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Long-Term Monitoring Sites and Trends at the Marcell Experimental Forest

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Introduction

Scoping for the Marcell Experimental Forest (MEF) site began in the 1959 (Chapter 1) and the MEF was formally established in 1962 to fill a geographic and ecological void in the experimental forest network of the U.S. Department of Agriculture (USDA) Forest Service (Bay 1962). Six research watersheds were designated and instrumented during the 1960s to study the ecology and hydrology of lowland watersheds with uplands that drain to peatlands. The hydrological and meteorological measurements at these six research watersheds form a core of long-term data on air temperature, precipitation, streamflow, groundwater levels, and water chemistry. New instruments and measurements have been added incrementally to expand baseline monitoring and broaden research themes beyond the original scope of hydrological research. The MEF is one of few long-term research programs on the hydrology and ecology of undrained peatlands in boreal forests. No other site in the Experimental Forest and Range Network of the Forest Service and few sites around the globe have studied the hydrology and biogeochemistry of peatland watersheds with the intensity or longevity as on the MEF. In this chapter, we describe the research sites, report long-term data collected at the MEF, and discuss emerging trends.

Climate

The climate at the MEF is strongly continental with moist warm summers. Winters are dry, cold, and sunny. Air temperatures range from −45°C to +38°C (Figure 2.1). Mean annual temperature since 1961 is 3.4 ± 13.0°C (±1 standard deviation). The monthly mean temperature is 18.9 ± 3.3°C during July and −15.1 ± 8.2°C during January. Lakes begin to freeze in November and are usually ice free by early May.

Mean annual air temperature has increased by 0.4°C per decade (linear regression, $p = 0.0005$) since 1961. Most of the warming occurred during winter months (Figure 2.1). Mean air temperature has increased by 0.7°C per decade during winter months from January to March ($p = 0.0053$) and by 0.3°C per decade during summer months from June to August ($p = 0.0088$).

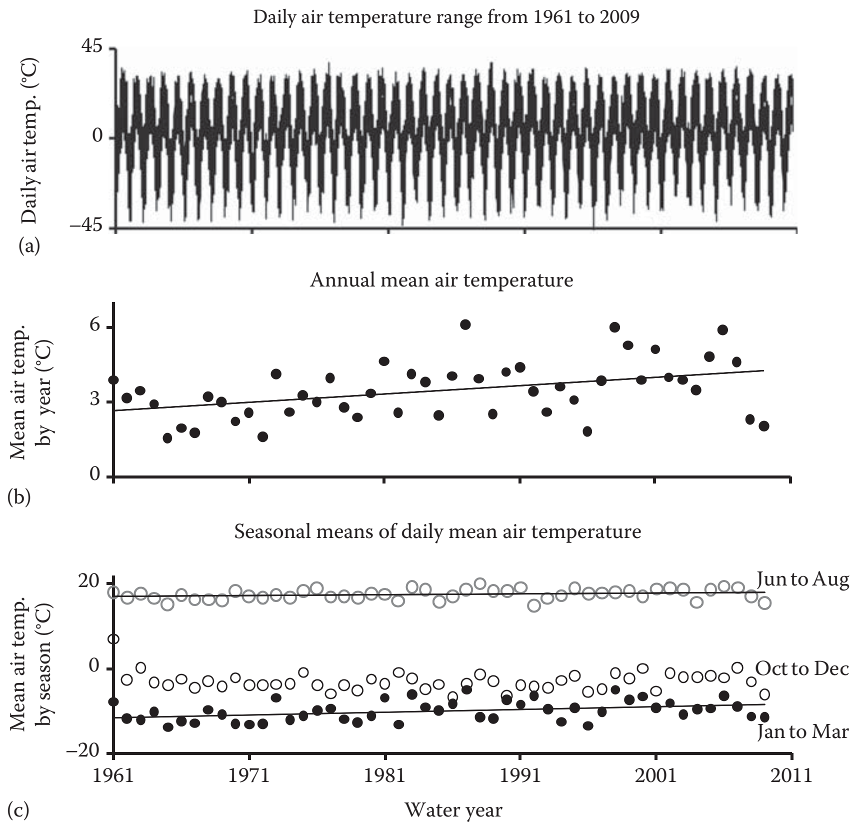

FIGURE 2.1
Daily air temperatures from 1961 to 2009 (a). The mean annual air temperature has increased significantly since 1961 (linear regression, $p << 0.05$) (b). The mean air temperature during the January to March and June to August periods has increased significantly since 1961 while no change occurs for the October to December period (c).

Mean air temperature has not significantly changed during autumn months from October through December.

Annual precipitation averages 78.0 cm (±1 standard deviation of 11.0 cm), ranges from 46.2 to 98.7 cm, and has not significantly changed since 1961 (Figure 2.2a). More precipitation occurs during summer months than winter. For example, mean precipitation is 8.9 cm during August and 2.1 cm during February. About one-third of the precipitation occurs as snowfall. Snow typically begins to accumulate in November or December and melts in late March or April. A mid-winter thaw of several days is common. The maximum annual snow water equivalent under aspen cover has significantly decreased since 1962 ($p = 0.041$) with no change under black spruce cover or in open (treeless) areas (Figure 2.2b). The rate of decline under aspen cover is 1.2 cm per decade.

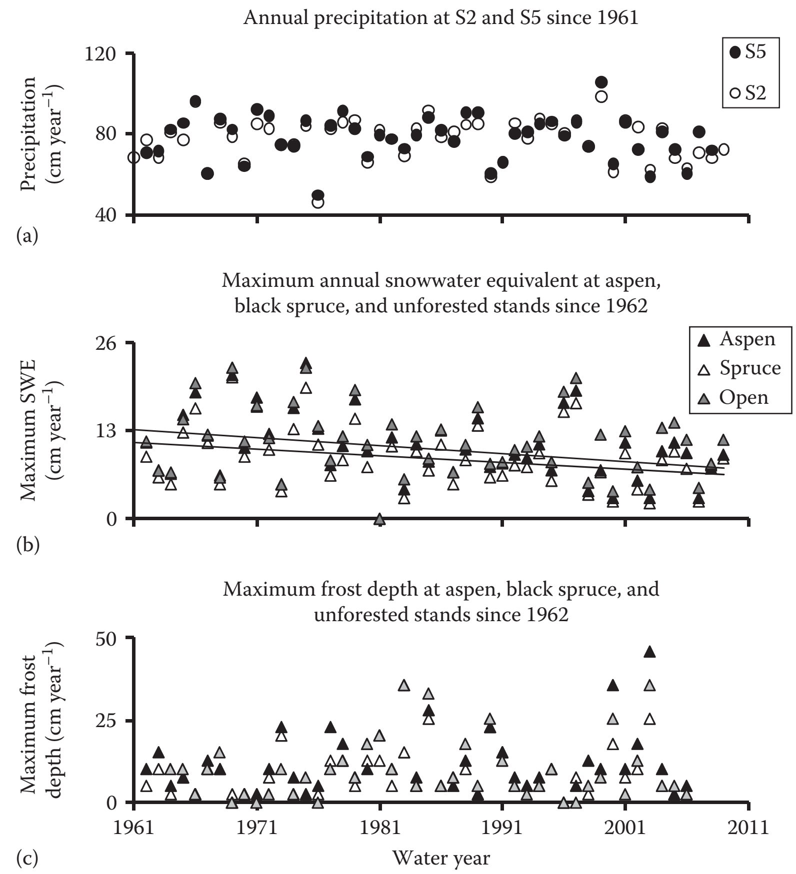

FIGURE 2.2
Annual precipitation during water years has not changed since 1961 (S2) or 1962 (S5) (linear regression, $p > 0.05$) (a). Maximum annual snow water equivalents have decreased under aspen cover since 1961 ($p = 0.041$) with no change under the black spruce canopy in bogs or in the treeless (open grass) site (b). Maximum frost depth under aspen cover, under black spruce cover, and in the grass area has not significantly changed since 1962 (c).

Geographic, Lithological, Geological, and Hydrological Setting

The MEF, which includes uplands, lakes, and wetlands, is spread across two land areas, the North and South Units, situated in the Marcell Hills of north central Minnesota (Chapter 1, Figure 1.1). The MEF was 925 ha at the time of establishment during 1962 (Bay 1962). The size increased to 1141 ha in July

2004 to include land around a new Marcell Research Center headquarters, the Bog Lake fen study area, and other forest plots.

The lakes and peatlands on the MEF formed in ice-block depressions among low-elevation hills that were deposited as glacial moraines and outwash (Wright 1972; Chapter 4). Shallow post-glacial lakes and ice-block depressions slowly filled with organic soils. The peatlands at the MEF include fens, poor fens, and bogs (Gorham 1956, 1990). The organic soils in peatlands are typically less than 3 m deep in glacial lake beds but may exceed 10 m in ice-block depressions. Glacial drifts are 45–55 m thick and form a regional groundwater aquifer above pre-Cambrian Ely greenstone and Canadian Shield granite and gneiss bedrock. The layer directly above the bedrock is 8 m of dense basal till which is overlain by sandy outwash that is up to 35 m thick.

Soils of the MEF were surveyed during autumn 1967 to classify and map soil types (Paulson 1968). Sandy outwash is exposed over one-third of the MEF. These soils include Menahga sands (mixed frigid, Typic Udipsamment), Graycalm loamy sands (isotic, frigid, lamellic Udipsamments), Cutaway loamy sands (fine-loamy, mixed, superactive, frigid oxyaquic Hapludalfs), and Sandwick loamy sands (loamy, mixed, superactive, frigid Arenic Glossaqualf). On the remaining two-thirds of the MEF, the sandy outwash is covered by a clay loam till that contains fragments of limestone and shale and a 10 cm layer of loess. These soils are Warba sandy clay loam (fine-loamy, mixed, superactive, frigid haplic Glossudalfs), Nashwauk sandy loam (fine-loamy, mixed, superactive, frigid oxyaquic Glossudalfs), and Keewatin fine sandy loam (fine-loamy, mixed, superactive, frigid aquic Glossudalfs). Invasive nonnative earthworms have been observed in upland soils throughout the MEF since the 1970s, likely affecting the thickness of the O and A horizons (Hale et al. 2005).

The deep glacial deposits of northern Minnesota form a large regional aquifer. Fens intersect this aquifer and groundwater discharges or laterally flows through the fens. Other peatlands are perched above the aquifer and do not have groundwater inputs from the regional aquifer (Bay 1968, 1969; Verry and Boelter 1975). Clay loams along with a thin layer of glacial flour (silt, very fine sand, and clay) line the peat-filled, ice-block depressions and restrict the vertical flow of water into the underlying sands. Water in such perched peatlands originates solely from precipitation inputs to the perched watershed (Chapters 4 and 7). These wetlands are bogs with surrounding laggs. Hillslopes rise a maximum of 20 m from the nearly flat peatland surfaces to upland summits. However, the bogs are slightly domed to heights about 10–20 cm above the laggs. Water flows to the laggs from both the uplands and raised bogs. On mineral soil hillslopes, the depth to the clay loam soil usually is less than 1 m deep. These clay layers have low hydraulic conductivity and water flows preferentially along lateral pathways in the overlying sandy loams to the peatlands (Timmons et al. 1977; Verry and Timmons 1982; Tracy 1997). See Chapters 4 and 7 for a discussion of flowpath connections among uplands, peatlands, and underlying aquifers.

Atmospheric Deposition

Long-term data collected at the National Atmospheric Deposition Program (NADP) site at the MEF show declines in sulfate wet deposition since 1979 ($p < 0.0001$, Figure 2.3). Total nitrogen in wet deposition at the MEF is in

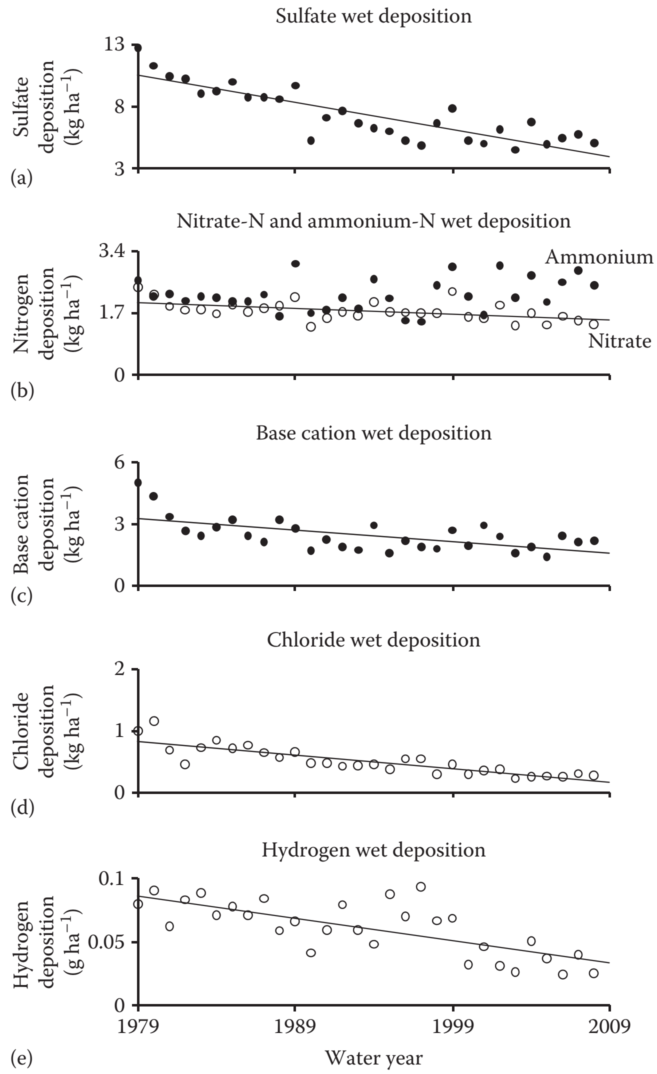

FIGURE 2.3
Wet deposition of sulfate (a), nitrate (b), base cations (c), chloride (d), and hydrogen (e) have decreased (linear regressions, $p < 0.002$) during the decades since 1978.

the same range as that in many forests in the northeastern United States where the effects of nitrogen deposition on ecosystem processes are widely acknowledged (Aber et al. 2003; Driscoll et al. 2003). Ammonium in wet deposition at the MEF has not changed since 1979. Nitrate deposition, which is three- to fourfold larger than ammonium deposition, has decreased since 1979 (Chapter 8). Wet deposition of chloride, base cations (the sum of calcium, magnesium, potassium, and sodium), and hydrogen has decreased since 1979 ($p < 0.0001$). Monson (2009) detected a regional decrease in mercury concentrations in wet deposition during the 1980s and increases from the 1990s to the present. Data from the MEF Mercury Deposition Network (MDN) site were included in that study.

Vegetation and Forest Management

Before European settlement in the late 1800s, white (*Pinus strobus*), red (*Pinus resinosa*), and jack (*Pinus banksiana*) pine were dominant in the overstory canopy, which included mixed northern hardwood species. Today, most forest stands in northern Minnesota are primary successional mixed hardwoods with trembling aspen (*Populus tremuloides*), bigtooth aspen (*Populus grandidentata*), balsam poplar (*Populus balsamifera*), paper birch (*Betula papyrifera*), and balsam fir (*Abies balsamea*). Stands dominated by aspen are prolific on upland soils throughout the region. No remnant virgin pine stands remain on the MEF and most pine stands were planted or regenerated naturally starting during the 1930s (Chapter 12). Red and jack pine grow on sandy upland soils along with mixed stands of aspen, paper birch, balsam fir, white spruce (*Picea glauca*), and red maple (*Acer rubrum*). Basswood (*Tilia americana*), sugar maple (*Acer saccharum*), aspen, and paper birch grow on richer sandy loam tills. A 1968 vegetation survey on the MEF revealed many upland aspen stands that were 50–60 years old (Verry 1969). These stand ages correspond to establishment after large fires during 1915 and 1917 that burned the original logging slash left after clearcutting (Chapters 4 and 12).

Prior to widespread logging of upland forests in the late 1800s and early 1900s, the primary natural disturbances that affected vegetation in northern Minnesota were wildfires, windstorms including tornados, and native insects and diseases. Presettlement fire history of the MEF has not been reconstructed. However, fire was important prior to European settlement as documented by other regional studies (Clark 1990a,b; Heinselman 1999). The effects of past natural disturbance regimes still are evident as many black spruce stands on peatlands are even-aged. This stand structure is suggestive of regeneration after catastrophic disturbance. Blowdown effects are limited to small forest patches. Logging has had a much greater contemporary influence over forest composition and structure than natural disturbance.

At the MEF, upland understory species include mountain maple (*Acer spicatum*), serviceberry (*Amelanchier* spp.), red columbine (*Aquilegia canadensis*), sasparilla (*Aralia nudicaulis*), big-leaved aster (*Aster macrophyllus*), dogwoods (*Cornus stolonifera*, *Cornus rugosa*), hazels (*Corylus cornuta*, *Corylus americana*), veiny pea (*Lathyrus venosus*), bracken fern (*Pteridium aquilinum*), dwarf raspberry (*Rubus pubescens*), largeflower bellwort (*Uvularia grandiflora*), lowbush blueberry (*Vaccinium angustifolium*), and arrowwood (*Viburnum dentatum*).

