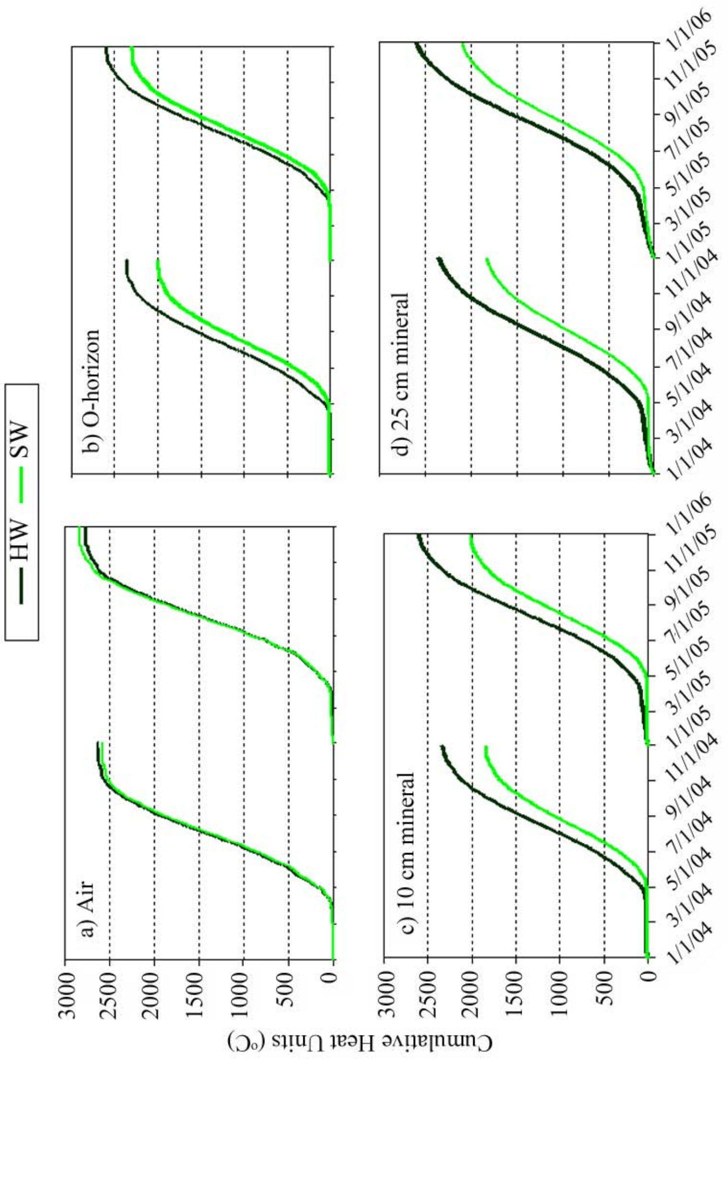

Figure 4. A comparison of heat unit accumulations between hardwood and softwood forest types.

Table 2. The number of HOBO data loggers needed to estimate, with 90% confidence, the temperature of air and soil horizons within 0.5°C, based on the equation $n = (t^*SD/E)^2$ (Weiss 1999); where n=number of HOBO data loggers, t = Student's t-value (α = 0.10, n – 1 df), SD = standard deviation, and E = the acceptable error.

	Number of HOBO Dataloggers (n)[†]			
Forest Type	Air	Organic	Mineral (10 cm)	Mineral (25 cm)
Hardwood	6	4	3	5
Softwood	3	8	8	2

[†]Decimals are rounded up to the next highest integer.

to the other sensor estimates that averaged 50+ non-operational days. Equipment malfunction is the pragmatic consideration contributing to variance in temperature data among sensors. The most important source of variance in these types of temperature data is the high degree of variability in natural ecosystems. For example, the estimate of eight sensors for measuring temperature at the 10-cm depth in the mineral soil for softwood stands was largely driven by a single sensor that produced lower temperature values than the other data logger positions in that compartment, resulting in a low mean temperature of 3.96°C (compared to the overall mean of 5.29°C). However, this data logger had a complete data record with no non-operational days. There was no significant correlation between the number of days sensors were non-operational and the number of sensors required in our estimates to meet the criteria for these calculations.

Precipitation

Annual precipitation is the total amount of water input to BBWM expressed as a depth, and includes rain, snow, sleet, and hail that could be deposited into the Belfort™ Universal Precipitation Gauges. Annual precipitation at BBWM ranged from 896 mm (2001) to 1910 mm (2005) during the collection period from 1988 to 2005, with an overall mean of 1320 mm yr^{-1} (Figure 5). There were no long-term trends evident in annual precipitation totals during the study period, 1988–2005. Monthly precipitation totals for the period (Figure 6) tended toward spring and fall maxima as we might expect for Maine

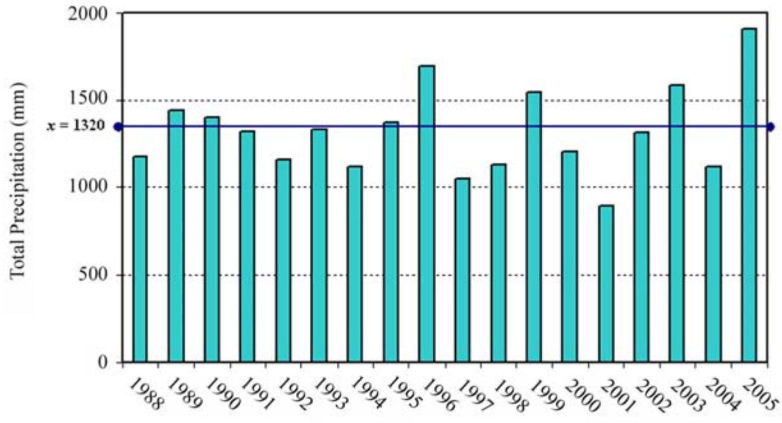

Figure 5. Annual precipitation depth and 18-year mean (1988–2005) for BBWM.

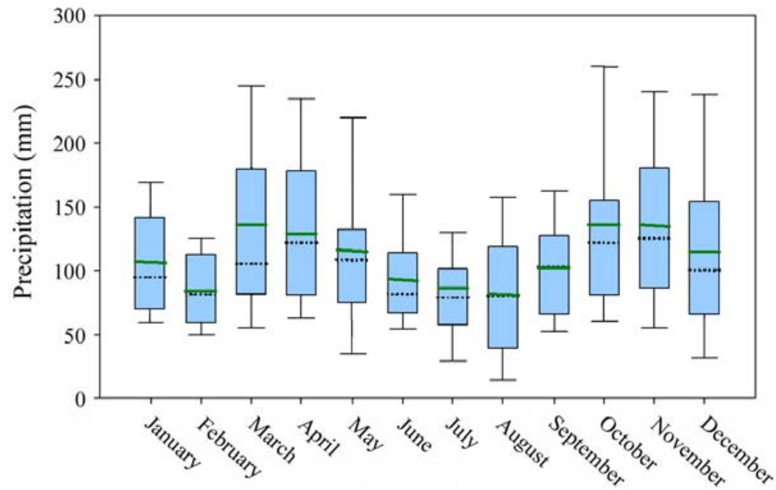

Figure 6. Descriptive statistics for monthly precipitation depths (1988–2005) for BBWM. Solid cross bar is the median; dotted cross bar is the mean. Boxes represent the 25th and 75th percentiles; whiskers the 10th and 90th percentiles.

from the 30-year norm (NOAA 2002). Mean precipitation totals for all months during this period have been relatively consistent at 92 ± 25 mm. Some years have exhibited a relatively constant monthly precipitation total throughout the year (e.g., 2004) while others (e.g., 1996) had high variation among months with relatively wet and dry months in the same year. During the 18-year monitoring period at BBWM, monthly precipitation totals ranged from as little as 3 mm (August 1996) to as much as 386 mm (March 1999).

Soil Moisture

Soil moisture measurements represent an estimate of volumetric soil water content (i.e., m^3 water per m^3 soil), expressed as a percentage. The minimum value with these sensors would be 0% in a completely dry soil, with a maximum of 40.5% as reported by the manufacturer. The latter value would correspond to saturated soil with total soil pore volume between 40% and 50% of the total soil volume. Volumetric water content reflects water held by soils under a tension in capillary films around soil particles, but can also include free water in soil macropores during wet periods or under conditions of impeded drainage. The sensors for soil moisture in this study were in freely drained soils from a moderately well drained soil drainage class. Therefore, we expect that water in excess of the retentive capillary forces of the soil would drain relatively quickly under normal conditions. If water tended to be stagnant enough to allow prolonged conditions of low oxygen, redoximorphic features would have developed more extensively than is evident in these soils.

The soil moisture sensors used in this study provide an integrated measure of soil moisture across their 20-cm length. Table 3 shows descriptive statistics for soil moisture in the upper 20 cm of the mineral horizon in the East Bear watershed. Volumetric soil moisture during the study period ranged from 12.13% to 36.26%, with an overall mean of 19.98% (Table 3). Soil moisture in the East Bear softwood stand was significantly higher than in the hardwood stand ($P < 0.001$). Mean softwood soil moisture was 22.73% during the 18-month monitoring period vs the mean hardwood soil moisture of 17.20% (Table 3). Figure 7 shows the time series for mean daily volumetric soil moisture in both the hardwood and softwood stands at BBWM during the measurement period. Soil moisture in softwood stands fluctuated between ~20% and ~30%, while soil moisture in the hardwood stand was less variable, ranging between ~15% and ~20%. We would expect freezing to result in a zero read-

Table 3. Descriptive statistics for East Bear Brook soil moisture (%) June 2004 to November 2005.