Peatlands may be forested or open (grass or shrub covered with no forest overstory species). When forested, black spruce (*Picea mariana*), eastern tamarack (*Larix laricina*), and northern white cedar (*Thuja occidentalis*) are common overstory species. In the lagg zones that surround raised-dome bogs, speckled alder (*Alnus incana*) and willow (*Salix* spp.) may grow. The peatland understory has a variety of *Sphagnum* species (including *Sphagnum angustifolium*, *Sphagnum centrale*, *Sphagnum fuscum*, and *Sphagnum magellanicum*), and bog shrubs including bog birch (*Betula pumila*), leatherleaf (*Chamaedaphne calyculata*), Labrador tea (*Ledum groenlandicum*), cotton grass (*Eriophorum angustifolium*), and bog rosemary (*Andromeda glaucophylla*). Other understory species include grass pink orchid (*Calopogon tuberosus*), pink lady's slipper (*Cypripedium acaule*), round-leaved sundew (*Drosera rotundifolia*), horsetail (*Equisetum arvense*), creeping snowberry (*Gaultheria hispidula*), bog laurel (*Kalmia polifolia*), buckbean (*Menyanthes trifoliata*), Schreber's feathermoss (*Pleurozium schreberi*), haircap moss (*Polytrichum* spp.), pitcher plant (*Sarracenia purpurea*), bog cranberry (*Vaccinium oxycoccos*), blueberry (*Vaccinium angustifolium*), blue flag iris (*Iris versicolor*), and three-leaved false Solomon's seal (*Smilacina trifolia*). Flora in open fens and understory species of forested fens include speckled alder (*Alnus rugosa*), lady fern (*Athyrium filix-femina*), marsh marigold (*Caltha palustris*), sedges (*Carix* spp.), bunchberry (*Cornus canadensis*), jewelweed (*Impatiens capensis*), seeded hop sedge (*Carex oligosperma*), rannock rush (*Scheuchzeria palustris*), and cattail (*Typha latifolia*), as well as many bog species.

Aboveground tree and shrub basal area and stem density of upland and wetland species were estimated during a 1968 vegetation survey of the research watersheds (Verry 1969). Simultaneous measurement of both upland and peatland vegetation on all watersheds has not occurred since 1968 and remeasurement is now a priority. Upland vegetation at the S4 watershed was resurveyed during 1971 after harvest, every 2 years from 1972 to 2002, and during 2008. During 2008, vegetation survey plot centers were monumented for the first time. During all previous surveys, data were collected from the same general locations but not from permanent plots. Black spruce seedlings on the S1 bog were counted during August 1971 to assess reproduction after black spruce stripcutting during 1969 (Chapter 12) and recounted during November 1976 after the leave strips were clearcut during 1974 (Verry and Elling 1978). During September 2009, all trees less than 5 m tall with diameters at breast height greater than 2.4 cm were measured on 163 plots measuring 4.9 m^2 along a 20×20 m grid that spanned the entire S1 bog. Aspen biomass on the uplands of the S6 watershed was measured during 1980 and prior to cattle grazing of the watershed during 1981 and 1982. The basal area of red pine and white spruce on the S6 uplands was calculated during 1983 at the time of planting and heights were remeasured during 1987, 1996, and 1999 on 40 plots measuring 40.5 m^2. Beyond the research watershed boundaries, 600 points were surveyed along 20 transects across the entire North and South Units to measure aboveground vegetation during 1992 and 1993 (Chapter 9). These data along with measurements of soil and woody debris were used to estimate carbon storage in the landscape. Aboveground biomass of woody, herbaceous, and *Sphagnum* species was measured between 2001 and 2005 on 16 grid points in a 1 km^2 area of the South Unit that included the S2 watershed (Weishampel et al. 2009).

Instrumentation and Data Collection

Six research watersheds were instrumented in the 1960s (Bay 1962, 1967). Studies at these watersheds were designed to determine effects of forest management practices such as clearcutting of upland, bog, and fen forests as well as the conversion of an upland aspen forest to conifer cover on stream water yields (Chapter 13). Other areas at the MEF are used for short-term, intensive studies and new long-term monitoring sites have been added. At sites such as the S7 peatland ditching experiment (Boelter 1972b, 1972), studies were completed in the 1970s, after which monitoring was discontinued.

Stripchart, Manual, and Electronic Data Recording

Data are recorded from manual field measurements, on paper stripcharts by clock-driven stripchart recorders, and as computer-readable files by electronic dataloggers with time recorded in Central Standard Time. Data are collected and stripcharts are retrieved weekly at soil- and air-temperature stations, precipitation and stream gages, runoff plots, and recording-well sites. Stripchart recorders are cleaned and lubricated and batteries are changed yearly or as needed. Elevations of flume and weir structures as well as water table wells are resurveyed periodically to correct erroneous data that result from frost heaving or settling.

At least 40,000 stripcharts are archived in fireproof safes at the Forestry Sciences Laboratory in Grand Rapids, Minnesota. Stripcharts have not been scanned and the subdaily data have not been digitized except for stream stage and some upland runoff data. The nondigitized hydrological and meteorological data recorded on the stripcharts represent a vast archive of subdaily data that are available for research. As the MEF research budget permits, electronic sensors and data recorders will be obtained to cross-calibrate and eventually replace stripchart recorders.

Meteorological Measurements

A network of three Belfort Universal Recording weighing-type precipitation gages, 17 National Weather Service (NWS) standard 8 in. (20 cm) precipitation gages, and snow courses was setup during the 1960s to quantify water inputs to the research watersheds. Precipitation gages in larger clearings have Alter shields (Alter 1937) and the tops are positioned 1.5 m above the ground. The vegetation around each gage is trimmed as needed to maintain an open forest canopy in any direction extending upward at 45° from the gage orifice. During snow-free months, weekly water levels are measured as the calibrated depth to the closest 0.03 cm of rainfall and the gages are emptied. The gages are charged with antifreeze to melt snow and a thin layer of vegetable oil is added to prevent evaporation during autumn when freezing is first expected, refilled as needed throughout winter, and emptied during spring when temperatures remain above 0°C. When the gage is filled with antifreeze, precipitation is measured weekly with a temperature-compensated spring scale.

Universal weighing bucket gages continuously trace precipitation amounts on stripcharts that are retrieved weekly. Daily precipitation amounts are read from stripcharts in increments of 0.13 cm. At least two standard gages (Brakensiek et al. 1979) are measured in or near each research watershed. These gages are used to weigh precipitation amounts by area for each watershed by the Thiesen polygon method (Brakensiek et al. 1979).

Air temperature is measured at meteorological stations in the uplands and bog at S2 and the uplands at S5. Each station has an NWS louvered shelter (McGuiness et al. 1979) with a Belfort hygrothermograph stripchart recorder, minimum thermometer, maximum thermometer, and Onset HOBO recording digital thermometer. Minimum and maximum temperatures are recorded weekly to verify the continuously recorded air temperature on the hygrothermograph stripcharts. Daily minimum and maximum temperatures are read to the nearest degree Fahrenheit from the stripcharts. Temperatures are converted to degrees Celsius and mean daily air temperatures are calculated by averaging the daily minimum and maximum temperatures. Air temperature, rainfall, and other measurements have been made at automated micrometeorological stations at the Bog Lake fen, the NADP site, and under the aspen canopy in S2 since 2006 or 2007 (Table 2.1).

Snow depth and water equivalent are measured with Mount Rose tubes on snow courses (Figure 2.4) located in each of the dominant forest-cover types (open areas, aspen, aspen-birch, red and jack pine, black spruce, and mixed hardwoods). During the 1960s, measurements were made on as many as 21 snow courses that were distributed among the research watersheds. Measurements were discontinued on many of the courses during the 1970s and two courses were added during 1985. Snow courses under aspen and mixed aspen and birch covers include north, east, south, and west aspect exposures. Each snow course has 10 points with posts for hanging a calibrated weighing

TABLE 2.1

Meteorological Sensors at the Automated Campbell Scientific Meteorological Stations

Measurement	Instrument	Note
Wind speed and direction	RM Young 05103 anemometer	About 2 m above the ground
Photosynthetically active radiation	LI-COR LI190SB PAR sensor	About 2 m above the ground
Air temperature and relative humidity	Vaisala HMP45AC temperature and relative humidity probe	About 1.5 m above the ground
Soil moisture	Campbell Scientific CS616 water content reflectometer	Angled to a 15 cm depth in surficial soil
Surficial soil temperature	Campbell Scientific type-E TCAV soil temperature probe	Vertical in top 5 cm of soil
Rainfall	Texas Instruments TE525WS tipping bucket rain gage	About 1 m above the ground
Snow depth	Campbell Scientific SR50 sonic ranging sensor	S2 site only, about 2 m above the ground
Datalogging	Campbell Scientific CR1000 datalogger	

Note: The stations are located on the South Unit at the Bog Lake fen, the NADP site, and under the forest canopy in the S2 uplands.

FIGURE 2.4
Hydrological technician Art Elling using a Mount Rose snow tube to measure snow depth and water equivalent along the S1 upland snowcourse. The hanging scale is used to weigh the snow tube to determine snow water equivalent. (Photo courtesy of unknown photographer, USDA Forest Service, Grand Rapids, MN.)

scale. Depths in increments of 1.3 cm are measured around each location starting in late February and every 2 weeks thereafter until the snow is gone.

Frost depth is measured at about the time it is maximum, usually in late February. Most sites are measured once during the year except the S2 bog and Junction Fen snow courses where frost depth is measured until peatland ice melts. The frost-depth probe is a Lakes States penetrometer (Stoeckeler and Thames 1958) that was manufactured at a local machine shop from a 1.3-cm-diameter stainless-steel rod with a sharpened and slightly flared point. The bottom 45 cm is marked in intervals of 2.5 cm. The rod is placed on the soil surface and driven through the frozen soil by raising a weight 45 cm and pounding the weight against a smash plate. When the flared point breaks through the frost layer, the rod moves through the soil with less resistance, and frost depth is estimated to the nearest 2.5 cm. If the rod can be pushed into the soil by hand and no frost is encountered deeper, frost depth is recorded as zero. On the rare occasion that frost depth exceeds 45 cm, the depth is recorded as 45 cm.

Maximum snow and frost data are summarized for open areas (i.e., no overstory forest) in uplands and peatlands as well as for upland deciduous, upland conifer (red and jack pine), and bog conifer (black spruce) cover types by averaging data within these five categories. The data are not specific to any one watershed and are representative of the cover types that span the experimental forest.

Streamflow

Streamflow has been measured at as many as seven stream gages. Streamflow currently is measured at five 120° V-notch weirs that replaced earlier H-type flumes or weirs. The V-notch and flume bottoms were set to the elevations of the stream channels that drained bogs. Pools were excavated behind the stream gages and channels were contoured downstream to create a hydraulic drop. Stream gages at the outlets of the S2 and S4 watersheds are downstream from the peatlands. By contrast, stream gages and weir pools at the outlets of the S5 and S6 watersheds are adjacent to the bogs and pooled water backs into the bogs as water levels rise.

Water levels are recorded with a Stevens A35 recorder at the S2 gage and Belfort FW-1 stripchart recorders at the other stream gages. An A35 has a precision of 0.3 cm and an FW-1 has a precision of 0.6 cm. Stage measurements are verified with weekly point-gage measurements (Brakensiek et al. 1979) or a tape measure when spring ice prevents point-gage measurement. Data on stripcharts are stage and time corrected. Archived stripcharts from the S2, S4, S5, and S6 stream gages have been digitized with breakpoint-stage data stored in computer files. Stream discharge is calculated from stage–discharge relationships and daily streamflow is calculated by integrating the hydrograph area.

Insulated wooden shelters with propane heaters are placed over the weirs before the first freeze. If streamflow stops and water levels drop below the V-notch, a heater is turned off to conserve fuel until late spring when the propane lamp is relit to prevent ice formation in the V-notch. Flumes were also enclosed and heated during most winter.

Water Table Elevations

Water table elevations in uplands and peatlands are measured in each of the research watersheds and at Bog Lake fen. Water tables in bogs and fens are recorded at sheltered pools near the center of the peatland (Figure 2.5). Each recording peatland well has a float-driven, Belfort FW-1 stripchart recorder which is placed on a platform that is affixed to three or four galvanized steel posts (Chapter 1). The posts are anchored through peat into mineral soil. Stripcharts are changed weekly. Daily maximum water levels are read from stripcharts, and water levels are reported to the closest 0.3 cm. Recording-well stripcharts have not been digitized. Propane lamp heaters were added to the shelters incrementally between 1990 and 2005 to maintain an unfrozen pool for year-round operation. Before heating, ice was chipped from nearby satellite wells when the recording peatland wells were frozen and daily water levels were extrapolated from water table recession curves.

Non-recording wells made of 3.2-cm-diameter galvanized metal pipe were installed in the uplands and peatlands of most watersheds and monitored for at least several years when ice free. Many of the wells no longer are measured and remain in place. The non-recording wells in the peatlands are anchored in mineral soils beneath the peats (Chapter 1). Upland wells were drilled using mobile drill rigs. Most upland wells penetrate through confining till layers to measure water level in the regional aquifer. The wells terminate in 1.2–1.8 m long sand points. Rudimentary well drilling logs list the drill-hole lithology and well depths. Water table elevations are measured during the first week of every month and are reported relative to mean sea level at a resolution of 0.3 cm. The depth to water table was usually measured with a chalked tape measure. More recently, measurements have been made with an electronic well-depth sounder.

FIGURE 2.5
Hydrological technician Deacon Kyllander changing stripcharts on the FW-1 recorder at the water table well in the S2 bog. The heated shelter covers a small pool of open water and the metal enclosure contains the FW-1 stripchart recorder that is driven by a float, tape, and counterweight system. (South facing photo by A.E. Elling, USDA Forest Service, Grand Rapids, MN.)

Well 305 in the uplands of S3 is a 10-cm-diameter corrugated pipe in which a float and pulley system is used to record water levels. Well 305 is fully penetrating to bedrock and is screened throughout. Water levels are recorded continuously to a resolution of 0.3 cm with a Stevens A71 recorder on Type F stripcharts that are changed every 4 weeks. Daily maximum water levels are reported to the closest 0.3 cm.

Surface and Subsurface Runoff

Surface and subsurface runoff collectors at the S2 and S6 watersheds are based on a USDA Agricultural Research Service (ARS) design (Mutchler 1963). Runoff collectors were measured by the Forest Service for a study initially led by ARS scientists (Timmons et al. 1977). The surface runoff collectors (1.83 m wide and 18–23 m long) are bounded by galvanized sheet metal that is embedded vertically into the surface soil. At the downslope end, a galvanized sheet-metal trough funnels water into a polyvinyl chloride (PVC) pipe that is routed to a holding tank. A 1.82-m-long stainless-steel well point is buried perpendicular to the slope in a trench parallel to the base of the A horizon to capture subsurface runoff above a Bt horizon. Flow from a surface or subsurface collector is routed through a PVC pipe into a 700–800 L polyethylene tank that is enclosed inside a shelter (Figure 2.6). A bottom drain is removed manually to empty the tanks after flow stops, before tanks overflow, or when tanks are overflowing. A tank volume is read from a calibrated staff and recorded when the tanks are drained. Prior to 1982 at S6 and 1981 at S2, the tanks were galvanized metal that was coated with nonreactive paint (Latterell et al. 1974). Water levels in the metal tanks were recorded and total runoff volumes were calculated from stage–volume relationships. During the 1980s, heaters were installed inside the shelters

FIGURE 2.6
The photo of the nearly full tank of the S2S subsurface runoff collector shows the sample collection bucket, floats, counterweights, and water level recorders on March 24, 2009. The surface runoff tank is to the right of the subsurface tank and both are enclosed inside a shelter. The FW-1 stripchart is at the top center and the shaft encoder is near the center. (Photo courtesy of S.D. Sebestyen, USDA Forest Service, Grand Rapids, MN.)

to prevent freezing. Belfort FW-1 stripchart recorders with floats and counterweights have recorded water levels in the S2S and S2N tanks since 1986. Water levels in the S2S tanks have been measured with incremental shaft encoders and recorded every 5 min since April 2008, and since July 2010 at S2N. Each shaft encoder has a resolution of 0.3 cm. Water temperature and specific conductance are measured as runoff water flows through the pipe into the holding tanks.

Verry and Timmons (1982) used recession analysis of the S2 runoff-plot data along with S2 stream water yield to develop equations to separate daily S2 streamflow into bog and upland components. These relationships have been applied to the other research watersheds and estimated daily runoff data are reported on Forest Service (http://nrs.fs.fed.us/ef/marcell/data/) and HydroDB/ClimDB (http://www.fsl.orst.edu/climhy/) websites.

Soil Temperature and Soil Moisture

Temperatures in mineral and organic soils have been measured weekly since 1989 at depths of 5, 10, 20, 30, 40, 50, 100, and 200 cm at a resolution of 0.1°C (Nichols 1998). Temperatures at each depth are read weekly, typically between 10:00 and 13:30 CST, from an Omega handheld model HH-25TC digital type-T thermocouple thermometer. Thermocouples made from insulated type-T (copper/constantan) wire were inserted into holes along a 1.6-cm-diameter wood rod. Rods were inserted into augered holes in mineral soils or holes that were created by inserting and removing an equally wide metal rod in organic soils. Surficial soil (0–5 cm depth) temperatures are measured at the automated meteorological stations at the NADP site, the Bog Lake fen eddy-covariance site, and near the S2 south runoff plots.

Soil water content has been measured in upland mineral soils seasonally since September 1966 by the neutron probe technique (Brakensiek et al. 1979). A Troxler Model 105 Depth Moisture Gage was used until 1990 and a Series 4300 Gage since then. Soil moisture is measured in May before deciduous leaf emergence, in September during autumn leaf fall, and in November when soil water has recharged and soils have not yet frozen. Soil moisture is measured incrementally from 15.2 cm to a maximum of 305.0 cm at intervals of 30.5 cm. The neutron probe access tubes are 3.8-cm-diameter aluminum pipe. The neutron probe is not suitable for measuring soil moisture in the top 15 cm interval. Instead, a soil core is collected and soil moisture is measured gravimetrically. Soil bulk density and soil moisture at 15 bar were measured on soil samples that were collected when the access tubes were installed.

Beginning in 2008 and 2009, volumetric soil water content has been measured along two hillslope transects in S2 using Campbell Scientific CS616 Water Content Reflectometers. Data are recorded every 10 min. The reflectometers and co-located soil-temperature sensors were inserted parallel to the surface slope at the base of a mixed O/A horizon (depth of about 10 cm) and the interface above a Bt horizon (depth of 30–50 cm).

Water Chemistry

Water chemistry samples were first collected during 1964 to measure pH, specific conductance, and calcium concentrations of bog and stream waters at the research watersheds. Samples were collected occasionally during the 1960s and 1970s on a study-by-study basis (Bay 1970; Verry 1975; Timmons et al. 1977) and the number of analytes was expanded to include potassium, magnesium, sodium, phosphorus species, nitrogen species, chloride, sulfate, iron, aluminum, other trace metals, and alkalinity (Verry 1972). By 1969, the chemistry of rain, snow, throughfall, stemflow, upland runoff, soil, ground, stream, and peatland waters had been measured (Verry and Timmons 1977). Routine biweekly sampling of stream or peatland water from fixed locations in some research watersheds began during 1975. Water temperature is measured in the field for each sample and water chemistry is measured on unfiltered water samples. When water is present, peatland water samples are collected by dipping water with a clean ladle from depressions that are lined with 0.1 mm stainless-steel screen. Due to severe droughts and little streamflow at most of the watersheds during 1976 and 1988, few or no samples were collected during those years. At the upland runoff plots, surface and subsurface waters are collected after rainfall or snowmelt events. The runoff samples were dipped from the collection tanks before the 1990s. Water samples are now poured from 5 L stainless-steel pails that are suspended inside the larger polyethylene tanks.

Most samples were analyzed at the Regional Water Quality Lab of the Forest Service at Ely, Minnesota, before 1975; the University of Minnesota Soil Science Laboratory at St. Paul from 1975 to 1995; and the chemistry laboratory of the Forest Service at Grand Rapids from 1995 to the present. Samples from the S2 runoff plots, peatland, and stream were measured at the laboratory of the USDA ARS at Morris, Minnesota, from 1969 to 1973 (Timmons et al. 1977). Water chemistry has been measured with standard methods (APHA 1998). Instruments have been upgraded or replaced and analytical methods have been updated periodically. For example, total nitrogen is now measured colorimetrically by inline digestion and flow injection analysis which supplanted total Kjeldahl nitrogen measurements during 1997. The water chemistry data are currently being compiled from paper records and computer spreadsheets to prepare a comprehensive database of MEF solute concentrations.

Aerial Photographs and LiDAR

Low-altitude oblique aerial photographs of each research watershed have been taken occasionally to document forest cover, forest harvests, and recovery from experimental manipulations. Stereopair vertical aerial photographs from 1959 and 1966 are stored at the Forestry Sciences Laboratory archive at Grand Rapids. An airborne light detection and ranging (LiDAR) survey of ground topography and vegetation height on the South Unit was flown on August 16, 2005 by the Airbone1 Corporation (El Segundo, California). The return data were processed using proprietary techniques and provided to the Forest Service as tiled x, y, z computer files. Mean point density was 0.5 points per square meter.

The MEF Research Sites

The research watersheds were designated as S1, S2, S3, S4, S5, and S6 before differences in peatland types were widely recognized. The "S" before the watershed number corresponds to the "swamp" number. All watershed outlets are accessible by road. Trails through the uplands lead from roads to boardwalks that are used to access stations in the peatlands and minimize disturbance to sensitive wetlands soils and vegetation. When multiple identical instruments are distributed spatially within or among watersheds, the first digit in the site name typically indicates the watershed and the following numbers indicate the order in which the devices were installed. For example, well 201 was the first well installed in watershed 2 and gage 3-1 refers to precipitation gage 1 in watershed 3. In other cases, the letters N, S, E, or W may be added to the name to indicate the cardinal direction of the instrument in relation to the central peatland. For example, S2-E is a soil moisture site to the east of the S2 bog.

Each research watershed has a mineral soil upland and one or more peatlands that range in size from 2.0 to 12.1 ha and cover 12%–33% of the watershed area (Table 2.2). All peatlands have hummock and hollow microtopography (Verry 1984). Water levels are more variable at the S1 bog than the other peatlands. At S1, the water table fluctuates from several centimeters above the peat surface in hollows to a maximum depth of 1.4 m (Figure 2.7). The maximum depth to the water table in the other bog watersheds ranges from 0.7 to 1.0 m. Water tables vary to depths of 0.7 m at the Bog Lake fen and 0.6 m at the S3 fen. Water table elevations in the bogs are more variable than

TABLE 2.2

Areas and Elevations of the Research Watersheds

Watershed	Total Area (ha)	Area of Central Peatland (ha)	Area of Central Peatland (%)	Percent Upland	Outlet Elevation (m)	Maximum Elevation (m)
S1	33.2	8.1	24	76	412	430
S2	9.7	3.2	33	67	420	430
S3	72.0	18.6	23	77	412	429
S4	34.0	8.1	24	76	428	438
S5	52.6	6.1	12	88	422	438
S6	8.9	2.0	23	77	423	435

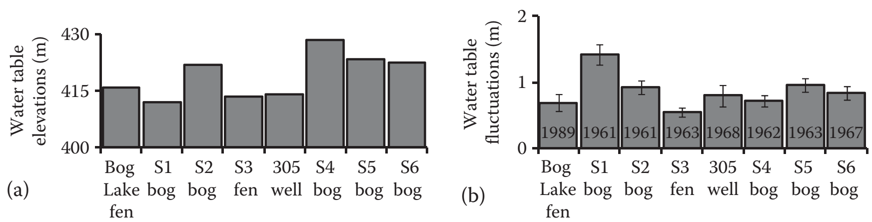

FIGURE 2.7
Mean peatland water table elevations at Bog Lake fen, the research watersheds, and the 305 uplands well (a). The bars show the total fluctuation ranges of the water tables and the error bars show ±1 standard deviation of the mean water elevation (b). The numbers inside the bars indicate the first year of measurements.

in the fens, particularly during droughts and in years that are wetter than normal (Figure 2.8). At the 305 well in the uplands of the S3 watershed, the water table has varied over an interval of 0.8 m since 1967 (Figure 2.7).

Annual precipitation is calculated for water years that begin on November 1 and end on October 31. This period reflects the accumulation of snow that begins in November and does not contribute to streamflow until snowmelt the following spring. Annual water yield via stream runoff is calculated for water years that begin on March 1 and end on the last day of February. The water year reflects the annual hydrologic cycle of Minnesota bog watersheds where intermittent flow begins during spring snowmelt and always stops during winter (Figure 2.9). The stream has flowed at the S2 watershed during every April and May whereas 90% of the Februaries since 1961 have had no streamflow (Figure 2.9b). Streamflow is least likely during February due to freezing air temperatures and the lack of water recharge from the snowpack. Monthly streamflows are highest during April and May in response to melting of the snowpack (Figure 2.9a). Streamflow often stops during summer when rates of evapotranspiration are highest despite the largest monthly inputs of precipitation (Figure 2.9b). About 40% of annual precipitation inputs to the perched watersheds may recharge the regional groundwater aquifer via deep seepage through the clay aquitard (Nichols and Verry 2001). Although annual water yield and streamflow amount during snowmelt have not changed since 1961 (Figure 2.10), snowmelt occurs about 3 weeks earlier in the year. With this change, snowmelt now occurs on average during the third week of April rather than the second week of May (Figure 2.10c).

Daily air temperature and precipitation amount are reported for the South Unit (S2 uplands) and North Unit (S5 uplands) on Forest Service and the HydroDB/ClimbDB websites. Other data reported currently on the websites include daily streamflow, daily peatland water levels, monthly upland water levels, and seasonally-available soil water of upland soils for each of the research watersheds; daily groundwater levels at one site; and maximum annual frost depth, snow depth, and snow water equivalent for hardwood, conifer, and open cover types.

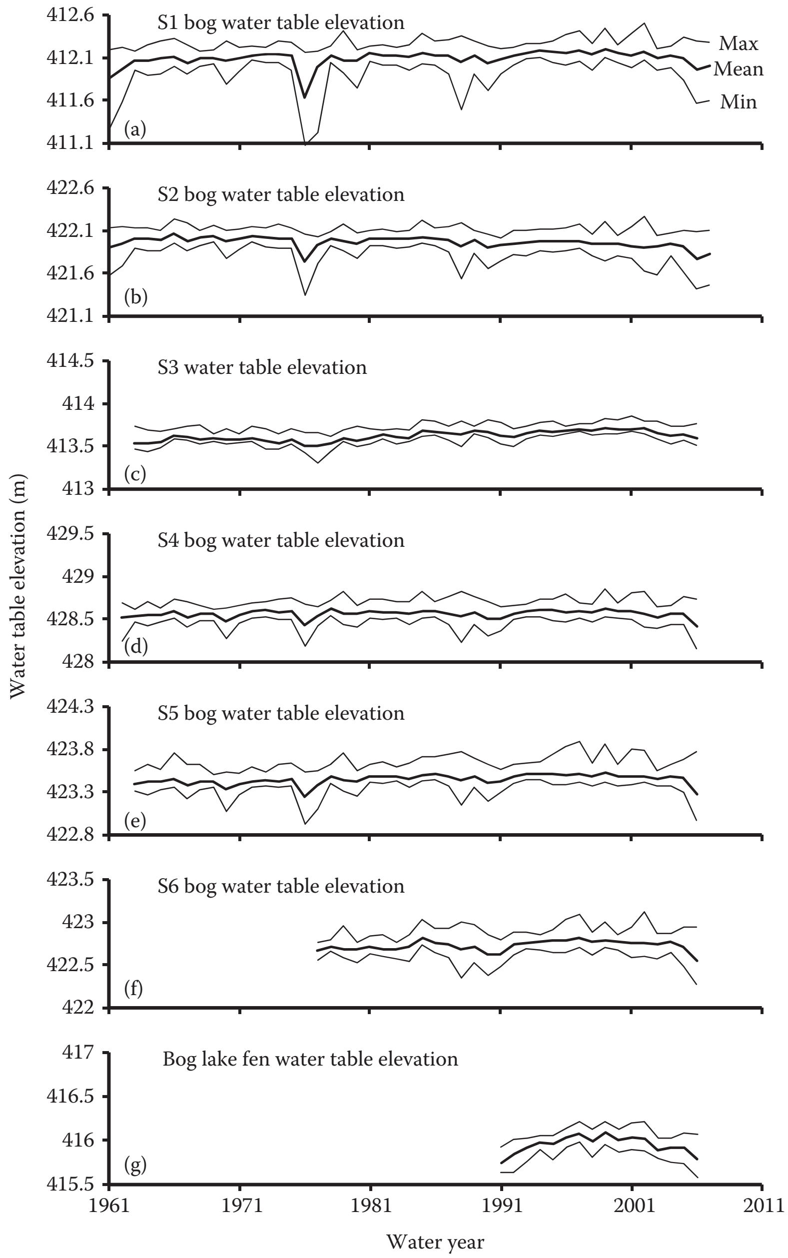

FIGURE 2.8
The mean annual, minimum, and maximum peatland water table elevations at the research watersheds and Bog Lake fen: (a) S1 bog water table elevation; (b) S2 bog water table elevation; (c) S3 bog water table elevation; (d) S4 bog water table elevation; (e) S5 bog water table elevation; (f) S6 bog water table elevation; and (g) Bog Lake fen water table elevation.

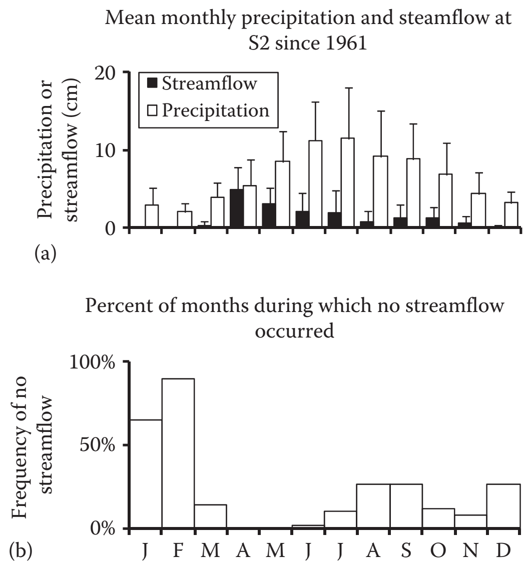

FIGURE 2.9
Mean monthly precipitation and streamflow amounts at the S2 watershed since 1961 (a). The frequency of months during which no streamflow occurs (b). The error bars show ±1 standard deviation.

Soil types and physical properties of mineral (Paulson 1968) and organic (Boelter 1962, 1964a,b, 1965, 1966, 1968, 1969) soils have been described for each research watershed. The chemical properties of peats including carbon, nitrogen, phosphorus, sulfur, calcium, magnesium, sodium, potassium, aluminum, iron, zinc, lead, and mercury content have been measured for various peatlands on the MEF.

S1 Watershed, South Unit

The S1 bog originally was called Cutaway Bog. The instruments, record lengths, and other details for measurements are listed in Table 2.3. The S1 watershed drains to the Prairie River via Cutaway Lake and eventually to the Gulf of Mexico via the Mississippi River. The 8.1 ha peatland is 610 m long, 152 m wide, and surrounded by 25.1 ha of upland hardwood forest (Figure 2.11). The peat fills two adjoining depressions such that the peat is 2–3 m deep near the middle of the bog with deeper pockets to the north and south. The peat is deepest (11 m) near the outlet. The S1 outlet is 412 m above mean sea level and the watershed has a maximum elevation of 430 m above mean sea level. A sand berm separates the S1 bog from an adjacent downgradient bog. Bog water flows through the berm via a stream and lateral subsurface seepage.

The peatland in S1 was used to study the effects of strip clearcutting on black spruce regeneration (Chapter 12), peatland hydrology (Chapters 6 and 13), and harvest effects on micrometeorology (Brown 1972a,b, 1976). During 1969, eight

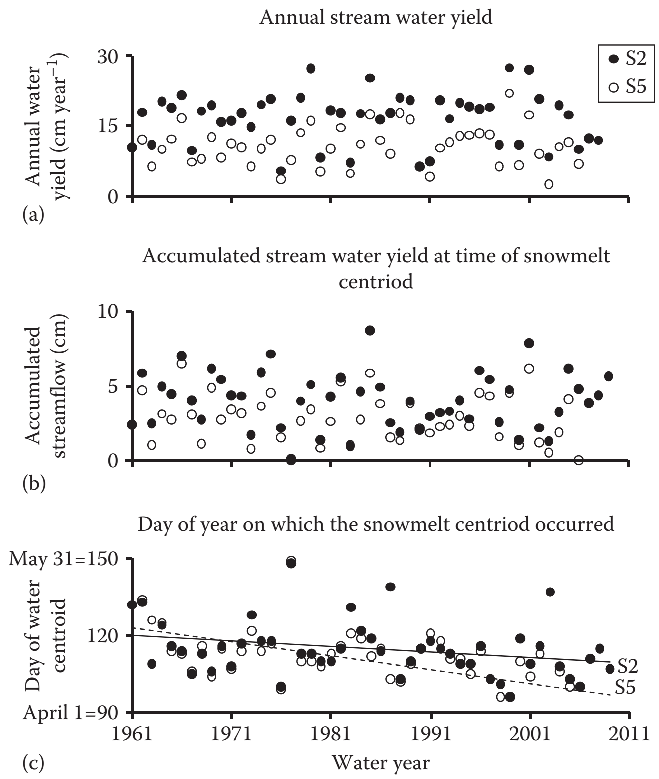

FIGURE 2.10
Annual stream water yield since 1961 (S2) or 1962 (S5) has not changed (linear regression, $p > 0.05$) (a). The accumulated water yield at the centroid of snowmelt has not changed ($p > 0.05$) (b). The day of the snowmelt centroid is about 20 days earlier in the 2000s versus the 1960s at S2 ($p = 0.047$) and S5 ($p = 0.011$) (c). The snowmelt centroid is the day when the accumulated streamflow exceeds 50% of the total flow between the start of snowmelt in March or April and June 1 of any given year, calculated similarly to Hodgkins and Dudley (2006).

33.5 m wide strips were cut and the remaining strips of black spruce were clearcut during 1974. The upland forest had two age classes of mature aspen, 44 and 52 years, with a mean basal area of 22 m^2 ha^{-1} during the 1968 vegetation survey (Verry 1969). Black spruce on the bog also had two age classes, 62 and 73 years. Mean height of black spruce was 12 m, crown closure was 75%, and basal area was 7.0 m^2 ha^{-1} (Verry 1969; Brown 1973). The upland cover has not changed substantially except for aging during the 40 years since the 1968 survey.