	Mean	SE	Median	Min	Max	Range	n
Overall	19.98	0.052	18.66	12.13	36.26	24.13	8363
Hardwood†	17.2	0.029	17.6	12.17	24.47	12.3	4158
Softwood†	22.73	0.081	21.27	12.13	36.26	24.13	4205

†Indicates significant difference in mean soil moisture between forest types.

ing, but it is unlikely there was frozen soil for any extended period of time in the upper pedon based on the temperature record (Figure 1) and these soil moisture results. Only during the months of July and August 2005 did softwood soil moisture drop below 20% for an extended period of time, and this was the only time when softwood soil moisture was less than hardwoods. Hardwoods exhibited their lowest soil moisture from January to February 2005 (Figure 7), and this was the only time that hardwood soil moisture fell below 15%. Higher soil moisture in softwood compared to hardwood stands was likely the result of lower insulation due to denser and perennial canopies in softwoods, and thus lower temperatures (Table 1), and

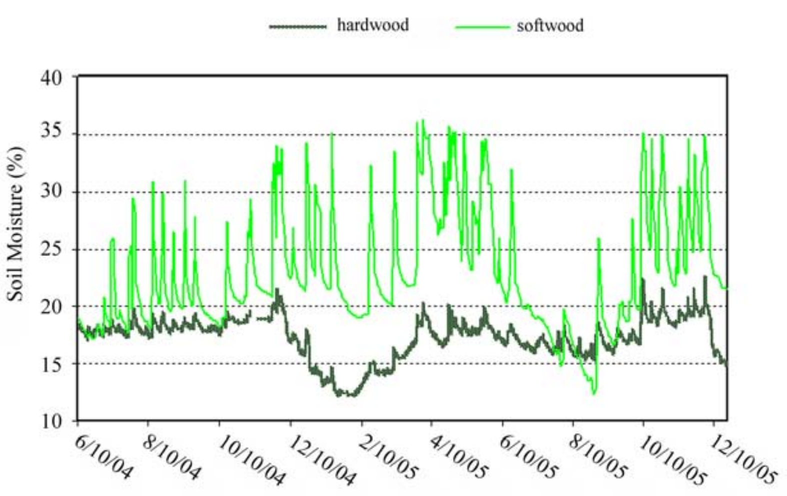

Figure 7. Mean daily soil moisture (%) for hardwood vs softwood stands ($P < 0.0001$).

shallower soil depths resulting in less total soil porosity for water storage when compared to the deeper soils lower in the watershed supporting hardwoods. These factors would lead to higher water-filled porosity along with lower evaporative loss of soil moisture. These differences must compensate for a potentially greater loss of moisture through foliar transpiration in softwoods compared to hardwoods (Penman 1963; Swank and Douglas 1974), and greater losses of moisture due to lateral flow because the softwoods tend to be on more steeply sloping and thinner soils than hardwoods.

The effects of individual precipitation events on soil moisture are interesting. Figure 8 shows a plot of the time series for soil moisture and precipitation depths for hardwoods and softwoods. There are periods of time in winter when there is no relationship logically evident between these parameters for either forest type due to snowcover. During the growing season, hardwoods (Figure 8a) showed a relatively small response in soil moisture to precipitation events compared to softwoods (Figure 8b). We interpret this to be the result of hardwood soils having lower soil moisture contents and deeper soils so that precipitation results in a smaller detectable increase in soil moisture content over the larger total soil volume. This suggests that softwood stands would be subject to more rapid lateral and surface flow with larger rain events, which could be important in determining the relative contribution of the hardwood vs softwood zones in this watershed to stream chemical export. Both soil moisture time series suggest a relationship between precipitation events and peaks in soil moisture. Softwoods (Figure 8b) were represented by a shorter period of measurement than hardwoods in this study, which limits our ability to discern linkages between precipitation events and sharp increases in soil moisture. Softwood soil moisture appears to be more responsive to precipitation events. This would be expected if these soils were generally wetter and had a lower soil volume due to less depth, causing them to be more easily saturated during precipitation events compared to hardwoods (Figure 8a). Both forest types showed a tendency for lower soil moisture in July and August. Softwoods appeared to show a more dramatic decrease in soil moisture over the late summer period in 2005 compared to hardwoods. This trend is reversed for both forest types in September as shorter days and cooler temperatures reduce evapotranspiration for both forest types (senescence and leaf fall essentially stop transpiration in hardwoods) and increased precipitation occurs. Hardwoods showed a marked decline in soil moisture during the coldest winter months of January and February