Streamflow was measured occasionally at a temporary wooden flume during 1960 and an H-type flume with wood cutoff walls was installed later that year. The cutoff walls heaved during the winter of 1970 and streamflow measurements were curtailed until May 1970 when the walls were again driven into a cemented "ortstein" sand layer. The wood cutoff walls were replaced with interlocking steel piling during October 1974. Ice damage

TABLE 2.3

S1 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Stream stage	S1 flume	0.61 m H-type flume with float driven FW-1 recorder	Daily 9/28/1960 to 12/2/1980	Wood cutoff walls replaced with sheet metal piling during October 1974
Precipitation	1-1	8 in. standard gage	Weekly 1/1/1961 to present	Clearing in black spruce forest
	1-2		Weekly 1/1/1961 to present	Clearing in black spruce forest
	1-3		Weekly 1/1/1961 to present	Clearing in aspen-birch forest
Snow depth, water equivalent, and frost depth	1-1	Mt. Rose snow tube and frost penetrometer	Annually 1962 to 1977	Aspen forest cover
	1-2		Annually 1962 to present	Aspen forest cover
	1-4		Annually 1968 and 1969	Black spruce forest
	1-5		Annually 1962 to 1977	Black spruce forest
	1-7		1972	Black spruce forest
	1-8		1972	Black spruce forest
Bog water table elevation	S1 Bog well a	Float-driven FW-1 recorder	Daily 8/11/1960 to present	In 1969 cut strip, heated since 2004
	S1 Bog well b	Chalked tape measure	Daily 7/25/1969 to 11/15/1972	In uncut strip of black spruce
	Non-recording wells		Occasionally 1961 to 1973	
Upland water table elevations	101	Chalked tape measure or electronic well probe	Monthly 8/21/1962 to present	3.4 m depth
	102		Monthly 8/28/1962 to present	8.3 m depth
	103		Monthly 8/7/1963 to present	18.0 m depth
	104		Monthly 9/17/1963 to 1/15/1973	15.5 m depth
	105		Monthly 11/16/1964 to present	3.9 m depth
	106		Monthly 11/16/1964 to present	5.7 m depth
	107		Monthly 11/16/1964 to 3/7/1967	Depth unknown
Upland soil moisture	S1-N	Neutron probe	Three times a year 9/5/1967 to present	Measured to 3.2 m
	S1-S		Three times a year 9/14/1966 to present	Measured to 3.2 m

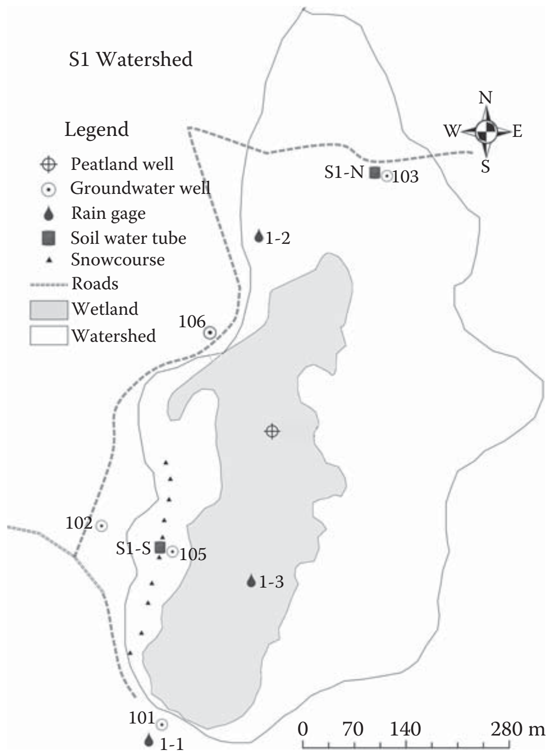

FIGURE 2.11
Map of the S1 watershed showing locations of monitoring equipment.

continued to be a problem for upkeep of the flume until streamflow measurements were discontinued and the flume was removed during December 1980. Mean stream water yield during preharvest water years from 1962 to 1968 was 8.2 ± 4.1 cm (mean ± standard deviation) and the mean ratio of annual stream runoff to annual precipitation was 0.11 ± 0.03. Biweekly sampling of stream water chemistry began during 1989. Samples are collected about 3 m upstream of the defunct flume cutoff walls.

Precipitation amount has been measured with standard gages at one upland and two bog sites since 1961. Peak annual snow depth and snow water equivalent were measured at two upland snow courses under aspen cover and one peatland snow course under black spruce cover from 1962 to 1977. Measurements still are made on one upland course on the western edge of the bog. Additional courses were measured during 1968, 1969, and 1972 to determine how stripcutting affected snow accumulation and melt. Precipitation, throughfall, and stemflow amounts were measured during 1969 and for several years during the early 1970s (Verry 1976; Verry and Timmons 1977) (Figure 2.12).

Water table elevations in the bog have been measured since 1960. After the 1969 stripcut, the original recording well, then in a clearcut area, was

FIGURE 2.12
Research hydrologist Sandy Verry collecting data at the black spruce stemflow plots in the S1 bog during June 1969. (Photo courtesy of R.R. Bay, USDA Forest Service, Grand Rapids, MN.)

augmented from 1969 to 1972 with a second recording well in an adjoining uncut strip. Water levels were recorded several times a year at 10 other non-recording bog wells from 1961 to 1973. Seven upland groundwater wells were installed from 1962 to 1964. Wells 101, 102, 103, 105, and 106 are measured regularly. Soil moisture is measured three times a year by the neutron probe technique near well 103 at site S1-N and near well 105 at site S1-S.

S2 Watershed, South Unit

The many studies of hydrological and biogeochemical processes at the S2 bog make this site one of the most studied peatlands on the planet. The instruments, record lengths, and other details for measurements at the S2 watershed are listed in Table 2.4. The oval-shaped S2 watershed is 9.7 ha (Figure 2.13). The 3.2 ha peatland is 305 m long and 107 m wide. The S2 outlet is 420 m above mean sea level and the watershed has a maximum elevation of 430 m above mean sea level. Mean stream water yield during water years from 1961 to 2009 was 16.7 ± 5.5 cm and the mean ratio of precipitation to stream runoff was 0.21 ± 0.05. The paleoecology and developmental history of the S2 peatland is described in detail in Chapter 4.

The S2 watershed is a control site that has been compared to forest vegetation and atmospheric deposition experiments on the S1, S3, and S6 watersheds. When inventoried during 1968, mean basal area of stands dominated by aspen was 23.2 m^2 ha^{-1} and the stand age was 50 years (Verry 1969).

TABLE 2.4

S2 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Stream stage	S2 weir	120° V-notch weir with float-driven Stevens A35 recorder	Daily 10/17/1960 to present	Concrete cutoff walls, weir replaced and operational on 7/18/1983
Stream-specific conductance and temperature		Campbell Scientific CS547 sensor	Every 5 min 11/20/2007 to present	Behind V-notch weir plate
Precipitation	South upland/2-1RRG 2-1 2-2	Belfort weighing bucket gage with stripchart recorder ETI Instrument Systems NOAH IV Total Precipitation Gage 8 in. standard gage	Daily 1/1/1961 to 9/13/2010 Daily 9/13/2010 to present Weekly 1/1/1961 to present Weekly 1/1/1961 to present	S2 open canopy meteorological station S2 open canopy meteorological station Clearing in aspen forest
Snow depth, water equivalent, and frost depth	2-1 2-2 2-3	Mt. Rose snow tube and frost penetrometer	Annually 1962 to present Annually 1962 to present Annually 1962 to present	Aspen-birch cover Aspen-birch cover Black spruce cover
Air temperature	South/S2 upland S2 bog	Belfort hygrothermograph Min/max thermometers HOBO Pro series temp sensor Belfort hygrothermograph Min/max thermometers HOBO Pro series temp sensor	Daily 1/1/1961 to present Weekly 1/1/1961 to present Every 15 min 7/8/1997 to present Daily 6/22/1989 to present Weekly 6/22/1989 to present Every 15 min 8/27/1999 to present	Inside an NWS shelter at the S2 open canopy meteorological station Under black spruce canopy inside an NWS shelter
Meteorological station	S2 Forest Met	Campbell Scientific meteorological station, see Table 2.1	Every 30 min 11/6/2007 to present	North-facing slope near S2S runoff collectors and soil moisture sites
Evaporation		Class A evaporation pan	Weekly 1963 and 1964	Beneath the black spruce canopy

(*continued*)

TABLE 2.4 (continued)

S2 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Evapotranspiration in bog	Plots 3 and 4 Plots 2-1, 2-2, and 2-3	Bottomless evapotranspirometers 3.0 m in diameter Bottomless evapotranspirometers 0.6 m in diameter	Occasionally 1964 to 1966 Occasionally 1966	Measured during growing season, beneath the black spruce canopy
Net solar radiation		Kipp and Zonen pyranometers	Occasionally 1968 and 1969	Above the black spruce canopy
Bog water table elevation	S2 bog well Non-recording wells	Float-driven FW-1 recorder Chalked tape measure	Daily 7/20/1960 to present Occasionally 1961 to 1973	Heated since 1992
Peat soil temperature		Type-T thermocouple	Weekly 7/18/1989 to present	Depths of 5, 10, 20, 30, 40, 50, 100, and 200 cm
Upland water table elevations	201 202 203 204	Chalked tape measure or electronic well probe	Monthly 8/7/1962 to 1/15/1973 Monthly 8/14/1962 to present Monthly 8/7/1962 to 1/15/1973 Monthly 8/21/1962 to 1/15/1973	11.8 m depth 14.1 m depth 15.1 m depth 14.8 m depth
Upland soil moisture	S2-E S2-S S2-W S2S S2N	Neutron probe Campbell Scientific CS616 water content reflectometers	Three times a year 10/31/1967 to present Three times a year 4/30/1968 to present Three times a year 9/14/1966 to 5/6/1974	Measured to 2.4 m depth Measured to 3.0 m depth Measured to 3.2 m depth Two depths at down-, mid-, and up-hillslope positions

			Every 10 min 11/5/2008 to present	
			Every 10 min 11/12/2009 to present	
Upland soil temperature	S2S	Decagon EC-5 sensors	Every 10 min 8/12/2008 to present	Two depths at down-, mid-, and up-hillslope
	S2S	Campbell Scientific CS-107 soil temperature sensors	Every 10 min 11/5/2008 to present	Co-located with the water content reflectometers
	S2N		Every 10 min 11/12/2009 to present	
Upland runoff	S2N and S2S	Total volumes at surface and subsurface runoff tanks	Event-based 1969 to 1973	Metal tanks
	S2N and S2S	Total volumes at surface and subsurface runoff tanks	Event-based 2/19/1981 to present	Polyethylene tanks
	S2N and S2S	Tank water depths with float-driven FW-1 recorder at surface and subsurface runoff tanks	3/18/1986 to present	Most stripcharts have not been digitized
	S2S	Tank water depths at surface and subsurface runoff tanks with datalogged shaft encoder	Every 5 min 4/25/2008 to present	
	S2N	Tank water depths at surface and subsurface run-off tanks with datalogged shaft encoder	Every 5 min 7/4/2010 to present	
Upland runoff specific conductance and temperature	S2S	Campbell Scientific CS547 sensor	Every 5 min 11/22/2008 to present	
Soil respiration		LI-COR LI-8100 soil respiration chamber	Every 30 min 7/14/2009 to present	

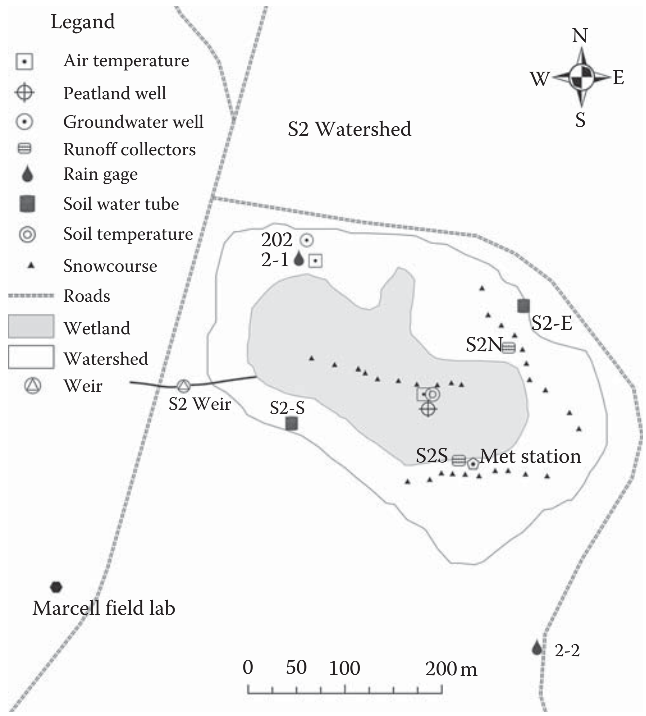

FIGURE 2.13
Map of the S2 watershed showing locations of monitoring equipment.

Mean age of black spruce in the S2 peatland during 1968 was 99 years and basal area was 13.3 m^2 ha^{-1}. The upland and bog forest cover types have not changed substantially except for aging since the 1968 survey.

A 120° V-notch weir was constructed and stripchart recording was implemented during October 1960. The original S2 weir was removed and the current V-notch weir and concrete cutoff walls were completed on July 18, 1983. In addition to streamflow measurements, specific conductance and stream water temperature have been measured since November 2007 with a probe that is suspended behind the V-notch and recorded every 5 min.

A small area of about 0.06 ha within the S2 uplands was clearcut for the South meteorological station where measurements began during 1961. This station includes an NWS shelter with minimum and maximum thermometers and a Belfort hygrothermograph to record air temperature and relative humidity. A temperature sensor has recorded air temperature every 15 min since 1997. Precipitation amount has been measured with a recording weighing bucket gage and a standard gage (site 2-1) since January 1961 at the South station. Weekly precipitation also is measured with a second standard gage (site 2-2) that is southeast of the S2 watershed. Snow depth, snow water equivalent, and frost depth are measured along a snow course transect that

FIGURE 2.14
Hydrological technician Clarence Hawkinson measuring water levels in the S2 evaporation pan during August 1963. (Photo courtesy of D.H. Boelter, USDA Forest Service, Grand Rapids, MN.)

extends from east to west across most of the bog. Similar measurements are made at upland snow courses on north- and south-facing hillslopes.

Air temperature, relative humidity, snow depth, volumetric soil-water content, rainfall, wind speed, wind direction, and forest-floor soil temperature have been measured every 30 min since November 2007 at a north-facing slope under the aspen canopy. Air temperature also has been measured in the S2 bog under the black spruce canopy with minimum and maximum thermometers since 1989, a Belfort hygrothermograph since 1989, and a HOBO temperature logger since 1999 inside an NWS shelter. Peat temperatures have been measured weekly in organic soils since 1989.

During 1963, two cylinders of galvanized sheet metal (0.9 m tall and 3.0 m in diameter) were inserted into the peat to form bottomless evapotranspirometers (Bay 1966). The top edges were set flush with hummock tops. Water levels were measured weekly inside an observation well to monitor changes in water table elevation from 1963 to 1966. Three additional evapotranspirometers (0.6 m in diameter) were installed and monitored during 1966. An NWS Class A evaporation pan was monitored several times a week during 1963 and 1964 (Figure 2.14). Total and reflected solar radiation were measured with Kipp and Zonen pyranometers that were suspended on a 39.2 m long cableway above the black spruce canopy in S2 (Berglund and Mace 1972). Measurements were made occasionally between August 1968 and August 1969 as instruments cycled back and forth along the cableway that was suspended 13.1 m above the bog surface from two galvanized steel towers.

Water table elevations are reported since July 1960 from a recording bog well site near the high point of the bog dome. Water table elevations were measured several times a year at eight other non-recording bog wells from 1961 to 1973. Four upland groundwater wells were installed during 1962. Water levels have been measured monthly at well 202 on the north side at the South meteorological station since 1962. Other wells to the west (201 near the weir), east (203), and south (204) of the bog were monitored from 1962 to 1972. Paired surface and subsurface runoff collectors were installed on the north and south hillslopes of the S2 bog during 1969 (Timmons et al. 1977). Site S2N is the south-facing runoff plot to the north of the bog and S2S is the north-facing runoff plot south of the bog.

Soil moisture in mineral soils is measured three times a year by the neutron probe technique north (S2-E since 1967) and south (S2-S since 1968) of the bog along the watershed boundaries. Another soil-moisture site, S2-W near the weir, was measured from 1966 to 1975. Long-term measurement of volumetric soil moisture and temperature at down-, mid-, and upslope positions along a north-facing transect began during August 2008. Measurements are recorded every 10 min. Identical measurements at a south-facing transect began during November 2009. These monitoring sites are near each of the upland runoff collectors.

Precipitation, throughfall, and stemflow amount and chemistry were measured during the early 1970s and 1990s at S2 (Verry and Timmons 1977; Kolka et al. 1999). Regular biweekly sampling of stream water began during 1975. Samples are collected at the weir or from a depression in the lagg where the stream coalesces into the stream that flows to the weir. Stormflow samples have been collected at the V-notch with an ISCO automated water sampler since April 2008. Automated sample collection is triggered by threshold changes of stage. A monthly water sample has been collected from well 202 since 1987. Surface and subsurface event water samples from the S2N and S2S runoff collectors were analyzed during 1969, from 1971 to 1973, and since 1981. Higher-frequency runoff samples have been collected with ISCO automated water samplers at S2S since March 2008. Sample collection is triggered as water accumulates in the holding tank. These samples may be collected minutes, hours, or days apart depending on runoff rates. Event sampling of soil water from zero-tension lysimeters began during August 2009 after a year-long equilibration period of the samplers. The soil lysimeters were installed at about 10 cm depths in three soil pits along with soil moisture sensors located near the S2S runoff plots. Lysimeters were installed near the S2N runoff plots during November 2009 and event soil water sampling began during 2010 after equilibration.

Organic soil cores were collected at S2 to study peat physical properties (Boelter 1968; Nichols and Boelter 1984; Grigal et al. 1989), evaporation (Nichols and Brown 1980), paleoecology (Chapter 4), peat accumulation rates (Wieder et al. 1994; Gorham et al. 2003), trace metal accumulation rates (Urban et al. 1987, 1990), cation content (Urban et al. 1995), mineralization rates (Bridgham et al. 1998), phosphorus release rates (Knighton and Stiegler 1981), litter decomposition (Farrish and Grigal 1985), peat decomposition

(Farrish and Grigal 1988), atmospheric deposition of DDT (Rapaport et al. 1985), plant uptake of potassium (Buttleman and Grigal 1985), peatland sulfur transformations (Urban et al. 1989; Novák and Wieder 1992), methane production (Yavitt et al. 1997, 2000, 2005), and anaerobic methane oxidation (Smemo and Yavitt 2007). Continuing a history of chamber-based flux measurements of carbon trace gases at S2 (Harriss et al. 1985; Sebacher et al. 1986; Crill et al. 1988; Dise 1992, 1993), an automated soil respiration chamber was deployed at S2 during 2009 to measure carbon dioxide fluxes from a south-facing upland site every 30 min.

S3 Watershed, South Unit

The S3 watershed is 72.0 ha with an 18.6 ha fen. The fen is 610 m long and is 305 m wide where a lobe juts toward the east (Figure 2.15). Some publications incorrectly refer to the fen as the S3 bog. The instruments, record lengths, and other details for measurements at the S3 watershed are listed in Table 2.5. The S3 outlet elevation is 412 m above mean sea level and the maximum elevation in the watershed is 429 m. The stream draining the S3 fen flows perennially unlike streams in the other MEF research watersheds. Streamflow from S3 drains to Wilson Lake via a series of downgradient peatlands and eventually flows to the Mississippi River.

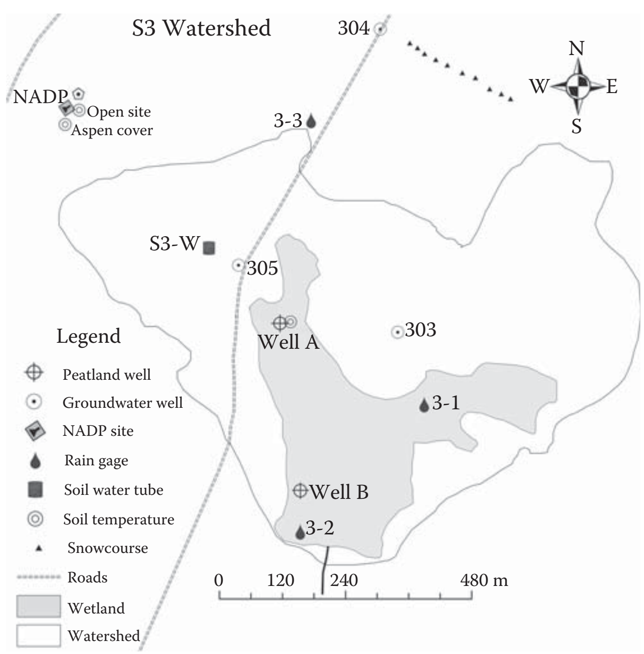

FIGURE 2.15
Map of the S3 watershed showing locations of monitoring equipment.

TABLE 2.5

S3 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Stream stage		Stage measurement with float-driven FW-1 recorder	Daily 8/17/1967 to 11/26/1975	In an open channel during ice-free periods
Precipitation	3-1 3-2 3-3	8 in. standard gage	Weekly 1/1/1961 to present Weekly 1/1/1961 to present Weekly 1/1/1961 to present	Clearing in alder and brush Clearing in black spruce forest Clearing in aspen forest
Snow depth, water equivalent, and frost depth	3-1 3-2 3-3	Mt. Rose snow tube and frost penetrometer	Annually 1962 to 1972 Annually 1962 to 1972 Annually 1962 to 1972	Aspen/jack pine-birch/balsam fir cover Aspen-jack pine/jack pine-birch/birch cover Black spruce cover
Fen water table elevation	S3 fen well A S3 fen well B Non-recording wells	Float-driven FW-1 recorder Chalked tape measure	Daily 9/1/1960 to present Daily 10/26/1966 to 11/28/1967 Occasionally 1961 to 1973	Heated since 1993
Peat soil temperature		Type-T thermocouple	Weekly 12/6/1989 to present	Depths of 5, 10, 20, 30, 40, 50, 100, and 200 cm
Upland water table elevations	301 302 303 304 306 307 308 309 310 311 312 313 305 recording well	Chalked tape measure or electronic well probe Float-driven Stevens A71 recorder	Monthly 8/7/1962 to 1/15/1973 Monthly 8/7/1962 to 1/15/1973 Monthly 10/23/1962 to present Monthly 8/21/1962 to present Monthly 9/1/1967 to 1/21/1971 Monthly 9/22/1967 to 1/21/1971 Monthly 9/22/1967 to 1/21/1971 Monthly 7/14/1968 to 1/21/1971 Monthly 5/27/1969 to 1/21/1971	5.4 m depth 7.3 m depth 16.7 m depth 11.8 m depth 19.8 m depth 5.3 m depth 18.3 m depth 6.2 m depth 5.7 m depth 9.1 m depth 7.1 m depth 13.7 m depth

TABLE 2.5 (continued)

S3 Instrumentation

Measurement	ID	Instrument	Record Period	Note
			Monthly 5/27/1969 to 1/21/1971	
			Monthly 7/11/1969 to 10/2/1970	
			Monthly 8/8/1969 to 10/2/1970	
			Daily 8/23/1967 to present	
Upland soil moisture	S3-E	Neutron probe	Three times a year 9/14/1966 to present	Measured to 3.2 m
	S3-W		Three times a year 9/14/1966 to present	Measured to 2.9 m

The upland forest on the north side was logged during the early 1960s as part of a Chippewa National Forest timber sale that was in progress while the MEF was established. The clearcut area was control-burned on October 4, 1963 and subsequently planted with red pine and white spruce. The remainder of the S3 uplands had aspen and two stands of different-aged jack pine during the 1968 vegetation survey when mean basal area in uplands was 37.6 m^2 ha^{-1} (Verry 1969). Prior to clearcutting on the fen, overstory vegetation in the fen included black spruce with balsam fir, tamarack, bog birch, and northern white cedar. The black spruce trees were 70–100 years old and 15–18 m tall with a basal area of 14.0 m^2 ha^{-1}. The fen was clearcut during the winter of 1972 to 1973 to study black spruce and white cedar regeneration (Chapter 12). Logging slash was scattered and burned on July 13, 1973 on 12 ha (86% of the surface) of the fen. The remaining 6.6 ha were not burned. During March 1974, 400,000 black spruce seeds per hectare were dispersed across the entire fen and 130,000 cedar seeds per hectare were sown in five 6.1-m-wide strips in the burned areas. Today, black spruce, alder, and willow are the most abundant overstory species. Recruitment of white cedar was poor as mortality was nearly 97% between 1974 and 1987 when black spruce and white cedar stocking were inventoried.

Hydrological monitoring began at S3 during 1961 when 10 peatland wells were installed. Peatland well A, the long-term site for peatland water table measurements, was instrumented with an FW-1 stripchart recorder. The other nine fen wells were non-recording and measured occasionally until 1973. Water levels at a second site, well B, were recorded on stripcharts from October 1966 to November 1967. Peat temperatures have been measured weekly near the recording well since December 1989.

Upland well number 302 was drilled in S3 as a part of a demonstration of a Hossfeld Prospecting drill in 1962. Upland wells (301, 303, and 304) were installed along the west and north sides of the fen during 1962 and other wells were drilled from 1967 to 1969. Wells 303 and 304 have been monitored monthly until the present. Other wells were drilled as part of seismic refraction study (Sander 1978; Chapter 4) and monitored for several years to calibrate an electric analog model of hydrology at the S3 fen (Sander 1976). Water levels at well 305 have been recorded on stripcharts since August 1967 and maximum daily water levels are reported. Soil moisture has been measured three times a year to the west of the fen (site S3-W) since 1966. Soil moisture was measured east of the fen (site S3-E) from 1966 to 1970.

Vegetation was cleared along a 30-m-long path downgradient from the S3 outlet. This 3–5-m-wide strip was ditched using dynamite during the summer of 1967 to create a channel in which to measure surface water flow. Plywood cutoff walls were erected to form a stable control area within the ditch. Water velocity and level were measured occasionally to develop a predictive equation for stream water yield using the regression between water stage and discharge. Water level in the ditch was recorded on stripcharts during the ice-free period from 1967 to 1975. Since this calibration period, the stream has not been gaged because beaver repeatedly built dams downstream of S3. The dams elevated water levels in the S3 drainage ditch. A regression between water level at the fen well in the S3 peatland and streamflow has been used to calculate monthly and annual water yields from S3 from 1963 to the present. Mean annual stream runoff at S3 was 6777 ± 3994 cm from 1964 to 2006. This value is the specific discharge relative to the surface delineation of the watershed and is large because groundwater inputs are from an aquifer that extends beyond the delineation of the watershed based on surface topography.

Precipitation inputs have been measured at three rain standard gages since 1961. Gage 3-1 is in the fen in the southeast lobe, 3-2 is in the fen near the watershed outlet, and 3-3 is off Wilderness Lake Road beyond the northern watershed boundary. Snow depth, snow water equivalent, and frost depth were measured from 1962 to 1972 along a snow course that extended across the fen and two upland courses alongside the fen. Snow depth, snow water equivalent, and frost depth have been measured since 1985 in a red pine stand that is north of the S3 watershed.

Routine stream water samples were collected biweekly from 1975 to 1987 and from 1994 to the present. Samples are dipped with a ladle from the slowly flowing water where several stream channels coalesce into the S3 outlet stream.

S4 Watershed, North Unit

The S4 watershed is 34.0 ha and has a maximum elevation of 438 m above mean sea level. An 8.1 ha diamond-shaped peatland (Figure 2.16) has a black

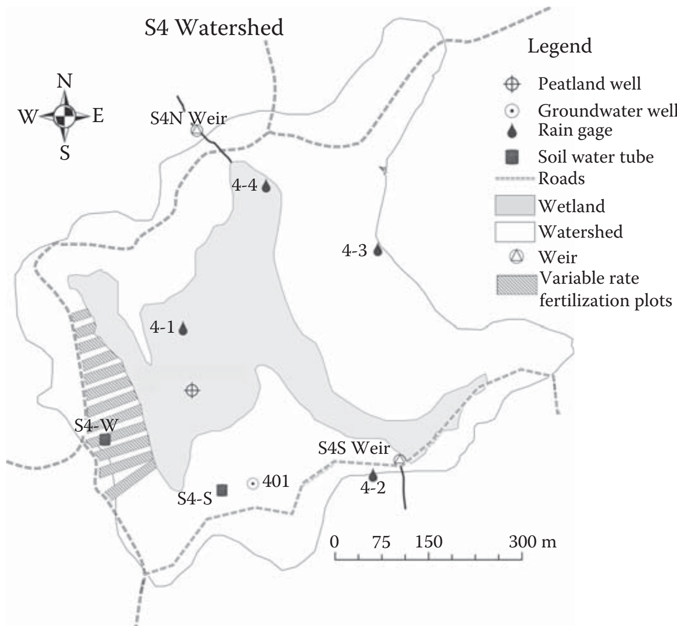

FIGURE 2.16
Map of the S4 watershed showing locations of monitoring equipment.

spruce forest that surrounds a 0.4 ha open bog and a small perennial pond (0.02 ha). The pond greatly expands in size during snowmelt. The instruments, record lengths, and other details for measurements are listed in Table 2.6. The S4 watershed has more sections of road within the boundaries than other MEF watersheds. The watershed sits atop the continental divide of the Mississippi and Hudson Bay drainages. Surface water flows from two outlets at 428 m above mean sea level and streamflow is measured at both outlets. About 70% of the stream water flows from the north outlet (stream gage S4N) to the Hudson Bay drainage with the rest flowing through the south outlet (stream gage S4S) to the Mississippi River (Verry 1972). Streamflow from both weirs is added to calculate the stream water yield from the entire S4 watershed. Mean stream water yield was 19.4 ± 5.1 cm year^{-1} and the runoff ratio was 46% ± 9% prior to upland clearcutting which began during 1970.

The 25.9 ha uplands of the S4 watershed were harvested progressively between 1970 and 1972. The upland forest was predominantly a 51-year-old mature aspen stand at the time that clearcutting began. About 2% of the upland forest was a mixed cover of 57-year-old paper birch and aspen. Basal area was 21.8 m^2 ha^{-1} and the S4 upland forest was understocked relative to the other research watersheds at the MEF during the 1968 vegetation survey (Verry 1969). Merchantable timber was removed from the S4 uplands during 1970 and 1972 (Chapter 13). All remaining non-merchantable trees on the

TABLE 2.6

S4 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Stream stage	S4N flume	0.61 m H-type flume with float-driven FW-1 recorder	Daily 3/29/1962 to 5/8/1984	Metal cutoff walls; measurements stopped 5/1984 when water was leaking and resumed when the flume was replaced with the weir
	S4N weir	120° V-notch weir with float driven FW-1 recorder	Daily 11/9/1984 to present	Concrete cutoff walls
	S4S weir	120° V-notch weir with float driven FW-1 recorder	Daily 4/11/1962 to 4/16/65	Metal cutoff walls
	S4S flume	0.45 m H-type flume with float driven FW-1 recorder	Daily 4/16/1965 to 11/1/1980	Concrete cutoff walls
	S4S weir	120° V-notch weir with float-driven FW-1 recorder	Daily 11/3/1980 to present	
Precipitation	4-1	8 in. standard gage	Weekly 1/1/1962 to present	Clearing in black spruce forest
	4-2		Weekly 1/1/1962 to present	Clearing in aspen forest
	4-3		Weekly 1/1/1962 to present	Clearing in aspen forest
	4-4		Weekly 1/1/1962 to present	Clearing in black spruce forest
Snow depth, water equivalent, and frost depth	4-1	Mt. Rose snow tube and frost penetrometer	Annually 1962 to 1972	Aspen cover
	4-2		Annually 1962 to 1972	Aspen cover
	4-3		Annually 1962 to 1972	Black spruce cover/open (treeless)
Bog water table elevation	S4 bog well	Float-driven FW-1 recorder	Daily 11/21/1961 to present	Heated since 2002
	Non-recording wells	Chalked tape measure	Occasionally 1962 to 1973	
Upland water table elevations	401	Chalked tape measure or electronic well probe	Monthly 9/17/1963 to present	16.8 m depth
Upland soil moisture	S4-E	Neutron probe	Three times a year 5/1/1968 to 11/8/1971	Measured to 2.6 m
	S4-S		Three times a year 9/14/1966 to present	Measured to 2.9 m
	S4-W		Three times a year 5/1/1968 to present	Measured to 2.3 m

uplands larger than 8.9 cm in diameter at breast height were cut during the summer of 1972. The black spruce forest on the central peatland of S4 was not harvested. Clearcutting northeast and west of the peatland began during December 1970 and continued through snowmelt in 1971. Half of the upland area, or 34% of the total watershed area, was clearcut before snowmelt in 1971. Cutting resumed the following autumn. When completed during January of 1972, 71% of the total watershed area was clearcut. The regrowing aspen forest was fertilized during 1978 with an ammonium-nitrate fertilizer that was applied by helicopter. Fertilizer was applied at 340 kg ha^{-1} across the uplands except in an area of nearly 3 ha that was reserved to study variable application rates. This study of fertilization at variable rates had 12 blocks in which fertilizer was applied in replicated amounts of 0, 168, 336, and 504 kg ha^{-1} (Berguson and Perala 1988). The fertilized plots were 15.2 m wide and extended west from the peatland upslope to Wilderness Trail Road. The plots were separated by buffers that were 10.0 m wide.

Streamflow at S4N was measured with an H-type flume with cutoff walls made of metal sheet piling from December 1961 to November 1984. The flume was removed and a V-notch weir with concrete cutoff walls was constructed during November 1984. Biweekly sampling of stream water at S4N began during 1975. No samples were collected from 1983 to 1988. Samples are collected upstream of the S4N stream gage and a road crossing to avoid road effects. The stream gage at S4S was built as a V-notch weir with metal cutoff walls. The gage was converted to an H-type flume during 1965. During 1980, the S4S flume was replaced with a V-notch weir with concrete cutoff walls. Routine biweekly water sampling at the S4S weir began in November 2008.

Weekly precipitation inputs have been measured at four standard gages since 1962. One gage is near the bog center, one is along the northeast edge of the peatland, one is on the divide between S4 and S5, and one is west of the S4S weir. Snow depth, snow water equivalent, and frost depth were measured along one snow course in the S4 bog and two courses in the uplands from 1962 to 1972.