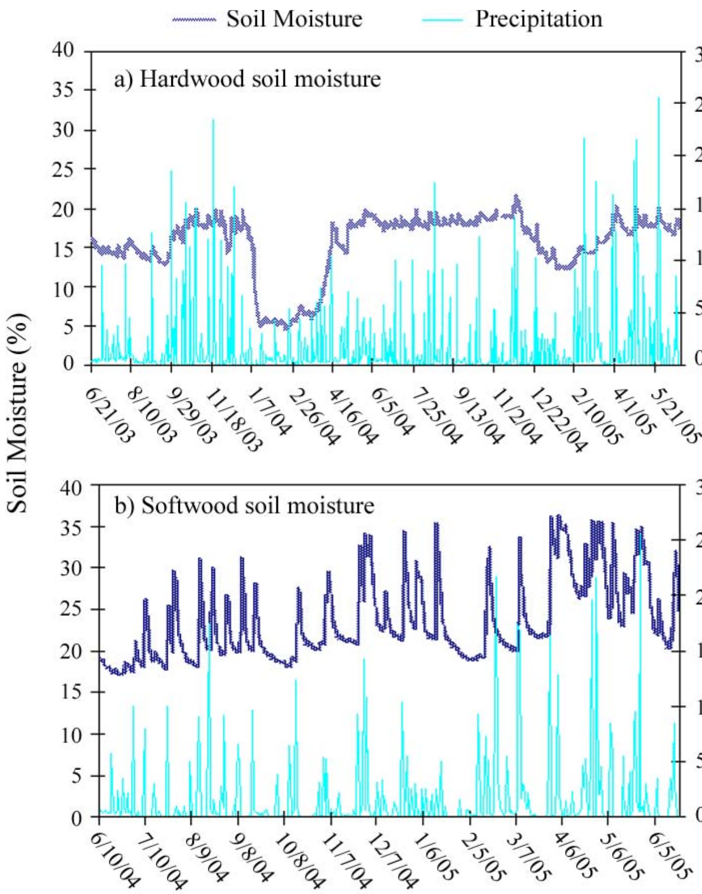

Figure 8. Daily precipitation vs daily soil moisture in East Bear hardwood (2003–2005) and softwood (2004–2005) stands.

of both 2004 and 2005. A more pronounced decline in hardwood soil moisture during the winter of 2004 vs 2005 seems primarily due to significantly less precipitation in 2004 vs 2005.

Streamflow

Streamflow in East Bear and West Bear represents the flux of water at the weirs exiting each watershed. In concept, this flux equals the total precipitation input of water to the watershed area minus the water lost to evapotranspiration, assuming minimal

water storage change on timescales of interest here. At BBWM, streamflow is the critical hydrologic output that is used to determine chemical mass balance for the watersheds (Norton and Fernandez 1999). Table 4 shows descriptive statistics for streamflow from 1988 to 2005 expressed as both streamflow and specific discharge. Given the nearly equal spatial extent of the paired BBWM watersheds, we focus on streamflow results in our discussion. There was no statistical difference in mean streamflow between East and West Bear streams during this period ($F = 0.06$, d.f. = 1, $P = 0.808$). Overall mean streamflow was 3.16 and 3.05 L sec^{-1} for East and West Bear, respectively.

Minimum mean streamflow occurred for both streams in 2001 (East Bear 1.29 L sec^{-1}; West Bear 1.22 L sec^{-1}) and maximum in 1996 (East Bear 5.23 L sec^{-1}) and 2005 (West Bear 4.57 L sec^{-1}) (Figure 9). Based on data collected at 3-hour intervals from May 2003 to December 2005, streamflow ranged from 0 L sec^{-1} to as much as 150 L sec^{-1}.

Figure 10 shows the time series based on data collected at 3-hour intervals for the period of time for air and soil temperature reported here. This time series shows that discharge peaks occur regularly throughout the year, and that there is a relatively good agreement between streams in their hydrologic behavior. Both streams showed a clear pattern of high flow during the spring and fall, with the lowest flow (commonly zero) during the summer. This reflects the importance of evapotranspiration in the hydrology of the ecosystem during the height of the growing season. Figure 11 shows East Bear precipitation event depths and streamflow. Close inspection shows a slight lag between precipitation and streamflow that varies by season.

Table 4. Descriptive statistics for annual streamflow (L sec^{-1}) and specific discharge (mm day^{-1}) at BBWM (1988 to 2005).