Bog water table elevations have been recorded on stripcharts since November 1961. Water table elevations were measured several times a year at four other non-recording bog wells from 1962 to 1973 when ice free. An upland groundwater well, 401, was drilled during May 1963. Monthly measurements began during September 1963. Soil moisture has been measured three times a year at upland sites to the south of the bog (S4-S since 1966) and to the west (S4-W) since 1968. Measurements to the east of the bog (S4-E) were made from 1968 to 1971.

S5 Watershed, North Unit

The S5 watershed drains to the Mississippi River, is 52.6 ha, and is square-shaped. The instruments, record lengths, and other details for measurements are listed in Table 2.7. The outlet elevation is 422 m above mean sea

TABLE 2.7

S5 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Stream stage	S5 flume S5 weir S5 weir	0.76 m wide H-type flume with float-driven FW-1 recorder 120° V-notch weir with float-driven FW-1 recorder 120° V-notch weir with float driven shaft encoder	Daily 3/29/1962 to 5/8/1984 Daily 11/9/1984 to present Every 15 min 4/9/2002 to present	Metal cutoff walls Metal cutoff walls Concrete cutoff walls
Precipitation	North/5-1RRG 5-1 5-2 5-3 4-3	Belfort weighing bucket gage with stripchart recorder 8 in. standard gage	Daily 1/1/1962 to present Weekly 1/1/1962 to present Weekly 1/1/1962 to present Weekly 1/1/1962 to present Weekly 1/1/1962 to present	S5 open-canopy meteorological station S5 open-canopy meteorological station Clearing in aspen forest Clearing in aspen forest Clearing in aspen forest on border with S4
Air temperature	North/S5	Belfort hygrothermograph Min/max thermometers HOBO Pro series temp sensor	Daily 1/1/1962 to present Weekly 1/1/1962 to present Every 15 min 7/8/1997 to present	Inside an NWS shelter at the S5 open-canopy meteorological station
Snow depth, water equivalent, and frost depth	5-1 5-2 5-3 5-4 5-5	Mt. Rose snow tube and frost penetrometer	Annually 1962 to present Annually 1962 to present Annually 1962 to 1974 Annually 1962 to present Annually 1962 to present	Birch-aspen/birch-balsam fir cover Aspen cover Balsam fir/open/cedar/mixed hardwood cover Black spruce cover S5 open-canopy meteorological station
Bog water table elevation	S5 bog well Non-recording wells	Float-driven FW-1 recorder Chalked tape measure	Daily 11/21/1961 to present Occasionally 1962 to 1973	Heated since 2002

TABLE 2.7 (continued)

S5 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Upland water table elevations	501 502	Chalked tape measure or electronic well probe	Monthly 2/13/1963 to present Monthly 2/13/1963 to 1/15/1973	10.3 m depth 13.1 m depth
Upland soil moisture	S5	Neutron probe	Three times a year 9/14/1966 to present	Measured to 2.3 m

level and the watershed has a maximum elevation of 438 m. Upland soils and five small satellite wetlands drain into a 6.1 ha central peatland. The central peatland stretches east to west across most of the watershed and has a lobe that extends toward the southern boundary of the watershed (Figure 2.17). Black ash grows on one of the satellite wetlands and black spruce on the others.

The S5 watershed is similar in size to the S1 and S4 watersheds and is a control site for comparison of experimental manipulations on those two watersheds. During 1968, the S5 uplands had stands of aspen (two age classes), white cedar, white spruce, balsam fir, red and white pine, and mixed hardwoods. Mean basal area was 23.6 m^2 ha^{-1} and mean age was 100 years. Mean stand age was older than other uplands due to a patch of old-growth white cedar (Verry 1969). The stand age of black spruce on the central peatland was 100 years and basal area was 13.3 m^2 ha^{-1}. The upland and bog cover types have not changed substantially except for aging since the 1968 survey.

The North meteorological station is a 0.15 ha clearcut area in the uplands north of the S5 bog. Measurements began during 1961. This station includes an NWS shelter with minimum and maximum thermometers to measure weekly extremes of air temperature and a Belfort hygrothermograph to continuously record air temperature and relative humidity. Air temperature has been recorded every 15 min with a temperature sensor since 1997. Precipitation amount is measured with a weighing bucket gage (site 5-1RG) and a standard gage (site 5-1). Weekly precipitation amount has been measured at two other standard gages since 1962. Gage 5-2 is on the S4 watershed boundary and 5-3 is along the southeast edge of the watershed. Snow depth, snow water equivalents, and frost depth have been measured in the forest opening at the S5 meteorological station since 1962. Snow and frost measurements also have been made along one bog and two other upland snow courses since 1962.

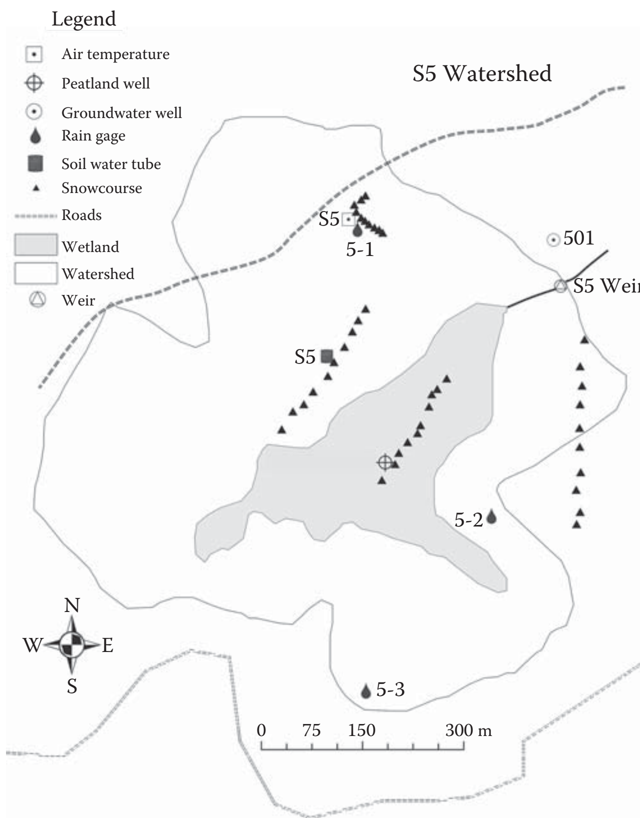

FIGURE 2.17
Map of the S5 watershed showing locations of monitoring equipment.

An H-type flume with metal cutoff walls was installed at the S5 outlet during 1961. The flume was removed and replaced with a V-notch weir with concrete cutoff walls during September 1982. Mean stream water yield from 1962 to 2006 was 11.0 ± 4.1 cm year^{-1}, mean runoff ratio was $14\% \pm 4\%$, and mean annual precipitation was 78.6 ± 11.2 cm year^{-1}. Biweekly sampling of stream water at S5 began during 1975. No samples were collected from 1983 to 1988. Samples are collected upstream of the weir pool.

Bog water table elevations have been recorded on stripcharts since November 1961. Water table elevations were measured several times a year at three other non-recording bog wells from 1961 to 1973 when ice free. Upland well 501 is beyond the eastern border of the watershed near the weir and has been measured monthly since July 1963. Well 502, near precipitation gage 5-2, was measured monthly from 1963 to 1972. Upland soil moisture has been measured three times a year since 1966 by the neutron probe technique at a site north of the S5 bog well.

S6 Watershed, South Unit

The S6 watershed is 8.9 ha with a narrow peatland that is 2.0 ha (Figure 2.18). The instruments, record lengths, and other details for measurements are listed in Table 2.8. The S6 watershed drains via peatlands, Scrapper Lake, and the Prairie River to the Mississippi River. The outlet is 423 m above mean sea level and the watershed has a maximum elevation of 435 m.

During 1980, the upland forest at the S6 watershed was clearcut to study the effects of harvesting and conversion of aspen to conifers (Chapter 13). The watershed was fenced and grazed with cattle from 1980 to 1982 to suppress aspen regeneration, and replanted with white spruce and red pine seedlings during 1983 to convert the uplands cover to conifers (Chapter 12). The herbicide Garlon 4 was sprayed on upland

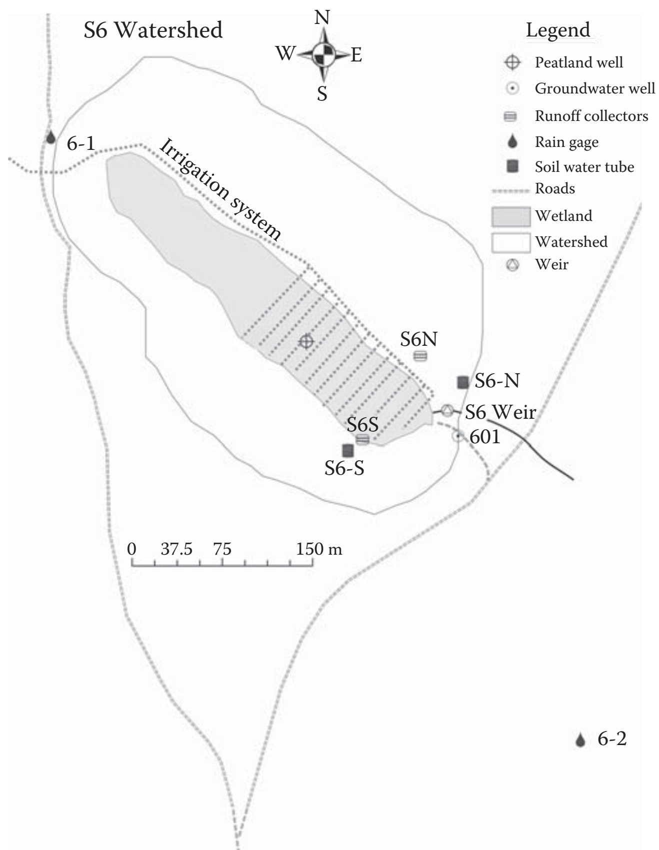

FIGURE 2.18
Map of the S6 watershed showing locations of monitoring equipment.

TABLE 2.8

S6 Instrumentation

Measurement	ID	Instrument	Record Period	Note
Stream stage	S6 flume S6 weir	0.45 m H-type flume with float-driven FW-1 recorder 120° V-notch weir with float-driven FW-1 recorder	Daily 4/9/1964 to 6/5/1974 Daily 3/1/1976 to present	Concrete cutoff walls
Precipitation	6-1 6-2	8 in. standard gage	Weekly 1/1/1964 to present Weekly 1/1/1964 to present	
Snow depth, water equivalent, and frost depth	6-1	Mt. Rose snow tube and frost penetrometer	Annually 1965 to 1969	Black spruce cover
Bog water table elevation	S6 bog well Non-recording wells	Float-driven FW-1 recorder Chalked tape measure	Daily 9/17/1964 to 6/25/1974 and 4/19/1977 to present Occasionally 1968 to 1973	Heated since 2001
Upland water table elevations	601	Chalked tape measure or electronic well probe	Monthly 7/6/1982 to present	
Upland soil moisture	S6-N S6-S	Neutron probe	Three times a year 11/2/1967 to present Three times a year 9/18/1985 to present	Measured to 2.3 m Measured to 3.2 m
Upland runoff	S6N and S6S S6N and S6S	Total volumes at surface and subsurface runoff tanks Total volumes at surface and subsurface runoff tanks	Event-based 4/13/1978 to 9/13/1984 Event-based 10/16/1984 to present	Metal tanks Polyethylene tanks

vegetation on August 3 and 4, 1987 to kill willow, paper birch, and hazel that invaded the site and shaded the shorter conifers. From 2001 to 2008, sulfate was added to the downstream half of the peatland to simulate levels of wet sulfate deposition that occurred during the 1970s prior to sulfur-emission controls (Chapter 11). The study was designed to assess effects of sulfate deposition on methylmercury production in peatlands (Jeremiason et al. 2006).

A metal H-type flume with concrete cutoff walls was constructed during 1963. A crack in the cement wall was found and repaired during autumn 1973. Winter frost heaved the concrete structure during February 1974, creating a crack that was deemed irreparable. The flume was replaced with a V-notch weir and streamflow measurements resumed on March 1, 1976. The weir blade was set 7.6 cm too high, causing water to occasionally back up into the bog until the weir blade height was corrected on July 1, 1977. Water levels were low during the drought of 1976 and the mistake went unnoticed until June 1977, when water levels rose after the drought. Even after correct placement to the depth of the original stream contour, the change from a rectangular to a V shape caused higher water levels that backed into the peatland during high flows. The change in stream gaging structure makes the comparison of post-1976 to pre-1974 data impossible because evaporation and transpiration in the bog are sensitive to water level (Nichols and Brown 1980; Chapter 6). As a result, only 4 years of data from 1976 to 1979 are used to calibrate the watershed. Mean annual runoff was 16 ± 7 cm year^{-1} and mean annual runoff ratio was $20\% \pm 7\%$.

Weekly precipitation inputs have been measured with two standard gages since January 1964. One gage, 6-1, is west of the watershed next to Wilderness Trail Road. The other gage, 6-2, is about 300 m south and east of the S6 weir. Snow depth, snow water equivalent, and frost depth were measured along one snow course under the black spruce and tamarack canopy in the bog from 1962 to 1972.

Bog water table elevations have been recorded on stripcharts since September 1964. Water levels are not reported from July 1974 to April 1977 due to the leaking flume wall and the temporarily incorrect height of the replacement weir notch. The change in stream gaging structure also makes the comparison of post-1977 to pre-1974 water table elevation data impossible. Water table elevations were measured several times a year from 1968 to 1973 at four other non-recording bog wells when ice free.

Paired surface and subsurface runoff collectors were installed on hillslopes to the north (site S6N) and south (site S6S) of the S6 bog during 1978 to measure runoff during snowmelt and storm events. Trees on the runoff plots were hand-felled during the clearcutting to prevent mechanical disturbance of soils on the plots. Well 601 near the eastern border of the watershed has been measured monthly since July 1982. Soil moisture has been measured three times a year by the neutron probe technique at S6-N since 1967 and at S6-S since 1985.

Biweekly sampling of stream water at S6 began during 1978. Samples are collected upstream of the weir pool. Stormflow samples have been collected occasionally with an ISCO automated water sampler since April 2008. Samples from the S6N and S6S runoff collectors have been analyzed since 1979.

Other Study Sites

During other short-duration studies, measurements have been made at research sites beyond the six core research watersheds.

Bog Lake Fen Study Area, South Unit

Bog Lake fen is a poor fen that is about 20 ha (Figure 2.19). The poor fen surface is slightly concave in cross section. The instruments, record lengths, and other details for measurements are listed in Table 2.9. Except for a small area near a pond at the north end with black spruce, Bog Lake fen is an open peatland with sparse tamarack among *Sphagnum* species, sedges, pitcher plant, leather leaf, and bog cranberry. Organic soils are up to 3 m deep where the long-term measurements are made. The primary research activity at the Bog Lake fen is measurement of trace gases. The site also has been used to measure controls on methylmercury production in a series of 40 mesocosms

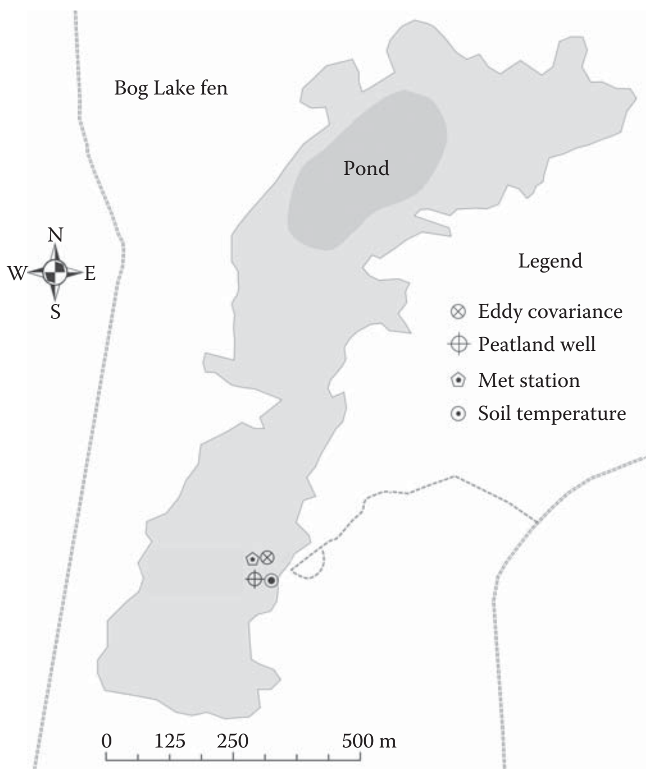

FIGURE 2.19
Map of the Bog Lake fen showing locations of monitoring equipment.

TABLE 2.9

Bog Lake Fen Instrumentation

Measurement	Instrument	Record Period	Note
Water table elevation	Float-driven FW-1 recorder	7/19/90 to present	Heated since 1990
Wind speed and direction	Campbell Scientific CSAT3 3-dimensional sonic anemometer	6/2/06 to present	10 Hz data
CO_2 and H_2O vapor	LI-COR LI-7500 infrared gas analyzer	6/2/06 to present	10 Hz data
Methane	Campbell Scientific trace gas analyzer TGA 100A	4/23/09 to present	10 Hz data
Wind speed and direction, relative humidity, rainfall, PAR, peat temperature, peat soil moisture	Meteorological station, see Table 2.1	6/29/06 to present	Every 30 min
Net radiation	Kipp and Zonen CNR1 net radiometer	6/2/06 to present	
	Radiation and Energy Balance Systems Q7.1 net radiometer	7/10/07 to present	
Peat temperature	Type-T thermocouple	7/18/89 to present	Depths of 5, 10, 20, 30, 40, 50, 100, and 200 cm
Peat heat flux	Hukesflux HFP01SC Heat flux plates	6/2/06 to present	
Soil respiration	LI-COR LI-8100 single long-term soil respiration chamber	2006 and 2007	1 week a month
	LI-COR LI-8100 long-term soil respiration system with four chambers	6/29/06 to present	

(Mitchell et al. 2008; Figure 2.20) and study anaerobic methane oxidation (Smemo and Yavitt 2007).

Bog Lake fen is where the eddy covariance technique was first used to measure peatland methane fluxes during 1990. The system included a tunable diode laser absorption spectrometer and other instruments that are listed in Table 2.10 (Kim and Verma 1992; Verma et al. 1992a,b; Clement et al. 1995). Eddy covariance and chamber measurements of methane fluxes were compared from January 1991 to October 1992 (Verma et al. 1992b; Clement et al. 1995). Vegetation, water level, nitrogen additions, and sulfur additions were evaluated for their impact on methane emissions (Smith 1993). Carbon dioxide fluxes also were measured with chambers on hummocks and hollows to investigate microtopographic effects on gas efflux (Kim and Verma 1992).

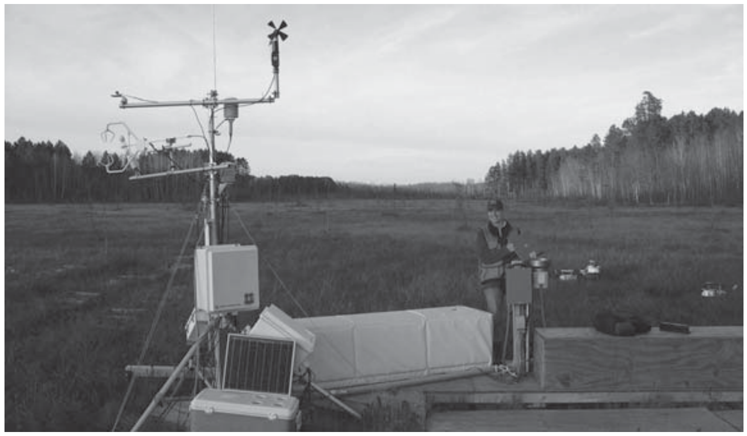

FIGURE 2.20
Hydrological technician Donna Olson maintaining the eddy covariance and meteorological systems at Bog Lake fen during November 2009. Mesocosms for several mercury studies are the square boxes to the left of the eddy covariance and meteorological station. Several soil respiration chambers are to the right of Donna. (North-facing photo by Carrie Dorrance, USDA Forest Service, Grand Rapids, MN.)

TABLE 2.10

Bog Lake Fen Instrumentation to Measure Methane Emissions Using Eddy Covariance, July 1990 and January 1991–October 1992

Measurement	Instrument
Eddy correlation	Campbell Scientific 1-dimensional sonic anemometer and krypton hygrometer, A.I.R. Lyman-alpha hygrometers, Kaijo Denki 3-dimensional sonic anemometers, fine-wire thermocouples
Methane	Fast-response, closed-cell, tunable diode laser absorption spectrometer
Wind speed and direction	Cayuga Development three-cup anemometers
Relative humidity	Vaisala HMP35C aspirated ceramic wick psychrometers
Total solar radiation	Eppley Laboratories PSP pyranometer
Photosynthetically active radiation	LI-COR LI-190SA quantum sensors
Net radiation	Radiation and Energy Balance Systems Q6 net radiometer
Leaf area index	LI-COR LAI-2000 area meter
Peat temperature	Platinum resistance thermometers
	Copper-constantan thermocouples
Peat heat flux	Radiation and Energy Balance Systems HFT-1 heat-flow transducers

Source: Kim, J. and Verma, S.B., *Biogeochemistry*, 18(1), 37, 1992; Verma, S.B. et al., *Boundary-Layer Meteorol.*, 58(3), 289, 1992a; Verma, S.B. et al., *Suo*, 43(4–5), 285, 1992b; Clement, R.J. et al., *J Geophys. Res. D, Atmospheres*, 100(D10), 21047, 1995.

Long-term eddy covariance measurement of water vapor and carbon dioxide fluxes was established at Bog Lake fen during June 2006. Measurements now are taken year round. The system includes an open-path infrared gas analyzer, sonic anemometer, and other meteorological instruments (Table 2.10, Figure 2.20). A trace gas analyzer (Campbell Scientific TGA 100A) was added during April 2009 to quantify methane flux.

Soil respiration from peat at Bog Lake fen was measured every 30 min for 1 week each month during 2006 and 2007 using a LI-COR LI-8100 automated soil respiration chamber. Carbon dioxide flux from the chamber was measured on a *Sphagnum* lawn next to the boardwalk. Since July 2009, soil respiration from a hollow, a hummock, and two areas of *Sphagnum* lawn has been measured with a LI-COR LI-8100 four-chamber automated system.

Peat temperatures have been measured weekly in organic soils since 1989 and every 30 min in organic soils south of the eddy covariance system since September 2006. Daily water table elevations have been recorded on strip-charts at a peatland well since July 1990. Biweekly sampling of surface water began during 1991. Samples are dipped with a ladle from a small pool of open water along the edge of the peatland.

S7 Watershed, South Unit

The S7 peatland was the site of a large-scale drainage experiment that was monitored from 1966 to 1970 (Boelter 1972b). The S7 watershed is 7.0 ha and has an oval-shaped bog that is 2.1 ha. The maximum elevation of 434.5 m is on the divide between S6 and S7. The peat is up to 7 m deep in the bog center (Boelter 1972b). A stream drains S7 on the north border where a sandy berm creates a narrow topographic high that separates the perched S7 bog from a downgradient fen. The outlet was 415.9 m above mean sea level before installation of an H-type flume and control structure with stop gates to manipulate water levels. The wooden structure was not maintained after the S7 study was discontinued during 1970. The structure has decayed, water leaks through the wood cutoff walls, and the elevation of the drainage stream now is below that of the experiment.

The black spruce stand in the S7 bog was 75–80 years old when the S7 experiment began. Black spruce trees were removed from a 135-m-long strip through the center of the bog and a drainage ditch that was 2 m wide and 1.25 m deep was excavated with dynamite. Four transects of wells and piezometers extend perpendicular to the ditch and were measured from 1966 to 1970 (Boelter 1972b). The wells were positioned at 1.25, 2.5, 5.0, 10.0, 20.0, and 50.0 m from the ditch. Nests with piezometers screened at 0.5, 1.0, 1.5, 2.0, and 2.5 m were 5.0 and 10.0 m from the ditch.

The upland deciduous forest was clearcut along the S6 and S7 border during 1980 and planted in red pine and white spruce during 1983. The remaining uplands forest is mixed hardwoods including aspen, birch, and sugar maple. During June 2009, three subsurface runoff collectors were installed on the north-facing hillslope. Each runoff collector is 10.0 m wide and drains to a tipping bucket gage to measure outflow. Trees on the hillslopes above two of the three runoff collectors will be harvested during 2012 to study the effects of harvesting on methylmercury production and transport from hillslopes to peatlands.

S8 Bog, South Unit

The S8 bog has scattered black spruce and tamarack trees near a 1.0 ha study area where water levels were manipulated inside experimental chambers (Boelter 1972a). *Sphagnum* spp., Labrador tea, leatherleaf, cotton grass, and sedges grew inside the tanks. A 1.5-m-deep ditch was excavated through the center of the bog during July 1968 to control drainage from six bottomless 1-m-deep tanks (1.5 × 1.8 m). Each water-level treatment (0.0, 0.3, and 0.6 m below the lowest hollow in each tank) was replicated. Water levels were monitored inside the tanks from 1968 to 1970. The study site has been inactive since 1970.

Junction Fen, South Unit

Junction Fen is an open poor fen in the South Unit. This fen has incorrectly been called a bog in other publications. The peatland has no inlet or outlet streams. Vegetation includes few seeded hop sedge, rannock rush, bog cranberry, and *Sphagnum* spp. (*Sphagnum angustifolium*, *Sphagnum capillifolium*, and *Sphagnum fuscum*). Junction Fen is the site of several short-term studies, for example the measurement of methane emissions (Dise 1992, 1993; Dise et al. 1993; Dise and Verry 2001). Long-term data from Junction Fen include peat temperature since 1989, snow depth and snow water equivalents since 1985, and frost depth since 1985.

National Atmospheric Deposition Program/National Trends Network/Mercury Deposition Network, South Unit

The MEF was designated the first operational site of the NADP on July 7, 1978. The site is a 0.23 ha forest clearing on the South Unit and is closest to the S3 watershed (Figure 2.15). Samples of wet deposition are collected weekly from an Aerochem wet–dry collector. Precipitation amount was measured with a recording weighing bucket gage from 1978 to 2010. Stripcharts were collected weekly and forwarded to the NADP central laboratory in Illinois. A digital ETI Instrument Systems NOAH IV Total Precipitation Gage replaced the weighting bucket gage during March 2010. Total daily precipitation is reported in publications and on the website of the NADP (http://nadp.sws.uiuc.edu/). Weekly precipitation has been measured with a standard precipitation gage since January 1980.

The MEF was a pilot site of the MDN from October 1993 to December 1994, during which collectors and protocols for mercury atmospheric deposition

FIGURE 2.21
Hydrological technician Carrie Dorrance downloading data from the ozone sensor at the NADP site on July 21, 2009. (North facing photo by Josh Prososki, USDA Forest Service, Grand Rapids, MN.)

were evaluated at the NADP site (Vermette et al. 1995). Along with 14 other sites, the MEF was part of a transitional mercury-monitoring network during 1995 that became the MDN in 1996.

Air temperature, relative humidity, snow depth, volumetric soil water content, rainfall, wind speed, wind direction, and soil temperature have been measured every 30 min since 2006 (Table 2.1). Temperatures in mineral soils have been measured weekly since July 1989 under the adjacent aspen canopy and in the open under grass cover. Ozone concentration has been measured every 30 min since June 2009 with a 2B Technologies Model 202 Ozone Monitor (Figure 2.21). Atmospheric deposition of DDT (Rapaport et al. 1985) and lead (Eisenreich et al. 1986) has been measured during short-term studies at the NADP site.

Long-Term Soil Productivity Study Area, South Unit

The MEF was also a pilot site for the Long-Term Soil Productivity (LTSP) project. The LTSP is a study of the effects of soil compaction and forest-floor removal on forest productivity and soil physical and chemical properties (Powers et al. 2005). A contiguous area of 4.9 ha was clearcut during the winter of 1991 and individual treatments were superimposed within the clearcut area (Chapter 12). Two control plots and seven treatment plots form an arc to the east of the NADP site. The harvest area extends partially into the western edge of the S3 uplands. Seven 30 × 40 m plots were prepared during the winter of 1991 to simulate mild and severe effects of harvesting practices on site productivity. Pretreatment measurements were made during the fall of 1990. Posttreatment measurements were made 1, 5, 10, and 15 years after harvesting. Overstory and understory biomass were measured for trees and shrubs on each treatment plot. Soil bulk density and soil strength (with a cone penetrometer) were measured on all plots.

Marcell Field Laboratory, South Unit

The Marcell Field Laboratory was the primary support facility at the MEF from 1963 to 2006 when the Marcell Research Center opened. The one-story building (Figure 2.22) had two bunkrooms, a kitchen, a bathroom, laboratory benches, and storage space. The building was razed during July 2010. The stand-alone garage will be retained for storage.

An NWS Class A evaporation pan (McGuiness et al. 1979) was monitored weekly from 1967 to 1972 along with air temperature at the Marcell Field Laboratory. Measurements were made in an open area to the north between the driveway and the aspen forest. Air temperature was measured inside a louvered weather shelter with a hygrothermograph, minimum thermometer, and maximum thermometer.

An open fen northwest of the Marcell Field Laboratory was the site of several studies. During 1963, two cylinders of galvanized sheet metal were inserted to form bottomless evapotranspirometers that were 3.0 m in diameter (Bay 1966). Water levels were measured weekly inside observation wells from 1963 to 1966. Additional evapotranspirometers were installed and monitored during 1965 (0.6 m in diameter) and 1966 (1.5 m in diameter). Air temperature was measured inside a louvered weather shelter with a hygrothermograph, minimum thermometer, and maximum thermometer. Actual

FIGURE 2.22
The Marcell Field Lab in the early 1960s. (West-facing photo by an unknown photographer, USDA Forest Service, Grand Rapids, MN.)

BOX 2.1 TECHNICAL SUPPORT FOR LONG-TERM MONITORING AT THE MEF

The long-term data collection requires diligence and devotion. Forest Service technicians are responsible for the collection of long-term data, data processing, and instrument maintenance. Hydrological technicians also plow snow and sometimes repair roads. Once each week on Tuesday, two hydrological technicians retrieve stripcharts, make measurements, and collect NADP/MDN samples. Clarence Hawkinson, the first hydrological technician on the MEF project, worked from 1960 until his death in 1974. Art Elling began working at the MEF in September 1969 and retired in January 2005. Richard "Deacon" Kyllander has worked on various projects at the MEF since 1981. With the opening of the Marcell Research Center during 2006, Kyllander became the facility manager and he was the first employee to be stationed at the MEF rather than the Forestry Sciences Laboratory in Grand Rapids. Carrie Dorrance was hired as a hydrological technician during 2005 and he manages the MEF databases. Donna Olson was hired during 2005 to install and maintain the Bog Lake eddy covariance system as well as analyze data.

Other Forest Service employees have played important roles. Bob Barse was a forestry technician for the S1 and S6 harvests. John Elioff has installed, maintained, and measured the Lake States LTSP sites, including the MEF pilot site, since the 1990s. Doris Nelson and Dwight Streblow frequently contributed to data collection during the 1980s and 1990s. Nelson also has assisted chemists Don Nagle, Will Pettit, and John Larson during the analysis of water, soil, and plant-tissue chemistry samples. The facilities managers, Lester Weller, Ramon Sanders, and Eric Troumbly, have maintained the buildings at the MEF, helped with the installation of field instruments, and assisted with weekly measurements as needed. Student workers have been hired during many summers to assist with fieldwork, data collection, and site maintenance.

evaporation was measured with a Class A evaporation pan and rainfall was measured with a standard gage. Solar irradiance was measured with a Belford recording pyrheliometer from July 18 to October 19, 1966. Total and reflected solar radiation were measured with Kipp and Zonen pyranometers that were suspended on a 33.5-m-long cableway 2 m above ericaceous shrubs, sedges, and various *Sphagnum* spp. between August 1968 and August 1969 (Berglund and Mace 1972). The open fen research area was last used for a study of trace gas emissions in which metal chambers were sunk in the peat and enclosed beneath transparent plastic greenhouses to cause warming. The study was not completed.

FIGURE 2.23
The Marcell Research Center on August 7, 2008. (Northeast-facing photo by Stephen Sebestyen, USDA Forest Service, Grand Rapids, MN.)

Marcell Research Center, South Unit

The Marcell Research Center (Figure 2.23), opened in 2006, has a conference room, kitchen and dining area, office for the site manager, and wet chemistry laboratory with deionized water, fume hood, and laboratory benches. An adjacent building has a two-bay garage and heated workshop. Four bunkrooms are available for students and researchers upon request.

References

Aber, J.D., C.L. Goodale, S.V. Ollinger, M.-L. Smith, A.H. Magill, M.E. Martin, R.A. Hallett, and J.L. Stoddard. 2003. Is nitrogen deposition altering the nitrogen status of northeastern forests? *BioScience* 53(4):375–389.

Alter, J.C. 1937. Shielded storage precipitation. *Monthly Weather Review* 66(7):262–265.

APHA 1998. Standard methods of the examination of water and wastewater, 20th edition. American Public Health Association/American Water Works Association Water Environment Federation, Washington, DC.

Bay, R.R. 1962. *Establishment Report, Marcell Experimental Forest (Chippewa National Forest and Adjacent Private, Itasca county, and State of Minnesota Lands)*. Grand Rapids, MN: USDA Forest Service.

Bay, R.R. 1966. Evaluation of an evapotranspirometer for peat bogs. *Water Resources Research* 2(3):437–441.

Bay, R.R. 1967. Techniques of hydrologic research in forested peatlands, USA. In *Proceedings of the XIV IUFRO Congress*. Munich, Germany, September 1967. Section 11, edited, pp. 400–415, IUFRO.

Bay, R.R. 1968. The hydrology of several peat deposits in northern Minnesota, USA. In *Proceedings of the Third International Peat Congress*. Quebec, Canada: National Research Council of Canada, pp. 121–218.