	Mean	SE	Median	Min	Max	Range	n
Streamflow							
East Bear	3.16	0.23	3.10	1.29	5.23	3.93	18
West Bear	3.09	0.20	3.03	1.22	4.57	3.35	18
Specific discharge							
East Bear	2.48	0.18	2.43	1.01	4.11	3.09	18
West Bear	2.59	0.17	2.54	1.02	3.83	2.81	18

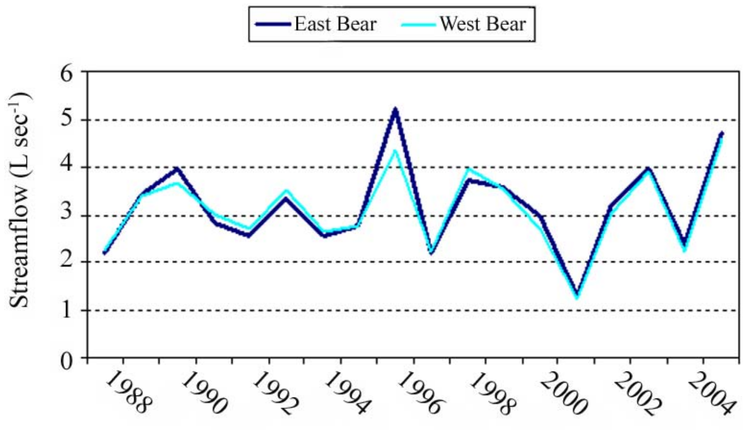

Figure 9. Annual streamflow time series by watershed.

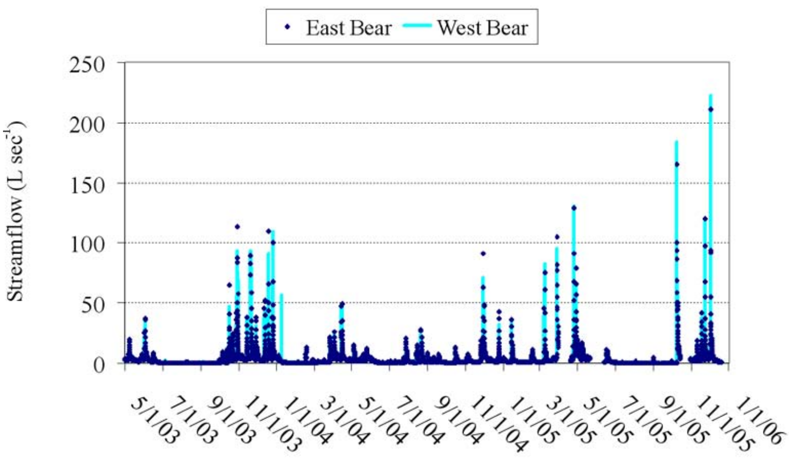

Figure 10. Time series for streamflow at BBWM.

Figure 12 and 13 focus on the spring and fall when transitions between senescence and active canopy evapotranspirtation alter hydrological linkages in the watershed. Figure 12a shows the details of the hydrologic linkage between precipitation events and streamflow in East Bear in the spring of 2004, with precipitation events resulting in a peak in streamflow in April that disappears after the beginning of June. This reflects (a) the soils having had the time to drain spring snowmelt, and (b) having a significant component of the hydrologic flux from the watershed being loss through tran-

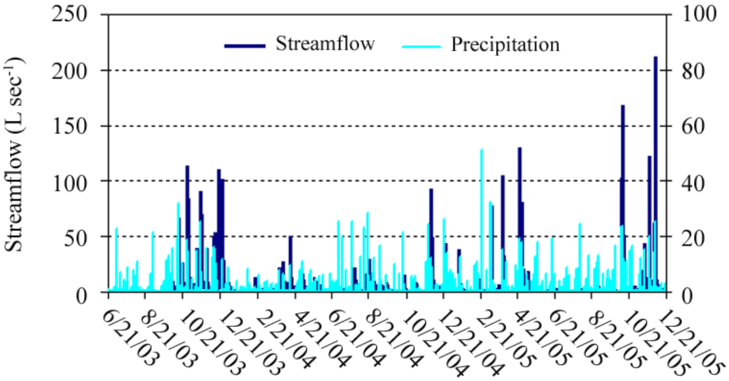

Figure 11. Precipitation events and streamflow at East Bear Brook.