Bay, R.R. 1969. Runoff from small peatland watersheds. *Journal of Hydrology* 9(1):90–102.
Bay, R.R. 1970. Water table relationships on experimental basins containing peat bogs. In *Symposium on the Results of Research on Representative and Experimental Basins. Proceedings of the Wellington Symposium*, December 1970, UNESCO/International Association of Hydrological Sciences, Paris, France, Vol. 96, pp. 360–368.
Berglund, E.R. and A.C. Mace. 1972. Seasonal albedo variation of black spruce and sphagnum-sedge bog cover types. *Journal of Applied Meteorology* 11(5):806–812.
Berguson, W.E. and D.A. Perala. 1988. Aspen fertilization and thinning research results and future potential. In *Minnesota's Timber Supply: Perspectives and Analysis*, eds. A.E. Ek and H.M. Hoganson. Grand Rapids, MN: University of Minnesota, College of Natural Resources and Agricultural Experiment Station, pp. 176–183.
Boelter, D.H. 1962. A study of some physical properties of several peat materials and their relation to field water conditions in the peat bog. PhD dissertation. St. Paul, MN: University of Minnesota.
Boelter, D.H. 1964a. Laboratory techniques for measuring water storage properties of organic soils. *Soil Science Society of America Proceedings* 28(6):823–824.
Boelter, D.H. 1964b. Water storage characteristics of several peats *in situ*. *Soil Science Society of America Proceedings* 33:433–435.
Boelter, D.H. 1965. Hydraulic conductivity of peats. *Soil Science* 100:227–231.
Boelter, D.H. 1966. Hydrologic characteristics of organic soils in Lakes States Watersheds. *Journal of Soil and Water Conservation* 21(2):50–53.
Boelter, D.H. 1968. Important physical properties of peat materials. In *Proceedings of the Third International Peat Congress*. Quebec, Canada: National Research Council of Canada, pp. 150–154.
Boelter, D.H. 1969. Physical properties of peats as related to degree of decomposition. *Soil Science Society of America Proceedings* 33:606–609.
Boelter, D.H. 1972a. Preliminary results of water level control on small plots in a peat bog. In *The Use of Peatland for Agriculture, Horticulture, and Forestry. Fourth International Peat Congress Proceedings*. Ontanienmi, Finland: International Peat Congress, Vol. 3, pp. 347–354.
Boelter, D.H. 1972b. Water table drawdown around an open ditch in organic soils. *Journal of Hydrology* 15(4):329–340.
Brakensiek, D.L., H.B. Osborn, and W.J. Rawls. 1979. Field manual for research in agricultural hydrology. *Agriculture Handbook 224*. Washington, DC: U.S. Department of Agriculture.
Bridgham, S.D., K. Updegraff, and J. Pastor. 1998. Carbon, nitrogen, and phosphorus mineralization in northern wetlands. *Ecology* 79(5):1545–1561.
Brown, J.M. 1972a. Effect of clearcutting a black spruce bog on net radiation. *Forest Science* 18(4):273–277.
Brown, J.M. 1972b. The effect of overstory removal upon surface wind in a black spruce bog. Research note NC-137. St. Paul, MN: USDA Forest Service.
Brown, J.M. 1973. Effect on overstory removal on production of shrubs and sedge in a northern Minnesota bog. *Journal of the Minnesota Academy of Science* 38(2–3):96–97.
Brown, J.M. 1976. Peat temperature regime of a Minnesota bog and the effect of canopy removal. *The Journal of Applied Ecology* 13(1):189–194.
Buttleman, C.G. and D.F. Grigal. 1985. Use of the Rb/K ratio to evaluate potassium nutrition of peatlands. *Oikos* 44(2):253–256.

Clark, J.S. 1990a. Fire and climate change during the last 750 year in northwestern Minnesota. *Ecological Monographs* 60(2):135–159.
Clark, J.S. 1990b. Twentieth-century climate change, fire suppression, and forest production and decomposition in northwestern Minnesota. *Canadian Journal of Forest Research* 20(2):219–232.
Clement, R.J., S.B. Verma, and E.S. Verry. 1995. Relating chamber measurements to eddy correlation measurements of methane flux. *Journal of Geophysical Research, D, Atmospheres* 100(D10):21047–21056.
Crill, P.M., K.B. Bartlett, R.C. Harriss, E. Gorham, E.S. Verry, D.I. Sebacher, L. Madzar, and W. Sanner. 1988. Methane flux from Minnesota peatlands. *Global Biogeochemical Cycles* 2(4):371–384.
Dise, N.B. 1992. Winter fluxes of methane from Minnesota peatlands. *Biogeochemistry* 17(2):71–83.
Dise, N.B. 1993. Methane emission from Minnesota peatlands: spatial and seasonal variability. *Global Biogeochemical Cycles* 7(1):123–142.
Dise, N.B., E. Gorham, and E.S. Verry. 1993. Environmental factors controlling methane emissions from peatlands in northern Minnesota. *Journal of Geophysical Research, D, Atmospheres* 98(D6):10583–10594.
Dise, N.B. and E.S. Verry. 2001. Suppression of peatland methane emission by cumulative sulfate deposition in simulated acid rain. *Biogeochemistry* 53(2):143–160.
Driscoll, C.T., D.R. Whitall, J.D. Aber, E.W. Boyer, M.S. Castro, C.S. Cronan, C.L. Goodale, P.M. Groffman, C.S. Hopkinson, K.F. Lambert, G.B. Lawrence, and S.V. Ollinger. 2003. Nitrogen pollution in the northeastern United States: Sources, effects, and management options. *BioScience* 53(4):357–374.
Eisenreich, S.J., N.A. Metzer, N.R. Urban, and J.A. Robbins. 1986. Response of atmospheric lead to decreased use of lead in gasoline. *Environmental Science and Technology* 20(2):171–174.
Farrish, K.W. and D.F. Grigal. 1985. Mass loss in a forested bog: Relation to hummock and hollow microrelief. *Canadian Journal of Soil Science* 66(2):375–378.
Farrish, K.W. and D.F. Grigal. 1988. Decomposition in an ombrotrophic bog and a minerotrophic fen in Minnesota. *Soil Science* 145(5):353–358.
Gorham, E. 1956. The ionic composition of some bog and fen waters in the English lake district. *Journal of Ecology* 44(1):142–152.
Gorham, E. 1990. Biotic impoverishment in northern peatlands. In *The Earth in Transition: Patterns and Process of Biotic Impoverishment*, ed. G.M. Woodwell. New York: Cambridge University Press, pp. 65–98.
Gorham, E., J.A. Janssens, and P.H. Glaser. 2003. Rates of peat accumulation during the postglacial period in 32 sites from Alaska to Newfoundland, with special emphasis on northern Minnesota. *Canadian Journal of Botany* 81(5):429–438.
Grigal, D.F., S.L. Brovold, W.S. Nord, and L.F. Ohmann. 1989. Bulk density of surface soils and peat in the north central United States. *Canadian Journal of Soil Science* 69(4):895–900.
Hale, C.M., L.E. Frelich, P.B. Reich, and J. Pastor. 2005. Effects of European earthworm invasion on soil characteristics in northern hardwood forests of Minnesota, USA. *Ecosystems* 8(8):911–927.
Harriss, R.C., E. Gorham, D.I. Sebacher, K.B. Bartlett, and P.A. Flebbe. 1985. Methane flux from northern peatlands. *Nature* 315(6021):652–654.
Heinselman, M.L. 1999. *Boundary Waters: Wilderness Ecosystem*. St. Paul, MN: University of Minnesota Press.

Hodgkins, G.A. and R.W. Dudley. 2006. Changes in the timing of winter-spring streamflows in eastern North America, 1913–2002, *Geophys. Res. Lett.*, doi:10.1029/2005GL025593.

Jeremiason, J.D., D.R. Engstrom, E.B. Swain, E.A. Nater, B.M. Johnson, J.E. Almendinger, B.A. Monson, and R.K. Kolka. 2006. Sulfate addition increases methylmercury production in an experimental wetland. *Environmental Science and Technology* 40(12):3800–3806.

Kim, J. and S.B. Verma. 1992. Soil surface CO_2 flux in a Minnesota peatland. *Biogeochemistry* 18(1):37–51.

Knighton, M.D. and J.H. Stiegler. 1981. Phosphorus release following clearcutting of a black spruce fen and a black spruce bog. In *Proceedings of the Sixth International Peat Congress*, August 17–23, 1980, Duluth, MN. Eveleth, MN: W.A. Fisher Company, pp. 577–583.

Kolka, R.K., E.A. Nater, D.F. Grigal, and E.S. Verry. 1999. Atmospheric inputs of mercury and organic carbon into a forested upland/bog watershed. *Water, Air, and Soil Pollution* 113(1):273–294.

Latterell, J.J., D.R. Timmons, R.F. Holt, and E.M. Sherstad. 1974. Sarption of orthophosphate on the surface of water sample containers. *Water Resour. Res.*, 10(4), 865–869.

McGuiness, J.L., W.C. Mills, and P.R. Nixon. 1979. Climate. In *Field Manual for Research in Agricultural Hydrology*, eds. D.L. Brakensiek, H.B. Osborn, and W.J. Rawls. Washington, DC: U.S. Department of Agriculture, pp. 215–237.

Mitchell, C.P.J., B.A. Branfireun, and R.K. Kolka. 2008. Assessing sulfate and carbon controls on net methylmercury production in peatlands: An in situ mesocosm approach. *Applied Geochemistry* 23(3):503–518.

Monson, B.A. 2009. Trend reversal of mercury concentrations in piscivorous fish from Minnesota Lakes. *Environmental Science and Technology* 43(6):1750–1755.

Mutchler, C.K. 1963. *Runoff Plot Design and Installation for Soil Erosion Studies*. Washington, DC: USDA Agricultural Research Service.

Nichols, D.S. 1998. Temperature of upland and peatland soils in a north central Minnesota forest. *Canadian Journal of Soil Science* 78(3):493–509.

Nichols, D.S. and D.H. Boelter. 1984. Fiber size distribution, bulk density, and ash content of peats in Minnesota, Wisconsin, and Michigan. *Soil Science Society of America Journal* 48(6):1320–1328.

Nichols, D.S. and J.M. Brown. 1980. Evaporation from a sphagnum moss surface. *Journal of Hydrology* 48(3–4):289–302.

Nichols, D.S. and E.S. Verry. 2001. Stream flow and ground water recharge from small forested watersheds in north central Minnesota. *Journal of Hydrology* 245(1–4):89–103.

Novák, M. and R.K. Wieder. 1992. Inorganic and organic sulfur profiles in nine Sphagnum peat bogs in the United States and Czechoslovakia. *Water, Air, and Soil Pollution* 65(3):353–369.

Paulson, R.O. 1968. *A Soil Survey of Marcell Experimental Forest*. Grand Rapids, MN: USDA Soil Conservation Service.

Powers, R.F., S.D. Andrew, F.G. Sanchez, R.A. Voldseth, D.S. Page-Dumroese, J.D. Elioff, and D.M. Stone. 2005. The North American long-term soil productivity experiment: Findings from the first decade of research. *Forest Ecology and Management* 220(1–3):31–50.

Rapaport, R.A., N.R. Urban, P.D. Capel, J.E. Baker, B.B. Looney, S.J. Eisenreich, and E. Gorham. 1985. "New" DDT inputs to North America: Atmospheric deposition. *Chemosphere* 14(9):1167–1173.

Sander, J.E. 1976. An electric analog approach to bog hydrology. *Ground Water* 14(1):30–35.

Sander, J.E. 1978. The blind zone in seismic ground-water exploration. *Ground Water* 16(6):394–397.

Sebacher, D.I., R.C. Harriss, K.B. Bartett, S.M. Sebacher, and S.S. Grice. 1986. Atmospheric methane sources: Alaska tundra bogs, an alpine fen, and a subarctic boreal marsh. *Tellus* 38B:1–10.

Smemo, K.A. and J.B. Yavitt. 2007. Evidence for anaerobic CH_4 oxidation in freshwater peatlands. *Geomicrobiology Journal* 24(7):583–597.

Smith, K. 1993. Methane flux of a Minnesota peatland: Spatial and temporal variables and flux prediction from peat temperature and water table elevations. MS thesis. St. Paul, MN: University of Minnesota.

Stoeckeler, J.H. and J.L. Thames. 1958. The lake states penetrometer for measuring depth of soil freezing. *Soil Science* 85(1):47–50.

Timmons, D.R., E.S. Verry, R.E. Burwell, and R.F. Holt. 1977. Nutrient transport in surface runoff and interflow from an aspen-birch forest. *Journal of Environmental Quality* 6(2):188–192.

Tracy, D.R. 1997. Hydrologic linkages between uplands and peatlands. PhD dissertation. St. Paul, MN: University of Minnesota.

Urban, N.R., S.J. Eisenreich, and E. Gorham. 1987. Aluminum, iron, zinc, and lead in bog waters of northeastern North America. *Canadian Journal of Fisheries and Aquatic Sciences* 44:1165–1172.

Urban, N.R., S.J. Eisenreich, and D.F. Grigal. 1989. Sulfur cycling in a forested sphagnum bog in northern Minnesota. *Biogeochemistry* 7(2):81–109.

Urban, N.R., S.J. Eisenreich, D.F. Grigal, and K.T. Schurr. 1990. Mobility and diagenesis of Pb and 210Pb in peat. *Geochimica et Cosmochimica Acta* 54(12):3329–3346.

Urban, N.R., E.S. Verry, and S.J. Eisenreich. 1995. Retention and mobility of cations in a small peatland: Trends and mechanisms. *Water, Air, and Soil Pollution* 79(1–4):201–224.

Verma, S.B., F.G. Ullman, D.P. Billesbach, R.J. Clement, J. Kim, and E.S. Verry. 1992a. Eddy correlation measurements of methane flux in a northern peatland ecosystem. *Boundary-Layer Meteorology* 58(3):289–304.

Verma, S.B., F.G. Ullman, N.J. Shurpali, R.J. Clement, J. Kim, and D.P. Billesbach. 1992b. Micrometeorological measurements of methane and energy fluxes in a Minnesota peatland. *Suo* 43(4–5):285–288.

Vermette, S.J., S.E. Lindberg, and N. Bloom. 1995. Field tests for a regional mercury deposition network—Sampling design and preliminary test results. *Atmospheric Environment* 29(11):1247–1251.

Verry, E.S. 1969. 1968 Vegetation survey of the Marcell Experimental Watersheds. Report GR-W2–61. Grand Rapids, MN: USDA Forest Service.

Verry, E.S. 1972. Effect of an aspen clearcutting on water yield and quality in northern Minnesota. In *Proceedings of a Symposium on Watersheds in Transition*, eds. S.C. Csallany, T.G. McLaughlin, and W.D. Striffler, Fort Collins, CO, June 19–22, 1972. Urbana, IL: American Water Resources Association, pp. 276–284.

Verry, E.S. 1975. Streamflow chemistry and nutrient yields from upland-peatland watersheds in Minnesota. *Ecology* 56(5):1149–1157.

Verry, E.S. 1976. Estimating water yield differences between hardwood and pine forests. Research Paper NC-128. St. Paul, MN: USDA Forest Service.
Verry, E.S. 1984. Microtropography and water table fluctuation in a *Sphagnum* mire. In *Proceedings of the 7th International Peat Congress*. Dublin, Ireland: The Irish National Peat Committee/The International Peat Society, Vol. 2, pp. 21–31.
Verry, E.S. and D.H. Boelter. 1975. The influence of bogs on the distribution of streamflow from small bog-upland watersheds. In *International Symposium on the Hydrology of Marsh-ridden Areas. Proceedings of the Minsk Symposium*, June 1972. Minsk, Byelorussia: UNESCO/International Association of Hydrological Sciences, Vol. 105, pp. 1–11.
Verry, E.S. and A.E. Elling. 1978. Two years necessary for successful natural seeding in nonbrushy black spruce bogs. Research Note NC-229. St. Paul, MN: USDA Forest Service.
Verry, E.S. and D.R. Timmons. 1977. Precipitation nutrients in the open and under two forests in Minnesota. *Canadian Journal of Forest Research* 7(1):112–119.
Verry, E.S. and D.R. Timmons. 1982. Waterborne nutrient flow through an upland-peatland watershed in Minnesota. *Ecology* 63(5):1456–1467.
Weishampel, P., R.K. Kolka, and J.Y. King. 2009. Carbon pools and productivity in a 1-km^2 heterogeneous forest and peatland mosaic in Minnesota, USA. *Forest Ecology and Management* 257(2):747–754.
Wieder, R.K., M. Novák, W.R. Schell, and T. Rhodes. 1994. Rates of peat accumulation over the past 200 years in five *Sphagnum*-dominated peatlands in the United States. *Journal of Paleolimnology* 12(1):35–47.
Wright, H.E. 1972. Quaternary history of Minnesota. In *Geology of Minnesota: A Centennial Volume*, eds. P.K. Sims and G.B. Morey. St. Paul, MN: Minnesota Geological Survey, pp. 515–592.
Yavitt, J.B., C.J. Williams, and R.K. Wieder. 1997. Production of methane and carbon dioxide in peatland ecosystems across North America: Effects of temperature, aeration and organic chemistry of peat. *Geomicrobiology Journal* 14:299–316.
Yavitt, J.B., C.J. Williams, and R.K. Wieder. 2000. Controls on microbial production of methane and carbon dioxide in three *Sphagnum* dominated peatland ecosystems as revealed by a reciprocal field peat transplant experiment. *Geomicrobiology Journal* 17(1):61–88.
Yavitt, J.B., C.J. Williams, and R.K. Wieder. 2005. Soil chemistry versus environmental controls on production of CH_4 and CO_2 in northern peatlands. *European Journal of Soil Science* 56(2):169–178.