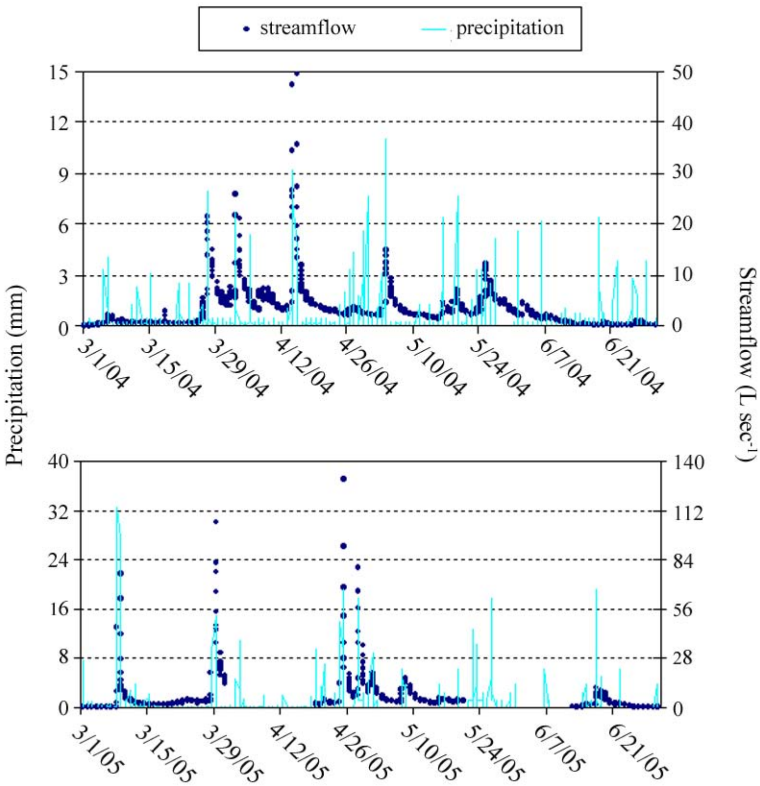

Figure 12. Precipitation events and streamflow at East Bear Brook during spring and summer (2004, 2005).

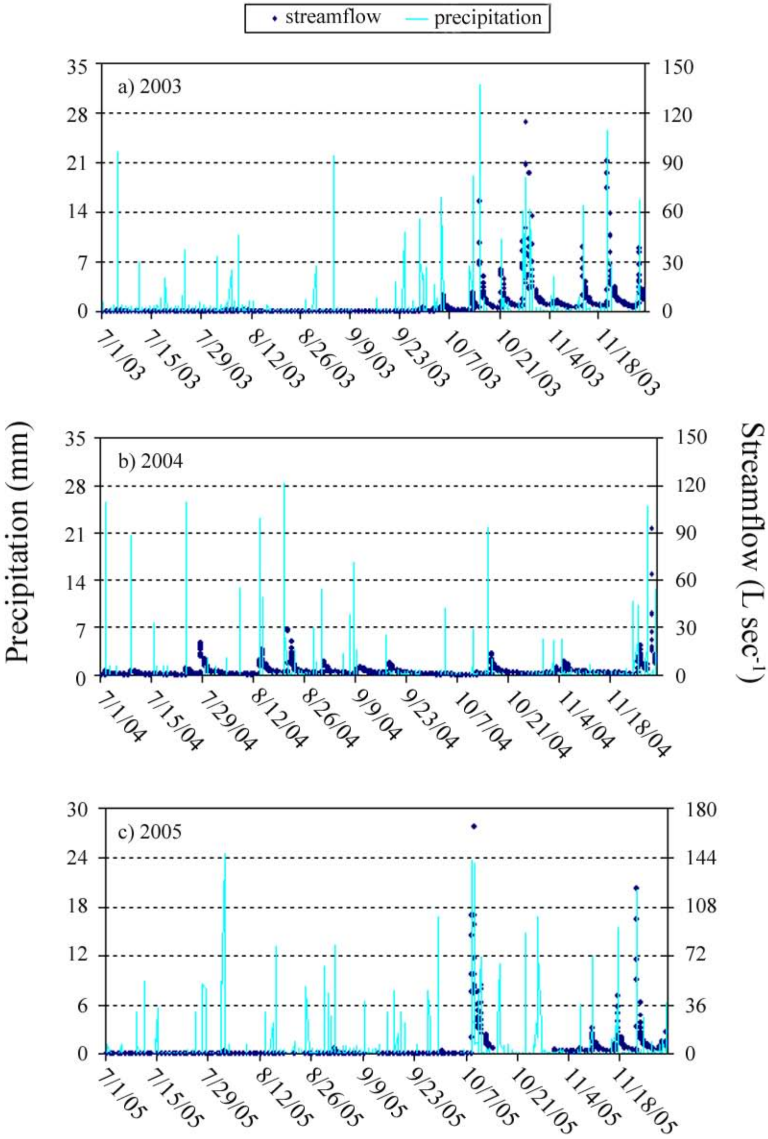

Figure 13. Precipitation events and streamflow at East Bear Brook during summer and fall (2003–2005).

spiration as water vapor from the forest canopy. A similar effect was evident in spring 2005 (Figure 12b), with each year showing its unique pattern of precipitation and streamflow events.

A similar mechanism operates in the hardwoods in the fall, as a result of senescence along with cooler temperatures. The fall transition results in the rapid cessation of transpirational losses, thereby re-establishing a more proportional linkage between precipitation and streamflow events. Figure 13a–c shows the time series for three years of data for East Bear. In all years, July and August appear to be a period of high transpirational demand by vegetation exposed to limited precipitation, low soil moisture, and higher temperatures. In the fall, senescence and leaf fall along with cooler temperatures result in a rapid loss of influence by evapotranspiration, resulting in a more direct and immediate effect of precipitation events on streamflow. Figures 13a and 13c show this effect most dramatically in 2003 and 2005. It appears that 2004 (Figure 13b) may have had a more even distribution of precipitation and the soils were never as dry, which is corroborated by the contrast between relatively even soil moisture in the summer of 2004 (Figure 7) compared to the declining soil moisture in 2005. In 2004, it was not until November that a marked difference in the responsiveness of streamflow to precipitation events was evident. Precipitation data for the period of October 14 to 30, 2004 (Figure 7) are missing.

The ability of precipitation to rapidly influence streamflow during periods of limited evapotranspiration is a reflection of the small size and relatively thin soils of these first-order stream watersheds. In larger watersheds measured in square kilometers with a deep regolith, a massive soil volume exists and takes time to drain and transfer the signal from precipitation or snowmelt events to increased streamflow. In contrast, the small forested watershed streams at BBWM show rapid response to precipitation or snowmelt events. This linkage is buffered by the role of evapotranspiration in forests that divert water into trees and export water vapor to the atmosphere. The ability of forests to transpire is a function of many factors, including temperature, total leaf surface area of the forest canopy, relative humidity, wind, sun exposure, and the availability of water to the roots. The Maine Geological Survey reports that the overall average for Maine is ~50% of precipitation inputs leave the landscape as runoff (i.e., streamflow and rivers) and about 30% to 40% of precipitation inputs leave the landscape by evaporation and transpiration with 10% to 20% groundwater recharge (http://www.maine.gov/doc/nrimc/mgs/explore/water/facts/water.htm). Although Maine is nearly 90% forested, these averages also include agricultural and urban lands that typically have a lower loss of water to

evapotranspiration. On the other hand, there are times that forest canopies increase the precipitation input to forest ecosystems by capturing fog and cloud moisture. Thus, the biological component of forested ecosystems plays a critical role in the characteristics of the hydrologic cycle. Annual hydrologic yield for West Bear ranged from 68% to 77% and East Bear ranged from 62% to 68% for the period 1987 to 1998 (Norton et al. 1999).

It is difficult to determine the relative spatial contributions of different forest components of the watershed to streamflow. During periods of low soil moisture and precipitation, streamflow is largely derived from groundwater moving deeper in soils, referred to as base flow. During precipitation events, particularly during seasons with high soil moisture contents and in shallow soils, upper portions of the soil increasingly contribute to streamflow. The contribution of water to streamflow from softwood, hardwood, or mixed forest types may also change with hydrologic conditions. Although we do not have the data to precisely identify water sources at BBWM, correlations between soil moisture in the major forest types and streamflow suggest hydrologic linkages. Table 5 shows correlation coefficients between soil moisture in hardwoods and softwoods and streamflow by season for the period of soil moisture measurements in this study (summer 2004 through fall 2005). In each season of both years, streamflow was positively and significantly ($P < 0.05$) correlated with soil moisture for softwoods, and the correlation coefficient was higher for softwoods than for hardwoods in all sea-

Table 5. Pearson correlation coefficients for streamflow vs soil moisture of hardwood and softwood stands in the East Bear watershed. P-values are in parenthesis. Means based on n values ranging from 681 to 736.

Season	Soil Moisture Hardwood	 Softwood
Winter '04	n/a	n/a
Winter '05	0.51 (0.07)	0.72 (<0.01)
Spring '04	n/a	n/a
Spring '05	0.59 (0.07)	0.70 (0.03)
Summer '04	0.81 (<0.01)	0.84 (<0.01)
Summer '05	0.44 (0.13)	0.75 (<0.01)
Fall '04	0.20 (0.52)	0.93 (<0.01)
Fall '05	0.62 (0.04)	0.75 (<0.01)

sons. Soil moisture was significantly correlated with streamflow in hardwoods for only two of the six seasons. The correlation between soil moisture in hardwoods and softwoods was highly variable by year and season, ranging from no correlation in spring 2005 to a strong correlation in summer 2004. These correlations are also suggested by the seasonal time series shown in Figure 14. A significant correlation is not evidence of a mechanistic relationship between these variables, but it suggests a parallel behavior that deserves investigation. We can speculate that the shallower soils supporting softwoods in the upper portions of the watershed are likely to “fill up” more easily during precipitation events. When precipitation inputs are enough to increase soil moisture in these shallow soils, it is more common that water input exceeds soil field capacity and drains from this portion of the watershed, contributing significantly to changing discharge. Hardwoods dominate the lower portions of the watershed and generally are on deeper soils. During the growing season when temperatures drive high rates of evapotranspiration, these soils end up drier and the soil moisture decline occurs to a greater depth. During dry periods, water is stored deeper in the soil, perhaps often without significant influences on the uppermost 20 cm of mineral soil where we were measuring soil moisture. The result is that there are periods of time when there is no direct linkage between precipitation events, the upper soil

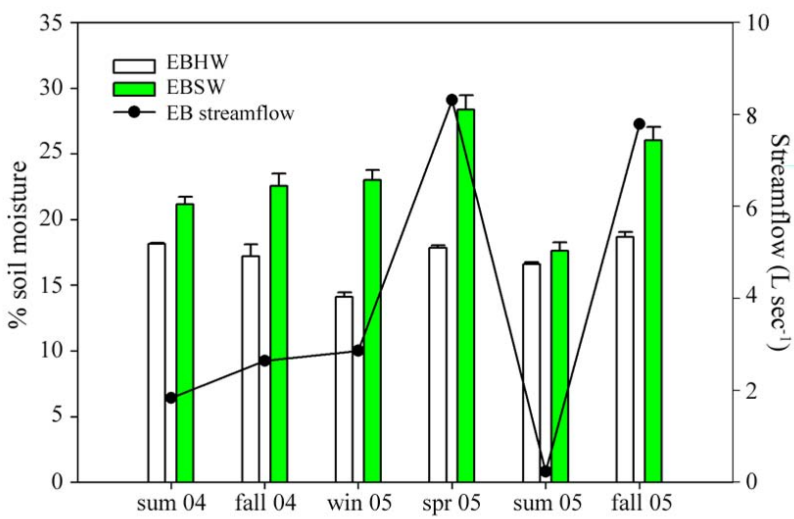

Figure 14. Seasonal plot of soil moisture by forest type and streamflow in East Bear.

moisture content, and streamflow. This was most prevalent during the fall of 2004 and in the relatively dry summer of 2005, when the greatest differences between forest types in their relationship to streamflow occurred.

Integration and Application in a Changing Climate

At BBWM, the program of physical measurements of temperature and moisture in the atmosphere, plants, streams, and soils was established to support ongoing biogeochemical research at the site. These data are critically important for the study of physical, chemical, and biological processes at BBWM and will be increasingly integrated into our science in the future. This becomes even more important in the 21st century as we experience a changing climate that will test our understanding of the relationships between ecosystem function at watershed and landscape scales, and climate. Figure 15 shows the complex interaction among multiple variables that have been discussed earlier.

These types of data are uncommon but essential for comprehensive assessments of forest ecosystem function. For example, studies of watershed response to atmospheric deposition of nitrogen in a warming climate require a mechanistic understanding of the behavior of air and soil temperature, soil moisture, streamflow, and the evolution of these variables over time. This study presents the initial data available from the BBWM program to address these information needs. Future research will build on this framework.

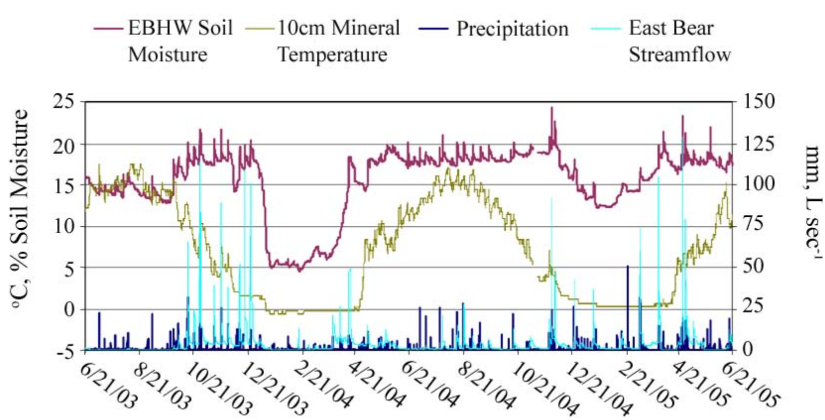

Figure 15. Precipitation, streamflow, soil temperature, and soil moisture at East Bear Brook.

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1865 THE UNIVERSITY OF MAINE

Maine Agricultural and Forest Experiment Station
5782 Winslow Hall
Orono ME 04469-5782

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A member of the University of Maine System